U.S. DEPARTMENT OF ENERGY | Office of Science

Basic Research Needs Workshop on Compact Accelerators for Security and Medicine

Tools for the 21st Century

May 6-8, 2019

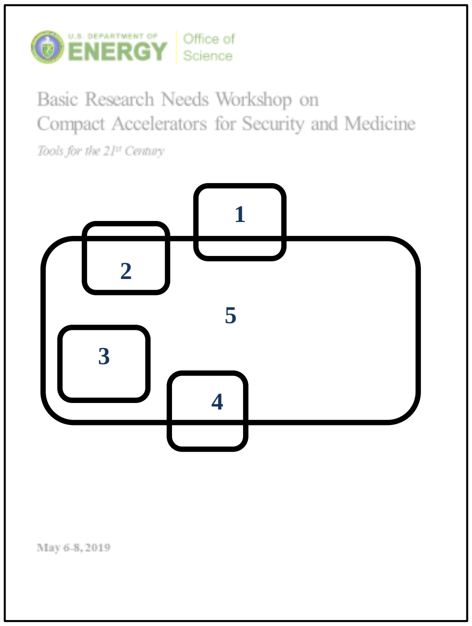
NIH NATIONAL CANCER INSTITUTE

U.S. DEPARTMENT OF HOMELAND SECURITY

NNSA National Nuclear Security Administration

On the cover:

1. Material testing under extreme conditions is essential for predicting the performance of mission-critical components for security. (Image credit: D. Funk, Los Alamos National Laboratory)
2. Additive Manufacturing offers the possibility of "printing" complex parts from a variety of materials. Inspecting finished parts requires a new generation of high brightness x-ray sources. (Image credit: Los Alamos National Laboratory)
3. Mobile VACIS system taking gamma-ray image of a truck. (Image credit: Los Alamos National Laboratory, https://en.wikipedia.org/wiki/Cargo_scanning#/media/File:Mobile_VACIS_Gamma-ray_System.jpeg)
4. Comparative dose distribution in VMAT (volumetric modulated arc therapy) & h-VMAT (hybrid-volumetric modulated arc therapy in bilateral breast cancer radiotherapy (Image credit: S.B. Subramanian, *et al.*, Cureus 2016, 8, 12, e914, Creative Commons License)
5. Electric field lines and modulus of the electric field generated by a (negative) charge first moving at constant speed and then stopping quickly to show the generated *bremsstrahlung* ("braking") radiation. This process is widely used to produce x-rays. (Image credit: Jacopo Bertolotti, 29 October 2018, Creative Commons License https://commons.wikimedia.org/wiki/File:Bremsstrahlung.gif)


U.S. DEPARTMENT OF ENERGY | Office of Science

Basic Research Needs Workshop on Compact Accelerators for Security and Medicine

Tools for the 21st Century

May 6-8, 2019

ACKNOWLEDGEMENT: This workshop was sponsored by the Department of Energy Office of Science, the National Institutes of Health National Cancer Institute, the Department of Homeland Security Countering Weapons of Mass Destruction Office, the Department of Energy Defense Nuclear Nonproliferation Office, and the Department of Defense Office of Naval Research.

Basic Research Needs Workshop on Compact Accelerators for Security and Medicine

Report of the Department of Energy Office of Science Workshop
May 6-8, 2019

Chair
Michael Fazio, SLAC National Accelerator Laboratory

Co-Chairs
George Laramore, University of Washington
Suresh Pillai, Texas A&M University

Panel Leads
Panel 1: Security Application
Ahmed Badruzzaman, Pacific Consultants and Engineers
Harry Martz, Lawrence Livermore National Laboratory

Panel 2: Medical Applications
Jeff Buchsbaum, National Cancer Institute
David Jaffray, MD Anderson Cancer Center
Mary-Keara Boss, Colorado State University

Panel 3: Materials and Sources for Accelerators
Andrea Schmidt, Lawrence Livermore National Laboratory
Jeff Calame, Naval Research Laboratory

Panel 4: Computer Design and Control of Accelerators
Sandra Beidron
John Cary, University of Colorado, Boulder

Panel 5: Engineering for Low-Cost, Rugged Accelerators
Mark Curtin
Arlyn Antolak, Sandia National Laboratory

Panel 6: Detector Technologies
Anna Erickson, Georgia Institute of Technology
Ron Tosh, National Institute of Standards and Technology

Panel 7: Future Accelerator Concepts
Tony Ting, Naval Research Laboratory (retired)
George Neil, Thomas Jefferson National Accelerator Facility (retired)

Plenary Speakers

Norm Coleman, National Cancer Institute
Eric Ford, University of Washington
James S. Welsh, Edwards Hines V. A. Hospital
Ahmed Badruzzaman, Pacific Consultants and Engineers
David Funk, Los Alamos National Laboratory
Shima Shayanfar, General Mills Corporation
Richard Vojtech, Department of Homeland Security

Report Writing

This report was prepared by the workshop chairs, panel leads, and panelists, with input from the workshop observers and broader community. Please see appendices A and B for a full list.

Office of Science Leads

Kramer Akli, Fusion Energy Sciences
Eric Colby, High Energy Physics
Manouchehr Farkhondeh, Nuclear Physics
L. K. Len, High Energy Physics
Eliane Lessner, Basic Energy Sciences

Co-Sponsoring Federal Agency Leads

Lance Garrison, Defense Nuclear Nonproliferation
Donny Hornback, Defense Nuclear Nonproliferation
Keith Jankowski, Department of Homeland Security
Namdoo Moon, Department of Homeland Security
Quentin Saulter, Office of Naval Research
Frederik Tovesson, Defense Nuclear Nonproliferation
Mark Wrobel, Defense Advanced Research Projects Agency

Special Assistance

Administrative
Christie Ashton, High Energy Physics
Queenie Huang, Stanford University
Donna Nevels and ***Daisy Sauceman***, ORISE

Editorial/Publication
Tiffani R. Conner, ORISE

In memorium
Tony Faucette (1971-2019)

Executive Summary

Accelerator-based radiation sources are ubiquitous tools for imaging and treatment in the fields of medicine and security that save millions of lives, impact billions of dollars of commercial goods annually, and fulfill a critical role in US national security. Today's commercially available accelerator technology has fallen significantly behind the state-of-the-art. Advancing and transferring state-of-the-art compact accelerator technology into broader use holds the promise of achieving greater control, power, and automation, which can significantly enhance society's ability to sense and control the world around us.

The Workshop identified a wealth of opportunities to advance these technologies from today's commercial baselines, largely based on half-century old developments, by employing emerging concepts in charged particle acceleration and radiation generation and detection, along with modern ways of thinking about and utilizing developments in systems engineering, advanced materials, supply chain management, manufacturing, advanced computation, energy storage, and artificial intelligence.

Many of the most important applications across security and medicine could be significantly impacted in the near term by moving advanced component and system technologies out of scientific research labs and by developing use-inspired benchtop demonstrators[1] in the next 5 years. On a somewhat longer timescale truly revolutionary impacts could be achieved, such as compact, narrowband coherent x-ray sources for inspecting computer chips, high contrast imaging of nuclear materials, and endoscopically mounted accelerators for cancer therapy.

Electron beam and x-ray technologies can play a major role in reducing the national security threat by eliminating reliance on radioactive isotopes such as ^{60}Co for medical treatment and industrial applications such as medical device sterilization, food processing, and sterile insect technology. Similarly, accelerator technology-based x-ray and neutron sources can have an immediate application for exquisite non-destructive characterization which is the cornerstone of advanced manufacturing, assuring the integrity of electronic supply chains, nuclear non-proliferation treaty verification and stockpile stewardship, and other security applications such as port of entry security, emergency response and radioactive waste storage. The oil and gas industry, which is of immense strategic value to the US, can also benefit from major technological advances in accelerator technology for improved geophysical well logging measurements.

Ionizing radiation has a wide-spread role in treating cancer patients. In developed countries, this is most often delivered with multi-megavolt x-rays from linear accelerators but elsewhere in the world gamma rays from radioactive sources such as ^{60}Co are used. Economic factors such as initial cost of equipment and reliability are important factors in this selection. From a security point of view, it would be advantageous to replace these gamma ray sources with low cost, reliable, self-diagnosing linear accelerator systems that can be operated and maintained by intermediate level personnel. A modular design with readily available and interchangeable components and upgradable software is critical to this.

Currently radiotherapeutic treatments are prescribed, planned, and executed in terms of physical radiation doses. What is needed is to work in terms of biologically effective dose distributions, both for tumors and for the critical organ systems that must be protected that also receive radiation during the treatment process. Commercial accelerators and sensors must be developed to allow the necessary research and modelling to be

---

[1] Specifically, "TRL-4". TRL, or Technology Readiness Level identifies the maturity of a particular technology for a particular purpose. See DOE G 413-3-4A for definitions.

carried out and validated in animal models and then translated into clinical practice. All this requires the dose to be produced, measured, and controlled with high resolution in space and time at the biological site in the patient and even to provide feedback that alters the treatment in real time for optimal effect.

All the above security and medical applications require compact accelerators ranging in power and size from megawatt beams at the several-meter-scale to watt beams at the centimeter-scale along with innovative detector technologies. A common theme emerging across many applications is the need for high average power and efficiency because of the impact on system size, cost, and deployability. As these systems are commercially deployed, they will have stringent requirements in terms of size, capability, power, and robustness. They must be reliable across the globe and must function in relatively harsh conditions. A systems perspective must be applied in prioritizing the R&D required to meet these performance criteria.

A highly diverse brain trust of 112 experts (see Appendices A and B) from national laboratories, academia, US Government Agencies, and industry was assembled for two and a half days that represented the fields of security, medicine, and accelerator and detector technology. The attendees included 22 physicians, veterinarians, and researchers representing the needs of the medical field, and 17 representing security applications on topics ranging from active interrogation and imaging, to medical device and pharmaceutical sterilization, to food safety, to replacement of radioisotopic sources for geophysical measurements, and stockpile stewardship. About 50 attendees, well known for their contributions to the field, represented the relevant aspects accelerator science and technology. Together they identified the common technology advances needed for both security and medical applications. The workshop identified 20 science and technology research themes that form 5 Priority Research Directions that will guide R&D investments for the next decade:

PRD 1: Revolutionize accelerator design to produce modular, interoperable, robust systems
PRD 2: Develop “smart accelerators” that produce expert results in difficult environments
PRD 3: See beyond present technological limits
PRD 4: Control effects and outcomes beyond present technological limits
PRD 5: Revolutionize the size to enable new and emerging applications

The ability to make and measure particles and radiation with exquisite precision in a manner that is robust and economical will change the world we live in at the global, the national, and the personal level. Our children and grandchildren could be cured of cancer by a treatment that is today impossible because we do not have the tools to experimentally understand the radiobiology or even the tools to perform the necessary preclinical, translational, and clinical research. A less appreciated benefit of investment in the area of compact accelerators is that it will put the tools needed for innovative research into the hands of many more researchers, not only in medicine, but also for chemistry, materials, manufacturing, as well as for discovery science, thereby increasing the pace of innovative research and development in these fields. The advanced technologies developed for compact accelerators could well help shape the next generation of billion dollar class machines built for discovery science. Transforming these advanced technologies into straightforward and economical products for security and medicine will have broad benefits to society.

Table of Contents

Acknowledgement of Reviewers

This Basic Research Needs Workshop report was reviewed in draft form by individuals with broad perspectives on the subject areas in this report. Their candid remarks were instrumental in improving the final report.

The Organizing Committee gratefully acknoledges the following individuals for reviewing portions of the draft report and providing constructive comments:

- Bruce Carlsten, Los Alamos National Laboratory
- Janet Conrad, Massachusetts Institute of Technology
- Benedick Fraass, Cedars-Sinai Medical Center

The reviewers were asked to provide comments and suggestions to improve the report, but were not asked to endorse its content. Consequently the appearance of their names here does not necessarily imply endorsement of the contents of this report.

1. Introduction

1.1 Motivation for the Workshop

The Office of High Energy Physics, as the US Department of Energy's (DOE) host office for the Accelerator Stewardship Program, conducted a Basic Research Needs (BRN) workshop to assess the accelerator and detector technology R&D needed to enable high-impact applications of accelerators to address radiation generating source challenges. The purpose of the workshop was to identify critical scientific challenges, fundamental research opportunities, and priority research directions requiring further study. Work in these areas will form the foundation for advances in applying compact accelerator technology to security and medical applications over the next decade and beyond. The workshop examined research that is relevant to the application of accelerator technology, including detector technology, and synergistic application-side research.

Responses to a 2014 Request for Information and subsequent discussions with other federal agencies identified several areas where compact accelerator technology advances could have strong impacts:

1. Replacement of radioisotopic sources by accelerator-based alternatives,
2. Ruggedized low-cost LINACs for global applications,
3. FLASH-radiotherapy (RT) and Very-high energy electron (VHEE) sources for radiotherapy,
4. Source-free brachytherapy (i.e., endoscopic particle accelerators),
5. Portable monochromatic high energy x-ray sources, and
6. Compact neutron generators[2].

In many cases the use of accelerator technology for these applications has performance advantages arising from the adjustability of the radiation characteristics and eliminating the need for radioisotopic radiation sources. However, the barriers to significant commercial deployment of accelerator technology include cost, reliability, regulatory approval, suitable detector technology, wall plug efficiency, portability (in some cases) and market resistance to risk. Many of these applications are currently satisfied by existing, well-proven technologies; however, recent advances in the accelerator technology have lowered the cost and increased the reliability of accelerator systems, warranting a re-examination of the technology use cases.

This BRN workshop identified opportunities and barriers to market adoption in the technology applications noted above. Near-term accelerator technology R&D opportunities were identified that, if developed to TRL-4 in the next 5 years, could enable high-impact solutions for medical, security, and other applications. The workshop also provided a longer-term look-ahead, examing more speculative (low TRL) concepts and approaches that on a time scale of 10-20 years could provide transformative capabilities.

1.2 Prior Workshops and Reports

The Compact Accelerators for Security and Medicine Workshop is the next workshop in a series that began with the October 2009 Symposium and workshop on "Accelerators for America's Future" (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf) sponsored by the DOE Office of High Energy Physics to assess the potential for particle accelerator technology for solving important societal problems beyond Discovery Science. The report from this workshop led to the 2011 "Accelerator R&D Task Force" (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-

---

[2] Restricted in this case to conventional technologies for neutron generation, such as D-T fusion, DPF, and Z-pinch.

stewardship/Report.pdf) that formulated the strategy for the Accelerator Stewardship program that was authorized by Congress in 2014. Since then a series of Requests for Information and topical workshops have occurred that include:

- Ion Beam Therapy Workshop (2013) (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Workshop_on_Ion_Beam_Therapy_Report_Final_R1.pdf)
- Laser Technology for Accelerators (2013) (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Lasers_for_Accelerators_Report_Final.pdf)
- Request for Information on Energy and Environmental Applications of Accelerators (2014) (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/E-ERFI_Responses_All.pdf)
- Energy and Environmental Applications of Accelerators (2015) (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf)

This workshop is intended to assess the technical gaps that must be bridged to improve current and enable future applications in security and medicine and to generate identify the high-impact R&D in the form of Priority Research Directions (PRDs) to achieve these advances.

The workshop draws on significant accumulated experience from the security and medical domains.

Key predecessors in the security domain include the

- Office of Science and Technology Policy (OSTP), National Science and Technology Council (NSTC), and President's Council of Advisors on Science and Technology (PCAST) Reports (e.g., the 2016 "Transitioning from High-Activity Radioactive Sources to Non-Radioisotopic (alternative) Technology" report [https://www.hsdl.org/?view&did=797521])
- National Nuclear Security Administration (NNSA), Department of Homeland Security (DHS), Department of Defense (DOD) reports
- International Atomic Energy Agency (IAEA) documents
- National Academy of Science (NAS) studies (e.g., the 2008 Radiation Source Use and Replacement report)

And in medicine include the

- National Cancer Institute (NCI) reports, and
- IAEA and ICEC (International Cancer Expert Corps) reports.

1.3 Workshop Charge

This Basic Research Needs Workshop was charged to answer seven questions:

Q1) Assess the state of any existing accelerator and non-accelerator-based technologies currently deployed for the application. Document cost and performance criteria to be used as a benchmark for analyzing alternatives based on accelerator technology,

Q2) Document current and proposed Federal and State environment, safety, and health regulatory requirements for the application and identify any issues with regard to these regulations,

Q3) Develop performance criteria for accelerator-based systems for the application. Consider total system costs for production and operation. Assess the potential financial and/or application benefits if the accelerator technology meets the criteria. Document specifications for the accelerator and detector components of the system,

Q4) Identify technical gaps between the current state of the art of accelerator technology compared to the above specifications. This may include accelerator-related technologies such as power supplies or magnet technology,

Q5) Identify synergistic application-side R&D relevant to the application of accelerator technology to security, medical, and other application challenges, paying particular attention to R&D needed to develop detectors to support the application,

Q6) Specify R&D activities needed to bridge technical gaps, and any additional analysis and testing required to validate their use,

Q7) Develop a prioritized list of R&D; estimate rough order-of-magnitude costs to complete required R&D.

The workshop outcome consists of this report, which describes high-impact opportunities for accelerator technology to impact security, medical, and other application challenges, technical and economic gaps requiring further accelerator R&D, and an approximate cost and time scale to accomplish this R&D. The report also includes the outlines of R&D roadmaps for the different technology areas, with particular attention given to technology transfer to industry. Since this is not a FACA report, instead of developing a list of prioritized R&D topics the attendees were asked to gauge the impact that advances in the R&D themes are expected to have on the various mission applications. These are summarized in the Table 5.2.

1.4 Outline of Applications of Accelerator Technology in Security and Medicine

The two agendas for security applications identify how advanced compact accelerator technologies can provide major advantages for non-invasive probing and radiation processing applications that now depend heavily on radioisotopes posing security, safety, and environmental risks:

- New technologies for non-invasive probing for interrogation of geological media, radiography for non-destructive testing (NDT) and evaluation of structures
- Technologies for industrial radiation processing include sterilization of medical devices and pharmaceuticals, food processing (for food safety quality), phytosanitary applications (to prevent the accidental introduction of insects and pests that could threaten agriculture) and equipment to render harmful insects sterile to control their population.

There are three parallel agendas here for the medical application space:

- New technologies to allow the complexity of radiation therapy to be hidden from the user for greater access and quality globally
- New technologies for robust systems (i.e., systems that work at low cost and with very high reliability)
- New technologies to explore the power of radiation in biology (e.g., radiation allowed us to discover cancer stem cell paradigm and there are new emerging frontiers – FLASH-RT, GRID-therapy, microbeam, advanced imaging, etc.)

1.5 Structure of the Report

This report serves to document the outcome of the Basic Research Needs Workshop on Compact Accelerators for Security and Medicine. The five cross-cutting Priority Research Directions identified by the workshop are presented in Chapter 2, followed by specific discussions of the needs for each of the Security (Chapter 3) and Medical (Chapter 4) applications. Appendices E and F provided additional detailed documentation for some of the security applications. Chapter 5 and Appendix G describe 18 distinct technology R&D themes identified, divided into near-term and long-term categories. Chapter 6 provides additional information from the panel discussions.

Chapters 3 and 4 contain a "Roadmap for Development" for each of the security and medical application areas in the near term and the longer term. Each of the Roadmap R&D topics has a rough estimate of cost, time duration, and distribution of effort across labs, universities, and industry. It should be noted that these estimates were done as part of the 2-1/2 day workshop and as such are not the result of a rigorous, detailed analysis. The estimates are simply intended to provide a sense of scale for the required effort and have not been vetted or normalized beyond the workshop discussions.

2. Priority Research Directions

PRD 1: Revolutionize accelerator design to produce modular, interoperable, robust systems

> *When is start-to-end system co-design essential, and when is component optimization appropriate? Can engineering standards be defined to increase reliability and interoperability? How can systems engineering ideas be incorporated into part designs to ease repair, shipping, inventory, manufacturing, and recycling challenges, and to ultimately drive down costs and downtime? Can affordable, ruggedized, compact accelerators be designed that facilitate autonomous dose delivery be built with sufficient modularity, ease of repair, and robustness for use around the world?*

Accelerator systems in use today range from highly specialized facilities used as tools for discovery science to smaller systems for specialized applications that include both security and medicine and are produced in quantities of a few hundred per year. The systems at both ends of the spectrum typically require a highly skilled workforce to operate and maintain them. The systems are relatively fragile and in most cases are stationary installations. They all rely on the availability of a "1st world" infrastructure for maintenance and reliability such that a service technician is readily available on short notice and replacement parts can be obtained in just a few days. There is little or no standardization of components and software across the various manufacturers of these systems. Improvements tend to be incremental. The technologies employed in many cases have been relatively unchanged for decades.

As one starts to examine the evolving needs across the multitude of application areas in security and medicine common themes emerge that have the potential to dramatically impact cost, reliability, performance, and the extent of deployment both geographically across the globe and within the US across industries, the medical delivery system, and research facilities. The themes include:

- Establishing engineering standards that enable multiple sources of components (RF power sources, power supplies, accelerator structures, targets, control systems, diagnostics) and software to be used interchangeably;
- Modularity in design so that when improved components become available that increase capability and reliability they can be easily inserted;
- Employing advanced manufacturing approaches that enable more capable component performance, faster availability to remote locations, and lower cost;
- Eliminating as much as possible the need for highly skilled operators that in many locations are simply not available or affordable.

As an analogy one can take the automobile, which is a relatively high-tech device. There are a handful of major automakers and they produce a multitude of models. If one needs a new alternator, or radiator, or even an engine, one can go to the neighborhood auto parts store and obtain a generic replacement part. If one is less adventurous, the vehicle can be taken to either the dealer or an independent shop for repair. (Even in remote corners of the world people can keep their vehicles operational). A modern vehicle is a complex piece of high-performance machinery with 10s to a hundred microprocessors controlling many functions yet the cost is relatively modest, even at the high end, compared to an accelerator system. Investment made during development leads later on to reduced lifecycle costs.

The challenge before us is this: how do we design, build, and operate systems that are robust, reliable, easy to repair, and do all these things with a workforce that is technically relatively unskilled and on a global scale?

A linear accelerator for medical use is a complex device from an engineering point-of-view. It must deliver a beam to the target reliably and in a verifiable manner. It utilizes many system modules including power supplies, RF sources and waveguides, target assemblies, control systems, communication with electronic medical records and treatment planning software, and patient positioning devices. Currently the hardware and control software are prepackaged by a vendor and sold as a unit, along with a maintenance plan but there is flexibility on the electronic medical record and treatment planning system that can be utilized.

Is it possible to design this system using a modular approach that would allow the user to selectively “build” the accelerator unit to fit their particular needs without sacrificing the compatibility of the various units? For this to be possible, there needs to be a rigorously enforced set of standards for communication and interconnectivity among the various modules which would be a non-trivial achievement given the current economic model. If successful, this would allow for increased competition among suppliers which should ultimately drive down costs and facilitate repairs, particularly in low- and middle-income countries (LMICs). It should also allow for the user to upgrade modules selectively without having to purchase an entire new unit to stay current with evolving technology.

One drawback to this approach is how to ascertain the reason for one module not properly working with another and which vendor is responsible for solving the problem? With a vertically integrated system the user can be reasonably sure that the entire system will work as described in the purchasing specification document. Perhaps a new class of “assembler” companies would evolve to fill this niche but then is that very much different from the current system of a few large corporate suppliers?

It would be appropriate to apply a systems engineering approach to the overall problem while being mindful of the underlying economic realities of implementing any proposed solution.

As we move forward with the R&D to develop advanced components for systems with greatly enhanced performance (such as FLASH-RT) we have the opportunity to “engineer the systems” from the ground up that address all the various constraints and requirements mentioned above and can employ advanced manufacturing techniques for fabrication and assembly.

Comprehensive diagnostics can be integrated so that state of health is constantly assessed and failures can be anticipated and preemptively addressed. Control systems need to be upgradeable as sensors are improved and operating software becomes more sophisticated and capable.

Perhaps we can evolve these systems in a way similar to what has happened with personal computers where a non-computer expert can utilize the computer along with available peripheral devices and software developed and provided by others to do a variety of new tasks that range from creating music to controlling a telescope for astronomy.

PRD 2: Develop "smart" accelerators that produce expert results in difficult environments

> *Can machine learning enable real time energy and dose tailoring to provide the best quality data and outcomes, and provide early detection and self-diagnosis of needed repairs? How "autonomous" can accelerator-based systems be made? Can data science, including artificial intelligence techniques, provide appropriate cybersecurity protection of accelerator control and data storage systems? Can engineering standards be defined to ensure data systems interconnect and interoperate across subsystems and vendors?*

It is critical for the United States to develop the capacity to build advanced data science techniques (such as artificial intelligence (AI) and machine learning (ML)) into scientific infrastructure in a granular, sustainable fashion. It is becoming clear that there is a positive feedback loop between scientific discovery velocity, complexity management, safety, intrusion detection, and artificial intelligence capacity. The capacity to develop "smart", or in this context machine learning devices (MLD), will be a strategic capacity necessary for moving toward the 22nd century. The accelerator-based system presents an ideal laboratory in this context. It can and should serve as a platform for fundamental engineering and science in the translational space that AI can enable to move the country forward and validate the science.

First, we need to develop smart accelerator systems to deliver personalized, contextually rich optimization of care. We know that different types of matter interact with radiation differently and in a time dependent fashion that can potentially be used to develop fingerprints of clinical outcomes or other signature metrics in the case of security applications. The same tissue type (applies to materials of interest as well) has a different response from person to person and from clinical situation to clinical situation. We know that different tissues (kidney versus muscle versus lung) develop different responses to radiation but we lack a real-time capacity to measure and address this and in response to optimize therapy. It would be of immense value if accelerator-based treatment systems could measure changes in tumor stopping power during the entire treatment time, changing dose and dose rate in a rule-based fashion to avoid debilitating side effects and improve the outcome. Presently we only evaluate the patient before the beam is turned on and after it is done, with few exceptions. Collecting real-time dynamic data that is tagged with the metadata that is needed for machine learning (and secures patient-identifiable information) will facilitate the development of better models of normal tissue toxicity or item identification. In this manner, changes from the normal can be better studied and machine learning algorithms can be developed.

Critical to radiation source advances is a need to develop detector processes and systems, from physical detectors to matrices of nanoparticle, self-assembling biosensor detectors given intravascularly to patients to create rich data sets of high dimensionality and robustness. In this context, radiation producing systems could develop patterns of dose delivery designed to selectively trigger certain sensors but not others. Such sensor responses could then be used in real time to adapt the treatment and help enhance tissue radiation response. For example, it may be possible to identify a subset of patients that would benefit from a varied dose rate during treatment either by changing DNA damage repair kinetics, drug susceptibly, or some other combination of factors. The only way to develop this capacity is via data-science-enabled accelerator-based radiation systems.

Second, complex systems fail, and failure has a high price. For patients, it can increase risk of suffering painful and permanent side effects and even death. Failing hardware and software has significant financial risks from lost revenue and downstream repair costs because of unnoticed collateral damage. Having systems that continually self-assess and adjust for dynamic variation in their function is inherently desirable. Downtime can be avoided with such systems and costs can be decreased. One can envision machines that can repair themselves or change operating parameters to compensate for degradation or failures while simultaneously providing a warning to the operators and notifying the manufacturer of the failing subsystems. Failure patterns can be assessed only if machines are properly outfitted with appropriate sensors and self-diagnostic software, and are securely linked so that areas that need improvement can be identified and rapidly corrected. This crosses over into the other PRDs of this report, namely PRD 1. Machines capable of high-level self-diagnosis will lead to increased security on a host of levels as well. A dynamic fingerprint that cannot be predicted by an external actor would yield a higher level of security and could be employed in this context to validate findings and confirm beam identity making it nearly impossible to change a system and not have that change be noticed. Such capabilities would depend upon sophisticated programming and implementation of appropriate network/cybersecurity standards.

Third, like many of today's existing scientific particle accelerators, the machine operation complexity will need to be managed because even properly trained professionals cannot manage more than a few dynamic data streams at one time. These future accelerator systems must be properly designed to include advanced data science attributes (sensors, algorithms, and computational hardware) to accommodate thousands of data streams that the human brain alone cannot process. Given the simultaneous need to train a large number of specialist operators globally given an estimated need of well over 10,000 machines globally, having a data-science-driven machine that makes operation simple and robust will be critical. Preparing the necessary number of trained individuals to address the current and future global need will be a growing challenge.

To put this into context, to operate in the increasing complexity of data-driven cancer treatment, control systems that permit personalized/contextual treatment delivery, and the corresponding mission space for security applications, treatment devices need to move from analog and first generation digital capabilities to fully integrated sensors and a control system based on modern data-science-based techniques. This has been done with military equipment in both autonomous or semi-autonomous (human-in-the-loop) forms, and we have benefitted immensely from that transition. One example is the inherently unstable B-2 bomber, that has benefited from controls enabled through intensive monitoring of systems (sensors) and advanced control and computing architectures. One thing to note is that the B-2's carefully thought-out systems engineering architecture permitted upgrades, such as computing hardware. Similarly, the transition is underway now in transportation with autonomous vehicles. We need to design future accelerator systems to have human-in-the-loop semi-autonomous control and evolve these systems to the point where the equivalent of the "operating system" will be automatically updated like smart phones are today.

PRD 3: See beyond present technological limits

> *Is better inspection and imaging possible with closely integrated, higher-capability sources, detectors, and computing resources? How can detection algorithms be improved in speed and accuracy? How can spectrum agility, bandwidth control, coherence and polarization control be optimally exploited? Can compact new sources of x-rays be developed that offer unprecedented monochromaticity, coherence, and tunability? Can high-fidelity imaging simulations for x-ray sources with a range of energy spreads and energy-integrating detectors be developed?*

Enhanced abilities to "see" within things is of critical and strategic and importance to the United States. Improved capabilities to non-destructively characterize items and products will have long term impacts benefitting quality of life of Americans as well as protecting the homeland. Technologies are needed to result in paradigm-changing capabilities for cancer screening, cancer treatment, medical imaging, food security, food quality and food safety, advanced manufacturing, securing our electronics supply chains, emergency response, cargo screening, border security, nuclear stockpile stewardship, international treaty verification, and nuclear waste management. The same advanced technologies are also needed as tools to enable the research and development that is required to advance the applications enumerated above. For example, the capabilities produced by the advanced technologies make possible preclinical, translational, and clinical research that cannot be done today because present systems cannot deliver desired dose rates, energy spectrum, bandwidth, and ability to shape spectral and temporal parameters of the radiation pulse. On the security side threats can be characterized and then recognized with speed and accuracy that have been elusive with existing technology.

The suite of technologies to achieve these end goals include not only improved and brighter ionizing radiation sources, but also their corresponding detectors, computational tools, algorithms and user interfaces. Therefore, to "see" beyond our current technological limits we need long-term research investments in highly miniaturized compact and brighter radiation sources, improved detectors and improved computational tools for non-destructive characterization (NDC) that allow for modularity but yet allows for integration and cross platform interoperability. Achieving these goals has two great impacts: (1) we put new and highly capable tools into the hands of the researchers that greatly increase the velocity of discovery, and characterization and (2) systems that are deployed as workhorses for applications like threat detection at our borders or food sterilization are much more capable, reliable, and robust thereby significantly enhancing our security and safety.

We need compact, multi-energy (MeV – GeV), intense, monochromatic, machine-based high-energy x-ray sources, and high flux, short pulse neutron sources. Research to make major improvements in detectors that can advance new detector materials, reduce detector cost, improve their scalability and detector operation is needed. Alongside these hardware improvements, there is an overarching research need for improved computational tools for NDC that allows modularity yet cross-platform integration and also allows for expanded simulations. Similar computational tools are needed for full system operations that can emulate the systems real-time.

Present technology imposes limits on the results achieved in cancer treatment by radiation therapy and in the use of radiation to sterilize medical and food products. Beam output in terms of spectrum, dose rate, flux, and stability can be improved through research in source and detector technology and development of an integrated systems approach to accelerator design incorporating high level data-science techniques and tight integration with sensors, controls, analysis, and computational resources. This systems integration approach will simplify operation, reduce the need for highly trained personnel, and increase reliability. Smaller-sized, less expensive units will allow medical care costs to be decreased for those with existing accelerator-based systems and improve availability of advanced imaging to those in need.

PRD 4: Control effects and outcomes beyond present technological limits

> *Are better treatment outcomes, better preclinical results, and better control of pathogens and contaminants possible with closely integrated, higher capability sources, detectors, and computing resources? How can dose rate be increased without sacrificing accuracy or safety? What new sources, detectors, and controls are needed to support ultrahigh dose rates in a clinical setting? What radiobiology must be studied? How can energy spectrum and real time dose control be optimally exploited to reduce collateral dose? How can the flux and efficiency of x-ray sources be increased? Can very low cost, high flux sources be developed?*

New science is pointing toward a need to improve the operational capability of the accelerator system by an order of magnitude, particularly in the domain of dose rate but additionally in the domains of beam monochromaticity with the concurrent need to improve collimation robustness, materials, thermal management engineering, and overall operational advances to allow for these changes. These advances would enable revolutionary patient treatment modalities, more rapid preclinical research, and a more secure food chain, among other outcomes.

Very recent scientific data point to a new radiobiology with very high dose rates (on the order of 100 Gy/s) showing sparing of normal tissue but not tumors. (For comparison, state-of-the-art clinical treatment systems can only deliver 0.16 Gy/s.) Most reported data is for mouse models with some other mammalian data (feline). There is one current case from Europe reported in humans for small skin lesions that seemed to confirm normal tissue sparing without loss of tumor control. The existing data are very early and not collected in a statistically valid fashion. To move this into routine clinical use means having the capacity to treat target volumes which can be up to 30 cm in diameter and can be at a depth of 30 cm. The treatment systems do not exist today that can deliver these dose rates.

If additional work verifies this phenomenon, and the therapy with ultra-high radiation dose rates (FLASH-RT) shows it is possible to decrease normal tissue toxicity very significantly without losing tumor control, cancer therapy will be fundamentally changed for the better. The primary limitation of an effective therapy is its toxicity and to decrease this significantly would make a treatment more useful for patients. The issues needed to understand and confirm these findings are significant and we lack the technical ability to create the radiation dose rates to both validate the research and subsequently to deliver this therapy.

We presently have only a rudimentary understanding of the biology of FLASH and are in the early, discovery phases of this research. To date the data that exist have been achieved using either customized electron beam devices that are modified linear accelerators (target is removed) or are laboratory-based devices with limited radiation field size and energy. We lack the ability to do calibration of dose rate at these very high levels.

Presently, no clinically approved device that is linear accelerator (LINAC) based can deliver this dose rate and it is unclear if the radiation field sizes needed for real tumors (more than a spot from a proton nozzle or a small electron field at shallow depth) are adequate. It is not yet clear that proton FLASH will work as the spots have to move over time and the speed of the delivery may not be the same as whole field rapid delivery.

To achieve a clinical device that is useful, one would need to develop multiple new capabilities.

(1) An improved collimation of electrons and photons is needed that ideally has no moving parts and can address the challenge of high dose rate delivery. Current targets producing x-ray photon

beams cannot handle the heat that such a dose rate would create, and computational and detection components to measure the dose rate and be able to distinguish 50 Gy/s from 51 Gy/s in a robust, valid fashion do not exist. Current methods for collimation use a dynamically moving set of tungsten “teeth” to modulate beam fluence. To achieve high dose rate delivery in a controlled fashion an entirely new way of thinking about how to “aim” such a beam will be needed since nothing we now have can move fast enough if any movement is needed at all. Thus, the current standard method may need to be abandoned to allow for the proper use of ultra-fast dose delivery.

(2) The components of the device will need to be able to cope with the on/off and overall dose rate and the associated step function of heat production. In this context different methods for photon production will need to be explored as “targets” currently cannot address this demand. Electronics will need to be able to calibrate doses at these dose rates very precisely. Local and/or edge computing must be employed for rapid calculations and analysis. A formal misadministration happens when a dose of over or under 10% of prescribed dose is given to a patient. Thus, devices will need to be able to deliver 20 Gy with ideally under a 1% variance while doing such at 100 Gy/s. This will have to be done globally, robustly, affordably and in a fashion that can be validated. A similar set of demands can be envisioned for applications that require precise doses to discover unique characteristics of certain materials in complex, possibly challenging physical environments.

(3) The biology of FLASH needs to be studied in depth and systems need to be developed to allow this to happen that are affordable and laboratory/small animal compatible. Systems that can deliver ultra-fast therapy therefore need to be very small so that they can occupy the spaces currently designed to house animal irradiators with typical less than 1 MeV shielding in place. The cost control and miniaturization issues in the medical arena directly correlate with the technological development needed to deliver accelerator systems for security applications that would be easily transportable and capable of rapid surveys in the appropriate theatre of operation.

(4) Concomitantly, imaging technology must be developed to capture this dose delivery so as to image from it and potentially optimize imaging at this speed – to create a new imaging technology space of ultrahigh speed x-ray imaging with high dose rates. This might allow new methods of treatment and threat identification. As we have learned in computing, electronics, transportation, communication, imaging, and many other technology spaces, significant decreases in the cycle time required from the beginning to the completion of an operation requires new technology developments and ways of thinking, and even completely new concepts of operation (CONOPS). This requires integration of support technologies such as sensors, computational resources, and data-science techniques deployed locally to handle the high data rates. If we are able to synergistically evolve both sensing and radiation source technologies the potential for revolutionary outcomes is enormous in both the medicine and security arenas. These revolutionary outcomes will be possible provided the tools, not available today, are developed to enable the basic and applied research to be done on the required scale.

PRD 5: Revolutionize the size to enable new and emerging applications

> *What are the key components that drive the Size, Weight, and Power requirements for each application? Can accelerator-based systems be miniaturized to function in tight crawl spaces, in pipes, down boreholes, and on the tip of an endoscope? Can systems be engineered to provide accurate performance in hostile environments?*

A revolution in accelerator size has far-reaching implications for more than two-thirds of the research themes identified during the workshop. For some applications such as few-cm-scale endoscopic accelerators needed for medical procedures and radiation sources for well logging that replace radioisotope based sources and fit in a 3-1/2 inch diameter borehole, a revolution in accelerator system size is absolutely essential to render these applications possible at all. For systems that are meters in scale a revolution in size is the difference between a stationary installation and one that is transportable and versatile, or an advanced oncology treatment system (such as FLASH-RT) that can be retrofit into an existing treatment vault or that requires the construction of a new expensive vault and infrastructure. Depending on the application, a reduction in size by a factor of 2-3 for some applications to 1-2 orders of magnitude in others is game-changing and opens up both new applications and new concepts of operation.

Size is influenced by many parameters and if we can change the size significantly we change many aspects of the system. These parameters include the efficiency of (1) the target in converting the particle beam to the radiation of choice, (2) the accelerator structure in coupling the RF or laser energy into the beam to accelerate it, (3) the source that generates the RF or laser energy that provides the power to the accelerator structure, and (4) the power supplies and power modulators that energize these RF or laser power sources using wall-plug AC power. Since efficiency ultimately determines how much waste heat must be dissipated, accelerator system efficiency ultimate determines the size of the facility infrastructure that includes water cooling, air cooling, and HVAC systems. The stark reality is that an efficiency increase in any part of the system ripples back upstream to reduce the overall system requirements and corresponding size, weight, and power (SWaP) in dramatic ways. For example, an increase in target conversion efficiency or accelerator RF to electron beam conversion efficiency results in smaller RF power sources, smaller power supplies and modulators, and less prime power needed from the AC or battery source, along with reduced demand for cooling systems and the power needed to run the cooling systems. It could also mean the difference between using a klystron powered by a high voltage modulator and a solid state RF amplifier system operating at orders of magnitude lower voltage – 10s of volts vs. 10s-100s of kilovolts. Other factors that influence size include the sensitivity and noise performance of the detector system, i.e., the more sensitive the detector, the fewer particles or photons that are needed for sensing/imaging applications. Systems engineering practices need to be employed to develop the ultimate system for each application.

To achieve a revolution in size requires sustained R&D across many of the technical areas encompassed by this Workshop. The technical areas requiring R&D vary depending on the specific application under consideration. A general statement can be made that more efficient power sources, whether RF or laser based, will have a significant impact on SWaP due to the systems-wide impacts. Although a detailed analysis of specific R&D required has not been done for each application several examples can be examined to illustrate the discussion. In a superconducting accelerator system that would be employed for applications at the high average power end of the spectrum such as for medical sterilization or food processing, the ability to operate the accelerator at 4K (Kelvin) instead of 2K has an enormous impact on the size and complexity of the cryogenic system, reducing helium piping by a factor of 3, the size and complexity of the helium refrigeration plant by a factor of 20, and its power consumption by as much as a factor of 5. The R&D required to achieve operation at this higher temperature is exciting and ranges from materials science of superconducting materials and material behavior under loading from intense RF fields to new types of superconducting accelerator architectures that are less complex, with fewer components, and more robust. If operating temperatures considerably above 4K are achieved then the wins are even greater, but the likelihood of this is a decade or more in the future. In a medical system that would be used for FLASH radiation treatment, a much more efficient RF power system would have a big impact on the overall size and portability of the system and ultimately the geographical extent to which the system gets deployed both domestically and globally. A treatment system that can FLASH treat the patient using stored energy (for example in a battery) over a few seconds, and can then use the available electric grid to recharge the battery while setting up the next patient for treatment will dramatically increase the penetration of these systems at the global level. The battery makes the system immune to short-term AC power reliability because a patient can be treated without the fear of power interruption during treatment. Advances in normal conducting accelerator architectures resulting in significant increases in efficiency are already being demonstrated in the laboratory and could likely achieve TRL-4[3] at the system level in the next 3-5 years.

At the other end of the spectrum we have endoscopic accelerators for medicine and NDC in very tight or inaccessible places and radiation sources for well logging that are needed to replace radioisotope based sources and are required to function in very hostile environmental conditions where high temperatures and pressures are the norm. Where accelerator concepts exist for these ultra-compact applications they tend to be no higher than TRL-2 (i.e., technology concept formulated), particularly when one considers the system level maturity. The radiation sources for these applications require major technological breakthroughs and systems engineering on a scale at a level never before considered. Many of the system components needed simply do not exist today, such as laser based devices for neutron and photon sources, compact targets that can dissipate the energies required to generate sufficiently high intensity beams, and drivers that have a high repetition rate with an acceptably small energy spread. In addition to the accelerator itself, numerous subsystems (injectors, beam transport magnets, and power sources) must also be miniaturized. The challenge of producing narrowband MeV x-rays with an accelerator is daunting when compared with ^{60}Co or AmBe sources that are just a few cm in size. Producing narrow band MeV radiation is very challenging now, even in a laboratory environment where SWaP is not a consideration.

---

[3] TRL, or Technology Readiness Level identifies the maturity of a particular technology for a particular purpose. See DOE G 413-3-4A for definitions.

3. Security Applications of Compact Accelerators

3.1 Introduction

Accelerators provide non-isotopic, and thus less risky and in many cases higher performance, sources of ionizing radiation for a variety of applications. The applications can be broadly categorized into non-invasive probing and industrial radiation processing. Non-invasive probing includes interrogation of geological media, radiography for NDT and evaluation of structures, online and bulk analysis in resource industries and probing of cargo and other items for contrabands such as narcotics, special nuclear materials, munitions, etc. Industrial radiation processing can range from sterilization of medical devices and pharmaceuticals, food processing (for assuring food safety and improving food quality), phytosanitary applications (to prevent the accidental introduction of insects and pests that could threaten agriculture), to rendering harmful insects sterile to control their population.

At present, several of these applications are largely reliant on radioisotopes, thereby posing security risks from the possibility of these sources being diverted for nefarious activities. Suitable compact accelerators and associated technologies would prevent or significantly reduce the risk and would likely allow new measurements. Several applications already rely on generator-based technologies, but could benefit from novel compact accelerator technologies. This Chapter will discuss these two groups of application, identify how novel compact accelerator-based technologies can potentially offer significant advantages, and the basic research needed to overcome the associated challenges. For many of the applications wall-plug efficiency is critical because efficiency is a major driver of system size, weight, and power (SWaP), and in some cases drive power availability is problematic.

This Chapter is divided into 5 broad application areas:

1) Non-invasive Probing with Small Sealed Sources, including:
    a. Geological Probing, and
    b. Non-destructive Testing of Structures;

2) Radiography for Non-destructive Characterization, including:
    a. Advanced Manufacturing,
    b. Electronics Supply Chain Assurance,
    c. Nonproliferation and Treaty Verification,
    d. Emergency Response,
    e. Stockpile Stewardship,
    f. Port Security, and
    g. Radioactive Waste Management;
3) Food Processing;
4) Sterile Insect Technology; and
5) Sterilization of Medical Devices and Pharmaceuticals.

After introductory remarks, the Section will address the seven Charge Questions for each of the above-noted application areas. The response to Charge Questions 1, 2, 3, and 5 is provided mainly by the Applications Panels. Responses to Charge Questions 4, 6, and 7 are provided primarily by the Technology Cross-cut teams.

3.2 Application Area 1: Non-invasive Probing with Small Sealed Sources

3.2.1 Introduction

Small sealed sources (^{137}Cs, ^{60}Co, ^{192}Ir, ^{75}Se, ^{241}Am) (up to 300 Ci) are utilized in probing of geological media for well logging, NDT of structures, and on-line and bulk analysis in resource industries. [Ellis-2007; Ellis-1995; ASME-2017; Lim-2005] Since small sealed sources are often mobile and used in remote locations, they pose both security and safety risks. These applications utilize equipment and instruments that have to withstand high temperature and pressure conditions. [Badruzzaman-2015] Integrated detectors and simulation tools are also critically important for well logging and NDT. Geological probing and radiographic NDT of structures are widely utilized around the world and have quite exacting characteristics.

3.2.2 Background and State of Application Development (Q1)

A brief description of these applications is given below. Further details of the application and current state of application development are provided in Appendix E.

Well logging refers to mapping techniques for exploring the subsurface through a well-bore to determine rock and fluid properties of the geological formation surrounding the well. Applications of well logging include determining hydrocarbons accumulation (oil/gas), aquifer identification, fundamental earth science studies, identification of geological fractures, quantification of mineral deposits, and environmental monitoring. [Ellis-2007, Ellis-1995] The major ionizing radiation sources used in well logging are ^{137}Cs emitting 662 keV and Am-241 in a mixture of beryllium (Be) emitting a spectrum of neutrons with an average energy of 4.3 mega-electron-volts (MeV). Devices with Am-Be neutron sources and ^{3}He detectors record interactions with hydrogen nuclei to estimate neutron porosity that allows for locating gas and identification of reservoir rocks.

Non-isotopic source based porosity (NMR (nuclear magnetic resonance), acoustic, D-T (deuterium-tritium) neutron generators, and density from inelastic x-rays with a D-T neutron generator) have been marketed by the industry. National Academy of Sciences had recommended replacement of Am-Be sources by D-T generators of ^{252}Cf sources the ^{137}Cs source was left alone. [NAS-2008] None of the marketed alternatives have proved to be replacement quality. More recent promising developments include a low-energy (>300 keV) x-ray and neutron generators other than D-T. [Simon-2018; Bondarenko-2017; Jurczyk-2018; Badruzzaman-2019] Well logging detectors rely on neutron (^{3}He detectors) and gamma counters and spectrometers. Photon detectors have witnessed significant advances in scintillators. [Roscoe-1991; Radtke-2012] D-T generator tools are beginning to replace Am-Be-based mineralogy tool. [Pemper-2006; Radtke-2012] See Appendix E for more details.

Non-Destructive Testing (NDT) uses industrial radiography (primarily gamma radiography) to inspect the safety and quality of solid metal, welded systems, and structures to assure design quality and operational specifications. [ASME-2017] This could include inspection of pipes, boilers, turbines, and structural supports, for flaws or anomalies. [Twomey-1996] Failures in such systems can be catastrophic.

Gamma radiography utilizes isotopes such as ^{192}Ir (~370 keV), ^{75}Se (~215 keV), ^{60}Co (~1.22 MeV) and ^{169}Yb (~63-308 keV) (206-612 keV) and is useable in extreme temperature conditions and tight spaces. [Shilton-2017] Non-isotopic source-based technologies (such as x-ray radiography) can potentially replace gamma radiography, but require a different form factor as discussed later.

3.2.3 Regulatory Framework (Q2)

In the US, the use of well logging sources is a governed by the Nuclear Regulatory Commission (NRC) under 10 CFR 50, Part 39. [NRC-1987] and subsequent amendments. Gamma radiography cameras and projectors used in NDT utilize sealed sources and their licenses are governed by 10 CFR 34. [e-CFR-2019] The security challenges of small sealed sources in well logging and NDT and its ramifications of NRC regulations for well logging sources are detailed in Appendix E.

3.2.4 Economic Analysis (Q3)

Well logging: Uncertainties in porosity would have significant economic ramifications to the US economy. [Badruzzaman-2009] For example, scaling the data in the reference to the 2017 US reserve of 35 billion barrels (US Energy Information Administration, International Energy Statistics) and assuming a nominal average porosity of 30-pu[4] (likely an optimistic value) with 1-pu porosity uncertainty would lead to US reserves being uncertain by 1.155 barrels. At $70/barrel, this would amount to approximately $80.85 billion. Porosity uncertainties could alter the strategic position of the US in petroleum production. Thus, compact machine-based mono-energetic photon source (~662 keV) would have a significant economic and strategic value to the US economy, but without the risk of a radiological dispersal device (RDD) incident with a ^{137}Cs source and associated cost. NDT of structures is the backbone of the US industrial and technological pre-eminence. Gamma radiography sources used in NDT cost only around $20,000. However, a radiological device incident during NDT could financially ruin the industry and have massive economic ripple effect across the US economy.

3.2.5 Performance Criteria (Q3)

The required performance criteria for generator-based technologies for oil well logging and NDT were developed during the course of the BRN workshop. Details are provided in Appendix E. A summary of these are listed below for the two applications are listed below.

Oil Well Logging

Generators: Radioactivity-free machine sources with following attributes for each measurement type.

> *A radiological device incident during NDT could financially ruin the industry and have massive economic ripple effect across the US economy.*

- Photon source (for density): ~1 MeV, 10^{10}-10^{11} photons/sec initially; 10^{11}-10^{12} photons/sec in longer term
- Neutron generators: > 2 MeV, Am-Be equivalent (15 Ci) or higher activity: $2\text{-}4\text{x}10^{7}$ n/s initially to 10^{9} n/s longer term for porosity; ≥ 4 MeV, 10^{8} n/s initially, 10^{9} n/s longer term for n-gamma spectroscopy for mineralogy
- Accuracy: Density: 0.01 gm/cc; Neutron porosity: 1.5 porosity unit (pu)
- Generator cost: Neutron: $100,000 to $200,000; Density: $200,000
- Form factor: Tool diameter Varied- ~4 in. (mainly) to 1.7 inches; Length < 12 ft. + up to 6 ft. more for generator and electronics
- Reliability: Near-zero generator failure; Require machine learning and data-science-based Predictive Health Management (PHM) systems
- Tolerances: Temp: 150°C - 200°C; Shock: LWD- 1000G, wireline 40G; No active cooling
- Operation: 500-1000 hours initially; > 2000 hours in longer term

---

[4] One pu equals 1% by volume.

- Detectors: Photons- Crystal density 50-100% higher than NaI, energy resolution of $LaBr_3$ or better but without radioactivity in the crystal, and better timing resolution vs. $LaBr_3$ (~1-ns in the longer term). API detectors
- Imaging: Fast-pulse, API; neutron imaging, advanced density imaging

Non-Destructive Testing of Structures

- Sources: x-ray radiography
- Significantly miniaturized. [(4 in. diameter, 9 in. long); lightweight (<50 lbs.)]. Access to crawl spaces (measuring inches)
- Energy output: ~350 KeV (average energy) (~1 MeV Bremstalung) –equivalent to 300 Ci cobalt source
- Power Efficiency: High
- Ruggedness: Extreme. Capable of operating in extreme temperatures (below 0ºC and > 100ºC)
- Detectors and Imaging: High resolution, high-contrast images are critical

3.2.6 Technical Gaps (Q4)

Some key limitations (technical gaps) that are required to reduce security risks in well logging and NDT by transitioning to non-isotopic sources are listed in the following table. This is a precursor to the specific R&D topics and research roadmap presented later. Appendix E provides a detailed examination of the current technical gaps and preferred technical solutions.

Requirement	**Present Technical Limitation/Need**
Accelerator based replacement of neutron Am-Be sources in well logging	• D-T generator: lower porosity sensitivity, presence of tritium and designation as dual-use technology/hardening against tritium leak, advanced interpretation. D-T generator will meet the initially desired generator yields of $\geq 10^7$ to 10^8 neutrons/sec. Will need R&D to enhance to desired higher yield with a compact accelerator • D-D generator: Unacceptably low nominal neutron yield and shallower depth of investigation/ higher power design needed to increase neutron yield. • D-^{7}Li: Unacceptably low nominal neutron yield and high-temp intolerant target/ higher power design and hardened target • (α-Be) DPF: A major challenge in general; a grand challenge if below 200 Mev desired/ Long-term R&D • Long-term: Short (~1 ns) neutron pulses using laser based sources; ability for neutron imaging • Time of flight (ToF) measurements in well logging with extremely short (~1 ns) pulses. • High gradient accelerators with compact drive power (laser or THz) fed through a tethering structure downhole for logging or NDT confined spaces augmented high-repetition rate laser drivers being developed can be of interest in the long term.
Accelerator-based replacements for compact sealed gamma sources	• Current S- and C-band accelerators-Size, weight and their RF electronics drivers; poor conversion efficiency from beam power to x-ray production, survivability in harsh operating conditions/ Smaller X-band accelerators and novel klystrons, RF electronics at higher frequency could help but would be challenging

	• High gradient accelerators merit examination: Mono-energetic high-energy x-ray source, at the head of the boring or inspection device preferable for well logging and NDT. Superconducting radiofrequency (SRF) based beam drivers to power the SWFA structures needed.
Form factors for machine-based radiographic sources for well logging and NDT	• Current fusion generators will fit. Form factor-fit for DPF is not certain. High-gradient accelerators will be too large without the advances suggested in Appendix E.
Detectors	• Neutrons: ^{3}He gives total neutron counts/Neutron spectrum measurement would be desirable. Diamond-based detectors developed will be of interest but will be expensive. • Photon detectors limited to 25 ns resolution ($LaBr_3$)/Need resolution below 10 ns • $LaBr_3$ contains radioactivity preventing use in natural GR detection and requiring correction in other applications. • Need to withstand harsh environmental conditions (up to 200^{o}C). Silicone-based organic scintillators • Photon imaging is rudimentary/Needs improved resolution • Neutron imaging nonexistent/Develop API imaging for directional information and n-gamma photon imaging for rock and fluid parameters • Neutron and API imaging are of interest
Enhancement of photon detection with scintillation	• High density, high light yield, fast time when paired with a pulsed source.
Engineering	• <500W power supplies. 1.7 in.-3.5 in. diameter device x <12ft. length. Currently, no active cooling. High operational reliability in downhole environment (temperature, pressure, shock, vibration). High-temperature, rugged detectors in well logging tools. Fast, high-temperature electronics (FPGAs, processors, memory) for well logging. High-temperature HV generator components (HVHT diodes, resistors, capacitors) for well logging. • NDT requires portable ruggedness, capability to operate in tight spaces and extreme environments (temperature and space), long (12-15 years) lifetime
Diagnostic and computational capabilities	• System diagnostics and fault detection required at the minimum. Machine learning and data science-based fault detection and machine protection as predictive health monitoring needed. • Simulations: Need improved particle tracking algorithms; more complete cross-section libraries for better spectroscopy; dynamic visualization of radiation transport.

3.2.7 Synergistic Application –Side R&D (Q5)

Synergistic application and discovery research are needed for developing ruggedized, high flux compact/miniaturized accelerators. Similarly, research in high temperature pulse height discriminating crystal materials (for spectroscopy and simultaneous neutron detection), rugged photomultiplier tubes (PMT) and/or solid state detectors to replace the current state of the art, ^{3}He tube, with neutron detection is needed. Neutron imaging and gamma imaging will significantly enhance well logging and NDT of structures applications. Crystals faster than 25 nanoseconds ($LaBr_3$) decay for finer time-energy spectra would allow extraction of additional information

Development of fast, high-temperature electronics components (field-programmable gate arrays (FPGA), processors, memory) for downhole Pulse Height Analysis and other detector related data acquisition applications and generator controls and development of high temperature, high voltage generator components, such as high-voltage high-temperature (HVHT) diodes, resistors and capacitors would add much synergy across multiple applications. Advances in simulation techniques will allow for optimizations and failure analysis. Ability for real-time dynamic visualizations of radiation transport and detector response will significantly advance well logging and NDT of structures. Research in diagnostic systems for accelerators and detector reliability is critically important for off-shore well logging and NDT of structures. Similarly, research in thermal insulation and/or electronically cooled systems for radiation- and temperature-hardened solid state electronics is critically important. Predictive health management with AI would benefit across applications.

3.2.8 Required R&D to Bridge Technical Gaps (Q6)

The near and long-term R&D areas enumerated below are intended to illustrate the possibilities identified by the Workshop, however the various topics and approaches are not prioritized.

Accelerator Technology Development	
Accelerator-based replacements for compact sealed neutron sources:	
Near Term R&D (1-5 Years)	Longer Term R&D (> 3 years)
Development of compact commercial D-T sources that are cost competitive with radiological sources	Develop associated-particle and coincidence gamma time-of-flight measurements systems to enable spatial characterization for downhole imaging
Rugged tool-specific high-temp components	Extremely short pulse neutron generators or new source-detector concepts
2.5 MeV miniaturized/compact D-D source $\geq 10^7$ n/s	
Small-diameter D-T generator platform with agnostic detector integration	Tritium-leakage mitigation technology for use in D-T generators
D-^{7}Li generator with 10^7-10^8 n/s neutron yield	Technology to address the risk from dual-use nature of D-T generators
Developments in compact neutron source power supply, electrostatic accelerator, and ion source technology	

Accelerator-based replacements for compact sealed gamma ray sources	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
New accelerator configurations, Robust accelerator structures and cathodes/guns, Improved passive heat transfer methods, Higher frequency ultra-compact accelerating structures (in particular dielectric-loaded structures), New profoundly ultra-compact vacuum electronic RF sources at higher frequencies ($\geq$ 20 GHz)	Compact multi-stage hybrid structures capable of accelerating a beam, directly producing x-ray or gamma-like radiation in an exotic, ultra-compact interaction structure, and decelerating the used beam allowing RF energy recycling
Miniaturized (4-9 in) light weight (< 50 lbs.) x-ray sources for NDT of structures	
Solid-state driven accelerators with new types of high temperature-compatible wide-bandgap microwave transistors	Demonstration of a working accelerator in the desired form factor and required total beam power using such high temperature transistors as the RF sources
Alternative methods of creating gamma rays by induced nuclear reactions in targets; New types of higher efficiency electron beam to photon conversion targets; Create high voltages in extremely compact	Novel beam-wave or beam-material interaction mechanisms for more directly producing x-rays from electron beams

packages for new types of higher efficiency accelerators and particle beam to photon conversion	
Adapt additive manufacturing concepts into the accelerator and RF source fabrication, including depositing thin-films onto AM-structures for high-Q cavity and low-sparking surface finish	Incorporate all the various component advancements into a completely working instrument with the desired form factor and full desired ruggedness

High Gradient Accelerators – LWFA	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
Demonstrate performance and stability of electron beams at 1-10 MeV from a LWFA using mJ few fs laser pulses	Integration of broadening and self-compression in transport system
Few-cycle laser broadening and compression at few mJ energies, using COTS 7mJ-class 30 fs drive laser at kHz repetition rates	Miniaturize laser focusing, gas target system and heat management for accelerator head at cm then at mm scale
Flexible laser transport and dispersion management to deliver compressed few cycle pulse to LWFA	

High Gradient THz Accelerators for compact x-ray or mono-energetic high energy x-ray sources	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
High accuracy THz accelerator structures of a few 10's of cm or shorter length; Electron-beam THz source (50% efficient)	THz electron injector; Improved laser-driven THz sources
MW-class switches for power distribution and RF compression	
Laser-driven THz source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ)	System integration. Performance and stability development

LWFAs for mono-energetic high energy x-ray sources	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
kHz laser drivers at few hundred mJ/10fs scale to enable average flux	
Compact high gradient LWFA at ~20-100 MeV energies	Controlled Thomson/Compton scattering from LWFA beam to generate mono-energetic photon beams of controllable energy and direction; Precision control of electron and scattering laser beams. Deceleration of electrons after photon production to mitigate undesired bremsstrahlung

SWFA/PWFAs for mono-energetic high energy x-ray sources	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
Thermally managed dielectric or metallic structures capable of high gradient with MHz repetition rate	
Collinear beam-driven acceleration technology with improved efficiency: control of temporal shape, formation and transport of drive and witness bunches	High charge electron drive beams at ~10 MeV from an SRF photo-injector followed by SRF booster cavity. Follow with system integration, performance and stability development

Detectors	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)

Lowering the cost of the detector materials, Dopants to improve light generation and spectroscopy	Detection and signature development: rastering, resolution, material distinction
Materials for alternatives to ^{3}He for neutron detection	Materials for Neutron detectors to resolve, fast, epithermal and thermal neutrons
Radioactivity-free scintillators with at least the energy and timing resolution of $LaBr_3$	Radioactivity-free photon detectors with 1-2 nanosecond timing resolution with energy resolution of $LaBr_3$
Better resolution x-ray-based imaging hardware for NDT of structures	Neutron, API, and higher resolution gamma imaging hardware for well logging

Engineering	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
Engineering of accelerating structures, sub-component, control systems, and detectors for NDT	Engineering and manufacturing of sources, detectors, electronics, etc., and assembling them in full system a for well logging

Diagnostic and Computational Capabilities	
Near Term R&D (1-5 Years)	Longer Term R&D (> 5 Years)
Making the Monte Carlo codes more flexible and with easier setup and visualization.	Develop environmentally-hardened, fast-solid state electronics for on-board computing
Incorporate ML/AI analysis algorithms	Develop integrated control system architecture with ML training and AI decision making logic
Provide downloadable, open-source libraries that can be used directly by Monte Carlo codes	Incorporate advanced, dynamic visualization techniques in applications for generator/detector technology
	Full nuclear cross-section libraries for spectroscopy and API simulation
High resolution gamma imaging software for rocks and for structures	Neutron imaging software for API and rock imaging

3.2.9 Roadmap for Development (Q7)[5]

Accelerator Technology Development

Accelerator-based replacements for compact sealed neutron sources:
Near Term: *Develop compact commercial D-T sources that are cost competitive with radiological sources*. *Develop miniature form factor small D-T generators*, 2 years, $2 to $3 million. *Tool-specific high-temp components and ruggedization needed*, 2 years, $2 to $3 million. *Small-diameter D-T generator platform with agnostic detector integration*, 2 years, $2 to $3 million. *2.5 MeV miniaturized/compact D-D source with* 10^7-10^8 *n/s*, 2 years, $2 to $3 million. *D-*^{7}*Li generator with 100-fold neutron output*, 2 years $2 to $3 million. *Developments in compact neutron source power supply, electrostatic accelerator, and ion source technology* 2-3 years, $3 to $4 million.
Longer Term: *Develop associated-particle and coincidence gamma time-of-flight measurements systems to enable spatial characterization for downhole imaging, extremely short pulse neutron generators or new source-detector concepts*, 5 years, $2 to $3 million. *Miniaturized and ruggedized neutron generators with yield of* 10^9 *n/s: Cost estimate TBD. Develop zero tritium leakage technology for D-T generators: cost estimate TBD. Technology to mitigate dual-use nature of D-T generators: Cost estimate TBD.*

Accelerator-based replacements for compact sealed gamma ray sources:
Near Term: *Robust accelerator structures and cathodes/guns, university, 2 years $2 to $4* million followed by industry research 2 years, $2 to $4 million, Higher frequency ultra-compact accelerating

---

[5] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

structures (in particular dielectric-loaded structures), national accelerator facility or national lab, 4 years, $10 to $15 million. *Develop new profoundly ultra-compact vacuum electronic RF sources at higher frequencies (≥ 20 GHz),* university, 3 years, $3 million followed by industry 2 years, $3 million. *Improved passive heat transfer methods*, university, $1 to $1.5 million followed by industry research, 2 years, $1 to $1.5 million. *Solid-state driven accelerators with new types of high temperature-compatible wide-bandgap microwave transistors,* university, 3 years, $2 to $4 million followed by industry research $4 to $10 million, 2 years. *Adapt additive manufacturing concepts into the accelerator and RF source fabrication, including depositing thin-films onto AM-structures for high-Q cavity and low-sparking surface finish,* industry and university, 3-4 years, $10 to $15 million. *Alternative methods of creating gamma rays by induced nuclear reactions in targets;* university-industry-national labs partnership, 2-4 years, $2 to $6 million. *New types of higher efficiency electron beam to photon conversion targets*, university, 3-4 years, $3 to $8 million. *Create high voltages in extremely compact packages for new types of higher efficiency particle beam to photon conversion,* industry or national lab, 2-4 years, $2 to $4 million.
Longer Term: *Demonstration of a working accelerator using high temperature transistors as the RF sources in the desired form factor and required total beam power*, 3 years beyond near-term efforts, $5 to $12 million. *Incorporate the remaining component advancements into a completely working instrument with the desired form factor and full desired ruggedness*, industry, 5 years beyond near-term efforts, $5 to $10 million. *Novel beam-wave or beam-material interaction mechanisms for more directly producing x-rays from electron beams*, university, 5 years, $5 to $10 million in association with National lab and industry research 3-4 years, $15 to $25 million. *Compact multi-stage hybrid structures capable of accelerating a beam, directly producing x-ray or gamma-like radiation in an exotic, ultra-compact interaction structure, and decelerating the used beam allowing RF energy recycling,* 10+ years, several 10's of million dollars investment.

Future Accelerator Concepts

"Future concepts" are low TRL approaches that are not expected to reach the maturity of laboratory benchtop demonstration (TRL 4) in 5 years, but on a longer time scale could prove to have high impact if the R&D is fruitful. The approaches below are not prioritized, but are cited as possibilities.

LWFA accelerators

Near Term: *Demonstrate performance and stability of electron beams at 1-10 MeV from a LWFA using mJ few fs laser pulses*: 2 years, $2 million. *Few-cycle laser broadening and compression at few mJ energies, using COTS 7mJ-class 30 fs drive laser at kHz repetition rates*. 2 years, $1 million. *Flexible laser transport and dispersion management to deliver compressed few cycle pulse to LWFA*, 3 years, $2 million.
Longer Term, *Integration of broadening and self-compression in transport system*. *Miniaturize laser focusing, gas target system and heat management for accelerator head at cm then at mm scale*. 4-5 years, $5 million.

High gradient THz accelerators for compact x-ray or mono-energetic high energy x-ray sources

Near Term: *High accuracy THz accelerator structures of a few 10's of cm or shorter length*, 2 years, $1 million. *Electron-beam THz source* (50% efficient) 5 years, $5 million. *MW-class switches for power distribution and RF compression*. 2 years, $1 million. *Laser-driven THz source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ)*. 3 years, $3 million.
Longer Term: *THz electron injectors*. 4 years, $3 million. Improved laser-driven THz sources, 4 years, $3-5 million. *System integration*. *Performance and stability development*. 5 years, $5 million.

LWFA accelerators for mono-energetic high energy x-ray sources

Near Term: *Compact high gradient LWFA at ~20-100 MeV energies*, 4 years, $6 million. *kHz laser drivers at few hundred mJ/10fs scale to enable average flux:* 5 years, $15 million.
Longer Term: *Controlled Thomson/Compton scattering to generate mono-energetic photon beams of controllable energy and direction.* 5 years, $3 million. *Precision shaping and control of the laser and accelerator is needed for photon beam energy spread, tuning and stability*. 5 years, $5 million. *Deceleration of electrons after photon production to mitigate undesired bremsstrahlung*. 5 years, $3 million.

SWFA/PWFA accelerators for mono-energetic high energy x-ray sources

Near Term: *Collinear beam-driven acceleration technology with improved efficiency: control of temporal shape, formation and transport of drive and witness bunches*; 2 years, $2 million. *Thermally managed dielectric or metallic structures capable of high gradient with MHz-scale repetition rate*. 5 years, $5 million.
Longer Term: *High charge electron drive beams at ~10 MeV from an SRF photoinjector followed by SRF booster cavity*; 5 years, $5 million. *System integration. Performance and stability development*. 3 years, $5 million.

Detector Technology Development

In the next 3-5 years, the main priority for the detector R&D development is lowering the cost of the detector materials while maintaining the desired performance. Silicon-based neutron-gamma detectors are based on low-cost materials, but will require a significant investment into light readout (possibly via silicon photomultipliers (SiPM) or similar technologies) as well as dopants to improve light generation and spectroscopy. Detectors based on wide-ban semiconductors can provide an option for high-temperature operation of detectors, but their relatively high cost needs to be addressed.

Detectors

Near Term: 3-5 years. *Lowering the cost of the detector materials, Dopants to improve light generation and spectroscopy*
Neutrons: Alternative to ^{3}He
Radioactivity-free scintillators with performance similar to $LaBr_3$
Longer Term: *Detection and signature development: rastering, resolution, material distinction*. 3 years, $5 million
Neutron detectors with fast, epithermal and thermal neutron discrimination capability
Radioactivity-free photon detectors with 1-2 ns timing resolution and $LaBr_3$ *equivalent energy discrimination*
Neutron imaging hardware for use with compact accelerators

Engineering

Near Term: *Engineering and manufacturing of accelerating structures, sub-component, control systems, and detectors for NDT*, 3-5 years, $5 to $10 million.
Longer Term: *Engineering and manufacturing of sources, detectors, electronics, etc., and assembling them in a full system for well logging*, 5-10 years, $5 to $10 million (can leverage some tasks from NDT).

Design, Computational, and Controls Capabilities

Near Term: *Making the Monte Carlo codes more flexible and with easier setup and visualization*. 3 years, $500,000/year. *Incorporate ML/AI analysis algorithms*. Multi-year, $10 million. *Provide downloadable, open-source libraries that can be used directly by Monte Carlo codes*, multi-year, $400,000/year. Incorporate PHM algorithm to go with PHM hardware.

Long Term: (Hardware): *Develop environmentally-hardened, fast-solid state electronics for on-board computing*. $10 million. *Develop integrated control system architecture with ML training and AI decision making logic,* $10 million. (Simulation): *Incorporate advanced, dynamic visualization techniques in applications for generator/detector technology, full nuclear cross-section libraries for spectroscopy and API simulation*. (Visualization): Working with data visualization experts in the DOE national laboratory complex and in academia, several millions of dollars investment. Incorporate PHM diagnostic hardware that is miniaturized and ruggedized.

3.3 Application Area 2: Nondestructive Characterization

3.3.1 Introduction

Non-Destructive Characterization involves the use of electromagnetic energy (e.g., x-rays), particles (e.g., neutrons), and/or acoustic probes to measure properties of objects without adversely affecting their functionality. There are several NDC applications that need improved x-ray, high-energy x-ray, and neutron sources, as well as detectors and computational capability. The workshop identified 7 critically important NDC application areas:

1. Advanced Manufacturing
2. Electronics Supply Chain Assurance
3. Nonproliferation and Treaty Verification
4. Emergency Response
5. Stockpile Stewardship
6. Port Security
7. Radioactive Waste Management

A consistent theme across many application areas is the need for average power and increased wall-plug efficiency.

3.3.2 Background and State of Application Development (Q1)

A brief descriptive background and selected highlights of present status and needs are given below for each NDC application.

Advanced manufacturing (AM) methods combine microstructural design, using flexure and screw theory as well as topology optimization, with advanced additive micro- and nano-manufacturing techniques. [Spadaccini-2015] These methods create new material systems (including mechanical metamaterials) with previously unachievable property combinations, correspondingly requiring high-spatial resolution NDC to ensure performance. Manufacturing techniques include projection micro-stereolithography (PμSL), direct ink writing (DIW), and electrophoretic deposition (EPD). These methods are used to generate three-dimensional micro- and nano-scale architectures with multiple constituent materials in the same structure.

Present metrology methods for traditional and advanced manufactured materials include:

- Point scans to create a structural surface image (Coordinate measurement machines – CMM).
  - Advantages: High resolution, handles complex external geometries
  - Disadvantages: Slow, cannot measure inaccessible interior surfaces
- 2D area scans (laser and white light)
  - Advantages: Fast, reasonable spatial resolution
  - Disadvantages: Geometrical restrictions, cannot measure inaccessible interior surfaces
- 3D volume data (CT, ultrasound)
  - Advantages: Fast, 3D surfaces including interior, material properties; spatial resolution
  - Disadvantages: Resolution limited by detectors and source; artifacts; identifying surfaces

Current NDC methods are not able to meet most AM needs; hence advancements are needed in NDC technologies. [MForesight-2018] Given that AM parts are complex 3D structures, x-ray computed tomography (CT) has been one of the most heavily applied NDC methods to characterize AM parts and assemblies [Thompson-2016] but CT has limitations. Increased spatial resolution, penetration, and material discrimination are among the needs.

Electronics supply chain assurance will be an increasingly challenging NDC application in the future. The United States does not have a comprehensive electronics supply chain assurance program to certify that parts incorporated into US critical systems do not contain elements that are fabricated under untrusted conditions. The DOD Joint Federated Assurance Center (JFAC) is concerned with malicious parties gaining control of systems or information through the supply chain. Electronics NDC requires spatial resolutions from ~10 nm (for integrated circuits) up to ~1 µm (for printed circuit boards). X-ray CT using a synchrotron source has been demonstrated for inspecting integrated circuits [Bajura-2011], but new techniques and are needed with improved spatial resolution, larger fields of view, and higher throughput rates.

For printed circuit board inspection, industrial x-ray CT systems with 10-200 µm spatial resolution are currently commercially available. These CT systems use ~160 kV bremsstrahlung (polyenergetic) sources and flat panel detectors with pixel sizes ranging from 100 to 200 µm. Currently, integrated circuits are mainly inspected by destructive techniques that involve delayering and imaging by scanning electron microscopes. [Zhang-2019] There is a need for increased spatial resolution on order of 5-50 nm and decreased image reconstruction artifacts such as streaks and bleed through from other layers for NDC of ICs. Researchers are exploring x-ray nano-CT systems (including emerging commercial systems) and ptychography. [Rodenburg-2007; Maiden-2012; Bajura-2011; Holler-2017; Li-2019a]

Electronics supply chain assurance would benefit from development of advanced x-ray sources (produced by compact accelerators), detectors, and development of algorithms for preprocessing, reconstructing, and post-processing data for conversion to a net list, etc. Bright, tunable monochromatic x-ray sources, efficient high-spatial-resolution detectors, and improved algorithms could help overcome the current limitations of CT for this application.

Nonproliferation and treaty verification are areas in which advanced, active NDC is critical. Examples include screening and interdiction (e.g., at nuclear facilities or foreign ports), detection of hidden special nuclear material, treaty and weapon dismantlement verification, “fingerprinting” of individual weapons, and safeguards including fuel cask content verification. There is strong overlap with the port security applications detailed below for identification of unauthorized nuclear material in cargo, with Emergency Response, and with stockpile applications. Due to the thick targets that are of interest (i.e., where passive radiation signatures are not effective), use of high energy x-rays in the 1-9 MeV range is required. Spatial resolution at cm-scale is needed, and in many cases finer spatial resolution would be beneficial. Some information on material composition can be derived from dual-energy x-ray radiography using the contrast in material cross sections versus energy. [Martz-2017b] Specific identification of nuclear material via photofission and nuclear resonance fluorescence (NRF) signatures is of interest but not routinely fielded due to dose and signal specificity issues. NRF additionally requires either high dose or very narrow energy spread (below 1% and preferably more like 0.1%).

Accelerator-driven active interrogation methods could offer essential capabilities to detection and characterization across a broad range of nonproliferation and treaty verification applications where shielding or geometry limit the usefulness of passive signatures. Many needs are presently unmet, since current technologies largely rely on bremsstrahlung photons that involve a broad energy spread and cannot generate a sufficiently specific signature, and they also cause an unacceptable dose to targets and/or surroundings. Surveys of applications [Geddes-2017; Martz-2017b; Ledoux-2018; Melton-2015] have assessed the gaps in current performance and indicate potential for mono-energetic high energy x-ray photon sources (MPS) to address current gaps, some of which overlap with Stockpile Stewardship needs. In many cases, mono-energetic photons and neutrons offer complementary sensitivity, and additional benefit is available using both sources. [Cutmore-2010; Lehmann-2003] Overall, while highly promising MPS and/or neutron methods have been demonstrated at scientific facilities [Geddes-2017], to be useful, they are not presently feasible for widespread use because the required accelerator systems are too large using conventional technology.

Emergency response teams use nondestructive characterization techniques such as x-ray radiography to inspect suspicious packages or parked vehicles. Several portable x-ray sources are currently available, ranging from battery-powered x-ray tubes with energies up to 350 keV (e.g., from MinXray and Golden Engineering) to betatron sources (e.g., from JME) with energies up to 2 MeV.

Emergency responders need improved portable, rugged equipment that can be quickly fielded to provide critical information regarding potential threats and to render them safe. In some cases, x-ray systems above 1 MeV or neutron systems are required to inspect objects embedded in metal or other highly-attenuating material. Large-area x-ray and neutron detectors are needed to quickly image large objects without the need for repositioning and acquiring multiple exposures. Improved signal and image processing capabilities are needed for in-field decision making.

Stockpile stewardship is part of the National Nuclear Security Administration (NNSA) mission; it requires static and dynamic characterization using x-ray and neutrons. Presently, this type of work is done on a variety of ‘large platforms,’ most notably OMEGA at Rochester, the Z-machine at Sandia, and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). Additional resources for Radiation Effects Analysis include the Weapons Neutron Research beamlines at LANSCE (Los Alamos Neutron Science Center) [LANL-2019], and the Hermes III and Saturn platforms at Sandia National Laboratories. Sandia National Laboratories is proposing the Combined Radiation Environments Survivability Test (CREST). [NNSA-SIR-2019] All these are extremely large facilities. Rapid characterization of production components utilizing neutron and x-ray imaging, including CT, is needed to facilitate product qualification. Such systems would be applied to pit tubes, detonators, valves, pits, etc. Presently, for pit inspection, LINACs, and microtrons (room-size 10-20 MeV accelerators) are utilized, [CoLOSSISweb-2010; SandTR-2009] and characterization is time-consuming, often taking a day to a week.

Key to improving these capabilities is the development of bright, compact, low-to-modest energy x-ray sources. Likewise, the development of compact, bright, 10s of keV coherent x-ray sources for materials science, material production (Materials for the Future) and High Energy Density Physics studies will enable increased performance and capabilities. The development of robust compact sources of monochromatic 3-4 MeV x-rays would have significant impact in the area of Radiographic Characterization (Dynamic and Static). The development of bright pulsed neutron sources would also significantly impact Radiographic Characterization, as neutrons offer complementary data to x-ray radiographic techniques, which will improve the overall understanding of weapons systems and their performance. [SSMP-2018]

Port security, i.e., security at airports as well as at land/sea ports of entry, is another application area of great importance. Low-energy (<200 keV) x-ray radiography and CT screening technologies are deployed at airports to inspect carry-on and checked luggage; typically conventional dc x-ray tubes are used as the sources. These x-ray systems are used to determine density and sometimes elemental composition of items within luggage. [Champley-2019] For inspecting cargo at land and seaports, high-energy x-ray radiography (at 3-9 MeV) is currently the leading method due to its ability to penetrate most cargos. The x-rays are produced by broad spectrum bremsstrahlung from electrons accelerated by LINACs, typically powered by magnetrons for lower cost and are limited to 800 pulses per second with duty factors below 0.1%. The low duty factor is not a problem for standard radiography, but it limits spectroscopic applications since single-photon counting is adversely affected by pile-up (when multiple photons hit a detector element within a short time interval). Betatrons produce a fraction of the output of LINACs and also rely on bremsstrahlung, but they can be used for low-dose applications like mobile scanners. They are also less expensive than LINACs. The main drawbacks of betatrons are reliability, low duty cycle, short life, and required extra shielding. Wide-band bremsstrahlung x-ray sources require high doses to penetrate cargo since many of the x-rays they produce are of lower energy and are preferentially attenuated. Narrower-band sources would not suffer from this problem and penetration and material discrimination can be achieved with lower doses.

Reduced dose, increased penetration x-ray sources, having better spatial resolution from reduced source spot size and detector pixel sizes, as well as better automated threat detection algorithms of material composition and structure, are all needed. Port security applications also need more intense sources, more narrowband sources, more efficient detectors, and fast high performance automated threat detection. Additional emerging needs include high energy MPSs of 7-10 MeV for detection of nuclear materials in cargo, and neutron-based screening methods.

Radioactive waste management encompasses the by-products industries like mining, defense, medicine, scientific research, and nuclear power generation. NDC methods for radioactive waste management, referred to as nondestructive assay for radioactive waste barrels, has been developed over the past 20 years. [Croft-2006] The radioactive waste can remain radioactive for few months, years, or even hundreds or thousands of years and the level of radioactivity can vary. In general, radioactive waste classes or types are based on the waste's origin [IEER-2012], not on physical and chemical properties of the waste that could determine its safe management. Accordingly, advancements in NDC are needed to identify the constituents and quantify them.

Transmission nuclear resonance fluorescence and has been identified [Shizuma-2012] as a most promising method to more precisely assay thick samples of shielded fissile material of unknown composition, but is not presently available due to photon source constraints. Large fixed-facility experiments indicate narrow-band MPSs can enable such signatures. However, these sources are not commercially available and the required accelerator systems are too large using conventional technology.

3.3.3 Regulatory Framework (Q2)

New compact accelerator-based radiation sources for NDC would be expected to adhere to regulations limiting the radiation exposure to the public and to the personnel carrying out the NDC operations. Furthermore, the new NDC methods must not leave behind activated products in excess of regulated limits. Accordingly, new accelerator-based NDC techniques and their shielding and operation protocols must be developed with statutory radiation limits considered from the onset. For example, for AM parts NDC, the limitations on current cabinet-based x-ray systems are applicable, which do not allow an exposure beyond 5 microsieverts in 1 hour at any point 5 cm outside the external surface. [CFR21-1020.40-2018] More generally, dose limits established by the US Nuclear Regulatory Commission (NRC) regulation 10 CFR Part 20 and Occupational Safety and Health Administration (OSHA) regulation 29 CFR 1910 are 0.05 Sv/yr for radiation workers [NRC-2018a] and 1 mSv/yr for the general public. [NRC-2018b]. In some applications, the regulatory burdens for accelerator-based processes can be less restrictive than for conventional technology.

3.3.4 Economic Analysis (Q3)

Each of the seven application areas for NDC has significant economic impact, and by extension, advancements in NDC enabled by new compact accelerators would provide significant improvements in the underlying economics and expansion of those sectors. At present, for example, AM already accounts for 13% of jobs in the US and contributes \$3.1 trillion to the economy. [Brulte and Co.-2016] New imaging and characterization NDC would be expected to markedly increase the economic role of AM. Likewise, the US Department of Commerce found the output of the Computer and electronic products industrial sector to be \$385 billion. [BEA-2018] Improved NDC of electronics would be expected to increase the output of the economic sector, and the increased assurance of the supply chain and decrease in failures would improve profitability and decrease associated risks. In another example, civil aviation in 2014 generated \$1.6 trillion in economic activity, or 5.1% of US gross domestic product. [FAA-2017] The Airport Security Market is set to grow from its current market value of more than \$9 billion to over \$16 billion by 2024. [OIA-2018] With improved accelerator-based security systems, this growth might be expected to be on the order of a factor of 2 higher. For another example, the \$16.5 billion NNSA budget request includes \$8.0 billion to sustain and modernize the US nuclear stockpile and \$1.6 billion for nuclear nonproliferation. The use of improved compact accelerator-based NDC in support of the development of advanced weapons manufacturing techniques as well as their use in assessing the integral performance of weapons systems has the potential to significantly impact future budgets, with the potential to save billions. In the longer term, advancements in microstructure-level imaging of manufactured components via new bright, coherent, and monochromatic x-ray sources apply broadly to the tailored manufacture of products for any application. The associated development of application-specific materials will lead an economic renaissance that could ultimately lead to trillions in economic growth.

Advancements in microstructure-level imaging of manufactured components via new bright, coherent, and monochromatic x-ray sources apply broadly to the tailored manufacture of products for any application. The associated development of application-specific materials will lead an economic renaissance that could ultimately lead to trillions in economic growth.

3.3.5 Performance Criteria (Q3)

Detailed performance criteria were developed for the various accelerator-based NDC applications and accelerator / radiation-producing subcomponents. An abbreviated listing of some key attributes for transformational capabilities are provided below as examples.

x-ray-Based NDC

- PC Board or Packaged Electronics CT: tunable energy 50-300 keV, effective spot size 0.05-0.5 mm, energy spread 10%, brightness 10^{11} photons/μm^2/s, non-coherent.
- IC Ptychography: tunable energy 5-20 keV, effective spot size 0.5-4 μm, energy spread 0.1%, brightness 10^{8}-10^{12} photons/μm^2/s, coherent.
- Screening (Radiography): tunable energy 3-9 MeV, energy spread 10-20%, tunable intensity 10^{10}-10^{12} photons/s, rep. rate 1-50 kHz, rapid rastering to 80 Hz.
- Nuclear Resonance Fluorescence: tunable energy 1-7 MeV, energy spread < 1% (and preferably closer to 0.1%), intensity 10^{10} photons/s, rep. rate > 1 kHz, slow rastering.

- Secondary Screening (Photofission): tunable energy 6.5-14 MeV, energy spread 20-40%, intensity 10^{11} photons/s, rep. rate > 1 kHz, slow rastering.
- Stockpile Stewardship: tunable energy 1-9 MeV, energy spread 20-30%, intensity > 10^{11} photons/s, rep. rate > 5 MHz, medium rastering.
- Emergency Response (High Energy Radiography): max energy 1-4 MeV, energy spread < 70%, output 2 mSv/s at 1 m, weight < 50 kg with power supply, power <10A at 120 V.
- Compact x-ray FEL: tunable energy 1-42 keV, effective spot size 5 μm, energy spread 0.1-1%, intensity 10^{11}-10^{12} photons in 50 fs, coherent, variable pulse structure, system size < 10 m.
- High Energy Flash Radiography: energy 3 MeV quasi-mono, tuning +/- 2 MeV in 200 ns, variable pulse (typical 10 MHz burst of 50 ns pulses), dose 0.5 Gy, size < 20 m, weight < 50 tons.
- Port Screening (Cargo): lower cost, more compact, energy 1 to 10 MeV, moderately narrowband (<10% spread) dual energy, wider pulse width, lighter shielding, higher source efficiency.

Neutron-Based NDC

- Luggage or Container Screening: peak flux 10^{15}-10^{16} n/s, average flux 10^{10}-10^{11} n/s, pulse length <100 ns, rep. rate 100 Hz, forklift- to truck portable
- Container Radiography: peak flux 10^{17} n/s, average flux 10^{12} n/pulse, pulse length < 100 ns, rep. rate 100 Hz, truck portable
- Waste / Debris Assay: peak flux > 10^{19} n/s, average flux 10^{12} n/pulse, pulse length < 10 ns, low to moderate rep. rate, truck portable

Detectors for NDC

- AM and Electronics NDC: detectors with higher spatial resolution
- Compact x-ray FEL: detectors matched to pulse structure and optimized for the x-ray energies
- Emergency Response (x-ray): resolve at least 2 line pairs per mm, large area (> 2500 cm^2)
- Luggage / Cargo Screening and General (x-ray): detectors with higher stopping power, higher light output, capability to reject scatter (e.g., high efficiency Cerenkov, energy sensitive), more immune to radiation damage.

Computation and Control for NDC

- General: Automatic NDC system design and operational optimization; image analysis.
- Monochromatic Sources: Automated tuning of energy and slewing, improved stability.
- Port Security: Recognition and analysis of all contraband and cargo manifest variation, reduction of false alarms.

Although there are numerous specific NDC performance requirements that reflect back to the accelerator-based source/system, the detectors, and computation, an overall examination of the above listing and the larger Appendix reveals some common areas of need. In summary, greatly enhanced performance or entirely new regimes of operation and methodology are required most strongly in the following topical areas:

- Compact energy and intensity tunable, monochromatic (<1% and preferably 0.1% energy spread), extremely bright x-ray and high energy x-ray sources (inverse Compton scattering and x-ray FEL mechanisms are both considered important).
- High flux compact sources of moderately-narrowband (<10% energy spread) x-rays, with low-energy (<50 keV) sources, as well as moderate-energy sources (<500 keV) that can be pulsed >1 kHz, being considered equally important.
- Efficient, rugged, portable x-ray sources and associated fieldable large area detectors.

- High flux compact neutron sources.
- High spatial resolution, high sensitivity, fast response detectors; energy-resolving detectors.
- Computer simulation, design, and automated optimization of entire NDC systems, simulation of the interaction of the NDC radiation with the subject objects, and better image construction and automatic detection algorithms.

3.3.6 Technical Gaps (Q4)

Some key limitations (technical gaps) that currently prevent the achievement of the required performance and the implementation of new types of accelerator-based NDC systems are summarized in the following table, along with brief statements of the general path forward to overcome the limitations. This is a precursor to the specific required R&D topics and roadmap that would overcome the gaps, which will be presented in Sections 3.3.8 and 3.3.10.

Requirement	Present Technical Limitation and Need
Intense monochromatic x-ray sources	• Only available in huge synchrotron and FEL sources consuming 1000s to 10,000s of square meters of facility area. Need new mechanisms of producing monochromatic x-rays and more compact x-ray FELs.
Efficient x-ray production	• Bremsstrahlung from collisions of electrons with dense metal targets produces broadband radiation with weak high energy tail and is very inefficient. Need more direct methods of x-ray production.
More compact multi-MeV RF LINACs	• Present relatively low frequencies and low accelerating gradients in conventional LINACs. Need higher frequency structures, and methods to raise the shunt impedance, and higher wallplug efficieny.
More compact overall accelerator system	• Relatively large size, low specific power of RF sources and associated modulators. Need higher frequency, higher power density, higher efficiency RF sources operating at lower voltages.
Compact 100 MeV to GeV energy accelerators	• Relative immaturity of advanced high gradient accelerator concepts, especially laser and plasma wakefield. Need to raise TRL, beam quality, total energy, average power, and wallplug efficiency.
High flux, high energy compact accelerators	• Power requirement, losses, and physical size of accelerator. Need high rep. rate superconducting RF beam drivers and wakefield concepts.
Monochromatic high energy x-ray sources	• Present inverse Compton scattering sources do not create the necessary flux or quality. Need a factor of 1000 increase in flux, smaller spot size, higher gradients, and more narrow spectrum in such sources.
Higher flux, shorter pulse neutron sources	• Limitations on the source ion beam current density, total current, and accelerating voltage, and mechanism of pulse formation. Need more compact, higher TRL versions of short pulse, high flux neutron sources.
Improved detectors	• Cost and scalability of present detector materials and the present mechanisms of detector operation. Need novel materials and manufacturing concepts, and new energy-resolving detectors.
Improved computer design of NDC systems and operational simulation	• Current methods of design are piecemeal, with individual disparate codes for each sub-component. Need integrated design and simulation.

3.3.7 Synergistic Application-Side R&D (Q5)

Synergistic application and signature research is needed in detection methods to exploit high spatial resolution and material contrast that is made possible by MPSs. Backscatter time of flight imaging is an emerging possibility due to the femtosecond pulsed beams of the MPS, and could enable single-view 3D information without CT and with reduced dose, provided sufficient research is performed on new imaging algorithms directly tailored to this new technique. Research is also needed on interpreting other types of responses, including use of polarization and isomer signatures uniquely accessible using such MPS sources. An important synergistic area of NDC is scientifically understanding the connection between material or component performance and its microstructure, with the latter acquired in unparalleled detail by new compact x-ray FELs.

3.3.8 Required R&D to Bridge Technical Gaps (Q6)

The primary R&D required in the near and longer-term is presented below, organized by technology type or topical area of need. The perceived relevance to the various NDC applications is numerically scored on a 0-4 scale (lowest to highest relevance).

<table>
<tr><th colspan="8">High energy x-ray tunable MPS, and Low- to moderate-energy x-ray tunable MPS</th></tr>
<tr><td colspan="2">Advanced Manufacturing</td><td>3</td><td colspan="2">Electronics Supply Chain Assurance</td><td>4</td><td>Nonproliferation and Treaty Verification</td><td>3</td></tr>
<tr><td>Emergency Response</td><td>3</td><td>Stockpile Stewardship</td><td>3</td><td>Port Security</td><td>3</td><td>Radioactive Waste Management</td><td>3</td></tr>
<tr><td colspan="8"><i>Inverse Compton scattering-based MPS</i></td></tr>
<tr><td colspan="4">Near-Term R&D</td><td colspan="4">Longer Term R&D</td></tr>
<tr><td colspan="4">Shorter, higher-gradient RF LINAC structures at frequencies above 20 GHz; accelerators with high shunt impedance using ordinary metals at ~77K. High gradient, low-loss dielectric-loaded accelerator structures</td><td colspan="4">Much more speculatively, LWFA for GeV/cm scale gradients to enable 10’s of cm scale fieldable devices</td></tr>
<tr><td colspan="4">Compact higher power (> 10 MW peak) vacuum electronic-based RF sources at frequencies > 20 GHz; e.g., harmonic gyro-amplifiers</td><td colspan="4">Ultra-compact, high efficiency laser sources for providing accelerating fields in LWFA structures</td></tr>
<tr><td colspan="4">Compact higher efficiency RF pulse compressors with larger power multiplication factor</td><td colspan="4"></td></tr>
<tr><td colspan="4">Enable operation of RF sources and accelerators at >1 kHz rep. rates (thermal management, avoid pulse heating breakdown and multipactor)</td><td colspan="4"></td></tr>
<tr><td colspan="4">Cold, low-emittance electron sources, and injectors producing tighter monoenergetic bunches</td><td colspan="4">Full control of bunching structure and behavior at the Angstrom level</td></tr>
<tr><td colspan="4">Improve pulse-to-pulse stability of electron bunch energy and charge, and position control of both the laser and the electron beams</td><td colspan="4">Higher repetition rates of the inv. Compton laser source (> 1 kHz) and higher energy laser pulses (> 1 J/pulse)</td></tr>
<tr><td colspan="8"><i>Compact x-ray free electron laser-based MPS</i></td></tr>
<tr><td colspan="4">Near-Term R&D</td><td colspan="4">Longer Term R&D</td></tr>
<tr><td colspan="4">Microfabricated magnetic undulators at the 5 to 50 micron period length scale (including by lithography, additive manufacture, with in-situ magnetization, etc.)</td><td colspan="4">Microfabricated undulators in 3D arrays suitable for use with multiple electron beams or other extended geometries like multiple sheet beams</td></tr>
<tr><td colspan="4">Novel methods of inducing periodic transverse motion in electron beams at the micrometer to nanometer-scale</td><td colspan="4">Undulation via standing or traveling-wave optical fields, or laser-induced dense plasma quasi-crystals or other plasma-related phenomena</td></tr>
<tr><td colspan="4">True RF energy recycling from the beam emerging from the FEL interaction, e.g. energy recovery LINAC</td><td colspan="4">Very speculatively, LWFA and PWFA for GeV beams with 10’s of microns transverse dimensions suitable for micron-scale wigglers. Methods to generate arrays of such beams with synchronized bunching</td></tr>
<tr><td colspan="4">Active control of photon production and steering</td><td colspan="4"></td></tr>
<tr><td colspan="4">Theoretical analysis of ultra-compact FELs driven by lower-energy beams. Coupled computer codes for</td><td colspan="4">Use of AI to discover idealized compact XFELs with optimal radiation characteristics and efficiency, and automatically design XFELs for specific requirements</td></tr>
</table>

end-to-end modeling of combined accelerator, short period FEL, and ERL	

High flux compact sources of moderately-narrowband (<10% energy spread) low energy (< 50 keV) x-rays and moderately narrowband (<10% energy spread), moderate-energy (< 500 keV) x-rays that can be pulsed at 1 kHz or above

Advanced Manufacturing	3	Electronics Supply Chain Assurance	4	Nonproliferation and Treaty Verification	3		
Emergency Response	2	Stockpile Stewardship	3	Port Security	3	Radioactive Waste Management	2

Near-Term R&D	Longer Term R&D
Shorter, higher-gradient RF LINAC structures at frequencies above X-band. Dielectric-loaded accelerator structures or structures of ordinary metals cooled to moderate cryogenic temperatures. Additively-manufactured accelerator structures	Ultra-high rep. rate (> 1 MHz) SWFA technology, including a drive bunch accelerator delivering specifically shaped bunches optimized for SWFA and PWFA. SRF-based beam drivers to power the SWFA structures. Thermal management of SWFAs
Ultra-compact vacuum electronic RF sources operating >10 GHz at lower voltages (< 20 kV), and overall efficiency >80%; e.g., multi-beam klystrons, sheet beam klystrons, or new crossed field devices	Further mm-wave scaling of VE devices by improvements in electron gun miniaturization, cathode current density, magnetic materials, beam-wave interactions in circuits fabricated by additive methods
Compact accelerators driven entirely by RF solid-state microwave transistors (wide bandgap materials such as GaN HEMTs). Distributed RF to allow adjustment of the beam energy and tuning for optimum performance in generating a desired x-ray spectrum	Advanced (>5kW peak power each) microwave and mm-wave transistors for extremely high rep. rate, high duty cycle operation for ultra-compact RF sources integrated directly into accelerator structure
Structured single-crystal x-ray generating targets, engineered at the atomic scale for enhanced conversion over narrower bandwidths by making use of combined electron and x-ray diffraction	Exotic types of plasma, optical, or molecular-scale undulators, or improved methods of frequency upshifting from optical sources via new types of beam-wave and beam-wave-matter interactions

Efficient, rugged, portable x-ray sources and associated detectors

Advanced Manufacturing	0	Electronics Supply Chain Assurance	0	Nonproliferation and Treaty Verification	1		
Emergency Response	3	Stockpile Stewardship	2	Port Security	3	Radioactive Waste Management	0

Near-Term R&D	Longer Term R&D
Miniaturized electron LINACs (including dielectric-loaded accelerators) and betatrons immune to shock, vibration, and high ambient temperatures	
Lightweight, high energy density batteries, ultra-compact power converters and modulators	
New anode materials; understanding anode aging	
Large area (>2500 cm^2) x-ray detectors in scalable materials (e.g., am-Si), readout electronics that are shielded or radiation hardened; detector packaging	Large area x-ray detectors composed of lightweight, highly flexible materials with embedded flexible data processing electronics that are radiation-resistant

Detectors (general NDC-related)

Advanced Manufacturing	3	Electronics Supply Chain Assurance	2	Nonproliferation and Treaty Verification	2		
Emergency Response	2	Stockpile Stewardship	3	Port Security	4	Radioactive Waste Management	2

Near-Term R&D
Energy-resolving detectors that can operate >10^6 photons per second
Detector materials for improved sensitivity, reducing the cost of efficient yet radiation-resistant scintillators

Improved detector calibration and failure identification
Large scale detectors with fast response time and rapid parallel readout to enable higher frame rate capturing
Detectors with increased efficiencies at > 1 MeV with both dynamic (MHz) and quasi-CW (Hz) rates

High flux neutron sources

Advanced Manufacturing	2	Electronics Supply Chain Assurance	1	Nonproliferation and Treaty Verification	3		
Emergency Response	2	Stockpile Stewardship	3	Port Security	3	Radioactive Waste Management	1

Near-Term R&D	Longer Term R&D
Higher flux compact sources of protons, deuterons, and other ionized nuclei for neutron production in targets.	Active cooling of electrodes. Alternative neutron-producing nuclear reactions in targets
Higher total voltage and higher voltage gradient dc accelerator technology (structures and power supplies)	Reduction in pulse length (<1 microsecond) at the higher voltages
More compact RFQ-based proton/deuteron accelerator technology enabled by higher operating frequencies. Also combination of compact RFQ and short linac for 10 MeV, 0.25 mA proton/deuteron accelerator	Precision manufacture of RFQs by additive manufacturing or related technologies
More compact, reliable, robust z-pin. for high flux, high brightness < 10 ns pulsed neutron sources. Demonstration of NRTA with a portable source	Shaped anode or a re-entrant cathode that "quenches" the pin. in z-pin. sources; Laser-based short pulse, fast-risetime neutron sources

Computer simulation and control (general NDC-related)

Advanced Manufacturing	3	Electronics Supply Chain Assurance	3	Nonproliferation and Treaty Verification	2		
Emergency Response	2	Stockpile Stewardship	3	Port Security	1	Radioactive Waste Management	2

Near-Term R&D	Longer Term R&D
Improved methodologies to link presently disparate computer codes for end-to-end simulation of electron sources, injectors, accelerators, radiation-producing interaction circuits, and energy-recovery systems	Comprehensive framework for running modeling tools in concert in ways that make the hand-offs transparent to the user. Artificial intelligence and other machine learning for discovery of new performance regimes
Comprehensive simulation of the NDC interrogation physics of the objects to be studied, for various choices of source characteristics, to allow proper design and specification of the source to meet the requirements	Completely coupled end-to-end source simulation with NDC application simulation with automated optimization for the proposed task. Completely optimal automated control of the operational NDC system
Coupled modeling between accelerator physics, plasma physics, and optical physics for emerging types of unconventional accelerator and radiation source concepts	Implementation on over a wide of distributed computing systems, coupled with optimization algorithms
Automated image reconstruction algorithms	Improved reliability automated threat or defect detection
First principles physics simulation of detectors, including materials, radiation interaction, packaging, cross-talk. Validation with experimental data	Use of the first-principles simulations for optimal engineering of new types of detectors. Understanding of failure mechanisms and devising of better detectors

3.3.9 Barriers to Commercialization and Technology Introduction (Q6)

The primary barrier is the high cost of creating a prototype and the limited initial market and the associated lack of economies of scale. The commercialization is further hampered by the need for simultaneous highly specialized and precision technology on multiple subsystems (i.e., RF, accelerators, injectors, lasers), which limits the applicability of commercial-off-the-shelf (COTS) products. Considerable R&D will be required to encourage the transition and provide an initial customer base. However, the performance advantages offered by improved accelerator-based NDC systems would be unsurpassed by any competing technology. Small markets (such as for emergency response) could be expanded if additional applications for portable x-ray sources were identified. For neutron sources, a large barrier to commercialization is that there is currently no proof of concept for using neutron sources in a screening setting. The shielding needed with neutron equipment is more difficult and expensive since neutrons can bounce around corners.

Roadmap for Development (Q7)[6]

The roadmap for NDC is presented below, organized by technology type or topical area of need.

High energy x-ray inverse Compton scattering MPS

Near Term: *High gradient, high shunt impedance RF LINACs > 20 GHz via ordinary metals at cryogenic temperatures*, national lab, 4 years, $8 to $12 million. Dielectric loaded accelerators for low losses and high gradients, national accelerator facility or national lab, 4 years, $12 to $15 million. *Compact higher power (> 10 MW peak) vacuum electronic RF sources at > 20 GHz based on harmonic gyro-amplifiers or other overmoded concepts*, university, 3 years, $2 to $4 million; in association with industry or national accelerator facility, 2-3 years, $6 to $9 million. *Improved RF pulse compressors*, national accelerator facility, 2 years, $5 million. *Low emittance cold electron sources and tighter monoenergetic injectors*, national accelerator facility or national lab, 4 years, $8 to $12 million. **Longer Term:** *Further improvements to electron beam bunch tightness and control*, national lab, 3-5 additional years, $8 to $15 million. *Higher energy, higher repetition rate laser sources for the inverse Compton scattering process*, 5 additional years, national lab or industry, $10 to $20 million. For LWFA development (considerably more speculative and higher risk future concepts): *Compact high gradient accelerators at 20-500 MeV energies with precision shaping and control of laser and accelerator*, 5 years, $15 million. *Application of LWFA to inverse Compton scattering*, 5 additional years, $5 million. *Reduce LWFA energy spread < 1% and improve electron beam/photon control*, 10 years, $5 million. *Energy recovery mitigating undesired bremsstrahlung (reduces shielding)*, 5 years, $3 million. *Laser drivers at a few J/pulse and 30 fs pulse*, 5 years, $25 million; *Long term path to 20 kHz-50 kHz laser drivers*, 10 additional years, $45 million.

Compact x-ray FEL-based MPS

Near Term: *Theoretical and simulation analysis of ultra-compact FELs*, university and industry, 2-3 years, $2 to $6 million. *Microfabrication and materials science of micron-scale magnetic undulators*, University, 4 years, $3 to $6 million; augment in parallel with industry, 2.5 years, $2 to $4 million. *Advanced non-magnet-based undulator concepts*, university, 3-5 years, $5 to $10 million. *True RF energy recycling by energy recovery LINAC*, national accelerator facility, 4 years, $10 to $15 million. **Longer Term:** (All are highly speculative future concepts) *GeV-level electron beams in < 0.5 m length by LWFA technology, combined with μm-scale or other advanced undulators as well as energy recovery from residual bunched beam*, national accelerator facility or national lab, 10 years, $20-40 million; *3D arrays of microfabricated undulators and arrays of LWFA beams with synchronized bunching and extraction*, 5-10 additional years, $20 to $30 million. *Undulation using optical fields or laser-induced dense plasmas*, university, 5 years, $3 to $5 million.

High Flux, compact, moderately narrowband, low- to moderate energy x-ray sources

Near Term*:* *Short, high gradient RF LINACs > 10 GHz via dielectric loading or ordinary metals at cryogenic temperatures*, national accelerator facility or national lab, 4 years, $8 to $12 million. *Additively manufactured accelerator structures*, industry and national accelerator facility, 3-4 years, $3 to 4 million. *Compact vacuum electronic RF sources > 10 GHz based on multiple beams, sheet beams,*

---

[6] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

innovative interaction circuits, university, 3 years, $3 to $6 million; augment in parallel with industrial or national accelerator facility program, 4 years, $10 to $15 million. *Higher powered RF transistors more suitable for accelerators and demo of a transistor-driven 10 MeV accelerator*, industry, national accelerator facility, national labs, 3-4 years, $5 to $12 million. *Higher efficiency electron to photon conversion targets or mechanisms*, University, 3-4 years, $3 to $8 million.
Longer Term: *Continued scaling of vacuum electronic devices to mm-wave regime by advanced manufacturing, miniaturization, and new concepts*, industry and university, 4-8 years, $10 to $15 million. *Advanced (>5kW peak power ea) RF transistors and direct integration into high rep. rate, high duty cycle accelerator*, industry and national accelerator facility or national lab, 6 years, $10 to $20 million. For SWFA development: *High charge drive electron beams at ~10 MeV, 10 mA from an SRF injector*, 5 years, $5 million. *Electron bunch shaping technology for high rep. rate beam drivers with controlled energy gain*, 3 years, $3 million. *Thermally managed dielectric or metallic structures for high gradient, high average power, and ~1MHz rep. rates for 20-500 MeV beams*, 7 years, $7 million; *Further system integration, performance and stability development*, 5 years, $7 million.

Efficient, rugged, portable x-ray sources and associated detectors

Near Term: *Determine via use-case models, a fundamental requirements list. Determine if a single new accelerator design is feasible, or how many different designs are adequate*. National lab, 2 years, $2.5 million; *Modify existing LINAC or betatron designs or develop new ones to meet the size requirements*, industry and national lab, 2-3 additional years, $5 million. *Advanced batteries and power converters*, Industry, 3-4 years, $3 to $10 million. *New durable anode materials*, university or industry, 2-3 years, $2 to $3 million. *Large area detectors*, industry or national lab, 4 years, $10 to $15 million. (Overall - leverage accelerator structure and RF source research described in prior topics).
Longer Term: *Modify the compact designs or implement new ones to meet the environmental (durability) requirements*, industry, 3 additional years, $5 million; *Design a control system to fit the intended use and operating conditions*, industry, 2 additional years, $2 to $3 million. *Lightweight flexible large area detectors with integrated electronics*, industry or national lab, 7-10 years, $15 to $25 million.

Detectors (general NDC-related)

In the next 3-5 years, the research and development in large-area imaging is necessary. Optimization of overall imaging area, acquisition time and detector element size are of particular interest. Imaging arrays for homeland security, for example scanning of cargo containers, will face additional challenges of need of high-performance crystals with digital readout. Lowering the cost of digital electronics is necessary to make scanning systems more affordable.

Accelerator-based monochromatic high energy x-ray sources and also monochromatic low- to moderate-energy x-ray sources place new requirements on imaging detector arrays. For example, monochromatic sources make material identification via relative photon transmission rates possible and importantly practical. However, conventional detector arrays, such as cadmium tungstate crystals or even NaI detectors, may not yield the desired information due to lack of resolution or poor timing, and imaging processing software may need to be adapted to handle multiwavelength imaging data. In order to maximize information extracted from active interrogation with spectrally selective sources, advances in detector technology and image processing must therefore be made.

Near Term: *Energy resolving detectors compatible with high photon rates*, industry or national lab, 4 years, $6 to $10 million. *High efficiency detectors for monoenergetic sources*, industry or national lab, 3-4 years, $6 to $10 million. *New materials for detectors*, university, 3-5 years, $2 to $5 million. *Radiation resistant detectors*, national lab, 4-5 years, $8 to $15 million. *Large scale detectors with fast response and rapid readout*, industry or national lab, 4 years, $10 to $15 million.

High flux neutron sources

Near Term: *Higher flux ion sources for target bombardment*, 2 years, industry, $1 to $2 million. *Higher voltage and higher gradient pulsed dc accelerator technology*, industry, 2-4 years, $2 to $4 million. *More compact RFQ technology enabled by higher operating frequencies*, university, 2-3 years, $2 to $4 million, followed by national accelerator facility or national lab, 2 additional years, $8 to $12 million. Combined compact RFQ and short linac for 10 MeV, 0.25 mA proton or deuteron accelerator, industry or national lab, 4 years, $15 million. *Compact, robust z-pin. for intermediate flux levels and pulse lengths,* national lab and industry, 4 years, $5 million.
Longer Term: *Alternative neutron-producing reactions*, University and National lab, 4 years, $2 to $4 million. *Increasing the TRL and rep. rate of microsecond-scale sources*, Industry, 5-6 years, $4 to $6 million. *Additive manufacture of high frequency RFQs*, University/Industry, 3 additional years, $5 million. *Increasing the TRL of shorter (<10 ns) high flux sources (including z-pin. and laser-based technologies)*, National lab and Industry, 5-10 years, $10 to $30 million.

Computer simulation and control (general NDC-related)

Near Term: *Improved methodology to link accelerator component codes*, industry, 3 years, $3 to $5 million. *NDC interrogation process simulation linked to sources*, industry and national lab, 4 years, $8 to $14 million. *Detector physics simulation*, university and Industry, 3-4 years, $2 to $5 million. *Coupled modeling of multi physics (accelerator, plamas, optics) in unconventional schemes*, industry, 4 years, $4 to 8 million.
Longer Term: *Comprehensive end-to-end RF source, accelerator, NDC system simulation framework and codes*, industry, 6-8 years, $10 to $15 million; *Subsequent automated optimization and accelerator controls*, industry and national accelerator facility, 3 additional years, $6 million. *Simulation-based optimization of detectors, and understanding and mitigating failure*, university and Industry, 6 years, $8 to $12 million.

3.4 Application Area 3: Food Processing

3.4.1 Introduction

Ionizing radiation technology is currently being used for food processing in over 60 countries, mainly for food safety, phytosanitary treatment, or for preventing the sprouting of potatoes. ^{60}Co is the primary technology that is used in the vast majority of such processing facilities around the world. These cobalt-60 facilities range from very large capacity (> 1 MCi) facilities in the United States and China to relatively small facilities (100 - 400 kCi) spread around in different regions of the world, e.g., Mexico, Morocco, the Philippines, India, and Sri Lanka.

3.4.2 Background and State of Application Development (Q1)

Except for a ^{60}Co facility in Mexico that was specifically designed and built for treating fresh produce, almost every other ^{60}Co facility is used primarily for other purposes such as medical device sterilization and irradiating other non-food items. A vast majority of the irradiation facilities in Asia, Latin America, Europe, and Africa are wholly government-owned and -operated or have limited private involvement. There are a few multinational company-owned facilities around the world, e.g., in Asia, Mexico, and Europe. In the United States, there are only privately-owned ^{60}Co irradiation facilities. Around the world, spices appear to be the primary food ingredient that is treated for food safety and quality reasons by irradiation technologies. [Kume-2008] There is now a small but growing volume of fresh produce that is being treated by this technology for phytosanitary treatment purposes (USDA-APHIS). The doses that are used for these two applications are very different. In the US, spices are treated to doses in the 5 kGy – 30 kGy range while for phytosanitary applications the federal regulations do not allow doses above 1 kGy. In the US, only a handful of irradiation facilities were built specifically for food processing. These include the x-ray (5 MeV) and ^{60}Co facility in Hawaii, the e-beam (10 MeV) facilities in Texas and Iowa and a ^{60}Co facility in Mississippi. China is believed to be operating a large 10 MeV e-beam facility along the China-Vietnam border for food. The number of machine source-based food irradiation facilities is slowly growing in the world with facilities already operating or under validation in Thailand, Australia, Pakistan, and Vietnam.

Today, S-band LINACs and Rhodotron-based electron beam technologies are the only commercially-available replacement technologies for ^{60}Co. [Pillai-2017] The large capital expense for these technologies precludes them from being adopted as in-house technologies. The aspetic food packaging industry is already utilizing a low energy (~150 keV) e-beam-based surface sterilization technology. Low-energy e-beam (≤ 300 keV) for in-line food processing is emerging. Buhler, Inc. has launched a low energy (< 300 keV) in-line e-beam pasteurization system (Laatu™) for whole spices such as black peppers. The fresh produce industry relies on multiple locations for harvesting (due to seasonality of the produce). Therefore, the availability of transportable compact accelerators customized for phytosanitary doses (≤ 1 kGy) can make a major impact on reducing the reliance on ^{60}Co. Specific food industry segments have specific incentives for adoption of replacement technologies. For phytosanitary applications (≤ 1 kGy), in-house capabilities will facilitate better “control” of their products, and potentially a better quality product. For food safety applications (> 1 kGy), the availability of in-house technologies will help reduce and control costs, provide greater flexibility in managing inventory, facilitate new product formulations and also protect against supply chain disruption. Therefore, for the food industry, low cost, robust, shelf shielded in-line (in-house) accelerator based technology is of high priority. The ability to treat pallets of food with x-rays is of high priority also. Therefore, R&D to improve the power conversion (e-beam to x-ray) efficiency, use of advanced technologies to convert electrons to photons without metallic convertors can make a significant impact on the adoption of these technologies. Accelerator-based food irradiation solutions (small footprint, compact, rugged, variable power systems) are needed to meet this market.

3.4.3 Regulatory Framework (Q2)

There is a well-developed regulatory framework supporting the use of ionizing radiation in food processing in different parts of the world. In the US, the FDA has established a specific set of food items that can be treated with ionizing radiation (gamma/e-beam or x-ray) and the maximum doses that can be delivered to these products and the intended application [FDA-2019]. However, the regulations vary considerably in different countries. Around the world, regulatory agencies do not differentiate between the various sources of ionizing radiation such as ^{60}Co, electron beam, or x-ray. The regulatory parameter in a vast majority of countries is the maximum dose that can applied for a particular commodity. However, when x-ray are used as a source of ionizing radiation, the US allows energies no higher than 7.5 MeV, while the rest of the world does not permit x-rays generated from electron energies greater than 5.0 MeV for food processing. The maximum electron energy for e-beam processing is 10 MeV.

3.4.4 Economic Analysis (Q3)

The spice industry is the largest segment of the food industry that is currently utilizing ionizing radiation technologies. In 2018, the total dollar amount of imported spices was approximately $1.7 billion [Ferrier-2011]. According to industry projections, the seasonings and spice markets are expected to grow 6% annually and by 2023 the market is expected to be valued at $30 billion [PandS-2018]. In 2018, approximately 19 million pounds of Mexican guavas were treated with gamma irradiation [USDA-FAS-2018]. The market value of imported fresh guavas and fresh mangoes is still relatively small. In 2018, was estimated to be around $21 million and $429 million respectively [USDA-2019].

3.4.5 Performance Criteria (Q3)

Details the accelerator performance criteria required for the food industry are provided in the bulleted listings below. The applications of accelerator technology in the food industry spans food safety, food quality, extension of shelf-life, phyto-sanitary treatment, the sterilization of food packaging, and modification of packaging material properties.

Food safety applications

- Core technology: electrons or x-ray photons
- Target minimum and upper doses: 1 kGy (for fresh foods) – 30 kGy (for spices)
- Energy requirements and energy spread: fully tunable between 300 keV – 10 MeV. Research still needed to understand energy spread effects on Dose Uniformity Ratio (DUR) and biological response
- Effective source size: > 2 cm
- Pulse structure: CW, pulse train bursts, single pulses, interleaved energies. Pulse structure should be designed to deliver uniform dose on a moving product and biological effects. Research needed to determine effect of intensity or flux on DUR and biological response
- Power requirements: 10 kW (inline) to 50 kW (in-house)
- Directionality: unidirectional
- Desired throughput: *maximum* ~1 kg/second (~8000 lbs/hour)
- Machine automation requirements: Full automation preferred-active dose monitoring
- Ancillary equipment: Automated product handling/conveyor and cooling systems
- Footprint (Size, shape, and shielding): Has to be compact to be flexible to be used in-line or in-house
- Weight (including any shielding): Lighter the better. Self-shielded preferably
- Operating conditions: Ambient/room temperature
- Portability: Not of high priority. Ability to be integrated in-line or used in-house. In rare cases, transportability preferable to be moved to off site for temporary operations using plug-in

connectors. Has to be robust. Preferably capable of operating with electrical generators in areas with poor electrical grid system
- Cost of acquisition for fully integrated system: $5 million

Phytosanitary treatment applications

- Core technology: electrons or x-ray photons
- Target minimum and upper doses: 100 Gy – 1000 Gy
- Energy requirements and energy spread: fully tunable between 300 keV – 10 MeV. Research needed to determine energy spread effects on DUR and biological response
- Effective source size: > 2 cm
- Pulse structure: CW, pulse train bursts, single pulses, interleaved energies. Pulse structure should be designed to deliver uniform dose on a moving product and biological effects. Research needed to determine effect of intensity or flux on DUR and biological response
- Power requirements: 10 kW (inline) to 50 kW (in-house)
- Directionality: unidirectional
- Desired throughput: *maximum* 40 kg/second (~30,000 lbs./hour)
- Machine automation requirements: Full automation preferred-active dose monitoring
- Ancillary equipment: Automated product handling/conveyor and cooling systems
- Footprint (Size, shape, and shielding): Has to be compact to be flexible to be used in-line or in-house
- Weight (including any shielding): Lighter the better. Self-shielded preferable
- Operating conditions: Ambient/room temperature
- Portability: If possible transportable to be moved to off site for temporary operations using plug-in connections. Has to be robust. Preferably capable of operating with electrical generators in areas with poor electrical grid system
- Cost of acquisition: ≤ $5 million

3.4.6 Technical Gaps (Q4)

Some key technical gaps or current technology limitations are tabulated below. This is a precursor to the specific required R&D topics and proposed research roadmap to fill these technical gaps.

Requirement	**Present Technical Limitation and Need**
Compact, variable energy, and variable power	• None of the commercial accelerators are available in a compact, self-shielded variable energy, variable power configuration. Conventional RF sources and accelerators only produce high efficiency at their maximum power point, limiting flexibility, and creating poor efficiencies that hamper the economics of high dose, high throughput food sterilization. Need a combined RF source / accelerator technology that retains high efficiency over a broad range of beam powers
High power accelerators	• The technology of choice for producing high average power relativistic beams is superconducting radiofrequency (SRF) accelerators, but advanced skills are needed to develop, install and maintain such systems at present. Accelerating cavities are currently fabricated out of bulk niobium that must be refrigerated to 2K with flowing sub-atmospheric pressure superfluid liquid helium, which are severe barriers limiting adoption. Need to develop accelerating cavities operating at > 4K temperatures to simplify refrigeration systems (allowing conduction cooling from closed loop cryocoolers) and thus reduce refrigeration system size by 20X or more. Need higher gradient SRF accelerating cavities (for shorter LINACs), combined with a SRF-based LINAC injector (for simplification, compactness, robustness)

Common modular design framework and assembly process	• Lack of accelerator designs customized for the different food industry applications. Need a common modular design framework and assembly process for a family of accelerators that could be applicable to various applications, and in particular a range of closely related applications at different power levels and working area requirements
Application specific accelerators for food processing	• In-house applications are presently small footprint, robust, compact e-beam accelerators (max 5 MeV). Power requirements must to be compatible with current industry expectations of 10,000 to 20,000 pounds per hour (5-10 tons/hour). x-ray pallet irradiators capable of replacing large ^{60}Co source-based facilities have challenging economics for food safety applications (which require high doses), but are marginally suitable for phytosanitary (low-dose) treatments. Machine reliability statistics and optimized e-beam or x-ray facility designs for specific applications are either lacking or based on limited experience. Megawatt-level electrical service requirements using conventional accelerators and inefficient x-ray conversion (i.e., tantalum targets) are unaffordable for food industries. Need alternative accelerating structures with much lower power requirements to achieve the desired accelerating gradients and beam power in CW operation, including the use of materials like RF superconductors with profoundly lower losses. Need robust, more efficient, high-power electron-to-photon converters for x-ray-based sterilization. Need better thermal management of RF sources, accelerators, and targets
Medium to high energy tunable accelerator systems	• Limitations on tolerable power consumption, cooling requirements, size, and weight cannot be met with conventional room temperature pulsed accelerators. The challenges for x-ray systems are 10x-20x more severe than e-beam systems and are thus even more difficult. Only the low energy (< 1 MeV) e-beam systems are commercially available today for in-line integration. Need medium to high energy accelerator systems customized for in-line or end of line configuration
Compact, high reliability, ruggedized accelerator technology for the applications	• Compact, ruggedized accelerator technology lacking. Most RF LINACs operate at S-band (~3 GHz) or C-band (~5 GHz), with the associated size of the accelerator structure relatively large. Many conventional lower-frequency RF sources are large, high voltage devices. Present more-compact X-band LINACs (~10 GHz) produce lower beam power due to a lack of suitable RF source powers at the higher frequencies. Typical accelerator structures (and their RF sources) are not rugged, having cavities made from soft metals like copper and fragile electron guns with ceramic-to-metal seals. Systems have to be reliable since the industry deals with perishable commodities. Need higher frequency LINACs and compact RF sources, and more physically robust accelerator structures and electron guns
Fully integrated accelerator + product handling conveyance system	• None of the accelerators available today is commercially available as a fully integrated system with the product handling system. Installation qualification and performance qualification can take 12 months. Need significant overall engineering for reliability and a prototype for testing to enable turnkey systems. Superior data science (including control) techniques are required
Compact, ruggedized accelerator technology for global use	• RF sources with a single, high-powered amplifier or oscillator are subject to single point of failure of a very high cost item, and inventories of expensive spare parts and repair expertise are prohibitive. The high voltage supplies of such single source systems are subject to failure in hot, high humidity environments. Need a lower voltage, distributed RF source technology (with less expensive, smaller components) that tolerates individual source degradation / failures without compromising overall accelerator performance
Reliability	• Need accelerator systems with no performance deficit and minimal failure modes
Transportability	• Need accelerator systems for phytosanitary applications that can be transportable to different harvesting locations within a country

Dosage guidelines for the industry	• Fundamental knowledge about how microbial pathogens and the different insect stages respond to varying beam energies and dose rates is still in its infancy

3.4.7 Synergistic Application-Side R&D (Q5)

Synergistic application and signature research is needed in understanding how microbial pathogens and the different insect life stages respond to varying electron/photon energies and dose-rates. This information can be used for bespoken accelerator design and operating conditions for food safety and or phytosanitary applications.

3.4.8 Required R&D to Bridge Technical Gaps (Q6)

Accelerator technology development	
Near-Term R&D	Longer Term R&D
Theoretical research ideas and exploratory simulations on new accelerator designs.	Develop accelerators that cost around $250,000 and designed with final system integration (product conveyance, and user-friendly control panels).
Develop (theoretical, simulate, and lab prototypes) new types of efficient vacuum electronic RF sources at higher frequencies than 10 GHz. Research on higher gradient, more compact linear accelerator structures at frequencies above 10 GHz (and methods to fabricate them accurately and inexpensively).	Develop commercially viable and robust RF sources and associated accelerators operating at the higher frequencies. Emphasize system integration, performance, and stability development.
Improved solid-state RF sources with higher power and efficiency at 2-6 GHz frequencies. Research on solid-state transistors at frequencies of 10 GHz or higher that can produce 5 kW power in a package not more than 2x the volume of a present-day 500 W, 5 GHz device.	Develop accelerators that are compact, medium energy (3 MeV – 5 MeV) ruggedized accelerators for in-house food industry applications.
Initial proof of principle SRF accelerator systems. Research on generating electron beams at >1 MeV from an SRF injector. Identify candidate materials for advanced SRF cavities which could operate at 4K and above including modification of existing bulk niobium surfaces and multilayers.	Development of advanced superconducting accelerators which could meet the need for higher power output at high efficiency in a compact, robust and efficient package.
	High temperature, superconducting accelerator structures for robust efficient (> 10 kW) turnkey systems especially for reaching the upper range of desired x-ray dose levels (3 kGy/s) from compact, high gradient accelerators that only require 10-20 kW of power.
Higher frequency Rhodotron-like devices with greater compactness. Theoretical and experimental investigations of the frequency- and acceleration gradient-scaling characteristics of Rhodotrons towards operation at microwave frequencies.	Rhodotron-like devices with alternative cavity and electromagnetic field configurations, novel beam bending and recirculation strategies and geometries, and higher gradients.
Develop more robust S-band accelerator structures and improved lower-voltage multiple-beam klystrons. Examine power-combined magnetrons for powering S-band LINACs. Higher power density, low cost multiple-beam klystron sources that operate at lower voltages (few 10's of kV).	
Improved cathode technology, especially more rugged cathodes for the electron sources of S-band accelerators that can tolerate vibration and insults to	Develop transportable, ruggedized e-beam accelerators (10 MeV, 10 kW) customized for phytosanitary applications that can be moved across different

the accelerator vacuum quality, are needed to ensure transportability and minimize service needs.	locations (to match harvesting seasons) and would only minimal integration and qualification at the site.
Low-cost, rugged solid-state transistor RF sources at S-band, and accelerator structures with distributed solid-state RF sources along its length for extreme compactness, and ability for adjustable beam energy while maintaining maximum RF source efficiency, as well as tolerance for isolated source failures.	Demonstration of an S-band working accelerator (in the desired form factor and required total beam power and energy) using microwave transistors as the RF sources. Demonstrate robustness, lifetime, and serviceability in a harsh field environment.
Development of smart PID (proportional-integral-derivative) control for accelerators, implementation of innovative self-contained energy storage solutions, and incorporating next-generation insulating materials and efficient electrical components are technologies that could help to realize low cost and reliable power to accelerator and associated auxiliary systems.	
Performance improvement and cost reduction by the use of additive manufacturing and modular designs with common component and design framework applied to RF sources and accelerator structures.	Transition these additive manufacturing and modular concepts to an industrial scale.

Electron beam to x-ray photon conversion	
Near-Term	Longer Term
Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures or by direct beam-wave interaction methods. These could include nanostructure engineered crystalline targets making use of electron and x-ray diffraction, or nano-channel targets.	Revolutionary types of plasma or optical undulators, or new types of beam-wave or beam-material interactions or frequency upshifting methods. Full scale demonstration of effective and compact high efficiency direct methods to produce x-rays from bunched beams in advanced undulators.
Theoretical and modeling research on methods that allow energy recycling and improve the efficiency of the generation of x-rays from high energy electron beams, to reduce the required beam power and to lessen the thermal management challenges.	Implementation of a highly efficient energy recovery from the residual LINAC beam, and methods of electron beam to photon conversion that are more compatible with energy recovery.

Alternate shielding materials	
Near Term	Longer Term
Transportable x-ray shielding technologies for portable accelerators beyond solid concrete and lead, including pumpable liquids, emulsions, muds, and slurries.	
New computational codes to include the radiation shielding simulations and help find the best solutions for the genre of machine, size, space, etc.	
Advanced light-weight metal foams, polymer-composites, and embedded glassy matrix materials that show promise for cost effective, compact shielding applications.	
Improved shielding materials compatible with small footprint, high throughput in-line/in-house accelerators.	

3.4.9 Barriers to Commercialization and Technology Introduction (Q6)

The key barriers to commercialization and technology introduction are the capital and operating costs. Current e-beam and x-ray systems are multi-million dollar investments making cost a key barrier. Lack of "affordable" turn-key integrated in-house or in-line accelerator systems customized for commercial food safety and phytosanitary purposes is a current barrier. Presently, operational expenses (OPEX) and capital expenses (CAPEX) are extrapolated from medical device sterilization facilities and therefore not truly applicable. The lack of adequately trained technical workforce to manage industrial e-beam and x-ray systems in the food industry is not trivial.

Lack of "affordable" turn-key integrated in-house or in-line accelerator systems customized for commercial food safety and phytosanitary purposes is a current barrier.

Roadmap for Development (Q7)[7]

Accelerator technology development

Near Term*: Theoretical research ideas and exploratory simulations on new accelerator designs* university, 1 to 2 years, $0.5 to $1 million. *Develop new types of vacuum electron RF sources at higher frequencies than 10 GHz,* university, $3 to $6 million, 3 years. *Research on solid-state RF sources (improved transistors with higher power at the relevant microwave frequencies*), combination of solid-state device manufacturers/National labs/commercial accelerator industry 2-3 years, $4 to $10 million. *Research on improved lower-voltage multiple-beam klystrons,* microwave tube industry, 3-4 years, $5 to $10 million. *Research on power-combined magnetrons for powering S-band LINACs,* 3-4 years, $5 million. *Research on more robust S-band accelerator structures,* accelerator manufacturers, 3 years, $5 million. *Research on improved cathode technology,* university, 5 years, $5 million. *Research on higher frequency Rhodotron-like devices with greater compactness,* accelerator mfrs, 3-4 years, $5 to $10 million. Research should link all activities to system engineering practices as well as engineering co-design. Also must consider the end use including the control and computing requirements in design and operation phase. *Initial proof of principle SRF accelerator systems.* university, national lab 5 years, $5 million. *Research on technologies to fabricate lower cost accelerators and RF source structures by incorporating additive manufacturing, or modular designs with common component and design framework*, university, 2-3 years, $3 million. *Research on generating electron beams at >1 MeV from an SRF injector*; 3 years, $3 million.
Longer Term: *Develop commercially viable and robust RF sources and associated accelerators operating at the higher frequencies*, industry/National lab, 3-4 years, $10 to $15 million. *Demonstration of a working accelerator* (*in the desired form factor and required total beam power and energy using microwave transistors as the RF sources*) national lab/commercial accelerator manufacturer, 5-10 years, $5 to $12 million. *Development of advanced superconducting accelerators which could meet the need for higher power output at high efficiency in a compact, robust and efficient package* 10-15 years, $15 million. *System integration. Performance and stability development*. 4 years, $6 million. *Transition additive manufacturing, modular designs with common component and design framework to industrial scale* > 5 years, $5 million.

Electron beam to x-ray photon conversion

Near Term: *Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures or by direct beam-wave interaction methods,* university, 3-

---

[7] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

5 years, $5 to $10 million. *Theoretical and modeling* research *on methods that allow energy recycling*, 3-5 years, $5 to $10 million.
Longer Term: *Full scale demonstration of effective and compact high efficiency emission of x-rays from the beam*. Accelerator mfr, > 5 years, $15 to $25 million. *Research on direct methods of producing x-rays from bunched beams in a compact package*, National Lab, accelerator mfr. > 10 years, > $20 million.

Alternate Shielding materials

Near Term: *Research on alternative shielding materials*, university, 3 years, $0.5M to $1 million followed by industry involvement, $1 to $3 million.

Computational Tools

Near Term: *Develop the missing physics codes out to incorporate the dose distribution patterns in non-uniformly packaged foods and allow for surrogate models using intelligent techniques. Make all required software available to all researchers on multiple platforms e.g., HPC centers, and Air Force's Galaxy Simulation Builder to assemble optimization and designs studies of single to multiple components systems and sub systems, Develop semi-analytic approximate models for rapid analysis (and surrogate models). Develop new data storage formats with a higher level of header (descriptor) information that allows the data to be interpreted better between codes that employ different techniques of calculation. Develop new data storage formats with a higher level of header (descriptor) information that allows the data to be interpreted better between codes that employ different techniques of calculation* 3-4 years, $15 million. *Develop standardized control system user interfaces*, 2 years, $2 million.

Detector Technology R&D

Food and insect irradiation are characterized by very high doses and requirements for high-quality image processing. In the next 3-5 years, efforts related to electronic noise associated with imaging could lead to significant improvements in imaging. Additional improvements can be obtained from investment in algorithm development, including with the aid of machine learning approaches.

3.5 Application Area 4: Sterile Insect Technology

3.5.1 Introduction

Sterile insect technique or technology (SIT) is a method of controlling insect populations harmful to agriculture and human health by rendering a sufficient number of male species of these insects sterile and releasing them to mate with females to produce offspring that are harmless. [Dyck-2005] The technique is used around the world. It has been used to control fruit-fly pests such as the Mediterranean fruit-fly, the Mexican fruit-fly, and eradicate screwworm flies whose larvae invade open wounds and eat into animal flesh. SIT is part of a comprehensive pest management program for controlling insects. [Dyck-2005] Ionizing radiation is currently the method of choice for SIT programs around the world. [Bakri-2005] Male sterility is achieved through the effects of the ionizing radiation on the insects' reproductive cells. The insects are made reproductively sterile by inducing chromosome fragmentation of the gonial cells. Somatic cells are generally resistant to the ionizing radiation doses because they have lost their ability to divide.

Sidebar: *Preventing vector-borne diseases: A potential life-saving impact of Compact Accelerators*

Controlling mosquito populations would save thousands of lives at risk from vector-borne viral infections, dengue, chikungunya, yellow fever, and zika transmitted by female mosquitoes mainly of the species *Aedes aegypti.* Dengue alone has put about half of world's population at risk. World Health Organization (WHO) estimates that dengue cases increased from 2.2 million in 2010 to over 3.34 million in 2016. It has been reported in Texas, Hawaii and Florida and is endemic in Puerto Rico. A state-of-emergency was declared in the Philippines in July after over 630 people had died from the infection. In Bangladesh, to date in 2019, over 20,000 have been infected and nearly 200 have died from Dengue. In August, the IAEA sent a team to Bangladesh to explore use of SIT to combat the epidemic there. https://www.thedailystar.net/city/un-joint-team-help-control-aedes-mosquito-breeding-1787833

Compact, smaller footprint and low-cost accelerators can make the radiation-based sterile insect technology (SIT) more effective, accessible and affordable relative to current radioisotope- and x-ray based SIT's. The technique was developed by a USDA scientist in the late 1950's to control such pests as screwworm flies often fatal to both humans and animals, and the fruit fly. It involves "the mass-rearing and sterilization, using radiation, of a target pest, followed by the systematic area-wide release of the sterile males by air over defined areas, where they mate with wild females resulting in no offspring and a declining pest population."

Radiation-based SIT is an environmentally benign, fail-safe pest control mechanism and is thus preferable to genetics-based SIT. One such version of the latter, tested recently in Brazil to control the same mosquito species, *Aedes aegypti,* resulted in undesirable mutations and did not prevent breeding. https://gizmodo.com/genetically-modified-mosquitoes-are-breeding-in-brazil-1838146152

3.5.2 Background and State of Application Development (Q1)

The irradiation doses used in SIT programs range between 5 Gy and 300 Gy. In addition to damaging the reproduction function of the insects, the ionizing radiation can damage other cells thereby reducing their other functions such as ability to survive in the wild. So, the dose received by the insects has to be large enough to sterilize them but, low enough to not render them non-functional reproductively. Precise dosing is also critical, therefore, the DUR within the canister containing the insects has to be 1.0. Presently, photons from gamma sources such as ^{60}Co and ^{137}Cs are the most commonly employed technologies. Gamma sources are convenient because of the low dose rate, negligible temperature increase, and ability to penetrate relatively large canisters of insects. ^{60}Co is the favored gamma source technology because of the photon energy (1.17 MeV and 1.33 MeV) unlike ^{137}Cs which emits photons with 0.66 MeV energy. Batch type (self-contained dry-storage irradiators) and continuous process (panoramic gamma irradiators) are in use around the world. In some facilities, the amount of insects employed by SIT programs can be significant. Therefore, in these instances, panoramic irradiators capable of delivering high precision, DUR that is at almost unity are critically important. The ability to expose very large numbers of male insects is ideal. Given the security challenges associated with ^{137}Cs and ^{60}Co, alternate accelerator based technologies are urgently needed.

3.5.3 Regulatory Framework (Q2)

The SIT programs around the world are part of area-wide integrated pest management programs. Agricultural agencies around the world are closely involved in SIT programs. In the United States, the United States Department of Agriculture Animal and Plant Inspection Service and state agricultural agencies oversee the SIT programs.

3.5.4 Economic Analysis (Q3)

The use of SIT to control New World screwworm was successful in many parts of North America, South America, Africa, and in the Caribbean Islands. Economically SIT programs have been estimated to have saved \$796 million in the US, \$292 million in Mexico, and approximately \$80 million in Panama. If the screwworm is eradicated in South America, the economic benefits could potentially translate to \$3.5 billion in this region. [Vargas-Teran-2005]

3.5.5 Performance Criteria (Q3)

The primary goal of machine sources of ionizing radiation for SIT programs will be to deliver precise doses for sterilizing male insects that have been reared in specialized rearing facilities.

Given below are the requirements for new accelerator-based systems:

- Core technology: electrons or x-ray photons
- Target minimum and upper doses: 5 Gy – 500 Gy
- Energy requirements and energy spread: fully tunable 0.5 MeV – 5 MeV. Research is needed to determine energy and energy spread effects on DUR and biological response of insects
- Effective source size: > 2 cm
- Directionality: unidirectional
- Pulse structure: CW/pulsed. Pulse structure should be designed to deliver uniform dose on insects within a primary container
- Intensity or flux: Research is needed to get a clear understanding of dose rate on biological response in insects
- Ancillary equipment: Robust conveyor and cooling system, full automation including dose measurement and control. Ability to rely on generator sets if needed for prime power.
- Throughput: low to medium
- Equipment footprint: compact, modular
- Weight (including any shielding): light, self-shielded, compact, portable
- Power: Ideally < 1 kW
- Reliability: robust, transportable, tolerate ambient temperatures

3.5.6 Technical Gaps (Q4)

The technology gaps that exist today for SIT accelerators are summarized in the table below.

Requirement	Present Technical Limitation and Need
Accelerator technology for SIT applications.	• Accelerators customized for SIT programs are not commercially available. Only x-ray tube-based (150 – 225 kV) irradiators for SIT are currently available. The dose uniformity of x-ray tube based SIT irradiators can deteriorate over time, and replacement costs are not negligible. Compact panoramic or batch scale accelerator based x-ray systems customized for SIT are unavailable. Existing medical and security inspection accelerators that might otherwise be adaptable to SIT are hampered by the size, weight, and overall efficiency of the accelerator and high voltage (> 100 kV) RF sources that operate in S-band (~3 GHz) to X-band (~10 GHz). Need higher frequency, low cost accelerators and sources to allow much more compact SIT systems. Need cost effective means of producing high frequency accelerating structures at the required dimensional accuracy.
Ruggedized compact SIT accelerators for global use	• The reliability (no performance deficit, no failure modes) of current x-ray tube SIT systems is a key current technology gap. • Existing RF accelerators, however, lack a graceful failure mechanism due to the single high powered RF source used to energize them. Existing accelerator structures and the RF sources are highly sensitive to shock and vibration, and the high voltages required by their RF sources cause deterioration in high temperature and high humidity ambients. Vacuum or insulating ceramic-to-metal seals in accelerators are vulnerable to shock and corrosion. Need robust RF sources operating at lower voltages and robust accelerator structures.
Dose uniformity	• Existing x-ray tube systems are not tunable in energy and have a very broad low-energy spectrum. The x-ray dose distribution form typical accelerator targets is highly peaked at the center, and since SIT requires a very precise dose, it requires either complete shielding at the periphery and a thus a very small usable exposure area, or a flattening filter with a central partial absorption with tapering to the edges to achieve a uniform (but much lower) dose over a large area. Both existing techniques cause further system degradation in conversion efficiency due to wasted radiation. Need methods to produce x-rays with an intrinsically more uniform profiles.
Efficient conversion of e-beam to x-ray	• The typical (< 10%) conversion efficiency between accelerated electrons and the resulting x-rays from targets in conventional accelerators is too low, which makes the required accelerator beam power and the driving RF source power undesirably large, and creates thermal management problems. Need more direct, efficient methods of x-ray production.
Customized SIT accelerator design software	• Design software technical gaps include the lack of capabilities for end-to-end modeling from the acceleration through the x-ray production and collimation. Need optimization of usable x-ray production efficiency from wall plug to x-rays, and beam uniformity optimization from cathode to x-ray production.
Improved control systems and computational prediction	• Need Machine Learning (ML)/ AI software for finding optimum operational points from simulation data. Need central data repositories to house operational data. • Controls software should able to incorporate all downstream data (heating, x-ray production). Controls software should be able to provide compensations, peripheral interface control algorithms, and also protect against unwanted effects

3.5.7 Synergistic Application-Side R&D (Q5)

Minimum E-beam doses for inactivation of pupae: Most of the currently available information about minimum doses for inactivation of pupae and other insect life stages are derived for gamma sources (with significantly lower dose rates). There is a need for research on a) identifying minimum E-beam doses for inactivation of insects (at different life stages), b) identifying whether high dose rate E-Beam irradiation would create anoxic conditions in packaged produce and ultimately affecting insect viability. Advancing research in these areas will result in benchmarking the target minimum doses which will ultimately lead to improved machine specifications and operating parameters.

3.5.8 Required R&D to Bridge Technical Gaps (Q6)

Lower cost compact accelerators and RF sources	
Near Term R&D	Longer Term R&D
Investigations of methods to make lower cost accelerators and RF source structures by incorporating additive manufacturing	Develop rugged, compact, self-shielded, in-line low energy (0.5 MeV – 5 MeV), low power accelerator technology with final system integration as the goal
New types of ultra-compact vacuum electron RF sources at higher frequencies (> 20 GHz), and corresponding higher frequency accelerating structures	Incorporate higher frequency source and accelerator structure technology into a commercially manufactured SIT system
Research on higher powered solid-state RF sources at microwave to mm-wave frequencies with characteristics optimized for driving SIT accelerators	Demonstration of a working SIT accelerator in the desired form factor and required total beam power and energy using microwave transistors as the RF sources

Efficient conversion of e-beam to x-ray	
Near Term R&D	Longer Term R&D
Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures	Demonstrate suitably effective and compact high efficiency emission of x-rays from e-beam
Research on methods that allow energy recycling	Research on speculative fully-direct methods of producing x-rays from bunched beams in a compact package, in ways that allow the possibility of RF power recycling for high overall efficiency

Control Systems and Computation	
Near Term R&D	Longer Term R&D
Develop an HPC physics and engineering, multi-physics software suite capable of taking advantage of computational accelerators (e.g., GPUs) for end-to-end optimization and design of x-ray generating compact accelerators.	
Develop machine learning framework	
Adapt machine learning framework to simulation data	
Incorporate operational data and machine learning into a controls system	

3.5.9 Barriers to Commercialization and Technology Introduction (Q7)

The SIT market is small. Therefore, there is little vested interest in commercial investment into developing SIT-customized accelerators. For the targeted pricing to be realized, the eventual market must be large enough to bring in economies of scale in component procurement and manufacturing. A significant barrier is to identify a source of funding for the development period between prototype demonstration and creation of a self-sustaining market. Therefore, the R&D costs cannot be covered by a single manufacturer or group of potential customers, but would instead likely needed to be supported with substantial non-commercial investment, either individual governments, private non-profits, inter-governmental bodies. The others barriers are the cost and perceived operational complexity of an accelerator-based system compared to radioisotopes. For eventual customer adoption of the technology, the flexibility and benefits for SIT enabled by the precise energy control, narrowband spectrum, and dose uniformity must be clearly shown to be advantageous vs. present methods. The operational and maintenance requirements of accelerator-based systems have to be demonstrated to be acceptable to customers, and in particular less burdensome that those of present methods. The improved safety of a non-radioisotope, accelerator-based system and the benefits of a likely lower regulatory burden and oversight (and associated financial costs) must be accepted by customers as valid and economically sound.

Roadmap for Development (Q7)[8]

Overall, the SIT development roadmap has many similarities to some of the x-ray systems and gamma-level x-rays discussed in Security Application numbers 1 and 2, so if some of those applications are pursued, the investments there can be leveraged for SIT. However, if a dedicated accelerator-based SIT system is to be pursued independently, a suitable R&D roadmap is presented in the remainder of this section.

Lower cost compact accelerators and RF sources

Near Term: *Investigations of methods to make lower cost accelerators and RF source structures by incorporating additive manufacturing*, SBIR/STTR. 2-3 years, $2 to $3 million. *New types of compact vacuum electron RF sources at higher frequencies (> 20 GHz)*. University research, 1-3 years, $3 to $6 million, followed by industry, 2 years, $2 to $4 million. Perform in concert with corresponding *High frequency accelerator structure development*, industry or national accelerator facility, 2-4 years, $3 to $7 million. *Research on accelerators for SIT using solid-state RF sources* requires a portfolio of investments at a combination of solid-state device manufacturers, national accelerator facilities or national labs, and the commercial accelerator industry. Investments in the solid-state device industry for improved transistors with higher power at the relevant microwave frequencies would require $4 to $10 million over about 2-3 years.

Longer Term: *Transition Accelerator SIT technology to commercially viable product* $5 to $10 million 5+ years. It would be very important to involve potential customers at a global level during this transition process to ensure that any such developed product meets expectations, and that the product boasts flexibility and performance well beyond the methods it is intended to replace. Emphasis on cost reduction at every stage of the component sourcing and manufacturing process is particularly important to obtain a viable product. *Commercial ultra-compact SIT accelerator with the required total beam power and energy using microwave transistors as the RF sources*, national lab-industry partnership, 5+ years, $5 to $12 million.

Efficient conversion of e-beam to x-ray

Near Term: *Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures or by direct beam-wave interaction methods*, university and national labs, 3-5 years, $5 to $10 million. *Research on methods that allow energy recycling,* 3-5 years, $5 to $10 million.

Longer Term: *Demonstate suitable effective and compact high efficiency emission of x-ray from e-beam*, 5-10 years, $15 to $25 million. *Research on speculative fully-direct methods of producing x-rays from*

---

[8] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

bunched beams in a compact package, in ways that allow the possibility of RF power recycling for high overall efficiency, 10+ years, $10's millions.

Control Systems and Computation

Near Term*: Develop an HPC physics and engineering, multi-physics software suite capable of taking advantage of computational accelerators (e.g., GPUs) for end-to-end optimization and design of x-ray generating compact accelerators*, $3 million. *Develop machine learning framework,* $1 million, *Adapt machine learning framework to simulation data,* $1 million. *Adapt machine learning framework to operational data,* $1 million. *Incorporate operational data and machine learning into a controls system*, $2 million.

3.6 Application Area 5: Sterilization of Medical Devices and Pharmaceuticals

3.6.1 Introduction

The vast majority of medical devices in the US are single use devices. They are sterilized by one of multiple available technologies soon after manufacturing [IIA-2017]. The devices are often transported to commercial sterilization facilities for sterilization. The FDA requires a specific SAL (Sterility Assurance Level) depending on whether the product is invasive (10^{-6} SAL) or non-invasive (10^{-3} SAL). Ethylene oxide and ^{60}Co are the legacy sterilization technologies of the medical device industry. However, the increasing transportation costs, growing lack of available of sterilization capacity, and increasing sterilization cost increases are driving the need for alternate sterilization technologies such as e-beam and x-ray. The decreasing availability of ^{60}Co is a major driver for the need of alternate technologies such as e-beam and x-ray.

3.6.2 Background and State of Application Development (Q1)

The current breakdown of the medical device sterilization modalities in the US is as follows: ethylene oxide sterilization (~50%), ^{60}Co-based gamma sterilization (~40%), e-beam sterilization (~8%) and other modalities (~2%). Many of the major medical device manufacturers in the US and overseas rely on both in-house and commercial third party sterilization providers. Changing from one sterilization modality to another is not trivial for the medical device industry and, therefore, adoption of alternate technologies can be beset with both regulatory burden as well as technological challenges such as material compatibility and device functionality [Murphy-2019]. Some of the large medical device manufacturers in the US, Europe and Asia have in-house sterilization capabilities. Some of these manufacturers have both in-house gamma and or e-beam sterilization capability. Off-site or contract sterilization accounts for the largest share of the market. These facilities are characterized by high activity ^{60}Co sources and high energy (10 MeV) relatively high power (between 40 kW – 100 kW) accelerator technologies. However, current manufacturing paradigms are requiring that companies reduce the transportation costs, reduce the product losses from transporting inventory back-and-forth to an irradiation service center, and gain greater control of finished products. The requirement to “design for sterilization” is forcing companies to closely evaluate in-line or end-of-line sterilization activities.

Some medical device manufacturers have in-house (end-of-line) s-band LINAC and Rhodotron-based e-beam systems in operation already. These facilities can treat approximately in excess of 500,000 devices per hour and have a lower per unit cost for e-beam sterilization compared to gamma sterilization. There is one commercial sterilization service provider in Europe that utilizes high power x-ray system. Other similar systems are currently under design or construction in the US. Based on industry experts, the precise dose delivery and high throughput capabilities of e-beam sterilization technology is a major differentiator. The ability to deliver precise sterilization doses in turn reduces the chances for product failure and thereby also indirectly contributes to reduced costs for e-beam compared to other technologies. Therefore, the economic incentive for adopting e-beam technology exists. There is no industry-wide move to switch to in-house or end-of-line sterilization. The exact step where sterilization occurs in the manufacturing of a medical device will have a critical impact on the adoption of accelerator technology. Given the consolidation of the medical device industry over the past few years, and the globalized distribution of manufacturing centers necessitate a closer look at e-beam technologies that can be deployed in house in different parts of the world. There is a need for compact accelerators that can be deployed either in-house or in-line, or end-of-line. Also, the need for sterilization of sub-assemblies prior to final packaging and shipping facilitates the incorporation of bespoken in-line e-beam systems.

The requirement for in-house, in-line or end-of-line sterilization needs require accelerators that are robust, capable of easy integration and validation, and can withstand the harsh manufacturing conditions (including sub-optimal electrical grids) in some developing countries. There is significant diversity in the size, density, shape, and throughput of medical devices. Therefore, it is difficult to prescribe a standard set of accelerator specifications. However, what is not widely available today are in-line e-beam accelerators for the medical device and pharmaceutical industries such as shelf-shielded low to medium energy (2-8 MeV) e-beam accelerator systems. Robust, small footprint, easy to install, validate, and operate accelerators are needed. The availability of in-line and end of line sterilization capability can allow for better single piece manufacturing flow. There is a need for compact, robust easy to use accelerators globally. However, these in-line systems should be capable of up-times > 95% and be available to operate 24/7. Accelerators capable of delivering e-beam in the 3 MeV range are required for this purpose. The power requirement will be in the 60-100 kW. The DUR requirements can be stringent in such applications especially when single devices are treated under the beam. Adjustable energies and power settings are ideal for this purpose. Mid energy (2-8 MeV), low power accelerators can be quite attractive to small to medium sized medical device manufacturer.

Robust, small footprint, easy to install, validate, and operate accelerators are needed.

Given that a major of medical devices are sterilized off-site, there is growing interest in being able to perform pallet-level x-ray treatment. Major equipment providers are now gearing up to offer such large panoramic x-ray irradiation systems. Presently, there are only two such large x-ray pallet irradiators in commercial operation in Switzerland and in TINT in Thailand. In the US, x-ray conversion can take place for e-beam energies up to 7.5 MeV. However, in other countries the e-beam energy for conversion cannot exceed 5 MeV. Recent developments in accelerator technology such as SRF technology can make a difference in the technology options that are available to the industrial sterilization market especially the high power needs of large footprint, high energy x-ray and e-beam systems. The issue of complex shielding requirements with increasing energy cannot be overlooked. Therefore, alongside improvements in accelerator design, operation and efficiency, research in new shielding material is needed. Non concrete-based shielding can make a substantial impact on the adoption of in-house and in-line e-beam technology.

3.6.3 Regulatory Framework (Q2)

There is a mature regulatory framework surrounding the use of e-beam technology for the medical device and pharmaceutical industries. The ISO standard [ISO-11137:3-2017] specifically addresses the setting of sterilization doses, as well as the validation and routine control of ionizing radiation technology for the sterilization of medical devices. The ISO standard is agnostic in terms of the specific ionizing radiation modality (gamma or x-ray or e-beam). However, to switch from one modality to another, for example from gamma to e-beam or x-ray requires submission of paperwork to meet regulatory requirements. Thus, the regulatory environment for adoption of e-beam technology can be characterized as “ready-now”.

3.6.4 Economic Analysis (Q3)

The US has the largest medical device market in the world and is estimated at around $2 billion. There is a robust medical device manufacturing and assembly industry in Mexico, Latin America, Asia, and Europe where e-beam and x-ray sterilization capabilities are needed. The medical device industry is of strategic importance to the United States. The industry currently employs close to 500,000 people and has almost $140 billion impact on the US economy. [Frost and Sullivan-2016] It is estimated that the medical device industry grows between 5-7% annually in the US. Therefore, the sterilization market for services and equipment which is currently valued at around $2 billion annually is also expected to see strong growth over the foreseeable future. [Markets and Markets Research-2016; SelectUSA-2018] Large medical product manufacturers operate their own sterilization facilities as well as utilize 3rd party sterilization service providers. Smaller manufacturers—which comprise about 80% of the market—utilize third party providers. Due to the growing shortage of gamma irradiation capacity, there is a rapidly growing demand for accelerator-based e-beam and x-ray technology and technology service providers.

3.6.5 Performance Criteria (Q3)

The primary application of accelerator technology in the medical and pharma industries is for assuring a specific SAL. Therefore, minimum doses in the range of upwards of 8 kGy is routine. Given below are the performance criteria required of e-beam or x-ray sterilization systems customized for the medical device industry:

- Core technology: electrons or x-ray photons
- Target minimum and upper doses: 8 kGy – 25 kGy
- Energy requirements and energy spread: fully tunable between 1 MeV – 10 MeV. Research still needed to understand energy spread effects on DUR and biological response
- Effective source size: > 2 cm
- Directionality: unidirectional
- Pulse structure: CW/pulsed. Pulse structure should be designed to deliver uniform dose on a moving product and achieving the desired biological effects. Research needed to determine effect of intensity or flux on DUR and biological response
- Power and throughput requirements: from 15 kW to greater than 1 MW for high power e-beam and x-ray systems. Ability to handle high product throughputs is a necessity. Need for customized low power (5 kW) in-line to 100 kW end of line systems needed
- Ancillary technologies: full integrated control, dose measurement, product conveyance and machine cooling systems. Easy to operate user interfaces
- Equipment footprint: compact, small footprint systems needed
- Weight (including any shielding): Lighter the better. Self-shielded preferable. Alternatively, optimized shielding
- Reliability: very high priority for robust (>95%) uptime. Remove diagnostic, and machine health performance monitoring

3.6.6 Technical Gaps (Q4)

Some key technical gaps or current technology limitations tabulated below are a precursor to the specific R&D topics and proposed research roadmap to be discussed later.

Requirement	Present Technical Limitation and Need
Compact, variable energy, and variable power	• Compact, fully integrated, ruggedized, variable energy, variable power configuration accelerators are not widely available. Conventional RF sources and accelerators only produce high efficiency at their maximum power point, limiting flexibility, and creating poor efficiencies that are not compatible with high dose, high throughput medical and pharmaceutical sterilization. Need a combined RF source / accelerator technology that retains high efficiency over a broad range of beam powers. Conventional accelerators would likely need to have MW-level electrical service requirements to meet the full specifications, which is often too high for the economics of the intended application and presents thermal management problems. SRF technology can enable high powered accelerators having

	low electrical power consumption. Need to leverage the US investment on SRF technology, and utilize high powered SRF linear accelerators for emerging x-ray sterilization market.
Compact, modular, medium to high energy accelerator systems	• Medium to high energy systems customized for insertion into manufacturing (in-line or end of line configuration) are not widely available. Need a common modular design framework and assembly process for a family of accelerators suitable for various applications having different energy and power levels and working area requirements. Limitations on tolerable power consumption, cooling requirements, size and weight, cannot generally be met with conventional room temperature pulsed accelerators. The challenges for x-ray systems are 10x-20x more severe (due to poor conversion efficiency) than direct e-beam systems. Also needed are systems engineering and methods to control and monitor the performance. Intelligent techniques in the architecture, design, test and operational phases are needed.
Dosage guidelines for the industry	• Fundamental information about how dose rate and electron/x-ray photon energy affects microbial inactivation is still in its infancy. Prototype machine that can "dial in" many beam shapes and are fully outfitted with dose monitoring, etc., would be important, along with complementary modeling. The materials science, physics and chemistry of the end product need to be considered. The data from these studies can improve the physical models as well as help create surrogate models, can help with the systems optimization, anchoring of codes, etc. New codes that are also HPC compatible are needed.
Operator interfaces and control systems	• Need to design standardized user interfaces for machine control so any user of one machine can understand and operate another machine. Stringent control systems needed for stringent dose delivery requirements.
Machine reliability, active machine health monitoring	• Standardization is key to long life, the ability to repair with compatible spare parts, and ease of use by defining standards for the user interface. The machine should actively collect application and operational data which automatically feed the machine learning databases for active equipment monitoring and development of new reliable machines. Need accelerator systems with no performance deficit and minimal failure modes.
Computational tools	• A more complete set of computational tools that allows component level analysis, multiple component or subsystem analysis, as well as start-to-end simulations is needed. Tools needed to predict beam energy/dose rate effects on materials, size, shape, density as well as considerations for the beam diagnostics and radiation detectors for verification of current, power, dose, etc. along the machine. These tools need to be both first principles codes for detailed analysis as well as semi-analytic models to allow rapid, approximate calculations during the scoping of design and parameter space. Validated computational tools should be widely available.
System integration and operation	• None of the accelerators today are commercially available as a fully integrated system with the product handling sub-systems. Installation qualification and performance qualification can take 12 months. Need significant overall engineering for reliability and a prototype for testing to enable turnkey systems. Superior data science (including control) techniques are required.
Compact, ruggedized accelerator technology global use	• RF sources with a single, high-powered amplifier or oscillator are subject to single point of failure of a very high cost item, and inventories of expensive spare parts and repair expertise are prohibitive. The high voltage supplies of such single source systems are subject to failure in hot, high humidity environments. Need a lower voltage, distributed RF source technology (with less expensive, smaller components) that tolerates individual source

	degradation / failures without compromising overall accelerator performance.
Efficient conversion of e-beam to x-ray	• Bremsstrahlung from collisions of electrons with dense metal targets produces broadband x-rays with weak high energy tail and is very inefficient. Sterilization systems that directly irradiate with e-beams avoid this inefficiency, but the penetration depth of e-beams is much less than that of x-rays, unless very high energy electrons are used. In addition, e-beam irradiation is not suitable for all types of medical devices, particularly those with insulating polymers, which can be damaged by charge buildup and tracking. x-ray systems are more versatile from a product and operations standpoint, but more efficient methods of x-ray production are needed.

3.6.7 Synergistic Application-Side R&D (Q5)

Some of the current disposable medical devices have in-built disposable sensors (measuring pressure, flowrate, etc.). Many of such sensors were designed for EtO sterilization and have therefore not compatible with E-beam or x-ray sterilization since they become non-functional. There is an R&D need to either redesign such sensors for accelerator-based sterilization (ionizing, high-dose rate exposure) or develop novel coatings to protect such sensors from the detrimental effects of E-Beam /or x-ray sterilization doses. Similarly, a deeper understanding of the effects of dose rate or incremental dosing on microbial inactivation can help fine tune the doses employed in the medical device industry. The ability to interrogate survivors on devices and determine whether it survived particular sterilization doses and technology can be beneficial in understanding root causes of sterilization failures.

3.6.8 Required R&D to Bridge Technical Gaps (Q6)

The R&D required to bridge the current technical gaps in machine sources for sterilizing medical devices share many similarities to the food irradiation systems discussed in Security Application number 3. Therefore, these have not been repeated here in full detail. Rather, given below is a tabulation of near term and longer term R&D that is focused on the accelerator technologies particularly pertaining to the medical device and pharmaceutical industries.

Accelerator technology development	
Near Term R&D	Longer Term R&D
Develop a prototype of a tunable, low energy (2-5 MeV) high power (average power 10kW) CW LINAC using SRF accelerator technology customized for the medical device industry	Build a 4K SRF-based 10MeV, 60 kW protype machine
Research on high charge drive electron beams at ~10 MeV, average currents of 10 mA, from an SRF injector High efficiency reliable rf drive systems compatible with SRF LINAC requirements	Develop a compact SRF accelerator for generating 1 MW beam power to address x-ray sterilization needs
Higher frequency rhodotron-like devices with greater compactness	
Improved lower-voltage multiple-beam klystrons and power-combined magnetron sources for powering S-band LINACs	
More robust S-band accelerator structures	
New types of vacuum electron RF sources and accelerating structures at frequencies above 10 GHz	Develop commercially viable accelerator systems above 10 GHz
Research for improvement in transistors with higher power at relevant microwave frequencies	Demonstration of a working accelerator (in the desired form factor and required total beam power and energy) using microwave transistors as the RF sources

Lower cost accelerators and RF sources	
Near Term R&D	Longer – Term R&D
Research on technologies to fabricate lower cost accelerators and RF source structures by incorporating additive manufacturing, or modular designs with common component and design framework	Technology transfer and transition to accelerator laboratory and commercial accelerator industry
Research on electron bunch shaping technology for high-repetition rate beam drivers	Research on system integration. Performance and stability development
Research on thermally managed dielectric or metallic structures capable of high gradient and high-repetition rates and high average power, ~1-10 MeV	
Research on modeling and simulation techniques	

Efficient conversion of e-beam to x-ray	
Near Term R&D	Longer-Term R&D
Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures or by direct beam-wave interaction methods	Demonstrate suitable effective and compact high efficiency emission of x-ray from e-beam
Research on methods that allow energy recycling	Research on speculative fully-direct methods of producing x-rays from bunched beams in a compact package, in ways that allow the possibility of RF power recycling for high overall efficiency

Alternative Shielding Materials	
Near Term R&D	Longer Term R&D
Advanced light-weight metal foams, polymer-composites, and embedded glassy matrix materials	

3.6.9 Barriers to Commercialization and Technology Introduction (Q6)

Current FDA regulations require an extensive set of documentation to switch the sterilization modality completely. However, for better e-beam systems replacing existing e-beam systems, the barrier is lower since the underlying technology is the same. Nevertheless, extensive installation qualification, operational qualification and process qualifications are needed prior to the industry accepting a new LINAC technology. Additionally, proof of better performance in terms of throughput, ability to place in-line made possible by compactness, and the economics of operation compared to the status-quo are all barriers that must be overcome through demonstrations with rigorous test plans, quantitative analysis, and documentation. The CAPEX, lack of deep knowledge of e-beam and x-ray technologies, need for device functionality testing and device material compatibility are some of the contemporary challenges facing the quick switch over from gamma to e-beam or x-ray technologies.

Roadmap for Development (Q7)[9]

Overall, the accelerator-based medical and pharmaceutical sterilization development roadmap has many similarities to the food irradiation systems discussed in Section 3.4, so if some of those applications are pursued, the investments there can be leveraged. However, if a dedicated accelerator-based medical and pharmaceutical sterilization system is to be pursued independently, a suitable R&D roadmap is presented in the remainder of this section.

---

[9] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

Accelerator technology development

Near Term: *Develop a prototype of a tunable, low energy (2-5MeV) high power (average power 10 kW) CW LINAC using SRF accelerator technology*, 2-3 years, $2.5 million. *Research on high charge drive electron beams at ~10 MeV, average currents of 10 mA, from an SRF injector*; 5 year, $5 million. *High efficiency reliable rf drive systems compatible with SRF LINAC requirements*, 3-4 years, $3 to $6 million. *Research on higher frequency rhodotron-like devices with greater compactness*, industry, 3-4 years, $5 to $10 million. *Research on improved lower-voltage multiple-beam klystrons and power-combined magnetron soruces for powering S-band LINACs*, microwave tube industry, 3-4 years, $5 to $10 million. *Research on more robust S-band accelerator structures,* industry funding, 3 years, $5 million. *Research on developing new types of vacuum electron RF sources at higher frequencies than 10 GHz*, university, 3 years, $3 to $6 million. *Research for improvement in transistors with higher power at relevant microwave frequencies*, 2-3 years, $4 to $10 million. *Must link all activities to system engineering practices as well as engineering co-design. Also must consider the end use including the controls and computing requirements during the design and operation phase. Materials science and engineering underlying these topics must also be considered. Opurtunities exist to leverage other investments (e.g., the DOD) in RF source technology.*
Longer Term: *Build a 4K SRF-based 10MeV, 60 kW protype machine*, 4-5 years, $5 to $10 million. *Develop a compact SRF accelerator for generating 1 MW beam power to address x-ray sterilization needs,* national labs, 5 years, $5 to $10 million. *Development of commercially reliable sterilization accelerators operating above 10 GHz*, 3-4 years beyond near term effors, national or industry funding, $10 to $15 million. *Demonstration of a working accelerator in the desired form factor and required total beam power and energy using microwave transistors as the RF sources*, 4-8 years, $5 to $12 million.

Lower cost accelerators and RF sources

Near Term: *Research on technologies to fabricate lower cost accelerators and RF source structures by incorporating additive manufacturing, or modular designs with common component and design framework,* university, 2-3 years, $3 million. *Research on electron bunch shaping technology for high-repetition rate beam drivers*, 3 years, $3 million. *Research on thermally managed dielectric or metallic structures capable of high gradient and high-repetition rates and high average power, ~1-10 MeV,* 3 years, $3 million. *Research on modeling and simulation techniques and proof of principle demonstration*.
Longer-Term: *Technology transfer and transition to accelerator laboratory and commercial accelerator industry*, 5-10 years, $4 to $5 million. *Must link all activities to system engineering practices as well as engineering co-design. Research on system integration. Performance and stability development*, 5+ years, > $5 million. *Also must consider the end use including the controls and computing requirements in design and operation phase. Include underlying materials sciance and technologyies like 3D printing and investment casting for integration aspects*.

Alternative shielding materials

Near Term: *Alternative shielding from advanced light-weight metal foams, polymer-composites, and embedded glassy matrix materials*, university and industry, 2-3 years, $0.5 to $5 million.

Efficient conversion of e-beam to x-ray

Near Term: *Discovering and developing methods of production of x-rays (or gamma-energy photons) more efficiently from novel target structures or by direct beam-wave interaction methods,* university and national labs, 3- 5 years, $5 to $10 million. *Research on methods that allow energy recycling*, 3-5 years, $5 to $10 million.
Longer Term: *Demonstate suitable effective and compact high efficiency emission of x-ray from e-beam*, 5-10 years, $15 to $25 million. *Research on speculative fully-direct methods of producing x-rays from*

bunched beams in a compact package, in ways that allow the possibility of RF power recycling for high overall efficiency, 10+ years, $10’s of millions.

4. Medical Applications of Compact Accelerators

4.1 Introduction

Since the discovery of x-rays by Roentgen in 1895, ionizing radiation has been used in many areas of medicine. While most commonly thought of in connection with diagnostic imaging and cancer treatment, it is also used in the sterilization of equipment, blood products, and many other applications. Ionizing radiation can be produced by accelerating particles such as electrons, protons, or other ionic species and either using the particle beams directly or by using the secondary radiation generated by impacting charged particles with a target. Radioactive sources are also a source of ionizing radiation. Gamma-rays from a variety of isotopes including ^{60}Co and ^{137}Cs sources are commonly used for sterilization purposes but in developed countries generally are limited to brachytherapy or laboratory equipment. Special purpose devices such as the Gamma Knife, which utilizes 192 separate ^{60}Co sources directed at a central target, are an exception to this. However, other radioactive sources such as ^{125}I, ^{103}Pd, and ^{192}Ir are commonly used in brachytherapy applications in which a radioactive source is inserted into a tumor for a period of time to deliver a localized dose of radiation. In this section of the report we will consider how advances in accelerator technology can impact all these areas to improve treatment efficiency and safety and at the same time reducing cost to the health care system.

Comprehensive cancer treatment involves a combination of surgery, radiation therapy, chemotherapy, and more recently some forms of immunotherapy. These treatments are given either as a single modality treatment or as a planned combination of treatments. Linear accelerators are used to generate the majority of photon beams used in the radiotherapeutic treatment of cancer patients. In 2019, in the United States alone, there will be approximately 1.76 million new cases of cancer annually, excluding non-melanoma skin cancer, and approximately 0.6 million cancer related deaths. [McGee-2019] Approximately 50% of these patients will be treated with radiation at some point in their disease course, either as part of their primary treatment or as palliative treatment after recurrence of their initial tumor. Modern linear accelerators are technologically sophisticated devices which require highly-trained staff to operate reliably and a sophisticated maintenance program requiring a cadre of trained service people and a robust parts supply chain for optimal operation. These devices are expensive, typically costing $1.7 to $2.3 million (negotiated prices are often considerably less than list prices) with vendor service contracts in the range of $200,000 annually. In the United States there are approximately 4000 linear accelerators in cancer treatment centers, supported by Medical Physicists and utilized by Radiation Oncologists who are physicians with special training in the therapeutic use of radiation. However, these devices are not uniformly distributed and there are areas of the United States, such as Appalachia, the North American Indian tribal reservations, and the more sparsely populated areas where there are few treatment units and where a low-cost, robust unit would allow increased access.

World-wide in 2018 there were about 17 million new cancer cases annually in 2015 and about 9.6 million cancer deaths. [Parodi-2018] The majority of these deaths occurred in LMICs due to lack of adequate health care, including insufficient access to radiotherapy. It has been estimated that an investment in the order of $185 billion would be required to bring up the level of access to radiation therapy in LMICs and even then, the necessary infrastructure, including trained personnel, for reliably operating these systems would be lacking. The societal costs of inadequate cancer treatment is a huge economic burden to these countries and this will ultimately adversely affect the economies of the developed nations. Solving this problem involves rethinking the design and operation of medical linear accelerators to lower their initial and operating costs and to make them operate reliably in environments with suboptimal supporting systems and to automate their operation to a large extent such that personnel at intermediate skill levels can operate them. We refer to this as “robustness” in design and operation and developing the technologies to bring this about is one of the main thrusts of this workshop. It will be necessary to bring the cost of an accelerator therapy system into the range of ~$500,000 to $1 million to make it attractive for global placement, but lowering the ongoing operational costs is equally important to a successful operation.

Figure 4.1. *KAMPALA, UGANDA - JULY 2013: A Ugandan women receives radiation treatment for cervical cancer at the Mulago Hospital, in Kampala, Uganda, July 19, 2013. While Uganda was able to get a handle on the AIDs epidemic through ARV drugs and assistance from the international community, the country still struggles with how to treat and diagnose an overwhelming number of Cancer patients across the country. Thousands are currently being treated by only a handful of trained Oncologists in the entire country of Uganda; basic chemotherapy and Cancer medicines are often in short supply or unavailable, the radiation machine is outdated, in-patient beds are limited, and most Cancer patients can not afford transportation fare to reach diagnosis and treatment in Kampala from villages across the country. (Image credit: Lynsey Addario/Getty Images Reportage)*[10]

Although the overall cost-effectiveness and value of radiation therapy is well-established, its availability on a global scale is limited. There are many countries, particularly low- and middle-income countries (LMICs) where the availability is well below the internationally recognized standard of 1 treatment unit per 100-200 thousand people. Senegal, for example, has one unit where there should be an estimated 9. Ghana has 2 units where there should be 24. The IAEA estimates a need for at least 5000 more treatment machines in LMICs. [Abdel-Wahab-2013]. This gap in access, combined with the growing burden of disease globally makes this shortage increasingly acute. [Atun-2015]

Technology is one of the main drivers of this gap in access of care. [Atun-2015] While a major factor in high-income countries is the salaries of employees, in LMICs, where the gap is most acute, the main driver of cost is equipment. A survey of current accelerator technologies reveals the following major components: photon beams (4-18 MV) to treat deep-seated tissue, electron beams (6-20 MV) to treat relatively superficial tissue. These have largely supplanted ^{60}Co teletherapy units in high-income settings due to larger depth penetration, smaller spot size and higher outputs, though there some special purpose units like the Gamma Knife stereotactic radiosurgery unit (Elekta Inc.) which rely on ^{60}Co.

---

[10] Used with permission from Getty Images.

Importantly, any medical therapy device must consider the whole package of delivering therapy to the patient and not just the accelerator itself. This includes: (1) beam modifiers such as the multi-leaf collimator (MLC) which shape the beam and allow for intensity-modulated radiation therapy, and (2) image-guided systems such as cone-beam CT which provide improved accuracy by allowing image-based alignment just prior to treatment, (3) quality assurance systems which provide an independent verification that the therapy is delivered as intended. These ancillary needs should be considered in conjunction with accelerator design, since each is equally important to achieving effective and safe treatments.

Improvements can also be made in the current state-of-the-art linear accelerators used for cancer therapy in well-developed countries and so we want to take a global perspective on the accelerator needs in medicine. In this workshop we have identified 7 areas that we feel have great potential for improving the current status:

(i) Development of low cost, robust accelerators for human clinical use,
(ii) Development of accelerators tailored to preclinical and translational research needs including FLASH-RT
(iii) Development of detectors appropriate for modern radiotherapy such as high dose rate FLASH-RT and real-time image acquisition for image-guided radiotherapy,
(iv) Development of better collimators which are used to shape radiation beams used in therapy,
(v) Development of simplified operational and controls systems taking advantage of expert systems and neural network approaches,
(vi) Development of systems to shift planning and delivery away from physical dose distributions to biologically effective doses, and
(vii) Development of compact neutron beam sources appropriate for work on neutron capture therapy (NCT).

We discuss each of these areas below and explain why we feel the time is right for research and development investment. We also have included sections relating to accelerator-based neutron sources which would be important in allowing research in NCT to be more wide spread and could be key to bringing this conceptually-interesting approach into routine clinical use. A discussion of the process used and the results of a "brain storming" session that allowed the participants to produce ideas and concepts that may have been outside the main topic areas of the conference is in Section 6.2.

Beyond cancer care, ionizing radiation has proven to be exceptionally useful in the elimination of biological contaminants in medical devices and blood products. The global market for sterilization is estimated to be $8.5 billion in 2018 with 40-50% of disposable medical products being sterilized with irradiation techniques. [IAEA-2008] The development of compact, secure, and reliable irradiation sources (both x-rays and electrons) will support the anticipated global growth in disposable healthcare products. In addition, cost pressures are supporting the use of re-usable medical devices and radiation-based sterilization has benefits regarding complex devices with limited access sub-compartments. Current systems require substantial infrastructure for deployment including shielding, controlled environments, and reliable power sources. This aspect of medical radiation therapy has significant overlap with the security applications and is addressed in the security chapter given that the issues, technologies, and developmental needs are very similar.

4.2 Application Area 1: Development of low-cost, robust accelerators for clinical and preclinical use based upon a modular component approach

4.2.1 Background and State of Application Development (Q1)

In addition to the basic background information described above, there are some additional factors relating to the clinical and preclinical use of accelerators. Any medical therapy device must consider the whole package of delivering therapy to the patient and not just the accelerator itself. This includes: (1) beam modifiers such as the MLC which shape the beam and allow for intensity-modulated radiation therapy, and (2) image-guided systems such as cone-beam CT which provide improved accuracy by allowing image-based alignment just prior to treatment, (3) quality assurance systems which provide an independent verification that the therapy is delivered as intended. These ancillary needs should be considered in conjunction with accelerator design, since each is equally important to achieving effective and safe treatments.

With this as background, we consider the limitations of current technology as well as directions for growth for next generation technologies. One of the most important considerations is reliability. In many places current medical accelerators operate with an uptime in excess of 98%. This is acceptable in most high-income countries where service engineers are immediately available and supply chains are well established. One major vendor of medical linear accelerators, for example, has only 70 engineers to service all of Africa, the Middle East, and India. If there is a hardware issue with a treatment unit in this environment it may be many days or weeks before the problem can be addressed. In the meantime, patient treatments must stop if there is no other center nearby that can absorb the load. The end result is that an uptime of 98 or 99% may appear exceptionally good on paper, but the means of maintaining it may be unsustainable in an environment where there is not adequate support. In some countries treatment units, while available, are not in use because they cannot be maintained. [Reichenvater-2016]

The second need is in the realm of infrastructure. The linear accelerator depends on the local power grid, cooling systems, networking technology and other infrastructure. The next generation of technology should reduce the reliance on this infrastructure.

The third need is in the form factor of the LINAC and the need to develop a very small source of radiation for research and the clinic that might ultimately be digital and “array-able.” New “on a chip devices” are coming forward presently and may offer significant improvement in delivery of radiation, from collimation to brachytherapy compatibility, to array use, and finally to cost. They make a strong argument that the LINAC need not weigh more than 10 pounds or cost more than a few thousand dollars with replaceable “bulbs” that would be very low cost.

New “on a chip devices” are coming forward presently and may offer significant improvement in delivery of radiation, from collimation to brachytherapy compatibility, to array use, and finally to cost.

Most radiation oncology treatments utilize external radiation sources. However, there is another treatment approach, brachytherapy, which utilizes the introduction of a controlled radiation source directly into the body, has clear advantages for targeting dose, preserving adjacent tissues and limiting damage to surrounding organs. Several commercial brachytherapy products exist, but the majority incorporate naturally radioactive materials that cannot be turned off and on and have limited control of dose distribution.

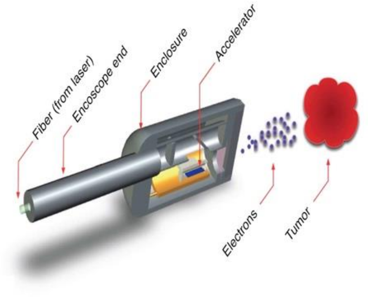


Figure 4.2. *Conceptual illustration of an encapsulated endoscopic electron accelerator for medical radiation applications mounted on the end of an optical fiber, power by a fiber-transported laser system with a small accelerator head which could use either dielectric or plasma based acceleration technologies. Such methods deliver much more concentrated dose than conventional methods resulting in lower dose to healthy tissue. Image credit: [Travish-2011]*

An ultracompact, self-contained multi-MeV electron source would enable minimally invasive cancer treatments and alterable dose deposition in real-time, thus providing the benefits of brachytherapy while offering much better dose control. Encapsulated devices would ideally have variable electron energies in the 1-10 MeV range, a footprint that is millimeter-scale, and accommodate a wide range of emission angles for various treatment modalities (Figure 4.2). Unwanted dose to nearby healthy tissue and critical structures could be intrinsically reduced (up to 30-fold) as compared to photon therapy, due to the finite range of the accelerated electrons. This enables up to a 3-fold increase in dose to the lesion together with a 10-fold reduction in dose to adjacent structures. The manufacturing and operating costs are anticipated to be much lower than those for conventional radiation therapy machines, and the robustness of such systems compared to conventional accelerators should be even more favorable.

Developments in this application area aim to produce complete particle accelerator systems that are miniaturized into mm or cm scale devices using semiconductor chips, plasma media or terahertz (THz) structures. Such systems could be powered by modern solid state lasers and use flexible power delivery conduits. The three main technical paths offer realistic paths to source-free brachytherapy using accelerators small enough for endoscopic application are: dielectric ‘accelerators on a chip’ (DLA), laser plasma wakefield accelerators (LWFA), and THz structures.

DLA have the potential to create ultra-compact accelerators using structures that are constructed using the same nanofabrication methods used in the integrated circuit industry. The dielectric and semiconductor materials required have damage limits corresponding to acceleration fields’ orders of magnitude larger than conventional radiofrequency accelerators, allowing for a factor 100 or more reduction in size. Such materials are also amenable to rapid and inexpensive complementary metal–oxide–semiconductor (CMOS) and micro-electromechanical system (MEMS) fabrication methods. These technological developments (Figure 4.3), combined with new concepts for efficient field confinement using optical waveguides and photonic crystals [Hughes-2018], and the first demonstration experiments of near-field structure-based laser acceleration conducted within the last few years [Peralta-2013; Leedle-2018; Black-2019; McNeur-2016; Niedermayer-2018; Cesar-2018] have set the stage for making integrated laser-driven micro-accelerators or DLAs for a variety of real-world applications. [England-2014] Current research efforts in the US and Europe aim to produce a first working prototype with MeV class electrons in a “shoebox” size device by 2020.

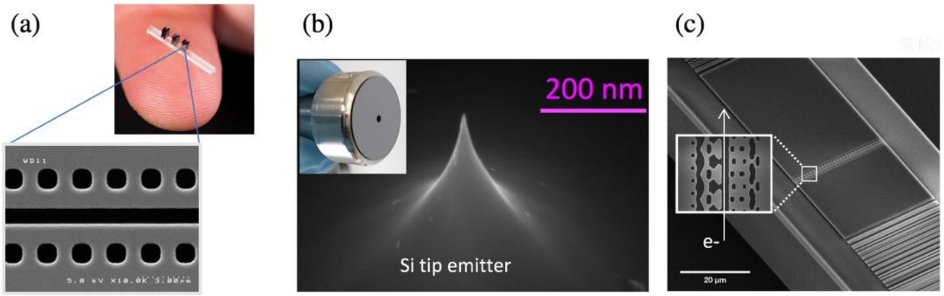


Figure 4.3. *Examples of recent developments in making integrated photonic particle accelerators, include (a) monolithic silicon accelerator devices [Chang-2014], (b) demonstration of compatible nanotip field emission sources and incorporation into cm-scale miniaturized electron gun (inset). [Ceballos-2019], and (c) integration with on-chip waveguide systems coupled to an external fiber laser. [Sapra-2020]. Image credits (a) SLAC[11], (b), Ceballos and Leedle[12], and (c) Reprinted with permission from AAAS.[13]*

Laser-plasma wakefield accelerators offer a second path to ultra-compact devices, using the very high fields that can be sustained by plasma waves. Acceleration to > 10 MeV energies over mm length scale has been demonstrated. Research must now address minimization of the laser energy delivery time based on recent generation devices to produce MeV electrons using mJ in a few fs laser pulses. THz accelerators using flexible power conduits offer a third technology option.

The near term R&D challenges across the candidate technology are detailed in the technology sections and include optimizing, fabricating, and demonstrating proposed designs for electron injection, acceleration coupling, transport, and focusing to realize few-MeV-class acceleration first in cm scale devices and then mm-scale devices. Reliable operation suitable for operation by users not expert in laser/accelerator science, and either durable or disposable designs, are needed. For DLA, cascading of multiple acceleration stages is needed to reach useable average beam powers in the few mW range. For LWFA, compact compression and gas target systems are needed. Given the rapid progress in this area, demonstration of prototypes based on either technology for medical applications is achievable on a 5 year time scale, with development and exploration of commercialization options on a 5-10 year scale. There has already been some preliminary commercial interest. Varian Medical Systems has submitted a patent in this area and Hamamatsu Photonics is an active scientific partner on existing R&D programs. Developments should target the desired parameter ranges in Table 4.1 (a and b).

Finally, the technology needs to be simplified and automated in a way that reduces the current reliance on highly trained staff. Such staff are not available in many countries. Medical physicists, for example, are considered essential to maintaining the technology, however, there are fewer than 400 medical physicists currently in the whole of Africa. This situation is unlikely to substantially change in the coming decades.

In summary, there is an acute need for more radiation treatment units in the global context. [Zubizaretta - 2017] Current technology, however, is not sustainable for many countries.

---

[11] SLAC, "Accelerator on a Chip." Accessed https://www6.slac.stanford.edu/sites/www6.slac.stanford.edu/files/images/2015-1030-9427-accel_on_a_chip.jpg

[12] Used with permission from Ken Leedle (inset) and Andrew Ceballos (electron microscope image) [Ceballos-2019].

[13] From N.V. Sapra, Yang, K.Y., Vercruysse, D., Leedle, K.J., Black, D.S., England, R.J., Su, L., Trivedi, R., Miao, Y., Solgaard, O., Byer, R.L., and Vučković, J. On-chip integrated laser-driven particle accelerator. Science 367(6473), Jan. 3, 2020. Reprinted with permission from AAAS.

Current State

The maximum machine dose rate for a patient approved device is about 2400 cGy/min at 15 MV for up to 40x40 cm (open field). The effective dose rate falls to about 10-50 % of this when multileaf collimator (MLC) motion beam modulation is involved in intensity modulated radiotherapy (IMRT). A typical LINAC at 10 MV with a current of 50 microamps has a beam that operates at about 300 pulses per second. Current machines have flat panel systems that can collect orthogonal images and via cone beam software can collect volumetric data collection this data. Some systems have multi-detector systems in place in addition to or in the place of flat panel detectors. Machine quality assurance is a time consuming, typically manual process for physicists with daily, weekly, monthly and annual tasks set by regulation. LINACs require temperature and pressure compensation and the commissioning of these machines can take weeks to months.

Electronic medical record systems are layered on top of these machines. These include systems to record and verify the clinical elements of the treatment plan to assure consistent treatments over the multiple fractions. More granular data about machine performance are not included. The spot dose rate and other fine parameters are typically not saved after the completion of a fraction or if saved, are in a format that is proprietary. Automation in this space is underway due to the view that doing such will save time, decrease cost, and increase safety.

Most commercial LINACs used in the medical environment are S-band systems that fit well within the typical C-arm orientation of a clinical LINAC. X-band units exist within several commercial systems, two examples are an early CT based helical device and a robotic device. Magnetic resonance (MR) imaging technologies are being merged with delivery systems. The first version of the MR-guided RT systems used a ^{60}Co source but newer systems employ higher MR field strength and integrated LINACs to deliver dose. Typical fully functional clinical RT systems cost approximately $2.5 million (excluding the support contracts, software maintenance contracts, and facility costs) and MR-guided RT systems are in the range of $6 million.

Desired State

The next version of a LINAC should offer state of the art capacities that can exist anywhere in the world and deliver a level of care that will be considered correct anywhere in the world.

In this context, expertise can be distributed and shared given a common platform and processes can be developed to share and interact as demand requires so that teams have more virtual hands. Additionally, the scaling of systems will allow and promote investment in addressing the complexity of the process via computational systems that are modular, open, robust, and potentially in the cloud (or can be cloud oriented for verification and back-up use). This would then be more sustainable given the standardization of system, integrated control environment, and increasing operational simplicity inherent in advanced software designed for such a purpose.

Modularity and standards-based interfaces would allow smaller units of function to be developed and enhanced, opening up competition and global integration. Detector units could be improved by one company and easily utilized in another company's LINAC device. Big data software analysis packages could see and interrogate sensors and systems across the entire space using standard query code. Adaptive interfaces for unique electrical and other infrastructure demands could be standardized affordably. By maximizing the market space, the world's engineers and companies would be incentivized to invest in solving problems that otherwise would be too small in scale to address. Finally, these machines should be both affordable enough and scalable enough to fit within the space of a pre-clinical center and to expand with future technologies avoiding obsolescence. Additionally, these systems should allow interface and imaging components if not the same LINAC components to deliver hadron therapy via LINAC so as to lower costs and improve global access if these beams prove to be useful once Level 1 evidence available. Finally, these machines need to be easy to manufacture, repair, deliver, use, maintain, and tolerate environmental extremes, be able to run without external power for significant periods of time, have a standard form factor, be sold in large numbers, and be extremely reliable. A major challenge will be to develop a control system and quality control system that will work without error in such a modular system.

4.2.2 Regulatory Framework (Q2)

a. Clinical
    i. The use of different kinds of ionizing radiation in healthcare has a robust regulatory framework in the United States and developed countries but less so in LMICs
    ii. 510k is a well-used framework for innovation in RT
    iii. FDA submissions for new forms of RT
b. Preclinical
    i. No animal-specific regulation
c. Potential concerns:
    i. Shielding: Elevated dose rates may exceed the design limits of currently used treatment rooms when FLASH and VHEE are used
    ii. Laser hazards for plasma-based accelerators
d. Security concerns:
    i. NNSA – radiological dispersal device risk – ^{137}Cs higher risk than ^{60}Co for example; developing LINACs that can replace various types of sources is considered advantageous
    ii. NRC – regulations are robust for isotopes in the clinic, but removal of isotopes in the clinic would simplify clinical operations and likely decrease accidental exposures because LINACs have the ability to be turned off
e. Summary: Current regulatory framework is robust and minor adaption of current regulations will be able to address all the discussed new technologies. Animal framework is likely adequate if IRB approvals and such are conducted per standard animal ethical standards.

4.2.3 Economic Analysis (Q3)

The economic analysis for LINACS is complex and multifactorial. It encompasses acquisition cost, operation costs, repair contract cost, parts cost, bunker design costs, staffing costs, and ultimately the cost in terms of patient lives saved (less loss of productive people) and decreased side effect costs. From a domestic point of view, LINAC treatments affect about half of all patients at one point in their diagnosis and with fees from $5,000 for palliative single fraction care to upwards of $30,000 or more for complex, definitive courses like stereotactic body radiation therapy (SBRT). Simply adding one additional treatment machine can significantly reduce the number and cost of treatment interruptions.

Taken further, machines that are more reliable, easier to work with and so need fewer human resources, and that are less resource intensive inherently make economic sense. Furthermore, development of sophisticated methods and engineering to avoid side effects avoids costly medical care for patients to treat those side effects. A more potent and important argument can be made regarding economics and that is the global avoidance of loss of life would mean for the world if more LINACS could be deployed. A recent Lancet article summarizes the need and investment required world-wide. By 2025, LMICs will need to raise $46 billion to cover just the needs for radiotherapy infrastructure. In this context, thousands of machines and experts are needed now and more will be needed in the future.

4.2.4 Performance Criteria (Q3)

Macroscopic Accelerator Requirements

Source Property	Now [*]	Threshold [*]	Objective [*]
Particle. [McGee-2019]	Photon/Gamma		High Energy x-ray
Effective Source Size	2mm/1.5 cm		2 mm
Directionality	Emitting into 40x40 cm^2 @ 1m		Emitting into 40x40 cm^2 @ 1m
Tunable energy range	6 MVp/Ebar=1.25		6-10 MVp
Tuning speed. [Parodi-2018]	<1 cGy delivered		<1 cGy delivered
Energy spread	Bremsstrahlung up to peak potential/spectrum		Bremsstrahlung Spectrum
Pulse structure. [Kirsh-2018]	3us@10ms/isotope		Flexible
Intensity or Flux	3-12 Gy/min (>1Gy/min)		>10 Gy/min
Stability/Jitter Requirements	Source position stable relative to collimation (<0.5mm displacement)		Same
	Dose control better than 2% or within 1 cGy on total dose delivered to a subject in ideal conditions		
Uptime in high service setting	>98.5%		99%
Uptime in low service setting	30%		99%
Cost	$1-3 million		$0.5-1.0 million and robust with lower operating costs
Failure prediction	n/a		On vacuum/components
Automation Needed. [Boss-2014]	Integrated safety systems; motion control		QA/Safety/Calibration/Planning
Size	Fits within 600 ft^2 shielded bunker		Fits in a shipping container
Weight	2-5 tons		
Power	Supply 50 kW for /500W for ^{60}Co		Works in unstable power setting
Portability	Not portable		Drop-ship capable
Acceleration/Shock	Not tolerated except earthquake		same
Op. Temp range	HVAC control – 15ºC-30ºC		15ºC-45ºC

[1] - electron, x-ray, high energy x-ray, neutron

[2] - for example, the maximum allowable time to change between beam energies

[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.

[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)

[*] - "Now" - values available from current commercial products

[*] - "Threshold" - minimum increase in performance that would **meaningfully impact** the application

[*] - "Objective" - desired increase in performance needed to provide a **transformative improvement** in the application

Microscopic Accelerator Requirements:

Source Property	**Now [*]**	**Threshold [*]**	**Objective [*]**
Particle. [McGee-2019]		electron	electron
Effective Source Size		mm	<mm
Directionality		Broad angle, including scatter.	2 pi or dual direction
Tunable energy range		1 MeV Brems	10 MeV
Tuning speed. [Parodi-2018]		n/a	n/a
Energy spread		Bremsstrahlung	+/-1 MeV
Pulse structure. [Kirsh-2018]			
Intensity or Flux		10 Gy/min	50 Gy/s or higher
Stability/Jitter Requirements			
Size (head only, not supply)		cm scale	mm scale (and directional)
Size (support systems)		No requirement	No requirement
Uptime in high service setting	days to 1 week (limited by field emitter lifetime)		> 1 week, plus ability to rapidly swap out disposable "chips"
Cost	\$300,000 to \$600,000 (cost driver is the laser)		< \$300,000 (market-driven laser costs decrease over time, chips can be mass produced at minimal cost per unit)
Failure prediction	None		Online tuning feedback
Automation needed	None, manual tuning		automated feedback control enabled by high rep. rates
Size	12x6 in. footprint, not including laser dimensions		2-3 mm x 3 cm footprint, plus external rack-mounted laser
Weight	10 pounds, using conventional UHV components		few ounces, encapsulated in a sealed vacuum tube
Power	1 Watt of average laser power		< 100 W of average laser power (with increase in beam power, aided by improved coupling efficiency)
Portability	low to moderate		highly portable
Ruggedness	low to moderate		encapsulated designs would enable high ruggedness
Op. Temp Range	room temperature +/- 2^{o}F		room temperature < 1^{o}F stability, with active heat dissipation and temperature regulation

[1] - electron, x-ray, high energy x-ray, neutron
[2] - for example, the maximum allowable time to change between beam energies
[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.
[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)
[*] - "Now" - values available from current commercial products
[*] - "Threshold" - minimum increase in performance that would **meaningfully impact** the application
[*] - "Objective" - desired increase in performance needed to provide a **transformative improvement** in the application

4.2.5 Technical Gaps (Q4)

Among the most important technological gaps are the size, weight, and lifetime of the vacuum electronic RF sources (klystron or magnetron) needed to drive the accelerator, as well as the high voltage pulsed power supply (> 100 kV) needed to power them. The lack of a graceful failure behavior of such sources, and a single point failure creating a total system failure behavior of these components, is another problem. The difficultly in producing cost-effective RF sources that would be more amenable to being stocked as onsite spare parts provides a further complicating factor. Another technology gap that drives compactness concerns the efficiency of the RF sources; devising methods to raise the efficiency would result in smaller prime power supplies, and would also reduce size and heat removal capacity of RF source cooling system. With most medical accelerators being either S-band or C-band, which are physically large due to the wavelength-dictated size the accelerating structure, the RF source, and the intervening waveguide components, scaling to higher frequencies (above ~15 GHz) for these baseline clinical units would allow additional compactness if sufficiently accurate accelerating structures could be reliably and cost effectively made, and if appropriately powered RF sources were available at the higher frequencies. At both today's lower frequencies and especially at higher frequencies, the durability of the accelerating structure and the ability to maintain its structural integrity, frequency tuning, and alignment in the presence of shock, temperature extremes, and other rough handling, is in need of improvement. The thermionic cathodes used as the electron source in both the accelerator electron gun and in vacuum electronic-based RF sources presents power consumption, lifetime, and complexity of repair problems, particularly for the accelerator electron gun. The inability of a standard accelerator to maintain an exceptionally good vacuum (below 10^{-9} torr) in the presence of extensive power failures or high target heat loading is another notable technology gap.

The design of these systems brings new challenges to the modeling software needs. In modeling of traditional, larger accelerators, one can separate the various physical processes of electromagnetics, charged particle transport, parasitic losses (due, e.g., to multipacting), and thermal transport. The resulting current system of modeling relies on a series of "handoffs" between different software packages. This current state of modeling is both human intensive and slow. It is human intensive because each of these data transfers relies on developing and running custom software.

The single most critical technological gap in LINAC design, the beam collimator, has been expanded into a full application in this chapter (Application 4) – beam modulation and shaping. Currently this aspect of a LINAC has the most mechanic parts, the highest failure rate, and if replaced by blocks the most significant impact on beam modulation delivery.

DLA, LWFA, and THz accelerators for endoscopic accelerators

Technology gaps for the in silicon LINAC are present in heat, collimation and power dimensions. Advanced compact high gradient accelerators are ultra-compact sources but limited in their ability to produce high average current beams. The inherent charge-per-pulse of these accelerators is too low. High repetition rate laser drivers are still being developed for laser-driven advanced accelerators. High repetition beam-driven particle sources are available for plasma wakefield accelerators (PWFA) and structure wakefield accelerators (SWFA) but making them compact and portable is still awaiting development.

Accessing these benefits requires development of MeV sources at cm to mm scale which is a good fit to high gradient advanced accelerator concepts and, in particular, laser-plasma and laser-structure based accelerators, and THz accelerators. Such accelerators and systems at present are at somewhat early TRLs but substantially more advanced than other advanced approaches because they can use existing laser drivers. Testing is realistic in the 5 year time frame.

4.2.6 Synergistic Application-Side R&D (Q5)

Current needs include the following:

- MV FLASH photon – efficient – duty cycle – dose rate needs integrate all aspects of the technology development needs
- VHEE FLASH – 100-200 MeV – better depth-dose characteristics as compared to photons
- System design challenges – improved modelling of complex systems benefits many areas of science and engineering.
- Photonic powered linear accelerator of 3cm length – tiny LINACs may prove to allow whole new areas of use not currently envisioned
- Neutron dosimetry in proton radiotherapy
- Dose and Dose Rate Reconstruction
    - Photon counting arrays
    - Energy range
    - Spatial resolution
    - 3D linear energy transfer (LET) measurement system
- Activation By-product Imaging
    - FLASH and VHEE enabled
    - Photo- and proto- activation
- pO2 - Oxygen depletion imaging
    - Measure this on the time scale of oxygen depletion
    - Optical methods – see oxylite technology – oxygen mediated fluorescent decay
- Robust Performance/Security/Safety Detector
    - Unstructured detectors feeding machine learning frameworks
    - Prompt Gamma systems for range verification
    - Proton range estimation that can also detect electrons and photons – proton/photon/electron CT etc.
- Fiducial and Image-guidance Detectors
    - Isotope trackers
    - MR-guided proton/heavy ion/electron/gamma/flash flexible detectors
    - Fully integrated imaging with control system integration vs simply hybrid.
- Re-look at the femtosecond-nanosecond chemical trajectory post-RT
    - optimize the drug side of the equation; non-drug interventions as well; hypocapnia
    - simulation tools for physical chemistry; radical modelling; nanoscale modelling
    - FLASH biology – nuclear event linkage
- Computational/Digital
    - system engineering that allows for in/out of modular components, is super reliable, and gets standardized interface and API’s so that it ultimately becomes universal and robust (and open)
    - big data input and output (collection) built into the system

        - written is easy to maintain code
        - allows regulations to be easy to adapt (entire device need not be re-510k'd for component changes, less cost and red-tape)
    - LINAC imaging with energy tunability rather than using x-ray tubes to be evaluated with detectors, multiple energy exposures, and high throughput capacity, likely to be closely aligned with security applications

4.2.7 Required R&D to Bridge Technical Gaps (Q6)

Research on how to more effectively fabricate vacuum electronic RF sources like klystrons or magnetrons in ways that would reduce costs (by 10x), increase the attractiveness of maintaining inventories of spare parts at the accelerator site, and facilitate rapid service would be needed. Specifically, research and development on creating a flexible, modular design and fabrication methodology with common families of pre-engineered guns or cathodes, beam transport systems, beam collectors, and interaction structures at various frequencies and powers that can be quickly combined without extensive setup and engineering costs is a means to solve these technical challenges. Research on additive manufacturing of some vacuum electronic source components would be an important topic within this area (Section 5.3.3).

Research on accelerators driven entirely by solid-state microwave transistors (wide bandgap materials, for example, GaN HEMTs) as the RF sources, including new accelerator structures specifically amenable to accommodating multiple transistors per cavity, would be of interest in achieving compactness and eliminating the reliability problems associated with conventional RF sources requiring extremely high voltage pulsed power supplies. Research on understanding the impacts of such a distributed architecture on efficiency and reliability is therefore also needed (Section 5.3.2). The cost of the transistors is a significant impediment to further progress, so methods of fabricating microwave transistors at 10x to 100x lower cost than at present should be researched, for the typical output power (500 W peak at 5.5 GHz). From the standpoint of easing the burden of integrating large numbers of transistor packages, fundamental device research aimed at increasing the output power of a single packaged transistor by 10x (to 5 kW peak at 5.5 GHz, and preferably at higher frequencies of 10-30 GHz), while keeping unit costs essentially unchanged, would be an especially interesting topic. Research on the benefits of higher duty cycle accelerator operation, made possible by microwave transistors, and its impact on different dosing waveforms, would be useful as a potential means to deliver the same dose at a lower overall power consumption.

Device-level research on microwave transistor structures (and constituent semiconductor materials) specifically designed for the relatively high impedance, narrowband resonant load characteristics of accelerator structures would be of interest. This is in stark contrast to present-day microwave transistors that are actually designed and optimized for overly low voltages (~50 V) and very high currents to power broadband communications applications, which are very different from the requirements of powering accelerators. Research on entirely new classes of transistors that avoid the discrepancy between transistor terminal current-voltage characteristics and the accelerator load behavior would result in less complex matching circuitry much higher efficiency. Research on transistor devices and accelerator powering topologies allowing highly efficient class C amplifier operation or even class D switched mode operation could ultimately allow efficiencies approaching 95%.

Research on higher current, more robust cold-cathode technology based on field emitters, especially for the accelerator electron gun (but also for the cathodes of vacuum electronic RF sources), would be important to avoid the typical thermionic failure and produce beams with lower emittance to reduce beam interception and thermal loading in accelerator structures. Cathode research on the issue of emittance in microfabricated field emitter arrays and methods to control it with multiple focusing electrodes to control beamlet spread, and research to improve the resistance of such cathodes to ion back-bombardment and arcing, are both topics of note. Quantum mechanical density functional theory (DFT) modeling of nano-emitters to understand surface states and the effects of absorbed impurities would elucidate fundamental limits on performance and suggest methods of improvement.

Improving the durability of the accelerator structure could be accomplished by developing methods of depositing high RF conductivity normal metals on robust structural metals (that avoid deformation) in ways that allow the high conductivity film to maintain its characteristics and adhesion in spite of high RF currents, high surface electric fields, and a large amount of thermal cycling. Improvement in the vacuum levels and avoidance of outgassing in the accelerator structure, gun, and target, to the point where power interruptions can be tolerated.

For advanced compact high gradient accelerators, research into how to inject substantially more charge to be trapped for acceleration would be required. This will require further research into: (1) improving the efficiency of energy transfer from the driver to the accelerated beam in main accelerator section, (2) high average current beam sources, and driver technology. Robust operation regimes and miniaturized devices must be developed. The structure based technologies (SWFA and DLA) will benefit from advances in materials and fabrication processes for both dielectric and metallic materials.

There is a need for integrated modeling capability that can simultaneously compute the electromagnetic fields, the transport of charged particles (electrons) through those fields, the extent of parasitic multipacting losses, and the thermal transport.

Compact clinical and preclinical accelerator-based therapy systems would benefit from using shielding/collimator materials that improve operational performance, safety, and minimize overall size and weight. Optimization of the shielding must account for factors such as workload, use and occupancy, and regulations on maximum permissible exposure and their effect on design. Research is needed on advanced light-weight metal foams, polymer-composites, and embedded glassy matrix materials that show promise for cost effective, compact shielding applications.

A reliable source of power is central to accelerator-based medical systems especially in regions with a poor electrical grid system and are subject to harsh environmental conditions. An early disciplined system engineering approach toward highly efficient accelerator design and development could incorporate technology that results in more continuous, affordable, and sustainable operations (Section 5.3.6).

The ultrahigh dose rates required for FLASH-RT will require considerable research and engineering on accelerator design. This is discussed more completely later in the report.

LWFA for Endoscopic Accelerators

Sources at the mm to cm scale are required with clinically relevant dose-rates of ~10 Gy/min at a range of ~4 cm. Variable electron energy from 1-10 MeV is desirable on a pulse-by-pulse basis during treatment. Wide angle emission is needed, potentially including use of a scatterer (ideal is ~2π). This confers extra degrees of freedom for planning and provides the clinician the ability to improve the dose delivery options and the therapeutic index.

THz Accelerators for Endoscopic Accelerators

In order to have substantial impact towards possible applications, performance in energy, beam charge, size, and brightness need to be much improved. The R&D needed include mm-scale MeV sources powered with laser-driven THz source, development of injectors, laser-driven source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ).

4.2.8 Barriers to Commercialization and Technology Introduction (Q6)

There are two levels of barrier in this space, intrinsic and extrinsic. Both are surmountable and it is possible to overcome them in the short term. The intrinsic issues are those that are part of the problem in this context, so the development and technological needs. Funding support of the science will allow issues of dose rate, size, computational infrastructure, tolerance to harsh environments, overall size, overall reliability, etc., to be developed. Potential extrinsic technology introduction barriers can occur when trying to replace established isotope-based systems with a perceived costly and complex accelerator-based therapy system.

Roadmap for Development (Q7)[14]

The research on a flexible, modular design and fabrication methodology for vacuum electronic RF sources for accelerators could be done through a combination of the microwave power tube industry, the modeling and simulation software industry (those specializing in EM software and beam-wave interactions), and research university, including internship opportunities for students with industrial partners. This research effort would require 3-4 years and a total cost between $3 and $6 million.

Research on solid-state driven accelerators with commercially available wide-bandgap microwave transistors would be best performed at a combination of DOE national laboratories and research university. Costs of completely developing and demonstrating this technology in a working accelerator at several MeV and suitable for medical applications would cost between $15 and $30 million, and would require 3-5 years to complete. At this point it would be ready to transition to commercial accelerator manufacturers. The problem of reducing the cost of the wide bandgap transistors is a complex process, but progress is already being made due to the driving forces from the commercial communications industry. For the accelerator application, it might be possible to merely take advantage of these trends without additional funding. However, to achieve really high pulsed powers (to 5 MW peak at microwave frequencies) in a compact transistor package is an accelerator-specific task that would require funding at both university specializing in semiconductor device development and fabrication ($2 to $4 million total over 3-5 years), followed by transition to the wide-bandgap semiconductor device industry with total additional development costs of $10 to $20 million, over a duration of 3 years.

For the fundamental studies of new types of transistor structures and materials more suited to the problem of driving high impedance, narrowband accelerator structures, the bulk of the research is most suited towards research university specializing in solid state device research and electronic materials research. Many such university have the smaller scale semiconductor and dielectric materials synthesis facilities and small microfabrication lines suitable for making demonstration solid-state devices. The fundamental research effort would require 4-6 years at a total cost of $2 to $4 million. This could then be transitioned to the commercial wide-bandgap semiconductor industry that has the capabilities for mass production. To speed transition, it would be most useful if the earlier university work used processes that were reasonably consistent with the fabrication lines used by industry, so some university-industry partnerships as the earlier university work reaches its conclusion would be useful. The industry research would take about 3 additional years at a cost of around $10 million.

Research on better cold cathodes could take place at university at the $2 to $5 million dollar total level, with durations of 2-3 years. The program could consist of both experimental fabrication and testing, as well as theoretical surface chemistry modeling. Transition to the semiconductor industry would take an additional 2-3 years and total expenditures of $4 to $8 million.

---

[14] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

Research on improving the vacuum levels, by way of better passive getters, could be performed in industry for about $1 million total over 2 years. Development of durable normal RF coatings over robust metals could be performed at a university for about $1 million total over 3 years, followed by transition to the commercial accelerator industry for an additional $2 million total over 2 years. Development of accelerator fabrication and processing strategies for lower outgassing and compatibility with ion pumps and long shutdowns should be performed in the commercial accelerator industry, for a total cost of $2 to $4 million over 2-4 years.

In computational needs, development of improved design codes can go hand in hand with the research into algorithms and methodologies. This would most likely rely on public-private partnership, most probably with small business independent software vendor willing to modify its development roadmap. Such an effort would take a team of roughly 6 staff (2 for computational engine, 1 for graphical user interface, 1 for infrastructure, 2 for analysis of experimental data, modelling, and code validation) over 3 years, for a total cost on the order of $4 million.

The goal of advanced accelerator research in this area is to carry ideas relating to the production of relativistic electron and ion beams from small scale laboratory tests presently underway to practical application in the field. This involves R&D to improve the performance of such devices in terms of power, control and efficiency, but more importantly to make the devices reliable, compact and robust so they are practical in a clinical setting when operated by non-physicists. Since there are a number of possible approaches presently studied for such application the development plan in each area is specific to that particular approach. We detail those approaches below.

LWFA/THz for Endoscopic Accelerators

Radiation driven compact high gradient accelerators such as LWFA and THz are natural candidates for endoscopic application. However, the extreme smallness and flexibility required of the tether are still quite removed from the present maturity of these two accelerator types. Quick and substantial investment in these areas for these two accelerators may allow rapid maturation in the near future to change the landscape for endoscopic medical applications.

1) LWFA

a) Electron beams at 1-10 MeV from a LWFA using mJ few fs laser pulses: initial demonstrations accomplished, performance and stability development in progress. 2 years, $2 million.
b) Few-cycle laser broadening and compression at few mJ energies, using COTS 7mJ-class 30 fs drive laser at kHz repetition rates. 2 years, $1 million.
c) Flexible laser transport and dispersion management to deliver compressed few cycle pulse to LWFA. 3 years, $2 million. Longer term, integration of broadening and self-compression in transport system.
d) Miniaturize laser focusing, gas target system and heat management for accelerator head at cm then at mm scale. 4-5 years, $5 million.

2) THz accelerators

a) THz electron injectors. 4 years, $3 million
b) 100 cm scale structures. 2 years, $1 million
c) MW-class switches for power distribution and RF compression. 2 years, $1 million
d) Electron-beam THz source (50% efficient) 5 years, $5 million
e) Laser-driven THs source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ). 3 years, $3 million
f) System integration. Performance and stability development. 5 years, $5 million

4.3 Application Area 2: Expanded operational parameters for beam delivery and management including ultra-high dose rate delivery

4.3.1 Background and State of Application Development (Q1)

The basic background for understanding the use of accelerators in cancer treatment throughout the world is described in Section 4.2.1. Additional factors to consider when considering future technology relate to the fundamental challenge of curing cancer with any form of therapy.

A foundational challenge to curing cancer that pertains to any therapy is to increase the therapeutic index, i.e., cancer killing vs. collateral injury to the patient. Cancer becomes incurable in any patient for whom the treatment required to eradicate the cancer has toxic effects beyond what the patient can tolerate. The primary means by which the therapeutic index of radiation therapy has been increased in the modern era has been to create a physical dose differential between tumors and normal tissues through precise targeting and conformal dose shaping. Nevertheless, normal tissues in close proximity to tumors necessarily receive approximately the same dose as the tumors, and the larger the treatment volume (size and number of target lesions) the lower the dose that can be delivered safely, restricting the curative potential of the treatment.

Recently, a fundamentally different paradigm for increasing the biological therapeutic index of radiation therapy has emerged in preclinical research of FLASH irradiation. FLASH refers to ultra-rapid delivery of radiation doses at rates in the range of approximately 50 to 1000 Gy/sec in delivery times of microseconds to a fraction of a second. By comparison, the highest dose rates achievable in state-of-the-art clinical treatment systems are orders of magnitude lower at approximately 10 Gy/min (0.16 Gy/sec). To date, experiments from a growing number of radiobiology laboratories has demonstrated a “FLASH effect” of substantial normal tissue sparing without compromising tumor killing compared to the same doses of conventional dose rate irradiation. The majority of the experimental data demonstrating the FLASH effect has been in mouse models [Favaudon-2014; Loo-2017; Montay-Gruel-2017, -2018, -2019; Simmons 2019], but it has also been shown recently in cat veterinary patients and mini-pigs [Vozenin 2019], and a first-in-human case report. [Bourhis-2019] In these models, the normal tissue sparing effects of FLASH have been shown in lung (fibrosis) [Favaudon-2014], intestinal tract (GI radiation syndrome) [Loo-2017], skin (necrosis) [Vozenin 2019; Bourhis 2019], and brain (neuroinflammation and neurocognitive impairment). [Montay-Gruel-2017, -2018, -2019; Simmons-2019] Concomitantly multiple tumor types studied in these models including subcutaneous, orthotopic, syngeneic, xenograft, and spontaneous have all demonstrated equal response to both FLASH and conventional dose rate irradiation for the same doses, and preliminarily superior response to FLASH in some models. In addition, the FLASH effect has been observed for multiple radiation types including electrons, synchrotron generated x-rays, and protons.

A fundamentally different paradigm for increasing the biological therapeutic index of radiation therapy has emerged in preclinical research of FLASH irradiation.

While this remarkable phenomenon appears to be reproducible across multiple laboratories and settings, research into its underlying radiobiological mechanisms is only beginning. Physico-chemical modeling and initial experimental data provide evidence that radiochemical oxygen depletion that can be achieved by sufficient doses delivered at FLASH rates but not conventional dose rates may afford normal tissue sparing, perhaps especially in hypoxic stem cell niches. [Spitz-2019; Vozenin 2019; Montay-Gruel-2019; Pratx-2019] Limited experimental data *in vivo* and *in vitro* suggest no difference in DNA damage but reduced expression of inflammatory mediators such as TGF-β, and reduced senescence after FLASH compared to conventional dose rate irradiation of normal tissues and cells. [Favaudon-2014; Buananno-2019] Understanding of the differential effects of FLASH on tumors compared to normal tissues remains limited, although differential iron metabolism has been suggested [Spitz-2019], and preliminary observations of differential tumor immune cell infiltration and vascular endothelial collapse have been described. [Stanford-2019]

The specific parameters required to produce the FLASH effect remain incompletely characterized. Preclinical studies show that when administering 10 Gy single fraction whole brain irradiation, the cognitive sparing of FLASH diminishes when the dose rate falls to 30 Gy/sec or less (or the irradiation time increases to 0.33 sec or longer). [Montay-Gruel-2017] To isolate the impact of irradiation time, whole brain FLASH delivered in ≤0.16 sec demonstrated cognitive sparing whereas a conventional delivery time of 240 sec did not, despite the same total dose, dose per pulse, and number of pulses [Simmons-2019], indicating that total delivery time is an important parameter independent of the pulse structure. Extrapolating to the clinical treatment setting, these suggest that irradiation of the entire treatment volume, inclusive of all beams from different directions (with intensity-modulation) to achieve dose conformity, should be administered with a dose rate exceeding 50 Gy/sec and/or with a total delivery time of less than 0.3 seconds.

Given the transformative potential of FLASH radiation therapy, basic research on accelerator technologies to enable research to advance the mechanistic understanding of FLASH through preclinical experimentation and clinical translation of FLASH to patient care is needed. Preclinical irradiation of small volume targets (the size of a mouse) at FLASH dose rates has been done using existing clinical or research dedicated electron linear accelerators, a synchrotron x-ray beamline, and clinical proton therapy systems. [Schüler-2017; Jaccard 2018; Patriarca-2018; Montay-Gruel-2018] These technologies can also be extended to treat small volume superficial targets such as skin tumors in larger animals and humans. [Vozenin 2019; Bourhis 2019] Translating FLASH to general clinical radiation therapy of deep-seated target volumes (up to several liters total volume) in humans will require capabilities far beyond those of current commercial radiation production technologies.

Treating deep-seated targets with high spatial conformity requires radiation species with adequate penetration and minimal entrance and/or exit dose along the beam path, as well as sharp lateral penumbra. This would include (in order of increasingly favorable depth-dose characteristics): x-rays (6-15 MV energy), very high-energy electrons (VHEE) (100-250 MeV energy), protons (70-250 MeV energy), and heavier ions. Furthermore, clinically practical solutions that will benefit the millions of patients diagnosed with cancer each year, including the majority who live in low-middle income countries with limited access to radiation therapy, requires that the technology solutions be compact, robust, power-efficient, clinically efficient/high patient throughput, user-friendly/automated, and economical. [Pistenmaa-2018] Critical factors for clinical implementation include rapid volumetric imaging and robust safety (beam monitoring and control) systems specifically designed for integration with extremely rapid delivery of radiation therapy.

4.3.2 Regulatory Framework (Q2)

The regulatory framework is described in Section 4.2.2. Existing policies and procedures for use in humans will be employed in this context to permit the use of these methods in human trials and then standard care if deemed safe and effective.

4.3.3 Economic Analysis (Q3)

The relevant economic analysis is described in section 4.2.3.

4.3.4 Performance Criteria (Q3)

Source Property	**Now [*]**	**Threshold [*]**	**Objective [*]**
Particle. [McGee-2019]	Research devices only at present only		Photon and Electron
Effective Source Size	Research only		2 mm
Directionality	Research only		Emitting into 40x40 cm^2 @ 1 m
Tunable energy range	Research only		6-10 MVp
Tuning speed. [Pardodi-2018]	Research only		<1 cGy, but to be determined based on engineering limits imposed by dose rate
Energy spread	Research only		Bremsstrahlung Spectrum
Pulse structure. [Kirsh-2018]	Research only		Single pulse for a full field ideally, to be determined what is allowable based radiobiological research that is ongoing
Intensity or Flux	Research only		>100 Gy/s
Stability/Jitter Requirements	n/a		Source position stable relative to collimation (<0.5 mm displacement). Dose control better than 2% or within 1 cGy on total dose delivered to a subject in ideal conditions
Uptime in high service setting	n/a		99%
Uptime in low service setting	n/a		99%
Cost	n/a		$0.5-1 million but robust with lower operating costs
Failure prediction	n/a		On vacuum and components
Automation Needed. [Boss-2014]	n/a		QA/Safety/Calibration/Planning
Size	n/a		Fits in a shipping container
Weight	n/a		Transportable
Power	n/a		Works in unstable power setting
Portability	Not portable		Drop-ship capable
Acceleration/Shock	n/a		Tolerated as technology allows
Op. Temp range	HVAC control – 15ºC-30ºC		15ºC-45ºC

[1] - electron, x-ray, high energy x-ray, neutron
[2] - for example, the maximum allowable time to change between beam energies
[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.
[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)
[*] - "Now" - values available from current commercial products
[*] - "Threshold" - minimum increase in performance that would **meaningfully impact** the application
[*] - "Objective" - desired increase in performance needed to provide a **transformative improvement** in the application

4.3.5 Technical Gaps (Q4)

No current commercial LINAC based system is in use to deliver VHEE or FLASH radiotherapy to humans. The work at present is limited to pre-clinical research, primarily in mice. Two commercial vendors have publicly announced FLASH therapy capability on proton systems that are deployed in the clinic but no trials are currently accruing human patients and little to no data exist on these methods. It is unclear if these machines can deliver the dose rate to the whole field in question or even if the whole field needs to be treated at exactly the same time or whether it is acceptable for various areas of the field to see dose at different time points. Thus, the use of the word "gap" is really almost too focused a word. We lack the tools to deliver the dose at the high rate reliably, to measure it, to modulate it, and to do quality assurance on such plans. This represents a broad space of interrelated needs and engineering challenges.

Thus, there are considerable technology gaps from the accelerator perspective to deliver FLASH RT dose rates for research and clinical treatment, with the FLASH RT machine needing to deliver several orders of magnitude higher dose rate (at least 50 Gy/s to as much as 300 Gy/s) vs. a standard oncology LINAC (0.02 Gy/s to 0.2 Gy/s). This in turn creates a need for difficult-to-meet increases in operating parameters of the accelerator in regard to higher RF power, duty cycle, and accelerator beam current, as well as with regards to thermal management of the accelerator structure and any x-ray producing target (if used). As a point of reference, a typical S-band fixed-vault medical accelerator (x-ray/electron modes) might operate with a peak RF power of 2.5-5.0 MW at ~3 GHz, an RF duty cycle of 0.1%, a beam energy of 4, 6, or 10 MeV, and have a total time-averaged accelerator beam current of 0.1-0.15 mA (averaging interval includes both RF pulse on and RF pulse off regions of repetitive modulation). One cannot simply raise the duty factor all the way to 100% in a conventional accelerator with these parameters, since both the RF sources and the accelerator structure will not be able to cope with the thermal loading of many megawatts steady-state.

In a typical medical accelerator the beam loading (portion of RF power that gets converted into beam energy) is only 20-30%, with the balance of RF power being dissipated in the walls of the accelerator structure. This is effectively wasted power. When x-ray therapy is used, which is typical for most solid-organ cancers which require the much larger penetration depth of x-rays (compared to electrons of the same energy), the conversion efficiency between electron beam power and x-ray power is only about 5-7% in a typical dense metal target. Thus, achieving FLASH RT levels of radiation requires large increases in all accelerator operating parameters, and the burdens are particularly severe with x-rays due to the poor conversion efficiency. Achieving these significant operating parameter increases while retaining a compact accelerator configuration is even harder to achieve.

VHEE involves the direct use of accelerated electrons for medical treatment, but at much higher energies (>100 MeV) compared to a standard LINAC used in the direct electron irradiation mode. High energy electrons can penetrate tissue to much greater depths compared to lower energy electrons, giving them a vertical dosing profile in tissues that strongly resembles that of x-rays of 6-10 MeV energy employed in a typical clinical accelerator. VHEE can be used for conventional dose rates, with the technical challenge in that case being the achievement of such high energies in a compact accelerator. However, it has a strong advantage when combined with FLASH RT modalities. Since there is no x-ray converter, performing FLASH RT with VHEE produces irradiation 15-20 times more efficiently from the accelerator to tissues compared to x-rays; thus, the burdens of achieving FLASH RT dose rates using VHEE is substantially reduced. Even with VHEE, it is still challenging to create the desired dose rates in a compact accelerator. Scattering properties of these very high energy beams are quite different from those in the energy ranges in clinical use today. These will need to be understood in order to properly make clinical use of these beam. Several accelerator technologies relevant to this application are discussed below.

DLA for FLASH-RT

Advanced compact high gradient accelerators are ultra-compact sources but limited in their ability to produce high average current beams. The inherent charge-per-pulse of these accelerators is too low. High repetition rate laser drivers are still being developed for laser-driven advanced accelerators. At the projected high rep-rates of 10 kHz and higher, the averaged charge and hence average dose rate may be of interest, especially for high energy beams and require development. High repetition beam-driven sources are available for PWFA and SWFA but making them compact and portable is still awaiting development.

LWFA/SWFA/PWFA and THz for FLASH-RT

Conventional RF LINACs cannot deliver x-ray dose rates in short (<500 ms) pulses at >60 Gy/s required for FLASH-RT due to pulsed heating limitations. For medical therapy, high peak current, high peak intensity x-ray sources may enable a new treatment modality that can offer superior performance to existing RT. For advanced compact high gradient accelerators, this is the area where the low rep-rate, high energy electron production of these accelerators would be most suitable for near future (<5 or slightly >5 years) development in this application. These accelerators are potentially tunable so one can address the need for control of time structure and dose delivery in the pulses. PWFA and SWFA may be good candidate accelerators since both the driving and witness (accelerating) bunches could be of high charge. LWFA can also scale to high charge using either high intensity regimes or long driver wavelengths, or high repetition rate in 'bursts' can be used over short duration . As for the higher energy (250 MeV) FLASH applications, the LWFA scheme would be more appropriate for development since the footprint could probably be kept compact even at the higher energy outputs.

LWFA/SWFA/PWFA and THz for VHEE

The ability of conventional LINACs to deliver VHEE (>100 MeV) electrons is limited to large devices due to the limited accelerating gradient (<10 MV/m) imposed by electrical breakdown of the accelerator. High gradient acceleration is needed and advanced compact high gradient accelerators are the candidates. The LWFA scheme would be appropriate for development since the footprint could probably be kept compact at the required higher energy outputs. Dose rates for VHEE appear to require similar electron currents to other LWFA applications and appear potentially realistic at kHz repetition rates. Similarly, compact SWFA/PWFA and THz accelerators need to be developed to take advantage of the high gradient acceleration they are offering.

4.3.6 Synergistic Application-Side R&D (Q5)

- Emphasize the curative capacity of RT and the security aspect of RT both save lives and prevent suffering
- MV FLASH photon – efficient – duty cycle – dose rate needs integrate all aspects of the technology development needs
- VHEE FLASH – 100-200 MeV – better DD characteristics as compared to photons
- System design problems – how do you do model this? Improved modelling of complex systems is a need that crosses all aspects of science, so those areas can be used in this problem set and new methods developed here will improve other areas of science
- Dose and Dose Rate Reconstruction
    - Photon counting arrays
    - Energy range
    - Spatial resolution
    - 3D LET measurement system
- Activation By-product Imaging
    - FLASH and VHEE enabled
    - Photo- and proto- activation
- pO2 - Oxygen depletion imaging
    - Measure this on the time scale of oxygen depletion
    - Optical methods – see oxylite technology – oxygen mediated fluorescent decay
- Robust Performance/Security/Safety Detector

        - Unstructured detectors feeding machine learning frameworks for safety and quality
        - Prompt Gamma systems for range verification
        - Proton range estimation that can also detect electrons and photons – proton/photon/electron CT etc.
    - Dedicated FLASH Dosimetry and Constancy Technologies (indirect and direct)
        - Current sensors vs ionization system
    - Fiducial and Image-guidance Detectors
        - Isotope trackers?
        - MR-guided proton/heavy ion/electron/gamma flash
        - Fully integrated imaging with control system integration vs. simply hybrid
    - Re-look at the femtosecond-nanosecond chemical trajectory post-RT
        - optimize the drug side of the equation; non-drug interventions as well; hypocapnia
        - simulation tools for physical chemistry; radical modeling; nanoscale modeling
        - FLASH biology – nuclear event linkage
    - Computational/Digital
        - system engineering that allows for in/out of modular components, is super reliable, and gets standardized interface and API's so that it ultimately becomes universal and robust (and open)
        - big data input and output (collection) built into the system
        - written, easy to maintain code
        - allows regulations to be easy to adapt (entire device need not be re-510k'd for component changes, less cost and red-tape)

4.3.7 Required R&D to Bridge Technical Gaps (Q6)

Overall, to advance the underlying accelerator science and technology sufficiently to achieve a 3 to 4 orders of magnitude increase in accelerator output radiation flux, a simultaneous push across all the limiting factors must occur.

Methods to increase the accelerator duty factor by at least a factor of 10 would require research on enhanced cooling technology for both the RF sources (RF interaction circuits and beam collectors) and the accelerator structure itself (Section 5.3.2). In the extreme limit of a single short duration, extremely high power pulse, or a short series of more moderately powered pulses, methods to incorporate items like phase change thermal materials directly into the accelerator or RF source structure, in conjunction with refractory metals with high conductivity RF coatings, would be an important area of research. Accelerator structures could be made more immune to thermal mechanical distortion and detuning by the use of low thermal expansion, non-magnetic materials over-coated with high quality metal RF coatings to maintain high electromagnetic quality factor. For x-ray FLASH, methods to handle the increased thermal loading of the target also have to be addressed, in particular for high powers under short duration (Section 5.3.5).

Research on higher powered vacuum electronic RF sources requires moving beyond single beam klystrons and therefore research considering multiple beam, sheet beam, or stacked sheet beam geometries. Such approaches can allow dramatic increases in peak power, increases in average power, and increases in efficiency, all without requiring higher voltages. Ultimately, vacuum electronic RF sources that make use of the electron cyclotron resonance of spiraling electron beams such as gyrotrons or gyro-klystrons should be researched for accelerator applications, particularly for use at higher frequencies. The over-moded nature of the RF circuits within these sources allows for much higher average power dissipation. Another important area of research would be on more compact pulse compressors with greater efficiency and a larger power multiplication factor.

Research on modified or new accelerator structure topologies is needed to allow an increase accelerator beam loading to greater than 80%, with a simultaneous increase in shunt impedance. A possible approach might be the use of ordinary cooled metal cavities (to 77K, which is relatively easy to achieve), which for the case of copper increases the conductivity by a factor of about 8. Another approach might involve alternative accelerating structure concepts utilizing low-loss dielectrics instead of metals, or some other means to break the constraining relationship between metal conductivity and shunt impedance. Research on dielectric-loaded accelerator structures presents opportunities for increasing the accelerating gradient, especially if combined with higher frequency operation (above 12 GHz) and concurrent RF source research involving higher power production and greater source efficiency at these frequencies (Section 5.3.2). Such high-gradient research and technology development is also especially important for VHEE, in order to keep the accelerator length sufficiently compact while producing the required 100 MeV or higher energies.

Improvement in the efficiency of x-ray production from targets bombarded by the accelerated electrons, or more direct methods of producing x-rays from electron beams, is an important area of research for x-ray FLASH applications (Section 5.3.5). Possible topics might include nanostructure (atomic-level) engineered crystalline targets making use of electron and x-ray diffraction, nano-channel targets, or more speculatively, revolutionary types of plasma or optical undulators, or new types of beam-wave or beam-material interactions.

For advanced compact high gradient accelerators (non-endoscopic), research into how to inject substantially more charge to be trapped for acceleration is required for high dosage applications such as FLASH and VHEE. This will require further research into: (1) improving the efficiency of energy transfer from the driver to the accelerated beam in main accelerator section, (2) high average current beam sources, and (3) driver technology. Research into how to miniaturize the accelerator and improve the flexibility of the delivery of the electron beam and its derived radiation is also important for applications such as endoscopic configurations. The structure based technologies (SWFA and DLA) will benefit from advances in materials and fabrication processes for both dielectric and metallic materials. Several accelerator technologies relevant to this application are discussed below.

LWFA/SWFA/PWFA and THz for FLASH-RT

High-peak current, high-peak intensity x-ray sources could be obtained with the advanced compact high gradient accelerators of LWFA, SWFA, PWFA, and THz accelerators. Each technology requires its own subsystems that need to be developed and tested. LWFA requires improved injection schemes that can trap more electrons to be accelerated for high dose generation, and improved efficiencies of both the laser drivers and the energy transfer from the driver to the accelerated beam. SWFA/PWFA require electron sources capable of generating intense bunches of <10 MV electrons with controllable bunch shapes. Structures and plasma must be capable of supporting high repetition rates with economic means of adequate cooling of the accelerating structures and the x-ray conversion targets. THz structures have now demonstrated GV/m fields, electron beam acceleration and importantly emittance preservation of high charge bunches (>pC). Technical gaps include electron injectors and THz sources.

LWFA/SWFA/PWFA and THz for VHEE

High-gradient acceleration could dramatically reduce the footprint compared to conventional accelerators, thus enabling compact VHEE sources. VHEE can be obtained with the advanced compact high gradient accelerators of LWFA, SWFA, PWFA, and THz accelerators. Each technology requires its own subsystems that need to be developed and tested. LWFA requires improved laser technologies that can better transfer driver energy to the accelerated beam for compact high energy operation. SWFA/PWFA require electron sources and structures/plasma that are capable of generating and supporting higher acceleration gradients for very high energy beam production while keeping a compact foot print. THz structures have now demonstrated GV/m fields, electron beam acceleration and importantly emittance preservation of high charge bunches (>pC). Technical gaps include electron injectors and THz sources.

4.3.8 Barriers to Commercialization and Technology Introduction (Q6)

No specific barriers to commercialization exist outside of the standard need to collect data, conduct clinical trials, and obtain locally relevant regulatory clearances (e.g., FDA approval).

Roadmap for Development (Q7)[15]

The goal of advanced accelerator research in this sub-topic is to carry research relating to the production of higher dose rate relativistic electron and ion beams from small scale laboratory tests presently underway to practical application in the field. This involves R&D to improve the performance of such devices in terms of dose rate, beam parameter range, control and efficiency, but more importantly to make the devices reliable, compact and robust so they are practical in a clinical setting when operated by non-physicists. Since there are a number of possible approaches presently studied for such application the development plan in each area is specific to that particular approach. We detail those approaches below.

Improved thermal management for higher duty cycle operation in conventional accelerator structures, and in particular for rapid thermal rise induced by high powered short pulse bursts or a longer single pulse, will require a mixture of university research over 3 years for $2 to $3 million dollars total, followed by research at an national accelerator facility for an additional 3 years at a total cost of $10 million. This could be followed by transition to a commercial accelerator systems company for several additional million dollars.

Research on accelerators with high beam loading, 77 K cooled structures, and high gradients would be most suited for a national accelerator lab with a 3-4 year duration with a total budget of $7 to $15 million total. Transition to industry could occur by additional funding of $1 to $2 million total over 2 years.

R&D related to higher frequency gyro-devices, as well as on new classes of over-moded or alternative geometry klystron-like devices, would be suitable for both university research for theoretical research and experimental demonstrations at low duty, followed by development at a national accelerator facility or national laboratory. The university component could be accomplished with $3 to $5 million total over 3-5 years, while the national laboratory/accelerator facility component could follow at about $10 to $15 million total over an additional 2-3 years. Transition to industry would occur during or following the national lab/accelerator facility investment. The RF pulse compressor research could occur at a national accelerator facility over about 4 years at $10 million total.

Discovering and developing methods of producing x-rays more efficiently from novel target structures or by direct beam-wave interaction methods would require significant investment both at the university level and at national accelerator facility or national laboratories. A university program at $5 to $10 million total over 3-5 years could explore potential concepts with modeling and simulation techniques and some proof of principle demonstration, but a $15 to $25 million total additional investment at an accelerator laboratory would be needed to fully demonstrate suitably effective and compact high efficiency emission of x-rays from the beam.

---

[15] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

Needs by device type:

LWFA/SWFA/PWFA and THz for FLASH-RT and VHEE

The following compact high gradient accelerators vary substantially in their relative maturity in development towards ultra-high dose rate applications. LWFA, for example, has shown great successes in high energy generation in a compact configuration and is the one most likely to deliver practical utility closer to the 5 year horizon of interest. The listed research topics for this candidate are closer to device optimization than to proof-of-principle demonstration of underlying physics. The return for investment towards eventual practice is thus quite high for this compact accelerator scheme and its required laser drivers. Similarly, PWFA carries much higher beam charge quite suitable for high dose rate applications but the compactness factor is a bit challenging. SWFA and THz may offer better prospects for compactness but they are still quite lacking of maturity. Suitable investment in these accelerators may bring up quickly their respective capabilities to be considered for clinical development in the ultra-high dose rate applications.

1) LWFA

a) Compact high gradient accelerators at ~20-100 MeV energies. Precision shaping and control of the laser and accelerator is needed for photon beam energy spread, tuning and stability. LWFA: 5 years, $5 million.
b) Controlled Thomson/Compton scattering to generate mono-energetic photon beams of controllable energy and direction, and ability to raster beam across a patient. LWFA: 5 years, $3 million.
c) Deceleration of electrons after photon production to mitigate undesired bremsstrahlung. LWFA: 5 years, $3 million.
d) kHz laser drivers at few hundred mJ/10fs scale to enable average flux: 5 years, $15 million.
e) Detection and signature development: rastering, resolution, material distinction. 3 years, $5 million.

2) SWFA/PWFA

a) Electron beams at >1 MeV from an SRF injector; 3 years, $3 million.
b) Electron bunch shaping technology for the beam driven structures to control the energy gain; 3 years, $3 million.
c) Thermally managed dielectric or metallic structures capable of high average current, ~20-100 MeV. 6 years, $6 million.
d) System integration. Performance and stability development. 4 years, $6 million.

3) THz accelerators

a) THz electron injectors. 4 years, $3 million.
b) 100 cm scale structures. 2 years, $1 million.
c) MW-class switches for power distribution and RF compression. 2 years, $1 million.
d) Electron-beam THz source (50% efficient) 5 years, $5 million.
e) Laser-driven THs source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ). 3 years, $3 million.
f) System integration. Performance and stability development. 5 years, $5 million.

Generalized needs:

a) FLASH radiation LINAC sources: compact, high-current, pulsed sources of electrons and protons compatible with respective linear accelerator designs for conventional energy electrons (6-15 MeV) for photon conversion, very high-energy electrons (>100 MeV), and protons (70-250 MeV).
b) RF power sources: compact, high-efficiency, economical RF power sources capable of producing peak RF power of several MW to >100 MW in a small physical footprint and compatible with conventional power utilities infrastructure.
c) Power storage and modulation solutions: compact technologies to store and convert electrical power from conventional utilities and/or solar power to deliver peak power levels required for the RF sources. Novel pulse compression strategies to increase the peak power are also applicable.
d) Compact, moderate gradient with high RF-to-beam efficiency and/or high-efficiency, high-gradient linear accelerator structures capable of producing photon, VHEE, or proton beams with FLASH dose rates in a clinically practical form factor and economical cost.
e) Novel solutions and/or geometries for delivering treatment beams from multiple directions simultaneously or in rapid sequence to produce highly conformal dose distributions with FLASH dose rates, ideally without slow mechanical motion or patient collision risk.
f) Novel photon production and dynamic intensity-modulation strategies to produce highly conformal dose distributions compatible with FLASH delivery speed, ideally without slow mechanical motion or complexity.
g) RF energy modulation and deflection strategies for rapid 3-D scanning of protons. This overlaps with the need to develop collimation without moving parts to attain very rapid speed and adjustments.
h) Rapid non-destructive beam monitoring solutions with charge/current, energy, and spatial position monitoring for beam control and feedback, compatible with FLASH dose rates without saturation.
i) Software/hardware solutions for automated real-time image analysis and plan adaptation compatible with FLASH delivery speed.
j) Development of a number of novel technologies with the potential to address some of these needs is underway, with much room and great need for additional research and development of solutions.

4.4 Application Area 3: Development of improved radiation detectors for dose distribution measurement and real time monitoring

4.4.1 Background and State of Application Development (Q1)

Radiation detectors are critical to advances in radiation's application to medicine. The success of radiotherapy as a mature part of cancer care was enabled by robust dosimetry technology and protocols that assured relatively consistent doses to be delivered across a population of patients and thereby producing consistent, predictable clinical results. There are many different applications of detector technology in the field of radiation therapy. Benefit will be realized by coupling improved detectors with advanced accelerator based sources such as mono-energetic gammas which can increase resolution and reduce dose.

Absolute Dosimetry: The accurate measurement of radiation quantities, such as, fluence (particles/area) or dose (J/kg) is critical to the safety and efficacy of radiation use in medicine. Substantial effort has been invested in the theory of radiation dosimetry to allow measurements to be related to the underlying physical quantities. This has resulted in international standards for radiation dosimetry that assure radiation quantities being delivered are consistent across the globe to within approximately 5%. Any advances in radiation production that change the dose rates (including time structure), spectra, linear-energy-transfer (heavier particles), or radiation transport (presence of B fields) will also challenge the current detectors and/or dosimetry protocols. Therefore, advances in accelerator technology may require corresponding advances in detector technologies.

Detector Arrays for Dosimetry: Substantial effort goes into the design of the radiation dose distributions delivered in radiotherapy to assure tumor control and avoid side effects. While advances in computing have enabled highly accurate predictions of dose delivered in patients, there is a continued need to verify the dose distributions actually delivered by the radiation treatment device. Current approaches involve point-based measurements of dose in combination with relative measures using sparse arrays (typically solid-state detectors, e.g., diodes, MOSFETs, plastic scintillators) or 2D sheets of film (e.g., radiochromic films). These technologies have allowed the safe development and deployment of complex forms of radiotherapy, including IMRT, but have required substantial oversight by medical physicists. The development of large-scale 3D sensing technology that can also accommodate the growing importance of the dose rate time structure is required to both simplify current RT dosimetry efforts and support new technologies.

Patient Dosimetry: Measurements of dose delivered to the patient is also of significant interest and a means of verifying the entire dosimetry calculation and delivery chain. Improvements in these technologies using small optical sensors or ingestible devices would provide additional support for new technologies to be rapidly and safely translated to clinical care. Investigators have also explored the use Cerenkov emissions on the patient's surface for these purposes. The development of novel dosimetry approaches to non-invasively image the dose delivered within the patient is also of great interest and has been suggested as a possible development in the context of MR-guided RT systems.

Control System Detectors and Sensors: Next generation accelerators will include significant advances that will make current methods of monitoring and control obsolete. Orders of magnitude higher dose rates will challenge the linearity and response times of current beam monitoring technologies. Smaller accelerators will force the field to seek alternatives to ionization chamber technologies that rely on high voltage and temperature and pressure controls. Integration of beam positioning and steering detectors to support dynamic modulation/painting of ionizing beams will require substantial miniaturization or the development of alternative detection systems. In addition, long-term performance is key for success in these systems for safety and calibration reasons, as a result, radiation hardness will also be a requirement in these compact detector systems.

Big Dosimetric Data: In addition to scaling up the measurement capacity, these new detector systems have driven the development of software platforms that are able to analyze and extract insights from the measurements. Furthermore, the data derived from these measurements are directly compared to the predicted dose and the resulting differences are being used to further refine the physics models used in the simulation process. This paradigm creates opportunities to re-think the measurement approaches to optimize the measurement.

4.4.2 Regulatory Framework (Q2)

The general regulatory framework is discussed in Section 4.2.2.

Radiation dosimetry devices and practices are not uniformly regulated around the world, however, the International Commission on Radiological Units (ICRU) has provided guidance on radiation dosimetry for almost a century and served to create a remarkably high degree of consistency in dose delivery around the world. The dosimetry standards themselves are always evolving as new technologies or practices are developed. These standards include the devices, the procedures, and the calculations and are arrived at by a collaboration between the global Medical Physics community (through their professional organizations e.g., the AAPM), national standards laboratories (e.g., NRC, NIST, NPL), and other international organizations (e.g., IAEA). Individual jurisdictions place licensing requirements on the delivery of the radiation dose to an individual patient as prescribed with penalties for failure to deliver dose within specified tolerances.

In regards to the control systems, these are an integral part of the radiation treatment machine and are regulated through the medical device approval process in the corresponding jurisdiction (e.g., the FDA in the United States and through CE Marking in the European Union).

4.4.3 Economic Analysis (Q3)

See Section 4.2.3.

4.4.4 Performance Criteria (Q3)

The performance criteria for radiation detectors depend substantially on the application.

Absolute Dosimetry: Detectors used for absolute dosimetry require sufficient understanding of the underlying energy deposition processes to allow measured quantities to be related to physical processes. In the past, these have included calorimetric, stoichiometric, or gas ionization processes. In addition, the absolute dosimetry systems need to be reproducible to allow sufficient precision in measurement to act as standards across global standards labs. Given the requirement of clinical dosimetry to be well within 5 percent, absolute dosimetry needs to be capable of achieving accuracy and precision to well within 1 percent. [IAEA Report TRS-398-2000]

Detector Arrays for Dosimetry: These systems are often used to measure the relative distribution of dose in a radiation field. The linkage to a dosimetric standard is through either a reference measurement done simultaneously or through the use of a previously calibrated radiation beam of known consistency. The requirement here is for excellent linearity over 3 orders of magnitude to accommodate measurements of applied radiation fields ranging from the highest doses in the tumor (e.g., 2-20 Gy) to the lowest doses (<0.02Gy) to adjacent normal structures. It is not uncommon to have detector-to-detector corrections across the array applied to achieve linearity and eliminate variations in detector offset (i.e., associated with dark current). This includes addressing the differential energy dependence of the detector as compared to the tissue of interest. It is also important that these detectors can operate with the planned radiation fields directly, as opposed to some scaled version, as these tests are seen as verifying the entire radiation production process and need to be faithful to the machines operations at the time of treatment. Monitoring the radiation delivery between individual 'control points' is helpful to confirm more complex radiation delivery systems but places additional linearity challenges on these detectors.

Detector systems that are too fragile, too complex, require excess calibration steps, or have a limited lifetime will not be adopted in the hectic setting of a radiation therapy center.

Patient Dosimetry: Verification of patient-specific dosimetry tolerates relative dosimetric precision of approximately 5% at therapeutic dose levels. Other variations in the overall application of these detectors become dominant – these include variation in spatial placement of the detector, use in areas of steep dose gradients (on the skin), and the compounding uncertainty present in the delivery of a clinical radiation field. The linearity, size, and ease of use of the detector is of critical importance if they are to provide clinical value. Systems that are too fragile, too complex, or that require excess calibration steps, or have a limited lifetime will not be adopted in the hectic setting of a radiation therapy center.

Control System Detectors and Sensors: Unique performance criteria for control systems sensors are largely related to speed and robustness. Non-linearities can be managed by corrections within the control system. Absolute dosimetric performance of these 'monitoring chambers' are achieved through digitally-enabled calibration processes tied to absolute dosimetry standards overseen by Medical Physicists. That said, the ability to develop absolute standards that are directly integrated with the accelerator's control system (e.g., particle counting approaches), would have advantages from a global safety and quality perspective. There have been recent efforts to develop more elaborate radiation detectors that sense the radiation field after the beam modulation phase to assure system performance using the beam itself. Such approaches augment the current optical and electromechanical readout systems. [Islam-2009]

4.4.5 Technical Gaps (Q4)

LWFA/SWFA/PWFA and THz Accelerators for Mono-Energetic Imaging

Advanced compact high gradient accelerators have the potential to enable use of advanced x-ray imaging methods currently restricted to large scientific facilities in clinical settings. Medical imaging would benefit greatly from reduced dose, higher contrast to do tissue discrimination using multiple energies. [Caroll-2003] Improved spatial resolution down to micron scale can also enable sensitive imaging including phase contrast [Schleede-2012] to detect early abnormalities. The ability of conventional LINACs to deliver high energy electrons (>100 MeV) is limited to large devices due to the limited accelerating gradient (<10 MV m−1) imposed by electrical breakdown of the accelerator. High gradient acceleration is needed.

Accessing these benefits requires development of mono-energetic sources with narrow divergence and small emission spot size, which is a good fit to high gradient advanced accelerator concepts and in particular laser-plasma and laser-structure based accelerators. Such accelerators and systems are early TRL at present. They do this by making high energy accelerators more compact, but are currently limited in their ability to produce high average current beams. High repetition rate laser drivers are still being developed for laser-driven advanced accelerators. At the projected high rep-rate of 10 kHz, the averaged charge and hence average dose rate will be appropriate for imaging. High repetition beam-driven sources are available for PWFA and SWFA but making them compact and portable is still awaiting development.

These technologies will challenge the existing control system detectors employed in radiation treatment systems. More compact sensing elements that can provided verification and control of the high rep-rates would be advantageous for control and for internal diagnostics. Fast photonic dosimetry and readout systems that are radiation hard should be considered an important development.

4.4.6 Synergistic Application-Side R&D (Q5)

Advances in MV FLASH photon and electron therapy represent a significant opportunity to re-examine the chain of dose control. Approaching these new systems from a system design perspective that leverages sensors and computational models could transform cost and management complexity. Improved modelling of complex systems is a need that crosses all aspects of science, so those areas can be used in this problem set and new methods developed here will improve other areas of science. For example, photonic powered linear accelerator of 3 cm length may prove to allow whole new areas of use not currently envisioned much like the silicon chip provided new uses for computers relative to the large machines of the prior generation based on vacuum tubes and mechanical gears. Simply integrating these devices into the traditional LINAC paradigm would be a lost opportunity. There are numerous areas of radiation therapy that could be re-explored with these technologies that would require innovations in detector technology.

Detectors that measure the interaction of the radiation field with the patient and their underlying biology is of great interest. Beginning with highly accurate reconstructions of the dose applied in 3D and advancing to real-time measures of the dose rate and LET within the body. Interaction by-products could also be measured to validate the treatment process as it progresses. Approaches such as activation by-product imaging through short-pulse control and monitoring. The time-structure control would also open the door to monitoring the impact of the beam on oxygen (pO2, sO2) depletion. Oxygen-mediated fluorescent decay is currently deployed in the form of a point-based probe to assess pO2. For detector design, new or expanded first principles codes will be required that are high performance computing (HPC) compatible. It is expected that extensive simulations will be required to design improved radiation detectors. As there is much data on existing detectors and materials, this data can be incorporated into a detector surrogate model. Since there is a desire for the detectors to be small, there is a need to extensively explore the detector system through simulation. For example, in the packaging of the detectors, how will the radiation and heat and small proximity effect the performance, cross talk, etc. Simulations in the design process are needed for not only the first principles but also for the engineering. This design process may benefit from HPC facilities. The detectors will require improvements in parallel with the controls (timing readout) and we will be able to use data science techniques to rapidly interpret the data. Simulations and experimental data of ultra-fast time scale processes that could be measured through optical techniques need to be incorporated into a model and linked to the control system for futuristic treatments.

From a safety and monitoring perspective, the speed of FLASH delivery raises significant performance and safety concerns. Current delivery systems operate at a rate that human interrogation of each step is feasible. New approaches will be required to provide confidence in the FLASH delivery process.

Unstructured detectors feeding machine learning frameworks for safety and quality that leverage new information sources (e.g., prompt gamma systems in the case of protons; transmission sensors in the case of photons). It is likely that new dedicated FLASH dosimetry detectors, constancy sensors, and computing models will be required.

The development of imaging detectors will also be a byproduct of these developments. The need to synchronize the patient position with the FLASH puts additional demands on the image-guidance platforms. Novel fiducial systems or image-guidance detectors may be required. As a minimum, more fully integrated imaging with control system integration is likely as opposed to the current 'hybrid/adjacent' model employed in image guided radiotherapy (IGRT) systems wherein the imaging and treatment subsystems are not operating as a single integrated system.

The development of fine time control of radiation opens up the opportunity to synchronize with other biological processes as well as other interventional processes, creating the exciting potential of high temporal resolution combined modality therapies and effectively re-examining the femtosecond-nanosecond chemical trajectory post-RT to optimize therapeutic effect. New sensors that can monitor the physiological and biochemical state for timing and manipulation is promising. These include radiation effect modifying drugs and non-drug interventions as well, including microenvironment manipulations (e.g., hypocapnia). These approaches would require simulation tools for physical chemistry (e.g., radical and nanoscale modelling) with linkages to the resolving biology (e.g., nuclear event linkage; indirect cascade; repair).

The impact on computational/digital system engineering to support these more integrated platforms should also be considered. Making addition measurements at this scale with the potential for adaptation of the intervention to uncontrolled physiological processes may represent a significant computational challenge.

4.4.7 Required R&D to Bridge Technical Gaps (Q6)

HPC compatible detector design codes that include multi-physics effects that can be easily added to the start to end simulations and modeling approaches are needed. The detectors need to be able to read out, process, and send information to the overall controls architecture. We might need on-device computing. The detectors need to be small that leads to many design and fabrication problems. Maintaining calibration standards for the detectors is important. We must monitor if the detectors fail or decrease in quality as the detectors are a critical safety component.

4.4.8 Barriers to Commercialization and Technology Introduction (Q6)

Similar to those in 4.2.8.

Roadmap for Development (Q7)[16]

The development roadmap of detectors is described in Sections 5.4.1 and 5.4.2.

---

[16] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

4.5 Application Area 4: Development of improved beam collimators for field shaping

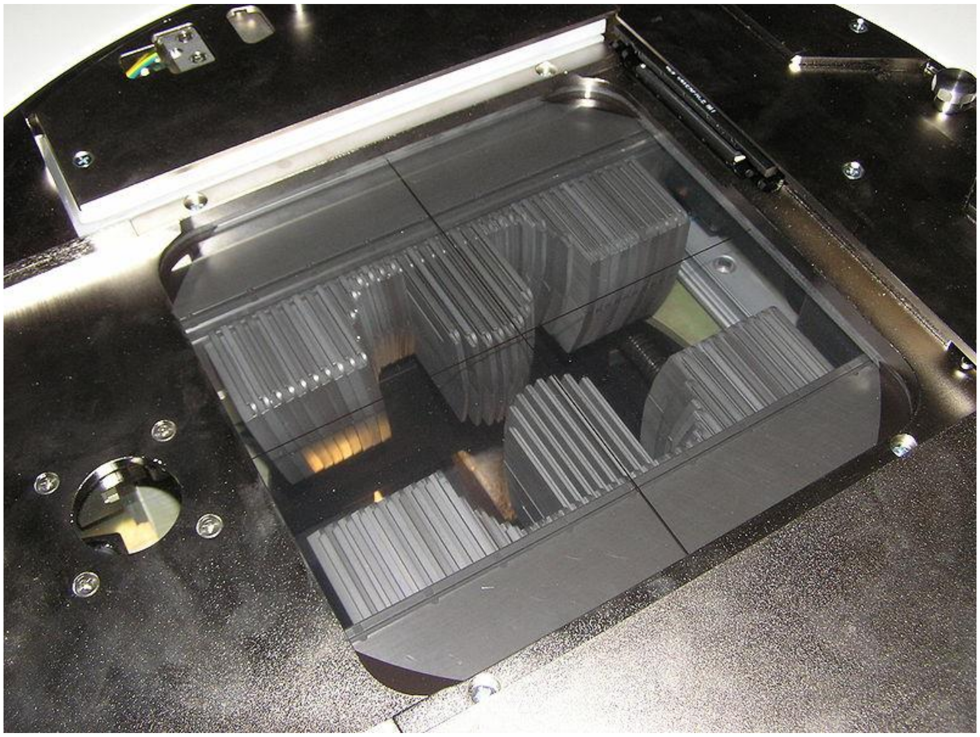


***Figure 4.4**. A Multi-Leaf Collimator (MLC) is shown without the typical coverings of a LINAC device. These units collimate beams via moving tungsten leaves that are positioned with mechanical motors. As such, they represent a current point of failure in even the most mature LINACs. (Image credit: Wikimedia Commons[17])*

4.5.1 Background and State of Application Development (Q1)

In radiation therapy, the pattern of dose deposited within the patient needs to be tailored to the underlying 3D anatomy – delivering the prescribed dose to the defined tumor volume while minimizing the dose delivered to adjacent normal tissues, as well as, keeping the dose to the rest of the body as low as reasonable achievable. Methods to achieve this depend significantly on the form of the radiation. In the case of photon beams, it has been achieved through the use of high density and/or atomic number shielding elements situated between the source and the patient that are places in the radiation field. In the context of particle therapy the radiation dose pattern can be shaped by similar collimation systems or can the beam can be scanned and modulated in intensity and energy to generate the desired 3D dose pattern in the patient. Of course, these beams can be applied from selected directions relative to the patient to further enhance control of the dose pattern.

In the case of photon therapy, early systems used simple rectangular field shapes combined with low-melting point metals that were cast into specific shapes for each patient. Advances in electromechanical capability and the development of 'inverse planning' techniques drove the development of multi-leaf collimators that could change shape during radiation delivery. The current state of the art "standard" medical LINAC unit employs an MLC to shape and modulate the otherwise fairly uniform fluence

---

[17] From Wikimedia Commons, used here without changes under the Creative Commons Attribution-Share Alike 2.5 Generic license. https://commons.wikimedia.org/wiki/File:Multi_leaf_collimator.jpg, accessed 1/17/2020.

pattern. As shown in Figure 4.4, leaves typically made of tungsten are placed in an array to open or close to varying degrees to control the distal radiation exposure. Systems have evolved from binary states to dynamic movement and varying dose rate control of the beam itself to create complex three and four dimensional dose maps in patients.

The MLC has moving parts that demand highly precise movement and positioning. These also need to move rapidly and have significant mass so that the demands on the motion control hardware are not insignificant. Thus, the MLC is currently one of the weakest links in the LINAC system as grit, dust, and wear and tear play a role in component failure and movement that falls out of specifications.

Adding to the inherent compromise that the MLC represents to robustness, the advent of very high dose rate delivery goals force the velocity of the mechanical MLC to become the major roadblock to shaped high dose rate treatment that is conformal and modulated. The conclusion from field use is that an outside-the-box solution is needed to address the issues of the MLC both at standard dose rates and ultimately for the very high dose rates that may in the near future be part of clinical practice. Thus, the goal is to develop a device class and surrounding technology that allows dose shaping and modulation with no moving parts. Innovative systems should explore x-ray lens technologies, coded apertures, alternative drive and control technologies, support for 4π beam arrangements, and computational support to include modulator system constraints directly in the inverse planning process.

The conclusion from the field use is an outside-the-box solution is needed to address the issues of the MLC both at standard dose rates and ultimately for very high dose rates that may in the near future be part of clinical practice.

In the context of particle therapy, methods of controlling the charged particle beam during therapy are under continuous innovation. Efforts to minimize beam divergence while controlling beam placement in the body are a major focus of the industry. In addition, energy control affects dose placement in depth and is also an area where current technologies force a trade-off in dose control and overall accelerator efficiency.

In general, the collimation or beam transport components of the medical accelerator have grown to represent a major cost component and a relatively high failure-rate subsystem as well. Innovative approaches that permit dose painting in 3D (and even 4D for motion affected anatomy) need to be advanced.

4.5.2 Regulatory Framework (Q2)

The regulatory framework is discussed in Section 4.2.2.

4.5.3 Economic Analysis (Q3)

The economic analysis was discussed in Section 4.2.3.

4.5.4 Performance Criteria (Q3)

X-ray Collimation Requirements

Source Property	Now [*]	Threshold [*]	Objective [*]
Particle. [McGee-2019]	Photons		Flexible Photon including FLASH
Modulation	100 : 1		1mm
Directionality	Emitting into 40x40cm^2 at 1m		Extend operation range to include emitting into 6x6cm^2 at 0.5m
Control	Motorized Metal		No mechanical failure points/ minimal moving parts
Slew Rate	1cm/sec at 1m from the source		1mm/sec at 0.5m
Energy	Up to 25MV		Up to 10MV
Leakage	0.1%		0.1%
Programmable	Serial modulation through sequenced metal moving		Random access modulation through digital control
Uptime in high service setting	>98%		No Failure Modes
Uptime in low service setting	n/a		No Failure Modes
Integrated Performance Monitoring	Motion Control		Dose/fluence measures
Automation Needed. [Boss-2014]	Manual calibration		Self-calibrating Geometry
Size	Fits within 20 cm space between source and subject		Fits within 20 cm space between source and subject
Weight	Minimize		Minimize
Power			Works in unstable power setting
Portability			Attractive for vehicle mounted systems in the future
Acceleration/Shock			Capable of being mounted in transport vehicle
Op. Temp range	HVAC control – 15ºC-30ºC		15ºC-30ºC

[1] - electron, x-ray, high energy x-ray, neutron

[2] - for example, the maximum allowable time to change between beam energies

[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.

[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)

[*] - “Now” - values available from current commercial products

[*] - “Threshold” - minimum increase in performance that would **meaningfully impact** the application

[*] - “Objective” - desired increase in performance needed to provide a **transformative improvement** in the application

4.5.5 Technical Gaps (Q4)

The technical gaps depend on the form of the radiation therapy. In addition, there are opportunities to pursue highly specialized collimation systems for specific applications.

Conventional Intensity Modulated Radiotherapy: A major barrier associated with current MLC technology is reliability, servicing requirements, use of toxic/strategic metals, and overall cost. For general photon therapy machines, the development of novel materials, propulsion systems, and motion control technologies needs to be explored to allow modulation instead of simply shaping of the beam. Innovations in x-ray target design should also be considered to optimize the design of a complete fluence production and control architecture. The potential for programmable multi-source systems that share common collimator systems should be explored.

Disease-site Specific Opportunities: The creation of machines dedicated to specific cancers should also be considered. Such approaches have been used in the past. For example, the gamma-knife system has 192 ^{60}Co sources and a very specific, mechanically simple collimation system. It is very effective in treating small cancerous and benign lesions in the brain. Such platforms create an opportunity to mature innovative approaches to clinical application. For example, in the late 1990s several investigators explored the application of x-ray lens technologies (Emax of ~60 keV) for radiotherapy. Creating highly effective and robust collimation solutions for specific radiotherapy applications should also be explored.

FLASH Radiotherapy: The short time periods of irradiation involved with techniques like photon FLASH place additional constraints on intensity modulators. Given that FLASH is a dose rate dependent effect, modulation must be constrained to maintain the dose rate while also modulating the dose. This constraint is complex and requires a complete re-thinking of the ideal collimation system. In addition, the placement of adjacent FLASH fluence patterns (with their associated penumbra) elevates the dependence on precision in field placement within the body. That said, if FLASH works well to reduce normal tissue toxicity, the modulation requirements may be substantially diminished. The same argument could apply to the need for image-guidance technologies in the context of FLASH. One possible outcome is that FLASH machines have simpler collimation systems to achieve the same therapeutic ratio. Regardless, development of FLASH collimation technology should not take existing collimation systems as the starting point for design.

4.5.6 Synergistic Application-Side R&D (Q5)

The delivery of radiation with all current forms of LINAC for human cancer therapy depends on beam shaping with rare exceptions like total body radiation. These devices allow the fluence of the beam to change and may be critical to allow physical dose to be mapped into a specifically heterogeneous biologic dose.

Biology of Micro-beam and Grid Therapy: The development of ultra-high precision collimation technologies would drive new radiobiological research. For example, the interesting observations of micro-beam irradiation and grid-therapy approaches are providing valuable insight into the biological and physiological processes associated with oxygenation and repair. The clinical feasibility of effecting these approaches is a recognized barrier to advancing preclinical and cellular studies to clinical research.

Precise Spatial Modulation of Radiation Dose: The development of IMRT and IGRT technologies have enabled hypofractionated treatments to be pursued and in parallel have stimulated numerous lines of radiobiological research including vascular targeting hypotheses and the activation of immune response, particularly in combination with recent advances in immunotherapy agents. Greater degree of dose control, including sub-region targeting, will allow clinical testing of radiobiological concepts such as targeting the heterogeneity within the tumor itself. This line of research will drive the development of novel functional and molecular imaging approaches to provide the targeting information.

High Temporal Resolution Control: The development to FLASH therapy approaches open the opportunity to coordinate deoxygenation with the location and re-oxygenation capacity of normal tissues.

The development of collimation technologies that support this paradigm would support pre-clinical model development and provide a pathway to transition to clinical studies.

Fluence-field Modulated Imaging: The application of inverse-solution, intensity modulation to CT imaging was first proposed by Bartolac et al. [Bartolac-2011] In this paradigm, the inverse solution seeks to maximize regional contrast-to-noise while minimizing the overall dose to the patient. The potential for dose management and efficiency in screening applications of imaging and in inspection processes are significant.

Highly Integrated Beam Generation and Control Systems: Extensive physics-based simulation with transport codes anchored previously to experiment are required for the various methods of beam pre-shaping to be fully exploited for dose pattern manipulation. It is expected that to be able to do this beam shaping rapidly, local high-performance computational tools will be required in close proximity the system and that specialized fast sensitive detectors will be needed for validation of the beam shape created. For example, fast control to set all of the upstream devices for collimation (i.e., laser shaping at cathode, specialized targets and target patterns) and through fast, non-invasive electron beam diagnostics. The entire system must be set for a specific beam shape rapidly. The machine set-points will be derived from massive simulation efforts from the start of the accelerator to the final biological effect. This model will be continually updated and improved with experimental data to reflect the actual machine. Once a dose and shape are specified in the treatment protocol, the entire machine can be rapidly set to produce the desired result. Need to insure that to meet this virtual collimator (modulation and shaping), we need the systems to have the ability for continuous gathering of all data from sensors to continue to refine models, address failures, etc. All data must be passed to central data repositories for continuous learning from the data.

4.5.7 Required R&D to Bridge Technical Gaps (Q6)

Structured Targets and Beam Control in x-ray Production: Research on new ways of beam steering for VHEE by using photocathodes and temporal-spatial changes in cathode emitting area, but laser phase masking or other approaches, would be an important topic. Beam optics simulation research on how such beams evolve down an accelerator structure would have to be performed. This could also apply to multiple beamlet approaches with laser modulation of the beamlets at the photocathode (“rastering”). Alternatives to photocathodes could include field emitter arrays with individually addressable emitters or small groups of emitters. Accelerator structures with multiple beams and multiple beam tunnels, somewhat like in a multi-beam klystron, could also be investigated (Section 5.3.2). Studies on the nature of the pattern of x-rays generated from a target illuminated by any such spatial-temporally modulated beams would also be of importance. The possibility of deflecting the accelerated beam with a limited number of discrete electrodes prior to the target can be studied as another means of rastering.

Multiplexed, Multisource Technology: For photon FLASH, accelerator systems with multiple smaller accelerators originating from different angles and transverse positions, that can be multiplexed in time, would be advantageous, provided that much more than 16 beams are used (e.g., 64 beams, 4x as many as in the planned Phasor system). Development of modelling platform to support the multiphysics nature of RF, acceleration, heating, will be required.

Spot Size Lensing Technologies: The development of large scale lensing technologies of photon energies requires all elements of the photon optics to be considered. Acceptance angles and magnification of lens elements will drive the development of smaller emission targets. Methods of thermal energy dissipation need to explore to these novel approaches.

Inverse-planning and Dose Modelling for Simulation/Computation: Current modulators have largely been built in isolation of the planning process and in isolation of the underlying physics and engineering constraints. This has resulted in the reduction to binary 'beam aperture' collimation systems. Completely new models of modulation could be explored in a joint optimization problem that employs clinical cases, physics-based models, and engineering constraints to seek alternative modulator designs. For example, a 160 leaf MLC could be out-performed by the highly optimized trajectory of a photon source of variable energy and two 3D shielding blocks that are moved (translated and rotated) in precise juxtaposition to the known patient anatomy. Such integrated approaches are ripe for consideration given recent advances in computational performance, machine learning, and robotics.

Development of Multilayer Modulation Technologies: Current binary approaches to modulation have developed from the starting point of relatively flat fluence patterns arriving at the collimation system. Existing clinical beam modeling software has been developed for the purpose of modelling these beams. As a result, IMRT is largely deployed as a series of small 'open fields'. An alternative approach is to consider true intensity modulators. Such an approach would require the development of high performing beam models (i.e., beam hardening effects; extra-focal models; collimator scatter) to be included in the inverse planning process that optimizes modulator parameters.

HPC compatible first principles codes that include all high-intensity effects that can simulate the entire system start to end, including all beam shaping/collimation methods to induce collimation are required. $4 million.

A simulated model of the entire system is required to determine a surrogate model. This might mean additional codes, modification to existing codes, stitching between the codes, marrying biological effect simulated and experimental data. We need to be able to develop controls architecture including fail-safe, machine learning approaches and perhaps new algorithms tailored to accelerators that will allow us to be able to push one button and permit an ultrafast dial in response of the entire system described above to permit the necessary beam shaping to avoid physical collimation, $2 to 3 million.

4.5.8 Barriers to Commercialization and Technology Introduction (Q6)

Need for Tight Integration with LINAC Control Systems: The medical accelerators are regulated devices from a human health (i.e., FDA) and radiation safety which is regulated by the various states and not the NRC. The collimation system is seen as both a modulator and part of the safety system of the accelerator as a whole. Advancing new collimation technologies to clinical practice requires tight collaboration with the current vendors of these devices. This results in a 10-15 year maturation cycle for the release of new collimation technologies. This is accelerating with better modelling tools in the early design and prototyping cycles. These included multi-physics approaches and incorporate serviceability in the mechanical modelling, thereby derisking the investment.

Academia-Industry Cooperation: Investment in photon collimation technology has been a fairly niche activity dominated by a few companies (i.e., Varian, Elekta, Tomotherapy) and academic institutions (i.e., DKFZ, University of Wisconsin). That said, there are many examples of collimation technology now in clinical use that came from collaboration between these types of organizations.

Roadmap for Development (Q7)[18]

Research on the simulation of beam optics evolution down an accelerator with rastered photocathodes or field emitter arrays, or simulation of post-accelerated beam deflection, etc. could be performed at

---

[18] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

university. Studies of the relationship between rastered beams on a target and the resulting changes in emitted x-ray pattern could also be performed in a university environment. The combined effort for such endeavors could be done for $0.6 million total over 3 years. Research on the possibility of a true multi-beam accelerator would be best suited for DOE accelerator laboratories, at a total cost of $6 to $15 million over 3-5 years, followed by a transition to industry for about an additional $3 to $5 million dollars total over another 2 years.

Full spatial control of x-rays with photon flash using a multiplexed accelerator system with significantly more than 16 beams would take 10 years at a total budget of $50 million or more. The merits of this type of complex system would have to be clearly demonstrated before any transition to industry.

4.6 Application Area 5: Optimization and development of treatment planning and delivery control systems to allow for real-time biologic and volumetric treatment adaptation

4.6.1 Background and State of Application Development (Q1)

The basic background relating to the use of accelerators in medicine is described in Section 4.2.2. Computer software integration and "burying the complexity" goals that are universal to this and really all aspects of medical devices and to security devices is developed in the computational areas of Chapter 5.

Treatment planning systems run alongside and atop treatment machines in a critical fashion so as to manage dose delivery, on treatment imaging, and safety systems. Treatment planning systems that are open source exist and can be obtained, streamlined, and redeployed with customization to include open API's for new LINACs, potentially for commercial LINACs, and calculation engine exportation to whatever is the current, optimal solution (cloud or local).

The true frontier in this space is the conversion of treatment planning and delivery based on physical dose to one based on biological dose. In this context we need to define biological dose as dynamically changing with the patients' response to therapy. And, as a result, to be something that we measure during treatment so as to optimize treatment.

Operation of the LINAC with some type of volumetric imaging system that can collect isocentric biological information in real-time is a complex engineering problem, especially in the context of high fluence treatments.

Communication with local and cloud-based systems to allow for increased computational performance to address real-time data that is evaluated with AI and machine learning to search for patterns associated with success, toxicity, and other issues the treatment team needs.

Examples of existing open source planning systems that could serve along with adaptation of Monte Carlo platforms (e.g., Geant4) include PlanUNC (https://sites.google.com/site/planunc/) and CERR (https://github.com/cerr/CERR?w=CERRWiKi). However, the great majority of treatment planning systems in clinical use are proprietary to only a few vendors.

4.6.2 Regulatory Framework (Q2)

The current regulatory framework is described in Section 4.2.2. Treatment planning systems are regulated in the United States, for example, by the Food and Drug Administration. These platforms are rapidly adopting AI-based approaches and excessive regulatory constraints may prevent tuning of AI-based solutions to higher performance for personalized care and local challenges.

4.6.3 Economic Analysis (Q3)

The aspects of interfacing LINACs into the greater medical and related infrastructures makes having a robust, easy to operate yet secure, open, and standardized treatment planning and control systems for LINACs critical to their success. To delivery complex, robust dose maps to patients these machines cannot run without computer control. And they cannot be competitive against commercial products from around the globe without a means to implement and attach new components to expand their capacity and user space. This can only be done with efficient computer control infrastructure as described in this application. Simply having machines self-diagnose to detect early device problems and connect to service to order parts and repair could save many missed days per machine and require fewer support staff to be in place, saving more resources. Finally, these systems can detect error and incorrect use. Avoiding just one medical event/error can make the economic value of a computational infrastructure more than pay for itself.

4.6.4 Performance Criteria (Q3)

The computer system controlling a modern LINAC as desired in this application would be real time multithreaded and multitasking operating systems that would be open source, run on the latest hardware, and be easy to use. Performance in this context is not the traditional "computer speed in doing a calculation" but in the construction of a working environment where work can be done intuitively and robustly by those with varying degrees of education and training. Additionally, to perform in this context will require routine, stable extended uptime, ease of use by all, error and wear detection, and enhanced security. Please see the computational infrastructure areas of Chapter 5 for more complete performance criteria.

4.6.5 Technical Gaps (Q4)

The technical gaps are discussed in the computational infrastructure sections of Chapter 5.

4.6.6 Synergistic Application-Side R&D (Q5)

There are no existing first principles start-to-end simulation capabilities, codes, or models marrying the source through an accelerator to the end including biological effects that can handle the new high-dose rate treatment.

Computational code within these new LINAC systems could be designed to optimally work with AI and machine learning systems to better address tumor change and host/normal tissue change that will allow the data generated in treatment to be validated, stored, and optimized for research.

The development of adaptive radiotherapy has been enabled by imaging systems that can monitor the patient's disease and normal anatomy through the course of therapy. To maximize the patient's likelihood of complication-free cure, the radiation beams should be continuously re-designed as the therapy progresses. This adaptation of the beam to the evolving physiology and biology represents a substantial engineering feat from a control system perspective. Lack of suitable clinical and biological is an even bigger issue. The volume of imaging data and pre-existing priors needed to be considered, including the clinical objective, when combined with the constraints of the delivery system requires the development of next generation platforms for multidimensional data processing and provenance tracking. Such systems will direct which measurements are required to maximize benefit within constraints.

> *To maximize the patient's likelihood of complication-free cure, the radiation beams should be continuously re-designed as the therapy progresses.*

Detector science will be very closely intertwined with computational capacity so as to develop optimal, fast detectors that can address huge data streams. Standards will need to be developed to allow groups to modularize and optimize systems over time and manufacturer.

4.6.7 Required R&D to Bridge Technical Gaps (Q6)

The R&D to bridge the existing computational technical gaps is discussed in the computational infrastructure areas of Chapter 5. The development of Monte Carlo code that is part of this process will require new levels of performance to add biologic assessment.

We need to develop a host of biological “sensors” that can be introduced into patients to give volumetric, real-time biological information to inform the system. For example, a series of MRI labels or other types of agents that give specific molecular event information to a system could allow real-time imaging and analysis of tumor and normal tissues responses and to then adapt the treatment to the patient.

We need to develop a data base of clinical data, including organ function parameters and biomarkers linked to observed toxicities to inform the clinical decision process.

4.6.8 Barriers to Commercialization and Technology Introduction (Q6)

Current vendors without volumetric biologic data capacity may prevent new systems from being deployed on their machines.

Physiciological image guidance is currently lacking in the LINAC space for commercial treatment machines. Functional MRI deployment on LINACs is needed.

Roadmap for Development (Q7)[19]

The roadmap for development of these systems runs in parallel to the implementation of the more formal control systems infrastructure that is discussed in the computational infrastructure areas of Chapter 5.

---

[19] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

4.7 Application Area 6: Plan and deliver radiation treatments to optimize biologically effective dose rather than physical dose

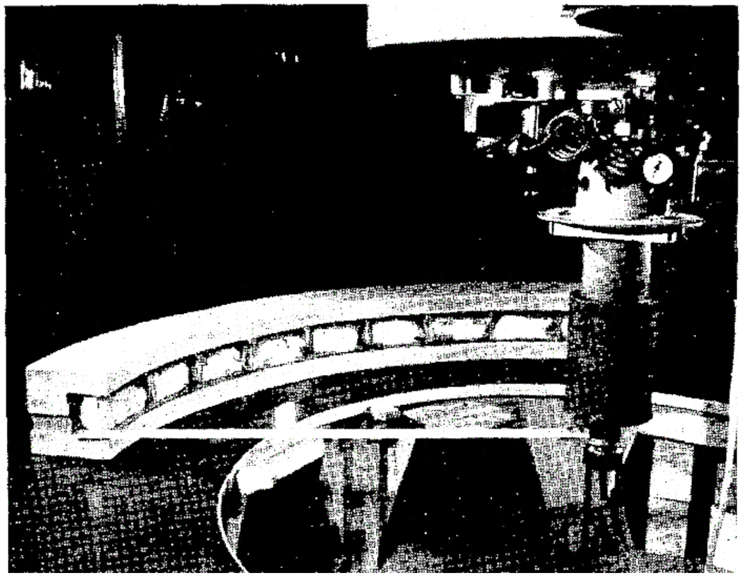


Figure 4.5. *Apparatus for exposing rats under conditions of maximal scatter from a 250 kvp x-ray generator. (Image credit: Radiobiological Dosimetry [ICRU-1962]).*

4.7.1 Background and State of Application Development (Q1)

The ultimate goal is to cure the cancer with minimal sequellae to the patient. This means thinking in terms of the biologically effective dose rather than the physical dose which is the output of commercial treatment planning systems. The potential for this approach to improve the ‘therapeutic ratio’ is of significant interest to the radiation oncology community by making this proven treatment less toxic for current applications. It could also open new applications that may have been abandoned or not pursued due to concerns of toxicity. It is too early to predict the impact of the technology but it is likely to cast new light on traditional issues including causes of radioresistance or the differences in acute and chronic toxicity, including aspects of the tumor microenvironment responsible for radiation toxicity. [McGee-2019] There have been remarkable developments in the planning capabilities of biologically optimized treatments, with focus on relative biological effectiveness (RBE) modeling for determination of RBE-weighted doses. The recently enabled comparison of dose prescriptions from different underlying RBE models is expected to provide a better understanding of various radiation approaches, their underlying biology and the role of fractionation. [Parodi-2018] All treatment planning at present, with rare exceptions in particle beam therapy, is focused on physical dose delivery, measurement, optimization, and shaping. Recent efforts from the NCI have yielded the beginning of interest in biologic treatment planning, initially in proton and hadron therapy but ultimately in all forms of therapy. [Parodi-2018; Kirsh-2018]

The development of new cancer treatments cannot be studied in humans without significant preclinical research – the risks of new agents and methods can be immense and through preclinical studies we learn that some things are not safe and can even be lethal. In this context, modern medical research depends on animal models to study safety, mechanism, and to refine techniques. The history of the use of radiation in medicine has led to numerous biological insights. [Boss-2014] These include the discovery of the double helix using x-ray crystallography, the earliest work on DNA repair – a cornerstone of biological systems, and the development of the cancer stem cell hypothesis. It should be anticipated that additional groundbreaking biological insights related to the temporal response of biological systems to high controlled radiation patterns in time and space will emerge as a by-product of new irradiation technologies.

Before bringing a new treatment into clinical use, it is necessary to perform a considerable amount of laboratory and translational research. This often involves the use of implanted or induced tumors in rodent models. Genetically altered mice are available to test specific mechanistic hypotheses and developments in CRISPR technology will accelerate understanding of the underlying biology of radiation response. Laboratory animal models are critical for advancing radiobiology research as important initial radiobiology discoveries are generated in the lab. With respect to preclinical radiation research, laboratory animal research serves as frontline screening for efficacy and toxicity of experimental radiation and combination therapeutics approaches. Additionally, preclinical laboratory research is necessary to define mechanisms of normal tissue and tumor treatment effects through controlled manipulation of the animals' cells and physiology *in vivo*. However, when considering the translational potential of laboratory research, it has been realized that findings in laboratory animal models may not represent the clinical experience in cancer patients. One reason for this may be that currently much animal work is done using radioactive sources or low energy orthovoltage systems and may not compare to results when radiotherapy is administered with advanced systems that are used to treat humans. Therefore, there is a need for laboratory-based radiobiology research programs to have access to affordable, compact, reliable systems with which to perform radiobiology research in cells and lab animal models. Pre-clinical irradiation devices that most closely represent the radiation physics and conformality as applied in humans is increasingly important. In recent years, there has been substantial research and commercial successes in developing pre-clinical irradiators, however, these do not directly mimic the beam characteristics of clinical systems which are predominantly in the megavoltage range (6 – 18 MV accelerating potential). In addition, the development of security risks associated with radioisotope-based irradiators (e.g., ^{137}Cs) has resulted in the adoption of kilovoltage range bremsstrahlung systems (e.g., 225-320 kVp). These systems have substantial low energy spectral components with associated differential biological effects, unless filtered appropriately. Given the value of radiotherapy to cancer care, further investment into the development of sources capable of supporting maximally-relevant radiobiological research should be considered.

An emerging technology in preclinical and radiobiological LINAC space is the small animal radiation research platform (SARRP, SmART). [Guardiola-2018; Deng-2007; Johnstone-2019] These devices are essentially fully functional clinical radiation machines scaled down to the dimensions of a laboratory animal. An example is shown in Figure 4.4. They include much of the complexity and capacity of human scale devices: arc therapy, IMRT, on board imaging, and promise to allow therapy to laboratory animal models to more closely mimic the radiation delivered to humans. The capacity to further miniaturize these devices to use them for partial radiation of even smaller volumes like 3D cultures could allow the development of whole new paradigms for rapid screening of drug combinations, toxicity profiling, and other areas of hypothesis-driven research on far more affordable models than the mouse. [Guardiola-2018; Johnstone-2019] Using these devices in a magnetic field is feasible and something that would be desired in the field, so ferrous-free LINACs and associated devices would be of great value in this space (detectors, etc.). [Deng-2007] The effects of combined cell stressors on biological systems require further investigations, since there are recent reports of enhancement of carbon ion effects in a longitudinal magnetic field, but not a perpendicular magnetic field. [Inaniwa-2019]

Novel methods for FLASH and endoscopic therapy as well as advanced imaging using mono-energetic gamma photons from advanced compact accelerators are being developed to advance medical outcomes. Pre-clinical radiobiological investigations of high-dose, ultra-high dose rate and spatial dose fractionation are ongoing in human normal and tumor cells *in vitro* using several key molecular and cellular end-points and using laser-sourced electrons in the VHEE range (≥100 MeV), or ions (currently including protons, with other ions up to carbon planned).

These investigations use a leading facility, one of only a few worldwide, where research access to ultra-high dose rate radiations is available to follow up on basic mechanisms underlying the intriguing FLASH effect reported to indicate differential biological impact to normal and tumor tissues at high doses (>10 Gy) and ultra-high dose rates (>40-100 Gy/s).

The goal of the research is to confirm recent reports of radio-resistance of cells from normal tissues, but not tumor cells, and to investigate potential underlying mechanisms of action of FLASH radiobiology to drive biologic treatment planning. The capture, transport, and absolute physical dose calibration of FLASH proton beams have recently been published. [Bin-2019]

Separately, ultra-compact laser plasma electron accelerators at energies of a few to 10 MeV are being developed to enable endoscopic brachytherapy tools. Laser focusing, gas target system and heat management systems are being developed towards miniaturized accelerator heads at cm then at mm scale, and for flexible power delivery fibers. This could enable up to a 3-fold increase in dose to the lesion together with a 10-fold reduction in dose to adjacent structures, but these changes need to be confirmed in the laboratory.

Lastly, studies are ongoing to improve medical imaging. Imaging could benefit strongly from a range of capabilities enabled by compact mono-energetic photon sources [Geddes-2017] providing reduced dose (potentially 10-100x lower) which would allow x-ray and CT imaging to be conducted more routinely, higher contrast, material discrimination using multiple energies for fine distinction of different tissues or improved imaging of soft tissue in the presence of bone [Carroll-2003], and improved spatial resolution down to micron including phase contrast [Schleede-2012] to detect tissue abnormalities earlier and hence improve treatment.

Accessing these benefits requires compact mono-energetic sources with narrow divergence and small emission spot size, which are being developed based on laser-plasma acceleration and Thomson scattering. [Geddes-2015] The integration of compact and novel imaging and treatment technologies will allow a comparison of an array of radiation sources to be tested on the same platform and holds significant appeal as a powerful tool to advance medical outcomes.

An additional level of preclinical radiation research involves the field of comparative veterinary oncology. Just like humans, companion animals develop cancer naturally throughout their lifetime. The field of Comparative Oncology offers an important preclinical model for translational radiation research through veterinary clinical trials. Advanced radiotherapy techniques have been integrated into veterinary oncology centers. These centers treat spontaneous animal tumors and have standardized clinical linear accelerators with image guidance. Radiotherapy protocols range from conventionally fractionated courses to hypofractionated courses, including stereotactic radiosurgery and stereotactic body radiotherapy. [Nolan-2018] Experimentally, FLASH radiation, spatially fractionated radiation therapy (GRID) therapy, and mini-beam radiotherapy have been explored in companion animals. [Vozenin-2019; Nolan-2017; Cranmer-Sargison-2015] There are numerous active comparative oncology trials investigating the combination of radiotherapy and experimental therapeutics or immunotherapy. There is an existing network of veterinary radiation oncology centers within the American College of Veterinary Radiology (Veterinary Radiation Therapy Oncology Group, VRTOG) and within the National Institutes of Health's National Cancer Institute (Comparative Oncology Group).

Radiobiology Research

Current State

Current laboratory based irradiators utilize x-rays in the 160-320 kVp range generated via Bremsstrahlung production, and most systems offer integrated radiation shielding into the unit design. There are advanced small animal irradiator systems with image-guidance and treatment planning capabilities. There are still numerous facilities operating ^{137}Cs-irradiators and ^{60}Co-irradiators; however there is pressure due to security concerns to eliminate these systems from laboratories. As radiation research laboratories move away from isotope sources, there will be a need for consistency in experiments with respect to beam quality, dosimetry, and RBE. There are challenges in preclinical research for *in vitro* and *in vivo* experiments with laboratory animals to generate accurate dosimetry information for the small field sizes and energies associated with experimental results.

Preclinical research performed with veterinary patients utilizes megavoltage linear accelerator systems. These are standard commercially available systems as used clinically for human cancer patients. As with translating laboratory based research to clinical results, there is a need for confirmation of consistency of experimental data with respect to RBE between kVp and MV energies and the associated dose rates for radiation exposure. The development of highly integrated ecosystems for automated radiobiological experimentation is critical if advances in accelerator and related technologies are going to reach clinical impact.

4.7.2 Regulatory Framework (Q2)

In the area of preclinical research, standard radiation safety regulations exist for researchers. There are no animal-specific regulations. With respect to security concerns, laboratories operating ^{137}Cs and ^{60}Co systems are responsible for complying with the National Nuclear Security Administration and minimizing radiological dispersal device risks. In summary, the current regulatory framework is robust for preclinical radiation research. The animal framework is likely adequate if Institutional Animal Care and Use Committee (IACUC) and Institutional Review Board (IRB) approvals and such are conducted per standard animal ethical standards. Radiation system operators will have to adhere to standard radiation use regulations for a given device and situation. All of these issues can be adapted, as needed, so none of the technology thought to be required appears to be blocked by major regulatory hurdles at this time.

4.7.3 Economic Analysis (Q3)

The economic impact discussed in Section 4.2.3 needs to be expanded upon in this context slightly. Biologic treatment planning refines treatment to further broaden the therapeutic index, making cure more likely and/or side effects less likely. While more costly in the short term than generic therapeutic strategies, with time and scale, this and other approaches to expand the therapeutic index will ultimately save money for society. Additionally, if biologic dose can be defined in a global context with other treatments, proper use of chemotherapeutic, biologic, and immunologic agents can be achieved saving money by avoiding the use of expensive agents if not biologically advantageous for an individual patient.

4.7.4 Performance Criteria (Q3)

Desired State

With the requirement for preclinical radiation research to lead efforts for optimizing biologic effective doses, there is a need for greater precision and control in experimental radiation conditions in order to push the limits of radiobiological science. An opportunity for real-time tissue microenvironmental manipulation and integrated bioresponse readout mechanisms in experimental animals would greatly advance the field. An incorporated system for automatic data collection and analysis support would allow researchers to be more productive and effective in performing and completing their experiments.

With respect to translating RBE across the LET spectrum, it is imperative that the preclinical radiation research community identifies a reproducible, well-characterized low LET reference beam. The previous isotopes of reference (^{60}Co) are being phased out due to cost and security. Looking to the future, generating a monoenergetic x-ray source may be possible with a Thomson scattering approach or via laser-driven plasma accelerator.

A Hadron irradiation device is desired for radiobiology research with field sizes ranging from 0.5 mm up to 60 mm diameter and dose rates from 50-300 Gy/s. The system should have energy >50 MeV and multiple particle beams (p, He, Li, C). Ideally, integrated or adjacent image-guidance (MR/PET/CT) would be possible for optimal dose delivery with respect to target tissues.

As interest builds in the clinical potential for FLASH and VHEE radiotherapy, the preclinical radiation research community will be integral in determining safety and efficacy of this new technique. A desired VHEE source for preclinical application would be 250 MeV; however, it would be highly desirable if the system could also include options for experiments ranging from low dose rate (<50 cGy/hr.) to FLASH dose rate (>50 Gy/s). This time structure and control of dose pulse will provide a programmable architecture for biological research to probe the effects of variation of dose in space and time.

There are similar desired traits between accelerator systems in the clinical and preclinical space. In both fields, the aim is to operate accelerator systems which are robust and reliable. In the preclinical radiation research community, accelerator systems which are compact (considering laboratory space) and affordable (considering the funds available to scientists) are high priorities. Preclinical radiation trials performed with veterinary cancer patients will need to operate through animal cancer centers which purchase or have access to these newer clinical accelerator systems in order to provide the most predictive, translational results for human applications.

The Pre-Clinical LINAC for Radiobiological Effectiveness Research

Source Property	**Now [*]**	**Threshold [*]**	**Objective [*]**
Particle. [McGee-2019]	Photon/Gamma		Photon/Electron/Hadron
Effective Source Size	2 mm/1.5 cm		0.1 mm
Directionality	Emitting into 10x10 cm^2 @ 0.2m		Scales from mouse to dog to mini-pig, so variable and modular
Tunable energy range	0.1-10 MV		0.1-10 MV
Tuning speed. [Parodi-2018]	<1 cGy delivered		<1 cGy delivered
Energy spread	Bremsstrahlung up to peak potential/spectrum		Bremsstrahlung Spectrum
Pulse structure. [Kirsch-2017]	3μs @10 ms/isotope		Flexible
Intensity or Flux	3-12 Gy/min (>1 Gy/min)		>100 Gy/s
Stability/Jitter Requirements	Source position stable relative to collimation (<0.5 mm displacement)		Same
Dose Control	Better than 2% or within 1 cGy on total dose delivered to a subject in ideal conditions		
Uptime in high service setting	>98.5%		99%

Uptime in low service setting	30%		99%
Cost	$1-3 million		$0.1-1M but robust, lower operating costs
Failure prediction	n/a		On vacuum/components
Automation Needed. [Boss-2014]	Integrated safety systems; motion control		QA/Safety/Calibration/Planning/OS is the same as the Human Clinical System
Size	Fits within 600 ft^2 shielded bunker		Fits in a shipping container (or some smaller standard unit)
Weight	2-5 tons		
Power	Supply 50 kW for /500 W for ^{60}Co		Works in unstable power setting
Portability	Not portable		Drop-ship capable, could be “wheeled” around to allow campus movement or possible use on a truck, so self-shielding is desirable if small
Acceleration/Shock	Not tolerated except earthquake		tolerated
Op. Temp range	HVAC control – 15°C-30°C		15°C-45°C

[1] - electron, x-ray, high energy x-ray, neutron
[2] - for example, the maximum allowable time to change between beam energies
[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.
[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)
[*] - “Now” - values available from current commercial products
[*] - “Threshold” - minimum increase in performance that would **meaningfully impact** the application
[*] - “Objective” - desired increase in performance needed to provide a **transformative improvement** in the application

4.7.5 Technical Gaps (Q4)

Photon Sources for Radiobiology

The most challenging technical gap is the achievement of FLASH levels of dose rate (> 50 Gy/s) in x-rays from a compact machine. This is a much harder problem compared to FLASH from electrons since the conversion efficiency to x-rays from electrons at the target is only 5-7%, thus photon FLASH requires about 20 times more beam power than in the electron case. This will require simultaneous increases in duty factor, accelerator beam loading, shunt impedance, and also much higher accelerating gradients made possible by dramatically higher source powers as well as higher operating frequencies.

Hadron-capable LINAC-based Sources for Radiobiology

Present-day accelerators are designed for producing only one type of radiation or particle, for example one machine produces and accelerates protons, a second machine produces and accelerates electrons, photons, etc. Having a separate expensive machine for each type of ion is prohibitively expensive, and it weakens the ability to perform research on the differential effects of irradiation with different ions within a single, controllable set of experiments in a given laboratory. Standard linear accelerators cannot accommodate a change between electrons and ions without (at best) extensive offline physical modifications, and once completed, a profound drop in acceleration efficiency, or at worst, they will not work at all with a different ion. A machine is needed that combines different ions and photons/electrons to allow laboratory scientists the broadest opportunities to conduct advance radiobiological research under controlled, affordable conditions where beam quality combinations can be explored.

Electron Sources for Radiobiology

The primary technical gap for this application is directly associated with the requirement to produce FLASH dose rates (> 50 Gy/s minimum, with a maximum dose rate near 300 Gy/s being desirable) from a compact accelerator. Most standard clinical machines produce a few 10's of Gy per minute in electron mode (0.1 to 0.5 Gy/s). For effective Flash electron penetration into tissues, the accelerator must produce beams simultaneously classified as VHEE with about 100 MeV energy. Accelerators with a higher gradient, longer duty cycle, and higher beam current are required to bridge this requirements gap.

Additionally, mono-energetic sources could enable x-ray and CT imaging with reduced dose and higher quality images.

Neutron Sources for Radiobiology

(please see Application 4.8 in this chapter)

4.7.6 Synergistic Application-Side R&D (Q5)

Efforts to optimize biologically effective dose rather than physical dose for radiation treatments will increase the curative capacity of RT and prevent suffering. With respect to preclinical research, laboratory based systems will need to be compact, affordable, and robust. For veterinary cancer centers, the systems must be affordable in order to allow purchase and maintenance. Alternatively, veterinary trials may be integrated into clinical research facilities within the medical community.

Paying particular attention to R&D needed to develop detectors to support the application. *Preclinical research would be an important avenue for detector development…*

- R&D relevance across Medicine Applications
    - MV FLASH photon – efficient – duty cycle – dose rate needs integrate all aspects of the technology development needs
    - VHEE FLASH – 100-200 MeV – better dose vs depth characteristics as compared to photons
    - System design problems – how do you do model this? Improved modelling of complex systems is a need that crosses all aspects of science, so those areas can be used in this problem set and new methods developed here will improve other areas of science
    - Photonic powered linear accelerator of 3cm length – tiny LINACs may prove to allow whole new areas of use not currently envisioned much like the silicon chip provided new uses for computers relative to the large machines of the prior generation based on vacuum tubes and mechanical gears
    - Dose and Dose Rate Reconstruction
        - Photon counting arrays
        - Energy range
        - Spatial resolution
        - Norm and the Voxetes
        - 3D LET measurement system
    - Activation By-product Imaging
        - FLASH and VHEE enabled
        - Photo- and proto- activation
    - pO2 - Oxygen depletion imaging
        - Measure this on the time scale of oxygen depletion

        - Optical methods – see oxylite technology – oxygen mediated fluorescent decay
    - Robust Performance/Security/Safety Detector
        - Unstructured detectors feeding machine learning frameworks for safety and quality
        - Prompt Gamma systems for range verification
        - Proton range estimation that can also detect electrons and photons – proton/photon/electron CT etc.
    - Dedicated FLASH Dosimetry and Constancy Technologies (indirect and direct)
        - Current sensors vs ionization system
    - Fiducial and Image-guidance Detectors
        - Isotope trackers?
        - MR-guided proton/heavy ion/electron/gamma flash
        - Fully integrated imaging with control system integration vs simply hybrid.
    - Re-look at the femtosecond-nanosecond chemical trajectory post-RT
        - optimize the drug side of the equation; non-drug interventions as well; hypocapnia
        - simulation tools for physical chemistry; radical modelling; nanoscale modelling
        - FLASH biology – nuclear event linkage
    - Computational/Digital
        - system engineering that allows for in/out of modular components, is super reliable, and gets standardized interface and API's so that it ultimately becomes universal and robust (and open)
        - big data input and output (collection) built into the system
        - written is easy to maintain code
        - allows regulations to be easy to adapt (entire device need not be re-510k'd for component changes, less cost and red-tape)

4.7.7 Required R&D to Bridge Technical Gaps (Q6)

Photon Sources for Radiobiology

Research is needed to create compact, higher powered, higher frequency more efficient RF sources, much like for what is needed for electron FLASH described below, except the RF power levels for photon FLASH need to be at least 10 times higher (Section 5.3.2). Research on vacuum electronic devices that use over-moded output structures, in particular much more compact versions of gyroklystron amplifiers or gyrotron oscillators (or other sources in the gyro-device family) would be needed, with particular attention to devices using some combination of permanent magnets and harmonics of the electron cyclotron frequency. New concepts for over-moded cavity linear beam (klystron-like) vacuum electronic devices with multibeam or sheet beam geometries would be a similarly important area of interest. Another topic of research would be the development of novel RF pulse compressors, to further raise the peak output power, but with concepts that are much more compact and have higher efficiency and a larger multiplication factor. Methods to greatly increase the beam loading of the accelerator structure, to levels above 80%, would be critical, with a simultaneous increase in shunt impedance. Possible approaches include the use of ordinary cooled metal cavities (to 77K), or new structure concepts involving dielectrics or some other means to break the constraining relation between metal conductivity and shunt impedance. The investigation of the applicability of photocathodes and associated RF injectors to produce complicated pulse trains within the short FLASH dose, and the larger issue of how to improve photocathode lifetime, would also be areas of research interest.

<u>*Hadron Sources for Radiobiology*</u>

Formally outside of the scope of this workshop, compatibility and mutual research capacity with hadron beam devices or functionality would be evaluated in the context of work in this space. LINACs that create x-rays and electrons may ultimately be used alongside or in combination with those able to deliver protons and ions.

<u>*Electron Sources for Radiobiology*</u>

Research is needed to create compact, higher powered, more efficient RF sources, to allow the creation of much higher acceleration gradients that are consistent with a beam energy of 100 MeV from a compact accelerator (Section 5.3.2). Possible approaches include new vacuum electronic RF sources based on multi-dimension electron flow geometries, including multi-beam, 2D sheet or annular beams, beams with a radial flow geometry, or 3D beams based on stacked 2D beam ensembles. Such RF sources would allow extremely high total output power per unit weight and volume by an increase in the total beam current without space charge problems or the need for exceptionally high voltages. Another possible avenue of research would be to use higher frequency accelerator structures and RF sources, with the goal of raising the gradient without triggering breakdown, and to allow a shorter structure. Solid state RF source solutions, with the inherent possibility of distributed powering of the accelerator at a higher duty cycle, is another useful area of exploration. Methods to increase the accelerator duty factor would require research on enhanced cooling technology for both the RF sources (RF interaction circuits and beam collectors) and the accelerator structure. In the extreme limit of a single short duration, extremely high power pulse, or a short series of more moderately powered pulses , methods to incorporate items like phase change thermal materials directly into the accelerator or RF source structure, in conjunction with refractory metals with high conductivity RF coatings, would be an interesting area of research.

Another possibility to increase duty factor with development over the longer term is the introduction of higher temperature operation of SRF accelerators. Such systems could provide the potential for continuous wave (CW) operation of the beam or any modulation desired within that envelope. CW SRF systems naturally match well with robust solid state RF sources and so are synergistic with advances in this area.

4.7.8 Barriers to Commercialization and Technology Introduction (Q6)

The major barrier to commercialization of this technology is cost. Small animal devices can be so costly that it is difficult for a majority of scientists or even departments to justify their costs (or collect the sum needed even if the cost is felt to be justified). Addressing biologic treatment planning via software is already underway with commercial treatment planning software vendors, but it’s very primitive and will require much more translational research to occur before being truly useful in the clinic. Making LINACs affordable and modular (Application 1) will likely significantly aid this application because with lower costs will come increased market size and device deployment.

> *The development of more automated, reproducible preclinical research platforms for radiobiology research would increase scientific yield and would accelerate consistent adoption of novel scientific methods, as well as, lead to validation of scientific results across the globe.*

The second major barrier to commercialization is lack of a market because of a low number of expert scientists in the field at this time. There is a declining population of radiobiologists globally and without those users device sales will be difficult. There is room, of course, if the devices were to be made to be affordable to help rekindle interest in the science and literally grow the human resources side of this space.

A third barrier relates to the substantial level of combined scientific (i.e., biology, physics, computing) and technical (i.e., engineering, robotics) expertise required to effectively apply these technologies. The development of more automated, reproducible preclinical research platforms for radiobiology research would increase scientific yield and would accelerate consistent adoption of novel scientific methods, as well as, lead to validation of scientific results across the globe. The growing expectation that scientific results are supported by strong data provenance should be considered in the system design of these new pre-clinical radiobiology platforms.

Finally, it could be said that using a human oriented machine is the ultimate in translation, but is the most difficult thing to accomplish in reality due to rules about animals on clinical devices that are now common. Few departments have the resources to have a relatively modern LINAC in place for animal research. Thus, if the goals of this project are achieved, an affordable LINAC footprint will be achievable for research purposes that is equal to the capabilities of a full human compatible device that is contemporaneous.

A potential barrier to technology introduction (i.e., radiation research laboratories moving away from using isotope sources) is the need to establish consistency between the accelerator-based and the legacy isotope-based radiation experiments in terms of beam quality, dosimetry, and RBE.

Roadmap for Development (Q7)[20]

Photon Sources for Radiobiology

Initial research on compact, higher powered, high frequency gyro-devices, as well as on new classes of over-moded or alternative geometry klystron-like devices, would be suitable for both university research for theoretical research and experimental demonstrations at low duty, followed by development at a DOE accelerator lab or DOE national lab. The university component could be accomplished with \$3 to \$5 million total over 3-5 years, while the DOE lab component could follow at about \$10 to \$15 million total over an additional 2-3 years. Transition to industry would occur during or following the DOE lab investment. The RF pulse compressor research could occur at a DOE accelerator lab over about 4 years at \$10 million total. Research on accelerators with high beam loading, 77 K cooled structures, and high gradients would be most suited for a DOE accelerator lab with a 3-4 year duration with a total budget of \$7 to \$15 million total. Transition to industry could occur by additional funding of \$1 to \$2 million total over 2 years. Photocathode research is best performed at a DOE national lab over 5 years, with a total cost of about \$10 million.

Electron Sources for Radiobiology

The development of higher powered vacuum electronic RF sources, both at conventional microwave frequencies and at higher frequencies above 20 GHz, would require a combination of university research at about \$3 to \$6 million dollars total over 3 years to theoretically investigate new types of multi-dimensional electron flow devices and perform proof-of-principle lab experiments, followed by another 3-4 year program in the microwave tube industry and the DOE accelerator labs at the \$10 to \$15 million total dollar range. Research on alternative solid-state sources has been discussed previously in relation to

---

[20] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

the Global Radiotherapy application. Improved thermal management for higher duty cycle operation, and in particular for rapid thermal rise induced by high powered short pulse bursts or a longer single pulse, will require a mixture of university research over 3 years for $2 to $3 million total, followed by transition to commercial research at either a microwave tube company or an accelerator systems company. Research on advanced high temperature SRF systems for compact CW operation will require 10 years and $15 million of investment. It is important to perform such research at a laboratory experienced in the development of SRF coating systems such as exists at a couple of national laboratories and a few university. Details are presented in Section 5.3.8 below.

Future Accelerator Concepts

The goal of advanced accelerator research in this sub-topic is to carry research relating to the production of improved biological effective dose rate. Accelerator design can impact this via tight control of beam and photon parameters over relevant ranges. This involves R&D to improve the performance of such devices in terms of dose rate, beam parameter range, control and efficiency, but including making the devices reliable, compact and robust so they are practical in a clinical setting when operated by non-physicists. Since there are a number of possible approaches presently studied for such application the development plan in each area is specific to that particular approach. We detail those approaches in Chapter 5.

4.8 Application Area 7: Development of compact neutron beam sources appropriate for neutron capture therapy

4.8.1 Background and State of Application Development (Q1)

Application of neutrons for the radiotherapeutic treatment of cancer has been a subject of clinical and research interest since the discovery of the neutron by Chadwick, in 1932. For example, fast-neutron radiotherapy [Kirsh-2018], which involves geometric targeting of a well-collimated high energy (average neutron energy 15-20 MeV or greater) neutron beam onto the anatomical target region was first used by Robert Stone at Lawrence Berkeley National Laboratory in 1938. [Stone-1948] Neutron capture therapy is a somewhat different form of neutron-based therapy, first proposed as a general concept by Gordon Locher. [Matifar-2010] In NCT, an elemental or isotopic species having a high neutron interaction cross section is selectively taken up in the malignant tissue following the administration of a suitable boron targeting agent, which can be either a chemical compound or a nanoparticle based structure. In current preclinical and clinical practice the isotopic species of greatest interest is B-10 (yielding Boron NCT, or BNCT). At an appropriate time after boron targeting agent administration, the treatment volume is exposed to a field of thermal neutrons generated by the application of an external neutron beam produced by a small nuclear reactor or a suitable accelerator-based system. The thermal neutrons interact with the B-10, which has a very high thermal-neutron capture cross section (3838 barns at 2200 m/sec). Each boron-neutron interaction produces an alpha particle and a lithium ion. These energetic charged particles deposit their energy within a volume that is comparable to the size of the malignant cell, leading to a high probability of cell inactivation by direct DNA damage. This process, illustrated in Figure 4.6, offers the possibility of highly selective destruction of malignant tissue, with cellular-level sparing of neighboring normal tissue. In a sense, BNCT can be viewed as a targeted high LET radionuclide therapy with a mechanism for switching the emissions of the radionuclide on only at a selected location in the body.

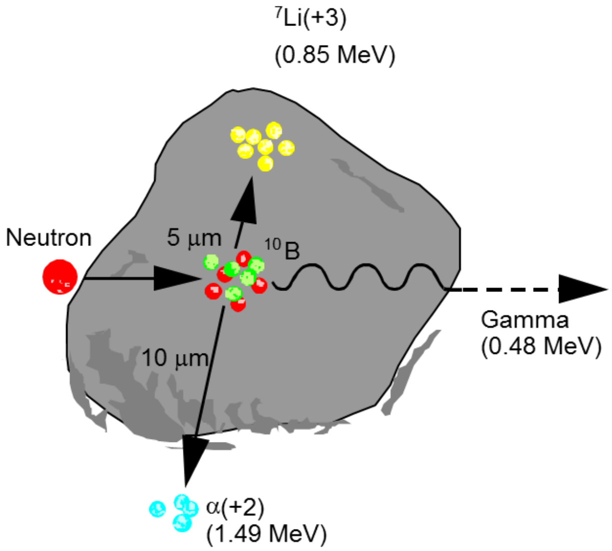


Figure 4.6. *Basic biophysical mechanism of Boron Neutron Capture Therapy [US Department of Energy, Idaho National Laboratory]*

Initial human trials began in the 1950s using reactor based, thermal neutron beams and simple boron compounds. Both the beams and the boron compounds were suboptimal and there was a poor clinical outcome in terms of tumor control and toxicity. Subsequent trials have used epithermal reactor beams and other classes of compounds that were still suboptimal in many regards. Results of the various recent clinical studies of "modern" (since 1994) epithermal-neutron BNCT have been encouraging, but they do not yet constitute a significant breakthrough for BNCT as a clinical modality. In general, most reports [Busse-2003; Capala-2003; Diaz-2003; Joensuu-2003; Kankaanranta-2012] indicated that treatment can be conducted safely, with efficacy that was likely comparable to that of the best alternative standard treatments, with normal tissue complications that were viewed as manageable. Conclusive statistical proof of substantially improved patient outcomes relative to standard treatments remains to be demonstrated via the continuing development of more effective boron targeting agents and widely-deployable, more compact, cost-effective, practical epithermal neutron sources.

> *Conclusive statistical proof of substantially improved patient outcomes relative to standard treatments remains to be demonstrated via the continuing development of more effective boron targeting agents and widely-deployable, more compact, cost-effective, practical epithermal neutron sources.*

A number of research groups began to explore the possibilities of accelerator neutron sources for epithermal-neutron BNCT, and an international Workshop on the subject sponsored by the US Department of Energy was held late in 1994. [Nigg-1994] Participants included researchers from the US, Canada, the United Kingdom (UK), Russia, Japan, Switzerland, Italy, Australia, Germany, Israel, and India. Topics covered included extensive discussions of various accelerator types and their advantages and disadvantages, computational studies of various systems, and various experimental studies focused on basic physics as well as practical engineering issues. The meeting produced a clear (and as it turned out very prescient) consensus that at least one, and probably more than one practical approach to the realization of a clinical-scale epithermal neutron source would in fact emerge from the various development efforts then underway.

Two types of accelerator neutron sources are of interest for BNCT research and clinical trials. The first group of accelerator neutron sources is composed of existing, approved, and routinely-operational, clinical fast-neutron facilities, which can be modified for exploration of NCT-augmented fast-neutron therapy with minimal incremental cost and effort. [Buchholtz-1997; Laramore-1994, -1995; Nigg-2000] The second group of accelerator neutron sources is composed of various developmental facilities designed to produce an epithermal neutron beam for BNCT as the primary therapy. These latter facilities, and additional more advanced facilities of the same type yet to be constructed, are the primary subjects of this section, and the specific current status and future development and deployment needs for such facilities are described in detail.

Low-energy protons impinging on a lithium target constitute the most popular method for accelerator-based systems designed to serve as neutron sources for epithermal-neutron BNCT. While some other approaches to the generation of low-energy neutrons using a light-ion accelerator, such as the proton-beryllium and the deuteron-beryllium interactions, have also been of interest, the focus in this report will be on the use of lithium as the target. The threshold proton energy for the ^{7}Li(p,n)^{7}Be interaction of interest is approximately 1.9 MeV and the typical proton energy in practical accelerator systems is 2.5 MeV. The neutrons produced by 2.5 MeV protons impinging on a lithium target have a maximum energy of approximately 800 keV in the forward direction with a relatively soft spectrum below this energy. Adjustment of the proton energy can permit further "tuning" of the neutron spectrum at the target if desired. As a result, less subsequent filtering and moderation of the neutron source emanating from the target may be required to produce the desired epithermal source spectrum, relative to the case with the fission neutrons produced by a reactor. Furthermore, studies have shown that the spectral quality of an optimized accelerator neutron source of this type can in fact be nearly ideal, with biophysical performance that is demonstrably superior to the best reactor-based neutron sources. [Wheeler-1999] Higher beam energies are required for the proton-beryllium and deuteron-beryllium reactions resulting in a harder neutron spectrum that requires more filtering and moderation.

Generation of neutrons by a low-energy light-ion accelerator is a rather inefficient process in terms of neutron current at the irradiation port per incident charged particle on-target, creating a requirement for rather high particle currents and associated power deposition rates in the target. There are thus many interrelated design factors to consider in connection with the optimization of such systems, and there were many lively discussions prior to the previously-mentioned 1994 workshop regarding whether or not a practical and deployable accelerator neutron source could actually be developed for clinical-scale BNCT applications at reasonable cost.

Ion Beam Applications Incorporated has constructed an epithermal neutron delivery system that has been installed at Nagoya University in Japan. [Ono-2018; Stichlebaut-2006] This system features a 3 MeV, 20 mA proton beam generated by a dynamitron and incident on a high-performance lithium target, with subsequent moderation and filtering of the resulting neutron source using a high-density MgF_2 beam shaping assembly with a Pb reflector. This system was originally designed to be mounted on a gantry although the initial installation did not actually include this feature. At the moment the Nagoya facility is intended to be used for preclinical research only.

Kyoto University Research Reactor Institute (KURRI) and Sumitomo Heavy Industries, Ltd. have developed a cyclotron-based epithermal neutron source for BNCT. It has been installed at KURRI in Osaka prefecture. [Ono-2018] This facility consists of a proton cyclotron, a beam transport system and an irradiation and treatment station. In the cyclotron, negative hydrogen ions are accelerated and extracted as a 30 MeV, 1 mA proton beam. The proton beam is transported to a beryllium neutron production target. The resulting neutrons, with a broad energy spectrum extending up to about 30 MeV or so, are moderated to lower energies by lead, iron, aluminum and calcium fluoride. The aperture diameter of the neutron collimator can range from 100 mm to 250 mm. The peak thermal neutron flux generated in a water phantom by this device is 1.8×10^9 neutrons/cm^2/sec at 20 mm depth. Various pre-clinical tests have been completed using BPA. Clinical trials for malignant brain tumors began recently. [Ono-2018]

In the US, a partnership composed of Helsinki Central Hospital (Finland) and Neutron Therapeutics Company (US and Finland) has just announced the installation and initial physics testing of an integrated, hospital-based, accelerator epithermal neutron delivery system. [Koivunoro-2019] This system, illustrated in Figure 4.7, is composed of an electrostatic proton accelerator operating at 2.6 MeV and 30 mA, with a novel rotating lithium target design. This particular combination of proton beam energy and current impinging on a lithium target provides a significantly more desirable "softer" overall neutron energy spectrum than is the case for the cyclotron system described above, while still producing an effective thermal neutron flux in the target tissue that meets generally accepted intensity requirements ($>10^9$ n/cm^2-s). Furthermore the overall system has been designed with both Finnish and US medical device regulatory guidelines in mind. Once commissioned, it will permit resumption of the extensive Finnish preclinical and clinical BNCT research program that was suspended in 2011 due to the closure (for unrelated reasons) of the FiR-1 research reactor-based epithermal neutron facility just north of Helsinki, which had been used for all of the previous clinical trials in Finland. The first clinical trial using the new facility will be a hospital-sponsored phase I-II study of BNCT for recurrent cancer of the head and neck. Future clinical studies are planned for glioblastomas and other indications.

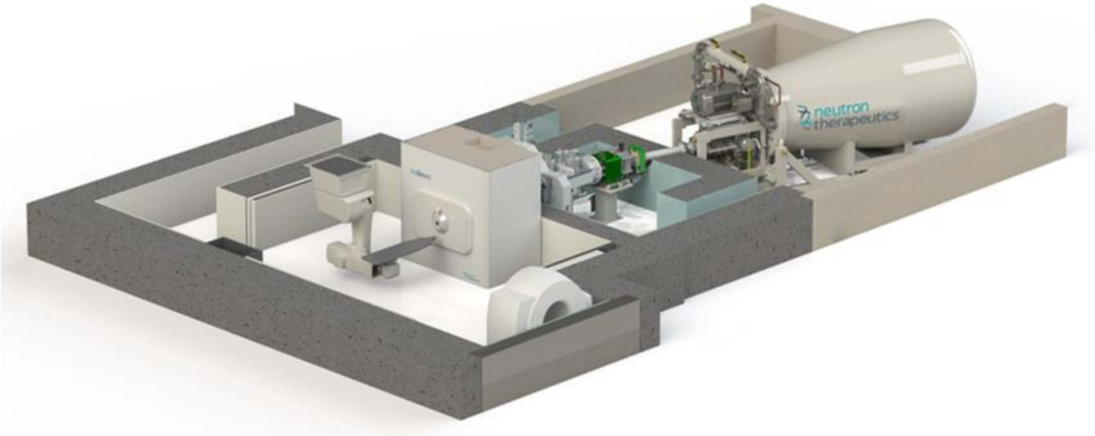


Figure 4.7. *Overview of Clinical Accelerator-Based Epithermal Neutron Source Facility for BNCT at Helsinki University Hospital (Illustration provided by Neutron Therapeutics Inc.).*

RF linear accelerator-based approaches for BNCT are also under investigation [Ceballos-2001; Ono-2018; Stichelbaut-2006; Wei-2009], which can leverage portions of compact LINAC-based technology envisioned for proton therapy. [Benedetti-2017] The strategy involves production of protons from a plasma-based source, followed by bunching and acceleration with a radio-frequency-quadrupole (RFQ) [Vretenar-2014] and sometimes with an additional proton RF drift-tube-LINAC (DTL) or other type of LINAC structure. For BNCT, the resulting proton beam is directed towards either a lithium or beryllium target to produce neutrons, which are subsequently moderated. The RFQ approach alone can produce protons with 3-5 MeV energy, while the DTL, if employed, typically boosts the energy to above 13 MeV. The required energy and average beam current for the protons are dependent on the choice of neutron-producing target reaction and the required neutron flux, but typical requirements are several 10's of mA for lower energy reactions and 0.5 to 10 mA if higher energies are used. For achieving overall system compactness in BNCT, approaches using only an RFQ for the entire proton accelerator are enticing and are the subject of considerable research [Fagotti-2008], including the push towards higher RF frequencies (e.g., 750 MHz vs the more typical 150-350 MHz) to reduce the length of the RFQ and benefit from tradeoffs that reduce overall system power consumption. [Vretenar-2016] It is also important to note that power consumption could in principle be drastically reduced with a superconducting RFQ. Superconducting RFQs were investigated in the late 1980s to late-1990s for proton and other ion acceleration to high energies for mostly non-medical purposes. [Wangler-1992; Pisent-2000] Emphasis subsequently shifted towards a combination of room temperature RFQs for bunching and initial acceleration only, followed by superconducting cavity-based- or traveling-wave LINACs to produce the majority of the beam energy. [Wang-2016; Ostroumov-2002; Mardor-2009] This change in configuration was motivated by overall system engineering and beam energy/quality requirements for the applications and not by compactness goals at lower energies (as desired for generation of neutrons for BNCT) that might once again favor a superconducting RFQ by itself.

With regard to the larger picture in the US, specifically in terms of potential near-term practical research applications of new, more easily deployable, neutron sources, it may be noted that most domestic BNCT research over the past 15 years or so has been focused on very basic *in-vivo* preclinical radiobiological studies related to manufacturing and testing of a few promising new boron targeting agents and combinations of agents using small-animal induced and implanted tumor models. [Hawthorne-2003] An example is the recently-completed preclinical testing of liposome-based boron targeting agents in an induced hamster oral mucosa tumor model that emulates human tumors of a similar type. [Heber-2012] This advanced targeting agent has been shown in that particular model to be capable of achieving tumor/normal tissue concentration ratios in the range of 10:1 and absolute tumor boron concentrations in the range of 60-70 ppm by weight in the time frame of approximately 48 hours post-administration. [Heber-2012] These results represent significantly improved biochemical performance compared to previous targeting agents approved for clinical trials. Thus additional translational preclinical testing in a spontaneous oral tumor model in a larger animal that more closely represents the human situation is now warranted. The most likely large-animal candidate for this would be a canine oral tumor model. In the near term, such testing for one or more new targeting agents could perhaps be done in collaboration with the BNCT research group in Finland, using the Helsinki accelerator facility.

Further in the future, it would also be useful to construct several accelerator-based epithermal neutron sources at suitable veterinary research centers and hospitals in the US, for use as research tools and also as engineering test beds for continuing improvement of the relevant enabling technology in terms of even better spectral quality and corresponding biophysical performance of the neutron source and reduced physical size and cost of hardware and electronics. Such future improvements might also include the realization of gantry-mounted systems to provide more flexible geometric targeting of the neutron beam. The overall idea would be to support extensive fundamental neutron and neutron capture radiobiology research as well as translational preclinical *in-vivo* research on additional advanced boron targeting agents and combinations of agents – always with a view toward ultimate coordinated clinical trials according to agreed-upon protocols using the most promising available boron targeting agents and accelerator neutron source capabilities.

4.8.2 Regulatory Framework (Q2)

The use of ionizing radiation in human medicine has a well-developed regulatory framework. NCT is unique in that it is the combination of the Boron compound and the neutron beam that is used in treatment and therefore both elements must be approved, most likely by different agencies. The quality of the neutron beam will be similar to the epithermal reactor beams that have already been used in NCT and therefore the 510k process should be applicable. There are no animal specific regulations that would apply to preclinical, in vivo studies although standard ethical regulations for animal studies would apply at an institutional level.

4.8.3 Economic Analysis (Q3)

The impact of development of devices to increase cure and/or decrease side effects was discussed in Section 4.2.3 in depth. With neutrons, combination therapy with drugs may be able to find new uses for old drugs and therefore have huge economic impact. Unless there are major improvements in outcome, a BNCT facility must be cost competitive with more conventional treatment facilities. Additionally, neutron biology will have an impact on space travel and survival on the battlefield. At this time, it is too soon to fully endorse these devices for use off protocol, but hopefully this will cease to be the case in the near future.

4.8.4 Performance Criteria (Q3)

The effective thermal neutron fluence that must be delivered to a tumor for an effective treatment is dependent upon the ^{10}B concentration in the tumor and its intracellular location. Assuming a concentration of ^{10}B in the range of 30-50 ppm uniformly distributed in the tumor cells, then a neutron fluence of the order of 10^{12} n/cm^2 must be delivered. To accomplish this in a reasonable treatment time of an hour or less, then the effective thermal neutron flux on target must be in the range of 10^9 n/cm^2/sec or greater. Higher ^{10}B concentrations will reduce the effective thermal neutron flux and fluence required. The high energy neutrons and gamma rays (GR) in the beam must be no greater than those in the best reactor produced epithermal beam.

Table 4.4: *Accelerator Neutron Source Requirements for Epithermal-Neutron BNCT*

Source Property	**Now [*]**	**Threshold [*]**	**Objective [*]**
Particle. [McGee-2019]	Neutron		Neutron
Effective Source Size	1 cm – 10 cm	Same	1 cm – 10 cm
Directionality	Neutron Current/Flux ratio greater than 0.7 at beam exit port.	Same	Neutron Current/Flux ratio greater than 0.9 at beam exit port.
Tunable proton energy range	1.8 MeV – 2.5 MeV		1.8 MeV – 2.5 MeV
Proton current	30 mA minimum	50 mA minimum	100 mA minimum
Tuning speed. [Parodi-2018]	n/a	n/a	TBD
Neutron energy spread	0.414 eV – 10 keV (Broadband)	Same	1 keV – 12 keV (Selectable 1 keV width narrow band within this range)
Pulse structure. [Kirsh-2018]	CW or Pulsed	Same	CW or Pulsed
Neutron flux at beam exit port	1.0x10^{9} n/cm^{2}-s (Broadband)	Same	1.0x10^{10} n/cm^{2}-s (Narrowband)
Neutron background KERMA per unit fluence	<5.0x10^{-13} Gy-cm^{2}/n	<2.0x10^{-13} Gy-cm^{2}/n	<1.0x10^{-13} Gy-cm^{2}/n
Incident gamma background dose	<10% of peak hydrogen neutron capture dose in critical normal tissue.	Same	Same
Stability/Jitter Requirements	Source position stable relative to collimation (<5mm displacement)	Same	Source position stable relative to collimation (<2mm displacement)
Dose accuracy	Neutron fluence control better than 2%	Same	Neutron fluence control better than 1%
Beam Direction Control	Fixed Horizontal	Fixed Horizontal and Fixed Vertical	Gantry-Mounted, Fully-Variable
Uptime in high service setting	>98.5%	Same	99%
Uptime in low service setting	30%	90%	99%
Cost	$1-3 million	<$2 million	$0.5-1.0 million and robust with lower operating costs
Failure prediction	n/a	n/a	On vacuum/components
Automation Needed. [Boss-2014]	None	Some	Extensive
Size	Fits within shielded bunker	Same	Fits in a shipping container
Weight	2-5 tons	Same	Same
Power	Proton beam on target: 75 kW	Proton beam on target: 125 kW	Proton beam on target: 250 kW
Portability	Not portable	Same	Drop-ship capable
Acceleration/Shock	Not tolerated except earthquake	Same	Same
Op. Temp range	HVAC control – 15°C-30°C	Same	15°C-45°C

[1] - Neutrons produced via the ^{7}Li(p,n)^{7}Be interaction within the device, with subsequent neutron spectral shaping via moderation and filtering.
[2] - for example, the maximum allowable time to change between beam energies
[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.
[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)
[*] - “Now” - values available from current commercial products
[*] - “Threshold” - minimum increase in performance that would **meaningfully impact** the application
[*] - “Objective” - desired increase in performance needed to provide a **transformative improvement** in the application

4.8.5 Technical Gaps (Q4)

- Present RFQ structures are still several meters long to achieve the 3-10 MeV energy needed for neutron reactions. This presents a challenge to compactness.

- Simultaneously achieving the required beam energy and average beam current in a single unit and avoiding the need for an additional post-RFQ accelerating section.

- Excessive RF power requirements and associated limitations on the duty cycle. This is closely coupled with problems of achieving the required thermal management from the vane structures.

- Superconducting RFQ technology lags far behind that of superconductive axisymmetric cavity-based LINACs.

- Poor conversion efficiency between the accelerated particles and neutron production.

- Robust high-power conversion targets (e.g., lithium) that can withstand the intense CW proton beams needed for BCNT (see Section 5.3.5). Liquid lithium targets have been demonstrated, but they are costly and mechanically complex, and safety is a concern. The rotating lithium target utilized by the Neutron Therapeutics system is a workable alternative.

- Simultaneously achieving the required beam energy and average beam current in a single unit and avoiding the need for an additional post-RFQ accelerating section.

- Development of new structures such as the RF-Interdigital structures provide post-RFQ acceleration with significantly higher acceleration efficiency than standalone RFQ structures offering a highly competitive alternative hybrid accelerator system for achieving CW beams up to approximately 12 MeV without the need to move to higher frequencies avoiding the attendant tolerancing and thermal management challenges while achieving compactness.

- Development of new accelerator structures better matched to the energy/beam current regimes offers an alternative development path to extending the “energy/beam current range” of standard RFQ structures.

4.8.6 Synergistic Application-Side R&D (Q5)

Complementing the BCNT neutron source R&D is the advancement of new shielding/collimating materials that can minimize the unwanted accelerator-produced fast neutron/gamma flux to no greater than that obtained from the best reactor-produced epithermal neutron beams. Optimization of the shielding must account for factors such as workload, use and occupancy, and regulations on maximum permissible exposure and their effect on design. Advanced metal hydrides can provide higher neutron shielding capability compared to conventional materials thereby reducing the thickness and weight of the necessary shielding. Lead is commonly used for gamma shielding, but there are concerns associated with its environmental and toxic hazards. Research is needed on advanced metal foams, polymer-composites, and embedded glassy matrix materials that show promise for cost effective, compact gamma shielding applications.

4.8.7 Required R&D to Bridge Technical Gaps (Q6)

Research on higher frequency RFQs (1 GHz and above) is an important topic, since the overall length of the accelerator can be decreased at higher frequencies. The tradeoffs between compactness, achievable gradient, and total RF power requirements at the higher range of frequencies needs to be investigated. Particular attention must also be given to fabrication tolerance issues, which becomes more demanding at higher frequencies. Tolerance parameters are particularly challenging in the short initial cells, when the particles are still moving slowly. Additive manufacturing methods need to be explored (see Section 5.3.3), while giving strict attention to maintaining the required low outgassing, achieving a very low surface roughness, and meeting the tight tolerance requirements.

Improvements are needed in RFQ accelerator designs to enhance focusing and to maximize acceptance of the input dc beam and quickly eliminate non-captured particles at low energy, to avoid excessive interception heating. These issues are most challenging for short, high gradient designs. Additional improvements are required to guarantee RF field symmetry and to avoid spurious modes. Improved tuning strategies for RFQs are needed, as are better tuner designs exhibiting lower loss.

Improved solid-state RF systems tailored to powering RFQs need to be developed for compact overall form factor and reliable operation (see Section 5.3.2). Devising RFQs having characteristics better suited to distributed solid-state RF sources represent another interesting approach.

Research into alternative nuclear reactions in target materials under proton or deuteron bombardment that might have improved neutron yields are an important topic. Another key area is the study and exploitation of neutron production from the acceleration of light ions into proton-rich targets (rather than accelerating protons into light metal targets). The accelerated ion approach can greatly increase the downstream directionality of the neutron production, and also may provide opportunities for improved overall neutron production with a thorough exploration of possible nuclear reactions. This requires the development of ion sources for the appropriate light element with a predictable degree of ionization (and thus charge to mass ratio) and compact RFQs designed for the heavier species.

Research into superconducting RFQs should be re-established, specific to the beam energy, average current, and particle species required for production of neutrons in targets. Designs that can maintain sufficiently low temperatures near the surfaces of the RFQ structures are challenging, particularly at higher RF frequencies. Methods of applying suitable superconductive coatings to the finely detailed shapes of RFQ surfaces with sufficient quality and uniformity need to be developed.

Improved thermal management techniques are required for targets (see Section 5.3.5), so that they can dissipate the high heat flux deposited by impinging flux density of accelerated protons or other ion species. Such thermal management must be done in a way that does not compromise the efficiency of neutron production and maintains an overall compact system form factor (including ancillary heat transfer equipment). Heat removal from the accelerating structure vanes is likely a limiting factor for average power and duty cycle capabilities, so research on better thermal management is imperative in this region as well.

4.8.8 Barriers to Commercialization and Technology Introduction (Q6)

BNCT represents a binary (two-stage) cancer therapy which employs both biotechnologies for high-specificity ^{10}B intra-cellular delivery to cancer cells coupled with accelerator technologies to deliver spectrally-optimized neutrons to induce the $^{10}B(n,\alpha)^{7}Li$ interaction, resulting in localized (intra-cellular) energy deposition within ^{10}B-loaded cancer cells while sparing healthy cells. BNCT therapy offers substantial benefits over standard cancer therapies and has demonstrated impressive clinical results for challenging and recurrent cancers (refractory cancers).

Accelerator-driven neutron sources offer the ability to provide superior spectral distributions as compared to the neutron spectrum from reactors. In general accelerator-based neutron sources offer superior neutron flux distributions, compact footprint, compatibility with hospital environment, reduced cost, improved reliability, and limited safety/security concerns. Low-energy proton LINACs used with Lithium or Beryllium targets offer the capability to reach CW neutron source operations in support of BNCT. Typical BNCT treatments are carried out in one or two fractions, as opposed to 10 to 30 fractions required for conventional x-ray or primary proton radiation treatments potentially resulting in reduced treatment costs and improved quality of life.

The barriers to commercialization for BNCT can be partitioned into three primary factors:

a) Development and classification of optimized ^{10}B delivery agents specifically the classification of these delivery agents as drugs subject to the FDA approval process which can result in costs upwards of several hundred million dollars and substantial approval cycles
b) Development of spectrally-optimized, CW neutron sources for high-throughput patient treatment facilities
c) Ability to fast-tract clinical studies within the US

The primary barriers to commercialization of accelerator-based CW neutron sources are:

a) High-efficiency, low-energy CW proton accelerator systems coupled with robust proton-neutron conversion targets enabling delivery of optimized neutron flux to the patient
b) Low-cost RF amplifier systems
c) Low-beam-loss systems to optimize efficiency and reduce radiation shielding requirements

Multiple alternatives have been championed for accelerator-target configurations in support of BNCT including high-energy proton beams, alternative targets, and moderators to optimize the spectral distribution of neutrons delivered to the patient. However lower-beam-energy solutions offer reduced capital costs, operational costs, shielding requirements, and hardware disposal costs. Engineering challenges for the development of accelerator/target systems in support of BNCT are primarily associated with lifecycle cost and technical challenges associated with achieving minimum beam loss in the CW accelerator system.

Roadmap for Development (Q7)[21]

Research on higher frequency, more compact RFQ structures would be a combination of design and simulation studies, followed closely by experimental prototype fabrication and testing. This could be accomplished by a combination of university research at $3 to $6 million total over 3 years, and research at a national accelerator facility or national laboratory at $10 to $20 million total over an additional 3-5 years. Industry could be directly involved with the fabrication process during the research, which would simplify an ongoing transition. If additive manufacturing methods are considered, a combination of university research and SBIR/STTR programs would need to be initiated as simultaneous additional tasks, which would cost about an additional $5 million total over 3 years.

Improved target and RFQ structure thermal management strategies could be studied at a national laboratory or national accelerator facility. The cost would be approximately $3 to $7 million total over 3-5 years.

---

[21] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

For R&D on superconducting RFQs, this would be best established at a national accelerator facility with experience in other types of superconducting accelerators. Costs would be approximately $25 million total over 5 years. Transition to industry would likely take an additional 5 years at a total additional cost of about $10 to $15 million.

Research into alternative target reactions for neutron production could take place with a combination of more speculative university efforts and intensive research at a national laboratory. University costs would be about $3 to $4 million total over 3 years, and research at national laboratories, which could occur concurrently, would cost $10 to $15 million total over about 4-5 years.

Improved utilization of solid-state sources for compact RFQs, and RFQs more specifically designed for such sources, would be research topics most suited to a national accelerator facility or national laboratory. Efforts should concentrate on methods to distribute the sources along the RFQ rather than external power combiners. The cost would be approximately $10 to $15 million total over 4-5 years.

Conclusion

Current technology imposes limits on the results achieved in cancer treatment by radiation therapy and in the use of radiation to sterilize medical and food products. Beam output in terms of spectrum, dose rate, flux, and stability can be improved through research in source and detector technology and development of an integrated systems approach to accelerator design incorporating high level AI/Neuronetwork operational control and monitoring will simplify operation, reduce the need for highly trained personnel, and increase reliability. Smaller sized units and less expensive units will allow medical care costs to be decreased for those with LINACs and for those in need of LINACs to more easily afford to acquire sufficient numbers of units to address the local population's needs properly. New uses for LINACs will emerge in brachytherapy and imaging as the units become smaller and replacement of sources and x-ray tubes is possible. In the future radiation treatments will be planned in terms of their biological effects on tumors and normal tissues and not in terms of the physical doses delivered. The major impediment to the clinical use of BNCT is the lack of tumor specific ^{10}B carriers. However, availability of accelerator-based neutron sources is key to supporting this work and if successful, hospital based delivery systems will be required to make this technology widely available. The goals set forth in this chapter are achievable and mesh tightly with those of security. If achieved, the results will improve life for the population on all scales and will optimize resource utilization.

5. Research and Development Themes in Accelerator and Detector Technology

5.1 Introduction

The more than 30 distinct accelerator applications identified for security and medical applications (as defined in Chapters 3 and 4, and Appendices E and F) require R&D on over 200 distinct issues, which have been grouped together into the broad R&D themes of this chapter. R&D advances are clearly indicated for electron sources (especially as used to produce x-rays), neutron sources, and detector technology, and here have been divided into near-term and long-term R&D themes.

An overwhelming majority of the issues identified above require advances in electron accelerator technology, so it is useful to provide some additional classification of electron accelerator needs.

Four Principal Types of Electron Accelerator are Needed

While the applications differ significantly in beam delivery requirements, the underlying accelerator performance, SWaP, automation, and cost targets are the primary challenges that dominate the early-stage R&D needed. Additional questions of beam delivery, reliable power, packaging, and development of application-specific expert operating systems are vital at later stages of development.

In most cases, bremsstrahlung sources—perhaps combined with energy selection to achieve bandwidth requirements—are adequate for the photon-based applications, although higher fluence sources will require innovation in targets to operate reliably at very high power. For applications requiring coherent, intense, tunable, narrow bandwidth x-rays in a compact footprint existing approaches are inadequate and not scalable. Innovative approaches are clearly required.

The fluence requirements defined in Chapters 3 and 4 may be translated into accelerator requirements by assuming a radiation generation mechanism and using the corresponding efficiency of the process in converting electron beam power to x-rays. Table 5.1 below assumes for most cases that an optimum thickness high-Z bremsstrahlung target is used. A description of the absolute x-ray yield calculation is provided in Appendix G. Together with Kramer's law, this methodology was used to estimate the primary electron beam power requirements using the fluence requirements in Chapters 3 and 4 for use cases where bremsstrahlung was the likely conversion process. Conversion efficiency of electron beam power to photon beam power is for most cases very poor, ranging from a few percent for broadband applications with high electron beam energy to a few parts per million for applications requiring narrowband, low-energy photon sources.

Ultra-low Power Portable systems – designed primarily for emergency response to perform radiography on either moderate density or high density objects. These systems must be person-portable, rely on either battery power or limited line power, and be low cost. Beam energies range from a few hundred kilovolts

Table 5.1. The four principal types of compact electron accelerator identified for security and medical applications.

	Type I	**Type II**	**Type III**	**Type IV**
General Type	Ultra-low Power Portable	Low- to Moderate-Power	Moderate- to High-Power	High Energy
Example Applications	Emergency Response	Portable Conventional Radiotherapy, Radiography, Down well (DW), Chip & Circuit Inspection (CCI), Electronic Brachytherapy (eB), Pre-clinical RT Machine (PCRT), FLASH-RT	Secondary Screening, High Flux Radiography (HFR), HEDP, NDT, Sterile Insect Technology (SIT), Food Safety (FS), Phytosanitary Treatment (PT), Medical Sterilization	NRF, Ptychography, XFEL, MPS for Screening, MPS for Radiography
Energy Tuning Range	LE Radiography: 0.3-0.4 MeV HE Radiography: 1-4 MeV	NDT, DW, CCI, HEDP: 0.1-1 MeV Others: 1-14 MeV FLASH-RT: 6-250 MeV	NDT, HEDP: 0.1-1 MeV SIT: 1-5 MeV Others: 300 keV - 10 MeV	500-1500 MeV
Beam Power	1 W	eB: 50 W FLASH-RT, CCI, DW: 100 W Others: 300-500 W	HEDP: 500 W NDT, Secondary Screening:1000 W HFR, SIT, FS, PT, Med Ster: 100 kW	100 W
Desired Maximum Accelerator Size (accelerator only)	10x10x30 cm	eB [intra-cavitary only]: 1x1x1 cm NDT, Down well: 10 DIA x 22 L cm PCRT, FLASH-RT: 20x20x25 cm Others: 10x10x60 cm	Inspection, HEDP: 10x10x60 cm ≥10 kW-class: 100x100x250 cm	NRF, Screening : 10x10x60 cm Ptychography: 20x20x250 cm XFEL: <10 m long
Special Features	LER: <12 kg, battery power, <300 W HER: <50 kg, line power, <1.2 kW	eB: Can be sterilized Inspection: 50 micron spot size Down well: 200 C operation	Inspection: Spot size <1 micron	NRF: 1-7 MVp tuning range XFEL: <5 micron spot size, <50 fs pulse length
Target Capital Cost	<$100k	eB: < $600k NDT, Down well <$200k Portable Radiotherapy: <<$3M Others: <$1M	SIT, Food Safety: <$5M	XFEL: <$20M
Assumed X-ray generating mechanism	Bremsstrahlung	Bremsstrahlung, or none (eB, FLASH-RT)	Bremsstrahlung	ICS or XFEL

to 4 MeV at less than a watt of beam power to provide broadband (i.e., bremsstrahlung) photons from 300 kVp-4 MVp.

Low- to Moderate-Power systems – designed to provide either electron beams up to 250 MeV for cancer therapy, or to provide higher fluence photon sources in the 100 kVp-14 MVp range. Beam power requirements range from 50 Watts to more than 500 W to provide the necessary fluence. Some uses require ultracompact formats—for example electronic brachytherapy sources must fit in an endoscope, and down-well source must fit in a 10 cm bore. For cancer therapy dose control must be very precise (2%), for other applications spectral agility is important.

Moderate- to High-Power systems – designed to provide high- to very-high-flux photon sources for high speed inspection of dense objects, sterilization of medical devices, food, and sterilize harmful insects. Photon energies in the 300 kVp-10 MVp range are needed, with beam powers ranging from 500 Watts to more than 100 kW to provide the necessary fluence. In some cases (medical sterilization, SIT) dose uniformity must be precisely controlled.

High Energy systems – designed to provide extremely narrowband and/or coherent sources of photons. These devices are typically not bremsstrahlung sources, but require more complex radiation generation processes such as inverse Compton scattering or undulator radiation to produce photons in the required energy range and narrow bandwidth. These systems typically require energies on the order of 1 giga-electron-volt (GeV) and while beam power requirements are modest, beam quality becomes critical.

Clearly, innovations in high efficiency x-ray generation methods can reduce beam power requirements and have a profound impact in the compactness of sources.

Application Mapping to Technology R&D Themes

The technology R&D needed to close the technical gaps and realize the high impact applications discussed in Chapters 3 and 4 are summarized in this Chapter. Eighteen “research and development themes” were identified by the workshop, and are here presented in three sections: Near-Term Accelerator Themes, Long-Term Accelerator Themes, and Detector Technology Themes.

Themes categorized as “near-term” are expected to be able to reach TRL-4 within 5 years given the resources outlined here. Themes categorized as “long-term” are of a more fundamental and preliminary nature, but which may over a longer term yield transformative changes in the security and medical applications described above.

To guide the reader, the working groups developed an R&D summary table (Table 5.2, next page) that connects the applications of Chapters 3 and 4 to the R&D themes found in this chapter. A darker color indicates a stronger need for R&D to advance the particular application.

Table 5.2. *R&D summary indicating the impact that advances in the research themes outlined in this chapter are expected to have on security and medical applications.*

		Chapter 5 R&D Themes																				
		Integrate Measurement and Simulation with Operation	Transform the Design Process	Fault Tolerant and Intuitive Systems	Modular, Flexible, High Power Density RF Sources	Transformative Accelerators for FLASH and VHEE	Accelerator-Based High Energy X-Ray Sources	Accelerator Materials by Quantum Chemistry- and Physics-Enabled Design	Develop High-Flux and Shorter Pulse Neutron Sources	Improved Accelerator System Efficiency	Advanced Manufacturing	System Health & Controls	Converters for High-Power Density Pulsed Beams	Low Cost and High Reliability Accelerator Powering Systems	Robust Multi-Particle and/or High-Rate Detectors and Systems	Dosimetry for Emerging Accelerators	Endoscopic Accelerators	Compact Superconducting RF Accelerators	Advanced Laser Accelerators and Drivers	Advanced Beam-Driven Accelerators	Mono-Energetic Photon Source
		5.2.1	5.2.2	5.2.3	5.2.4	5.2.5	5.2.6	5.2.7	5.2.8	5.3.1	5.3.2	5.3.3	5.3.4	5.3.5	5.4.1	5.4.2	5.3.6	5.3.7	5.3.8	5.3.9	5.3.10
Security Applications		Computing			Materials & Sources					Engineering					Detectors		Future Concepts				
Non-invasive probing with small sealed sources	**3.2**	1	1	1	1	0	2	2	2	1	1	2	1	1	2	0	1	0	1	1	2
NDT of Structures		1	1	1	1	0	2	2	1	2	1	1	1	2	1	0	1	0	1	1	2
Non-Destructive Characterization	**3.3**	1	1	1	1	1	2	1	1	2	1	1	1	1	1	1	0	1	2	1	2
Advanced Manufacturing		2	1	1	1	0	2	1	1	2	1	1	1	1	1	1	1	2	2	2	2
Electronics Supply Chain Assurance		2	1	1	1	0	2	2	1	2	1	1	2	1	1	1	0	2	2	2	2
Nonproliferation and Treaty Verification		1	1	1	2	1	2	1	2	2	1	1	1	1	2	1	0	2	2	2	2
Emergency Response		1	1	1	2	1	2	2	2	2	1	2	1	2	1	1	2	1	2	1	2
Stockpile Stewardship		2	1	1	1	1	2	1	2	2	1	1	2	1	2	1	0	2	2	2	2
Port Security		1	1	1	2	1	2	1	1	2	1	2	2	1	2	1	0	2	2	2	2
Radioactive Waste Management		1	1	1	1	1	2	1	1	2	1	1	1	1	1	1	1	1	2	2	2
Food Processing	**3.4**	1	2	2	2	0	1	1	0	2	1	2	2	2	1	1	0	2	1	2	1
Sterile Insect Technology	**3.5**	1	1	1	1	0	1	0	0	1	0	1	1	1	1	1	0	1	1	1	1
Sterilization of Medical Devices and Pharmaceuticals	**3.6**	1	2	2	2	0	1	1	0	2	1	2	2	2	1	1	0	1	1	2	1
Medical Applications																					
Low-Cost Robust Accelerators for Clincial and Preclinical Use	**4.2**	1	1	1	2	1	1	1	1	2	2	2	2	2	1	1	2	1	2	1	1
Expanded Operational Parameters for Beam Delivery and Management	**4.3**	2	2	2	2	2	1	1	1	2	1	1	2	1	2	2	1	2	2	2	1
Improved Radiation Detectors for Dose Meas. and Realtime Monitoring	**4.4**	1	1	1	2	1	1	1	1	1	1	2	2	2	2	2	1	2	2	2	2
Improved Beam Collimators for Field Shaping	**4.5**	2	1	1	1	1	1	1	2	1	2	1	2	1	2	1	1	1	1	1	1
Optimization and Development of Treatment Planning	**4.6**	1	1	1	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1	1
Optimize Biologically Effective Dose Rather than Physical Dose	**4.7**	1	2	1	2	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1
Compact Neutron Beams for Neutron Capture Therapy	**4.8**	2	2	1	1	1	1	1	0	2	1	1	2	1	1	1	0	1	0	0	0

Legend

2	R&D advances are critical to making this application possible
1	R&D advances will substantially impact this application
0	R&D is not needed for this application

5.2 Near-Term Accelerator Technology Themes

5.2.1 Research Theme 1: Integrate Measurement and Simulation with Operation

Scientific challenge to be addressed

- Medical Application Area 5: Optimization and development of treatment planning and delivery control systems to allow for real-time biologic and volumetric treatment adaptation
- Medical Application Area 6: Plan and deliver radiation treatments to optimize biologically effective dose rather than physical dose

Summary of required R&D

- Research into fast, error and noise tolerant algorithms for dose optimization.
- Development of fast (reduced or capable of taking advantage of modern and emerging computer hardware) simulations that can be put into a control system.
- Development of simulation codes with pluggable controls-system interfaces.
- Development of simulation codes capable of handling feedback to be able to provide new predictions depending on observations.
- Development of AI/ML methods that can learn on treatment data and provide improved treatment plans.
- Develop data standards that can be applied to both simulations and measurements.

Scientific Impact of R&D

- Improved understanding of treatment systems, from accelerator to diagnostics.
- Improved optimization and feedback modeling will have application far beyond radiation use for treatments.

Potential Impact on the Application

- Ability to modify treatments in real time given observations, thus having patient specific treatments.
- Ability to have treatments that minimize toxicity while maximizing effectiveness.

5.2.1.1 Background

Deployment of compact accelerator systems into production, clinical, and remote field environments will require a high degree of automation suitable for effective utilization by non-experts. This automation level will require fast and accurate determination of the accelerator state coupled to decision-making capabilities at local (i.e., device head) and remote (i.e., operator) locations. Simplicity and ease-of-use for the non-expert operator places additional burdens on the accelerator's control systems to quickly integrate data streams from disparate sources with a (possibly complete) catalog of anticipated performance and behavior metrics.

5.2.1.2 Scientific challenge to be addressed

Issues must be discovered and resolved in the field post-deployment

Once a compact accelerator device deploys to the field, successful operation will depend on its ability to self-diagnose the machine state and any trending behavior, environmental changes, and signals originating from remotely situated operators or users.

A minimal set of non-invasive diagnostic systems feeding a real-time data acquisition system can provide essential read-back of the accelerator state. The set must be complete enough to provide adequate redundancy for decision-making functions, but not encumber the accelerator support systems or interfere with functional constraints on size, weight, and power. Onboard or remote expert systems based on artificial intelligence (AI) models for detection, monitoring, and decision-making will make use of networks and electronic components hardened for tolerance to environmental stresses such as high radiation fields, excessive temperatures and pressures, vibration, dust, humidity, or corrosive atmospheres.

Issues must be known, cataloged, and resolutions determined pre-deployment

An automated, expert system is trained to recognize patterns and conditions as they develop, and to respond according to pre-established procedures or decision logic. This must needs to be conducted on full-scale prototype machine examples. This training encompasses start-up and shut down system checks which evaluate system readiness and the return to a ‘safe’ state for access or maintenance. Simulations of device behavior provide a set of measurable parameters for functionality and performance that may indicate needs for particular diagnostic systems. Studies of errant behavior due to particular failure modes of components, logic, or environmental changes can also point to specific patterns of signals that require intervention by the expert system, including the exercise of machine protection logic and notification to remote operators. A catalog of fault events and test cases will need to be exhaustively probed, in simulation as well as in integrated system testing and machine learning phases, so that the high level control logic is adequately trained to operate semi-autonomously.

Operations and Monitoring

Once an accelerator system is deployed and operational, a relationship is established between the controls logic and supporting systems of the accelerator and the remote human operator. In some cases, the operator may be tasked with remote operation of multiple, semi-autonomous accelerator systems. The level of autonomous self-governing by the accelerator will vary depending on the specific application. In many cases of interest, the human operator will establish operating guidelines and safety envelopes, and then permit the expert logic to make decisions that fine tune its actions and monitor continued operability.

Presently a “human operator” debugs the machine according to his knowledge and experience. We want this to be performed by an automated machine, in times much faster than a human response. This will pave the way to develop ultra-fast machine corrections, a field never explored before.

The challenge is to create a “virtual operator” that will understand the origin of the discrepancies (based on measured data, or by running a set of simulations, obtaining the correction of the drifting parameter/s). It must detect faults, in that case the comparison is voided.

An accelerator system is currently envisioned to provide beams of particles or photons as one part in a multi-step process. As such, the role of the accelerator system in the overall process is bounded and may be governed by constraints. This limits the requirements on the control, monitoring, and decision-making logic.

User Interface

The interface with the user or operator provides a means to establish operating conditions and constraints. It should provide a simple means to initiate automated start up and shut down procedures, and to provide monitoring of critical accelerator performance and process variables. On encountering errant conditions that require operator intervention, the user interface will inform the user of the fault condition and current status of the accelerator.

Using the Accelerator Model

Accelerator systems are composed of multiple subsystems that together determine the state of the machine and its functional behavior and performance. On-line accelerator models are typically used during the commissioning and tuning stages to predict and validate performance characteristics. High fidelity, multi-particle beam dynamic simulations are computationally expensive and do not, as yet, provide real time feedback. So, a reduced physics model is generally used to provide low lag-time monitoring capabilities during operation.

A reduced physics model is introduced to capture only the essential characteristics of the beam and support system behavior, providing a measure of self-consistency with available diagnostic signals. An expert, either human operator or artificial intelligence, accesses the results of the on-line model to assist in further decisions. The expert may use the model to optimize accelerator parameters (e.g., magnet power supplies, RF cavity phases and amplitudes) in response to changing conditions, or to investigate root causes between predicted and observed behaviors. In this latter case, an investigating agent may be instantiated to conduct independent tests against the model in parallel to operations, providing additional training data to the control and monitoring agent. The reduced physics model may be augmented to incorporate additional details or processes in an effort to identify the root cause of deviating behavior. An example is to incorporate fast transient behaviors otherwise absent in the reduced model from, say, more detailed source emission models.

System Self-Checks

Automated start up and shut down procedures will initiate and validate sub-system self-check tests. During start up these self-checks are critical to provide input to the Run Permit System and to unlatch interlocks that prohibit switching of power and beam operation. During beam operations, each subsystem will employ self-check diagnostics to validate the state of system set points. The read back of these set points may be integrated with the on-line accelerator model, or provide direct input to the expert control agent. Switching of operating modes, safe shut down or pausing of beam production is authorized through simple or model-based reflex agents.

Metrics based on diagnostics, detector readings or production monitors are also observables and may be used to gauge the overall performance of the accelerator system. Comparison with model predictions may indicate deviation from learned or predicted behavior, resulting in agent-initiated actions.

Decision Making and Intervention

An AI-based expert control system manages a hierarchical cast of agents to integrate monitoring and decision-making functions. These agents are employed at all phases of operations, from start-up processes through production and shut-down. Agents will manage the collection of system self-checks and performance monitoring to direct the operation of the accelerator and associated subsystems.

On occasion where the AI training is determined to be incomplete, the high level agent may request user intervention to complete a decision and initiate new action. Additional training may then be requested and performed.

Development and System Characterization

Full scale prototype testing and extensive operational and lifecycle studies are necessary to determine:

- Acceptable performance envelopes under realistic or simulated conditions
- Points of failure and signatures of failure
- Appropriate meditation or mitigation responses to changes in conditions or system failures
- Regimes of validity for reduced physics models

- Minimal required suite of system and beam diagnostics

Expert system training

Training of expert systems is a laborious and time intensive process to repeatedly sample normal and abnormal machine behavior under all operating modes and states, as well as the transitions between modes and states. Full-scale testing permits the design and subsequent evaluation of predictive algorithms that the expert agents will need to employ to maintain machine performance and equipment or personnel safety.

Lifecycle studies

Lifecycle studies will indicate trends in machine behavior, component failure modes and rates. Detailed behavior during power conditioning activities as well as observable effects from particle source aging will need to be understood and recognized from system or beam diagnostic signals. Changes in control and monitoring systems must also be recognized and understood – this can include changes in background noise that affect diagnostic signal acquisition, filtering, and measurements; abrupt changes in electrical grounding and shorting; changes in risetime, waveform shape, and amplitude and timing jitter for pulsed systems; changes in or collapse of network communication systems; and others.

Diagnostic systems

Complete system characterization requires extensive diagnostic and measurement capabilities to fully probe the machine state as it determines overall performance. Invasive and noninvasive beam diagnostics will measure specific beam parameters and their evolution through specific operating modes and processes. Measurement and correlation of beam parameters during machine lifecycle studies identify classes of changes in beam intensity or quality that directly affect machine performance. Exhaustive measurements with more complete diagnostic suites can be utilized to pare down the required diagnostics for ultimate production use by comparing with machine state variables, component age (e.g., sources), and various performance metrics. Additionally, more invasive diagnostic packages can be designed for periodic maintenance and field servicing functions.

Comparison of models and model reduction

Comprehensive physics models and simulations are needed to capture essential processes in the machine operation and beam evolution. Time-dependent, multi-particle simulation codes are typically employed as very high fidelity models, but are very expensive and time consuming to run. Benchmarking these comprehensive physics models against the prototype machine behavior validates the model and the low level understanding of the primary processes affecting overall performance. The comprehensive models are critical components to specifying required diagnostic systems, and validating the minimal set of diagnostics for production.

Start to end simulations are essential to capture the beam behavior in different operating modes. Working at various levels of the physics model detail, specific beam parameters and processes are captured and tracked:

- Peak and average current and particle intensity
- Beam energy, energy spread
- Longitudinal beam pulse and microbunch structure
- Beam centroid trajectory and transverse offsets
- Transverse beam envelopes
- Transverse and longitudinal phase space, correlations, microstructure
- Instability thresholds and growth rates

Start to end simulations employing the full physics packages, including models of diagnostic systems, provide full validation when benchmarked against prototype machine behavior and model operations during commissioning and production. Predictive algorithms on machine state and performance are testable against the comprehensive model.

Reduced physics models that are capable of running in real time are essential tools for the control and monitoring expert agents. These are used to validate expected machine behavior against observed behaviors, and to inform decision-making processes. These reduced models are derived from the comprehensive models and deemed to be valid in specific operating regimes. Various reduced models may be employed in different operating modes, and may be based on multi-particle, single particle, fluid, envelope, or kinetic descriptions.

Challenges and Opportunities

Real world realization of a complex machine include a very high number of discrepancy variables that are not present in the theoretical machine model. The main discrepancies between the ideal model and reality are, to cite a few:

- Misalignments
- Deviations in components/sources
- Tolerances, non-linearity in components
- Noise
- Faults

The challenge of an automated machine is to run the system in the presence of the above disturbance factors. Automation must be able to iteratively solve inverse problems and calculate deviations, including machine misalignments that were not measured before, and correcting discrepancies on sources, correcting tolerances, non-linearities, etc. In case of a fault the corresponding measurement must be discarded.

Measurements are achieved through diagnostics placed along the machine, giving information about the beam parameters along the machine. Due to the expensive cost, their presence is limited. The operator must be able to understand the machine status by using the limited amount of information provided along the machine. In a fully automated machine, additional diagnostic can be introduced to allow the machine learning kernel a deep understanding. Additional research can be established to strategically reduce the number of diagnostics in order to reduce the total cost. Diagnostic measurements are limited by tolerances, noise, and low sensitivity, factors that can still limit the machine understanding.

An intelligent computing system must be developed in order to record, understand and track the above discrepancies and deviations. The algorithm can be based on machine learning, AI and genetic algorithms. It must be able to take operator decisions, and make assumptions as a “human operator”. Assumption decision can be supported by real-time simulations.

The main computer must collect the data from diagnostics, run real time simulations, and compare the real time simulations and measurements for understanding of the machine behavior and identify the machine model, handling the fault events.

Upon identification of machine model, the virtual operator can be able to change parameters (i.e., beam trajectory). Control system need to be developed to create an efficient and fast control. More obstacles arise due to limitations in controlling the machine. For example saturation of the dipole corrector currents. In this case the AI must be able to understand the limitation of the machine and perform another corrective strategy. Since the machine model can vary, it must be updated real-time by re-performing the above operations.

Due to the high amount of data streaming, ultra-fast parallel computing is required. Hardware for fast computing the developed software, in real-time. It can be with parallel computing and/or FPGA.

5.2.1.3 Summary of required R&D

Develop an intelligent computing system that will record, understand and track the above discrepancies and deviations, by using:

- AI/ML
- Genetic algorithms
- Ultra-fast parallel computing
- Real time simulations
- Comparison of the real time simulations and measurements for understanding of the machine misalignments and drifts

Need an intense activity to develop:

- Software for automating the machine processes, with real time simulation for guessing and correcting the machine parameters
- Hardware for fast computing the developed software, in real-time. It can be with parallel computing and/or FPGA
- Tests of the above

Research in:

- Converting basic human choices in automatic machine operations
- AI – genetic algorithms
- parallel computing and/or FPGA
- real time simulation and evaluation of errors
- real-time feedback
- Machine fault handling

5.2.2 Research Theme 2: Transform the Design Process for Compact Accelerators

Scientific challenge to be addressed

- Security Application Area 2: Nondestructive Characterization
- Medical Application Area 1: Development of low-cost, robust accelerators for clinical and preclinical use based upon a modular component approach.
- Medical Application Area 2: Expansion of operational parameters for beam delivery and management including ultra-high dose rate delivery.

Summary of required R&D

- Research into algorithms for unified modeling of electromagnetics, beam transport, multipacting, and thermal transport.
- Research into fast multivariate optimization methods for large-scale simulations.
- Development of HPC and graphics processing unit (GPU) enabled software for above described modeling.
- Development of interfaces that enable accelerator design software to be used by non-PhD engineers.

Scientific Impact of R&D

- Faster cycle time from concept to physical design to physical prototype to finished product.

Potential Impact on the Application

- New compact, portable accelerator designs for use in nondestructive characterization.
- New designs for compact accelerators for clinical and preclinical use will be enabled,
- New designs for compact accelerators that can provide a wider range of operational parameters for beam delivery

5.2.2.1 Background

There are numerous criteria that must be satisfied by an accelerator design. It must have a sufficient number of electrons injected into the accelerator structure. The electromagnetic fields must be powered up to the energy density needed to have the desired acceleration. At that energy, the surface fields should not be so large as to cause breakdown (conventional structures) or quench (superconductors). The accelerator cavity should be examined for parasitic losses, in particular for multipacting, where electrons can impact the surface, releasing other electrons, which can release more by impact, until one has an exponentially growing population of electrons that can sap the electromagnetic energy or, worse, cause material damage resulting in a need for cavity replacement. The surface heating of a cavity by the electromagnetic fields results in heat that must be conducted away to prevent thermal damage. In addition, the cavity should address stress analysis issues, which at their worst are cavity destruction due to excessive forces from any of the above processes but can even be small deformations that change the cavity tuning.

Beyond this, one has the integration of the accelerator with the downstream devices that convert the accelerated electrons into the radiation needed for the application. Downstream devices include high-Z materials for x-ray generation, wigglers, also for x-ray generation. Beyond that may be collimators, to provide the beams of the needed divergence. Here again there may be thermal issues associated with deposition into the collimator. The problem here is how to get the data out of one model (the accelerator) and into another (e.g., the wiggler). This is both a data conversion issue as well as an issue of how to do the beam transport in between.

Finally, to model the full system, one must be able to see how it will operate under feedback, i.e., the results from downstream must be conveyed back to the accelerator, perhaps for real-time optimization. This may bring in stability issues, such as the Nyquist criteria for linear systems, but now less easily computed, as an accelerator is a highly nonlinear system.

The goal of this is to be able to design the fully integrated system: accelerator, downstream devices, and feedback to use in an optimization system. Design involves optimization coupled with a sensitivity analysis as the absolute optimum operating point may not be robust to small changes in parameters, and so one must have a system that facilitates parameter scans and computation of figures of merit (FOMs) easily with minimal human intervention and without requiring the writing of scripts to convert data between formats. Ultimately, one wants software that can orchestrate the entire process, including the efficient calculation of the optimal system through parameter variation and FOM optimization.

5.2.2.2 Integration within the accelerator

Within the accelerator cavity, multiple processes occur. As noted above, there are the fields, the injection of particles into those fields, the acceleration of the particles, the dynamics of stray particles (multipacting), and the loss of energy of the fields due to surface resistance. In one workflow, this involves multiple steps with several distinct software applications. One application is used to mesh the interior of the cavity and solve for the electromagnetic fields of a mode. If there are static magnetic fields, those are often computed by yet another computational application. Yet another application imports those fields onto a grid, then tracks the particles through those fields. An application of this sort can also do the multipacting, if it has the appropriate surface physics. Finally, from the surface electromagnetic fields, one can compute energy loss and/or whether the system will break down or quench.

As one can see from the description, this is a labor intensive process, requiring human intervention at multiple points, for writing data translation software, for executing the various application sequentially, and for data analysis and visualization at each stage. Low hanging fruit would be to develop standards for translating data between the various computational applications. This would be useful regardless. However, this would still be a sequential process. Moreover, this process misses important physics. For example, importing fields and tracking particles does not take into account beam loading, such that the fields can change due to the presence of the particles. This latter requires a self-consistent simulation.

Some of the physics for the above processes is not well known. A glaring example is that of breakdown, for which research is underway. But as well, secondary electron yields as needed for studies of multipacting are not as well-known as desired. Research in these areas is needed for the longer term, but development based on what we know now can take place.

The new, required research in this area would be towards providing an optimal approach that would allow easy calculation of all of these effects. One approach is to move towards a Multiphysics code that allows one to represent all of the physics on a single computational grid. Another could be to develop a more efficient coupling approach under a user environment developed to house the various computational activities. Of course, the latter would need two-way coupling to compute the feedback between, e.g., particle acceleration and field modification.

5.2.2.3 Integration with the cavity vessel

As noted above, heat is deposited into the cavity vessel through surface heating and/or particle deposition from stray particles. Again, the current state is that separate computational applications for each of these processes are run in sequence. Often, these two computational applications have different grids, as the grids are developed with different goals, e.g., the size of the grid cells is chosen to represent the physics to be modeled, and since the physics is different the grids may be different. Consequently, one must interpolate the data from one grid to the other, and these can lead to accuracy loss and numerical violation of energy conservation e.g., the energy computed to be given up by the electromagnetic field may not match the energy that the thermal modeling tool imports. Hence there is a need for code coupling methods that are conservative.

In addition, one must take into account that coupling in both directions may be needed. The heating of the accelerator material may change its resistivity, which will then change the electromagnetic fields, but more importantly feed back into the energy deposition. If this is important, then two-way coupling is needed. In addition, one must overcome the large time-scale differential. Thermal processes occur on millisecond time scales, while the fields are oscillating on nanosecond time scales. There has been work on algorithms that would cover this large scale separation. Those would have to be implemented and tested for this case.

One could also explore a collocated Multiphysics application, where the various fields are all represented on a single grid/mesh. Here one faces the difficulties of overcoming spatial scale separations, and there is the issue of allocating memory for fields that are not needed throughout the simulation.

5.2.2.4 Forward integration with downstream modeling

The output of the accelerator are accelerated charged particles. Those then are the input for the radiation device. This implies a needed coupling. For example, when the output device is a bremsstrahlung x-ray generator, one typically uses a Monte Carlo code, such as Geant4, to compute the production of x-rays and their spectrum from the incoming electrons. The Monte Carlo model expects the data describing the incoming beam in a particular form that likely does not match up to the form from the output of the accelerator. Therefore, there must be a conversion in some form. One approach is to develop a standard, such as OpenPMD [OpenPMD-n.d.], and then have the accelerator code write to this standard, and have the radiation transport code read this standard. This will require the development of plugins for Geant4 and coding for accelerator modeling code. Such an approach with data standards and libraries that codes can link to for data I/O conversion has been taken within some institutions to support their code availability and their specific workflow, but we need it to be spread across the accelerator developers and designers community.

There are similar issues for analysis of x-ray generation by a wiggler. In this case, the beam needs to be transported to the wiggler, then an FEL modeling code, which must operate at much finer spatial discretization, would be employed.

In either case, the output would be the spectrum of x-rays, which one could then use directly on a target, or (especially in the case of bremsstrahlung radiation) one would further transport through the collimator. This could take place in a Monte Carlo code again. The output would then be a deposition profile in the final target. For this, much of the software exists, but it is not in easily usable form.

5.2.2.5 Feedback

Ultimately, one would like to simulate the full system, including as controlled. The output of the diagnostic of the previous section can then be used in a feedback loop to modify the parameters of the modeled accelerator. This enables the testing of various feedback methods to see how rapidly they converge to the right solution and/or whether their use leads to an instability of the entire system.

5.2.2.6 Optimization

Optimization has been available to accelerator physicists for quite some time, but has had mixed levels of use. For beamline optimization of magnetic steering coils, it's had a long history. For device and component optimization, its use has been limited for multiple reasons. One reason is the computation resources required to do multi-parameter optimizations often requires use of a HPC cluster. There are several issues here: first, the use of optimization methods takes some level of experience with them and how to set and change their parameters and which method to use and when, and this causes researchers to hesitate using them; second, remote access and how to get an account and time on the clusters is uncertain, and also protocols to using them and choosing simulation time and queues is difficult to understand; and third, many codes are not available on the HPC clusters because they are not ported to LINUX, or they are commercial and have some licensing requirement. There are many real and perceived barriers. Research is needed to determine how to ease the use of HPC or how to make codes sufficiently performant that optimization can be done on local workstations, perhaps with compute devices, such as GPUs.

Pareto curve: The ability to use multi-objective or multi-criteria optimization and its support by optimization libraries such at DAKOTA is gaining popularity. What is coined Pareto decision making based on fitting data to a Pareto curve is used by many to balance out the multi-objectives and presents a method of mutually satisfying the competing criteria. The application of the Pareto front curve as an optimization process is prevalent throughout the commercial manufacturing domain for understanding and minimizing failure points and improving manufacturing. Our community needs to embrace this method and bring it to application for accelerator component, device, and system design. This requires the community to more easily and readily have access to computers required to apply the techniques as well as making the use and application of these techniques more ubiquitous. The development of a User Design Environment alluded to earlier where the user can also orchestrate the optimization from their local desktop or laptop is required, and the technology exists for such an environment to be developed for accelerator design and development.

Adjoint methods: With regard to the optimization of devices or systems, another powerful tool that can be used in the design process is acquiring a sensitivity function that describes how the system is affected by small changes in parameters. A sensitivity function using an adjoint approach based on a form of reciprocity approach implicit in Hamilton's equations of motion can be developed, for example, in the case of beam optics. Typically it is expected that the sensitivity function can be calculated for an N-dimensional parameter space with N+1 computations to predict the gradient of the metric. However, using the adjoint method this requirement can be reduced to as little as two calculations; a base case, and then a custom formulated perturbed case for the specific metric. Such methods have been applied to many other areas of science and engineering, and are now gaining attention in RF circuit design and beam optics. Combining a way to efficiently inform the optimization with the sensitivity to various parameters through a potentially large reduction in computations is a powerful tool that the accelerator community should take advantage of, and much research into its application and method development is required.

Artificial Intelligence (AI) / Machine Learning (ML): Recently, the application of ML is becoming more common in accelerator development. This Data Science approach is a subset of the field of AI. AI attempts to mimic human decision making logic, and includes Machine Learning that employs complex statistical algorithms to improve task performance as experience increases. It can further drill down into deep learning as a subset of machine learning, where the algorithms can self-train often through the use of neural networks. However the use of ML seems to fit the accelerator component/device design approach as the expert designer is used to coach or teach the algorithm how to do some aspect of the design process, and learns in this way. There are four common methods of ML, including Supervised Learning (e.g., classifying characteristics of images which have a target); Unsupervised Learning (e.g., where there is no target such as predicting what choice might be made by a human, and clustering of humans into groupings); Semi-Supervised Learning (e.g., combining categorical like in Supervised, but with clustering to help decide on classifications and choices such as lane choice in GPS devices); and Reinforcement Learning (e.g., optimization of solutions where targets are not always available like with autonomous vehicle control). There is much to be gained at every aspect of accelerators form design and development to ultimate system control including safety and accelerator aging and maintenance. The community is seeing the huge benefits of applications of Machine Learning to analysis and development and the software design environments and solution must include and support the use and application of these methods.

5.2.2.7 Ease of use

Most accelerator modeling codes have been developed for use by specialists. However, for design to be taken up by a wider range of designers as needed, e.g., by industry, these codes must be made easier to use. This includes development of graphical user interfaces that allow easy import of geometries as defined by CAD files, such as STEP, and parameterized geometry, setup of parameters for optimization, setup of scans and optimization runs, standard data analysis and visualization, to name a few requirements. Here, in addition, if HPC resources are to be used, the user interface should allow easy use of such resources. These qualities are required in the Design Environment discussed above, where such environments enable both rapid design, but also more robust designs, as they support the workflow approach to component, device and system analysis, design and development.

5.2.3 Research Theme 3: Fault Tolerant and Intuitive Systems

Scientific challenge to be addressed

- Security Application Area 3: Food Processing
- Security Application Area 4: Sterile Insect Technology
- Security Application Area 5: Sterilization of Medical Devices and Pharmaceuticals
- Medical Application Area 5: Optimization and development of treatment planning and delivery control systems to allow for real-time biologic and volumetric treatment adaptation
- Medical Application Area 6: Plan and deliver radiation treatments to optimize biologically effective dose rather than physical dose

Summary of required R&D

- Research into methods for determining sensitivities of integrated systems.
- Research into methods for providing an intuitive view of integrated systems.
- Development of easy-to-use interfaces that run on minimal hardware, such as tablets and smart phones.

Scientific Impact of R&D

- Increase in scientific output with easier use of complex medical instruments.
- Increase in scientific results with systems that have less maintenance and other downtime.

Potential Impact on the Application

- Less training will be required for effective use of radiation treatment systems.
- Systems with greater uptime fraction. Will be able to treat more patients, sterilize a greater volume of devices.
- Systems that are easier to use will be deployable in regions where the skilled labor pool is not as deep.

5.2.3.1 Background

An important part in bringing a complex system into widespread use is making the human interface to that system intuitive. If the control of that system “makes sense” fundamentally, the operator(s) will be more comfortable with systems operation and will be less prone to mistakes.

Accelerators are inherently a complex system with multiple subsystems which work must work in harmony to eventually produce the desired beam. Although the design and operation of the system—as a whole—is a complicated and demanding problem, the end-user (operator) should not need to know the details of how that system produces the beam in order to be an efficient and productive user. Millions of people drive automobiles every day but only a small portion of them really understand the inner workings of an internal combustion engine.

However, the different overarching types of accelerators—those for medicinal treatments, those used in research, and those used in imaging and industrial environments—each have a different form of “intuitive design”. It is not feasible, nor desirable, to attempt a unified human interface design for the different forms of accelerator. The operator in a hospital should not be expected to understand the detailed operation of a scanning accelerator at the airport. Likewise, a grad student using a scientific accelerator should not be allowed to operate a medical accelerator without rigorous training despite any commonality in the operational interfaces of those two accelerators.

A control system design guide should be created and disseminated to the medical device manufacturers. While it may not be feasible to force them to adhere to these guidelines, the market may naturally favor those who do comply with these guidelines—another factor in the decision on which system to purchase.

5.2.3.2 Medical Applications

It is likely the medical accelerators are the most difficult to design an intuitive control system for while maintaining safety and efficacy. These machines may be used multiple times per day with varying operators and patients. Furthermore, the treatments can be very different from patient-to-patient with unique setup requirements for each one. This complicates the end-goal of making an intuitive control system.

In order to address this more difficult problem (that of creating conceptually intuitive medical accelerator control systems) it will be helpful to consider the overall operation of a generalized treatment program and then begin considering the off-normal cases where the treatment deviates from the ideal operating regime.

The fundamental operation of a medical accelerator has a subset of standard parameters for operation which should be presented in a uniform section on a panel or computer screen. The layout of these parameters along with labels and units should be consistent from one machine to the next. An operator should be able to see in a quick glance what these parameters are and determine if they are reasonable and within bounds. Of course the control system will be designed to permit only reasonable entries for all parameters required for the treatment, but until autonomy is fully realized, the operator is the final check on multiple levels.

On another panel or screen, treatment specific parameters should be presented in a similar manner to the basic screen (consistent layout where appropriate, consistent units). These values will be individually relevant to the specific treatment and type of machine delivering the therapy. Although the specifics of a given machine may not lend itself to inclusion in a design guide, the layout and location of these variables may. For example, many beam therapy machines utilize slits to mask certain areas of the patient from receiving radiation in undesirable locations. Some of these slits may move during the treatment (dynamic), while others are stationary. However, the idea of a slit and masking is common enough that the presentation to the operator can be called out in a design guide.

During treatment, the machine should report back status in a common and in a clear manner to allow the operator to quickly determine if anything anomalous is occurring. Values such as beam current, voltage, accumulated does, etc. should be up-front and easy to interpret. Along with that, any patient feedback system (video, audio) should be presented on the same screen.

Finally, a common set of buttons (both physical and virtual) should be agreed upon to allow rapid deactivation (scram) of the beam with further indicators showing status of any engineered interlocks required for safe operation.

5.2.3.3 Industrial Applications

The industrial accelerator lives in a very different environment than that of the medical devices. They are often on-location in the field doing inspections or surveys, or part of an assembly line doing sterilization of foodstuff or equipment. As such these machines need far less information passed on to an operator for normal day-to-day operations. In fact, the operator for these machines may be only peripherally trained on the internals of their operation with the manufacturer relying heavily on engineered controls and expert installation/setup.

For example, an accelerator used on an assembly line for sterilization of medical equipment may look to the casual observer like just another “box” on the line which the pieces run through. Operation will likely be completely automated and integrated into the factory SCADA system.

However, the setup of this machine is where uniformity and consistency make a difference. When the plant engineer needs to change the way the accelerator operates and “opens the hood” to change these parameters, a consistent and intuitive interface will make that task more efficient. Similar to the medical devices, a uniform layout will pay off during these maintenance tasks when the machine is off-line and possibly the entire line is shut down awaiting the reprogramming of the accelerator.

5.2.3.4 Security and Inspection Applications

The accelerators used in security applications occupy a middle-ground between the medical and industrial. While not as turn-key as the industrial machines, they do not need constant adjustment from object to object which require continued operator input. Take for example a scanning accelerator at a border or airport. Ideally the operator is simply monitoring the operation of the machine and peripherals (transfer belt, image recognition subsystem, etc.) and concentrating on making sure all pieces are properly scanned and classified. However, depending on the particular object, some deviation from “normal” beam operation may be required. Again, intuitive design will pay off in efficiency. An operator trained on one particular machine should be capable of operating another similar machine with minimal retraining. This includes the ability to “penetrate” an object more thoroughly if necessary. The control scheme to allow the change in beam parameters should be specified in the design guidelines as well as when/how to reset those parameters back to a normal operating range.

The same principles of intuitive design for security applications can be utilized in military inspection applications with more restrictive guidelines as dictated by the particular organizational CONOPS (for example, location specific idiosyncrasies, environmental considerations, diverse operator experience, etc.) Given that the operation of these devices may be in areas not tightly controlled or even outdoors, a unified method of signaling operation and allowing shutdown is important. Finally, these accelerators may be part of a larger system which supply power and other inputs as part of a larger mission. Similar to the assembly line accelerator, these inputs and outputs should be presented as part of the accelerator control system in a consistent manner.

5.2.3.5 Fault tolerant design of control systems for use in compact accelerators

Fundamentally, the design of any compact accelerator should consider fault tolerant design from the hardware itself as well as the control system design. The goal being to maximize the up-time of the accelerator system and prevent unanticipated downtime.

The consequence of a fault can vary from simply delaying the desired outcome of a particular irradiation (for example, halting an assembly line which utilizes an accelerator as a process step in an assembly line), to endangering a patient who is undergoing treatment or diagnoses with a medical accelerator.

Well documented fault-tolerant design practices should be borrowed from agencies such as NASA (see, for example, “Fault Tree Handbook with Aerospace Applications [Fault Tree Handbook-2002], which is likely more relevant to modern designs than the older NRC publication “Fault Tree Handbook” [NRC-1981] to do a full fault-tree analysis of the accelerator system as a whole. This includes not only identifying components and assigning risk factors to each, but also incorporating software risk analysis in terms of the likelihood and consequence of software induced failures.

Common approaches to fault tolerant design include redundant subsystems where feasible (for example, if a pulsed magnet power supply failure is considered a moderate risk, overall system design can include a backup supply along with the means to monitor operation and switch over to the backup if a failure is detected), system health checks (both locally at the fault-prone component level, and higher up at the control system level), and general machine protection monitoring systems which will mitigate the damage should a fault still occur.

Another important area to be considered is that of fault prediction—how to anticipate via metrics that a particular subcomponent is nearing end-of-life or about to fail. Having mathematical models of how a particular component operates and being able to monitor that operation allows one to observe these components as they perform their day-to-day operation. With marginal machine-learning methods applied to these datasets, it would be possible to flag an out-of-normal operating regime and signal to the operator that a particular part is not behaving properly. Depending on the role that part plays in the overall operation of the accelerator, the operator (or perhaps the control system itself—given enough autonomy) would formulate a plan on how to deal with this anomaly. The response would vary from immediate shutdown, to flagging the unit for replacement at the next maintenance cycle, to simply establishing a "watch" status to see how the out-of-normal condition tracks over time.

The building of the fault analysis and response rules can be initially seeded with results obtained via simulation. Systems which are modeled for the use of simulated the operation of the accelerator itself can be given fault modes and rates. For use in the fault analysis, these rates can be increased to induce one or more faults at a high frequency than predicted for real-world operation. Simulated faults have the obvious benefit of being controlled by the researcher and are easily modified in both frequency and mode—but they also suffer from the "garbage in – garbage out" adage in that if the faults are not captured adequately (type, likelihood, mode), the results are meaningless (and possibly dangerous if too much trust is put into them). As always, simulation should be checked against physical systems when at all possible. However, a benefit of modern computing hardware including data gathering and archiving allows the accelerator design to collect massive amounts of data over many hours of operation. With access to this data, the accelerator designers can perform not only post-mortem analysis after a failure occurs, but also monitor multiple accelerator installations in near real-time and use the data from not only multiple runs, but multiple systems to refine the control system design in order to recognize impending faults and mitigate the issue before it becomes a gating problem.

5.2.4 Research Theme 4: Modular, Flexible, High Power Density RF Sources for Powering Reimagined Accelerator Structures

5.2.4.1 Background

The vast majority of present-day RF sources for accelerators are vacuum electronic devices. These devices include klystron amplifiers and magnetron oscillators for powering most electron LINACs at microwave frequencies, typically in S-band (2-4 GHz), C-band (4-8 GHz), and some in X-band (8-12 GHz), while for the highest operating frequencies (towards the mm-wave regime), research accelerators have been powered using gyro-devices. For accelerators like RFQs that operate at relatively low frequencies, the most commonly-used vacuum electronic RF sources have been power tetrodes or triodes. Some recent accelerators have used conventional solid-state transistors and conventional power combining, which is reasonably achieved at lower frequency. Compact electron LINACs operating at microwave frequencies, using new types of high-performance microwave transistors (based on wide-bandgap semiconductors) that power the accelerator in a spatially distributed manner along its length, are starting to be researched. Additional background and discussion of accelerator technologies is provided in Appendix G.

5.2.4.2 Scientific challenge to be addressed

- More compact, higher power, higher frequency vacuum electronic-based RF sources
- Solid-state RF sources with higher power and characteristics optimized for accelerators

The overall challenge is to create and develop new classes of high power RF sources more suitable for compact, high power density, fault tolerant, variable pulse train and tunable accelerators. This includes devising and developing new classes of vacuum electronic sources at f > 20 GHz capable of being operated at lower voltages (below 30 kV) but producing > 10x improvement in SWaP and 10x lower cost than present technology. Another goal includes advancing the underlying electronic materials science and fabrication technology to create solid state transistors capable of producing 5 kW peak power at frequencies above 10 GHz that are also deliberately tailored to the narrowband, high impedance characteristics of accelerators.

5.2.4.3 Summary of required R&D

- Higher frequency vacuum electronic RF sources with multi-dimensional electron flow
- Vacuum electronic RF source design and fabrication using pre-engineered modular components in a common framework, and implemented using additive manufacturing
- Solid-state RF transistor geometries, semiconductor materials, and fabrication methods to allow an order of magnitude increase in peak power production at more lower cost
- Device-level materials and structure research to create transistor RF sources optimized for the relatively high impedance, narrowband characteristics of accelerators

Create new classes of vacuum electronic devices employing multidimensional electron flow, including multiple round beams, two-dimensional sheet beam or annular beams, radial flow beams, and three-dimensional stacked sheet beams. This can allow the production of much higher RF power at higher efficiency from compact volumes, and overcome the space charge focusing problems that limit single beam devices. Operation at much lower beam voltages will also become possible, which is highly beneficial from a systems reliability standpoint and for reducing overall volumes by reducing the level of required electrical insulation. Vacuum electronic devices utilizing multidimensional electron flow will also enable higher frequency operation while maintaining the required high power levels, by allowing the use of larger surface area beam-wave interaction structures and by the power-combining effect of multiple round beams or higher-dimensional beams, or by allowing more overmoded structures.

Research on methods to more effectively fabricate vacuum electronic RF sources in ways that would reduce costs (by 10x), increase the attractiveness of maintaining inventories of spare parts at the accelerator site, and facilitate rapid service would be needed. Specifically, research and development on creating a flexible, modular design and fabrication methodology with common families of pre-engineered guns or cathodes, beam transport systems, beam collectors, and interaction structures at various frequencies and powers that can be quickly combined without extensive setup and engineering costs is a means to solve these technical challenges. Research on additive manufacturing of some vacuum electronic source components, such as the interaction circuit and particularly on the magnetic circuit pole pieces and permanent magnet materials, would be an important topic. Any advances in fabrication techniques developed for vacuum electronics would be equally applicable to fabricating accelerator structures at similar operating frequencies. Expanding the diversity of elements and compounds that can be additively manufactured by means of laser or electron beam sintering-based 3D printing, binder jetted powder-metallurgy-based 3D printing plus sintering, or by electroforming in a UV-LIGA microfabrication method would be critical. The strict accuracy, surface finish, and vacuum quality specifications uniquely associated with accelerators and vacuum electronics must be met.

Research on using solid-state microwave transistors (wide bandgap materials, for example, GaN HEMTs) as the RF sources for accelerators, including new types of accelerator structures specifically amenable to such sources, would be of great importance in achieving extreme compactness and ultra-high reliability. The distributed nature of single or groups of solid-state RF sources individually powering each cavity of the accelerator allows significant ability to adjust the accelerator performance, both in total energy and in the RF phasing of individual cavities. It also allows for more robustness, in which any single transistor malfunction associated with a cavity would only slightly weaken the accelerated beam, rather than resulting in its complete loss of beam. The cost of the transistors is a significant impediment to further progress, so methods of fabricating microwave transistors at 10x to 100x lower cost than at present should be researched, for the typical output power (500 W peak at 5.5 GHz). This could involve more effective methods of making wide-bandgap substrates, or hybrid technologies with wide bandgap materials overtop less expensive substrates, or transistor designs that employ fewer or simplified processing steps. Fundamental device research to increase output power of a single packaged transistor by 10x (to 5 kW peak at 5.5 GHz, and preferably at higher frequencies of 10-30 GHz), while keeping unit costs essentially unchanged, is important. Investigations into higher charge density solid-state two-dimensional electron gasses (2DEGs) in wide-bandgap semiconductor heterostructure devices, basic studies on solid-state electrical breakdown, and methods to integrate heat removal materials such as diamond would be important topics.

Device-level research on microwave transistor structures (and constituent semiconductor materials), specifically designed for the relatively high impedance, narrowband resonant load characteristics of accelerator structures, would also be an important topic. This is in stark contrast to present-day microwave transistors that are actually designed and optimized for overly low voltages (~50 V) and very high currents to power broadband communications applications. Research on entirely new classes of transistors that avoid the discrepancy between transistor terminal current-voltage characteristics and the accelerator load behavior would result in less complex matching circuitry and much higher efficiency. Possible approaches might include transistors based on heterostructures between two normally insulating alkaline earth or transition metal oxides that nevertheless forms a high charge density, conductive 2DEG. Although such 2DEGs have a lower mobility than conventional semiconductor 2DEGs, the parent materials potentially have very high breakdown voltages, which could provide the significantly higher voltage, lower current combination needed for accelerators. Transistors based on diamond as a semiconductor could be re-examined in consideration of the impedance characteristics needed by accelerators, and also for the high temperature capabilities needed for well logging accelerator applications. Enhancement in voltage capability of wide-bandgap high electron mobility transistors

(HEMT) might be possible with use of high dielectric constant materials to manage the electric field paths within the transistors.

5.2.4.4 Scientific Impact of R&D

- New classes of high power, compact RF sources needed for high-gradient accelerators
- Distributed RF sources integrated into accelerator structures for compactness and reliability
- Additive manufacture of RF sources combining conductive, dielectric, and magnetic materials, with broader payoffs for electromagnetic and electromechanical components
- Discovery and exploitation of new transistor materials and heterostructure configurations

The research would lead to vacuum electronic RF sources producing higher power at high frequencies, but operating at lower voltages allowing simplified power supplies, and created within a modular component fabrication framework enabling repurposing of designs for different applications. Solid-state sources with output characteristics matched to the unique loads and resonant behavior of accelerator structures would also result. Accelerators powered by such transistors would have fault tolerance and profound performance adjustability through distributed solid-state powering of accelerator cavities along the length of the structure.

5.2.4.5 Potential Impact on the Application

- Compact, lower-cost, higher reliability accelerators for global medical needs and security
- Higher powered compact accelerators for FLASH and VHEE RT, and for sterilization
- Ultra compact, efficient, high-temperature accelerators for well logging and radiography

The improved RF source technology would lead to more compact, lower-cost accelerators for global medical needs and security scanning, which would also exhibit much higher reliability and a more graceful degradation in performance rather than sudden catastrophic failures. The technological advancements in RF sources would allow a modular service approach for accelerators with lower cost spare parts and simpler field service. Much higher powered accelerators would also be possible with the advancements in RF sources, which would be particularly valuable for FLASH RT and VHEE in medicine. It will also lead to expanded acceptance of accelerators in sterilization applications due to smaller footprint vs present accelerators. Much more compact and efficient RF sources tolerating high temperatures would be especially valuable for well logging and NDT.

5.2.5 Research Theme 5: Transformative Accelerators for FLASH RT and VHEE

5.2.5.1 Background

As described in Chapter 4.3, radiation therapy at very high dose rate (FLASH RT) has significant potential to advance the treatment of cancer by reducing the damage to normal cells for a given radiation dose. FLASH RT requires a dose rate between 50 Gy/s to 1000 Gy/s, which is orders of magnitude greater than the highest dose rates achievable in state-of-the-art clinical treatment systems, approximately 10 Gy/min (0.16 Gy/s). A typical fixed-vault 6-10 MeV medical accelerator operating at S-band RF frequencies produces this conventional dose rate in x-rays using a total time-averaged accelerator beam current of 0.1 mA (averaging interval includes both the RF pulse on and RF pulse off intervals, with the pulse duty cycle of 0.1%). A corresponding FLASH RT accelerator would need to produce an average beam current between 30 and 620 mA during a short treatment time of ~0.3 s at the lower currents to ~0.01 s at high currents.

VHEE involves the direct use of accelerated electrons for medical treatment, but at much higher energies (100 – 250 MeV) such that the vertical dosing profile in tissues strongly resembles that of x-rays produced in a typical clinical accelerator. VHEE can be used at conventional dose rates, with the technical challenge in that case being the achievement of such high energies in a compact accelerator. However, it has a strong advantage as a source for FLASH RT modalities. Since there is no x-ray converter, performing FLASH RT with VHEE produces irradiation 15 to 20 times more efficiently from the accelerator to tissues compared to x-rays; thus, the burdens of achieving Flash RT dose rates when using VHEE are substantially reduced.

The accelerator technologies used in current clinical RT treatment systems, including capabilities and limitations, is discussed in Appendix G, “Supplemental Background and Reference Technical Information on Accelerators”. There are considerable accelerator technology gaps that must be bridged to deliver FLASH dose rates for research and clinical treatment, including not only the higher beam current, but also a higher duty cycle, increasing the conversion efficiency of RF power supplied to the accelerator into beam power, increasing the efficiency of converting the accelerated electrons to treatment x-rays, and better thermal management of the accelerator structure and any x-ray producing target. Additionally, for VHEE the accelerating gradient must be increased to achieve a compact footprint at higher electron energy.

5.2.5.2 Scientific challenges to be addressed

- Increase dose rate by 10,000X to deliver FLASH RT treatment
- Increase electron energy by 25X to deliver VHEE RT treatment

To deliver FLASH RT treatment, the dose rate delivered to the patient must be increased by 3 to 4 orders of magnitude compared to that delivered by contemporary RT machines. Can advances in accelerator science and technology produce systems that deliver this radiation flux at a precision, cost, size, and weight, comparable to present-day RT machines?

To deliver very high-energy electron RT treatment, the energy of the accelerated electrons must be increased by up to 25X compared to that delivered by contemporary RT machines. Can advances in accelerator science and technology produce systems that deliver this radiation flux at a precision, cost, size, and weight, comparable to present-day RT machines?

5.2.5.3 Summary of required R&D

- Improved thermo-mechanical capabilities of accelerator structures and x-ray targets

- Higher shunt impedance, higher gradient accelerator structures from cryogenically-cooled conventional metals, dielectric-loaded structures and higher frequency structures
- x-ray targets with improved conversion efficiency and novel conversion mechanisms
- Spatial-temporal modulated cold cathodes and multi-beam accelerators for rastering

Methods to increase the accelerator duty factor by at least a factor of 10 would require research on enhanced cooling technology for both the RF sources (RF interaction circuits and beam collectors) and the accelerator structure itself. In the extreme limit of a single short duration, extremely high power pulse, or a short series of more moderately powered pulses, research can examine the incorporation of phase change thermal materials directly into the accelerator or RF source structure, in conjunction with refractory metals having high conductivity RF coatings. Accelerator structures could be made more immune to thermal mechanical distortion and detuning by the use of low thermal expansion, non-magnetic materials over-coated with high quality metal RF coatings to maintain high electromagnetic quality factor. For x-ray FLASH, methods to handle the increased thermal loading of the target also have to be addressed, such as flow boiling in microchannels, or integrated microjets, in particular for transient high powers.

Research into new accelerator structure topologies is needed to allow the increase of accelerator beam loading to greater than 80% (allowing the use of a much higher beam current for the same RF drive power) with a simultaneous increase in shunt impedance. A possible approach might be the use of ordinary cooled metal cavities (to 77K, which is relatively easy to achieve), which for the case of copper increases the conductivity by a factor of about 8. Another approach might involve alternative accelerating structure concepts utilizing low-loss dielectrics instead of metals, or some other means to break the constraining relationship between metal conductivity and shunt impedance. Research on dielectric-loaded accelerator structures also presents opportunities for increasing the accelerating gradient, especially if combined with higher frequency operation (above 12 GHz) and concurrent RF source research involving higher power production and greater source efficiency at these frequencies. Such high-gradient research and technology development is also especially important for VHEE, to keep the accelerator length sufficiently compact while producing the 100 MeV or higher energies. Wakefield accelerators offer future concepts for compact VHEE and FLASH sources and must be developed to high current and repetition rate as indicated in Sections 5.3.8 and 5.3.9.

Improvement in the efficiency of x-ray production from targets bombarded by the accelerated electrons, or more direct methods of producing x-rays from electron beams, is an important area of research for x-ray FLASH applications. Possible topics might include nanostructure (atomic-level) engineered crystalline targets making use of electron and x-ray diffraction, nano-channel targets, or more speculatively, revolutionary types of plasma or optical undulators, or new types of beam-wave or beam-material interactions. New electron-to-photon conversion methods that allow the energy of any unspent portions of the electron beam to be recycled, or resonant deceleration that reduces the overall RF power requirements and thermal loading of the entire system, would be of importance.

Due to the extremely short duration of FLASH RT, it is not possible to mechanically direct the radiation spatial profile by gantry movements or selectively absorb it with mechanical multi-leaf collimators. It is likely impractical to simply steer the final energetic electron beam, either in direct treatment or prior to the x-ray target. Instead, research on laser phase masking of photocathodes, or other approaches to create temporal-spatial changes in cathode emitting area, would be an important topic, as would beam optics simulation research on how such beams evolve down an accelerator. Multiple parallel beamlet accelerators with laser modulation of the beamlets at the photocathode, to create a rastering prior to acceleration, could also be investigated. Field emitter arrays with individually addressable emitters or small groups of emitters could be investigated as an alternative to photocathodes. Fully RF- and beam-current multiplexed, modular accelerator structures creating several dozen to hundreds of individually time-domain modulated x-ray beamlets might be another promising approach for research.

5.2.5.4 Scientific Impact of R&D

- Reduction of RF drive power needed to achieve high average current / high energy beams
- Higher accelerating gradient will yield shorter, more compact accelerators
- Higher efficiency x-ray conversion will reduce thermal loading and required beam power
- Understand high dose rate radiation effects in electronic materials and components
- Discover and understand new high dose rate chemical reactions for materials processing

The research will also lead to new understandings of beam dynamics, emittance growth, and beam-accelerating structure interactions in high average current regimes. Better understanding / improvement of accelerator materials durability to breakdown and pulse heating will also occur.

5.2.5.5 Potential Impact on the Application

- Enable FLASH RT treatment from a compact accelerator system over the full desired range of high dose rates and including spatial-temporal modulation
- Enable VHEE RT treatment having reduced accelerator power compared to x-rays

Spatiotemporal modulation during the FLASH irradiation will also allow different treatment modalities, more flexible dose patterns that can be accomplished within the short FLASH duration, and will reduce the planning and setup burden on the operator. The short duration FLASH RT accelerators also eliminate deposition inaccuracies caused by breathing or other patient motion. Radiobiology using FLASH or VHEE will allow understanding of free radical creation and clearance from tissues under radiological stress and suggest new treatments. In addition to the medical impacts, the advances will also enable dual-use security applications, including more powerful accelerators for larger scale sterilization in food or medical applications with extremely short exposure times, while avoiding the use of radioisotopes such as ^{60}Co. The technology will enable much higher throughput for cargo screening security applications.

5.2.6 Research Theme 6: Accelerator-Based High-Energy X-ray Sources – Pushing the Boundaries for Ultrahigh Flux or Extreme Compactness

5.2.6.1 Background and Current Status

Ultrahigh Flux Monochromatic High Energy X-ray Sources

Tunable sources of high-brightness high-energy x-rays (HE x-rays) in the 0.5-10 MeV energy range for security applications can be achieved by an accelerator-based approach. This uses inverse Compton scattering, in which an incident lower-frequency photon is scattered off a highly relativistic electron (from the accelerator), which through the combination of relativistic Doppler upshift, radiation pressure, and recoil serve to boost the frequency of the scattered photon into the MeVp regime. An ongoing technology demonstration [Marsh-2012; Marsh-2017] is using a 250 MeV electron LINAC with a gradient of 70 MeV/m driven by a series of 50 MW X-band klystrons. Requirements are an extremely low emittance (<0.3 to 1 mm-mrad) high brightness electron beam, bunch charge and duration of 250 pC and 2 ps, rise/fall times <250 fs, and an energy spread < 0.1%. The beam and bunch quality can only be achieved by a photocathode-based RF injector for the linear accelerator. The incident, tightly focused, pulsed laser light for the Compton scattering off the beam is typically in the near-IR to visible (commonly 532 nm) typically has a pulse energy of ~1 J and a pulse length < 10 ns. A goal for the brightness of the resulting HE x-rays is ~10^{20} photons per (s-mm^2-mrad^2-0.1% bandwidth). Future concepts, such as wakefield accelerators, can also play a role and are covered in Section 5.3.10.

Extremely Compact Gamma Ray Sources

Extremely compact and highly robust gamma ray generators are needed for oil and gas well logging and for small confined-space radiography (such as inspecting pipes). An interesting class of such sources is based on the creation of a deuterium plasma via a low voltage electrical discharge, and then accelerating the deuterons to near 300 kV with a pulsed DC electrostatic field, where they hit a beryllium target and create GRs. A novel scheme to create the extremely high voltages and high spatial gradients is by means of stacked pyroelectric crystals (for example, $LiTaO_3$). [Chen-2013] An approach for higher dc power levels (50-500W) at 250kV voltage for a 3.5-in. diameter form factor was demonstrated under the Defense Advanced Research Projects Agency (DARPA) Intense and Compact Neutron Sources (ICONS) DARPA ICONS program for neutron generation. This size is suitable for open-hole oil and gas applications for mono-energetic gamma production by using different target materials. [Starfire-2019] Modeling and experimental table-top studies show extendibility to 500kV acceleration using a modified topology, high-gradient dielectrics, novel field shaping and stacking geometries.

5.2.6.2 Scientific challenge to be addressed

- Increase gamma ray flux by 1,000X over present inverse Compton scattering sources
- Ultra-compact gamma sources by particle beam-induced nuclear reactions in targets

An overall challenge is to create and implement a new generation of ultrahigh flux and precision accelerators for tunable, monochromatic HE x-ray sources based on inverse Compton scattering. The specific goal is to achieve a 3 orders of magnitude increase in gamma ray flux vs. that of present experiments. The x-ray energy spread must be improved to less than 0.1%.

Another overall challenge is to devise methods of creating more modest fluxes of gamma rays by means of induced nuclear reactions in targets from bombardment by accelerated particles. The entire system must fit into extremely compact packages and must be tolerant of punishing high temperatures and pressure environments. Besides the challenges of finding and exploiting suitable nuclear reactions, discovering and implementing new methods of producing the required accelerating voltages within the same compact package and harsh environment is also a difficult goal. Generating photon fluxes of interest using only 10-1000W prime power is also difficult. Advancement requires the re-examination of nuclear physics associated with low energy ion bombardment, and by non-conventional power supply mechanisms arising from intrinsic polarization in materials or from unusual circuit topologies, new semiconductor materials, new fabrication approaches, and improved dielectrics and insulation.

5.2.6.3 Summary of required R&D

- New types of photocathode materials with lower emission spread and longer lifetime
- Injectors with enhanced temporal and spatial control to angstrom levels
- Compact high power vacuum electronic RF sources > 20 GHz and RF pulse compressors
- High repetition rate, high pulse energy lasers with enhanced stability
- Alternative particle beam-driven, gamma ray-producing nuclear reactions in targets
- Compact high voltage generation and ion acceleration for gamma-producing reactions

Ultrahigh Flux Monochromatic High-Energy X-ray Sources

Research on new types of photocathodes having lower emittance and a more narrow energy spectrum from photo-excitation is needed to reduce the energy spread of the accelerator electron beam (and thus the resulting HE x-rays). A better understanding of the band structure in photocathode materials and deliberate engineering of it through quantum mechanical simulations of candidate materials systems, followed by experimental surface science to validate and test the predictions, is a promising approach. Efforts to understand the origins of intrinsic emittance in photocathodes and investigations to improve it, as well as discovering how to enhance the lifetimes of photocathode materials under realistic vacuum conditions, are also important.

Devising methods to create multiple types of temporal and spatial bunch trains in the accelerator and explore the behavior on x-ray production is needed. Methods of controlling bunching structure and behavior at the Angstrom level are ultimately required. Techniques to create more precise RF injectors producing tighter bunches at more uniform initial energy, and with better beam matching into the linear accelerator, must be developed. Multi-frequency RF injectors might provide a suitable means to tailor the source beam temporal and spatial bunching behavior. New ideas and associated research on methods of inducing controlled transverse bunching and subsequently converting it to longitudinal bunching could also be a promising topic.

A key area for research involves improvement in the accelerating gradient to allow higher beam energies from a more compact system. Accordingly, the development of compact higher power (> 10 MW peak) RF sources at frequencies above 20 GHz and associated shorter, higher-gradient accelerator structures at these frequencies is important. Gyro-amplifiers (including gyro-klystrons and gyro-traveling-wave-tubes) would be a strong candidate RF source for study, with research on compactness including harmonic cyclotron frequency operation and utilizing high energy density (HED) permanent magnets for beam confinement. Various types of linear beam klystrons employing over-moded, harmonic, or extended interaction regions might be another approach. Research on more compact and higher efficiency pulse RF pulse compressors with a larger power multiplication factor should be pursued to further increase the peak power, or as a means to ease the primary RF source power requirements. Concurrent research to enable the operation of RF sources, compressors, and the accelerators at greater than 1 kHz repetition rates, with regard to thermal management, thermal expansion, and pulse heating breakdown, is critical.

Since inverse Compton scattering sources require the precise counter-streaming targeting between the accelerated electron beam bunches and the laser beam pulses, advancements in laser technology are required. Research to achieve higher repetition rates of the source lasers (> 1 kHz) and higher energy laser pulses (> 1 J/pulse) are important topics. Achieving this performance at UV wavelengths would reduce the required accelerator energy. Understanding multi-photon scattering effects occurring with the use of intense laser beams, and their impact on x-ray linewidth vs. x-ray flux, are required. Improvements are also needed in the pulse-to-pulse stability, including energy and position control of both the laser and the electron beams, and the electron bunch charge. A reduction in final focus size of the electron beam, through minimization of emittance growth, is needed. Further reduction in spectral narrowness of the resulting GRs, using high energy x-ray optics and/or spectrometers, is important.

Extremely Compact Gamma Ray Sources

For alternative miniaturized gamma ray source technology using induced nuclear reactions in a target, research on ultra-compact, multi-hundreds of kV power generation is needed, which could include unusual types of piezoelectrics or pyroelectrics with different stacking geometries and dielectric packaging to avoid breakdown, or reinvigorated approaches with novel materials, layouts and topologies. Other poorly-explored solid-state phenomena leading to charge separation in response to external stimuli might be exploitable with novel materials chemistries or interface physical-chemical-thermal engineering. Many of the low-energy nuclear reactions that can occur in various target elements, in response to a wide variety of source particles and energies, have not been extensively researched in the past, due to lack of perceived importance. Research on fundamental low energy nuclear physics, directly seeking new gamma-ray emitting reactions, would therefore also be of interest, along with corresponding development of compact ion sources for the accelerated species. Possibilities for enhanced nuclear reaction rates include using spin-polarized source beams, or using such polarization to favor a gamma-ray producing nuclear reaction vs. a non-radiative reaction. How some of the source, acceleration and target technology discussed elsewhere in this report for electronic neutron sources could be repurposed for the creation of GRs via induced nuclear reactions in targets are also important topics.

5.2.6.4 Scientific Impact of R&D

- Compact laboratory sources of tunable gamma rays for physics, chemistry, and biology
- Improved gamma ray spectroscopy and analysis methods of liquids, solids, and gasses
- Fundamental study of nuclear recoil, resonance, hyperfine nuclear interactions

Effective gamma ray spectroscopy over a wide, precisely tunable energy range would be possible with the high flux monochromatic sources, compared to the limited individual energies provided by available radioisotope sources. The x-ray line width from inverse Compton sources is significantly narrower than that provided by filtered Bremsstrahlung, allowing probing and distinguishing the response from individual elements and compounds of interest, and for detecting and quantifying recoil, resonance, vibration, hyperfine nuclear interactions, and other narrowband phenomena. Improved ability to sense phenomena of interest in the presence of large amounts of spurious background material or noise will be possible with the advancements.

Ultra-compact gamma ray sources through induced nuclear reactions in targets would provide a completely new means of producing gamma radiation on demand, with increased safety and greater precision than present sources. Topics that can be studied with gamma rays include material composition and density, metal joint integrity, corrosion, and mechanical damage in structural materials and components. The widespread availability of compact, switchable gamma ray sources that have fewer regulations and can be positively turned on and shut off for safety, and provide a greater degree of directionality, would allow a wider suite of diagnostic applications to be developed. There is also the possibility of changing the underlying nuclear reaction by changing the target composition or the species of bombarding ion by changing the source emitter, which would allow significant flexibility for scientific and engineering studies.

5.2.6.5 Potential Impact on the Application

- NDC of hidden, mixed, or trace nuclear materials in port security, treaty verification and nonproliferation, stockpile stewardship, and emergency response
- Bright, high energy, high flux photon sources for electronics NDC
- Replacement of radioactive isotypes in well logging and confined space radiography

Extremely narrowband, tunable, high flux, compact HE x-ray sources would meet the all needs for nuclear photonics, in particular the identification of hidden nuclear materials and discrimination from other dense or high atomic number elements. This is critical for treaty verification and to prevent nuclear proliferation. Such sources would also be of great value for stockpile stewardship. Ultra-compact gamma-ray source technology can also leverage ultra-compact neutron source technology for dual-modality imaging and NDC. Narrowband, bright x-ray sources would be of importance for replacing synchrotron light sources for use in non-destructive evaluation of electronics, in particular integrated circuit ptychography. Ultra-compact sources of gamma rays would allow oil well logging and radiography of small confined spaces without the use of radioactive isotopes, easing the regulatory burden, increasing the range of prospective applications, and reducing the chances of a safety accident or terrorist incident.

5.2.7 Research Theme 7: Accelerator Materials by Quantum Chemistry- and Physics-Enabled Design

5.2.7.1 Background

Limits on performance, compactness, and cost reduction in accelerator systems are often directly impacted by the chemical and physical properties of the materials that are utilized in the accelerator. Whether the materials are dielectrics, conductive or structural metals, superconductors, or electron-to-photon conversion targets, as well as many other categories, the properties of conventional, known materials traditionally applied in accelerators are often not good enough to allow the enhanced accelerator performance goals to be obtained. It is prohibitive to experimentally search out new types of materials solely by synthesis and testing, but if such explorations are made computationally, the search could be more effectively performed and narrowed to promising candidates. Furthermore, if the underlying principles can be elucidated using such computational studies, these same techniques can be used to intelligently engineer new materials with even better performance. Recent advances in computational quantum chemistry and physics, along with machine learning to identify and exploit hidden trends and correlations in the results, have made such computational searches for candidate materials and materials-by-design optimizations possible. Such computational methods are routinely used in pharmaceutical discovery (drug design) and have recently been used with great success in discovering higher energy density polymer materials for electrical energy storage capacitors. [Kim-2016; Ramprasad-2017] It seems likely that such techniques could be used for finding and optimizing new accelerator materials.

5.2.7.2 Scientific challenge to be addressed

- Superior dielectric materials for ultra-compact dielectric-loaded RF accelerators
- Improved conductor and superconductor materials for high RF field accelerator structures
- Higher efficiency x-ray production from electron beam targets

A key challenge is the achievement of higher gradient, higher shunt impedance, lower loss accelerating structures enabled by dielectric-loading with new materials having vastly superior dielectric properties. One typically wants a relatively high dielectric constant, but most such existing dielectrics have a lower bandgap compared to traditional insulators, and hence they have undesirably lower electric breakdown thresholds. This roadblock could be overcome by discovering and intelligently engineering new dielectrics by quantum-mechanical chemistry and physics predictive computer codes. First-principles predictive codes and a materials-by-design approach can also be applied to the challenge of devising greatly improved metal alloys and coatings for use in accelerator structures, to achieve greater mechanical strength, better thermal properties, higher resistance to surface electric- and magnetic-field-induced breakdown, and enhanced superconductive behavior at high frequencies. In particular, the microscopic details of RF current flow through grain boundaries, oxide or other chemical inclusions, realistic surface profiles are critical. Physics- and chemistry-based modeling can also guide the invention of new nanostructured materials for efficient electron beam to x-ray conversion targets.

5.2.7.3 Summary of required R&D

- Quantum chemistry computations and machine learning for discovery of combined higher permittivity, higher breakdown strength dielectrics
- Coupled electromagnetic, thermal, quantum physical/chemical modeling at scales from microstructure- to atomic-level in normal metals and superconductors with high RF fields
- Multi-physical modeling of x-ray production in atomic-scale engineered materials

Research employing *ab-initio* DFT and *ab-initio* molecular dynamic modeling (abi-MD) of dielectrics, coupled with quantitative structure-property relation (QSPR) machine learning, is needed to identify new dielectric compositions of importance to accelerators. Such techniques would form a materials-by-design process that will lead to dielectrics with more controllable and previously unachievable combinations of higher dielectric constants, wider bandgap, higher breakdown strength, lower losses, and better thermal-mechanical behavior. By using such predictive tools and discovery process, it will also be possible to introduce a controllable dc resistivity that does not contribute to excessive microwave or mm-wave loss, but is sufficient to eliminate surface tracking from stray beam scraping. DFT and abi-MD can also assist in the discovery and exploitation of new charge-scavenging defect chemistries in dielectrics that enhance breakdown strength without contributing to RF loss.

Another important area of research is to apply DFT, abi-MD, and QSPR to better understand the interactions between high intensity electromagnetic fields and the conductive wall materials or coatings of accelerator structures. Effects such as pulse-heating-induced breakdown, as well as electromigration and other electric- or magnetic-field-induced and temperature-induced changes in grain boundary or alloy micro- to nano-structure, and anomalous high frequency loss mechanisms, could all be better understood using these computational tools. Methods of utilizing the appropriate computational tools and coupling them between the atomic scale to the micron-scale would have to be devised. Materials design and strategies to overcome such problems would be discovered and new materials could then be synthesized and demonstrated. An additional benefit of such research would be a better understanding of mechanical strength and yielding behavior, as well as thermal expansion and fatigue, as it applies to materials used in accelerators. An extremely challenging but important problem for materials computational prediction and design would be for superconductive RF coatings on ordinary metals. This topic would involve all of the issues previously mentioned, with the additional complexity of predicting the behavior of the superconducting state and its interactions with grain boundaries, surface states, and the underlying base metal of the accelerator structure.

Research on x-ray production from novel target materials would aim to better model, at the atomic and inter-atomic scale, the full physical interactions between high energy electron beams and structured crystalline lattices of new materials. With the goal of devising new single-crystal materials for targets that have a higher efficiency of x-ray production, this extremely challenging modeling should employ combinations of many physical processes. These include quantum mechanical modeling of electron interactions with crystalline arrays of metal atoms, including all simultaneous effects of electron diffraction in lattices, electron interaction with outer and deep shell electrons of atoms and their subsequent evolution and x-ray production, and electron interaction with nuclei and associated x-ray emission. The modeling must also include x-ray diffractive effects in the lattice. Monte-Carlo modeling or a similar method could be used to study the wide stochastic range of electron trajectories and their interactions with atoms, with specific classes of interactions subjected to the smaller-scale quantum mechanical modeling. The types of lattices to be investigated should not be limited to just single metallic elements but also crystalline alloys of ordered metal atoms and crystalline compounds of metals and non-metals. More complex structured crystalline targets with tubular pores at the few-atom scales (reminiscent of zeolites but using high atomic number elements) might allow either efficient recycling or energy recovery of unspent electrons if the targets are thin enough, or perhaps even an atomic-scale undulator effect for direct x-ray production. Research of these possibilities is speculative but potentially high payoff.

5.2.7.4 Scientific Impact of R&D

- New regimes of accelerator performance of high gradients at low power consumption
- More electromagnetic, thermal, mechanical stress-resistant materials and structures
- Enhanced electron beam – atomic interactions and x-ray production in nanostructures

The research will result in vastly improved dielectric loaded accelerator structures that overcome the link between conductivity and shunt impedance that limits the performance of all-metal structures, allowing new regimes of accelerator performance in achievable gradient at low power consumption. Another key result will be an improved understanding of stray charge transport, RF breakdown, and RF losses in dielectrics, followed by the invention of new compositions that overcome the limitations posed by these mechanisms. The research will also lead to a deeper physical understanding of the relationship between surface material behavior at the atomic- through micron-scales under high intensity electromagnetic fields, and roles of chemical and physical changes at these scales have on RF breakdown (and how to mitigate it). Advances in understanding thermal and mechanical fatigue in pulse heating conditions would also result, with guidance on new materials with better properties. Although extremely challenging, a better understanding of how to predict and computationally optimize the behavior of superconductive RF coatings would be a significant advancement, as would the computation-based discovery of methods to improve the efficiency of x-ray production from electron-beam irradiated targets.

5.2.7.5 Potential Impact on the Application

- Compact, higher efficiency accelerator-based x-ray sources for well logging, all types of NDC, food processing, and sterilization
- High dose rate compact medical accelerators: FLASH, VHEE, and lab-scale radiobiology

Much greater efficiency in accelerators for medical and security applications will be a primary impact, allowing lower powered RF sources to be used in more compact overall machine sizes, without a decrease in the delivered radiation flux. Likewise, a much higher radiation flux would be delivered in the new accelerators for a given RF power consumption, which is relevant to FLASH RT and VHEE medical uses, as well as for sterilization systems for security applications. Compact research accelerators for laboratory-scale and pre-clinical radiochemical and radiobiological applications would also particularly benefit from the improved technology.

5.2.8 Research Theme 8: Develop High-Flux and Shorter Pulse Neutron Sources

5.2.8.1 Background

- Neutrons are a complimentary tool for many technical fields
- Many existing sources and national facilities are too large to be practical for many applications

It is clear from the requirements discussed at the workshop that development of neutron sources, particularly higher flux, smaller SWaP, and shorter pulse, is needed for many applications. Neutrons offer a unique complimentary tool for studying materials, processes and structures that are necessary for many technical fields including biology, pharmaceuticals, materials, security, energy, defense, etc. Most existing commercial sources or national facilities are too large to be practically used in many desired applications. Increasing neutron output while maintaining small SWaP is an enabler for many end-users. Many applications could be improved, or signal-to-noise of measurements increased, if these sources additionally were shorter pulse.

5.2.8.2 Scientific challenge to be addressed

- One big overarching challenge to be addressed is decreasing SWaP while keeping flux constant
- Another challenge is that while many applications could benefit from brighter, shorter-pulse devices, the technology used to make shorter pulse neutron sources tends to be lower TRL than conventional/commercial sources

Higher Flux, smaller SWaP

These two improvements go hand-in-hand. For virtually every application, there is a neutron source in existence which is high enough flux, but not small enough. Conversely, for almost every application there is a neutron source in existence which is small enough but not high enough in flux, with the possible exception of neutron capture brachytherapy.

Shorter pulse

For the majority of neutron source applications discussed in Sections 3.2 and 3.3, a shorter pulse than what is commercially available now could enable new capabilities or fixed signal-to-noise ratio for a lower dose. Given that a major barrier to entry for neutron sources is dose delivered to the operator or public, it is desirable to keep dose as small as possible while still being able to make the desired measurement with the desired accuracy. Typical neutron pulses from conventional sources are 1-100 µs. The advantages of a shorter pulse could be realized with pulses in the range of 1-100 ns, depending on the application.

Making neutron sources with a sufficiently shorter pulse than conventional technology will require a new technology altogether, as existing commercial sources are not bright enough to output a relevant number of neutrons in an extremely short pulse. Since they rely on solid targets that are already being cooled nearly as quickly as physically possible, simply increasing the incident number of ions on a target would lead to target melting and is not easily scalable. Additionally, conventional sources do not have a fast-enough turn-on/turn-off time to produce a sufficiently short pulse. Technologies to make these short-pulse sources exist, but they are typically laboratory sources, low TRL, and not ready for field deployment. The scientific challenge to be addressed here will be raising TRL of non-conventional laboratory-based neutron sources, as well as miniaturization. Other performance improvements, such as pulse-to-pulse consistency, may also be needed.

5.2.8.3 Summary of required R&D

- In the near-term, making smaller SWaP sources could be largely a development activity in which compact technologies already developed are applied to custom sources that are tailored to specific applications
- Additional R&D may be needed to further shrink components on conventional sources
- In the longer-term, shorter pulse technologies, like z-pinch and laser-based sources, must be developed to be more compact and more turn-key

Higher Flux, smaller SWaP

A compact SWaP was the dominant theme of a recent DARPA-sponsored program, ICONS, to improve neutron sources. In this program, teams of performers strove to create a 10^{11} n/s source in 8 liters and under 30 lbs. This particular set of requirements was meant to meet the needs for neutron imaging of a medium-sized object, such as a suitcase. However, there are applications that require higher flux sources and can also tolerate higher SWaP (e.g., neutron imaging of a cargo container) and there are also applications that do not need as much flux that require a much smaller SWaP (e.g., porosity measurements in oil and geothermal logging). Both smaller and larger sources could benefit from some of the advances made in the ICONS program, which included improvements to components such as portable ion sources and targets. The scaling of these components to sources that would meet the needs of all the applications outlined in Sections 3.2 and 3.3 is mostly a development activity, but for some applications would require a feasibility study to see if the required flux could be obtained within the required SWaP without additional R&D or component improvements.

Shorter pulse

Laser-based and z-pin based technologies already can produce short enough pulses to be relevant to the applications presented here. However, these sources tend to be lower TRL, and not ready for field deployment. They are also not as compact as the longer-pulse sources developed under the ICONS program. R&D is needed to shrink these systems, and to develop them to be more turn-key. In some cases, R&D is also needed to further shorten the pulse, produce a small spot size, or reduce operational variation.

Near-term vs. Long-term

Many of the development activities needed for higher flux/smaller SWaP sources are improvements or scaling of already existing high-TRL, or in some cases commercial, technologies, and thus are more likely to be realized in the next 5-10 years. Shorter neutron pulse sources, while ultimately desirable for improved signal-to-noise and lower dose to operator, are lower TRL and could take 10+ years to develop.

5.2.8.4 Scientific Impact of R&D

- Smaller and less expensive sources would have a high scientific impact on the global security community that researches active interrogation and neutron imaging techniques
- The availability of compact, inexpensive, and turn-key short pulse sources would enable research in the use of these short-pulse sources for higher resolution or better signal-to-noise measurements in active interrogation and neutron imaging techniques

The development of additional commercial sources that are either smaller SWaP than those currently on the market, higher yield for the same SWaP, or shorter pulse could have potential implications for the scientific community in that the global security research community uses commercial sources for active interrogation and neutron imaging R&D. Having smaller, less expensive, or higher yield sources allows for more affordable and more efficient R&D—for example higher yield sources could lead to making a particular measurement in a shorter time window. Smaller sources could allow for enough portability to move the source to different test objects of interest around the country (that may not be able to travel for security reasons).

The availability of shorter pulse sources enables R&D regarding how well those sources can be employed to increase signal-to-noise of existing measurements, or to make new measurements such as on-site neutron resonance transmission analysis (NRTA).

5.2.8.5 Potential Impact on the Application

- The development of smaller SWaP, inexpensive sources could potentially enable applications in homeland security such as luggage and cargo scanning, or lead to radiological source replacement in the oil well logging industry
- R&D to develop shorter pulses could eventually enable new ways to assay radioactive waste on site, new measurements for the oil well logging community, and lowered dose to the operator and public for the same quality of measurements in screening and radiography

Higher Flux, smaller SWaP

The development work associated with higher flux/small SWaP source could enable applications in well logging, cargo and luggage screening, and cargo radiography. In the case of well logging, an affordable and sufficiently small deuterium-only neutron source could enable a larger fraction of the well logging industry to replace radiological sources with accelerator-based sources, particularly among small logging companies. These small companies together make up a significant fraction of the industry but can neither afford neutron source development activities nor gain access to the proprietary sources being used by the larger companies. Advances in attainable electrostatic voltage, power and size could potentially enable the smaller cross-section ^{7}Li(d,n) reaction for production of an AmBe-like neutron spectrum at low energies, as well as a 13.3 MeV neutron line which could possibly be used for neutron-induced gamma-ray spectrometry without the inconveniences associate with tritium. More study is needed to understand the relative advantages/disadvantages of D-Li over the standard D-D and D-T reactions.

In cargo and luggage screening, neutron active interrogation is not currently used for many reasons, including lack of a suitably portable/affordable source. There are additional barriers to entry in this market, including acceptance of dose delivered to operators or public, and a collective consensus that scanning for fissionable materials is an important enough goal to justify the capital expense.

Shorter pulse

In well logging, a shorter pulse could enable neutron time-of-flight measurements, but the source would need to be extremely short, in the 1-2 nanosecond range. The only neutron sources that deliver this short of a pulse are laser-based and currently low TRL/not portable. A large amount of R&D would be required to produce a source this portable and short-pulse.

In secondary screening for luggage and cargo, a neutron source would be used to produce a differential die-away (DDA) signal that would indicate the presence or absence of fissionable materials. The DDA signal cannot be differentiated from the source signal when the source is on. Thus a shorter and brighter pulse with the same integrated yield allows the observer to look at the DDA signal earlier in time, when the signal level is higher. Nanosecond length pulses are not required, however, to significantly increase signal-to-noise on a DDA interrogation. An intermediate TRL technology, such as z-pinches which produce 10-100 ns short neutron pulses, would be applicable here.

In the case of radiography, including container radiography which is discussed in Section 3.3, a shorter pulse allows for a neutron image that purposefully time-gates out the scattered neutrons. When neutrons scatter, they change both their direction and energy slightly. The direction change makes them no longer "useful" signal, as they no longer appear to be coming from a point source. Thus they become part of the noise. The energy change makes them travel a little bit slower than the neutrons which are not scattered, which is convenient because they can then be ignored if the imaging detector has a time-gating capability. However, time-gating in order to differentiate scattered neutrons from transmission neutrons is only possible if the two types of neutrons have minimal overlap in time. A long neutron pulse smears out the arrival time of the neutrons, making the arrival time of the scattered neutron and transmission neutrons overlap. Here a mono-energetic 10-100 ns pulse is needed, depending on the neutron energy and source-detector distance.

In the last neutron source application discussed in Section 3.3, waste/debris assay, a shorter pulse again delivers a higher-fidelity measurement. Because NRTA is a time-of-flight technique, a shorter pulse translates into a shorter source-detector distance for a fixed energy resolution. Decreasing distance from the source to the detector increases signal by the inverse square of distance. So the effect of shortening a 20 ns source to a 10 ns source would be to increase signal by a factor of four without increasing the integrated dose.

5.3 Long-Term Accelerator Technology Themes

5.3.1 Research Theme LT1: Improved Accelerator System Efficiency

5.3.1.1 Background

Accelerator-based systems supporting medical and security applications span a broad range in physical size and power requirements. Performance goals such as beam energy, beam power or other qualifying beam parameters have been previously used as the defining metrics for accelerator development, but today the efficient and cost-effective utilization of power is becoming more important. Particle accelerators consist of individual subsystems that each consume energy. Subsystems are needed for auxiliary functions (cooling, vacuum) and instruments (particle detectors), while others are part of the power flow chain from grid to beam (RF system). For high-intensity beam accelerators used in medicine and security, the efficiency of individual steps converting grid power to RF power to beam power and finally to the desired secondary radiation are critical. Current accelerator systems typically only achieve beam-to-wall-plug power efficiencies of <10%. Ultimately, the specific application defines the requirements on the primary beam or the secondary radiation generated by the primary beam. The goal of high system efficiency is to maximize the intensity of the desired radiation available to the user with specific parameters per electric power from the grid. As a result, the efficiency of each subsystem must be optimized to the extent possible and the overall energy management properties of the accelerator system must be considered.

5.3.1.2 Scientific/technological challenges to be addressed

- Maximize delivered beam power and minimize required wall-plug power without substantial impact to system ruggedness and affordability

The primary drivers in the system-level efficiency are a combination of RF amplifier power conversion efficiency, cavity structure gradients, power dissipation into cavity structure, thermal management power efficiency, and converter efficiency for secondary radiation generation. Critical to optimizing accelerator efficiency is maximizing the delivered beam power while minimizing the total required electrical wall-plug power. Since much of the energy used in accelerator facilities ends up as waste heat, thermal management challenges exist in matching the amount produced to the local use needs and, in addition, in supporting functions such as building heating since the temperatures of the waste heat are typically too low. Challenges also exist in improving the electronic efficiency in generating the RF power. State-of-the-art klystrons can reach electronic efficiencies of ~65% at saturation but they are typically operated below saturation to allow stable amplitude control, resulting in a useable efficiency of around 50%. This efficiency is further reduced by the power consumption of the focusing coils and the cathode heater which can be significant in pulsed klystrons since heaters and solenoids are on even if no RF pulse is required. The efficiency of a klystron can be increased by employing a depressed collector, but such devices add complexity to the tube and must be carefully designed to prevent the reflection of electrons back into the interaction region. Although magnetrons claim up to 85% efficiency, this still needs to be proven for complete systems. In accelerators, magnetrons are only used in machines where a single RF source can cover the power needs (e.g., electron machines for medical applications). The combination of multiple devices requires a precise phase and amplitude control, which has not yet been achieved for multi-cavity accelerators. Gridded tubes are very tolerant to fluctuations of their high voltage supply and they have extremely short rise times, which makes short pulse operation more efficient than for klystrons (efficiencies to 70%). In pulsed mode, gridded tubes can be overdriven to achieve higher peak power, which is not possible for klystrons. Solid-state amplifiers combine cost-efficient RF power generation with the advantages of a modular system enabling the hot-swapping of single faulty modules during operation. They are found in a power range between 10 and 200 kW and some systems already operate at higher power values. Typical efficiencies for complete systems including power supplies are in the range of 45-55%. Adding cooling systems to the above RF sources typically reduces the quoted efficiencies by a factor of ~0.75. Reducing resistive losses at RF frequencies in the accelerator cavity structure, power couplers and RF distribution system also have compounding effect on system efficiency. Guiding and focusing the accelerator beam is typically done with electromagnets which add to the efficiency cost. To reduce resistive losses, larger cables can be used in these magnets, but this results in larger size, weight, and cost. Alternatively, permanent magnets could be used that do not require power and are compact, but tunability becomes more difficult and large aperture magnets are limited. Achieving improved accelerator system efficiency without substantial impact to system robustness is also key to achieving affordable, compact accelerator systems for medicine and security.

5.3.1.3 Summary of required R&D

- Reduce operational power cost to less than $1/RF watt
- Optimize subsystem efficiency and the overall energy management properties of the accelerator system
    - Realize higher electronic efficiency RF power generation
    - Reduce cryogenic cooling power by improving quality factor or raising operating temperature
    - Research alternative magnet technologies to reduce system size, weight, and cost

Most of the energy used in an accelerator system is eventually converted to heat and this power should be utilized as best as possible. For best recovery, the temperature of cooling circuits must be high for efficient thermal management. Ideally, heat recovery methods would be closely tied to the accelerator powering systems described in Section 5.3.5 and are designed in at the beginning stages of the system. Energy storage is extremely important for the pulsed operation of high-power klystrons or ramped magnets. The negative effects of a strongly fluctuating power load on the electricity grid can be avoided by a fast and efficient short-term storage device which continuously acquires an essentially constant power from the grid, stores it, and delivers high power pulses to the accelerator’s subsystems. The most cost-effective solution will depend on the application-specific requirements, but a fast and efficient power conversion and control unit is important in all cases.

The cost of commercial RF power sources depends on several factors to include frequency, peak and average power, mean time between failures (MTBF), mean time to repair (MTTR), and source lifetime. For room-temperature linear accelerators, the cost of a commercial RF amplifier can range from $7-$10/RF watt depending on the specifications. Ideally the power cost would be reduced to ~$1/RF watt, but the engineering of a more efficient subsystem must also reach the required power, maintain robustness, and have long life. Higher electronic efficiency RF power generation can be realized with new devices and concepts including IOT’s (inductive output tubes) with solid state drivers, magnetrons with better stability, and direct recovery electrical energy from spent RF technologies. IOTs directly modulate the density of the electron beam and can be operated at their maximum efficiency (~70%) without the klystron-like saturation, but further work is needed to improve their smaller gain and output power (currently <100 kW). Magnetrons have high efficiency (~90%), but they are not used for multi-stage accelerator applications due to being oscillators. New techniques to operate magnetrons in injection-locked mode with amplitude control methods for driving acceleration cavities should be developed. Cryogenic cooling power is a major contribution to total consumption in superconducting high-duty factor and CW LINACs. By either improving the quality factor or by raising the operating temperature, the cryogenic cooling power can be significantly reduced. New methods need to be developed to treat the niobium surface (e.g., nitrogen-doping, Nb3Sn coating) as well as improvement of other techniques (e.g., niobium over copper) for higher-temperature, lower resistance and higher quality factor. Resonance control of the narrow-band SRF cavities can reduce the RF power consumption so both active (piezo control) and passive (improving of the cavity mechanical properties) technologies should be developed.

Several alternatives to conventional electromagnets including pulsed magnets, magnets with high saturation materials, and superconducting magnets can increase efficiency under certain conditions, but the trade-offs associated with of cost, complexity, size, and weight need to be considered for their use in compact accelerator systems. The conversion of beam power into a rate of secondary particles is an important part of the energy conversion process. However, targets are complex multi-physics problems and in addition to the conversion efficiency, there are also thermomechanical problems and reliability aspects that must be considered. Computer aided simulation tools are the key for optimizing all kinds of conversion targets.

5.3.1.4 Scientific impact of R&D

- Enables the development of compact accelerator systems producing high average current and high energy beams

Particle accelerators consume a large amount of energy mainly in the form of the electricity required to drive the accelerator. If the surplus heat can be reused instead of wasted, significant amounts of energy can be saved, and this will reduce the negative impact on the environment. Optimizing the energy conversion of the electron beam in the output cavities of klystrons will allow using lower cathode voltages, removing the need for oil tanks, and permitting simpler modulators with faster rise times. Solid-state amplifiers combine cost-efficient RF power generation with the advantages of a modular system, which support hot-swapping of single faulty modules during operation. New magnet technologies can provide improved field quality, smaller size and weight, and more efficient beam transport. High-quality surface treatments and thin-film materials can reduce resistive losses and lower power demands. Improving system efficiency significantly impacts the development of next-generation compact accelerators by reducing operational and maintenance costs, enabling transportability, and contributing to the overall local energy management strategy.

5.3.1.5 Potential impact on the application

- Reduces capital, operating, and maintenance costs, increases system ruggedness, and simplifies operational functionality

Because of the worldwide scarcity of resources and increased awareness on resource problems, it becomes critical to optimize system efficiency as much as possible and to reassess the energy management aspects of an accelerator system. The benefits of improving system efficiency goes beyond the accelerator itself in reducing capital and operations costs, increasing ruggedness, enabling transportability, providing economic impetus for reusing generated surplus heat, and simplifying overall operational functionality.

5.3.2 Research Theme LT2: Advanced Manufacturing

5.3.2.1 Background

Advanced manufacturing comprises several technologies including:

- *Advanced Materials*: development of new materials such as lightweight, high-strength metals or high-performance alloys, ceramics, and composites or thin-film coatings such as high-conductivity, high-gradient (MeV/m), low-electron emission multilayers
- *Advanced Robotics*: systems capable of performing complex tasks with minimal human intervention using artificial intelligence and machine learning
- *3D Printing*: additive process of building objects, layer upon layer, from 3D model data as opposed to subtractive manufacturing methodologies like machining

The defined operations for medical and security accelerators put stringent demands on both the materials and fabrication techniques used to make them. Manufactured materials and components need to be compatible with ultra-high vacuum, high-power RF (radio frequency) structures, and the presence of high current particle beams. Accelerator-based systems could benefit significantly from advanced tools such as 3D printing, computer numerical control, robotic assembly, and electron beam melting in both the design and manufacturing phases of system development. For example, 3D printing allows complex hard-to-machine shapes to be made and, thus, reduces cost and enables optimizations of shapes for a given function with minimal material. [Frigola-2015] Conformal ion-assisted thin-film deposition post-3D printing can give desired surface and RF-field properties to use less material, increase throughput, lower cost. Commercially available modeling and simulation tools have evolved to enable reliable exploration of optimized baseline accelerator designs along with the ability to perform computer-based sensitivity analysis resulting in hardware specifications and tolerances. Employing AM for the design and manufacture of accelerator systems will greatly improve process efficiency, avoid costly errors, and improve system robustness.

5.3.2.2 Scientific/technological challenges to be addressed

- Manufacture of accelerator end-products with required material properties at the lowest possible cost
- Engineer new accelerator materials that are amenable for advanced manufacturing
- Develop techniques to reduce process variability and the sensitivity to process variations

Accelerator components are traditionally fabricated using a wide range and combination of techniques: sheet metal forming, machining, vacuum brazing and welding. Intrinsic to these processes is the desire to achieve a final in-service product with required material properties at the lowest possible cost. Advanced manufacturing has the potential to transform the manufacturing approach to meet the performance, cost, and robustness requirements of accelerator systems. [Jenzer-2019] Many of the technical challenges are similar to those faced by conventional processes: microstructural defects, shape retention, equipment capabilities, etc.

In many cases, the parts produced by these advanced technologies need to undergo subsequent post-processing (e.g., improving the knife-edges in the case of ultra-high vacuum parts) and better understanding is needed to determine how the manufacturing technologies can optimize this process. Further, because of the way they are built, parts produced by these technologies typically have a very rough surface which can impact their use in vacuum or for electrical impedance. Currently the most popular materials for 3D printing are limited to steels and alloys of aluminum, nickel, or titanium, but RF accelerator components require the use of oxygen-free electrolytic copper or pure niobium, neither of which is common within the AM industry.

5.3.2.3 Summary of required R&D

- Research vacuum compatibility of fabricated accelerator parts
- Increase understanding of manufactured component behavior near a beam
- Analyze the performance of complicated accelerator parts when conducting RF
- Explore new materials and new alloys for use in accelerator systems
- Research manufacturing of parts with several materials (e.g., metal and insulator)
- Determine how advanced manufacturing affects material properties

Advanced manufacturing includes rapid prototyping capability for fabricating and testing parts in reduced cycle times resulting in higher confidence of performance metrics and reduced cost in the development phase. Research is needed to qualify, validate, and verify the manufacturing technologies and accelerator parts having extremely tight tolerances. Methods must demonstrate the processes and procedures involved with providing lower-cost and higher efficiency (including weight reduction) accelerator structures and components. Research needs to be done in developing materials (e.g., oxygen-free electrolytic copper or niobium) into usable forms for some types of AM machines or combining multiple AM approaches together, such as powder-bed selective laser sintering with conformal ionized physical vapor deposition (PVD) coatings for accelerator-facing surface. The unique capabilities of advanced manufacturing (e.g., ability to fabricate complex shapes, tailor materials and properties, and handle functional complexities) offer design options that were previously unobtainable and that can address specific operational performance requirements. In any manufacturing process, the ability to achieve predictable and repeatable operations is critical, so techniques to reduce process variability and the sensitivity to process variations need to be developed for manufactured accelerator components.

5.3.2.4 Scientific impact of R&D

- Enables low cost and rugged accelerator design options that were previously unobtainable and that can address specific operational performance requirements

Advanced manufacturing technologies enable fabricating hard-to-machine accelerator parts and permit the engineering consideration of previously un-manufacturable designs. The ability to design a system with fewer, more complex parts rather than many simpler parts is an important benefit of AM. This aspect enables designs that are optimized for performance at a system level without making compromises for the sake of manufacturability at the subsystem level. For example, significant cost-saving and operational performance improvements can be realized when manufacturing highly complex-shaped accelerator components such as embedded cavities, cooling channels, and mesh structures, or using low cost base materials with functionalized surfaces for lower secondary emission yield in beam lines or higher cavity Q to lower power requirements or increase allowable gradient. In 3D printing, cost is proportional to the volume, not the complexity, of the part so, as the part's complexity increases, the cost to produce becomes more economical. The novel designs enabled by AM can improve a component's engineering and cost performance as well as lead to performance and environmental benefits, such as eliminating wet chemical plating because AM technologies can replicate any shape, the sustainability of the accelerator system is impacted since broken/worn parts no longer produced by the manufacturer can be re-built and repairs made. The manufacturing process reduces errors and development cycle time resulting in substantial cost savings and more robust component designs. Early assessment of the manufacturability of the design based on state-of-the-art manufacturing capability provides rapid turn-around on prototype fabrication, while predictions of operational performance aid in the timely commissioning of the assembled accelerator systems.

5.3.2.5 Potential impact on the application

- Permits development of more compact, robust, and less costly accelerator systems

- Enables rapid prototyping and manufacturing of complex parts with demanding specifications and tolerances

Current accelerator technology is based on conventional manufacturing processes that scale unfavorably to smaller dimensions, are difficult to implement, and are costly. Advanced manufacturing enables realization of more demanding specifications and tolerances of accelerator component parts and, thus, allows more compact, robust, and less costly accelerator-based systems to be manufactured. Advanced manufacturing impacts the developmental and capital costs associated with the accelerator systems, speeds prototyping and production, improves operational performance, and offers higher production reliability and repeatability. The manufacturing improvements obtained with these technologies will ultimately lead to greater global availability, accessibility, and sustainability of specialized accelerator systems used in medical and security applications.

5.3.3 Research Theme LT3: System Health and Controls

5.3.3.1 Background

Accelerator reliability is the probability that a system will perform a required function under stated conditions for a specified period-of-time. Therefore, the expected uptime, repair and maintenance times, idle times and unplanned occurrences all impact the reliability of a system. Repair and maintenance times are necessary to provide a reliable system over a long period-of-time. Unplanned occurrences such as power outages, failure of equipment, and weather are other factors and, although they are hard to plan for, they do need to be accounted for in reliability considerations. Reliability is also highly dependent on the type of the desired operation. If it is a short-time operation with long maintenance and repair time, then it is relatively simple to keep the reliability high. On the other hand, reliability will generally deteriorate if the operation is required for extended periods of uninterrupted service. Many medical and security applications are driving toward continuous operation to minimize downtime and improve operational performance. Critical to achieving this operational mode is high-accelerator-system robustness which can be characterized in terms of the three figures-of-merit: mean time between failures, mean time to repair, and system lifetime. The availability of an accelerator system can be expressed as availability = MTBF / (MTBF + MTTR) so the general approach to improve the reliability of any system is to increase MTBF and to decrease MTTR. Specifically, for accelerator operations where the supply-chain infrastructure is not as well-developed and spare parts inventory cannot be maintained on-site, it becomes critical to anticipate failures and responsible sub-assemblies for that failure. Careful monitoring and recording is important to achieve high availability. In terms of reliability, hardware has a finite lifetime as it goes through various stages (i.e., break-in, normal, wear-down) within this lifetime so it is important to track these stages to maintain the desired level of availability. Judicious incorporation of system health diagnostics and controls provides the ability to anticipate imminent failures and the subassembly responsible for the failure. The system health diagnostics can relay this information to the accelerator vendor which can then schedule a technician and ship a replacement part to the accelerator location. This would enable “a just-in-time” repair process to substantially reduce the MTTR while increasing the MTBF of the accelerator system.

5.3.3.2 Scientific/technological challenges to be addressed

- Artificial intelligence-based real-time system performance monitoring.
- Integration of system health diagnostics and controls at the design stage.

Particle accelerators are very complex machines and consist of thousands of components. With many components that could potentially fail, the accelerator’s uptime would be unacceptably low unless significant attention is paid to component reliability. A good understanding of the system’s health is therefore essential for achieving the required performance. Accelerator performance depends critically on the ability to carefully measure and control the properties of the accelerated particle beams. In conventional systems, it is not uncommon that beam diagnostics are modified or added after an accelerator has been commissioned. This reflects, in part, the increasingly difficult demands for high beam currents, smaller beam emittances, and the tighter tolerances place on these parameters (e.g., position stability) in modern accelerators.

Predictive analytics are needed to predict future events or behaviors based on past data. The basis of predictive analytics is the smart software, which is used to control predictive modeling functionalities. This would give accelerator users the opportunity to proactively implement mitigating solutions to prevent efficiency loss in operations. Predicting equipment performance and the estimation of the time to failure will reduce the effects of these uncertainties. In addition, predictive analytics can be implemented in everyday operations, making the accelerator system more efficient and safer.

5.3.3.3 Summary of required R&D

- Improved smart system-level diagnostics in ground-floor design and engineering of accelerator systems

Improved system diagnostics integrated with smart controls are needed that can target the MTBF and MTTR indicators of a system's operational health to predict system failures. A beam diagnostic essentially consists of the measurement device, associated electronics and processing hardware, and high-level applications. The system health diagnostics record system-level performance measurements in addition to system-level operational set points. For example, real-time diagnostics of the vacuum environment, coolant temperatures, flowrates, and pressures, power levels, and non-interceptive beam parameters can actively monitor the system health and predict failures. These measurements and set points can be transmitted to vendor home base and compared to the accelerator system operations database to predict potential failure scenarios that will be provided to the in-field operators (especially in remote locations). If required, the accelerator vendor will initiate communications with the in-field operators providing suggested changes to the operating configuration and/or coordinate shipment of replacement subassemblies and schedule a maintenance visit. This system monitoring avoids undesirable operating configurations and provides predictive failure scenarios that enable simultaneous shipment of replacement parts and scheduling of a service call to minimize MTTR and maximize MTBF.

The required R&D focuses on ground-floor design and engineering of accelerator systems to include optimally placed smart health diagnostics enabling model-based performance assessment. This technology will naturally employ artificial intelligence techniques to predict imminent failure modes along with potential solutions to extend operations until needed hardware and service skills can be dispatched to the in-field operations.

5.3.3.4 Scientific impact of R&D

- Optimized accelerator system performance metrics under varying environmental conditions

The impact of implementing smart diagnostics and controls in medical and security accelerator-based systems is improved operational performance, more automated operation and maintenance, higher reliability/availability, and lower overall operating costs. AI-based system health diagnostics will learn how to optimize application performance metrics under different environmental conditions expanding the capability of the accelerator system for different medical and security applications.

5.3.3.5 Potential impact on the application

- Improves accelerator reliability, automates maintenance, increases lifetime, and lowers cost.

Smart system diagnostics and automated controls will provide more robust and lower cost medical and security accelerator systems that have improved operational performance and lower downtime. These enhanced features will enable transportable medical systems with the ability to service a greater geographical area in harsh environments thereby providing greater accessibility of health care to a wider population. In industrial applications, operational costs can be significantly reduced if potential failure modes can be diagnosed and predicted early on (an example is avoiding the costly downhole retrieval of a malfunctioning well logging source). Improved accelerator operational performance with lower downtime also benefits cargo security applications that require high detection sensitivity with minimal impact to the speed of commerce.

5.3.4 Research Theme LT4: Converters for High-Power Density Pulsed Beams

5.3.4.1 Background

Many medical and security applications employ secondary radiation generated from the primary accelerator-generated beam interacting with a "converter" (target) material. The secondary radiation are usually x-rays (generated from accelerated electron beams), or high energy x-rays/neutrons (generated from accelerated ion beams). The typical x-ray converter is a high-Z (high atomic number) target that produces Bremsstrahlung radiation when the bombarding electrons are accelerated by the electric field of the target atoms. The drawback is that x-ray conversion efficiency is very low (<0.1%) and results in a significant amount of heat generated within the target material requiring an optimized thermal management system. Similarly, gamma ray and neutron radiation sources are produced when the accelerated ions in the incident beam slow down and interact with the atoms in the converter material causing nuclear reactions to occur. The primary beam's energy loss in the material depends on several factors including target material, beam type, beam current density, and beam energy. Medical applications such as FLASH ultra-high dose rate radiotherapy or BNCT and security applications such as high-throughput cargo inspection achieve high dose rates with high-peak-current beams that often result in damaging high-power density effects in the converter material.

5.3.4.2 Scientific/technological challenges to be addressed

- Increase dose rate and beam energy for medical radiotherapy.
- Increase ruggedization and operational lifetime of small sealed sources.
- Increase through-put and detection sensitivity for nondestructive characterization.
- Increase through-put, increase ruggedness, and lower cost for sterilization and irradiator applications.

Converters (targets) in high-power accelerators experience roughly the same levels of damage as the highest flux fission reactor cores and first walls of future fusion reactors. One of the key parameters that limit the achievable dose rate in medical and security accelerators is the temperature behavior of the converter material. Elevated temperatures may result in fatigue, recrystallization, creep, and vaporization. In some cases, target degradation from ion-induced sputtering is also an issue. Some modeling studies have indicated that the heat load is limited by both the surface temperature of the cooling tubes and by mechanical fatigue of the target surface. [Cho-2002] High performance targets for high-power density pulsed beam systems can be realized by proper choice of primary beam parameters coupled with target materials and geometry factors. Key to this optimization is addressing the scientific challenges associated with the target's physical (high production efficiency), structural (mechanical stress limits) and electrical (insulating) requirements, and the thermal management design (sufficient heat removal) to enable long target life and efficient production of secondary radiation.

5.3.4.3 Summary of required R&D

- Exploit novel conversion mechanisms to optimize converter performance
- Engineer innovative thermal management approaches to minimize target degradation

High-power target system design must broadly consider heat removal, structural integrity, pulsed beam effects, material behavior under radiation, robust fabrication, shielding, facility safety, and waste disposal. The R&D needed to realize such targets would focus on designs with optimal choice of materials and geometries that also include an integrated thermal management subsystem to optimize secondary radiation production efficiency while maintaining long operational lifetimes. Depending on the application, these targets would employ solid or flowing liquid materials and modeling/simulation can provide favorable candidate designs. Ideally, these designs would employ some type of real time performance monitoring to assist in predicting when target maintenance or replacement is needed.

5.3.4.4 Scientific impact of R&D

- Improves converter ruggedization and efficient production of desired radiation
- Reduces lifecycle costs by minimizing target degradation and maintenance

Improving converter/target efficiency and robustness can significantly reduce power and maintenance requirements to permit development of compact, transportable medical and security accelerator-based systems with reduced lifecycle costs.

5.3.4.5 Potential impact on the application

- Enables stable and efficient high-power beam production in compact accelerator systems

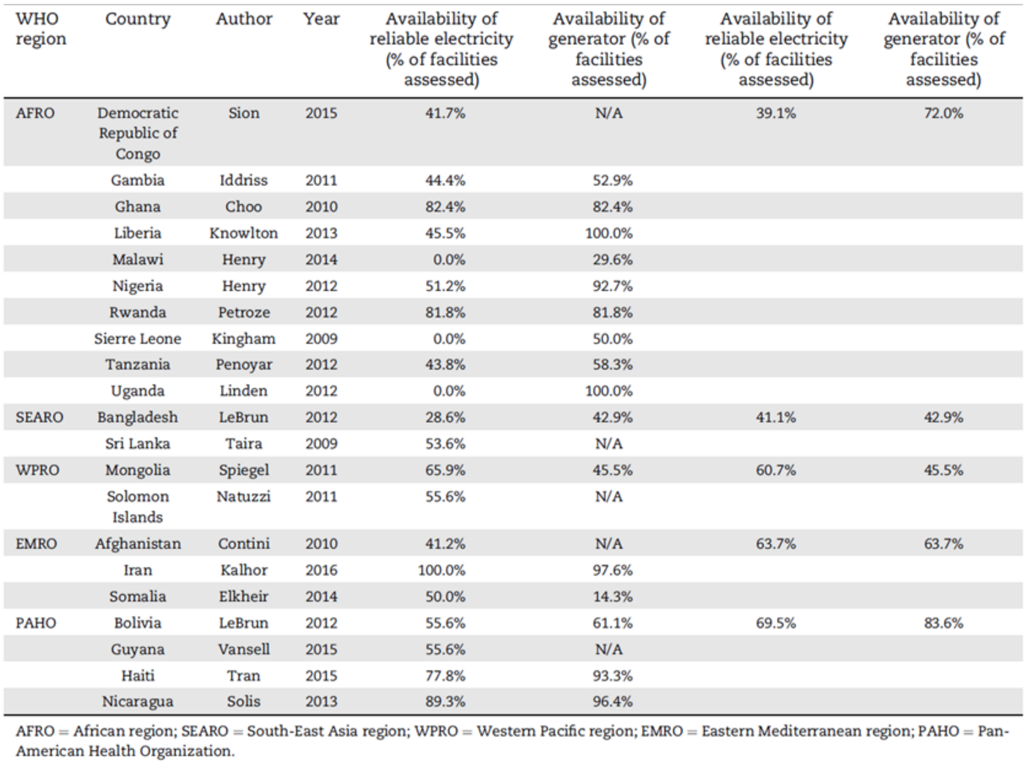
The development of improved high-power accelerator converters/targets will permit stable and efficient production of x rays, gamma rays, and neutrons needed in many medical and security applications including blood sterilization, medical instrumentation sterilization, food sterilization, FLASH radiotherapy, IMRT, BNCT, and high-throughput cargo inspections.

5.3.5 Research Theme LT5: Low Cost and High Reliability Accelerator Powering Systems

5.3.5.1 Background

A reliable source of power is central to any accelerator-based system and, in particular, to accelerators used in medical and security. The reliability of the power supply is determined by several interdependent factors. An interconnected power system basically consists of several essential components: generating units, transmission lines and loads (e.g., the accelerator system). During the operation of the generators, there may be disturbances such as sustained oscillations in the speed or periodic variations in the torque that is applied to the generator. These disturbances may result in voltage or frequency fluctuation that may affect the other parts of the interconnected power system. External factors, such as lightning, can also cause disturbances to the power system. All these disturbances are termed faults. When a fault occurs, it causes the generators to lose synchronism and become unstable. Other conditions such as steady-state stability, transient stability, harmonics and disturbance, collapse of voltage and the loss of reactive power also impact the reliability of the power system. The upkeep and the technical condition of a power system's infrastructure directly affects its operation and, therefore, the duration and frequency of power outages. Poor upkeep is further worsened when an economy faces external shocks or inclement weather. Access to reliable energy has been identified as a global priority and organized within the United Nations Sustainable Goal 7 [UNGoal7-2019] and the Electrify Africa Act of 2015. [ElectrifyAfrica-2015, Public Law No: 114-121] A recent study found that less than two-thirds of hospitals in LMICs have reliable electricity available (see Table 5.3). [Chawla-2018] Reliable power also

Table 5.3: *Availability of reliable electricity and generator facilities by country and region.*[22]



WHO region	Country	Author	Year	Availability of reliable electricity (% of facilities assessed)	Availability of generator (% of facilities assessed)	Availability of reliable electricity (% of facilities assessed)	Availability of generator (% of facilities assessed)
AFRO	Democratic Republic of Congo	Sion	2015	41.7%	N/A	39.1%	72.0%
	Gambia	Iddriss	2011	44.4%	52.9%		
	Ghana	Choo	2010	82.4%	82.4%		
	Liberia	Knowlton	2013	45.5%	100.0%		
	Malawi	Henry	2014	0.0%	29.6%		
	Nigeria	Henry	2012	51.2%	92.7%		
	Rwanda	Petroze	2012	81.8%	81.8%		
	Sierre Leone	Kingham	2009	0.0%	50.0%		
	Tanzania	Penoyar	2012	43.8%	58.3%		
	Uganda	Linden	2012	0.0%	100.0%		
SEARO	Bangladesh	LeBrun	2012	28.6%	42.9%	41.1%	42.9%
	Sri Lanka	Taira	2009	53.6%	N/A		
WPRO	Mongolia	Spiegel	2011	65.9%	45.5%	60.7%	45.5%
	Solomon Islands	Natuzzi	2011	55.6%	N/A		
EMRO	Afghanistan	Contini	2010	41.2%	N/A	63.7%	63.7%
	Iran	Kalhor	2016	100.0%	97.6%		
	Somalia	Elkheir	2014	50.0%	14.3%		
PAHO	Bolivia	LeBrun	2012	55.6%	61.1%	69.5%	83.6%
	Guyana	Vansell	2015	55.6%	N/A		
	Haiti	Tran	2015	77.8%	93.3%		
	Nicaragua	Solis	2013	89.3%	96.4%		

AFRO = African region; SEARO = South-East Asia region; WPRO = Western Pacific region; EMRO = Eastern Mediterranean region; PAHO = Pan-American Health Organization.

---

[22] Reprinted from Chawla, S., S. Kurani, S. M. Wren, B. Stewart, G. Burnham, A. Kushner, and T. McIntyre, Journal of Surgical Research, (223), p. 136-141 (2018) Journal of Surgical Research, (223), "Electricity and generator availability in LMIC hospitals: improving access to safe surgery," 136-41, Copyright (2018), with permission from Elsevier.

impacts national security and industrial applications which require high detection sensitivity and an uninterrupted flow of commerce.

5.3.5.2 Scientific/technological challenges to be addressed

- Reliable power source in remote or harsh environments

Accelerators used in medical and security are subject to rigid performance demands and, at the same time, are required to operate for extended periods of time with minimal downtime. In areas with low power reliability, voltage fluctuation and power outages can halt operations, damage equipment and affect operational performance quality. Generators are often the preferred mitigation to sustain regular operations, but generators are typically not used to provide much if any power to specialized equipment (such as accelerator high voltage power supplies, cooling systems, vacuum pumps, etc.) during outages and are only used for lighting and communications. [ODI-2014] Although renewable energy offers the potential of reliable alternative electricity, the upfront costs of sources such as solar photovoltaics or micro-hydropower can be perceived to be prohibitive (see Table 5.4). Access to more reliable, cleaner, and more sustainable energy sources is increasingly important in light of these realities as well as other economic, environmental, and climate realities. There is thus an urgent need to improve the geographic coverage, quality, and frequency of data collection on energy access in health care facilities.

Table 5.4. *Typical costs of conventional power systems for a small health clinic consuming 25 kWhr/day. [PoweringHealth-n.d.]*

Technology	System Size	Capital ($)	Operating ($/yr)	Operating/Maintenance Assumptions
Solar Photovoltaic (PV) System with Batteries	6 kW panels 100 kWh batteries	$55k system $10k batteries	$2550	1% of system cost per year (includes maintenance and component replacement; does not include security). Amortized cost of replacing batteries every 5 years (20% of battery cost)
Wind Turbines with Batteries	8.75 kW turbine 100 kWh batteries	$44k system $10k batteries	$2900	2% of system cost per year (includes maintenance and component replacement). Amortized cost of replacing batteries every 5 years (20% of battery cost)
Diesel Engine Generator	2.5 kW	$2000	$6400	$0.0075/kWh maintenance. $0.67/kWh fuel ($1/liter for fuel is used) operating at 4 kWh per day at 50% capacity and replacement of engine every 10 years)
Hybrid Systems	6 kW panels	$55k PV system $5k batteries $2k generator	$2200	1% of PV system cost per year. Battery replacement every 5 years. Replacement of engine every 10 years.
Grid Extension	n/a	$10k+ per mile	$900	$0.10/kWh

5.3.5.3 Summary of required R&D

- Disciplined system engineering of highly efficient accelerator systems and advanced controls
- Improved energy storage system cost, service life, durability, and power density
- Advanced insulating materials to improve reliability and reduce costs

The best solutions for insecurity of grid electricity are increasing generation capacity and reducing transmission and distribution losses. However, these solutions generally require commitment and resources available only at a national level and other national priorities oftentimes take precedence. In lieu of the latter, an early disciplined system engineering approach toward highly efficient accelerator design and development could incorporate technology that results in more continuous, affordable, and sustainable operational power. For example, the development of smart PID (proportional-integral-derivative) control for accelerators, implementation of innovative self-contained energy storage solutions, and incorporating next-generation insulating materials and electrical components are technologies that could help to realize low cost and reliable power to accelerator and associated auxiliary systems.

Smart Accelerator Control

A stable power system must have capability to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium. [Saadat-1999] Controllers are used in industry to make decisions about how control actions will be performed, what those actions will be, when they occur, and how their performance will be measured. Controllers are also responsible for reasoning about system state, diagnosing errors in control solutions, and taking pre-emptive control actions if needed. Power system stabilizers (PSSs) are the most widely used devices for resolving oscillatory stability faults and improving the power system damping. [Sumanbabu-2007] Traditionally, lead-lag structures have been used as power system stabilizers and various methods to optimize the parameters of the lead lag controller have been explored. PIDs are a control loop feedback mechanism used in a variety of applications requiring continuously modulated control. A PID controller tracks the error between the process variable and the set point, the integral of recent errors, and the derivative of the error signal. It computes its next corrective effort from a weighted sum of those three terms, then applies the results to the process, and awaits the next measurement. It repeats this measure-decide-actuate loop until the error is eliminated.

Recently, a PSS and PID controller combination has been studied for enhancing power system stability. [Kasilingam-2015] This study examined artificial intelligence, adaptive control, and population-based algorithms for tuning the PSS-PID and found that a swarm intelligence algorithm appeared to have the greatest potential for optimizing the power system analysis. Comparable results were found in another study that used a hybrid optimization scheme. [Abdul-Ghaffar-2013] and a PID control system for improving voltage stability was developed using the model reduction method. [Bamigboye-2016] A neural network-based PID has been demonstrated for controlling the water system of a klystron-powered electron gun [Edelen-2016] and a RF control system which includes amplitude and phase controllers to ensure efficient and stable operation of the accelerator has been described. [Mandi-2015] Medical and security accelerator operations with reliable beam power require highly dependable protection systems to avoid any damage-induced downtime. Advanced accelerator control methods will ensure a high-quality supply of power that include advanced supervisory control and data acquisition systems, load and short-term weather forecasting, and distributed intelligent control systems to enable self-healing.

Energy Storage

Storage systems can be designed with a broad range of technologies, each with its own performance characteristics that makes it optimally suited to providing necessary power to various applications. Conventional large-scale technologies, such as pumped hydro and compressed air energy storage, are capable of long discharge times (tens of hours) and high capacity. Alternatively, electrochemical batteries and flywheels are used in lower power applications or those suitable for shorter discharge times (a few seconds to several hours). Current energy storage technology (e.g., the battery) can contribute 30 – 40% to the total powering system cost (see Table 5.4, above) and are often limited by the performance of the materials used in their construction. Overcoming these limitations requires understanding the complex interactions that transfer ions or electrons in these devices and the physical and chemical processes that degrade them. Research and development to improve energy storage system costs, service life, durability, and power density are needed to enable new battery chemistries and component technologies, such as low-cost membranes for flow batteries, sodium-based batteries, high voltage capacitors, wide bandgap materials, and devices for power electronics. Integration of these technologies will enable the design of a new generation of energy storage devices that radically increase charge density and last longer by minimizing degradation from charge-discharge cycles.

Advanced electrical components, insulators, and electronics

Implementing smart components and electronics into an accelerator powering system not only improves operationally efficiency, but also increases resiliency to disruptive power source events. Power electronics, such as switches, inverters, and controllers, allow electric power to be precisely and rapidly controlled resulting in improved power supply reliability and responsiveness. Since the performance of electrical equipment and devices is essentially determined by the properties of their insulating materials, advances in new materials would improve the reliability of an accelerator's powering system, while also reducing costs. Insulator state-of-health diagnostics and monitoring tools will permit accelerator operators to know the overall insulation condition of their systems, streamlining maintenance costs in the process. Development of better insulator diagnostics will also permit longer operational lifetime and eliminate the costly shutting down of systems for maintenance.

5.3.5.4 Scientific impact of R&D

- Robust, stable, and economical power sources for challenging environments

The research would lead to robust power sources that meet accelerator system needs at minimal cost, increase operational efficiency, enable capability to handle dynamic supply and demand, improve reliability by consistently delivering high-quality power, and maintain critical operations with quick recovery to disruptions.

5.3.5.5 Potential impact on the application

- Removes barriers to wider adoption of radiotherapy for global medical needs
- Increases screening throughput and accuracy in remote security applications

In the US, radiation therapy is used to treat over 60% of cancer patients and is used in nearly half of the curative cases. However, there is a global underserved population with technology per capita two or more orders-of-magnitude lower than in the US. The barriers to wider adoption of modern radiotherapy are primarily due to the high capital/operating costs, requirement for highly-trained personnel, and availability of a reliable power supply. State-of-the-art medical accelerators have very high peak and average electrical draws, and require stable, reliable power that is often unavailable. An accelerator system incorporating technology that provides more continuous, affordable, and sustainable operational power will significantly impact the availability of safe radiotherapy and surgical care for global medical needs. Likewise, the technology will enable higher throughput for cargo screening security applications in remote areas and harsh environments.

5.3.6 Research Theme LT6: Endoscopic Accelerators

5.3.6.1 Background

The relatively large size of a MeV x-ray source limits many of its applications. If a very small source of accelerator based radiation is made available, many endoscopic applications would open up for research or the clinic such as source free brachytherapy (medicine), and for NDC applications such as structures and emergency response (security). New micro accelerators including "on a chip" and plasma-based devices are coming forward presently and may offer significant improvements to the delivery of radiation, collimation, compatibility with brachytherapy or NDC in tightly confined or mobile spaces, array use, and finally cost. The advance of such micro accelerators would make a strong argument that the LINAC need not weigh more than 10 pounds or cost more than a few thousand dollars via replaceable "bulbs" that would be very low cost. Can such systems be made compact at mm to cm scale, and affordable? Can flexible power delivery, cooling, and robust drivers be developed? Can such a system be made in a way that its operation is robust and reliable?

5.3.6.2 Scientific challenge to be addressed

Variable electron energy from 1-10 MeV is needed on a pulse-by-pulse basis during treatment. Wide angle emission is needed, potentially including use of a scatterer (ideal is ~2π). This confers extra degrees of freedom for the treatment planning process, thereby providing the clinician the ability to improve the dose delivery options. For NDC applications beam steering may be needed. Developments in this space aim to produce complete particle accelerator systems that are miniaturized into mm or cm scale devices using semiconductor chips, plasma media or THz structures. Such systems could be powered by modern solid state lasers and use flexible power delivery conduits. The use of lasers to power these accelerators is particularly attractive, due to the intense electric fields they can generate combined with the fact that the solid state laser market has been driven by extensive industrial and university demand toward lower cost and higher efficiency over the last 20 years. The lasers required are commercially available, rack-mountable, and have shoebox-sized to cabinet form factors. Three main technical paths of accelerator development would offer realistic passage to source-free brachytherapy using accelerators small enough for endoscopic applications: "accelerators on a chip" - DLA, LWFA, and THz structures.

DLA have the potential to create ultra-compact accelerators using structures that are constructed using the same nanofabrication methods used in the integrated circuit industry to make the microchips in our cell phones and laptop computers. The dielectric and semiconductor materials required have damage limits corresponding to acceleration fields' orders of magnitude larger than conventional radiofrequency accelerators, allowing for a factor of 100 or more reduction in size. Such materials are also amenable to rapid and inexpensive CMOS and MEMS fabrication methods, allowing them to be mass produced at low cost. These technological developments, combined with new concepts for efficient field confinement using optical waveguides and photonic crystals [Hughes-2018], and the first demonstration experiments of near-field structure-based laser acceleration conducted within the last few years [Peralta-2013; Leedle-2018; Black-2019; McNeur-2016; Niedermayer-2018; Cesar-2018] have set the stage for making integrated laser-driven micro-accelerators or DLA for a variety of real-world applications. [England-2014] Current research efforts in the US and Europe aim to produce a first working prototype with MeV class electrons in a "shoebox" size device by 2020.

LWFAs offer a second path to ultra-compact devices, using the very high fields that can be sustained by plasma waves. Acceleration to >10 MeV energies over mm length scale has been demonstrated. Research must now address minimization of the laser energy based on recent generation of few MeV electrons using mJ few fs laser pulses. [Salehi-2018; Guénot-2017] Robust regimes of operation need to be developed. Laser focusing, gas target systems and heat management systems must be miniaturized into an encapsulated device, first at cm and then at mm scale. Driving lasers are available based on milliJoule-class commercial “off-the-shelf” lasers with broadening and compression to a few cycle pulses, but should be developed for robustness and ease of operability. Flexible laser transport and dispersion management to deliver compressed few cycle pulses to the endoscopic accelerator are needed.

THz accelerators using flexible power conduits offer a third technology option. [DalForno-2018; Nanni-2018; Zhao-2019; Thompson-2008; Picard-2019; Kutsaev-2019; Moriguchi-2018; Matlis-2018; Li-2019b] THz structures have now demonstrated GV/m fields, electron beam acceleration and importantly emittance preservation of high charge bunches (>pC). Investigation into source-free brachytherapy with mm-scale MeV sources and laser-driven THz pulses is underway. Progress is being made in the three main R&D areas: (1) high power THz sources, (2) the metallic or dielectric structure, and (3) syncronization of the electron source to injector. The main approach under devleopment are THz devices that can be powered with a laser-driven THz source for easy synchronization to a photocathode laser for the injector to produce high brightness beams. R&D needed to deliver TRL-4 includes: development of injectors, 10 cm scale structures; using recent demonstration of MW-class switches for power distribution and RF compression to maximize electron-beam source (50% efficient) topologies; laser-driven source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ).

5.3.6.3 Summary of required R&D

The near term R&D challenges across the candidate technologies include optimizing, fabricating, and demonstrating proposed designs for electron injection, acceleration coupling, transport, and focusing to realize few-MeV-class acceleration first in cm scale devices and then mm-scale devices. Reliable operation suitable for operation by users not expert in laser/accelerator science, and either durable or disposable designs, are needed. For THz structures, the development of efficient THz power sources based on optical rectification with a laser is needed. For DLA, cascading of multiple acceleration stages is needed to reach useable average beam powers in the few mW range. For LWFA, compact compression, focusing and gas target systems are needed. Given the rapid progress in this area from first proof-of-concept to working benchtop devices over the last 4 years, with adequate funding and effort, laboratory demonstration of prototypes based on either technology for medical applications is achievable on a 5 year time scale, with development and exploration of commercialization options on a 5-10 year scale. There has already been some preliminary commercial interest.

5.3.6.4 Scientific Impact of R&D

Small (mm to cm scale) and low-cost devices allow small research labs, university groups, and in challenging medical and security environments to carry out cutting-edge physical research while enabling new applications with state-of-the-art technology. The accelerator technlogies developed for endoscopic applications require very high accelerating gradients to enable miniature devices. This development has strong synergy with other high gradient accelerator applications. The technologies that can produce a few MeV in mm for endoscopic applications can also produce hundreds of MeV in centimeters for applications using Compact Mono-Energetic Gamma Ray sources or VHEE or FLASH therapy. The development of LWFA, DLA and THz technologies for these applications are detailed in the respective sections. They additionally provide pathways to advancing fields outside this report, including the energy reach of High Energy Physics particle colliders and enabling compact Free Electron Lasers, photon and neutron sources, and accelerators relevant to many agencies.

5.3.6.5 Potential Impact on the Application

Miniature accelerators capable of delivering on-demand, tailorable MeV radiation sources have the potential to revolutionize medical brachytherapy and to enable unique security NDC applications where either operation in constrained space (e.g., machinery or pipes) or high mobility and flexible positioning (e.g., Emergency Response) are important.

Roughly half of all cancer patients in the US are treated with radiation, typically in electron/x-ray accelerator facilities, of which there are several thousand currently in service. With cancer cases expected to rise world-wide and access to therapy limited in challenging environments and low-income countries, ultracompact and low-cost accelerators are desperately needed to meet these needs. [Coleman-2019; Phillips-2015] Existing radiation oncology treatments rely largely on external radiation sources. Brachytherapy, which utilizes the introduction of a controlled radiation source directly into the body, has clear advantages for targeting dose, preserving adjacent tissues and limiting damage to surrounding organs. Several commercial brachytherapy products exist, but the majority incorporates naturally radioactive materials that cannot be turned off and on, are complicated and invasive to use, have limited control of dose distribution, and must be well shielded and controlled for safe operation. Due to the cm-scale penetration depth for few MeV electrons, direct electron irradiation can be used if an ultracompact, self-contained multi-MeV electron source is available. This would enable minimally invasive cancer treatments and alterable dose deposition in real-time, thus providing the benefits of brachytherapy while offering much better dose control. An encapsulated micro-accelerator built onto the end of a fiber-optic catheter **(see Figure 5.1)** could be placed within a tumor site using standard endoscopic methods, allowing a doctor to deliver the same or higher radiation dose to what is provided by existing external beam technologies, with less damage to surrounding tissue. Encapsulated devices (Figure 5.1) would ideally have variable electron energies in the 1-10 MeV range, a footprint that is millimeter-scale, and accommodate a wide range of emission angles for various treatment modalities. Unwanted dose to nearby healthy tissue and critical structures could be intrinsically reduced (up to 30-fold) as compared to photon therapy. This enables up to a 3-fold increase in dose to the lesion together with a 10-fold reduction in dose to adjacent structures. The manufacturing and operating costs are anticipated to be much lower than those for conventional radiation therapy machines, and the robustness of such systems compared to conventional accelerators should be even more favorable.

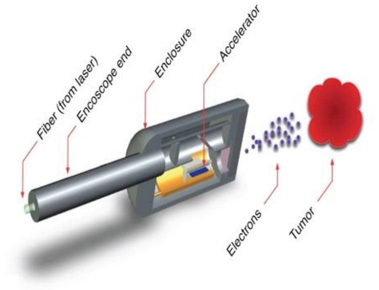


Figure 5.1.*Conceptual illustration of an encapsulated endoscopic electron accelerator for medical radiation applications. For medical brachytherapy, such accelerators deliver much more concentrated dose than conventional methods resulting in lower dose to healthy tissue. For security applications they enable high mobility and positioning of the accelerator or insertion into confined spaces. (Image credit: [Travish-2011])*

Industrial accelerators also have many other applications in the private and medical sectors, including material processing and NDT, food decontamination, cancer therapy, vacuum ultraviolet (VUV) photo-electron spectroscopy, and ultrafast electron microscopy. [Hamm-2013] Compact accelerators that enable brachytherapy could also have important impact in these fields.

5.3.7 Research Theme LT7: Compact Superconducting RF Accelerators

5.3.7.1 Background

Linear accelerators are a spinoff technology from High Energy and Nuclear Physics research and their use has been widely adopted in medicine, security, and industrial applications. Radiotherapy with electron and ion beams and the production of therapeutic isotopes has been broadly adopted by the medical community worldwide. Scanning and imaging using x-rays is a standard security practice in the US and elsewhere. In Industry, LINAC sources are used to crosslink polymers as well as sterilize medical instruments, fruit and spices. For some of these applications the performance can be substantially improved by providing a continuous train of beam pulses. The improvement in performance is achieved either through higher total beam power provided at 100% duty factor rather than the 0.1% or less typically available, or it might result from the ability to modulate the beam current or energy on a continuous basis providing discrimination in imaging, controlled variability in the penetration depth of the applied dose, or identification of particular materials through comparison of absorption spectra at various energies. Can such CW systems be made compact and affordable given that substantially more drive power is required at the higher duty factor and therefore more cooling for the system components? Can such a high power system be made in a way that its operation is robust and reliable?

5.3.7.2 Scientific challenge to be addressed

- Develop a high gradient robust superconducting accelerator which can operate CW at temperatures of 4.5K or above

Standard pulsed accelerators made of copper are limited to low duty factor because of the high microwave losses in their cavities. Typically, they produce a train of beam pulses for a length of 10 microseconds or less repeated less than 1000 times a second. There is little that can be done to extend the duty factor of such systems because they are limited by removing heat from the interior copper walls of the accelerator cavity, a mature technology which is already stretched to its limit. What can be done to achieve the advantages of CW LINAC operation in medical and security applications?

In the last two decades since the installation of the CEBAF accelerator the use of CW superconducting RF accelerators has been widely adopted for large scale high energy and nuclear physics research accelerators to take advantage of the higher duty factor available. Although the accelerator components of such systems are fabricated in industry, applying and utilizing the technology to produce relativistic beams requires many specialized skills and techniques. It is not particularly robust and it requires large superfluid liquid helium cooling systems. Can SRF technology be applied in such a way that it is compact, robust, and made practical for a small-scale system unsupported by an army of technicians? Can the supporting systems be simplified and made highly reliable?

The standard approach toward building a SRF linear accelerator is to fabricate a set of resonant microwave cavities out of ultrapure niobium and bathe the cavities in superfluid helium. This approach is in application in all of the countries performing advanced high energy and nuclear physics research. [Drury-2018] Advances have been made in the last several years in the surface treatment of the niobium material allowing higher gradient and lower power loss operation. There are various recipes in use around the world for preparing and treating the material use in superconducting cavity fabrication. Thermal annealing and nitrogen processing are among the approaches used in the most advanced labs. [Reece-2015] Gradients exceeding 45 MV/m and Q_0 greater than 4 x 10^{10} have been achieved. More advanced techniques utilize alternate materials and coating the cavity interior with a superconducting material. What is required to bring these alternate materials and coating technologies to practical application? Though still a study some successes with reasonable gradients and low residual resistances have been seen with functional subscale cavities operating with Nb_3Sn or other material plated on to a copper substrate. [Hall-2015] Other materials may also perform this function as might the use of multilayered approaches. Figure 5.2. shows a list of potential candidates for high temperature SRF application.

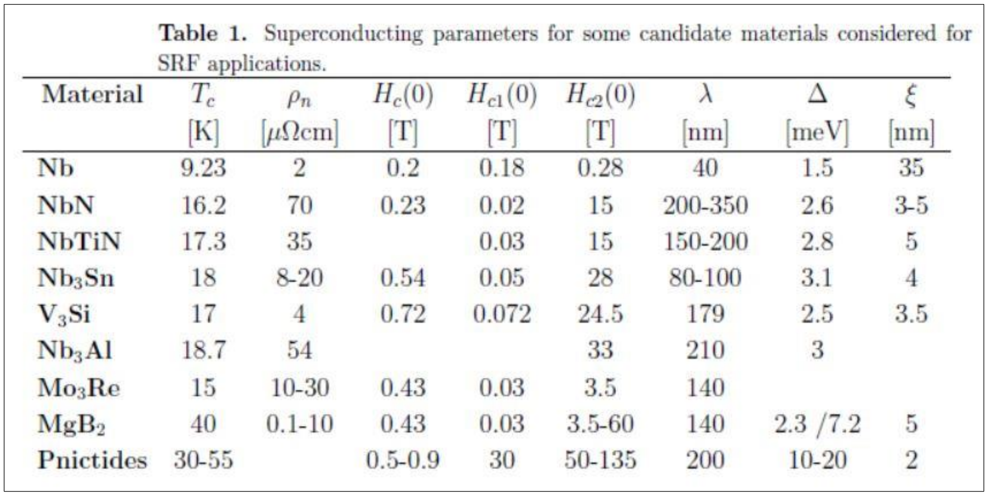


Table 1. Superconducting parameters for some candidate materials considered for SRF applications.

Material	T_c [K]	ρ_n [$\mu\Omega$cm]	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	λ [nm]	Δ [meV]	ξ [nm]
Nb	9.23	2	0.2	0.18	0.28	40	1.5	35
NbN	16.2	70	0.23	0.02	15	200-350	2.6	3-5
NbTiN	17.3	35		0.03	15	150-200	2.8	5
Nb_3Sn	18	8-20	0.54	0.05	28	80-100	3.1	4
V_3Si	17	4	0.72	0.072	24.5	179	2.5	3.5
Nb_3Al	18.7	54			33	210	3	
Mo_3Re	15	10-30	0.43	0.03	3.5	140		
MgB_2	40	0.1-10	0.43	0.03	3.5-60	140	2.3 /7.2	5
Pnictides	30-55		0.5-0.9	30	50-135	200	10-20	2

Figure 5.2. *Superconducting parameters for some candidate materials considered for SRF applications. From [Valente-Feliciano-2016], used by permission.*

Opportunities for a breakthrough exist with potentials for operation at 4 K and above, higher gradients, lower power losses, and substantially decreased fabrication costs. Any of these would support wider adoption of the technology in the international scientific, medical, and industrial community.

The most technologically advanced of these approaches involves forming a layer of Nb_3Sn on a substrate of pure Nb. At least four laboratories have demonstrated individual cavities relying on this approach: Cornell, Jefferson Lab, Fermi, and Wuppertal. [Posen-2017]

Figure 5.3 shows the comparative performance of such cavities.

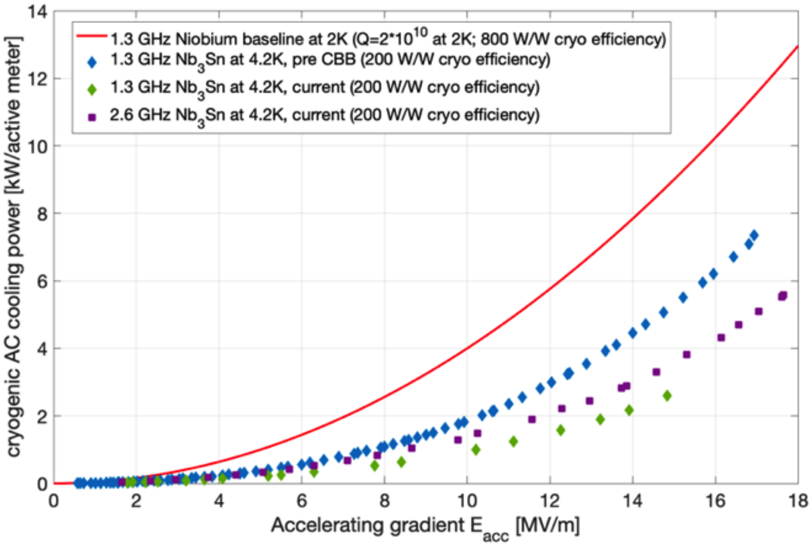


***Figure 5.3**. A comparison of relative refrigerator power for Nb cavity technology and Nb3Sn technology. (Courtesy G. Hoffstaetter, Cornell U.).*

While such improvements may seem modest in terms of the cryogenic power reduction the implications of just 2 K rise in operating point are substantial. It changes the entire refrigerator approach from a specialized, one-of-a-kind, large, finicky system to an off-the-shelf turn-key operation requiring only minimal maintenance.

5.3.7.3 Summary of required R&D

- Identify candidate materials for high gradient SRF accelerator operation above 4.5 K
- Develop technical approach to fabricate accelerator cavities from the candidate materials
- Demonstrate robust reliable performance of the materials under modest scale operation

The main complexity driver in present day SRF accelerators is the need to operate the superfluid helium refrigeration system at sub-atmospheric pressures to maintain the 2 K operating temperature required by the niobium cavities. A high impact goal of research in this area would be the ability to operate a superconducting accelerator at 4 K and higher temperatures. A change of 2 K in the operating temperature perhaps does not sound like much but it would have an enormous impact on the design and support infrastructure of the system. It would reduce the helium piping around the cavity by a factor of 3 or more; it would reduce the size and complexity of the helium refrigeration plant be a factor of 20. Such higher temperature operation can be achieved if alternative materials are developed beyond the present use of bulk niobium. As discussed above, one of the particular materials under study is the formation of Nb_3Sn on the surface of bulk niobium. This requires achieving uniform stoichiometry and uniform deposition on a complex interior cavity. Several laboratories are experimenting with this approach with encouraging results but more extensive testing and development is required to reliably produce with high yield the large area coverage needed on complex shapes. There are a number of other materials which offer the possibility of higher temperature operation and higher acceleration gradients. Such materials might be put down on niobium or possibly, with even more advantage, on copper or other substrates to allow conduction cooling from a self-contained closed loop refrigeration unit. Theoretical studies have indicated that multilayers of SRF materials could offer some advantages in higher field and lower rf loss operation. Identification, characterization, and ranking of the candidate materials would help progress in the field.

A key point to note in this approach for improvement is that changing the operating temperature from around 2 K to 4.5 K has an enormous impact on the advantages of the approach and technical viability. Improving the operating performance above 4.5 K, while beneficial, is more of an evolutionary improvement rather than the revolutionary step from 2 K to 4.5 K. SRF technology, medical and security applications would benefit enormously from a focused development program of high gradient high temperature SRF cavities. The technology is at the threshold of major achievement needing a small push to achieve practical goals with enormous worldwide benefits.

A further step in the materials arena would then be the development of practical application techniques to the interior of complex shapes such as RF cavities. This is a tricky problem since deposition must be done on the interior of a cavity, it must be fairly uniform in deposition with perhaps multiple materials in precise stoichiometry, and it cannot exhibit any contamination of surface roughness which would lead to field breakdown. The challenges are significant but even after such initial fabrication is achieved it will be necessary to determine whether such materials are long-lived and robust in an accelerator environment or suffer degradation or damage.

The initial steps toward this goal can certainly be made in the next 5 years with materials that have already shown promise but clearly a longer-term development is likely for more advanced materials and fabrication techniques. One way this might proceed is through several demonstration systems with modest goals of achieving 4 K operation in a compact 10 to 20 MeV LINAC in order to gain the experience required and begin to acquire data on longevity and reliability. Parallel basic study efforts could continue to study more advanced materials with higher performance. Efforts to advance coating production and application techniques would impact the overall viability of the process.

It is also recognized that the initial beam production in such accelerators must be done in a way that is compatible with the rest of the accelerator environment. Thus opportunities to improve the injectors of such accelerators and incorporate their operation in the rest of the superconducting system would be advantageous. This might require photocathodes compatible with a superconducting cavity environment or special engineering approaches to utilize existing cathode materials in a SRF system.

5.3.7.4 Scientific Impact of R&D

- Broad adoption of SRF technology for university and commercial level R&D and applications
- Significant performance improvements in research accelerators for nuclear, high energy physics and photon generation for basic science research

Research in the area of high temperature operation of SRF accelerators to achieve compact CW LINACs could have far ranging consequences in the application of accelerators in medicine, security, and industry. Achieving 4 K operation at 20 MV/m gradient is a goal within reach which could reduce the refrigerator power consumption by 5 times and reduce the LINAC length by 2 times. This would also have a major impact on future high energy and nuclear physics programs since facilities such as LCLS-II, CEBAF, FRIB, SNS, and others use present day niobium technology. All could benefit from factors of 2-5 reduction in power use at their helium refrigerators.

It is notable that there are many follow-on benefits of such high temperature, high gradient operation in medical and security applications. Reduced power losses also reduce support infrastructure such as cooling systems. Shorter LINACs from high gradients improves compactness which makes shielding easier and lower total mass leading to simpler installations and in some cases portability. CW operation with low loss makes the technology a natural fit to solid state rf drives which are robust, efficient, and reliable. Achieving turnkey operation of a robust, compact SRF LINAC system which change the paradigm from a national lab level facility to one which university, hospitals, and industry could reasonably utilize without major expense or expertise. All of these would lead to wider acceptance of CW LINAC sources for medical treatment, sterilization, radiography, and x-ray imaging.

5.3.7.5 Potential Impact on the Application

- Substantially wider set of practical applications which drives additional commercial investment and expansion of capabilities
- Substantial advance in the performance of scientific accelerators including lower costs and higher electrical efficiency

It is not an exaggeration to say an achievement of high temperature, high gradient SRF LINAC operation would be a game changer in the broad adoption of CW LINACs. There is no reason why one cannot imagine a CW 20 MeV, 2 mA average current superconducting LINAC on a single pallet complete with solid state rf source and conduction cooled closed loop helium cooler. Elimination of rotary machinery and high voltage systems would yield high reliability. This would literally be a box that one plugs in. Tell it what beam parameters are desired, push the “On” button, and it produces the 40 kW beam with an overall electrical efficiency of greater than 30%. Variable beam pulse structures could easily be produced for higher sensitivity in detection either pre-programmed or based on some feedback signal. The CW availability of the beam would permit, for example, 50 ms exposures for high dose rate medical treatments. Beam energies could be varied easily during the exposure. If one were producing Thompson scattered x-rays then modulating the energy on and off K-edge absorption could provide high contrast identification of materials. Higher energy beams in the 200 MeV range could produce more highly penetrating electrons or for imaging Compton gammas. It could produce an initial low-level beam for initial scanning and then if a questionable image is viewed automatically go into a higher sensitivity mode. In either case the level of the beam current i.e., dose rate could be controlled to match the acceptance rate of detection systems without excess dose that one would have to shield. For example, in sterilization of complex shapes, imaging could be used real time to match the delivered dose to the area/volume under treatment. Imagine a conveyor belt carrying by myriad prepackaged surgical instruments. Real time imaging would permit dose adjustment over the actual area of the instrument itself as it passes by.

So to reiterate, there is a driving need for compact, robust CW beam relativistic sources which potentially could be met by a new generation of superconducting accelerators based on advanced materials, design, and fabrication techniques. The consequences of such development would be broad ranging and enable substantial use of CW systems where presently the complexity, size, and reliability of existing technology prevents its adoption. A research program to uncover and apply advanced SRF materials is a potential means to achieve this goal in the 5-15 year time frame.

5.3.8 Research Theme LT8: Advanced Laser Accelerators and Drivers

5.3.8.1 Background

- Advanced laser based accelerators offer gradients hundreds to thousands of times higher and hence could provide smaller, more efficient systems

The size of accelerators and x-ray sources is a key limit to security and medical applications. Linear accelerators have wide applications in medicine, security, and industrial applications, growing as a spinoff technology from High Energy and Nuclear Physics research. Radiotherapy and the production of therapeutic isotopes have been broadly adopted by the medical community worldwide. Scanning and imaging using x-rays is a standard medical and security practice in the US and elsewhere, and also important in industry and nuclear nonproliferation. Despite its broad use, current technology has its limitations. The systems are bulky, requiring significant heavy shielding. Moreover, advanced methods proven at scientific facilities are not available to applications because the required accelerator systems are too large. As one example, imaging currently uses bremsstrahlung x-ray photons because this requires the lowest electron energy, but this also limits available performance. It is known that advanced mono-energetic gamma photon sources such as Thomson scattering offer dramatically better imaging (see Sections 5.2.6 and 5.3.10) but these require much higher electron energies and the accelerators for which are currently large, fixed facilities not suitable to applications. Similar potential and similar limits due to current accelerator sizes also exist in VHEE therapy (Section 5.2.5), endoscopic accelerators (Section 5.3.6), or FLASH therapy (Section 5.2.5). Potential also exists for expanding the use of x-ray Free Electron Lasers (XFELs) where present facilities are national lab scale with associated high costs for infrastructure and operation. Advanced laser based accelerators offer gradients hundreds to thousands of times higher and hence could provide smaller, more efficient systems. This could make advanced capabilities now accessible only in large scientific facilities available to applications. Such accelerators and systems are at low TRL at present. Can such systems be made compact at the room or vehicle size in the midterm, or made even smaller in the long term? Can robust high repetition rate drivers be developed to enable these sources? Can such a system be made in a way that its operation is robust, reliable, and affordable?

5.3.8.2 Scientific challenge to be addressed

- Advances in beam power and engineering robustness are needed to realize the potential of advanced accelerator techniques.

Applications have a broad range of energy demands ranging from mm scale devices at 1-10 MeV for endoscopic devices, to 500 MeV at few cm scale for VHEE and mono-energetic photon sources (MPS). Laser driven accelerators can be developed to address each. Laser and plasma accelerators can sustain ultrahigh gradients to bring the beam to high energies in centimeters or less and in a single or a small number of stages. LWFA has demonstrated acceleration of electrons in fields 1000 or more times those in conventional LINACs, generating energetic electron beams from a few MeV to multi-hundreds of MeV in distances of millimeters in the plasma, and up to 8 GeV in tens of centimeters. Laser-structure or DLA have the potential for 100 or more times reduction in size compared to conventional LINACs. New concepts for efficient field confinement and recent first demonstration experiments of near-field structure-based laser acceleration are setting the stage for progress. What can be done to get these technologies out of the laboratory and make them easy to use, rugged, and practical at the high repetition rates demanded by many applications?

Laser-plasma wakefield accelerators (LWFA) offer a strong path to ultra-compact devices, where over the past fifteen years there have been tremendous progress in LWFA driven by short pulse high peak power lasers. While many important ‘firsts’ have been demonstrated, including high-energy beams with low energy spread and high transverse quality, performance is still far from that theoretically achievable. There is a roadmap [AARDR-2016] that guides community efforts [AAC-2018] towards performances that can enable photon source applications of interest to security and medicine in the nearer term, and the challenging requirements of future colliders. The main issues for advanced plasma accelerators to reach TRL-4 level and to be ready for transition to applications are centered on improved control of the plasma structure and injection to create high quality stable beams, and on developing appropriate drivers to enable compactness, stability, and repetition rate. Robust regimes of operation need to be developed. Laser focusing, gas target systems and heat management systems must be miniaturized into an encapsulated device, first at cm and then at mm scale. LWFAs are now operating at a fraction of the charge and efficiency that is possible, are not stable at a facility level, and have produced energy spreads below 10% only for brief periods of operation. Across all of areas, research is therefore needed to advance the science of beam control, stability and quality. Injection control shows a path to both improve beam quality and beam charge significantly. New guiding and laser shaping techniques show promise to improve laser propagation and hence reduce the laser energy required to achieve a given electron energy. Simulations are now working routinely in coordination with experiments to design concepts and interpret results, giving confidence in the physics basis for further progress.

While the accelerator structures themselves are indeed compact and relatively straightforward, the system size and complexity is instead dictated by the laser driver source. The vast majority of existing short pulse laser systems (~100fs) are based on Ti-Sapphire lasers. While Ti-Sapphire has significant tuning bandwidth, is extremely durable and has excellent thermal transport, it suffers from several issues including low doping concentrations to maintain material stability, short upper-state lifetime requiring high pump intensities thus limiting options for CW pumping, and requirement of excitation in the green spectral region where efficient diode pumping is difficult. For these reasons, most systems rely on frequency doubled, Q-switched Nd-based pump lasers which are flash-lamp pumped. This significantly impacts both system size and efficiency, with typical wall-plug efficiencies of ~0.5%. Assuming a maximum available electrical power of 100kW, it may be feasible to build a 10TW, 1kHz Ti-Sapphire laser system that would be capable of producing 100MeV electrons from a laser-plasma accelerator. However, such a system would be far from compact and would require significant investment in controls to run reliably. New laser pumping schemes, and in the long term new laser media and architectures, must be developed to enable compact high rate accelerators.

5.3.8.3 Summary of required R&D

- Reduction in the size and increases in repetition rate and efficiency of laser-based drivers are needed for both laser- and laser-based-THz-sources for accelerators
- A full set of accelerator components (injector, diagnostics, focusing, etc.) suited to the micron- to 10s of micron-scale bunches of laser-driven and THz-driven accelerators are needed

Key R&D challenges of realizing the applications of laser-plasma accelerators include the stability and reproducibility of the laser-plasma-accelerated electron beams, and realizing high repetition rates at and above kHz. These goals are linked by the fact that the major fluctuation drivers – ground motion and air motion – fall off at hundreds of Hz. Active laser feedback holds the potential to solve these issues, but is only possible at laser repetition rates at kHz, or above, where the pulse frequency significantly exceeds the fluctuation frequency. To allow this, laser systems which currently have low efficiencies (<1%) and low average powers/rates (~1Hz) at the Joule energies and 10's of fs pulse lengths required for LWFA must be improved. Small mJ class systems are already at kHz such that low energy positionable and endoscopic accelerators are realistic in the near term. For higher energy systems, important advances are being made, as documented by three recent workshops. [LFA-2013; kBELLA-2018; BLI-2018] A near term path to % level efficiency and kHz rates is moving from flashlamp to diode pumping. New gain materials offer higher efficiency and hence higher rates. New-found technologies in laser gain media such as optical fibers with various impurity doping and multiplexing which stacks multiple pulses in a high repetition rate, provides a path to 10's of% efficiency and 10's of kHz rates. The most robust short pulse laser today has a laser wavelength of around 800 nanometers (nm) using a sapphire crystalline structured laser medium. LWFA technology can also be used with other longer wavelength lasers as drivers. In addition to stability and repetition rate, control of the laser profile is a key area of advancement needed to enable high performance LWFA methods to be realized. Rough cost of a stepping stone kHz few Joule system is at the $40 million level. Such development would leverage activity by DOE Office of Science, High Energy Physics on ultrafast lasers as well as synergistic work on longer pulse systems by the NNSA and DOD. Once such lasers and the associated LWFA techniques are developed in a laboratory setting, further integration will be needed to enable robust unattended field operations, following which commercialization can be considered.

DLAs have the potential to create ultra-compact accelerators using structures that are constructed using the same nanofabrication methods used in the integrated circuit industry to make the microchips in our cell phones and laptop computers. The dielectric and semiconductor materials required have damage limits corresponding to acceleration fields' orders of magnitude larger than conventional radiofrequency accelerators, allowing for a factor of 100 or more reduction in size. Such materials are also amenable to rapid and inexpensive CMOS and MEMS fabrication methods, allowing them to be mass produced at low cost. These technological developments, combined with new concepts for efficient field confinement using optical waveguides and photonic crystals, and the first demonstration experiments of near-field structure-based laser acceleration conducted within the last few years have set the stage for making integrated laser-driven micro-accelerators or DLAs for a variety of real-world applications. Current research efforts in the US and Europe aim to produce a first working prototype with MeV class electrons in a "shoebox" size device by 2020. Higher energies could follow.

THz-driven accelerating structures enable high-gradient electron/proton accelerators with simple accelerating structures, high repetition rates and significant charge per bunch. These ultra-compact THz accelerators with extremely short electron bunches hold great potential to have a transformative impact for free electron lasers, linear colliders, ultrafast electron diffraction, x-ray science and medical therapy with x-rays and electron beams. THz structures have now demonstrated GV/m fields, electron beam acceleration and importantly emittance preservation of high charge bunches (>pC). Investigation into source-free brachytherapy with mm-scale MeV sources and laser-driven THz pulses is underway. Progress is being made in the three main R&D areas: (1) high power THz sources, (2) the metallic or dielectric structure, and (3) synchronization of the electron source to the injector. R&D needed to deliver TRL 4 includes: development of injectors, 10 cm scale structures; using recent demonstration of MW-class switches for power distribution and RF compression to maximize electron-beam source (50% efficient) topologies; laser-driven source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ).

There are recent advances in laser materials that may provide more efficient and compact alternatives to Ti-Sapphire. For example systems based on Ytterbium can be directly diode pump using high-energy, high-efficiency ~970nm diode and are capable of producing bandwidth-limited pulse of ~150fs at 1030nm, though <ps pulse are more typically what have been achieved. This technology has led to high-repetition rate, mode-locked fiber amplifiers that have produced >W of power with wall-plug efficiencies >10%. More recently advances in thin-disc laser technology has enabled kW-average power systems producing 1J, <ps pulses at 1kHz with wall plug efficiencies of >10%. The pulse length is a bit too long for most laser wakefield accelerator applications. Shortening the pulse length and maintaining the average power at the canonical 10kW would be very desirable. Another material that is showing promise is Thulium-based laser amplifiers. By taking advantage of a cross-relaxation process, highly doped thulium (Tm) crystals can be pumped by ~800nm diodes to produce 1900nm light at high efficiencies. The emission line is sufficiently broad that <100fs pulses can be produced. The combination of longer wavelength and pulse duration are immediately advantageous for both LWFA and DLA. For LWFAs, the increased wavelength increases the pondermotive force, reduces the required densities of the plasma, and can lead to higher total accelerated charge. For DLA, the shift to longer wavelength moves the pulse into the transparency region of silicon, an ideal material for producing the dielectric accelerating structures. Currently, commercial high-repetition rate, mode-locked Tm: fiber amplifier exist with efficiencies comparable to Ytterbium systems. These lasers are already incorporated into planned DLA experiments. This technology can also be adapted to thin-disc architectures with various groups planning experiments demonstrating this technology. Development towards high efficiency and high average power is again the desirable research direction to take for this laser technology. In conclusion, advances in ultrashort pulse amplifier materials are enabling high-efficiency, high-average power, compact sources. Further investment, particularly Tm-based systems, is necessary to ensure compact, efficiency lasers to drive next generation accelerators. These advances in laser driver technology are necessary for enabling the development of both compact laser-plasma and laser-dielectric accelerators for medical and security applications.

5.3.8.4 Scientific Impact of R&D

- Laser- and THz-based accelerators inherently produce shorter, smaller particle bunches that may provide unique probes for microscopy of ultrafast processes
- Advanced acceleration techniques could lead to very compact sources of particles and radiation that are suitable for widespread use in university and industrial R&D labs

Small low-cost MPS devices allow small research labs, university groups, to carry out cutting-edge physical research while enabling new applications with state-of-the-art technology. Laser accelerators are themselves grand challenges in precision resonant phase space shaped particle beam generation, precision plasma physics and control of the particle-wave interactions. This includes injection of brighter (6D phase space), shaped bunches to efficiently load the structure; efficient acceleration including preservation of emittance and combination of stages of laser guiding to reach the laser depletion limit including tailoring of the waveguide and laser; and various regimes in scaling with laser wavelength, intensity and other parameters that would enable unique physics, bright injectors, and applications. They additionally provide pathways to advancing fields outside this report. In particular, the control of electron beam focusing for scattering and of deceleration required for such sources has strong parallels with and uses scaled versions of components relevant to future particle colliders to extend the energy reach of future high energy physics. They can provide unique, brilliant probes to enable more precise high energy density science (HEDS). The technologies are also relevant to enabling compact Free Electron Lasers, photon and neutron sources, and accelerators relevant to many agencies. Present XFEL facilities are highly oversubscribed but infrastructure costs prohibit the extensive expansion of such systems. Lastly, the required laser science to enable such accelerators is cutting edge optical science with broad applications. It is pushing the state of the art of ultrafast high energy systems with applications in industry and science.

5.3.8.5 Potential Impact on the Application

- Endoscopic accelerators for medicine and extremely compact radiation sources for (e.g.) nondestructive testing may be enabled by advanced accelerator techniques

LWFAs have potential to create: extremely compact mm-scale endoscopic accelerators at few MeV, high brightness MeV mono-energetic photon beams from 0.5 GeV-class electrons at room to truck or smaller scales, future compact XFELs, and new sources for VHEE and FLASH therapy. These applications would have high impact as detailed in the respective sections. Miniature accelerators capable of delivering on-demand, tailorable MeV radiation sources have the potential to revolutionize medical brachytherapy and to enable unique security NDC applications where either operation in constrained space (e.g., machinery or pipes) or high mobility and flexible positioning (e.g., Emergency Response) are important.

Industrial accelerators also have many other applications in the private and medical sectors, including material processing and non-destructive testing, food decontamination, cancer therapy, VUV photo-electron spectroscopy, and ultrafast electron microscopy. Compact accelerators that enable brachytherapy could also have important impact in these fields.

5.3.9 Research Theme LT9: Advanced Beam Driven Accelerators

5.3.9.1 Background

The size of accelerators and x-ray sources is a key limit to security and medical applications. Linear accelerators have wide applications in medicine, security, and industrial applications, growing as a spinoff technology from High Energy and Nuclear Physics research. The medical community worldwide has broadly adopted radiotherapy and the production of therapeutic isotopes. Scanning and imaging using x-rays is a standard medical and security practice in the US and elsewhere, and important in industry and nuclear nonproliferation. Despite its broad use, the current technology has limitations. The systems are bulky and require significant heavy shielding. Moreover, advanced methods in use at scientific facilities cannot be used for security and medical applications because the required accelerator systems are large and costly. As one example, current imaging technology uses bremsstrahlung x-ray photons because this requires the lowest electron energy, but this also limits available performance. It is known that advanced mono-energetic gamma photon sources such as Thomson scattering offer dramatically better imaging but these require much higher electron energies than are currently available. Similar potential and similar limits exist for various other medical and security applications including VHEE therapy or FLASH-RT. The potential also exists to greatly reduce the infrastructure required for XFELs. Advanced beam driven accelerators offer gradients tens to thousands of times higher and hence could provide smaller systems that are more efficient. This could make advanced capabilities now accessible only in large scientific facilities available to applications. Such accelerators and systems are early TRL at present. Can such systems be made compact at the room or vehicle size in the midterm, or made even smaller in the long term? Can robust high repetition rate drivers be developed to enable these sources? Can such a system be made in a way that its operation is robust, reliable, and affordable?

5.3.9.2 Scientific challenge to be addressed

Security and medical applications place a broad range of demands on the accelerator technology ranging from high-flux sources at 1-10 MeV energy for FLASH-RT sources to meter-scale devices at 500 MeV for VHEE and MPS. Beam driven accelerators can be developed to address each of these applications. Beam driven PWFA can sustain ultrahigh gradients to bring the beam to high energies in centimeters or less in a single or a small number of stages. PWFA has demonstrated acceleration of electrons in fields thousands of times greater than those in conventional LINACs, generating energetic electron beams from a few MeV to multi-hundreds of MeV in distances of millimeters in the plasma. Beam driven SWFA have potential for 10-100 times reduction in size compared to conventional LINACs. New concepts for high-gradient and high-efficiency structures and demonstration experiments will enable progress. What can be done to get these technologies out of the laboratory and make them easy to use, rugged, and practical at the high repetition rates demanded by many applications?

SWFA offer a strong path to compact, high-repetition rate and highly efficient sources, using high gradient structures driven by high current, shaped electron drivers. Metallic or dielectric structures utilizing different materials, geometries, and higher frequencies can provide high efficiency and high gradient operation while allowing for control of the beam breakup instability. Average acceleration of 150 MV/m in GHz structures and 300 MV/m in the THz have already been demonstrated, with concepts to approach GV/m scale underway. Over the past 10 years, there has been tremendous progress in structures driven by shaped electron drivers. Transformer ratio is the key to generating highly efficient, compact acceleration schemes. The first experimental demonstration of transformer ratio >2 happened ~10 years ago but demonstrations in the last 2 years have achieved transformer ratio >5 in both structures and plasmas and experimental plans to break the double digit threshold are ongoing. While many important ‘firsts’ have been demonstrated, including high-energy beams with low energy spread and high transverse quality, performance is still far from that theoretically achievable. There is a roadmap [AARDR-2016] that guides community efforts [AAC-2018] towards performances to enable photon source applications of interest to security and medicine in the nearer term, and the challenging requirements of future colliders. The main issues for advanced beam-driven accelerators to reach TRL-4 level and to be ready for transition to applications are centered on high-gradient, high-repetition rate capable metallic or dielectric structures, on developing shaped electron beam source driver technology, and control of beam instabilities. Robust regimes of operation need to be developed. Structures require heat management systems, high gradient capabilities, methods of damping beam-breakup modes and high shunt impedance for compact acceleration. Electron source development requires high-repetition rate, high current drivers coupled with compact shapers.

5.3.9.3 Summary of required R&D

The key R&D challenges for realizing the applications of beam-driven SWFA can be divided between the structure and the electron beam driver. Both metallic and dielectric structures require high-gradient operation, high-order mode suppression, high efficiency, transverse wakefield damping, RF breakdown mitigation, and broadband impedance matching. The technical challenges for the dielectric lined waveguides are induced metallization of the dielectrics at high electric field (>GV/m) and multipactor at long RF pulses. Metallization can be ameliorated with the choice of material and multipactor has been suppressed with a solenoid and TiN coatings but effort is needed to investigate other and better suppression techniques. We foresee that the future R&D will focus on developing full-featured, dielectric and metallic structures that integrate all of these technologies, in order to reach higher gradients. Drive beam R&D needs to focus on longitudinal beam shaping, general beam dynamics to control the beam breakup instability and the requirement of a low-emittance high-charge injector to produce the required beam. Recent investigations into improved shapes considering the multiple modes that can be excited by the drive beam in a structure should be refined via numerical simulations. In the near term, the compromise between optimal and practically achievable shapes should be understood via simulations for given structure designs. In the short-to-medium term, beamlines capable of forming the most promising shapes should be devised and experimentally demonstrated. In the medium term, it is expected that an experiment to demonstrate a significant transformer ratio with a temporally shaped bunch should be performed. The potential for ultrahigh-gradient in the SWFA THz regime requires the development of adequate electron sources capable of providing the required low emittance. The scheme enjoys active on-going development of wakefield structures and will leverage R&D on electron-beam shaping and high-brightness electron sources being actively explored for other applications of electron accelerators (e.g., free electron lasers). The investigation of BBU (Beam Break Up) instability via numerical simulation needs to be continued and supplemented by experiments for the cases of cylindrical dielectric lined waveguides (short term), planar dielectric and novel structures (midterm). For the latter case the use of longitudinally shaped flat beam should be explored.

The key R&D challenges for realizing the applications of beam-driven plasma wakefield accelerators (PWFA) can be divided between the plasma cell and the electron beam driver. The later shares many similarities with SWFA as outlined above and will not be repeated here. The main issues for advanced plasma accelerators to reach TRL-4 level and to be ready for transition to applications are centered on improved control of the plasma structure and injection to create high quality stable beams. Robust regimes of operation need to be developed. Drive beam focusing, gas target systems and heat management systems must be miniaturized into an encapsulated device, first at cm and then at mm scale. PWFAs are now operating at a fraction of the charge and efficiency that is possible, are not stable at a facility level, and have produced energy spreads below 10% only for brief periods of operation. Across all of areas, research is therefore needed to advance the science of beam control, stability and quality. Simulations are now working routinely in coordination with experiments to design concepts and interpret results, giving confidence in the physics basis for further progress.

Beam driven THz accelerating structures enable high-gradient accelerators with simple accelerating structures, high repetition rates and significant charge per bunch. These ultra-compact THz accelerators with extremely short electron bunches hold great potential to have a transformative impact for free electron lasers, linear colliders, ultrafast electron diffraction, x-ray science and medical therapy with x-rays and electron beams. THz structures have now demonstrated GV/m fields, electron beam acceleration and importantly emittance preservation of high charge bunches (>pC). Progress is being made in the three main R&D areas: (1) high power THz sources, (2) the metallic or dielectric structure and (3) synchronization of the electron source to injector. R&D needed to deliver TRL 4 includes: development of electron injectors, 10 cm scale structures; using recent demonstration of MW-class switches for power distribution and RF compression to maximize electron-beam source (50% efficient) topologies; laser-driven source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ).

5.3.9.4 Scientific Impact of R&D

Small low-cost MPS, VHEE therapy or FLASH-RT sources allow small research labs, university groups, to carry out cutting-edge physical research while enabling new applications with state-of-the-art technology. Beam driven accelerators are themselves grand challenges in precision resonant phase space shaped particle beam generation, precision plasma and structure physics and control of the particle-wave interactions. Successful development of an engineering designed SWFA-based accelerator would impact future directions in linear colliders, free electron lasers, ultrafast electron diffraction, and many other accelerator based fields. The research on drive beam shaping for enhanced transformer ratio is synergistic with the PWFA concept. It is worth pointing out that the development of advanced structures share many similarities with R&D related to DLA scheme and would therefore impact it as well.

5.3.9.5 Potential Impact on the Application

SWFAs and PWFAs have potential to create compact accelerators at a few MeV, high brightness MeV mono-energetic photon beams from 0.5 GeV-class electrons at room to truck scales, future compact XFELs, and new sources for VHEE and ultrahigh repetition rate accelerators for FLASH therapy. These applications would have high impact as detailed in the respective sections. Compact accelerators capable of delivering on-demand, tunable MeV photon sources have the potential to revolutionize medical and security applications where either operation in constrained space (e.g., machinery or pipes) or high mobility are important.

Industrial accelerators also have many other applications in the private and medical sectors, including material processing and non-destructive testing, food decontamination, cancer therapy, VUV photo-electron spectroscopy, and ultrafast electron microscopy.

5.3.10 Research Theme LT10: Mono-Energetic Photon Source

5.3.10.1 Background

Advanced imaging and characterization capabilities for both security and medicine enabled by mono-energetic photon sources have been demonstrated on large fixed facility mono-energetic high energy x-ray sources driven by conventional accelerators, but such sources are too large for clinical or field applications. Current portable photon sources, largely based on broadband bremsstrahlung photons, have important limitations: the systems are bulky, require significant heavy shielding, are limited by the allowable dose to targets and/or surroundings, and emit broad energy spread and angular spread. This results in limitations to penetration and signal specificity, where in many cases current accelerator systems cannot be used to generate a sufficiently specific signature. Imaging and NDC applications require varying photon energies from tens of keV to 10 MeV, but share the need for higher resolution, lower dose and improved material discrimination. [Geddes-2017; Martz-2016] MPSs have the potential to improve sensitivity at greatly reduced dose in existing applications and enable new capabilities in other applications, particularly where passive signatures do not penetrate or are insufficiently accurate. A schematic of a compact MPS is shown in Figure 5.4. MPS advantages include the ability to select energy, energy spread, flux, and pulse structures to deliver only the photons needed for the application, while suppressing extraneous dose and background. Accessing these benefits requires development of MPS with narrow divergence and small emission spot size which is a good fit to high gradient advanced accelerator concepts such as LWFA, SWFA, PWFA, and THz accelerators. New micro accelerators, for example based on laser plasma wakefield devices and other technologies are coming forward presently and may offer the ability to create mono-energetic sources in useful, compact packages. Such accelerators and systems are at low TRL at present. Can such systems be made that are compact at the room or vehicle size in the mid-term, or made even smaller in the long term? Can robust high repetition rate drivers be developed to enable these sources? Can such a system be made in a way that its operation is robust, reliable, and affordable? Note that development of such sources based on RF accelerator technology is covered in Section 5.2.6 of this report.

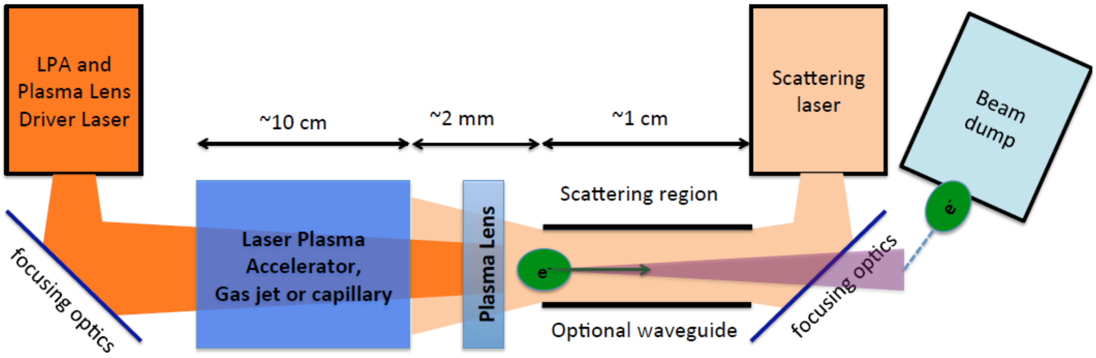


Figure 5.4. *Conceptual illustration of a mono-energetic photon source incorporating a compact laser driven accelerator, control of electron beam focusing, a scattering region where a second laser pulse generates photons with guiding to increase flux, and a deceleration section to mitigate shielding needs. (Image credit: S.G. Rykovanov, arXiv:1406.1832, (2018))*

5.3.10.2 Scientific challenge to be addressed

Imaging and NDC applications require varying energies from tens of keV to 10 MeV which in turn requires compact high gradient electron accelerators at energies from ~20-500 MeV energies. Precision shaping and control of the power source (laser or beam) and accelerator is needed to control photon beam energy spread, tuning and stability. Controlled Thomson/Compton scattering must be developed to generate mono-energetic photon beams of controllable energy and direction and with high flux. For radiography, CT, two-energy material discrimination and photofission signatures, modest energy spreads of 10-30% are needed. To access sensitive Nuclear Resonance Fluorescence signatures which can enable isotopic discrimination, analysis of elemental composition and inference of chemical composition, development of narrower energy spreads are needed at or below the 1% level. This requires precision electron beam control and scattering methods are required to access photon energy spreads at or below 1%. Variable energy over a factor of approximately 3-5-fold (e.g., from 3-9 MeV or from 1.5-7 MeV) is needed on a pulse-by-pulse to exploit some signatures. Deceleration of electrons after photon production to mitigate undesired bremsstrahlung and hence to reduce the size of the shielding is required. Size scale requirements vary from truck-sized for cargo scanning and some nonproliferation applications down to typically person-portable for emergency response.

MPSs open new signatures and methods due both to their narrow energy spread and other properties such as small emission spot, narrow-angle emission and very short pulse bursts of photons (down to femtoseconds). Detection and signature development is needed to exploit these capabilities. Sub-micron resolution will enable the gaining of more detailed information. Research is needed in detection methods to exploit high resolution and material contrast. Backscatter ToF imaging is an emerging possibility due to the femtosecond pulsed beams of the MPS, and could enable single-view 3D information without CT and with a reduced dose. Others include use of polarization and isomer signatures uniquely accessible using such sources. Development of compact sources benefits both security and medical imaging applications because the same advantages of dose and contrast apply to both. For some applications beam steering may be needed.

Developments in this area will aim to produce complete particle accelerator systems that are miniaturized to the truck or smaller scale with mm-cm scale effective source sizes. Truck scale accelerator systems based on SFWA/PWFA are under development. These systems can be powered by ~20 MeV SRF injectors that operate at MHz repetition rates with shaped beams to achieve ultrahigh fluxes of mono-energetic gamma rays. Even smaller scale accelerator systems can be reached using semiconductor chips, plasma media or THz structures. Such systems could be powered by modern solid state lasers which is particularly attractive, due to the intense electric fields they can generate combined with the fact that the solid state laser market has been driven by extensive industrial and university demand toward lower cost and higher efficiency over the last 20 years. Overall, there are several promising technical paths to realistic compact MPS in the future accelerator concepts: laser plasma wakefield accelerators, dielectric ‘accelerators on a chip’, structure wakefield accelerators, and plasma wakefied accelerators driven by shaped beams and THz structures.

5.3.10.3 Summary of required R&D

Accessing these benefits requires development of mono-energetic sources with narrow divergence and small emission spot size, which is a good fit to high gradient advanced accelerator concepts and in particular laser-plasma and laser-structure based accelerators. Such accelerators and systems are low TRL at present. Development is needed for high gradient accelerators at the GeV/cm scale to enable 10’s of cm scale clinical devices. Accompanying development is needed for controlled Thomson/Compton scattering to generate mono-energetic photon beams of controllable energy and direction, and ability to raster beam. Development of electron beam deceleration for disposal with low radiation production (hence mitigating shielding requirements) is important.

LWFAs offer a path to ultra-compact devices, using the very high fields that can be sustained by plasma waves. [Geddes-2015] Acceleration to > 500 MeV energies over cm length scale has been demonstrated, which is more than a thousand times smaller than conventional accelerators. Research must now address scaling of these results to the kHz rates required by applications. This requires development of kHz laser drivers at Joule class energies and 30 fs durations to enable average flux. Experiments have also demonstrated initial Thomson scattering photon production at energies ranging from keV to multi-MeV and at energy spreads in the tens of percent. Development is needed for reaching the laser energy required, and to develop the required scattering methods for higher flux and reduced energy spread. Electron deceleration has recently been demonstrated at low efficiency and needs to be developed to extract almost all of the beam energy to mitigate shielding requirements and improve the overall efficiency. Robust regimes of operation need to be developed. Laser focusing, gas target systems and heat management systems must be developed.

DLA have the potential to create ultra-compact accelerators using structures that are constructed using the same nanofabrication methods used in the integrated circuit industry to make the microchips in our cell phones and laptop computers. The dielectric and semiconductor materials required have damage limits corresponding to acceleration fields that are orders of magnitude larger than conventional radiofrequency accelerators, allowing for a factor of 100 or more reduction in size. Such materials are also amenable to rapid and inexpensive CMOS and MEMS fabrication methods, allowing them to be mass produced at low cost. These technological developments, combined with new concepts for efficient field confinement using optical waveguides and photonic crystals and the recent first demonstration experiments of near-field structure-based laser acceleration, set the stage for making integrated laser-driven micro-accelerators or “dielectric laser accelerators” possible. Current research efforts in the US and Europe aim to produce a first working prototype with MeV class electrons in a “shoebox” size device by 2020. Higher energies could follow to address photon sources.

THz accelerators using flexible power conduits offer a third technology option. THz structures have now demonstrated GV/m fields, electron beam acceleration and importantly emittance preservation of high charge bunches (>pC). Investigation into source-free brachytherapy with mm-scale MeV sources and laser-driven THz pulses is underway. Progress is being made in the three main R&D areas: (1) high power THz sources, (2) the metallic or dielectric structure, and (3) synchronization of the electron source to the injector. The main approach under development are THz devices that can be powered with a laser-driven THz source for easy synchronization to a photocathode laser for the injector to produce high brightness beams. R&D needed to deliver TRL 4 include: development of injectors, 10 cm scale structures; using recent demonstration of MW-class switches for power distribution and RF compression to maximize electron-beam source (50% efficient) topologies; laser-driven source development for higher efficiency (few % at mJ levels) and higher pulse energy (few mJ).

SWFA and PWFA accelerators can be used for very high repetition rate examination of objects. Recent work on a compact collinear wakefield accelerator module has shown the promise to operate at near 1 MHz repetition rates. This requires a drive bunch source capable of delivering specifically shaped bunches to generate ~250 MeV electron beam from SWFA and PWFA media. For high energy and high repletion rates, this requires the development of SRF based shaped beam drivers to power the SWFA structures or PWFA medium. Further, this requires development of structures and plasmas capable of handling the heat load. These accelerators would be most suitable for medium future (10 years) development in this application.

Research is needed in detection methods to exploit high resolution and material contrast. Backscatter time-of-flight imaging is an emerging possibility due to the femtosecond pulsed beams of the MPS, and could enable single-view 3D information without CT and with reduced dose. Development of compact sources benefits both security and medical imaging applications since the same advantages of dose and contrast apply to both. [Lewis-1997]

Given the rapid progress in this area from first proof-of-concept to working benchtop devices over the last few years, with adequate funding and effort, laboratory demonstration of prototypes based on either technology for medical applications is achievable, with development and exploration of commercialization options on a 10-15 year scale. There has already been some preliminary commercial interest. Developments should target the desired parameter ranges in Table 5.5, as well as operability in a clinical setting by users who are not accelerator experts.

Table 5.5. *Performance criteria for mono-energetic x-ray sources*

Application	**Energy (MeV)**	**Energy Spread**	**Photons/second**	**Rep. Rate**	**Rastering**
Medical CT and phase contrast	0.02-0.2	10-20%	10^{10}-10^{12}	1-50 kHz	Rapid, up to > 80 Hz
Screening – Radiography	3-9	10-20%	10^{10}-10^{12}	1-50 kHz	Rapid, up to 80 Hz
Screening - Photofission	6-9	10-30%	10^{11}-10^{12}	>1 kHz	Slow
Screening - NRF	1-7	<2%	10^{10}	>1 kHz	Slow
Secondary Screening - Photofission	6.5-14	20-40%	$>10^{11}$	>1 kHz	Slow
Treaty Verif. - NRF	1-7	<2%	10^{10}	>1 kHz	Slow
Safeguards - Transmission	6-8	20-30%	10^{10}	N/A	Slow
Emergency Response	1-3	20-30%	10^{10}	10-100 Hz	Slow
Stockpile	1-9	20-30%	$>10^{11}$	>1 kHz	Medium
HED/Dynamic	0.1-1	20-30%	$>10^{11}$	Burst	N/A

5.3.10.4 Scientific Impact of R&D

Compact, low-cost, MPS devices allow small research labs, university groups, and in challenging medical and security environments to carry out cutting-edge physical research while enabling new applications with state-of-the-art technology. These include precision nuclear physics, controlled radiation biology, using tunable photon energies. The accelerator technologies developed for MPS applications require very high accelerating gradients to enable compact devices. This development has strong synergy with other high gradient accelerator applications. The parameters needed are close to those needed for VHEE therapy, and techniques have substantial overlap with those for endoscopic accelerators or FLASH therapy. The development of LWFA, DLA, SWFA, PWFA and THz technologies for these applications are detailed in the respective sections. They additionally provide pathways to advancing fields outside this report. In particular, the control of electron beam focusing for scattering and of deceleration required for such sources has strong parallels with and uses scaled versions of components relevant to future particle colliders to extend the energy reach of future High Energy Physics. The technologies are also relevant to enabling compact Free Electron Lasers, photon and neutron sources, and accelerators relevant to many agencies.

5.3.10.5 Potential Impact on the Application

Medical imaging could benefit strongly from reduced dose (potentially 10-100 times lower), which would allow x-ray and CT imaging to be conducted more routinely. Higher contrast and the ability to do material discrimination using multiple energies could make possible fine distinction of different tissues (e.g., allowing earlier cancer detection), or improved imaging of soft tissue in the presence of bone (which is currently challenging). [Caroll-2003] At the same time, improved spatial resolution down to micron scale can also enable sensitive imaging including phase contrast [Schleede-2012] to detect abnormality earlier and hence improve treatment. Other medical applications include unique therapies such as gold nanoparticle therapy enabled by control of photon energy, and very tightly controlled microbeams for 'x-ray biopsy' (relevant to NIH and NCI, and the medical industry).

An extensive survey of nonproliferation and security applications [Geddes-2017], along with studies from different groups [Martz-2017b; Ledoux-2018; Milton-2015], indicate strong benefit to a broad range of applications including material screening at nuclear facilities, in luggage/cargo, and for emergency response as well as new capabilities in treaty/dismantlement verification, nuclear safeguards, stockpile and industrial NDC, dynamic and hydrodynamic and HEDS experiments. Controlling source energy and energy spread at the 20% level reduces radiography dose by a factor of 3-4, while additionally controlling angular spread removes scattering degradation and allows adaptation of dose resulting in higher contrast and overall dose reductions of 1-2 orders of magnitude. Secondary inspection using photofission is realistic in seconds through tens of cm of shielding, at doses 50 times lower than bremsstrahlung. New capabilities include nuclear safeguards where a narrow angle pulsed MPS could allow verification of the content of spent fuel containers, as well as NDA of nuclear fuel and other materials. Spatial resolution potentially can be enhanced to the micron scale, offering a path to a weapon fingerprint for treaty verification and detailed condition assessment for stockpile applications. Isotopic identification for cargo, treaty, and safeguards cases is realistic in minutes using NRF if source energy spread is at or below the percent level. Temporal resolution can also be improved, down to the femtosecond level. This enables high resolution backscatter time-of-flight imaging for single sided imaging and for 3D information without tomography, as well as new capabilities for time resolved science based NA-10 dynamic experiments, stockpile stewardship, and HEDS. New signatures such as polarized photofission or selective isomer activation offer 3D and isotopic information that would have impact across all these areas. For some applications, broad angle emission may be desirable and in these cases nuclear reaction based sources can address needs. [Geddes-2017] In other cases, neutrons offer complementary signatures to photons, and it has been indicated that the two signatures can offer improved performance when used together. [Rose-2016] These studies indicate that MPSs can address presently unsolved problems in nonproliferation, stockpile, security and related areas via conventional signatures and development of new signatures.

Industrial accelerators also have many other applications in the private and medical sectors, including material processing and non-destructive testing, food decontamination, cancer therapy, VUV photo-electron spectroscopy, and ultrafast electron microscopy. [Hamm-2013] Compact accelerators that enable MPSs could also have important impact in these field.

5.4 Detector Technology Themes

5.4.1 Research Theme 1: Robust Multi-Particle and/or High-Rate Detectors and Systems

5.4.1.1 Background

Detector technologies with application to compact accelerators in security can be classified as “imaging” or “characterization”. For example, applications such as cargo imaging require arrays of detectors working as a system in providing the spatial/density distribution of an object. On the other hand, detectors aimed at extracting maximum information about the object composition can perform energy spectroscopy or dual-particle analysis using both neutrons and photons. In some instances, both capabilities can be required, further complicating system design. A relatively unique aspect of these detection systems is the ability to work in the harsh environment associated with accelerators and the environmental challenges present in the locations they are used.

Imaging: The challenge associated with imaging applications is use of multichannel systems. Depending on size of the imaged object, the number of detector pixels can be large, on the order of hundreds to thousands affecting the cost and signal processing of the imaging system. Areas of food processing and sterilization typically employ x-ray sensitive imaging plates. However, nondestructive characterization may involve rather large objects requiring arrays of detectors.

Characterization: The primary challenge of characterization is extraction of energy information from the source or object. In this case, the detectors should have large density (for photon conversion), low deadtime and good light generation/collection. In some applications, neutron detection may be desirable. Detection of fast neutron generally relies on pulse shape discrimination (PSD) to separate neutrons from photons. The PSD technique uses the difference in pulse structure produced by electrons (resulting from gamma-ray interaction) and protons (resulting from elastic neutron recoil).

Neutron detectors: Plastics are commonly used due to their high content of hydrocarbons. The difference in the tail of the pulses is generally quantified using charge integration and is commonly performed with digital data acquisition systems. Three types of fast neutron detectors operating based on PSD are commonly utilized in neutron imaging arrays: liquid scintillators, plastic scintillators and crystal scintillators. Most of them are excluded from the discussion here due to their temperature sensitivity. It should be noted here that practical, robust and compact cooling systems for detectors could represent a separate R&D area. Other fast neutron detectors based on crystal instead of plastic have recently been shown to be promising, in particular, CLYC (Cs_2LiYCl_6: Ce) and CLLBC ($Cs_2LiLa(Br,Cl)6$: Ce) detectors. Both show superior light output as compared to organic scintillators and are commercially available, but remain rather expensive. Some detectors, specifically composites listed in Table 5.6, combine good energy resolution with an ability to detect fast and thermal neutrons. Recent developments in fast neutron-sensitive ^{4}He detectors could provide another avenue for gas detectors useful for application with accelerator sources. These detectors utilize a neutron recoil reaction to ionize the ^{4}He gas and create scintillation light. The light is collected and can be read out with a PMT or a SiPM. The main drawback of these detectors is relatively low efficiency and the need for pressurized gas. Another promising neutron detector is SiC (silicon carbide). Its possible applications include operation in harsh mixed neutron-gamma fields, where detection of fast neutrons may be prioritized.

5.4.1.2 Scientific challenge to be addressed

- Improve energy (<2% for scintillators at 662 keV) and spatial (<5 mm for large multipixel arrays) resolution of the detectors while maintaining low cost of the material

- Create new materials, that are cheaper (goal $10/cc), faster, more scalable and higher light-output than current scintillators

A number of new materials have entered the market in the recent years. These materials tend to be tailored to a specific application, addressing the main challenges of optimization between density, light output, scintillation light decay time and volume. New materials also include demands for low afterglow and an ability to create composites, for example metal-loaded plastics and organic-inorganic composites. Table 5.6 outlines a few select materials which could be used in both security and medical applications of accelerators.

Table 5.6. *New spectroscopic materials that are commercially available but remain very expensive.*

Material	Z_{eff}	Density (g/cc)	Light Yield (ph/MeV)	Energy resolution FWHM (keV @662keV)	Decay Times (ns)	Neutron Detection
$CeBr_3$	47	5.1	60,000	3-4	20	No
SrI_2: Eu	50	4.6	80,000	3	>1000	No
Tl_2LaCl_5: Ce	70	5.3	76,000	4	36	Yes
CLYC	45	3.3	19,000	4	1, 50, 5500	Yes
CLLBC	47	4.2	45,000	3	115, 500, 1500	Yes

Note that their spectroscopic abilities pushing energy resolution closer to the goal. All materials listed have large Zeff improving intrinsic efficiency of the detectors. Some of the new materials exhibit long decay times.

5.4.1.3 Summary of required R&D

- Material discovery for accelerated detector development to address harsh environmental conditions and need for fast timing and spectroscopy
- Alternative detector materials, including wide band-gap semiconductor technology
- Scalability of detectors, including arrays (>1000 pixels) and large area (>6 in. in diameter) for both neutron and photon detection
- Electronics for signal readout and data processing to extract spectroscopic/shape information from each pixel in the detector array (>1000 units) using electronic readout with low cost per channel (< $50-$100/channel)

Detector performance in accelerator environments requires excellent ability to perform dead-time reduction and pileup rejection. The intensity of the radiation flux can have a detrimental effect on detector performance, often causing high dead-time and signal pileup leading to loss of information, and issues with processing the pulses in the electronics in a timely manner. Reduction of these effects can be done with selection of appropriate detector materials as well as design of data processing electronics, indicating the priority in R&D to address this challenge. Decay times of nanoseconds are essential, especially for imaging applications. Operation in harsh environments, such as well logging, also requires the detectors to withstand elevated temperatures (up to 200^{o}C) as well as vibrational conditions. Currently, neutron-sensitive detectors are based on ^{3}He gas proportional tubes. Addition of fast neutron detection as well as the capability of gamma sensing would require advanced detectors, possibly scintillators or wide gap semiconductors. Furthermore, imaging in well logging applications would further drive the material requirements including capabilities of digital readout.

Efficiency of the detectors is an important part of R&D, especially as geometric factors of detector pixels decrease in large arrays. For most detectors, the efficiency is defined in various terms, typically starting with a conversion of a neutron/photon into a charged particle (conversion efficiency) and then collecting the information carriers generated by the charged particle. For scintillating detectors in particular, the collection of the information carriers – photons – is affected by self-absorption in the material and compatibility with the photon-sensitive device (PMT or SiPM). Hence, research of high-density scintillators with low self-absorption and high light output are critical in application to compact accelerators.

5.4.1.4 Scientific Impact of R&D

- High efficiency, high resolution detectors would allow for more compact systems for both imaging and characterization leading to shorter scanning times
- More radiation-resilient detectors would allow for improved operational times and reduced costs

Detector advances have multi-disciplinary impacts. New multi-particle (neutron/gamma) and/or multi-modal detector materials would be useful in applications beyond compact accelerators, but also in passive measurements. Furthermore, this R&D will enable advanced detector arrays at lower cost.

5.4.1.5 Potential Impact on the Application

- Enable faster and more accurate imaging/scanning in nondestructive imaging, food processing and sterilization applications
- Enable higher fluxes without damage to the detectors or increasing deadtime/pileup

Generally, use of compact accelerators for imaging or characterization requires consideration between radiation doses, which can lead to detector damage, scanning time and the quality of information/image. Detectors capable of operating in harsh environments could significantly speed up the process without compromising the other factors.

5.4.2 Research Theme 2: Dosimetry for Emerging Accelerators

5.4.2.1 Background

The needs for detector technologies for compact accelerators are acute in the area of preclinical radiation biology research and translational studies. In this field of research cells, small animals, and also large animals are irradiated and evaluated for the dosimetric effects. Once preclinical studies are reproduced and proven, the techniques are translated to humans for treatments of many types of disease. Shortcomings of radiation detection in this arena may prevent the successful translation of preclinical research to humans. Standardization of radiation detection is critical to the translation of preclinical radiation dosimetry research. With the advent of new compact accelerators, detector technologies must keep pace.

5.4.2.2 Scientific challenge to be addressed

As compact accelerator advances are implemented, the associated detector technologies must follow suit. Otherwise, lack of standardization will impede the scientific progress and accessible care for patients needing radiation therapy treatments.

Harmonization of preclinical radiation biology studies is a critical need for successful radiation therapy for cancer and other diseases. To “harmonize” this field, there are distinct scientific needs in the area of FLASH therapy detection, small-field dosimetry, and accurate absolute standards.

5.4.2.3 Summary of required R&D

There are several areas where additional scientific research would help achieve the goals of harmonization of radiobiology research. Some are in the physical detector characteristics and others are in the nature of the dosimeter, specifically the biological nature. Biological detectors are difficult to realize. There are lots of categories that are available for biological detection. Here we have narrowed down the research needs into the following areas for the harmonization of radiobiology dosimetry:

1. Instantaneous biochemical detection
2. Multiplatform preclinical experimental conditions
3. LET / RBE discrimination

5.4.2.4 Scientific Impact of R&D

With the successful development of detection technology for compact accelerators and preclinical radiation biology, the following items are resulting impacts:

- Biological *in-vivo* dosimeters
- Standards lab traceable dosimetry instrumentation and protocols
- Insight into transient biological response mechanisms

5.4.2.5 Potential Impact on the Application

The field of radiation therapy will be significantly advanced by better treatment outcomes and faster treatments. This will allow patients to be treated more economically and with more access to care. Achieving preclinical standardization and study consistency will ultimately lead to better treatment outcomes and more clinically transferable expertise. With successful detector technology advancements, dose rates can be a knob for radiation therapy treatments.

6. Panel Reports

6.1 Security Applications Panel

The radiological security applications panel's discussion of needs during the BRN workshop involved selected plenary talks as well as in-depth discussions during the break-out sessions. The plenary talks in this topic area focused on the needs for alternate sources and new sources for oil well logging, for food industry applications, national security needs in the realm of cargo and luggage screening, and for analyzing fissile materials. The central theme from these plenary talks was that there was an immediate needs for accelerator technologies to either replace radioactive sources and/or to develop new accelerator technologies for novel applications in well logging, food quality and safety, and security applications for ports of entry and for assaying fissile materials. The presentations were specifically focused on the workshop charges and set up the framework for the in-depth break out session discussions.

Given the need to accommodate the schedule of the different workshop attendees, there were two break-out sessions (1.5 hours) that focused on reviewing the specific Technology Perspectives Factual Document (TPFD) application areas and requirements, identifying whether any application areas were inadvertently missed and most importantly, delineating the specific accelerator requirements for each of the specific security application areas. Each of the breakout sessions had approximately 25-30 participants from the workshop attendees. The majority of time was spent identifying the specific needs for oil well logging, medical device sterilization, food industry applications, national security probing needs, and sterile insect technology. The workshop co-chair (Pillai) and the co-leads (Martz and Badruzzaman) were actively involved in leading and moderating the discussions.

These discussions yielded accelerator requirements for the different applications.

X-ray Requirements for Imaging of Electronics in Packaged Products

Requirement	**Integrated Circuit Ptychography**	**Circuit Board CT**	**Packaged Product CT**
Spot Diameter	0.5-4 µm	0.05-0.5 mm	0.1-0.5 mm
x-ray Energy	5-20 keV	50-200 keV	100-300 keV
x-ray Energy Spread	0.1%	10%	10%
x-ray Brightness	10^8-10^{12} ph/µm^2/s	10^{11} ph/mm^2/s	10^{11} ph/mm^2/s

Performance criteria for mono-energetic x-ray sources

Application	**Energy (MeV)**	**Energy Spread**	**Photons/s**	**Rep. Rate**	**Rastering**
Screening – Radiography	3-9	10-20%	10^{10}-10^{12}	1-50 kHz	Rapid, up to 80 Hz
Screening - Photofission	6-9	10-30%	10^{11}-10^{12}	>1 kHz	Slow
Screening - NRF	1-7	<1%, to 0.1%	10^{10}	>1 kHz	Slow
Secondary Screening - Photofission	6.5-14	20-40%	>10^{11}	>1 kHz	Slow
Treaty Verif. - NRF	1-7	<1%, to 0.1%	10^{10}	>1 kHz	Slow
Safeguards - Transmission	6-8	20-30%	10^{10}	n/a	Slow
Emergency Response	1-3	20-30%	10^{10}	10-100 Hz	Slow
Stockpile	1-9	20-30%	>10^{11}	>5 MHz	Medium
HED/Dynamic	0.1-1	20-30%	>10^{11}	Burst	n/a

Performance criteria for x-ray sources used for emergency response. Low-energy radiography is used for penetrating up to 4 cm of steel and high-energy radiography is used for thicker objects.

Requirement	**Low-Energy Radiography**	**High-Energy Radiography**
Spot Diameter	0.5-3.0 mm	~1 mm
Max. x-ray Energy	350-400 keV	1-4 MeV
x-ray Energy Spread	70% or less	70% or less
x-ray Output	70 mR/sec @ 30 cm	200 mR/sec @ 1 m
Weight	<12 kg w/battery	< 50 kg w/power supply
Power	10-15A @ 12-24V	10A @ 120V

Source requirements for high energy flash radiography

Source Property	**Now [*]**	**Threshold [*]**	**Objective [*]**
Particle	electron	Electron	x-ray
Effective Source Size	2 mm	1.5 mm	1 mm
Directionality	Forward peaked	Forward peaked	Forward peaked
Tunable energy range	18-20 MeV Bremsstrahlung	18-26 MeV Bremsstrahlung	3 MeV quasi-mono
Tuning speed	N/A	500 ns	200 ns
Energy spread	Bremsstrahlung	Bremsstrahlung	+/- 2 MeV
Pulse structure	4 pulses @ 2MHz (100 ns max pulse width; variable)	8 pulses at 5MHz (80 ns max pulse width; variable)	N pulses @ 10MHz (50 ns pulse max; variable intensity - pulse width or photon numbers)
Intensity or Flux	500 R	500 R	50 R
Stability/Jitter Requirements	+/-2 ns	+/- 0.5 ns	+/- 0.1 ns
Automation Needed	None	Mix Human/Machine	Auto-tune
Size	100 m LINAC	100 m	20 m
Weight	640 tons	100 tons	50 tons
Power	3.5 MW	3 MW	100 kW
Portability	No requirement	No requirement	No requirement
Acceleration/Shock	No requirement	No requirement	No requirement
Op. Temp range	15 to 25 C	15 to 25 C	15 to 25 C

[1] - Neutrons produced via the ^{7}Li(p,n)^{7}Be interaction within the device, with subsequent neutron spectral shaping via moderation and filtering.

[2] - for example, the maximum allowable time to change between beam energies

[3] - CW, pulse train bursts, single pulses, interleaved energies, etc.

[4] - None (experts must operate), Some (technicians can operate), Extensive (minimal training needed)

[*] - "Now" - values available from current commercial products

[*] - "Threshold" - minimum increase in performance that would **meaningfully impact** the application

[*] - "Objective" - desired increase in performance needed to provide a **transformative improvement** in the application

Acceleration requirements for the medical device industry. The primary application is the sterilization of medical devices and pharmaceuticals for assuring a specific Sterility Assurance Level

Source Property	**Current Technology**	**Objective (2-5 years)**
Particle[1]	Ebeam/gamma/[x-ray]	Ebeam and/or x-ray
Effective Source Size	2 cm	> 2 cm

Directionality	Unidirectional for ebeam	Unidirectional;
Tunable energy range	Tunable energy limited	Fully tunable between 1 MeV -10 MeV
Tuning speed[2]	Instantaneous (µsec)	instantaneous (µsec)
Energy spread	3% spread	R&D to determine energy spread effects on DUR and biological response
Pulse structure[3]	CW/pulsed/	Pulse structure should be designed to deliver uniform dose on a moving product and biological effects
Intensity or Flux		Clear understanding of dose rate on biological response
Stability/Jitter Requirements	stable -currently	Uniform dose - ≤10%
ancillary equipment	Conveyor system/cooling system maintenance intensive	Robust Conveyor and cooling system
Target minimum dose	8 kGy – 25 kGy	8 kGy – 25 kGy
Product throughput	Very high	Low – very high throughput
Cost (fully integrated)	In-line $5 million	In-line ~<$2.5 million (integrated)
Automation Needed[4]	None to full	Full automation preferred
Footprint (Size, shape, and shielding)	Compact to bulky	Compact
Weight (including any shielding)	heavy	Lighter the better/self shielded
Power	from 20 kW - 700 kW max	5 kW (inline) - 100 kW ; end of line
Portability	Limited. End of line or 3rd party	in-line and transportable , ROBUST; > 98% uptime
Op. Temp range	ambient	ambient

[1] electron, x-ray, gamma, neutron; [2]maximum allowable time to change between energies; [3]CW, pulse train bursts, single pulses, interleaved energies, etc.; [4]automation level

Accelerator requirements for the food industry. The applications of accelerator technology in the food industry span food safety, food quality, extension of shelf-life, phyto-sanitary treatment, the sterilization of food packaging, and modification of packaging material properties.

Source Property	**Current Technology**	**Objective (2-5 years)**
Particle[1]	Ebeam/gamma/x-ray	Ebeam and/or x-ray
Effective Source Size	2 cm	> 2 cm
Directionality	Unidirectional for ebeam	Unidirectional;
Tunable energy range	limited	Fully tunable between 1 MeV -10 MeV
Tuning speed[2]	Instantaneous (µsec)	instantaneous (µsec)
Energy spread	3% spread	R&D to determine energy spread effects on DUR and biological response
Pulse structure[3]	CW/pulsed/	Pulse structure should be designed to deliver uniform dose on a moving product and biological effects
Intensity or Flux		Clear understanding of dose rate on biological response
Stability/Jitter Requirements	stable -currently	Uniform dose - ≤10%
ancillary equipment	Conveyor system/cooling system maintenance intensive	Robust Conveyor and cooling system
Target minimum dose	150 Gy- 12 kGy	150 Gy – 15 kGy

throughput	Very high	Low – very high throughput
Cost (fully integrated)	$10-20 million	In-line ~$5 million (integrated)
Automation Needed[4]	None to full	Full automation preferred-active dose monitoring
Footprint (Size, shape, and shielding)	Compact to bulky	Has to be compact to be flexible to be used in-line or end of line
Weight (including any shielding)	heavy	Lighter the better/self-shielded if at all possible
Power	20 kW max	10 kW (inline) - 50 kW ; end of line
Portability	Limited. End of line or 3rd party	in-line and transportable, has to be robust, preferably capable of operating with electrical generators in areas with poor electrical grid system
Op. Temp range	ambient	Ambient/refrigerated operating conditions

[1] electron, x-ray, gamma, neutron; [2]maximum allowable time to change between energies; [3]CW, pulse train bursts, single pulses, interleaved energies, etc.; [4]automation level

Accelerator requirements for the Sterile Insect Technology (SIT). The applications of accelerator technology in SIT is to induce sterility in insects so that when they reproduce the off-springs are sterile and the populations are unable to multiply and spread.

Source Property	**Current Technology**	**Objective (2-5 years)**
Particle[1]	Gamma and x-ray	Ebeam and/or x-ray
Effective Source Size	2 cm	> 2 cm
Directionality	Unidirectional for ebeam	Unidirectional;
Tunable energy range	limited	0.5 MeV – 5 MeV
Tuning speed[2]	Instantaneous (μsec)	instantaneous (μsec)
Energy spread	3% spread	R&D to determine energy spread effects on DUR and biological response of insects
Pulse structure[3]	CW/pulsed/	Pulse structure should be designed to deliver uniform dose on insects within a primary container
Intensity or Flux		Clear understanding of dose rate on biological response needed
Stability/Jitter Requirements	stable -currently	Uniform dose - ≤10%
ancillary equipment	Conveyor system/cooling system maintenance intensive	Robust Conveyor and cooling system
Target minimum dose	10-100 Gy	5Gy -500 Gy
throughput	low	Low – medium throughput
Cost (fully integrated)	< $1 million	< $0.5 million
Automation Needed[4]	None to full	Full automation preferred
Footprint (size, shape, and shielding)	Compact	Compact, modular and ability to rely on generator sets if needed
Weight (including any shielding)	light-self shielded	Self shielded
Power	low	< 1 kW
Portability	compact	compact/robust/transportable
Op. Temp range	ambient	ambient

[1] electron, x-ray, gamma, neutron; [2]maximum allowable time to change between energies; [3]CW, pulse train bursts, single pulses, interleaved energies, etc.; [4]automation level

These accelerator specification tables were the basis for the subsequent discussions by the cross cutting technology and computation panels. These deliberations yielded the Priority Research Directions.

6.2 Medical Applications Panel

There were 5 main areas of concern that were studied by the Medical Applications Panel: (1) Development of rugged, reliable low-cost LINACs for low and middle income countries (LMICs), (2) Development of high intensity x-ray and electron source for FLASH-RT and VHEE radiotherapy, (3) Development of source-free brachytherapy units, (4) Development of portable monochromatic γ-ray sources, and (5) Development of compact neutron generators for NCT work. In our first session we assessed existing technologies including cost and performance criteria, assessed the regulatory picture for bringing new devices to market, assessed global needs for the technology and how it is currently utilized, and evaluated future possibilities for advanced design LINACs including laser driver and solid state beam steering and rotation. In our second session we concentrated on LINACs for FLASH-RT, the needs of the radiobiology and molecular medicine communities for basic and translational research, and the prospects for silicon-based electron sources for brachytherapy applications. In our third session we considered advanced accelerator technologies associated with fast neutrons and with epithermal neutron beams of use in NCT cancer treatments, and studied clinical imaging technologies. The findings of these sessions are presented in the body of this report.

At the end of the third session we devoted some time to trying to define some “blue sky topics” by asking each of the panel members and observers to “lean back, close your eyes, and think about what technological capabilities you would really like to have”. We did this in order to ensure that we did not overlook an important area due to the time pressure of primary objectives of the workshop. Each of the numbered items represents the response of one person to this question.

Panelists

1. Better identification of GTV and CTV relative to normal tissue
2. AI neural net for adaptive radiotherapy in real-time
3. Multi-modal image-guided integration with treatment machine
4. Coherent FEL-fed LINAC, compact at 10x10x10 meters volume total that can deliver attosecond pulses
5. Proton and helium radiography and CT for range determination; and characteristic x-ray monoenergetic sources
6. CERN carbon beam LINAC - but cheaper and smaller
7. Single pulse full dose flash LINAC
8. Portable FLASH unit that can be operated with an iPhone
9. Continuous delivery paradigm for RT (a Tesla paradigm)
10. Small affordable, robust, and beautiful physics. Elegant
11. Laboratory capacity to deep dive on the radiobiological effects
12. Heavy ion source with a biosensor for direct feedback
13. Continuously change energy and particle to keep the Bragg peak on target
14. Big data – continuous learning to improve cancer care (including diagnosis)
15. Make carbon ion therapy affordable to everyone
16. Biologically adaptive RT – AI to make Radiation Oncologists able to talk and listen more
17. Dual gun LINAC; FLASH + neutrons, that is temporally nuanced, has onboard robust and predictive diagnostics, allows treatment algorithm prediction data collection, and is inexpensive
18. Small lab-based systems that allow us to ion switch and dose paint that is energy switching, can paint tumor back to front is affordable, and is accessible
19. True system thinking in the design of radiation care process, technology, incentives

20. Optimize RT platform on a different scale that include system-level constraints - economic, social, infrastructure – a co-design paradigm to assure expertise at each scale

Observers

1. Flash Ion Gamma Science
2. High rep-rate Lasers and fibers
3. Long-life photocathodes
4. Robust, high fidelity, collimation systems
5. Modeling – linked to measurements – prediction
6. Flash data/specification
7. Compact tunable FEL
8. Proposals that fit within my mission; Compunction free position
9. Grants within mission scope – isotope production
10. Blackbox systems – safe for the patients when things go wrong (including when the operator)
11. Lab-based mixed ion irradiator
12. Small, cheap, operationally more stable accelerators
13. Doing ‘this’ in bulk – leverage the scale to get the objective – industrial engineering
14. Integrated imaging and radiation at the same time
15. Detector everywhere technologies – sensors on-board, in-board at attosecond and Angstrom scale
16. Dirt cheap ion machines with AI and NLP – fully patient accessible

We believe that output of this free association session largely parallels the main write up of the Medical Application Section (Chapter 4) of this report.

The following word plot (Figure 6.1 summarizes the frequency of responses in a given area:

__Figure 6.1.__ Word Cloud responses. (above by Jeff Buchsbaum and George Laramore using web based public tools at https://infogram.com/create/word-cloud)

6.3 Materials and Sources Panel

The Materials and Sources Crosscut Working Group focused on significant portions of the technology of particle accelerators (i.e., the “source” for the desired medical or security application), which consists of the accelerating structure, the RF sources or electrostatic field that provide energy for the acceleration process, and any converters to change the accelerated species to a different desired emitted species (i.e., to create x-rays, neutrons, high energy x-rays). The scope of the group also included accelerator physics and a great deal of the underlying materials science issues related to accelerator sources, including the physical/chemical material composition and fabrication technology for the accelerator structure itself (metals and dielectrics used in the RF structure), high voltage insulation, and converter materials. Note that superconducting materials and superconducting accelerators were not within the domain of the Materials and Sources group, as these are covered extensively by the Future Concepts group throughout the overall BRN report. Alternative acceleration concepts like laser and plasma wakefield mechanisms, etc. were likewise in the domain of the Future Concepts group and were thoroughly covered in the overall BRN report by that group, and not by Materials and Sources.

This panel report by the Materials and Sources Working Group provides information on the process that was used to examine the topics of the workshop, to identify technology gaps, and to develop a list of required R&D and condense it into technology themes. Simple bulleted listings of the key items identified as a result of the discussion process are provided below in this panel report as a summary. Note that great detail is not given here, since the main conclusions of the working group have been incorporated into the more extensive descriptions of the technology gaps, required R&D, and the research roadmap given under the Security Applications (Chapter 3) and the Medical Applications (Chapter 4) earlier in the overall BRN report. Furthermore, the details of the main technology themes examined by Materials and Sources and the conclusions therein have been incorporated into Chapter 5 of the overall BRN report, so only a brief summary list is provided here.

6.3.1 Summary of the Process Employed by the Panel

The panel session began with a review of the portions of the overall workshop charge by the panel co-chairs (Jeff Calame and Andrea Schmidt) that pertained to the Technology Crosscut working groups, and reiteration of the roles of the Materials and Sources group as one the Technology Crosscuts. It was emphasized that the role of the working group was to define technology gaps between what is doable now vs. the requirements of the Application Groups (security and medicine), and then to identify the areas and directions of research and development that would be needed to overcome the technical gaps, to prioritize such research, and to come up with a roadmap for development and technology transfer. Equally important were the instructions of what was not expected. It was emphasized that the working group was not expected to design explicit accelerator systems to meet the requirements (which would not be possible in the limited time available in any case), and likewise, it was not expected that the group explicitly try to solve specific problems.

Following the introduction and explanation of the charge, a number of short talks were given by selected working group participants, each with a 5 minute length plus 2 minutes for questions. The emphasis was to present opinions on current limitations, and initial thoughts on what R&D might be needed to move past obstacles, in order to seed the subsequent discussion. This was followed by a group exercise of sorting through the requirements documents and organizing them into one or two of the required technology focus areas of the workshop. Breakout sessions were held with subsets of the formal Materials and Sources working group members and observers (2 sessions in parallel, by 3 time blocks), as well as members of the medical and security applications working groups that had joined in the technology crosscut session. Everybody was an allowed equal participation in the breakout discussions, as there was no distinction made between regular participants or observers, or if they were formal technology group members or application group members. The participation in any given technology focus area was according to expertise and interest of the participants; in rare cases some people were ask to shift around to ensure a balance of participation. Discussion of technology gaps, required R&D, and priorities were recorded with a combination of written poster notes or computer keyboard entry by the session co-chairs. A follow-up evening session was devoted to combining and organizing the required R&D into a limited number of higher-level technology themes.

6.3.2 Contributed Talks by Panel Members to Initiate Discussion

Short talks to seed the upcoming discussion were presented on the following topics: (1) Present limitations on compact accelerators, key technology opportunities, and especially cost issues and the need to reduce costs of any prospective improvements (Craig Burkhart, SLAC); (2) Particle accelerators and opportunities in security and medicine, identifying the important performance metrics, sub-disciplines requiring attention , acceleration mechanisms, and the need for a coordinated university-national labs-industry joint effort (Thomas Schenkel, LBNL); (3) High gradient reliability, improvement of efficiency from the RF structure and RF sources, and improved accelerator robustness through solid-state RF sources providing distributed RF power (John Lewellen, Los Alamos); (4) Concepts and challenges for greatly increased acceleration gradient, beam loading, and shunt impedance in accelerators and avenues for more powerful RF sources (Sami Tantawi, SLAC); (5) Key opportunities in materials and sources for accelerators including high voltage insulation, additive manufactured magnets and dielectrics, tailored material properties, non-thermionic cathodes, thermal management, high gradient pulsed structures, and new magnet architectures (Nathaniel Pogue, LLNL); (6) Laser-Compton accelerator-based sources for bright, tunable, narrow bandwidth x-rays and high energy x-rays (Roark Marsh, LLNL); (7) High electric field gradient dielectrics for accelerators, including additive manufacturing (Michael Krogh, Complete Compact Aero Systems); (8) Advances in neutron generators, including both highly portable units and larger stationary systems, as well as (API) associated particle imaging (Charles Gary, Adelphi Technology); and (9) Summary of advanced in smaller, lighter, high brightness neutron sources, including human portable and cart-portable systems, as well as examples of neutron imaging capabilities (Brian Jurczyk, Starfire Industries).

6.3.3 Binning of Applications into Focus Areas

Our first full-group exercise was to bin the various applications identified during the previous security and medical sessions into the 6 different technology focus areas. A breakout session was held for each focus area in order to identify technical gaps and the required R&D. All applications for which a requirements table was generated was binned into at least one focus area (sometimes two). The applications were organized into the six technology focus areas as follows:

1. **Replacement of radioisotopic sources by accelerator-based alternatives:**
    a. Oil well logging/neutron measurement
    b. Oil well logging/gamma measurement
    c. Medical sterilization
    d. Food irradiation
    e. Sterile Insect Technology (SIT)
2. **Ruggedized low-cost LINACs for global use**
    a. Global Radiotherapy
    b. Photons for radiobiology research
    c. Luggage CT scanning source
    d. NII scanning x-ray (two different source needs)
    e. Medical sterilization
    f. Food irradiation
    g. Sterile Insect Technology
3. **FLASH-RT and Very-high energy electron (VHEE) sources for radiotherapy and security applications with similar radiation requirements**
    a. Electron source for radiobiology research
    b. Next generation x-ray collimators
    c. Hydro radiography
    d. Portable radiography
4. **Source-free brachytherapy (a.k.a. “electronic brachytherapy”)**

        a. Endoscopic radiation accelerator technology
5. **Portable mono-chromatic high energy x-ray sources**
    a. Photon sources for radiobiology research
    b. Gamma sources for oil well logging
    c. Portable radiography
    d. Mono-energetic pulsed x-ray
    e. Gamma sources for nuclear forensics, nuclear photonics, nuclear materials detection
6. **Compact neutron sources**
    a. Neutron sources for radiobiology research
    b. Neutron sources for BNCT
    c. Neutron sources for oil well logging
    d. Non-destructive evaluation (NDE) neutron sources
        i. Cargo radiography
        ii. Cargo SNM detection
        iii. Luggage SNM detection
        iv. Neutron resonance transmission analysis (NRTA)

6.3.4 Technology Gaps Identified

In the separate sessions for each technology focus area, we made a list of technology gaps to form a foundation for our R&D areas. After the end of the panel session, a merged list of all the noted technology gaps was prepared and is given here:

- 1 ns fast neutron pulse for time-of-flight neutron measurements for well logging.
- High-flux portable D-D sources.
- Angular resolution in density measurement.
- Associated particle imaging for well integrity analysis.
- High flux gamma source at >200 keV for cesium replacement.
- Neutron porosity and neutron prompt gamma capture measurements for geological applications where AmBe use is not allowed.
- Flexible dose control for food irradiation.
- In-line dose monitoring for food irradiation, medical device irradiation, and SIT.
- Better integration of accelerator with device for food irradiation, medical device irradiation, and SIT.
- Lower cost accelerators for food irradiation, medical device irradiation, and SIT.
- More compact accelerators for food irradiation, medical device irradiation, and SIT.
- Better usability for accelerators for food irradiation, medical device irradiation, and SIT.
- Localized efficient delivery of desired radiation into body through endoscopy.
- 100’s of tons processing capability per hour needed for the largest scale food irradiation applications. Implies very intense 3 kGy/s or higher exposure rates that will be very hard to achieve from a 100 kW power level accelerator.
- 10^{10} n/cm^2/s neutron sources for medical research.
- 10^{11} n/s/str into 2π, >=14 MeV neutron source with small spot size, small enough to fit on a truck that doesn’t require commercial driver’s license for neutron radiography of containers.
- 10^{11} n/s/str into 2π, >=14 MeV neutron source with small spot size, small enough to fit on a truck that doesn’t require commercial driver’s license for neutron radiography of containers, with <100 ns pulse width.
- Portable 2x10^{11}-10^{12} n/s/str into 2π for SNM detection in containers.
- Portable 2x10^{11}-10^{12} n/s/str into 2π for SNM detection in containers, with <100 ns pulse width, at 100 Hz.
- Short pulse (<100 ns) 10^{10} n/pulse neutron source for NRTA of waste/debris/raw materials.

- Compact vacuum electronic RF sources are lacking in sufficient peak and average power at higher frequencies (above 12 GHz).
- Vacuum electronic RF sources are typically a single point of failure, as are the pulsed high voltage power supplies in the 100 kV range.
- Present limitations on the duty cycle of RF sources (vacuum electronic and solid-state).
- Solid state sources at mid-microwave frequencies and higher are presently limited in power (500 W or lower peak power).
- Commercial microwave solid state sources are not optimized for accelerator applications.
- More compact pulse compressors.
- Thermal management of accelerator structures and targets for high flux and/or high duty cycle.
- Accelerators capable of being utilized for more than one species of particle for radiobiology research and ultimately for clinical use.
- Higher gradient accelerators are needed to allow compactness.
- Poor efficiency of electron to x-ray conversion process in conventional targets.

6.3.5 R&D Research Areas

During the breakout sessions, we discussed the list of technology gaps and formed a list of the needed R&D areas that would close the technology gaps. A merged list of these areas is provided below:

- Development of very compact, $>10^7$ n/s neutron sources for well logging.
- Development of very compact gamma ray sources with at least 200 keV photons.
- Higher energy density power supplies.
- Development of a few fs pulse length, mJ energy laser in a small fiber, 1 kHz rep. rate for driving microfabricated accelerator structures for endoscopy.
- Development of endoscopic plasma target.
- Research on efficient injection of electrons into MEMS accelerator.
- Scale-up of conventional neutron sources to higher yields while remaining truck-portable.
- Develop short pulse neutron source technologies (1ns, 20ns, 100ns).
- Research on alternative nuclear reactions in accelerator targets to more efficiently produce neutrons or gamma rays, or avoid the use regulated elements in targets.
- Higher powered distributed RF power sources based on solid-state (5kW peak power per packaged transistor at f > 9.3 GHz).
- Solid-state transistors (in particular HEMTs) with higher voltage output characteristics specifically engineered for the narrowband, higher impedance load requirements of accelerator structures.
- Technology for depositing high conductivity RF coatings on robust structure metals to make accelerator structures more mechanically durable.
- Higher efficiency vacuum electronic RF sources that can be driven at higher beam currents from a lower voltage power supply, based on multi-dimensional electron flow geometries (multi-beam, 2D beams, 3D beams based on stacked 2D ensembles).
- Gyro-amplifier vacuum electronics technology for high power generation above 20 GHz.
- Vacuum electronic sources having a flexible, modular design and fabrication methodology with common families of pre-engineered guns, beam transport, and interaction structures at various frequencies and powers that can be quickly combined; application of additive manufacturing to vacuum electronics to interaction circuits and beam transport magnetics.
- For e-LINAC electron source, want higher current, more robust cold-cathode cathode technology based on field emitters (arrays, carbon nanotube, etc.) to avoid typical thermionic failure, combined into RF gun/injector assembly for tighter beam bunching and better matching to the main accelerator structure.

- Cathode research on the issue of emittance in microfabricated field emitter arrays and the use of multiple focus electrode layers to control beamlet spread and limit overall emittance of the array.
- Density functional theory of nano-emitters to understand surface states and the effects of adsorbed impurities.
- Employ a materials-by-design approach for new materials in dielectric-loaded accelerators having a combination of high dielectric constant and high breakdown strength.
- Intrinsic design of accelerator structure and vacuum components for better ultra-high vacuum behavior (including better materials purity, lower outgassing, improved joining technologies, and higher temperature processing) to allow extended shutdowns without vacuum degradation, and to allow substitution of ion pumping for turbo pumping.
- Design and fabrication of a highly compact lower energy LINAC (1-2 MeV, electrons and x-ray output capability) with in-situ imaging and spectroscopy but with a similar dose rate (0.8 to 1.2 Gy/min) to standard clinical uses.
- Methods of creating variable millimeter to micron sized beam diameters (1-2 MeV electrons and x-ray) from a single accelerator.
- Methods of allowing a single accelerator to operate with different ions, including protons, deuterium, helium, lithium, carbon, etc., including multi-species emitters and injectors, and concepts like induction LINACs optimized for high gradients and multi-species use. Adaptable RF LINACs with adjustable tuning and phasing along the structure to allow different charge-to-mass ratio species to be efficiently accelerated.
- For Flash RT and VHEE, several simultaneous advancements are needed, including methods to greatly increase the beam energy (to over 100 MeV) and beam current in accelerators to increase the delivered flux rate by a factor of 1000 times. This includes techniques to increase the duty factor by at least 10x, increase the shunt impedance of the accelerator structure, increase the beam loading of the accelerator structure to over 80%, increase the acceleration gradient, improve the high frequency behavior by surface modification of the structure materials, utilize dielectric accelerating structures to decouple the performance-limiting link between metallic cavity conductivity and shunt impedance, utilize cooled ordinary metals in cavities (to 77K), and develop more compact and higher efficiency pulse compressors with a larger power multiplication factor. These R&D areas would also have a direct impact on high radiation flux accelerators for sterilization and other security applications.
- Explore the possibility of new target materials with enhanced electron to x-ray conversion efficient, including ordered metal crystals rather than polycrystalline metals, exploiting x-ray and electron diffraction effects, microchannel targets with atomic-scale organization
- Invent methods to spatially manipulate the x-ray pattern in photon FLASH, since there is no MLC and not enough time to mechanically scan the beam.
- Investigate beam steering for VHEE by using photocathodes and temporal-spatial changes in cathode emitting area via laser phase mask approach, and study how such beams evolve down the accelerating structure. This could also apply to multiple beamlet approaches with laser modulation of the beamlets at the photocathode (rastering). Alternatives to photocathodes would include field emitter arrays with individually addressable emitters or small groups of emitters.
- Explore the applicability of photocathodes and RF injectors in Flash to produce complicated pulse trains within the short FLASH dose.
- Improvement of photocathode life.
- Alternative methods to produce x-rays, such and free-electron lasers with microscale period undulators and multiple parallel microscale beams.
- Investigate methods for improved beam matching between a lower energy compact superconducting cyclotron proton source with a variable high-energy proton LINAC for proton flash applications.

- Develop more compact RFQ accelerators or other compact proton LINACs for proton therapy and as a proton source to create neutrons for BNCT via target nuclear reactions
- Investigate multi-frequency injectors as a means to change source beam behavior.
- Devise methods to create multiple types of bunch trains and explore the behavior on gamma ray production.
- Achieve higher repetition rates of the source lasers (>1 kHz) and higher energy laser pulses (>1 J/pulse).
- Develop high power RF sources and accelerator structures (and also targets) compatible with the > 1 kHz repetition rates, especially with regard to thermal management, thermal expansion, and pulse heating breakdown.
- Research to improve pulse-to-pulse stability, including energy, bunch charge, and position control of both the laser and the electron beam in inverse Compton gamma ray sources.
- Methods of controlling bunching at the Angstrom level for accelerator-based gamma sources.
- Methods of inducing controlled transverse bunching and converting it to longitudinal bunching.
- More speculative but high payoff methods of efficiently producing tunable gamma rays from accelerators and especially very small storage rings, for example mechanisms like relativistically upshifted electron-positron annihilation radiation.

6.3.6 Technology Themes Development

During an evening work session, the commonalities of the above-listed R&D topics were discussed and Technology Themes with a higher-level scope and organization were defined and populated. The five technology themes that resulted from the session were titled: (1) Modular, Flexible, High Power Density RF Sources for Powering Reimagined Accelerator Structures; (2) Transformative Accelerators for Flash RT and VHEE; (3) Accelerator-Based Gamma Ray Sources – Pushing the Boundaries for Ultrahigh Flux or Extreme Compactness; (4) Accelerator Materials by Quantum Chemistry – and Physics – Enabled Design; and (5) Develop High-Flux and Shorter Pulse Neutron Sources. A sixth prospective technology theme on multi-species hadron accelerators was not pursued directly, due to considerable overlap with a prior Workshop on ion therapy. Residual aspects of the topic that were sufficiently different from the prior workshop and still important to the present BRN workshop charge were incorporated to some extent in the medical chapter, as appropriate.

6.4 Design, Computing, and Controls Panel

The Computing, Controls and Design Panel covers an extremely broad range of topics from first principles physics, to first-principles physics simulation codes, to engineering simulation codes, to the systems engineering design process, to computing hardware, to the use of high-performance computing clusters, to controls system architectures, to controls hardware and on device computing, to basic controllers to advanced algorithms and methods such as AI as well as AI computing architectures and specialized hardware.

The formal mission is “To look at the advances in computer hardware and software R&D needed to (1) accurately simulate performance for design purposes, and (2) provide robust highly-automated accelerator control.”

For this reason, the panel was carefully assembled with individuals that had experience that bridges several of the areas listed above as well as the other cross-cutting groups and applications areas. The team members all have had multiple career roles and experiences including small and large companies, national laboratories, and in academia. All of the panel members have worked on accelerator-based projects concerning both traditional and advanced accelerators around the globe for a variety of services and agencies and understand the interplay between the controls, computing, and design involved in the design process. Some of the team members have fielded photon and/or particle sources which helped bring a sense of the issues and design considerations that can come into play in the field in terms of the panel's subject areas. Many of the team members also have worked in a variety of field, not only in accelerators (including in fire protection system, industrial controls, and adaptive security systems research), thus bringing a wide spectrum of experience in prioritizing research directions for various technology applications.

First, one of our team leads, who was assigned to the team quite early on, in November of 2018, provided extensive suggestions for potential team members for all of the groups. She contacted first the management and then the person or person directly. She provided all of these suggestions to the main organizing team at the Department of Energy directly and worked to provide a diverse list of individuals with the appropriate background and expertise to the team. She met with several individuals who were previous members of chairs of BRN report teams. Once the second team leader was also assigned, they compiled a list of persons with short biographical information from which the sponsors and application team heads could select with the given funding constraints. After these individuals were invited, the team interactions could begin. We held several conference calls amongst our team of Jim Amundson (Fermilab), Sandra Biedron (self), John Cary (UC Boulder and Tech-X), Massimo Dal Forno (Viewray), Richard Farnsworth (Brookhaven National Laboratory), Steve Lidia (FRIB) Michigan State University, John Petillo (Leidos), and Joshua Stein (Argonne National Laboratory).

Our team members spent an enormous amount of effort notifying colleagues of the workshop and the BRN goals and gathering related information. We did not merely concentrate on our own area as we wanted to hear some of the thoughts from those who would be employing such devices and map that into our own team's concern space. For instance, we requested information or even gauged a level of interest from colleagues in national laboratories, industry, academia, medical facilities, government, including county and more local government who also could benefit from said compact devices. We shared the feedback with the sponsors and application groups. Without going into specific requests or whom we spoke to, the general summary of the clear messages we received from these individuals is as follows grouped into the applications where appropriate.

Security - those concerned with security communicated several messages including turn-key operation, simple controls operation with interfaces such as a laptop computer or mobile phone fast detection times, confirmation of the results that could serve also in legal proceedings (forensics), portability if possible for use from cars and helicopters, larger units deployed around cities or counties but mobile if possible. Two medical device companies expressed extreme interest and one in fact stated (name withheld), "If we only had an all-electronic way through particle accelerators of sterilizing our components. Right now, chemicals that are wasteful for the environment are used. There are times when we cannot get something sterilized has sobering consequences, such as children not getting a new heart valve in time. Something needs to be done both on the process (without chemicals) and the regulations of how sterilization without chemical can rapidly move forward." Those who are responsible for bridge inspection in a heavily populated metropolitan area from the municipal and county sides suggested that they desperately require tools to inspect every structure they have and want to know how to best become involved. And the stories go on.

Medicine – We spoke to patients, machine builders, medical physicists, and physicians including oncologists. The main message we found was accessibility to treatment. We feel that more compact sources can address this. The next message we received was how does one truly determine the right treatment or suite of treatments from a source or suite of sources. We feel that computational methods of simulations, analysis of existing data, as well as data science tools to combine and analyze these simulations and experimental data can help address this latter message which is out of topic from the BRN but nonetheless interesting to ponder and address elsewhere. Other messages included frustrations that the medical systems are often pieces together with different components that are not working together – data is collected by the various sub-systems at different rates and cannot be correlated, data is not stored, there lies and abyss between the machine and the end use that could be refined through data and controls, etc.

General ideas collected:

- One concern we found in speaking with colleagues in these fields is how to best coordinate and collaborate across institutions and other boundaries. One person went so far in saying (paraphrased and name withheld) that the largest obstacle lies in not having the right people around the table funded to invent a solution as these devices cannot be realized by one person.
- Another concern we found was that institutions mostly driven by managers still turn to a simulation code they know. This become a limitation if the code does not contain adequate first principles science. So instead of developing a new code that is actually required, the results are simply not adequate. Another related message is that the same decisions are made not to employ the many high-performance computing centers for several reasons including – the codes cannot be used there as they are not designed to pair with HPCs, there is only one or few licenses (commercial codes), and the management may not be informed of the HPC utility. These concerns extended to the utilization of data science techniques for simulation, control, prognostics. These concerns extended to the fact that much data is not sufficiently logged at real-time for later use.
- Other sentiments included that for controls developments, the controls requirements must be defined at the start of the project. This requires that the interfaces and functions must include ever more refined input from the scientists, end users, and controls engineers.
- Several comments centered around the systems approach and funding. The very few data points we have on endeavors to build compact accelerators point to a need for true systems engineering approaches. There have been successes as well as sub-optimum solutions. A refined compact system will cost real money and the sponsors must realize that such systems will not realize themselves by plugging together pieces – it is a start to user end system that must be analyzed as an entire system. A smaller system does not in any way mean that it is less complex. It might be even more complex.
- For fieldable devices, we require turnkey, intuitive, minimal operator expertise.
- Open source control system frameworks offer many advantages.
- Use on device computing and local clusters that are modern, relatively inexpensive, and available.
- Realize machine protection also involves cybersecurity and cyber-robustness of the system.
- Diagnostics are key to understanding and controlling a machine.
- Redundancy designed into the systems will enable turn-kay control.
- Intelligent techniques can assist in first principles simulations, analysis of experimental data, understand multiple sources of data, and control. Advanced algorithms can easily learn from and find relationships between large numbers of variables and we should use these powerful tools to our advantage.
- How can we use techniques in other fields coupled to advanced data science to enhance the applications? [See for example, Metal Artifact Reduction in CT: Where Are We After Four Decades? LARS GJESTEBY et al., DOI: 10.1109/ACCESS.2016.2608621.
- How can we improve on the design and control of sub-systems with data science and more advanced control?
- How do we set standards (example IEEE or Mil) for fieldable devices?
- Can we do better than Monte Carlo methods?

Through the many conversations amongst ourselves, our own knowledge base and internal ideas collected, as well as in collegial inquiries with outside colleagues, we were able to assemble the pieces that led to the factual document in preparation for the BRN Workshop. The individuals that we contacted came from a wide variety of organizations, although their opinions do not represent necessarily that of their associated organization. Northwestern Medicine, ELI (including ELIMED and ELIMAIA), Argonne, Fermilab, LBNL, Daresbury, Coast Guard, AFRL, DEPS, RI Army Arsenal, DE-JTO, University of Michigan, University of Liverpool, LANL, Radiabeam, American Institute of Steel Construction, Industry – including Meyer Tool, Booz Allen Hamilton, nvidia – and Municipalities (such as Cook County, CPD, Santa Fe Police Department).

One of the first things we needed to do was to change the name of our team from Computer Design and Control to Computation, Control, and Design as there is a distinct need for computation across the field of compact accelerators and the specific applications including in the design phase and in control of operation phase. These three items are synergistic and computers do not stop being used when the design is complete. We have to think more about on-device computing on various components of the accelerator as well as sufficient local computational resources storage as well as CPU/GPU/etc., to permit the health monitoring of the system out to and including the intended application, system control, to perform predictive maintenance (prognostics, and to perform operational set point adjustments as components change over time due to aging, etc. If we really want near fielded or fielded compact systems to be turnkey, they systems must be self-sufficient and self-healing to the fullest extent possible. Of course, this means that the computing, control, and design or the systems are in constant handshaking with the engineering cross-cut area (as well as the detectors). The simulation codes based on a wide variety of first principles are needed for comprehensive simulations from the start to end of the system. The codes must be compatible with high-performance computations systems. We also need to make use of much experimental data from the system components such as targets, detectors, and other materials used throughout. We need to think more globally that the controls are not just for operation but it hand-shakes constantly with/through a variety of computational resources for upgrading the machine model and therefore the design. We need to use advanced concepts such as new approaches, implementations, and/or algorithms to operate easy to obtain components that are simple and near off the shelf, e.g., magnetrons, to make the systems cheaper and easier to maintain for systems facing extreme conditions or in locations with minimal engineering support. We need robust design tools to help us choose while modules, e.g., the RF source, to use in these compact systems.

Based on the exercise of assembling a variety of content for our section of the factual document, we also assembled many questions to be posed at the BRN Workshop with the hopes of them being, at least in part, answered. Here are open questions we posed for consideration at the workshop:

- What are the critical shortcomings in the current software offerings?
- What are the critical shortcomings in the current hardware offerings?
- Large-scale simulations are increasingly requiring many CPUs to obtain answers in reasonable time, but the costs of many-core licenses are high. How can accelerator design supporting agencies work with commercial entities to reduce costs?
- Working on supercomputers is largely a domain for expert computationalists. How can we maximize the accessibility of such capability, so that one need not be a computing expert to take advantage of such hardware?
- How can we formulate methods or procedures for non-data scientists to employ when trying to establish surrogate models of a highly complex system based on multiple data inputs?
- How can advanced optimization techniques be integrated with accelerator simulations to maximize the efficiency of simulation in the design and optimization process?
- What are the requirements for each of the genres we are discussing here for each type of medical accelerator, for each type of security accelerator, etc. There is not one solution to suit all.

- Define standards for performing a proper systems engineering architecture and systems engineering approach to meet requirements through the controls system including machine protection systems.
- How does one define a robust and near-autonomous control system while keeping costs down? What is the tradeoff? How robust is robust? What about self-healing and self-improving?
- Data archiving methods and granularity. Depending on the end use of the accelerator, data collection and archiving needs to be considered from the beginning. For a medical device, how is this accelerator going to store relevant data for (patient) diagnosis while honoring (region specific) HIPA like requirements? For national security operations, how is the accelerator going to be able to store data which may become classified due to the nature of its operation?
- Verification and Validation (As it pertains to the software tools to design accelerators, and to the control systems)

We then developed the *Computation, Controls, and Design Sub-Panel* agenda as seen at the end of this section. As noted in the agenda, we began by going around the room and each presenting the individual members' of the team's viewpoints at the high-level. Each member presented for 5-10 minutes. We then all discussed gaps in the design, computing and controls as a group based on the interactions in the plenary sessions and the workgroups from the previous day and immediate morning.

Our team participated in all aspects of the workshop, the plenary sessions and we distributed ourselves amongst the medical and security panel sessions in the afternoon and evening the first day.

The second day we participated by distributing amongst the applications sessions and then joined for the Mid-Workshop plenary session. In the afternoon, we broke out into the Technology Cross-cut panel sessions.

We began by going around the room and each presenting the individual members of the team's viewpoints at the high-level. Each member presented for 5-10 minutes. We then all discussed gaps in the design, computing and controls as a group based on the interactions in the plenary sessions and the workgroups from the previous day and immediate morning.

We discussed the cost of systems engineering and GUIs/Updates/APIs is not something that is familiar to the DOE. We discussed that most tools that we tend to use, even standard engineering codes, are not available on HPCs. This is an issue as the initial code designs can be quite conservative but to actually do a great design, we need sensitivity analysis performed at a massive scale further, for both "home computer" and HPC applications, the niche codes really need to be friendly and have an ease of access with backwards compatibility. For the eventual systems, we need to worry about digital hygiene and security as the machine configuration will be tied to computational models and might be updated near real time. In other words, we need to consider that design and control are integrated through computation. Why? Our goals are really to (1) analyze output and respond to user needs through machine configuration variation, (2) handle the variations between the machines (and the unknown differences of a single machine), (3) and have programmed maintenance.

One major concern is software. Again, the systems engineering practices done in industry and the DOD have not mapped 1:1 into DOE space. Such practices are needed in designing the software to tie an entire compact accelerator to the detector and to the end application. We need to use software engineering practices in the design of software and have extensive peer review of the software. This includes applying ethical practices when employing "smart" algorithms. This poses many questions to the stakeholders, including, "How do we certify or validate the software?" and how do we insure the software takes care of both the operational and the safety system requirements.

We feel that each machine needs to be developed (designed) for the ultimate use. There may or may not be the ability to re-use components or modules between the systems. It is likely however, that the design codes, much controls software, and much of the computational architecture will be able to be re-used. We can use AI (e.g., ML and optimization) in the process of designing the accelerator structure/unit. We need start to end design tools that are able to use computational resources to scan every parameters in and entire system. It is useful to have a real machine on which to anchor these design and computational tools. The model would be constantly updating. We need something outfitted with many diagnostics and having high repetition rate data streams.

Some experts felts that we could do a bunch more in terms of optimizing targets for applications. The medical applications visitors stressed developing full automation with the controls (the "iPad" model for radiation therapy controls). The security applications teams also visited and reiterated what they had stated in earlier discussions.

From Monday afternoon's security applications sessions we visited, the following were identified as key desirables at the system level:

- Dose uniformity
- Throughput rate
- Ease of use
- Cost
- Effects of radiation physics

These were common among the medical applications as well, in various degrees of reprioritization.

Down hole testing seems to be the most challenging from a device engineering standpoint, given the remote location, harsh environment, and desire to host sensory and decision-making faculties close to the working end of the borer.

From all of these sub-panel discussions, the team was able to formulate three general priority research directions and were written into the PRD templates provide by that DOE sponsors.

Sandra spoke on behalf of the group on Wednesday morning. She described that Systems engineering practices as defined by INCOSE (INCOSE - International Council on Systems Engineering) needed to be used in these compact devices (including end use). That there is a need for government/private company/academic/lab partnerships in research and development. That we need to be following design standards and/or guidelines such as those being put forth for intelligent systems by the IEEE Standard Society. Intelligent techniques developed for automation, data analytics, etc… developed can be mapped into and be of benefit to applications. She then covered the PRDs:

- Transform the design process for compact accelerators
- Integrate measurement and simulation with machine operation
- Develop fault-tolerant and intuitive control systems

Controls Computation and Design Sub-Panel Agenda

Sub-Panel Members: James Amundson, Sandra Biedron, John Cary, Massimo Dal Forno, Richard Farnsworth, Steve Lidia, John Petillo, S. Joshua Stein
Introduction and charge: Sandra Biedron and John Cary - 10 minutes
Sub-Panel Members Share High Level Thoughts: Each 5 minutes each with hard stops; two charts each (one on state of the art and one on vision for the future) - 40 minutes total
Note: for the discussions below, the leaders should prepare charts to help inform us of state of the art as well as the nudge points to launch discussions.)

Discussion of Design Processes today – what can we learn by analyzing what we do now, what others do in other fields (i.e., defense, aircraft, nuclear energy), and dreaming about would be the ultimate design tool that could enable compact accelerators? – John Cary and John Petillo - 30 minutes
The close integration of components in compact accelerators means that various components affect each other's performance, requiring multi-component to start-to-end simulation capability. Additionally optimization and sensitivity analysis and multi-physics simulations (electronic, thermal-mechanical, etc.) will be required, and on HPC clusters. This raises the questions of whether the chosen tools are available on HPC clusters; is there easy and sufficient access of HPC clusters to the researchers/designers; what are the licensing issues associated with bringing a new tool into the HPC environment; visualization of results created on the clusters. What tools do we have and what do we need? Is there a better user environment for the analysis for the design and optimization and tradeoffs, and including AI/machine learning?

Discussion of computing and controls – what can we learn from our colleagues in other fields – Led by Jim Amundson and Sandra Biedron - 30 minutes
"Binning" the genres of compact accelerators – are there innate differences on how to approach design, computational needs, and controls for the various types of accelerators desired based on the plenary talks and the TPFD? What are the requirements of these systems? Also address who is the operator and what is the frequency the device will be serviced – Led by John Petillo, Massimo Dal Forno, and S. Joshua Stein - 60 minutes
What commonality can we identify across the potential candidate accelerators? Should the compact accelerators be categorized (e.g., binned by power levels, portable vs. fixed, multi-use where the same machine can have different applications based on fitting various final-stage targets or no target at all). What part of the control interface can we have the same across the machines, and can we standardize the approach/philosophy for even those controls that are unique. Can we have one approach with the same controls? Can we standardize on the image processing tools. What's available, and how do they need to be developed to meet future needs. What neural network schemes are good enough and/or promising for next generation needs?

Discussion of modernizing the systems architecture of an integrated design, computing and controls "platform" for accelerators and how to (if possible) simplify it for compact machines. Led by Richard Farnsworth and Jim Amundson - 30 minutes
Can we reduce cost and complexity by not including every diagnostic and a reduced control set? Is there risk to that? Would there be controls that fit the experience of the user/operator? Can the compact accelerators be composed of a modular system, or would completed customized integrated systems be what is needed to suit compactness?

Discussion on a prototype machine versus the "fielded" compact source. Can we get everything we need to understand from one machine fully outfitted with diagnostics and taking data at a high repetition rate then morphing that into a lean and mean compact machine with just a handful of knobs? Is getting a compact machine just a one step process in terms of design, computing and control? Should the end user systems be fully integrated into the controls and design and computing processes? – Led by Steve Lidia and Richard Farnsworth – 30 minutes

Closeout and action items. Sandra Biedron and John Cary - 10 min

6.5 Engineering Panel

The Engineering Technology Cross-cut Working Group (ETCWG) focused on identifying compact accelerator engineering technologies that lead to reduced cost and ruggedization while meeting the operational performance requirements of medical and security applications. The group consisted of subject matter experts spanning a diverse range of accelerator expertise across multiple beam types. This group also had considerable experience in designing, engineering, fabricating, assembling, aligning, integrating and commissioning of accelerator-based systems. Many of the individuals had project management experience requiring an understanding of accelerator-based systems planning, pricing, scheduling, and project execution resulting in an accelerator product. The group included individuals from industry, national laboratories, government laboratories, and academia representing multiple engineering perspectives on accelerator-based systems for medical and security applications.

This panel report describes the process that was used by the ETCWG to identify gaps in accelerator technology related to cost reduction and ruggedization, specify the R&D needed to bridge those gaps, and formulate a set of high-level Engineering Technology R&D Themes. The technical results from the Workshop discussions were compiled and documented in both Chapter 3 (Security Applications) and Chapter 4 (Medical Applications), while the Engineering Technology R&D Themes were summarized in Chapter 5 of the BRN report.

6.5.1 Summary of the Process Employed by the Engineering Panel

The objective of the BRN Workshop on compact accelerators for medicine and security applications was to address technologies to replace radioisotopic sources, LINACs in low-to-middle-income countries, radiotherapy sources, endoscopic particle accelerators, portable monochromatic high energy x-ray sources, and compact neutron generators. BRN Workshop participants were partitioned into multiple working groups and participated in discussion sessions that focused on defining the research and development needed to advance the above accelerator technologies over the next decade and beyond. Medicine and security application working groups were charged with identifying specific technology improvements and innovations needed to enhance current capabilities or enable new ones. Technology cross-cut working groups were charged with identifying the technical gaps and R&D needed to bridge those gaps and, also, provide a roadmap toward technology transfer.

Prior to the Workshop, the Engineering working group contributed a section to the BRN's TPFD which described the motivation for the Workshop, the medical and security applications to be addressed, the current state-of-the-art and, for Engineering, the technological limitations related to cost reduction and ruggedization. A telecon was held with the working group panel shortly before the Workshop to review preliminary information and establish an agenda for the discussions. All Engineering panel members attended the medicine and security plenary sessions which were held the first day of the Workshop. This was followed by an informal panel session where the Engineering co-chairs reviewed the overall charge to the working group members and reiterated the roles of the group in terms of identifying technologies that would lead to reduced accelerator system cost and ruggedization. Based on the expertise of each working group member, the Engineering panel was then split into two sub-panels to cover both the security and medical discussion sessions which were being held in parallel. Several subsequent round-table breakout sessions were held that includes the Engineering working group panel, observers, and members of the medical and security applications working groups. Anyone who attended the Engineering break-out sessions could openly speak and contribute to the discussion. The focus of the break-out sessions was to gather the information gained by the two sub-panels and collectively work together to identify technology gaps, required R&D, and priorities which were recorded on written flip chart notes and computer keyboard entry by the session co-chairs. A final evening discussion session was devoted to combining and organizing the required R&D into a limited number of higher-level technology R&D themes which were presented at the closing Workshop report-out session.

6.5.2 Binning of Medical and Security Applications into Beam Types

Although extracting hard numbers/specifications can be challenging, the two Engineering sub-panels were able to identify accelerator-based values linked to specific applications from both the plenary sessions and the initial medical/security working group presentations. Since many alternative accelerator-based systems can be employed to deliver particle or photon beams, the Engineering panel attempted to extract beam-based requirements from an accelerator-agnostic perspective. A top-level system engineering approach was employed to distinguish various alternative accelerator candidate systems that can provide the necessary operational performance requirements for the medical and security applications of interest. Accelerator systems oftentimes are characterized by a limiting technology that ultimately constrains the achievable performance metrics or drives the lifecycle cost to make the system uncompetitive when compared to alternative candidate accelerator architectures. Further, assessing systems based on cost reduction or ruggedization is difficult from the perspective that decision makers may not be willing to attain specific accelerator performance metrics that could potentially also drive the cost (or ruggedness) of other systems within a system-of-systems architecture.

Accelerator systems that specifically target R&D-focused efforts within the medical and security application space are ideal candidates for early injection of a disciplined systems engineering approach to the accelerator system design phase. This approach is critical in addressing engineering technology shortfalls and identifying the critical technologies that will ultimately limit system performance. For example, sound system health and control systems enable early identification of critical requirements and the sub-system-level impacts on resulting specifications and tolerances across the system-of-system architecture/configuration. Computer-based modeling enables a broad range of hardware configurations to be assessed without the need to “cut metal”. Experience indicates that it is always better to spend more time doing it right the first time than to progress down the development path and backtrack due to some unforeseen/unanticipated problem. The goal of a disciplined systems engineering approach is to arrive at the desired performance goals while expending the least amount of resources (time and cost). The specific objectives of the Engineering Technology Cross-cut Working Group in this systems engineering approach were to determine the ruggedness and cost reduction factors of compact medical and security accelerators at the system-level.

The first step in the systems engineering approach was to define ruggedness/robustness and cost for accelerator systems with performance metrics defined by the medical and security working groups. While the meaning of “cost” is clear, the definition of “ruggedness/robustness” is to be “effective in all or most situations and condition” (https://www.dictionary.com/browse/effective) and, thus, clear definitions of “effective” and “situations and conditions” are also needed. The word effective is defined as “producing the intended or expected result” and the phrase “situations and conditions” is associated with the environmental conditions in which the accelerator system must operate and meet its operational performance requirements. With these definitions in place, the systems engineering approach proceeded by identifying the current state-of-the-art as a function of candidate accelerator-based systems and then identify which technologies specific to the candidate accelerator configuration limit the performance metric of interest. The spreadsheet-level identification of these technology gaps is accelerator-configuration dependent, however, many of these technology gaps may be common across multiple accelerator configurations. This systems approach process can be performed to estimate the most effective utilization of R&D investment resources targeting specific technology gaps.

6.5.3 Identified Technology Gaps

The systems approach of associating beam-based requirements with specific medical and security applications was performed at the top level. Candidate accelerator systems capable of achieving the beam-based performance requirements was added to the spreadsheet on a per-application basis. Depending on the experience base of the Working Group panel members, alternative candidate accelerator systems were evaluated along with associated technology gaps. This stage of the process resulted in substantial growth of candidate solutions with multiple biases becoming evident. For the Medical applications, the following Engineering cost and ruggedization technical gaps were identified:

Application	Cost Technical Gaps	Ruggedization Technical Gaps
Development of low-cost, robust accelerators for clinical and preclinical use based upon a modular component approach	• In LMICs, the main driver of cost is equipment, not salaries of employees (target \$0.5-\$2 million system cost) • Use of radioisotopes (e.g., ^{60}Co in specialized machines [Gamma Knife] and in developing nations) • System size and weight (fit in shipping container, drop-ship capable) • Availability of trained personnel for LINAC and target hardware maintenance and repair	• Reliability (no performance deficit; medical accelerators require highly trained service engineers and spare parts are scarce) • Dependence on local infrastructure (power grid, cooling systems, etc.) • Modular components • Target efficiency/robustness • Transportability robustness • Electrical grid stability • Ease of operation • Source alignment precision and stability • Source current magnitude and stability
Expansion of operational parameters for beam delivery and management including ultra-high dose-rate delivery	• Activation of surroundings • Elevated dose rates exceed licensed facilities • SWaP • Radioisotopic sources can't compete in this application	• Robust high-power converters (targets) • Robust high-peak current sources • Beam compression subsystems
Development of improved radiation detectors for dose distribution measurement and real time monitoring	• Additional research/understanding needed to calibrate dose delivered to cancer cells by radiation • SWaP • Affordability	• High reliability in environmental conditions (temperature, noise from background radiation) • Calibration
Development of improved beam collimators for field shaping	• Size and weight (must fit within 20cm space between source and subject) • Manual calibration	• Moving parts • Reliability (no performance deficit, no failure modes) • Dependence on local infrastructure (e.g., unstable power grid)
Simplification of accelerator operational and treatment planning systems to allow for real time treatment adaptation		
Plan and deliver radiation treatments to optimize biologically effective dose rather than physical dose	• SWaP (fit in shipping container) • High capital cost (\$1 to \$3 million) • High operating cost (no system health diagnostics)	• Operation in unstable power setting • Self-shielded • Operational reliability in environmental conditions (shock from earthquakes, temperatures from 15ºC to 45ºC) • Not portable • High reliability • Adaptively directional beam • Large beam spot size (0.2-1.5 cm diam.) • Efficient, high power converters
Development of compact neutron beam sources appropriate for neutron capture therapy	• SWaP • CW operation (neutron source and solid state RFA systems) • High efficiency proton LINACs	• Robustness of Li and Be neutron-generating targets • Significant fast neutron/gamma flux • Low epithermal neutron production efficiency • High reliability (no performance deficit, no downtime)

For the Security applications, the following Engineering cost and ruggedization technical gaps were identified:

Application	**Cost Technical Gaps**	**Ruggedization Technical Gaps**
Non-invasive probing with small sealed sources	• <500 W power supply for well logging • 1.7”-3.5” diameter x <12’ length • <$200,000 for accelerator-based alternative • Cost associated with transitioning from radioisotope-based well logging tools to accelerator-based • SWaP for accelerator-based photon and neutron sources	• No active cooling for well logging tool • High operational reliability in downhole environment (temperature, pressure, shock, vibration) • High-temperature, rugged detectors in well logging tools • Fast, robust, high-temperature electronics (FPGAs, processors, memory) for well logging • High-temperature HV generator components (HVHT diodes, resistors, capacitors) for well logging • Portable ruggedness for in-field radiographic NDT • NDT operations in temperature extremes (freezing to >100F) • Reliable power supply for NDT • Long lifetime
Radiography for nondestructive characterization	• Improved sensitivity with reduced dose • SWaP • Operating costs (cargo inspection)	• Shielding • High reliability • Reliable power supply
Food irradiation	• Capital and operating costs • In-line (integrated): ~$5 million	• Robustness of conveyor and cooling system • Automated dose monitoring • Light shielding (self-shielded preferred) • In-line/end-of-line and transportable • Operation with electric generators in areas with poor grid system • Variable energy, variable power • User-friendly control • Low to very high throughput • Reliability (no performance deficit, no failure modes) • Transportability (phytosanitary treatment) • Robustness of high-power electron-to-photon converters (targets)
Sterile insect technology	• Fully integrated <$300,000 • SWaP (compact, self-shielded, <1kW) • <$50,000 batch irradiators and ~$250,000 for in-line systems	• Robustness of conveyor and cooling system • Self-shielded • Modular • Operation with electric generators in areas with poor grid system • Transportable • User-friendly automated control • Reliability (no performance deficit, no failure modes) • Portability
Sterilization of medical devices and pharmaceuticals	• Fully integrated in-line: <$2.5 million • Transportation costs	• In-line and/or end-of-line operation • Self-shielding (non-concrete)

	• Losses from non-revenue generating inventory back-and-forth to irradiation center • SWaP	• Robustness and efficiency of electron-to-photon converters (targets) • Work in harsh manufacturing conditions • Work with sub-optimal electrical grid • Easy to operate

6.5.4 R&D Areas to Address Technology Gaps

The assessment of the difficulty of addressing the technology gaps was performed during the breakout sessions with the Engineering working group discussing the technology gaps and forming a list of the R&D needed to close the technology gaps. For the Medical applications, the following Engineering cost and ruggedization R&D areas to address the technology gaps were identified:

Application	**Cost R&D**	**Ruggedization R&D**
Development of low-cost, robust accelerators for clinical and preclinical use based upon a modular component approach	• Reduce SWaP via cheaper, more efficient accelerator structures and power sources • Additively manufactured accelerator structures and components • System parameter monitoring - to anticipate imminent hardware failures and maintenance needs (MTTR) • RFA Power efficiency - long term goal $1/RF Watt • Solid State RFA Power Efficiency - near term goal 70% wallplug to RF efficiency • Improved cavity power combiners (higher peak power operation) • Improved LINAC shunt impedance	• Technology to reduce reliance on local infrastructure (e.g., allow occasional power brown-outs or cooling system failure without disrupting operations) • System improvements that have tolerance to environmental conditions (temperatures to 45C, dust, etc.) • Self-diagnostics, automated control system, and simplified design to enable operation/maintenance without highly trained staff • Very stable accelerator structures • Reliable, stable electric power for medical accelerators via innovative energy storage technologies, smart PID controllers, and next-generation insulating materials and electrical components • Advanced, light weight shielding materials • Remote System Performance Assessment Diagnostics - just in time parts and service • Reduction of MTTR - improves up time • Solid State RFA - radiation/temperature tolerant sources • Robust cavity power combiners • Robust target materials and thermal management systems
Expansion of operational parameters for beam delivery and management including ultra-high dose-rate delivery	• Additively manufactured beam delivery system components • Research/pre-clinical stage - quantify medical efficacy and underlying radiobiology • Pulse format control (amplitude, shape, duration) and synchronization with radiobiologic diagnostics • Designs to enable proof of medical efficacy for high-dose-rate radiobiology effects	• Robust, temperature tolerant convertor (target) designs • Optimized thermal management system for convertors • Robust beam compression subsystem

Development of improved radiation detectors for dose distribution measurement and real time monitoring	• Low manufacturing/fabrication costs as resolution improves • High intrinsic efficiency	• Robust detector-grade materials • Shielding/collimators to reduce noise • Self-calibrating
Development of improved beam collimators for field shaping	• Self-calibrating geometry • Advanced collimator and shielding design and materials • Fast multi-leaf collimators	• No moving parts • Beam stability coupled with fast cavity scanning subsystems on distributed targets • Alternative electron beam scanning techniques to eliminate multi-leaf collimator
Simplification of accelerator operational and treatment planning systems to allow for real time treatment adaptation		
Plan and deliver radiation treatments to optimize biologically effective dose rather than physical dose	• Lower operating cost via improved operational efficiency • Lower capital cost (target $0.1 to $1 million) • Implement system health and controls	• Reliable, stable electric power • Very stable accelerator structures • Light-weight shielding/collimators • Robust, temperature tolerant convertor (target) designs
Development of compact neutron beam sources appropriate for neutron capture therapy	• More efficient CW Solid State RFA systems ($1/RF Watt) • New high shunt impedance structures to improve proton LINAC efficiency • Cost-effective Li and Be targets	• Robust, high efficiency, high-power targets • Very stable accelerator structures • Shielding/collimators to minimize fast neutron/gamma flux to no greater than those from the best reactor-produced epithermal beams

For the Security applications, the following Engineering cost and ruggedization R&D areas to address the technology gaps were identified:

Application	**Cost R&D**	**Ruggedization R&D**
Non-invasive probing with small sealed sources	• Cheaper, more efficient acceleration structures • More efficient power sources	• For well logging, the new structures must meet environmental requirements, but the main development is for high-temperature components. • Very stable compact new accelerator structures for NDT including more efficient power sources.
Radiography for nondestructive characterization	• Fast, high efficiency, energy-resolving detectors • Reliable automated threat recognition system in cargo inspection • Cheaper, more efficient acceleration structures • More efficient power sources	• High gradient accelerating cavities • Very stable new accelerator structures including more efficient, rugged power sources.
Food irradiation	• System cost <$250,000 • Cheaper, more efficient acceleration structures • More efficient power sources	• Very stable new accelerator structures • More efficient power sources • Improved shielding materials
Sterile insect technology	• Cheaper, more efficient acceleration structures	• Very stable new accelerator structures • More efficient power sources

	• More efficient power sources	
Sterilization of medical devices and pharmaceuticals	• Cheaper, more efficient acceleration structures • More efficient power sources	• Very stable new accelerator structures • More efficient power sources • Improved shielding materials

6.5.5 Technology Themes

Technology themes were generated by driving from specifics upward toward top-level binning into common themes providing an overall executive block diagram of beneficial R&D themes for advancing medical and security compact accelerator technologies. The 5 Engineering Technology Themes that resulted from this process were as follows:

(1) Improved Accelerator System Efficiency
(2) Advanced Manufacturing
(3) System Health and Controls
(4) Converters for High Power Density Pulsed Beams
(5) Low-Cost and Highly Reliable Accelerator Powering Systems

These themes are described in Chapter 5 of the BRN report.

6.6 Detector Panel

Deliberations of the Detector Panel have been captured in other sections of the workshop report.

6.7 Future Concepts Panel

The Future Concepts Panel met for the first time on May 7, 2019 after a day of introductory presentations and panel discussions on medical and security applications. Prior to this event there had been a number of teleconferences with the entire committee. In preparation for the Workshop both Future Concepts Panel Chairs had performed two major activities.

First, from the literature and their own experience they identified key scientists around the world involved in the development of advanced accelerators in order to get the broadest possible input for the committee's work. From this list they generated a prioritized list of potential invitees to the workshop and submitted this to DOE. Due to budgetary constraints only a small portion of the potential participants were eventually able to be invited to attend. A significantly larger group than the attendees were invited to provide input to the panel and much of this information was included in the presentations during the actual panel sessions and in the prepared background material.

A second major activity prior to the meeting was the assembly and production of an overview report on the status and direction of the technologies involved in future concepts. Called the Technology Perspectives Factual Document, or TPFD, this documents intent was to provide background to members of the complete panel so that all would have a basic knowledge of the field before the workshop began. (Other panels produced similar reports in their own area.) The TPFD saved valuable time during the workshop by eliminating the need for extensive and repetitive introductory talks from either the technical panels or applications panels.

A key desire of the workshop was to produce a set of ideas for future technological development which was application specific. That is, the goals of the development were specifically directed at the needs in the security and application areas rather than open ended research with non-specific goals. The TPFD and the applications panel sessions strived to identify particular needs that were not being met by existing systems: more compact, more efficient, robust and reliable, turnkey, self-diagnosing and calibrating, etc. Using the TPFD as a starting point the Future Concepts panel had presentations covering the major areas of technical development in the field. Attendees at that were not just experts in the technical development of accelerators but the group reached out to the medical and security applications committees so a number of those participants also attended to ensure that all major needs areas got addressed. A large number of technical development activities were consolidated into a set of themes which summarized the consensus views of needs for future development in a number of specific technical areas. Each was derived from a specific need identified by the technology panels and developed as an approach to resolve the technological shortcoming highlighted in the medical and security areas. This report was then generated by the committee members answering the CASM Workshop charge for each of the application areas, developing a possible roadmap for technology development and elucidating the major research themes for Future Accelerator Concepts which could resolve major technological shortfalls and make more viable the broad application of advanced accelerator technology.

A prioritized list of R&D, with estimates of level-of-effort, was developed for compact SRF[1]:

(1) Demonstration of small scale 10 MeV CW LINAC operating at 4K utilizing advanced cavity materials (Nb3Sn) and conduction cooling. Cavity gradient should be 10 MV/m or above. Operate the system for 6 months to verify robustness and lifetime of the materials. Characterize the beam and stability of the system (2.5 years, $3.5 million)

(2) Develop a photoinjector (5 years, $6 million. Possibly dual awards)

(3) Identify and characterize other materials beyond Nb3Sn which offer the potential of higher gradient and operation above 4K. Demonstrate ability to produce and apply these materials uniformly and effectively in the interior of a model cavity. (3 or 4 parallel programs, 4 years, $2.5 million)

(4) Develop and characterize a Version 2.0 high temperature compact SRF LINAC system. Goal should again be cavity operation through conduction cooling above 4K. In this system the operating gradient should be 15 MV/m or higher. The injector should be closely coupled to the rest of the LINAC in this upgraded version; ideally as a photocathode gun system in the same single cryomodule as the LINAC. ($5 million, 3 years after the initial Version 1.0 is performed).

(5) If new materials are found which offer substantially better performance or applicability (ease of manufacture, robustness, etc.) than Nb3Sn then apply the new materials technology to a demonstration system, first by demonstrating a prototype cavity and then a small LINAC system. (3 years $3.5 million)

(6) Develop a robust 4K cryocooler with twice the cooling power of any existing system and 30% higher electrical efficiency. (5 years $5 million)

(7) Develop high efficiency reliable rf drive systems compatible with SRF LINAC requirements. High power production from turnkey systems at frequencies up to 2.6 GHz is desirable. The systems should operate from modest voltages and be field replaceable. (7 years, $8 million)

(8) Develop a turnkey SRF LINAC control system including both beam, stand-by, and keep-alive functions and apply it to one of the high temperature demonstration test stands described above. (3 years, $3 million)

(9) Produce a prototype system incorporating all the advanced technologies developed in this effort as optimized for this particular application. Install and demonstrate its performance in a prototypical situation. (4 years, $8 million)

---

[1] Estimates of cost, time duration, and distribution of effort to advance the R&D are unvetted and unnormalized SWAGs, provided only to indicate scale.

References

References from Chapter 3

Well Logging and NDT of Structures

[ASME-2017] American Society of Mechanical Engineers (ASME). 2017. *ASME Boiler and Pressure Vessel Code: Nondestructive Examination*. Committee on Nondestructive Examination, ASME.

[Audutore-2005] Audutore, L., R.C. Barna, D. de Pasquale, U. Emanuele, A. Trifiro, M. Trimarchi, and A. Italiano. 2005. "A Compact 5 Mev S-Band Electron LINAC Based x-ray Source for Industrial Radiography," *Proceedings of Particle Accelerator Conference*, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/RPAP036.PDF (2005)

[Badruzzaman-1991] Badruzzaman, A. 1991. "Computational Methods in Nuclear Geophysics," *Progress in Nuclear Energy* **25**, 265.

[Badruzzaman-1998] Badruzzaman, A. 1998. "Multidetector Pulsed-Neutron Through-tubing Cased-Hole Density Measurement Sonde," US Patent No. 5,825,024.

[Badruzzaman-2002] Badruzzaman, A., T. Badruzzaman, P.T . Nguyen, and T. A. Zalan. 2002. "Oilfield Applications of Nuclear Modeling," *Proceedings of 12th Biennial American Nuclear Society Radiation Protection and Shielding Division Topical Meeting*, Santa Fe, NM.

[Badruzzaman-2005] Badruzzaman, A. 2005. "Nuclear Logging, Present and Future- An Operating Company Perspective," *Petrophysics* **46**, 3.

[Badruzzaman-2009] Badruzzaman, A., S. Barnes, F. Bair, and K. Grice. 2009. "Radioactive Sources in Petroleum Industry: Applications, Concerns and Alternatives," SPE 123593, *Proceedings SPE Asia Pacific Health, Safety, Security, and Environmental Conference and Exhibition*. Society of Petroleum Engineers.

[Badruzzaman-2014] Badruzzaman, A. 2014. "An Assessment of Fundamentals of Nuclear-Based Alternatives to Conventional Chemical-Source Bulk Density Measurement," *Petrophysics* **55**, 5, 413-434.

[Badruzzaman-2015] Badruzzaman, A., F. Dowla, H-T. Chen, A. Antolak, A. Schmidt, and S. Bakhtiari. 2018. "Scoping Study on Developing Alternatives to Radionuclide-based Logging Technologies," *LLNL-TR- 679101, October 30*, US Department of Energy, Lawrence Livermore National Laboratory, Livermore, California. Posted April, 2018. https://e-reports-ext.llnl.gov/pdf/803033.pdf

[Badruzzaman-2019] Badruzzaman, A., A. Schmidt, and A. Antolak. 2019. "Neutron Generators as Alternatives to Am-Be sources in Well Logging: An Assessment of Fundamentals," *Petrophysics* **60**, 1.

[Bondarenko-2017] Bondarenko, M. and V. Kulyk. 2017. "Radioactive Logging Tool with D-D Neutron Source for Investigation of Oil and Gas Reservoirs in Both Cased Wells and Logging-While-Drilling," *Workshop on Radioactive Well Logging Source Risk Mitigation, in ISTC and STCU Member States*.

[Chen-2013] Chen, A. X., A. J. Antolak, K.-N. Leung, T. N. Raber, and D. H. Morse. 2013. "Pulsed Pyroelectric Crystal Powered Gamma Source," *AIP Conference Proceedings* **1525**, 720.

[Day-1990] Day, S. N. J. and J. S. Petler. 1990. “Tool motion and borehole environments affect MWD neutron porosity measurements,” *Transactions of the 13th European Formation Evaluation Symposium*.

[de Beer-2006] de Beer, F. C. and M. F. Middleton. 2006. “Neutron Radiography Imaging, Porosity and Permeability in Porous Media,” *South African Journal of Geology* **109**.

[e-CFR-2019] e-CFR. 2019. *10 CFR part 34, Licenses For Industrial Radiography And Radiation Safety Requirements For Industrial Radiographic Operations*, https://www.nrc.gov/reading-rm/doc-collections/cfr/part034/

[Ellis-1995] Ellis, D.V., et al. 1995. “Adapting Wireline Logging Tools for Environmental Logging Applications,” *SPWLA 35th Annual Logging Symposium*.

[Ellis-2007] Ellis, D. V. and J. M. Singer. 2007. *Well Logging for Earth Scientists*, Second Edition, Springer, Dordrecht, The Netherlands.

[Evans-2000] Evans, M., R. Adolph, L. Vilde, C. Morris, P. Fissler, et al., 2000. "A Sourcess Alternative to Conventional LWD Nuclear Logging," Proceedings of the SPE Annual Technical Conference and Exhibition, SPE-62982.

[Eyl-1994] Eyl, K., H. Chapellat, P. Chevalier, C. Flaum, S. J. Whittaker, L. Jammes, A. J. Becker, and J. Groves. 1994. “High-Resolution Density Logging Using A Three Detector Device,” *Proceedings of the 69th SPE Annual Convention*.

[Flanagan-1991] Flanagan W. D., R .L. Bramblett, J. E. Galford, R. C. Hertzog, R. E. Plasek, J-R. Olesen. 1991. “A New Generation Nuclear Logging System,” *Proceedings of the SPWLA 32nd Annual Logging Symposium*.

[Galford-2009] Galford, J., J. Truax, A. Hrametz, and C. Haramboure. 2009. “A New Neutron-Induced Gamma Ray Spectroscopy Tool for Geochemical Logging,” *Transactions of the 50th SPWLA Annual Logging Symposium*. Also see SPE 123992, 2008, by the same authors.

[Hayward-2006] Hayward, P. and D. Currie. 2006. “Radiography of Welds using Selenium 75. IR 192 and x-rays,” 1*2th A-PCNDT, Asia-Pacific Conference on NDT*.

[Herron-1996] Herron S. L. and M. H. Herron. 1996. “Quantitative Lithology: An Application for Open- and Cased-hole Spectroscopy,” in *Transactions of the SPWLA 37th Annual Logging Symposium*.

[IAEA-1999] IAEA. 1999. “Safety Reports Series No. 13. ” *IAEA*, Austria, ISBN 92-0-100399-4

[IAEA-2003] IAEA. 2003. “Categorization of Radioactive Sources,” *IAEA-TECDOC-1344, Revision of IAEA-TECDOC-1191*, International Atomic Agency, Vienna, Austria.

[Jasti-1992] Jasti, J. K. and H. S. Fogler. 1992. “Application of Neutron Radiography to Image Flow Phenomenon in Porous Media,” *AIChE Journal* **38**, 481.

[Inanc-2009] Inanc, F., W. A. Gilchrist, R. Ansari, and D. Chace. 2009. “Physical Basis, Modeling, and Interpretation of a New Gas Saturation Measurement for Cased Wells,” *Transactions of the 50th Annual Logging Symposium of the Soc. of Petrophysicists and Well Log Analyst*.

[Jurczyk-2018] Jurczyk, B. J. 2018. "Compensated Neutron Logging Tool Using Neutron DD Generator for AmBe Replacement," *25th International Conference on the Application of Accelerators in Research and Industry (CAARI)*.

[Johnson-2014] Johnson, R. 2014. "Mobile Source Threat and Vulnerability Environment," *WINS Workshop on Security of Radionuclide Sources Used for Radiography and Well Logging*.

[King-1987] King III, G., R. L. Bramblett, A. J. Becker, G. W. Corris, and J. R. Boyce. 1987. "Density Logging Using An Electron Linear Accelerator as the x-ray Source," *Nuclear Instruments and Methods in Physics Research* **B24/25**, 990.

[LANL-2003/2008] LANL. 2003/2008. "A General Monte Carlo N-Particle Transport Code," Version 5, *LA-UR-03-1987, Los Alamos National Laboratory*, Los Alamos, NM. Published on April 24, 2003 and revised February 1, 2008.

[Lim-2005] Lim, C. S, and B. D. Sowerby. 2005. "On-line bulk Elemental Analysis in the Resource Industries Using Neutron-Gamma Techniques." *Journal of Radioanalytical and Nuclear Chemistry* **264**, 1, 15.

[Mickael-2002] Mickael, M., D. Phelps, and D. Jones. 2002. "Design, Calibration, Characterization, and Field Experience of New High-Temperature, Azimuthal, and Spectral Gamma Ray Logging-While-Drilling Tools," SPE 77481 *Proceedings of the SPE Annual Technical Conference and Exhibition*.

[NAS-2008] NAS. 2008. *Radiation Source Use and Replacement: Abbreviated Version*, Washington, DC: National Academies Press.

[Neuman-1999] Neuman, C. H., M. J. Sullivan, and D. L. Belanger. 1999. "An Investigation of Density Derived from Pulsed Neutron Capture Measurements," SPE 56647, *Proceedings of the SPE Annual Technical Conference and Exhibition.*

[NRC-1987] US NRC Regulations. 1987. *10 CFR Part 39, Licenses and Radiation Safety Requirements for Well Logging*, US Nuclear Regulatory Commission, 52 FR 8225.

[NRC-2006] Nuclear Regulatory Commission. 2006. "*Agreement State Report – Well Logging Source Damaged*," Event number: 42891, CA Report Number: 100706, a report from State of California to US Nuclear Regulatory Commission, October 8.

[Odom-1999] Odom, R. C., R. W. Streeter, and R. D. Wilson. 1999. "Formation Density Measurements Utilizing Pulse Neutrons," US Patent 5,900,627, April 4.

[Parker-2016] Parker, T. and P. Cooper. 2016. "Taking the Heat: Logging While Drilling at Extreme Temperatures," *IADC/SPE-180592-MS Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference*.

[Pemper-2006] Pemper, R., A. Sommer, P. Guo, D. Jacobi, J. Longo, S. Bliven, E. Rodriguez, F. Mendez, and X. Han. 2006. "A New Pulsed Neutron Sonde for Derivation of Formation Lithology and Mineralogy," SPE 102770 *Proceedings of the SPE Annual Technical Conference and Exhibition*.

[RadiaBeam-2019] RadiaBeam, 2019, "MicroLINAC Product Information," accessed April 4, https://www.radiabeamsystems.com/microLINAC

[Radtke-2012] Radtke, R. J., M. Lorente, B. Adolph, M. Berheide, S. Fricke, J. Grau, S. Herron, J. Horkowitz, B. Jorion, D. Madio, D. May, J. Miles, L. Perkins, O. Phillip, B. Roscoe, D. Rose, and C. Stoller. 2012. "A New Capture and Inelastic Spectroscopy Tool Takes Geochemical Logging to Next Level," *Proceedings of the 53rd SPWLA Annual Symposium*.

[Reichel-2012] Reichel, N., M. Evans, F. Allioli, M-L. Mauborgne, L. Nicoletti, F. Haranger, N. Laporte, C. Stoller, V. Cretoiu, E. El Hehiawy, and R. Rabrei. 2012. "NeutronGamma Density (NGD): Principles, Field Test Results and Log Quality Control of a Radioisotope-free Bulk Density Measurement," *Proceedings of the SPWLA 53rd Annual Symposium*.

[Rose-2015] Rose, D., T. Zhou, S. Beekman, T. Quinlan, M. Delgadillo, G. Gonzalez, S. Fricke, J. Thornton, D. Clinton, F. Gicquel, I. Shestakova, K. Stephenson, C. Stoller, O. Philip, J. M. L. R. Marin, S. Mainier, B. Perchonok, and J-P. Bailly. 2015. "An Innovative Slim Pulsed Neutron Logging Tool," *56th SPWLA Annual Symposium*.

[Roscoe-1991] Roscoe, B. A., C. Stoller, R. A. Adolph, J. C. Cheesborough, J. S. Hall, D. C. McKeon, D. Pittman, B. Seeman, and S. R. Thomas. 1991. "A New Through-tubing Oil-Saturation Measurement System," Paper 21413, *International Arctic Technology Conference*.

[Roscoe-1992] Roscoe, B. A., J. A. Grau, R. A. Manente, C. L. Melcher, C. A. Peterson, J. S. Schewitzer, and C. Stoller. 1992. "Use of GSO for Inelastic Gamma-ray Spectroscopy Measurement in the Borehole," *IEEE Transactions on Nuclear Science* **39**, 5.

[Roux-2005] Roux, I. J. 2005. "Is it Ultrasonic or is it Radiography inspection?" M Eng. (SA) RAE Engineering and Inspection Ltd., *2005 National Pressure Equipment Conference*.

[Schmidt-2012] Schmidt A., V. Tang, and D. Welch. 2012. "Fully Kinetic Simulations of Dense Plasma Focus Z-Pin. Devices," *Physical Review Letters* **109**, 20, 205003.

[Shilton-2017] Shilton, M. 2017. "Gamma Radiography," presentation to the *DHS/NNSA Alternative Technology Working Group, representing International Source Supplies and Producers Association (ISSPA)*.

[Simon-2018] Simon, M., A. Tkabladze, S. Beekman, T. Atobatele, M-A. De Looz, R. Grover, F. Hamichi, J. Jundt, K. McFarland, J. Mlcak, J. Reijonen, A. Revol, R. Stewart, J. Yeboah, and Y. Zhang. 2018. "A Novel x-ray Tool for True Sourceless Density Logging," *Petrophysics* **50**, 5.

[Smirnov-2018] Smirnov, A. V., R. Agustsson, M. Harrison, A. Murokh, A. Yu, S. Boucher, T. Campesee, K. J. Hoyt, E. A. Savin, and A. A. Zavadtsev. 2018. "Klylac Prototyping for Borehole Logging," *9th International Particle Accelerator Conference, Proceedings IPAC2018*, 1244-1246, DOI: 10.18429/JACoW-IPAC2018-TUZGBF5

[Twomey-1996] Twomey, M. 1996. "Inspection Techniques for Detecting Corrosion Under Insulation," *Inspectioneering Journal*, **Nov/Dec**.

[Ullo-1086] Ullo, J. J. 1986. "Use of Multidimensional Transport Methodology in Nuclear Logging," *Nuclear Science and Engineering* **92**, 2, 228-239.

[Wilson-1995] Wilson, R. D. 1995. "Bulk Density Logging with High-Energy Gammas Produced by Fast Neutron Reactions With Formation Oxygen Atoms," Paper NSS11-01, *Transactions of the IEEE Nuclear Science Symposium*.

[Zett-2012] Zett, A., M. Webster, H. Rose, S. Riley, D. Trcka, and N. Kadam. 2012. "Surveillance of Complex Displacement Mechanisms in Mature Reservoirs to Maximize Recovery," SPE 159185, in *Transactions of the Society of Petroleum Engineers Annual Technical Conference and Exhibition*.

Non-Destructive Characterization

[Akçay-2016] Akçay, S., M. E. Kundegorski, M. Devereux, and T. P. Breckon. 2016. "Transfer Learning Using Convolutional Neural Networks for Object Classification within x-ray Baggage Security Imagery," *2016 IEEE International Conference on Image Processing (ICIP)*, 1057.

[Amundson-2019] Amundson, J. 2019. "Computing for Future HEP Analysis," *2019 Meeting of the Division of Particles and Fields of the American Physical Society*.

[Bajura-2011] Bajura, M., G. Boverman, J. Tan, G. Wagenbreth, C. M. Rogers, M. Feser, J. Rudati, A. Tkachuk, S. Aylward, and P. Reynolds. 2011. "Imaging Integrated Circuits with x-ray Microscopy," *Proceedings of the 36th GOMACTech Conference*.

[Bauer-2014] Bauer, J., S. Hengsbach, I. Tesari, R. Schwiger, and O. Kraft. 2014. "High-Strength Cellular Ceramic Composites with 3D Microarchitecture," *Proceedings of the National Academy of Sciences* **111**, 7, 2453.

[BEA-2018] Bureau of Economic Analysis. 2018. *Underlying Detail of Industry Economic Accounts Data: GDP by Industry*, US Department of Commerce.

[Bendahan-2017] Bendahan, J. 2017. "Vehicle and Cargo Scanning for Contraband," *Physics Procedia* **90**, 242.

[Brady-2013] Brady, D. J., D. L. Marks, K. P. MacCabe, and J. A. O'Sullivan. 2013. "Coded Apertures For x-ray Scatter Imaging," *Applied Optics* **52**, 7745.

[Brown-1994a] Brown, D.R. 1994. "Cargo Inspection System Based on Pulsed Fast Neutron Analysis: An Update," *SPIE, Cargo Inspection Technologies* **2276**, 449.

[Brulte and Co.-2016] Brulte and Company. 2016. "These 3 Industries Are Getting Transformed By Advanced Manufacturing," https://www.brulteco.com/industries-getting-transformed-advanced-manufacturing

[Camp-2002] Camp, D.C., H. E. Martz Jr., G. P. Roberson, D. J. Decman, and R. T. Bernardi. 2002. "Non-Destructive Waste-Drum Assay for Transuranic Content by Gamma-Ray Active and Passive Computed Tomography," *Nuclear Instruments and Methods in Physics Research Section A* **495**, 69.

[Caroll, 2003] Carroll, F. E., M. H. Mendenhall, R. H. Traeger, C. Brau, and J. W. Waters. 2003. "Pulsed Tunable Monochromatic x-ray Beams from a Compact Source: New Opportunities," *American Journal of Roentgenology* **181**, 5, 1197.

[CFR21-1020.40, 2018] "Cabinet x-ray systems," *Code of Federal Regulations*, Title 21, Volume 8, Sec. 1020.40, 2018.

[Champley-2019] Champley, K. M., S. G. Azevedo, I. M. Seetho, S. M. Glenn, L. D. McMichael, J. A. Smith, J. S. Kallman, W. D. Brown, and H. E. Martz Jr. 2019. "Method to Extract System-Independent Material Properties from Dual-Energy x-ray CT," *IEEE Transactions on Nuclear Science*, **66**, 3, 674.

[CoLOSSISweb-2010] Lawrence Livermore National Laboratory. 2010. “Scientists Develop New CT Scanner To Image Nuclear Weapons Components,” https://www.llnl.gov/news/scientists-develop-new-ct-scanner-image-nuclear-weapon-components

[Croft-2006] Croft, S., D. S. Bracken, S. C. Kane, R. Venkataraman, and R. J. Estep. 2006. “Bibliography of Tomographic Gamma Scanning Methods Applied to Waste Assay and Nuclear Fuel Measurements,” *Proceedings of the 47th Annual Meeting of the INMM (Institute of Nuclear Materials Management)*.

[Cutmore-2010] Cutmore, N. G., Y. Liu, and J. R. Tickner. 2010. “Development and Commercialization of a Fast Neutron/x-ray Cargo Scanner,” *2010 IEEE International Conference on Technologies for Homeland Security (HST)*.

[Di Prima-2015] Di Prima, M., J. Coburn, D. Hwang, J. Kelly, A. Khairuzzaman, and L. Ricles. 2015. “Additively manufactured medical products – the FDA perspective,” *3D Printing in Medicine* **2**, 1.

[Du Plessis-2018] Du Plessis, A., I. Yadroitsev, I. Yadroitsava, and S. G. Le Roux. 2018. “x-ray Microcomputed Tomography in Additive Manufacturing: A Review of the Current Technology and Applications,” *3D Printing and Additive Manufacturing* **5**, 3, 227.

[Endrizzi-2018] Endrizzi, M. 2018. “x-ray Phase-Contrast Imaging,” *Nuclear Instruments and Methods in Physics Research A* **878**, 88.

[Estep-1994] Estep, R. J., T. H. Prettyman, and G. A. Sheppard. 1994. “Tomographic Gamma Scanning to Assay Heterogeneous Radioactive Waste,” *Nuclear Science Engineering* **118**, 3, 145.

[FAA-2017] Federal Aviation Administration. 2017. *The Economic Impact of Civil Aviation on the US Economy*, US Department of Transportation, Washington DC.

[FDA-2016] Food and Drug Administration. 2016. *Technical Considerations for Additive Manufactured Devices—Draft Guidance for Industry and Food and Drug Administration Staff*, US Food and Drug Administration, Center for Devices and Radiological Health, Silver Spring, MD.

[Gardner-2019] Gardener, D. F., S. Divitt, and A. Watnik. 2019. “Ptychographic Imaging Of Incoherently Illuminated Extended Objects Using Speckle Correlations,” *Applied Optics* **58**, 13, 3564.

[Geddes-2017] Geddes, C. G. R., B. Ludewigt, J. Valentine, B. J. Quiter, M-A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, and S. Pozzi. 2017. *Impact of Monoenergetic Photon Sources on Nonproliferation Applications*, Idaho National Laboratory, INL/EXT-17-41137.

[Gonzales-2013] Gonzales B., D. Spronk, Y. Cheng, Z. Zhang, X. Pan, M. Beckmann, O. Zhou, and J. Lu. 2013. “Rectangular Computed Tomography Using a Stationary Array of CNT Emitters: Initial Experimental Results,” *SPIE Medical Imaging* **86685K**, International Society of Optics and Photonics.

[Gonzales-2014] Gonzales B., D. Spronk, Y. Cheng, A. W. Tucker, O. Zhou, and J. Lu. 2014. “Rectangular Fixed-Gantry CT Prototype: Combining CNT x-ray Sources and Accelerated Compressed Sensing-Based Reconstruction,” *IEEE Access* **2**, 971.

[Greenberg-2019] Greenberg J. 2019. X-*ray Diffraction Imaging, Technology and Applications*, CRC Press, Boca Raton FL.

[Hall-2015] Hall, C., S. Biedron, A. Edelen, S. Milton, S. Benson, D. Douglas, R. Li, C. Tennant, and B. Carlsten. 2015. "Measurement and Simulation of the Impact of Coherent Synchrotron Radiation on the Jefferson Laboratory Energy Recovery LINAC Electron Beam," *Physical Review Special Topics–Accelerators and Beams* **18**, 030706.

[Harding-2009] Harding, G. 2009 "x-ray Diffraction Imaging - A Multi-Generational Perspective," *Applied Radiation and Isotopes* **67**, 2, 287.

[Harding-2012] Harding, G., H. Fleckenstein, D. Kosciesza, S. Olesinski, H. Strecker, T. Theedt, and G. Zienert. 2012. "x-ray Diffraction Imaging with Multiple Inverse Fan Beam Technology: Principles, Performance, and Potential for Security Screening," *Applied Radiation and Isotopes* **70**, 7, 1228.

[Holler-2017] Holler, M., M. Guizar-Sicairos, E.H.R. Tsai, R. Dinapoli, E. Muller, O. Bunk, J. Rabbe, and G. Aeppli. 2017. "High-Resolution Non-Destructive Three-Dimensional Imaging Of Integrated Circuits," *Nature* **543**, 402.

[IEER, 2012] Institute for Energy and Environmental Research. 2012. *Classifications of Nuclear Waste,* https://ieer.org/resource/classroom/classifications-nuclear-waste/

[JFAC-2015] Hurt, T. 2015. "Department of Defense Joint Federated Assurance Center (JFAC) Update," *National Defense Industrial Association (NDIA), 18th Annual NDIA Systems Engineering Conference*. US Department of Defense, Joint Federated Assurance Center.

[Katsouleas-2008] Katsouleas, T., R. Alarcon, J. Albertine, I. Ben-Zvi, S. Biedron, C. A. Brau, W. Colson, R. C. Davidson, P. G. Gaffney II, L. Merminga, J. Miller, B. E. Newnam, P. O'Shea, C. K. N. Patel, D. Prosnitz, and E. Zimet. 2008. *Scientific Assessment of High-Power Free-Electron Laser Technology,* Committee on a Scientific Assessment of Free- Electron Laser Technology for Naval Applications, Board on Physics and Astronomy, Division on Engineering and Physical Sciences, The National Academies, December.

[Lakes, 2001] Lakes, R., T. Lee, A. Bersie, and Y. C. Wang. 2001. "Extreme damping in composite materials with negative-stiffness inclusions," *Nature* **410**, 565.

[Ledoux-2018] Ledoux, R. J. 2018. "Advances in Nondestructive Elemental Assaying Technologies," *Applications of Laser-Driven Particle Acceleration*, Chapter 23, CRC Press.

[LANL-2019] Los Alamos National Laboratory 2019. "Weapons Neutron Research Facility at LANSCE," https://lansce.lanl.gov/facilities/wnr/index.php

[Lehmann-2003] Lehmann, E. H., P. Vontobel, and A. Hermann. 2003. "Non-Destructive Analysis Of Nuclear Fuel By Means Of Thermal And Cold Neutrons," *Nuclear Instruments and Methods in Physics Research Section A* **515**, 3, 745.

[Lewis-1997] R. Lewis. 1997. "Medical Applications Of Synchrotron Radiation x-rays," *Physics in Medicine and Biology* **42**, 7), 1213.

[Li-2019a] Li, S., G. Barbastathis, and A. Goy. 2019. "Analysis of Phase-Extraction Neural Network (PhENN) performance for lensless quantitative phase imaging," *Proceedings of the SPIE 10887, Quantitative Phase Imaging V*

[Li-2019b] Li, R. K., et al. 2019. "Terahertz-based Subfemtosecond Metrology of Relativistic Electron Beams," Physical Review Accelerators and Beams 22, 1, 012803.

[Lisowski-1990] Lisowski, Bowman, Russell, and Wender, “The Los Alamos National Laboratory Spallation Neutron Source”, Nuclear Science and Engineering, vol 106 p208-218 (1990).

[Liu-2008] Liu, Y., B. D. Sowerby, and J. R. Tickner. 2008. “Comparison Of Neutron And High-Energy x-ray Dual-Beam Radiography For Air Cargo Inspection,” *Applied Radiation and Isotopes* **66**, 463.

[Lu-2019] Lu, X., Y. Shao, C. Zhao, S. Konijnenberg, X. Zhu, Y. Tang, Y. Cai, H. P. Urbach. **2019**. “Noniterative Spatially Partially Coherent Diffractive Imaging Using Pinhole Array Mask,” *Advanced Photonics* **1**, 1, 016005.

[Maiden-2012] Maiden, A. M., M. J. Humphry, and J. M. Rodenburg. 2012. “Ptychographic Transmission Microscopy In Three Dimensions Using A Multi-Slice Approach,” Journal of the Optical Society of America **29**, 8, 1606.

[Mathuriya-2018] Mathuriya, A., D. Bard, P. Mendygral, L. Meadows, J. Arnemann, L. Shao, S. He, T. Karn, D. Moise, S. J. Pennycook, K. Maschhoff, J. Sewall, N. Kumar, S. Ho, M.F. Ringenburg, Prabhat, and V. Lee. 2018. “CosmoFlow: Using Deep Learning to Learn the Universities at Scale,” *ArXiv e-prints*, August.arXiv: 1808.04728v2.[astro-ph.CO] 9 Nov 2018

[Martz-2009] Martz Jr. H. E. and C. R. Crawford. 2009. “Overview of Deployed EDS Technologies,” *Technical Report LLNL-TR-417232*, Lawrence Livermore National Laboratory.

[Martz-2017a] Martz Jr. H. E., C. M. Logan, D. J. Schneberk, and P. J. Shull. 2017. X-*ray Imaging: Fundamentals, Industrial Techniques and Applications*, CRC Press, Boca Raton.

[Martz-2017b] Martz, Jr., H.E., S. M. Glenn, J. A. Smith, C. J. Divin, and S. G. Azevedo. 2016. “Poly- versus Mono-energetic Dual-spectrum Non-intrusive Inspection of Cargo Containers,” *IEEE Transactions on Nuclear Science* **64**, 1709, DOI:10.1109/TNS.2017.2652455

[Melton-2015] Melton, S., C. Moss, and R. Estep. 2015. “Study of the Requirements for Monoenergetic Photon Sources,” Los Alamos project report for DNDO.

[Milton-2016] Milton, S. 2016. “1D FEL Simulations Utilizing Laser Undulators,” *High-Brightness Sources and Light-Driven Interactions, Proceedings of the Compact (EUV and x-ray) Light Sources Conference*, OSA technical Digest (online), Optical Society of America, paper ET3A.3.

[MForesight-2018] MForesight: Alliance for Manufacturing Foresight Report. 2018. *Metamaterials Manufacturing: A Pathway to Industrial Competitiveness*, Bishop-Moser, J., C. Spadaccini, and C. Andres, (Eds.).

[Morton-2009] Morton, E., K. Mann, A. Berman, M. Knaup, and M. Kachelrie. 2009. “Ultrafast 3D reconstruction for x-ray real-time tomography (RTT),” *Nuclear Science Symposium Conference Record (NSS/MIC)*, IEEE, 4077.

[NAP-24A, 2015] *Weapon Quality Policy*, NNSA Policy Letter NAP-24A, approved 11-24-15.

[NIST-2017] National Institute of Standards and Technology. 2017. *A Guide to United States Electrical and Electronic Equipment Compliance Requirements*, document NISTIR 8118r1.

[NNSA-2017] “Prevent, Counter, and Respond: A Strategic Plan to Reduce Global Nuclear Threats.” 2017. DOE NNSA Report to Congress.

[NNSA-SIR-2019] NNSA Strategic Integrated Roadmap 2020-2044, May 2019.

[NRC-2013] Nuclear Regulatory Legislation. 2013. 112th Congress; 2nd Session, US Nuclear Regulatory Commission, *NUREG-0980* **1**, 10, September 2013.

[NRC-2018a] Nuclear Regulatory Commission. 2018. "Occupational Dose Limits for Adults," CFR 20.1201, subpart C.

[NRC-2018b] Nuclear Regulatory Commission. 2018. "Radiation Dose Limits for Individual Members of the Public," CFR 20.1301, subpart D.

[NRC-2018c] Nuclear Regulatory Commission. 2018. "High Level Waste: What We Regulate," https://www.nrc.gov/waste/hlw-disposal/what-we-regulate.html

[NRCP, 2003] National Council on Radiation Protection and Measurements. 2003. "Presidential Report on Radiation Protection Advice for the Pulsed Fast Neutron System Used in Security Surveillance: Part III Methods for the Determination of Effective Dose to Inadvertently Exposed Individuals," July 31.

[NCRP, 2007] National Council on Radiation Protection and Measurements. 2007, "Commentary No. 20 – Radiation Protection and Measurement Issues Related to Cargo Scanning with Accelerator-Produced High-Energy X Rays," December 5. NRCP

[OIA-2018] Outdoor Industry Association. 2018. "Airport Security Market to Grow at 7% CAGR from 2017 to 2024," https://outdoorindustry.org/press-release/airport-security-market-to-grow-at-7-cagr-from-2017-to-2024/, April 12, 2018.

[Overley-1995] Overley, J. C., M. S. Chmelic, R. J. Rasmussen, R. M. S. Schofield, and H. W. Lefevre. 1995. "Explosives Detection through Fast-Neutron Time-of-Flight Attenuation Measurements," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **99**, 728.

[Paganini-2018] Paganini, M., L. de Oliveira, and B. Nachman. 2018. "Calogan: Simulating 3d High Energy Particle Showers in Multilayer Electromagnetic Calorimeters with Generative Adversarial Networks," *Physical Review D* **97**, 014021.

[Paglieroni, 2018] Paglieroni, D. W., H. Chandrasekaran, C. Pechard, and H. E. Martz Jr. 2018. "Consensus Relaxation on Materials of Interest for Adaptive ATR in CT Images of Baggage," *Proceedings of the SPIE SI18D, SPIE Defense and Security Symposium,* Anomaly Detection and Imaging with x-rays (ADIX) III.

[Perry-2001] Perry, J. L. and T. D. Gamble. 2001. "Continuous High Speed Tomographic Imaging System and Method," US Patent 6236709B1

[PFNA-2002] "Assessment of the Practicality of Pulsed Fast Neutron Analysis for Aviation Security," Griffin, P. (chair), R. Berkebile, H. Boyton, L. Limmer, H. Martz, and C. Oster, Jr., Committee on Commercial Aviation Security, Panel on the Assessment of Practicality of Pulsed Fast Neutron Transmission Spectroscopy for Aviation Security, National Materials Advisory Board, National Research Council, Contract No. DTF-A02-99-C00006, 2002.

[PFNTS-1999] "The Practicality of Pulsed Fast Neutron Transmission Spectroscopy for Aviation Security," Griffin, P. (chair), R. Berkebile, H. Boyton, L. Limmer, H. Martz, and C. Oster, Jr., Committee on Commercial Aviation Security, Panel on the Assessment of Practicality of Pulsed Fast Neutron Transmission Spectroscopy for Aviation Security, National Materials Advisory Board, National Research Council, Report No. DOT/FAA/AR-99/17, March 1999.

[Rapiscan-2019] Rapiscan Systems, 2019. "RTT110 System," https://www.rapiscansystems.com

[Rodenburg-2007] Rodenburg, J.M. , A.C. Hurst, A.G. Cullis, B.R. Dobson, F. Pfeiffer, O. Bunk, C. David, K. Jefimovs, and I. Johnson. 2007. "Hard-x-ray Lensless Imaging of Extended Objects," *Physical Review Letters* **98**, 3, 034801.

[Rose, 2016] Rose, P. B., A. S. Erickson, M. Mayer, J. Nattress, and I. Jovanovic. 2016. "Uncovering Special Nuclear Materials by Low-Energy Nuclear Reaction Imaging," *Scientific Reports* **6**, 24388.

[Rynes-1999] Rynes, J., J. Bendahan, T. Gozani, R. Loveman, J. Stevenson, and C. Bell. 1999. "Gamma-Ray and Neutron Radiography as Part of a Pulsed Fast Neutron Analysis System," *Nuclear Instruments and Methods in Physics Research A* **422**, 895.

[SandTR-2009] "A CAT Scanner for Nuclear Weapons Components," 2009. *Science and Technology Review*, **July/August**, 12-17, Lawrence Livermore National Laboratory.

[Schaedler-2011] Schaedler, T. A., A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit, and W. B. Carter. 2011. "Ultralight metallic microlattices," *Science* **334**, 6058, 962.

[Schleede-2012] Schleede, S., F. G. Meinel, M. Bech, J. Herzen, K. Achterhold, G. Potdevin, A. Malecki, S. Adam-Neumair, S. F. Thieme, F. Bamberg, K. Nikolaou, A. Bohla, A. Ö. Yildirim, R. Loewen, M. Gifford, R. Ruth, O. Eickelberg, M. Reiser, and F. Pfeiffer. 2012. "Emphysema Diagnosis using x-ray Dark-Field Imaging at a Laser-Driven Compact Synchrotron Light Source," *PNAS* **109**, 44, 17880.

[Seifi, 2017] Seifi, M., M. Gorelik, J. Waller, N. Hrabe, N. Shamsael, S. Daniewicz, and J. J. Lwandowski. 2017. "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification," *JOM* **69**, 3, 439.

[Shizuma-2012] Shizuma, T., T. Hayakawa, R. Hajima, N. Kikuzawa, H. Ohgaki, and H. Toyokawa. 2012. "Nondestructive Identification Of Isotopes Using Nuclear Resonance Fluorescence," *Review of Scientific Instruments* **83**, 015103; https://doi.org/10.1063/1.3673002

[Singh-2003] Singh, S., and M. Singh. 2003. "Review of Explosives Detection Systems (EDS) for Aviation Security," *Signal Process* **83**, 1, 31.

[Sigmund-1997] Sigmund, O., and S. Torquato. 1997. "Design of materials with extreme thermal expansion using a three-phase topology optimization method." *Journal of the Mechanics and Physics of Solids* **45**, 60, 1037.

[Smith-1993] Smith, S.W. 1993. "x-ray Backscatter Detection System," US Patent 5181234, January 19.

[Spadaccini-2015] Spadaccini, C. M. 2015. "Mechanical Metamaterials: Design, Fabrication, and Performance," *Linking Engineering and Society. Bridge* **45**, 4, 28.

[Strecker-1993] Strecker, H. and G. Harding. 1993. “Detection of Explosives in Airport Baggage Using Coherent x-ray Scatter,” *Proceedings of the SPIE* 2092-48, 399.

[SSMP-2018] “FY2019 Stockpile Stewardship and Management Plan – Biennial Plan Summary,” DOE NNSA Report to Congress, October 2018.

[Sun-2010] Sun, Y. 2010. *Field Detection Technologies for Explosives*, ILM Publications, Glendale, AZ.

[Thompson-2016] Thompson, A., I. Maskery, and R.K. Leach. 2016. “x-ray Computed Tomography for Additive Manufacturing: A Review,” *Measurement Science and Technology* **27**, 072001.

[Wells-2016] Wells, D. 2016. *Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware*, Marshall Space Flight Center, Huntsville, AL.

[Zhang-2019] Zhang, D., G. van der Wal, P. Miller, D. Stoker, E. Matlin, N. Marri, G. Gan, J. Zhang, J. Asmuth, S. Chai, D. Weaver, M. Piacentino, S. Silverman, M. DiBattista, R. Chivas, C. G. Ferri, D. Taylor, J. Furlong, T. Harper, and D. Kobs. 2019. “Fast, Full Chip Image Stitching of Nanoscale Integrated Circuits,” Defense Technical Information Center report AD1075372.

Food Processing

[FDA-2019] US Food and Drug Administration. 2019. “Irradiation in the Production, Processing and Handling of Food,” CFR-Title 21, Part 179. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfCFR/CFRSearch.cfm?fr=179.26. Accessed October 27, 2019

[Ferrier-2011] Ferrier, P. 2011. “Irradiation of Produce Imports: Small Inroads, Big Obstacles,” Amber Waves. June 16. US Department of Agriculture-Agricultural Research Service.

[PandS-2018] P&S Market Research. 2018. “Seasonings and Spices Market Size to Reach $30 Billion by 2023,” https://www.globenewswire.com/news-release/2018/02/19/1361180/0/en/Seasonings-and-Spices-Market-Size-to-Reach-30-412-8-million-by-2023-P-S-Market-Research.html. Accessed October 27, 2019.

[Pillai-2017] Pillai, S. D. and S. Shayanfar. 2017. “Electron Beam Technology and Other Irradiation Technology Applications in the Food Industry,” *Applications of Radiation Chemistry in the Fields of Industry, Biotechnology and Environment*, (eds.) Venturi, M., and M. D’Angelantonio, Springer Verlag.

[Kume-2008] Kume, T., M. Furuta, S. Todoriki, N. Uenoyama, and Y. Kobayashi. 2008. “Status of Food Irradiation in the World,” *Radiation Physics and Chemistry* **78**, 222-226

[USDA-2019] United States Department of Agriculture, Economic Research Service, 2019. “Data Products – Fruit and Tree Nut Data – Data by Commodity,” https://www.ers.usda.gov/data-products/fruit-and-tree-nut-data/data-by-commodity/

[USDA-FAS-2018] US Department of Agriculture-Foreign Agricultural Service. 2018. “Global Agricultural Trade System (GATS),” https://apps.fas.usda.gov/gats/default.aspx, Accessed October 27, 2019.

Medical Devices

[Frost and Sullivan-2016] Frost and Sullivan. 2016. “2012 Medical Devices Outlook: Setting the Stage for What’s Next,” April 28, 2016, https://ww2. frost. com/frost-perspectives/outlook-healthcare-and-medical-devices-connectivity-test-industry-growth-opportunities/

[IIA-2017] International Irradiation Association. 2017. “White paper - A comparison of Gamma, E-Beam, x-ray and Ethylene Oxide Technologies for the Industrial Sterilization of Medical Devices and Healthcare Products. IIA,” August, 2017.

[Markets and Markets Research-2016] Markets and Markets Research, 2016, “Sterilization Equipment Market: By Type, Product, End User and By Region – Forecast to 2021,” September 2016.

[Murphy-2019] Murphy, M. K. , L. S. Fifield, S. D. Pillai, D. Staack, T. Faucette, L. Nichols, and J. Logar. 2019. “Filling Data Gaps Related to Material Effects in Polymer Medical Products from Ebeam and x-ray Sterilization. Abstract.” *International Meeting on Radiation Processing, IMRP19.*

[SelectUSA-2018] SelectUSA. 2018. “Medical Technology Spotlight,” U. S. Department of Commerce, accessed March 28, 2018, www.selectusa.gov/medical-technology-industry-united-states.

Sterile Insect Technology

[Bakri-2005] Bakri, A., K. Mehta, and D. R. Lance. 2005. “Sterilizing Insects with Ionizing Radiation,” *Sterile Insect Technique. Principles and Practice in Area-Wide Integrated Pest Management*. Dyck, V.A., J. Hendrichs, and A.S. Robinson (Eds). Springer, 233-268.

[Dyck-2005] Dyck, V. A., J. Hendrichs, and A. S. Robinson (Eds). 2005. “Sterile Insect Technique. Principles and Practice in Area-Wide Integrated Pest Management,” Springer. Dordrecht, The Netherlands. ISBN-10 1-4020-4050-4

[Vargas-Teran-2005] Vargas-Teran, M., H. C. Hofmann, and N. E. Tweddle. 2005. “Impact of Screwworm Eradication Programmes Using the Sterile Insect Technique,” *Sterile Insect Technique. Principles and Practice in Area-Wide Integrated Pest Management*. Dyck, V.A., J. Hendrichs, and A.S. Robinson (Eds). Springer, 629-650.

References from Chapter 4

[Abdel-Wahab-2013] Abdel-Wahab, M., J. M. Bourque, Y. Pynda, J. Iżewska, D. Van der Merwe, E. Zubizarreta, and E. Rosenblatt. 2013. “Status of Radiotherapy Resources in Africa: An International Atomic Energy Agency Analysis,” *Lancet Oncology* **14**, 4, e168.

[ACS-2019] American Cancer Society. 2019. *Cancer Facts and Figures 2019.*

[Atun-2015] Atun, R., D. A. Jaffray, M. B. Barton, B. Vikram, T. P. Hanna, F. M. Knaul, Y. Lievens, T. Y. M. Lui, M. Milosevic, B. O’Sullivan, D. L. Rodin, E. Rosenblatt, J. Van Dyk, M. L. Yap, E. Zubizarreta, and M. Gospodarowicz. 2015. “Expanding Global Access to Radiotherapy,” *Lancet Oncology* **16**, 10, 1153

[Bartolac-2011] Bartolac, S., S. Graham, J. Siewerdsen, and D. Jaffray. 2011. “Fluence Field Optimization for Noise and Dose Objectives in CT,” *Medical Physics Supplement* **1**, S2. doi: 10.1118/1.3574885. PMID: 21978144

[Benedetti-2017] Benedetti S., A. Grudiev, A. Latina. 2017, “High Gradient Linac for Proton Therapy,” *Physical Review Accelerators and Beams* **20**, 040101.

[Bin-2019] Bin, J., Q. Ji, P. Seidl, D. Raftrey, S. Steinke, A. Persaud, K. Nakamura, A. Gonsalves, W. P. Leemans, and T. Schenkel. 2019. “Absolute Calibration of GafChromic Film for Very High Flux Laser Driven Ion Beams,” *Review of Scientific Instruments* **90**, 5, 053301.

[Black-2019] Black, D. S., K. J. Leedle, Y. Miao, U. Niedermayer, R. L. Byer, and O. Solgaard. 2019. “Laser-Driven Electron Lensing in Silicon Microstructures,” *Physical Review Letters* **122**, 104801.

[Boss-2014] Boss, M-K., R. Bristow, and M. W. Dewhirst. 2014. “Linking the History of Radiation Biology to the Hallmarks of Cancer,” *Radiation Research* **181**, 6, 561-577.

[Bourhis-2019] Bourhis, J., W. Jeanneret-Sozzi, P. Goncalves-Jorge, O. Gaide, C. Bailat, F. Duclos, D. Patin, M. Ozsahin, F. Bochud, J-F. Germond, R. Moeckli, and M-C. Vozenin. 2019. “Treatment of a First Patient with FLASH-Radiotherapy,” *Radiotherapy and Oncology* **139**, 18.

[Buonanno-2019] Buonanno, M., V. Grilj, and D. J. Brenner. 2019. Biological Effects in Normal Cells Exposed to FLASH Dose Rate Protons. *Radiotherapy and Oncology* **139**, 51.

[Busse-2003] Busse, P. M., O. K. Harling, M. R. Palmer, W. S. Kiger, J. Kaplan, I. Kaplan, C. F. Chuang, J. T. Goorley, K .J. Riley, T. H. Newton, G. A. Santa Cruz, X-Q. Lu, and R. G. Zamenhof. 2003. “A Critical Examination of the results from the Harvard-MIT NCT program phase I clinical trial of neutron capture therapy for intracranial disease,” *Journal of Neurooncology* **62**, 1-2, 111.

[Cancer Research UK-n. d.] *Cancer Research UK*, www.cancerresearchuk.org, Accessed May, 2019

[Capala-2003] Capala, J. , H. B. Stenstam, K. Skold, P. Munck af Rosenschöld, V. Giusti, C. Persson, E. Wallin, A. Brun, L. Franzen, J. Carlsson, L. Salford, C. Ceberg, B. Persson, L. Pellettieri, and R. Henriksson. 2003. “Boron Neutron Capture Therapy for Glioblastoma Multiforme: Clinical Studies in Sweden,” *Journal of Neuro-Oncology* **62**, 135-144.

[Caroll, 2003] Carroll, F. E., M. H. Mendenhall, R. H. Traeger, C. Brau, and J. W. Waters. 2003. “Pulsed Tunable Monochromatic x-ray Beams From A Compact Source: New Opportunities,” *American Journal of Roentgenology* **181**, 5, 1197.

[Ceballos-2001] Ceballos C., J. Esposito, S. Agosteo, P. Colautti, et al. 2011. “Towards the Final BSA Modeling for the Accelerator-Driven BNCT Facility at INFN LNL,” *Applied Radiation and Isotopes* **69**, 1660-1663.

[Ceballos-2019] Ceballos, A. 2019. “Silicon Photocathodes for Dielectric Laser Accelerators,” PhD Dissertation Defense, Stanford University.

[Cesar-2018] Cesar, D., J. Maxon, P. Musumeci, X. Shen, R. J. England, K. P. Wootton, and S. Tan. 2018. “Enhanced Energy Gain in a Dielectric Laser Accelerator Using a Tilted Pulse Front Laser,” *Optics Express* **26**, 22, 29216.

[Chang-2014] Chang, C-M., and O. Solgaard. 2014. “Silicon Buried Gratings For Dielectric Laser Electron Accelerators,” *Applied Physics Letters* **104**, 184102.

[Cram,er-Sargison-2015]Cranmer-Sargison, G., C. Crewson, W. Davis, N. P. Sidhu, and V. Kundapur. 2015. “Medical Linear Accelerator Mounted Mini-Beam Collimator: Design, Fabrication And Dosimeteric Characterization,” *Physics in Medicine and Biology* **60**, 17, 6991.

[Deng-2007] Deng, H., C. W. Kennedy, E. Armour, E. Tryggestad, E. Ford, T. McNutt, L. Jiang, and J. Wong. 2007. “The Small-Animal Radiation Research Platform (SARRP): Dosimetry of a Focused Lens System,” *Physics in Medicine and Biology* **52**, 10, 2729

{Diaz-2003] Diaz, A. Z. 2003. “Assessment of the Results from the Phase I/II Boron Neutron Capture Therapy Trials at the Brookhaven National Laboratory from a Clinicians Point of View. ” *Journal of Neuro-Oncology*, **62**, 101.

[England-2014] England, R. J. and R. J. Noble, eds. 2014. “Dielectric Laser Accelerators,” *Reviews of Modern Physics* **86**, 1337.

[Fagotti-2008] Fagotti E., M. Comunian, A. Palmieri, A. Pisent, et al. 2008. “Fabrication and Testing of TRACO RFQ,” *Proceedings LINAC08 Conference*, 151-154.

[Favaudon-2014] Favaudon V., L. Caplier, V. Monceau, F. Pouzoulet, M. Sayarath, C. Fouillade, M. F. Poupon, I. Brito, P. Hupé, J. Bourhis, J. Hall, J. J. Fontaine, and M. C. Vozenin. 2014. “Ultrahigh Dose-Rate FLASH Irradiation Increases the Differential Response between Normal and Tumor Tissue in Mice,” *Science Translational Medicine* **6**, 245, ra93

[Geddes-2017] Geddes, C. G. R., B. Ludewigt, J. Valentine, B. J. Quiter, M-A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, and S. Pozzi. 2017. *Impact of Monoenergetic Photon Sources on Nonproliferation Applications*, Idaho National Laboratory, INL/EXT-17-41137.

[Guardioloa-2018] Guardiola, C., Y. Prezado, C. Roulin, and J. W. J. Bergs. 2018. “Effect of x-ray Minibeam Radiation Therapy on Clonogenic Survival of Glioma Cells,” *Clinical and Translational Radiation Oncology* **13**, 7.

[Hawthrone-2003] Hawthorne, M. F. and M. W. Lee. 2003. A Critical Assessment of Boron Target Compounds for Boron Neutron Capture Therapy. *Journal of Neuro-Oncology* **62**, 33.

[Heber-2012] Heber, E. M., P. J. Kueffer, M. W. Lee Jr., M. F. Hawthorne, M. A. Garabalino, A. J. Molinari, D. W. Nigg, W. Bauer, A. M. Hughes, E. C. Pozzi, V. A. Trivillin, and A. E. Schwint. 2012. “Boron Delivery with Liposomes for Boron Neutron Capture Therapy (BNCT): Biodistribution Studies in an Experimental Model of Oral Cancer Demonstrating Therapeutic Potential,” *Radiation and Environmental Biophysics* **51**, 195.

[Hughes-2018] Hughes, T. W. , S. Tan, Z. Zhao, N. V. Sapra, K. J. Leedle, H. Deng, Y. Miao, D. S. Black, O. Solgaard, J. S. Harris, J. Vuckovic, R. L. Byer, S. Fan, R. J. England, Y. J. Lee, and M. Qi, 2018. “On-Chip Laser-Power Delivery System for Dielectric Laser Accelerators,” *Physical Review Applied* **9**, 054017.

[IAEA Report TRS-398-2000] IAEA Report TRS-398: Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water IAEA. Vienna, Austria, 2000.ISSA 1011-4289.

[ICRU-1962] National Bureau of Standards, US Department of Commerce, *Radiobiological Dosimetry, Handbook 88, Recommendations of the International Commission on Radiological Units and Measurements (ICRU), Report 10e 1962*.

[Inaniwa-2019] Inaniwa, T. , M. Suzuik, S. Sato, A. Noda, M. Muramatsu,Y. Iwata, and N. Kanematsu, T. Shirai, and K. Noda. 2019. "Influence of a perpendicular magnetic field on biological effectiveness of carbon-ion beams," *International Journal of Radiation Biology* **95**, 9, 1346-1350, doi: 10.1080/09553002.2019.1625461

[Islam-2009] Islam, M. K. , B. D. Norrlinger, J. R. Smale, R. K. Heaton, D. Galbraith, C. Fan, and D. A. Jaffray. 2009. "An integral quality monitoring system for real-time verification of intensity modulated radiation therapy," *Medical Physics* **36**, 5420. PMID: 20095254.

[Jaccard-2018] Jaccard, M. , M. T. Durán, K. Petersson, J. F. Germond, P. Liger, M. C. Vozenin, J. Bourhis, F. Bochud F1, Bailat C1. 2018. "High Dose-per-Pulse Electron Beam Dosimetry: Commissioning of the Oriatron Ert6 Prototype Linear Accelerator for Preclinical Use," *Medical Physics* **45,** 2, 863.

[Joensuu-2003] Joensuu, H. , L. Kankaanranta, T. Seppala, I. Auterinen, M. Kallio, M. Kulvik, J. Laakso, J. Vähätalo, M. Kortesniemi, P. Kotiluoto, T. Serén, J. Karila, A. Brander, E. Järviluoma, P. Ryynänen, A. Paetau, I. Ruokonen, H. Minn, M. Tenhunen, J. Jääskeläinen, M. Färkkilä, and S. Savolainen. 2003. "Boron Neutron Capture Therapy of Brain Tumors: Clinical Trials at the Finnish Facility using Boronophenylalanine," *Journal of Neuro-Oncology,* **62**, 123.

[Johnstone-2019] Johnstone, C. D., F. Therriault-Proulx, L. Beaulieu, and M. Bazalova-Carter. 2019. "Characterization of a plastic scintillating detector for the Small Animal Radiation Research Platform (SARRP)," *Medical Physics* **46**, 1, 394.

[Kankaanranta-2012] Kankaanranta, L., T. Seppala, and H. Koivunoro. 2012. "Boron Neutron Capture Therapy in the Treatment of Locally Recurred Head and Neck Cancer: Final Analysis of a Phase I/II Trial," *International Journal of Radiation Oncology, Biology, Physics* **82**, 1, e67.

[Kirsh-2018] Kirsh, D. G., M. Diehn, A. H. Kesarwala, A. Maity, M. A. Morgan, J. K. Schwarz, R. Bristow, S. Demaria, I. Eke, R. J. Griffin, D. Haas-Kogan, G. S. Higgins, A. C. Kimmelman, R. J. Kimple, I. M. Lombaert, L. Ma, B. Marples, F. Pajonk, C. C. Park, D. Schaue, P. T. Tran, H. Willers, and B. E. J. Wouters. 2018. "The Future of Radiobiology." *JNCI: Journal of the National Cancer Institute* **110**, 4, 329.

[Koivunoro-2019] Koivunoro, H. 2019. Neutron Therapeutics Inc., Private Communication.

[Laramore-1995] Laramore, G. E. and T. E. Griffin. 1995. Fast Neutron Radiotherapy - Where Have We Been and Where Are We Going? *International Journal of Radiation Oncology, Biology, Physics* **32**, 879.

[Laramore-1994] Laramore, G. E., P. Wootton, J. C. Livesey, et al, 1994). Boron Neutron Capture Therapy: A Mechanism for Achieving a Concomitant Tumor Boost in Fast Neutron Radiotherapy, *International Journal of Radiation Oncology, Biology, Physics* **28**, 1135.

[Leedle-2018] Leedle, K. J., D. S. Black, Y. Miao, K. E. Urbanek, A. Ceballos, H. Deng, J. S. Harris, O. Solgaard, and R. L. Byer. 2018. "Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings," *Optics Letters* **43**, 2181.

[Locher-1936] Locher, G. L. 1936. “Biological effects and therapeutic possibilities of neutrons,” *American Journal of Rooentgenology* **36**, 1.

[Loo-2017] Loo Jr, B. W., E. Schüler, F. M. Lartey, M. Rafat, G. J. King, S. Trovati, A. C. Koong, and P. G. Maxim. 2017. “Delivery of Ultra-Rapid FLASH Radiation Therapy and Demonstration of Normal Tissue Sparing after Abdominal Irradiation of Mice.” *International Journal of Radiation Oncology, Biology, Physics* **98** (Supplement), E16.

[Mardor-2009] Mardor I., D. Berkovits, I. Gertz, A. Grin, et al. 2009. “The SARAF CW 40 MeV Proton/Deuteron Accelerator,” *Proceedings of the SRF2009 Conference*, 74-80.

[Matinfar-2010] Matinfar, M., I. Iordachita, J. Wong, and P. Kazanzides. 2010. “Robotic Delivery of Complex Radiation Volumes for Small Animal Research,” *International Conference on Robotics and Automation* **2010**, 2056.

[Maxim-2019] Maxim, P. G., S. G. Tantawi, and B. W. Loo Jr. 2019. “PHASER: A Platform for Clinical Translation of FLASH Cancer Radiotherapy,” *Radiotherapy and Oncology* (In press)

[McGee-2019] McGee, H. M., D. Jiang, D. R. Soto-Pantoja, A. Nevler, A. J. Giaccia, and W. A. Woodward. 2019. “Targeting the tumor microenvironment in Radiation Oncology: Proceedings from the 2018 ASTRO-AACR Workshop,” *Clinical Cancer Research* **18,** 3781. doi:10.1158/1078-0432.

[McNeur-2016] McNeur, J., M. Kozák, N. Schönenberger, K. J. Leedle, H. Deng, A. Ceballos, H. Hoogland, A. Ruehl, I. Hartl, R. Holzwarth, O. Solgaard, J. S. Harris, R. L. Byer, and P. Hommelhoff. 2016. “Elements of a Dielectric Laser Accelerator,” *Optica* **5**, 687.

[Montay-Gruel-2017] Montay-Gruel, P., K. Petersson, M. Jaccard, G. Boivin, J. F. Germond, B. Petit, R. Doenlen, V. Favaudon, F. Bochud, C. Bailat, J. Bourhis, and M. C. Vozenin. 2017. “Irradiation in a Flash: Unique Sparing of Memory in Mice After Whole Brain Irradiation with Dose Rates above 100Gy/s.” *Radiotherapy and Oncology* **124**, 3, 365.

[Montay-Gruel-2018] Montay-Gruel, P., A. Bouchet, M. Jaccard, D. Patin, R. Serduc, W. Aim, K. Petersson, B. Petit, C. Bailat, J. Bourhis, E. Bräuer-Krisch, and M. C. Vozenin. 2018. “x-rays can trigger the FLASH effect: Ultra-high Dose-rate Synchrotron Light Source Prevents Normal Brain Injury After Whole Brain Irradiation in Mice.” *Radiotherapy and Oncology* **129**, 3, 582.

[Montay-Gruel-2019] Montay-Gruel, P., M. M. Acharya, K. Petersson, et al. 2019. “Long-term Neurocognitive Benefits of FLASH Radiotherapy Driven by Reduced Reactive Oxygen Species,” *Proceedings of the National Academies of Science* **116**, 22, 10943.

[Niedemayer-2018] Niedermayer, U., T. Egenolf, O. Boine-Frankenheim, and P. Hommelhoff. 2018. “Alternating-Phase Focusing for Dielectric-Laser Acceleration,” *Physical Review Letters* **121**, 214801.

Nigg, D. W., Ed. 1994. *Proceedings of the First International Workshop on Accelerator-Based Neutron Sources for Boron Neutron Capture Therapy*, CONF-940976, Idaho National Engineering Laboratory.

Nigg, D. W., Ed. 2000. “Modification of the University of Washington Neutron Radiotherapy Facility for Optimization of Neutron-Capture-Enhanced Fast Neutron Therapy,” *Medical Physics* **27**, 359.

[Nolan-2017] Nolan, M. W. , T. L. Gieger, A. A. Karakashaian, M. N. Nikolova-Karakashaian, L. P. Posner, D. M. Roback, J. N. Rivera, and S. Chang. 2017. “Outcomes of Spatially Fractionated

Radiotherapy (GRID) for Bulky Soft Tissue Sarcomas in a Large Animal Model," *Technology in Cancer Research and Treatment* **16**, 3, 357.

[Nolan-2018] Nolan, M. and J. Dobson. 2018. The Future of Radiotherapy in Small Animals – Should the Fractions be Coarse or Fine? *Journal of Small Animal Practice* **59**, 9, 521.

[Ono-2018] Ono, K. 2018. "Prospects for the New Era of Boron Neutron Capture Therapy and Subjects for the Future," *Therapuetic Radiotherapy and Oncology*, **2**, 40.

[Ostroumov-2002] Ostroumov P. N., A. A. Kolomiets, D. A. Kashinsky, S. A. Minaev, et al. 2002. "Design of 57.5 MHz CW RFQ for Medium Energy Heavy Ion Superconducting Linac," *Physical Review Accelerators and Beams* **5**, 060101.

[Parodi-2018] Parodi, K. 2018. "The Biological Treatment Planning Evolution of Clinical Fractionated Radiotherapy using High LET," International Journal of Radiation Biology **94**, 8, 752.

[Patriarca-2018] Patriarca, A., C. Fouillade, M. Auger, F. Martin, F. Pouzoulet, C. Nauraye, S. Heinrich, V. Favaudon, S. Meyroneinc, R. Dendale, A. Mazal, P. Poortmans, P. Verrelle, and L. De Marzi. 2018. "Experimental Set-up for FLASH Proton Irradiation of Small Animals Using a Clinical System," *International Journal of Radiation Oncology, Biology, Physics* **102**, 3, 619.

[Peralta-2013] Peralta, E., A. K. Soong, R. J. England, E. R. Colby, Z. Wu, B. Montazeri, C. McGuinness, J. McNeur, K. J. Leedle, D. Walz, E. B. Sozer, B. Cowan, B. Schwartz, G. Travish, and R. L. Byer. 2013. "Demonstration of Electron Acceleration in a Laser-Driven Dielectric Microstructure," *Nature* **503**, 91.

[Pistenmaa-2018] Pistenmaa, D. A., M. Dosanjh, U. Amaldi, D. Jaffray, E. Zubizarreta, K. Holt, Y. Lievens, Y. Pipman, C. N. Coleman. 2018. "Changing the global radiation therapy paradigm," *Radiotherapy and Oncology* 128, 3, 393.

[Pisent-2000] Pisent A., M. Comunian, G. Bisoffi, A. Lambardi. 2000. "Applications of superconducting RFQ Linear Accelerators," *Proceedings 20th International Linac Conference*, 959-961.

[Pratx-2019] Pratx, G., and D. S. Kapp. 2019. Ultra-high Dose Rate FLASH Irradiation may Spare Hypoxic Stem Cell Niches in Normal Tissues. *International Journal of Radiation Oncology, Biology, Physics* (In press).

[Reichenvater-2016] Reichenvater, H. and L. D. Matias. 2016. "Is Africa a 'Graveyard' for Linear Accelerators?" *Clinical Oncology- The Royal College of Radiologists* **2,** 12, e179.

[Sapra-2020] Sapra, N., K. Y. Yang, D. Vercruysse, K. J. Leedle, D. S. Black, R. J. England, L. Su, R. Trivedi, Y. Miao, O. Solgaard, R. L. Byer, and J. Vučkovicć. 2020. "On-chip laser driven particle acceleration through inverse design," *Science* **03**, 367, 6473, 79

[Schleede-2012] Schleede, S., F. G. Meinel, M. Bech, J. Herzen, K. Achterhold, G. Potdevin, A. Malecki, S. Adam-Neumair, S. F. Thieme, F. Bamberg, K. Nikolaou, A. Bohla, A. Ö. Yildirim, R. Loewen, M. Gifford, R. Ruth, O. Eickelberg, M. Reiser, and F. Pfeiffer. 2012. "Emphysema Diagnosis using x-ray Dark-Field Imaging at a Laser-Driven Compact Synchrotron Light Source," PNAS **109**, 44, 17880.

[Schüler-2017] Schüler, E., S. Trovati, G. King, F. Lartey, M. Rafat, M. Villegas, A. J. Praxel, B. W. Loo Jr., and P. G. Maxim. 2017. "Experimental Platform For Ultra-High Dose Rate FLASH Irradiation Of Small Animals Using A Clinical Linear Accelerator," *International Journal of Radiation Oncology, Biology, Physics* **97**, 1, 195.

[Simmons-2019] Simmons, D. A., F. M. Lartey, E. Schüler, M. Rafat, G. King, A. Kim, R. Ko, S. Semaan, S. Gonzalez, M. Jenkins, P. Pradhan, Z. Shih, J. Wang, R. von Eyben, E. E. Graves, P. G. Maxim, F. M. Longo, and B. W. Loo Jr. 2019. "Reduced cognitive deficits after FLASH irradiation of whole mouse brain are associated with less hippocampal dendritic spine loss and neuroinflammation," *Radiotherapy and Oncology* **139**, 4. doi: 10.1016/j.radonc.2019.06.006

[Spitz-2019] Spitz, D. R., G. R. Buettner, M. S. Petronek, J. J. St-Aubin, R. T. Flynn, T. J. Waldron, and C. L. Limoli. 2019. "An Integrated Physico-Chemical Approach for Explaining the Differential Impact of FLASH versus Conventional Dose Rate Irradiation on Cancer and Normal Tissue Responses," *Radiotherapy and Oncology* **139**, 23.

Stichelbaut F., E. Forton, and Y. Jongen. 2006. "Design of a Beam Shaping Assembly for an Accelerator-Based BNCT System", Advances *in Neutron Capture Therapy 2006," Proceedings of the 12th International Congress on Neutron Capture Therapy,* ISBN 4-9903242-0-X, International Society for Neutron Capture Therapy.

[Stone-1948] Stone, R. S. 1948. Neutron Therapy and Specific Ionization, *American Journal of Roentgenology* **59**, 6, 771.

[Travish-2011] Travish, G. 2011. "What Could You Do with a Particle Accelerator on a Chip?" *Advances in Dielectric Laser Accelerators and Prospects for Applications*, presented at Varian Medical Systems. https://www.slideshare.net/gtravish/what-could-you-do-with-a-particle-accelerator-onachip

[Vretenar-2014] Vretenar M., A. Dallocchio, V. A. Dimov, M. Garlasche, et al. 2014. "A Compact High-Frequency RFQ for Medical Applications," *Proceedings LINAC2014 Conference*, 935-938.

[Vretenar-2016] Vretenar M., V. A. Dimov, M. Garlasche, A. Grudiev, et al. 2016. "High-Frequency Compact RFQs for Medical and Industrial Applications," *Proceedings LINAC2016 Conference*, 704-709.

[Vozenin-2019] Vozenin, M-C., P. De Fornel, K. Petersson, et al. 2019. "The Advantage of Flash Radiotherapy Confirmed in Mini-Pig and Cat-Cancer Patients," *Clinical Cancer Research* **25**, 1, 35.

[Wang-2016] Z. J. Wang, Y. He, H. Jia, W. P. Dou, et al. 2016. "Beam Commissioning for a Superconducting Proton Linac," *Physical Review Accelerators and Beams* **19**, 120101.

[Wangler-1992] T.P. Wangler, T.P., A. Cimbue, J. Merson, R. S. Mills, et al. 1992. "Superconducting RFQ Development at Los Alamos," *Proceedings 1992 Linear Accelerator Conference*, 627-629.

[Wei-2009] Wei J., H. B. Chen, W. H. Huang, C. X. Tang, et al. 2009. "Compact Pulsed Hadron Source – A University-Based Accelerator Platform for Multidisciplinary Neutron and Proton Applications," *Proceedings 23rd Particle Accelerator Conference*, 1360-1362.

Wheeler F. W., D. W. Nigg, J. Capala, P. R. Watkins, C. Vroegindeweij, I. Auterinen, T. Seppälä, and D. Bleuel. 1998. "Boron Neutron Capture Therapy (BNCT): Implications of Neutron Beam and Boron Compound Characteristics," *Medical Physics* **26**, 1237.

References from Chapter 5

[AAC-2018] Geddes, C. G. R. and J. L. Shaw. 2018. “Summary of Working Group 1: Laser-Plasma Wakefield Acceleration,” *Proceedings Advanced Accelerator Concepts Workshop*. doi:10.1109/AAC.2018.8659442

[AARDR-2016] *Advanced Accelerator Development Strategy Report: DOE Advanced Accelerator Concepts Research Roadmap Workshop,* 2016. https://www.osti.gov/biblio/1358081-advanced-accelerator-development-strategy-report-doe-advanced-accelerator-concepts-research-roadmap-workshop

[Abdul-Ghaffar-2013] Abdul-Ghaffar, H-I., E. A. Ebrahim, and M. Azzam, 2013. “Design of PID Controller for Power System Stabilization Using Hybrid Particle Swarm-Bacteria Foraging Optimization,” *WSEAS Tranactions on Power Systems* **1**, 8, 12.

[Bamigboye-2016] Bamigboye, O. O. 2016. “Development of a PID Control System in Distributed Generation for Improvement of Voltage Stability Using Model Reduction Method,” *International Journal of Latest Research in Engineering and Technology (IJLRET)* **02**, 07, 17.

[BLI-2018] *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, 2018. National Academies of Sciences, Engineering, and Medicine; Division on Engineering and Physical Sciences; Board on Physics and Astronomy; Committee on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers. https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

[Black-2019] Black, D. S., K. J. Leedle, Y. Miao, U. Niedermayer, R. L. Byer, and O. Solgaard. 2019. “Laser-Driven Electron Lensing in Silicon Microstructures,” *Physical Review Letters* **122**, 104801.

[Caroll-2003] Carroll, F. E., M. H. Mendenhall, R. H. Traeger, C. Brau, and J. W. Waters. 2003. “Pulsed Tunable Monochromatic x-ray Beams from a Compact Source: New Opportunities,” *American Journal of Roentgenology* **181**, 5, 1197.

[Cesar-2018] Cesar, D., J. Maxon, P. Musumeci, X. Shen, R. J. England, K. P. Wootton, and S. Tan, 2018. “Enhanced Energy Gain in a Dielectric Laser Accelerator Using a Tilted Pulse Front Laser,” *Optics Express* **26**, 22, 29216.

[Chawla-2018] Chawla, S., S. Kurani, S. M. Wren, B. Stewart, G. Burnham, A. Kushner, and T. McIntyre. 2018. “Electricity and generator availability in LMIC hospitals: improving access to safe surgery”, *Journal of Surgical Research* **223,** 136-141 and citations within.

[Chen-2013] Chen, A.X., A. J. Antolak, K.-N. Leung, T. N. Raber, and D. H. Morse. 2013. “Pulsed Pyroelectric Crystal Powerered Gamma Source,” *AIP Conference Proceedings* **1525**, 720.

[Cho-2002] Cho, Y. B. and P. Munro. 2002. “Kilovision: Thermal Modeling of a Kilovoltage x-ray Source Integrated into a Medical Linear Accelerator,” *Medical Physics* **29**, 9, 2101.

[Coleman-2019] Coleman, C. N. (NCI). 2019. *DOE Compact Accelerator Workshop: Opportunities to Address Substantial Challenges*, Opening plenary talk.

[DalForno-2018] Dal Forno, M., V. A. Dolgashev, G. Bowden, C. Clarke, M. Hogan, D. McCormick, A. Novokhatski, B. O’Shea, S. Bruno, S. Weathersby, and S. Tantawi. 2018. “Measurements of Electron

Beam Deflection and rf Breakdown Rate from a Surface Wave Guided in Metallic Mm-Wave Accelerating Structures. *PRAB* **21**, 9, 091301. doi:10.1103/PhysRevAccelBeams.21.091301

[Edelen-2016] Edelen, A. L., S. G. Biedron, B. E. Chase, D. Edstrom Jr., S. V. Milton, and P. Stabile. 2016. "Neural Networks for Modeling and Control of Particle Accelerators," *IEEE Transactions on Nuclear Science* **63**, 2, 1.

[ElectrifyAfrica] Electrify Africa Act, S. B. 2152, 114th Cong. (2015-2016). Public Law No: 114-121. https://www.congress.gov/bill/114th-congress/senate-bill/2152

[England-2014] England, R. J., R. J. Noble, K. Bane, D. H. Dowell, C-K. Ng, J. E. Spencer, S. Tantawi, Z. Wu, R. L. Byer, E. Peralta, K. Soong, C-M. Chang, B. Montazeri, S. J. Wolf, B. Cowan, J. Dawson, W. Gai, P. Hommelhoff, Y-C. Huang, C. Jing, C. McGuinness, R. B. Palmer, B. Naranjo, J. Rosenzweig, G. Travish, A. Mizrahi, L. Schachter, C. Sears, G. R. Werner, and R. B. Yoder 2014. "Dielectric Laser Accelerators," *Reviews of Modern Physics* **86**, 1337.

[Fault Tree Handbook-2002] Stamatelatos, M., J. Caraballo, J. Dugan, J. Fragola, J. Minarick III, and J. Railsback. 2002. *NASA*. http://www.barringer1.com/mil_files/NASA-FTA-1.1.pdf

[Frigola-2015] Frigola, P., R. Agustsson, L. Faillace, A. Murokh, G. Ciovati, W. Clemens, P. Dhakal, F. Marhauser, R. Rimmer, J. Spradlin, S. Williams, J. Mireles, P. A., and Morton, R. B. 2015. *Proceedings of SRF2015* **2015**, 1181. http://accelconf.web.cern.ch/AccelConf/SRF2015/papers/thpb042.pdf

[Geddes-2015] Geddes, C. G. R. , S. Rykovanov, N. H. Matlis, S. Steinke, J. -L. Vay, E. Esarey, B. Ludewigt, K. Nakamura, B. J. Quiter, C. B. Schroeder, C. Toth, and W. P. Leemans. 2015. "Compact Quasi-Monoenergetic Photon Sources from Laser-Plasma Accelerators for Nuclear Detection and Characterization," *Nuclear Instruments and Methods in Physics Research B* **350**, 116.

[Geddes-2017] Geddes, C. G. R., B. Ludewigt, J. Valentine, B. J. Quiter, M. -A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, and S. Pozzi. 2017. *Impact of Monoenergetic Photon Sources on Nonproliferation Applications*, Idaho National Laboratory, INL/EXT-17-41137, March 2017.

[Guénot-2017] Guénot, D., D. Gustas, A. Vernier, B. Beaurepaire, F. Böhle, M. Bocoum, M. Lozano, A. Jullien, R. Lopez-Martens, A. Lifschitz, and J. Faure. 2017. "Relativistic Electron Beams Driven by Khz Single-Cycle Light Pulse," *Nature Photonics* **11**, 293.

[Hamm-2013] Hamm, R. W. 2013. *Current and Future Industrial Applications of Accelerators Introduction to Industrial Accelerators*. Presentation, NA-PAC-13. R&M Technical Enterprises, Inc.

[Hughes-2018] Hughes, T. W. , S. Tan, Z. Zhao, N. V. Sapra, K. J. Leedle, H. Deng, Y. Miao, D. S. Black, O. Solgaard, J. S. Harris, J. Vuckovic, R. L. Byer, S. Fan, R. J. England, Y. J. Lee, and M. Qi, 2018. "On-Chip Laser-Power Delivery System for Dielectric Laser Accelerators," Phys. Rev. Applied 9, 054017.

[Jenzer-2019] Jenzer, S., N. Delerue, P. Manil, R. Gerad, P. Repain, H. Carduner, and A. Simar. 2019. *Proceedings of the 10th International Particle Accelerator Conference (IPAC2019)*, http://jacow.org/ipac2019/papers/thpts008.pdf

[Kasilingam-2015] Kasilingam, G. and J. Pasupuleti. 2015. "Coordination of PSS and PID Controller for Power System Stability Enhancement – Overview," *Indian Journal of Science and Technology* **8**, 2, 142.

[kBELLA-2018] *Report of Workshop on Laser Technology for k-BELLA and Beyond*. 2017. https://www2.lbl.gov/LBL-Programs/atap/Report_Workshop_k-BELLA_laser_tech_final.pdf

[Kim-2016] Kim, C., G. Pilania, and R. Ramprasad. 2016. “From Organized High-Throughput Data to Phenomenological Theory using Machine Learning: The Example of Dielectric Breakdown,” *Chemistry of Materials* **28**, 1304.

[Kutsaev-2019] Kutsaev, S. V., B. Jacobson, A. Yu. Smirnov, T. Campese, V. A. Dolgashev, V. Goncharik, M. Harrison, A. Murokh, E. Nanni, J. Picard, M. Ruelas, and S. C. Schaub. 2019. Nanosecond rf-Power Switch for Gyrotron-Driven Millimeter-Wave Accelerators” *Physical Review Applied* **11**, 3, 034052.

[Ledoux-2018] Ledoux, R. J. 2018. “Advances in Nondestructive Elemental Assaying Technologies,” *Applications of Laser-Driven Particle Acceleration*, Chapter 23, CRC Press.

[Leedle-2018] Leedle, K. J., D. S. Black, Y. Miao, K. E. Urbanek, A. Ceballos, H. Deng, J. S. Harris, O. Solgaard, and R. L. Byer. 2018. “Phase-Dependent Laser Acceleration of Electrons with Symmetrically Driven Silicon Dual Pillar Gratings,” *Optics Letters* **43**, 2181.

[Lewis-1997] Lewis, R. 1997. “Medical Applications of Synchrotron Radiation x-rays,” *Physics in Medicine and Biology* **42**, 7, 1213.

[LFA-2013] *Workshop on Laser Technology for Accelerators: Summary Report*, 2013. https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Lasers_for_Accelerators_Report_Final.pdf

[Li-2019b] Li, R. K., et al. 2019. “Terahertz-based Subfemtosecond Metrology of Relativistic Electron Beams,” *Physical Review Accelerators and Beams* **22**, 1, 012803.

[Mandi-2015] Mandi, T. K., S. Suman, H. K. Pandey, and A. Bandyopadhyay. 2015. “Design and Development of Low Level RF (LLRF) Control System,” *Proceedings of the 7th DAE-BRNS Indian Particle Accelerator Conference* **2015**, 21.

[Marsh-2012] Marsh, R. A., F. Albert, S. G. Anderson, D. J. Gibson, S. S. Wu, F. V. Hartemann, and C. P. J. Barty. 2012. “Ultracompact Accelerator Technology for a Next-Generation Gamma-Ray Source,” *Proceedings of the 3rd International Particle Accelerator Conference*, 3190.

[Marsh-2017] Marsh, R. 2017. “Compton-scattering x-ray Generation from Compact X-Band Accelerators,” *Lawrence Livermore National Laboratory LDRD Annual Report, Lasers, 15-ERD-067.*

[Martz-2017b] H. E. Martz, Jr. , S. M. Glenn, J. A. Smith, C. J. Divin, and S. G. Azevedo. 2016. “Poly-versus Mono-energetic Dual-spectrum Non-intrusive Inspection of Cargo Containers,” *IEEE Transactions on Nuclear Science* **64**, 1709. doi: 10.1109/TNS. 2017.2652455

[Matlis-2018] Matlis, N. H., S. W. Jolly, F. Ahr, V. Leroux, T. Eichner, A-L. Calendron, K. Ravi, H. Ishizuki, T. Taira, A. R. Maier, F. X. Kärtner. 2018. “Demonstration of 0.6 mJ Multicycle THz Pulses Via Chirp-and-delay Down Conversion of Broadband Lasers with Precise Spectral Phase Tuning and Large PPLN,” *2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*. IEEE.

[McNeur-2016] McNeur, J., M. Kozák, N. Schönenberger, K. J. Leedle, H. Deng, A. Ceballos, H. Hoogland, A. Ruehl, I. Hartl, R. Holzwarth, O. Solgaard, J. S. Harris, R. L. Byer, and P. Hommelhoff. 2016. “Elements of a Dielectric Laser Accelerator,” *Optica* **5**, 687.

[Milton-2015] Milton, S., C. Moss, and R. Estep. 2015. *Study of the Requirements for Monoenergetic Photon Sources*, Los Alamos project report for DNDO.

[Moriguchi-2018] Moriguchi, Y., Y. Tokizane, Y. Takida, K. Nawata, T. Eno, S. Nagano. and H. Minamide. 2018. “High-Average and High-Peak Output-Power Terahertz-Wave Generation by Optical Parametric Down-Conversion in MgO: LiNbO3,” *Applied Physics Letters* **113**, 12, 121103.

[Nanni-2018] Nanni, E. A., V. Dolgashev, S. Jawla, J. Neilson, M. Othman, J. Picard, S. Schaub, B. Spataro, S. Tantawi, R. J. Temkin. 2018. “Results from Mm-Wave Accelerating Structure High-Gradient Tests,” *IRMMW-THz*. IEEE, 2018.

[Niedemayer-2018] Niedermayer, U. , T. Egenolf, O. Boine-Frankenheim, and P. Hommelhoff. 2018. “Alternating-Phase Focusing for Dielectric-Laser Acceleration,” *Physical Review Letters* **121**, 214801.

[NRC-1981] Vesely, W., F.F. Goldberg, N.H. Roberts, and D.F. Haasl. 1981. *Fault Tree Handbook (NUREG-0492).* Systems and Reliability Research, Office of Nuclear Regulatory Research, US Nuclear Regulatory Commission, Washington, DC. https://www.nrc.gov/docs/ML1007/ML100780465.pdf

[ODI-2014] Scott, A., E. Darko, A. Lemma, and J-P. Rud. 2014. *ODI Briefing 01: How does Electricity Insecurity Affect Businesses in Low and Middle Income Countries?* https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9425.pdf

[OpenPMD-n. d.] Open Standard for Particle-Mesh Data Files. n.d. https://github.com/openPMD

[Peralta-2013] Peralta, E. A., K. Soong, R. J. England, E. R. Colby, Z. Wu, B. Montazeri, C. McGuinness, J. McNeur, K. J. Leedle, D. Walz, E. B. Sozer, B. Cowan, B. Schwartz, G. Travish, and R. L. Byer. 2013. Demonstration of Electron Acceleration In A Laser-Driven Dielectric Microstructure. *Nature* **503**, 91.

[Phillips-2015] Phillips, T. and Sahgal, A. 2015. An Interview with C. Norman Coleman, MD, FASTRO American Society for Radiation Oncology (ASTRO),” *American Society for Radiation Oncology (ASTRO)*. https://www.astro. org/About-ASTRO/History/C-Norman-Coleman. (Accessed: 7th June 2019).

[Picard-2019] Picard, J. F., S. C. Schaub, G. Rosenzweig, J. C. Stephens, M. A. Shapiro, and R. J. Temkin, 2019. “Laser-driven Semiconductor Switch For Generating Nanosecond Pulses From A Megawatt Gyrotron,” *Applied Physics Letters* **114**, 16, 164102.

[Posen-2017] S. Posen and L. Hall. 2017. “Nb3Sn Superconducting Radiofrequency Cavities: Fabrication, Results, Properties, and Prospects,” *Superconductor Science and Technology* **30**, 033004. doi: 10.1088 1361-6668/30/3/033004

[PoweringHealth-n.d.] Weynand, G. n.d. *US AID: Powering Health Electrification Options for Rural Health Centers*. http://www.poweringhealth.org/Pubs/PNADJ557.pdf

[Ramprasad-2017] Ramprasad, R., R. Batra, G. Pilania, A. Mannodi-Kanakkithodi, and C. Kim. 2017. “Machine Learning in Materials Informatics: Recent Applications and Prospects,” *npj Computational Materials* **3**, 54.

[Rose-2016] Rose, P. B., A. S. Erickson, M. Mayer, J. Nattress, and I. Jovanovic. 2016. “Uncovering Special Nuclear Materials by Low-energy Nuclear Reaction Imaging,” *Nature Scientific Reports* **6**, 24388.

[Saadat-1999] Saadat, H. 1999. *Power System Analysis*, McGraw-Hill International Editions.

[Salehi-2018] Salehi, F., A. J. Goers, G. A. Hine, L. Feder, D. Kuk, B. Miao, D. Woodbury, K. Y. Kim, and H. M. Milchberg. 2018. “MeV Electron Acceleration at 1 kHz with <10 mJ Laser Pulses,” *Optics Letters* **42**, 215.

[Schleede-2012] Schleede, S., F. G. Meinel, M. Bech, J. Herzen, K. Achterhold, G. Potdevin, A. Malecki, S. Adam-Neumair, S. F. Thieme, F. Bamberg, K. Nikolaou, A. Bohla, A. Ö. Yildirim, R. Loewen, M. Gifford, R. Ruth, O. Eickelberg, M. Reiser, and F. Pfeiffer. 2012. “Emphysema Diagnosis using x-ray Dark-Field Imaging at a Laser-Driven Compact Synchrotron Light Source,” PNAS **109**, 44, 17880.

[Starfire - 2019] Starfire Industries LLC, 2019. *nGen-400 Portable Neutron Interrogation Product Datasheet*.

[Sumanbabu-2007] Sumanbabu, B., S. Mishra, B. K. Panigrahi, and G. K. Venayagamoorthy. 2007. “Robust Tuning of Modern Power System Stabilizers Using Bacterial Foraging Algorithm”, *IEEE Congress on Evolutionary Computation* **2007**, 2317.

[Thompson-2008] Thompson, M. C. and B. W. J. McNeil. 2008. “Mode Locking in a Free-Electron Laser Amplifier,” *Physical Review Letters* **100**, 20, 214801.

[UNGoal7-2019] United Nations. 2019. “Sustainable Development Goal 7. Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All.” https:///sustainabledevelopment.un.org/sdg7

[Valente-Feliciano-2016] Valente-Feliciano, A-M. 2016. “Superconducting RF Materials other than Bulk Niobium: A Review. *2016 Superconductor Science and Technology* **29**, 113002.

[Zhao-2019] Zhao, L., Z. Wang, H. Tang, R. Wang, Y. Cheng, C. Lu, T. Jiang, P. Zhu, L. Hu, W. Song, H. Wang, J. Qiu, R. Kostin, C. Jing, S. Antipov, P. Wang, J. Qi, Y. Cheng, D. Xiang, and J. Zhang. 2019. “Terahertz Oscilloscope for Recording Time Information of Ultrashort Electron Beams. *arXiv:1902.03433*. doi:10.1103/PhysRevLett.122.144801

Appendix A. Workshop Participants and Authors

Jim Amundson	Fermi National Accelerator Laboratory
Arlyn Antolak†	Sandia National Laboratories
Ahmed Badruzzaman†	Pacific Consultants and Engineers and UCB
Joseph Bendahan	Rapiscan (ret.)
Stephen Benson	Thomas Jefferson National Accelerator Facility
Sandra Biedron†	self
Mary-Keara Boss†	Colorado State University
Jeff Buchsbaum†	National Cancer Institute of the National Institutes of Health
Craig Burkhart	SLAC National Accelerator Laboratory
Jeffrey Calame†	Naval Research Laboratory
John Cary†	University of Colorado, Boulder and Tech-X Corp
C Norman Coleman	National Cancer Institute and ICEC
Wesley Culberson	University of Wisconsin, Madison
Mark Curtin†	self
Colleen DesRosiers	Indiana University
James Deye	National Cancer Institute
Manjit Dosanjh	CERN
Joel England	SLAC National Accelerator Laboratory
Anna Erickson†	Georgia Institute of Technology
Richard Farnsworth	Brookhaven National Laboratory
Michael Fazio*	SLAC National Accelerator Laboratory
Eric Ford	University of Washington
Dave Funk	Los Alamos National Laboratory
Cameron Geddes	Lawrence Berkeley National Laboratory
Steven Glenn	Lawrence Livermore National Laboratory
Kathryn Held	NCRP
Michael Helle	Naval Research Laboratory
Georg Hoffstaetter	Cornell University
David A. Jaffray†	Ontario Cancer Institute, Princess Margaret Cancer Centre/UHN and Techna
Tom Johnson	Colorado State University

Samuel Joshua Stein	Argonne National Laboratory
Malcolm Joyce	University of Lancaster, UK
Mark Kemp	SLAC National Accelerator Laboratory
George Laramore**	University of Washington
John Lewellen	Los Alamos National Laboratory
Steve Lidia	Michigan State University
Charles Limoli	University of California, Irvine
Billy Loo	Stanford Medical
Roark Marsh	Lawrence Livermore National Laboratory
Harry Martz†	Lawrence Livermore National Laboratory
Malcolm McEwen	NRCC
Marc Mendonca	Indiana University
Stephen Milton	Los Alamos National Laboratory
George Neil†	Thomas Jefferson National Accelerator Facility (ret.)
David Nigg	Idaho National Laboratory
Jerry Nolen	Argonne National Laboratory
Suresh Pillai**	Texas A&M University
Philippe Piot	Northern Illinois University
Nathaniel Pogue	Lawrence Livermore National Laboratory
John Power	Argonne National Laboratory
Brian Quiter	Lawrence Berkeley National Laboratory
John Rathke	AES (ret.)
James Rosenzweig	University of California, Los Angeles
Thomas Schenkel	Lawrence Berkeley National Laboratory
Andrea Schmidt†	Lawrence Livermore National Laboratory
Jan Seuntjens	McGill University
Michael Sevilla	Oakland University
Shima Shayanfar	General Mills Corporation
Sami Tantawi	SLAC National Accelerator Laboratory
Jayakar Thangaraj	Fermi National Accelerator Laboratory
Antonio Ting†	University of Maryland
Ronald Tosh†	National Institute of Standards and Technology (Gaithersburg)

Aaron Tremaine	SLAC National Accelerator Laboratory
Richard Vojtech	DHS-CWMD
Maurizio Vretenar	CERN
James S. Welsh	Edward Hines VA Hospital
Marion White	Argonne National Laboratory
John Wong	Johns Hopkins
Eleanor Blakely Zizka	Lawrence Berkeley National Laboratory (ret.)

---

* Denotes Workshop Chair
** Denotes Workshop Co-Chair
† Denotes Panel Co-Lead

Appendix B Workshop Observers

Kramer Akli	DOE-FES
Fawaz Ali	AECL
Christie Ashton*	DOE-HEP
Ethan Balkin	DOE-NP
Steve Binkley	DOE-SC
James Bradshaw	NA-212
David Brown	Mevex Corporation
Jacek Capala	NIH-NCI
James Clayton	Varian Medical Systems
Eric Colby**	DOE-HEP
Glen Crawford	DOE-HEP
Massimo Dal Forno	Viewray Inc
Alberto Degiovanni	AVO ADAM (co.)
Manouchehr Farkhondeh	DOE-NP
Tony Faucette	Becton Dickinson
Richard Galloway	IBA Industries
Lance Garrison	NA-212
Charles Gary	Adelphi
Marissa Giles	DHS-CWMD
Weijun Guo	Halliburton
Robert Hamm	R&M Technical Enterprises
Donald Hornback	NA-221
Keith Jankowski	DHS-CWMD
Alan Janos	DHS-CWMD
Guy Jonkmans	DRDC/DRRC
Brian Jurczyk	Starfire Industries
Michael Krogh	Complete Compact Aero Systems
Willem Langeveld	Rapiscan
Robert LeDoux	Passport Systems
L. K. Len	DOE-HEP
Eliane Lessner	DOE-BES

Namdoo Moon	DHS-CWMD
Ceferino Obcemea	NIH-NCI
Rodney Parker	Stryker
John Petillo	Leidos, Inc.
David Pistenmaa	NIH-NCI
Jani Reijonen	Schlumberger
Quentin Saulter	DOD-ONR
Mark Shilton	QSA Global
Jim Siegrist	DOE-HEP
Michael Squillante	RMD Corporation
Dave Taylor	DHS-S&T
Fredrik Tovesson	NA-221
Bhadrasain Vikram	NIH-NCI
Steve Weiss	DHS-CBP
Mark Wrobel	DARPA

---

* Denotes Administrative POC
** Denotes Technical POC

Appendix C Workshop Charge

DOE Workshop on Compact Accelerators for Security and Medicine

BACKGROUND

The Office of High Energy Physics, as DOE's host office for the Accelerator Stewardship Program, is conducting a Basic Research Needs (BRN) workshop to assess R&D needed to enable high-impact applications of accelerator technology to address radiation generating source challenges. Responses to a 2014 Request for Information and subsequent discussions with other federal agencies have identified several areas where compact accelerator technology advances could have strong impacts:

(1) Replacement of radioisotopic sources by accelerator-based alternatives,
(2) Ruggedized low-cost LINACs for Low/Middle-Income Countries,
(3) FLASH-RT and Very-high energy electron (VHEE) sources for radiotherapy,
(4) Source-free brachytherapy (i.e., endoscopic particle accelerators),
(5) Portable monochromatic high energy x-ray sources, and
(6) Compact neutron generators.

In many cases the use of accelerator technology for these applications has performance advantages arising from the adjustability of the radiation characteristics, and eliminates the need for isotopic radiation sources. However the barriers to significant commercial deployment of accelerator technology include cost, reliability, regulatory approval, suitable detector technology, wall plug efficiency, portability (in some cases) and market resistance to risk. Many of these applications are currently satisfied by existing, well-proven technologies; however, recent improvements in the accelerator technology has lowered the cost and increased the reliability of these accelerators, warranting a re-examination of the technology use cases.

This BRN workshop will identify opportunities and barriers to market adoption in the technology applications noted above. The goal is to identify near-term accelerator technology R&D opportunities that, if developed, could enable high-impact solutions for medical, security, and other applications. Attendance at the workshop will be by invitation only.

WORKSHOP CHARGE

The BRN workshop will be asked to:

- Assess the state of any existing accelerator and non-accelerator based technologies currently deployed for the application. Document cost and performance criteria to be used as a benchmark for analyzing alternatives based on accelerator technology.
- Document current and proposed Federal and State environment, safety, and health regulatory requirements for the application and identify any issues with regard to these regulations.
- Develop performance criteria for accelerator-based systems for the application. Consider total system costs for production and operation. Assess the potential financial and/or application benefits if the accelerator technology meets the criteria. Document specifications for the accelerator and detector components of the system.
- Identify technical gaps between the current state of the art of accelerator technology compared to the above specifications. This may include accelerator-related technologies such as power supplies or magnet technology.

- Identify synergistic application-side R&D relevant to the application of accelerator technology to security, medical, and other application challenges, paying particular attention to R&D needed to develop detectors to support the application.
- Specify R&D activities needed to bridge technical gaps, and any additional analysis and testing required to validate their use.
- Develop a prioritized list of R&D; estimate rough order-of-magnitude costs to complete required R&D.

The workshop outcome will consist of a concise report describing high-impact opportunities for accelerator technology to impact security, medical, and other application challenges, technical and economic gaps requiring further accelerator R&D, and an approximate cost and time scale to accomplish this R&D. The report should include an R&D roadmap, with particular attention given to technology transfer to industry.

Appendix D Abbreviations and Acronyms

Abbreviation	Definition
AAPM	American Association of Physicists in Medicine
abi-MD	Ab-Initio Molecular Dynamic Modeling
AC	Alternating Current
ACSTL	TSA Air Cargo Technology List
AEA	Atomic Energy Act
AECL	Atomic Energy of Canada Limited
AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
AM	Advanced Manufacturing
ANL	Argonne National Laboratory
API	Associated Particle Imaging
ASME	American Society of Mechanical Engineers
ATD	Automated Threat Detection
ATR	Automated Threat Recognition
B	Boron
BBU	Beam Break Up
Be	Beryllium
BGO	Bismuth Germanium Oxide
BNCT	Boron Neutron Capture Therapy
BNL	Brookhaven National Laboratory
BPA	Boronophenylalanine (for neutron capture)
BRN	Basic Research Needs
C	Celsius
CAARS	Cargo Advanced Automated Radiography System
CAD	Computer Aided Design
CAPEX	Capital Expenditure
CASM	Compact Accelerators for Science and Medicine
CE	Certification marking
CEBAF	Continuous Electron Beam Accelerator Facility
CFR	Code of Federal Regulations
Ci	Curie (unit of radioactivity)
CMM	Coordinate Measurement Machines
CMOS	Complementary Metal–Oxide–Semiconductor
Co	Cobalt
CONOPS	Concept of Operations
COTS	Commercial-Off-The-Shelf
CPU	Central Processing Unit
CR	Computed Radiography
CREST	Combined Radiation Environments Survivability Test
Cs	Cesium
CT	Computed Tomography

CW	Continuous Wave
DAQ	Data Acquisition
DARHT	Dual-Axis Radiographic Hydrodynamic Test
DARPA	Defense Advanced Research Projects Agency
dB	Decibels
D-D	Deuterium-Deuterium
DDA	Differential Die-Away
DEG	*X*-Dimensional Electron Gasses
DFB	Distributed Feedback
DFT	Density Functional Theory
DHS	Department of Homeland Security
DHS-CBP	DHS - Customs and Border Protection
DHS-CWMD	DHS - Countering Weapons of Mass Destruction Office
DHS-S&T	DHS - Science & Technology
DIW	Direct Ink Writing
DLA	Dielectric Laser Accelerator
D-Li	Deuterium-Lithium
DNDO	Domestic Nuclear Detection Office
DOD	Department of Defense
DOD-ONR	DOD - Office of Naval Research
DOE	Department of Energy
DOE-BES	DOE - Office of Basic Energy Sciences
DOE-FES	DOE - Office of Fusion Energy Sciences
DOE-HEP	DOE - Office of High Energy Physics
DOE-NP	DOE - Office of Nuclear Physics
DOE-SC	DOE - Office of Science
DPF	Dense Plasma Focus
DRDC	Defence Research and Development Canada
DRRC	Demand Response Research Center
D-T	Deuterium-Tritium
DTL	Drift-Tube-LINAC
DUR	Dose Uniformity Ratio
E-beam	Electron beam
ECSE	Enhanced Capabilities for Subcritical Experiments
EDS	Explosive Detection System
EM	Electromagnetic
EPA	Environmental Protection Agency
EPD	Electrophoretic Deposition
ERL	Energy Recovery LINAC
ETCWG	Engineering Technology Cross-Cut Working Group
EtO	Ethylene Oxide
EV	Electron Volt
F	Fahrenheit
FAA	Federal Aviation Administration
FDA	Food And Drug Administration

FEL	Free Electron Laser
FF	Flattening Filter
FFCA	Federal Facilities Compliance Act
FFDCA	Federal Food, Drug And Cosmetic Act
FFF	FF-Free
FLASH-RT	FLASH radiotherapy
FM	Frequency Modulation
FNAL	Fermi National Accelerator Laboratory
FOM	Figures of Merit
FPGA	Field-Programmable Gate Array
FRIB	Facility for Rare Isotope Beams
fs	Femtoseconds
FXR	FLASH X-Ray
GeV	Giga-electron-Volt
GPS	Global Positioning System
GPU	Graphics Processing Unit
GR	Gamma Ray
GV	Giga Volts
GV/m	Gigavolts per Meter
HED	High Energy Density
HEDS	High Energy Density Science
HEMT	High Electron Mobility Transistors
HLMW	High-Level Mixed Waste
HLW	High-Level Radioactive Waste
HMI	Human-Machine Interface
HPC	High Performance Computing
HVAC	Heating, Ventilation, and Air Conditioning
HVHT	High-Volume High-Temperature
HW	Hardware
IACUC	Institutional Animal Care and Use Committee
IAEA	International Atomic Energy Agency
IC	Integrated Circuits
ICEC	International Cancer Expert Corps
ICONS	Intense and Compact Neutron Sources
ICRU	International Commission on Radiological Units
ICS	Inverse Compton Scattering
IGRT	Image-Guided Radiation Therapy
ILW	Intermediate Level Waste
IMRT	Intensity Modulated Radiotherapy
INCOSE	International Council on Systems Engineering
INGD	Inelastic (n-gamma) Density
IOT	Inductive Output Tubes
IR	Infrared
IRB	Institutional Review Board
ISO	International Organization for Standardization

ITAR	International Traffic in Arms Regulations
I-UID	Intrinsic Unique Identifier
J	Joule
JFAC	Joint Federated Assurance Center
K	Kelvin
keV	Kiloelectron Volt
kGy	Kilo Gray
kHz	Kilo Hertz
KURRI	Kyoto University Research Reactor Institute
kV	Kilo Volt
kVp	Kilovolt photon energy
kW	Kilo Watt
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBNL	Lawrence Berkeley National Laboratory
LCLS-II	Linac Coherent Light Source
LDMOS	Lateral Double-Diffused MOS
LET	Linear Energy Transfer
Li	Lithium
LIA	Linear Induction Accelerator
LINAC	Linear Accelerator
LLMW	Low-Level Mixed Waste
LLNL	Lawrence Livermore National Laboratory
LLP	Life-Limited Parts
LLW	Low-Level Radioactive Waste
LLMW	Low-Level Mixed Waste
LMIC	Low- and Middle- Income Countries
LWD	Logging-While-Drilling
LWFA	Laser-plasma Wakefield Accelerators
LWR	Light Water Reactor
MEMS	Micro-Electromechanical System
MESFET	Metal-Semiconductor Field Effect Transistors
MeV	Mega-Electron Volts
MgF2	Magnesium fluoride
mJ	Megajoule
ML	Machine Learning
MLC	Multi-Leaf Collimator
MLD	Machine Learning Device
MOA	Memorandum of Agreement
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistors
MPS	Mono-energetic high energy x-ray Photon Sources
MR	Magnetic Resonance
MTBF	Mean Time Before Failure
MTRU	Mixed Transuranic Waste
MTTR	Mean Time To Repair

MW	Mega Watt
MV	Mega Volt
NaI	Sodium Iodide
NARM	Naturally Occurring and Accelerator-Produced Radioactive Materials
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
NCI	National Cancer Institute
NCRP	National Council on Radiation Protection and Measurements
NCT	Neutron Capture Therapy
NDC	Non-Destructive Characterization
NDE	Non-Destructive Evaluation
NDSE	Neutron Diagnosed Subcritical Experiments
NDT	Non-Destructive Testing
NEA	Nuclear Enterprise Assurance
NIF	National Ignition Facility
NIH	National Institutes of Health
NII	Nonintrusive Inspection
NIST	National Insitute of Standards and Technology
nm	Nanometers
NMR	Nuclear Magnetic Resonance
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
NPL	National Physical Laboratory
NRC	Nuclear Regulatory Commission
NRCC	National Research Council Canada
NRF	Nuclear Resonance Fluorescence
NRTA	Neutron Resonance Transmission Analysis
NIST	National Institute of Standards and Technology
NSTC	National Science and Technology Council
NWPA	Nuclear Waste Policy Act of 1982
OFHC	Oxygen-Free High Conductivity
OPEX	Operational Expenditure
OSHA	Occupational Safety and Health Administration
OSTP	Office Of Science & Technology Policy
Pb	Lead
pC	Picocoulombs
PCAST	President's Council of Advisors on Science & Technology
PFNA	Pulsed Fast Neutron Analysis
PFNTS	Pulsed Fast Neutron Transmission Spectroscopy
PHM	Predictive Health Management
PIC	Peripheral Interface Controller
PID	Proportional, Integral, and Differential
PMT	Photomultiplier Tubes
pO2	Partial Pressure of Oxygen
PRD	Priority Research Direction

PSD	Pulse Shape Discrimination
PSE	Principal Structural Elements
psia	Pounds Per Square Inch Absolute
PSP	Photo-Stimulable Phosphor
PSS	Power System Stabilizers
pu	Porosity Unit
PμSL	Projection Micro-Stereolithography
PVD	Physical Vapor Deposition
PWFA	Plasma Wakefield Acceleration
QSPR	Quantitative Structure-Property Relation
R&D	Research and Development
RBE	Relative Biological Effectiveness
RCRA	Resource Conservation and Recovery Act
RDD	Radiological Dispersal Device
RF	Radio Frequency
RFQ	Radio-Frequency-Quadrupole
RPM	Radiation Portal Monitors
RT	Radiotherapy
S&T	Science and Technology
SAARP	Small Animal Radiation Research Platform
SAL	Sterility Assurance Level
SBIR/STTR	Small Business Innovation Research/ Small Business Technology Transfer
SBRT	Stereotactic Body Radiation Therapy
SCADA	Supervisory Control and Data Acquisition
SiC	Silicon Carbide
SiPM	Silicon Photomultipliers
SIT	Sterile Insect Technique or Sterile Insect Technology
SLAC	Stanford Linear Accelerator Center
SmART	Small Animal Radiation Therapy
SNF	Spent Nuclear Fuel
SNM	Special Nuclear Material
SNS	Spallation Neutron Source
sO2	Saturation of Oxygen in blood
SRF	Superconducting Radiofrequency
SSMP	Stockpile Stewardship and Management
SW	Software
SWaP	Size, Weight, and Power
SWFA	Structure Wakefield Acceleration
TGFβ	Transforming Growth Factor Beta
THz	Terahertz
TiN	Titanium Nitride
TINT	Thailand Institute of Nuclear Technology
Ti-Sapphire	Titanium-Sapphire Lasers
ToF	Time-of-Flight

Tm	Thulium
TPFD	Technology Perspectives Factual Document
TRL	Technology Readiness Level
TRU	Transuranic
TSA	Transportation Safety Administration
UHN	University Health Network
UHV	Ultra High Vacuum
UI	User Interface
UK	United Kingdom
US	United States
USDA	United States Department of Agriculture
USDA-APHIS	Animal and Plant Health Inspection Service
UV	Ultraviolet
UV-LIGA	Ultraviolet - Lithographie, Galvanoformung und Abformung
VHEE	Very High Energy Electron
VHF	Very High Frequency
VMAT	Volumetric Modulated Arc Therapy
VUV	Vacuum Ultraviolet
WIPP	Waste Isolation Pilot Plant
XDI	X-Ray Diffraction Imaging
XFEL	X-Ray Free Electron Laser
XRD	X-Ray Diffraction
YAP	Yttrium Aluminum Perovskite

Appendix E. Small Sealed Sources- Geological Probing and NDT of Structures

E-1. Geological Probing-Well Logging

E-1.1. Summary of Measurements and Applications

In well logging, radioisotope-based and electrical techniques play the primary role. [Ellis-2007] Of the four key geological formation properties, porosity, fluid saturation, permeability, and lithology (rock type) utilized to characterize a geological formation, radioisotope techniques determine porosity and lithology, electrical techniques supply the fluid saturation, and rock samples extracted downhole estimate the permeability. Porosity is the fraction of total volume that is porous, fluid saturation is the fraction of the pore volume holding the desired fluid (oil and/or gas in hydrocarbon exploration), and permeability relates to the ability of the fluid to flow through the rock. Lithology affects the other three parameters and also affects well construction decisions. Porosity and oil saturation together determine the reserves volume.

Porosity is arguably the most important parameter. An accuracy of ±1 pu is desired in clear formations to estimate the reserve accurately; one pu equals 1% by volume. The formation density determined using a 1.5-3.0 Curie (Ci) ^{137}Cs source is accurate to within ±0.01 gm/cc which translates to the desired ±1 pu porosity accuracy and thus provides the most accurate measure of porosity. Natural GRs from ^{40}K, ^{232}Th, and ^{238}U arising in the rock allow lithology determination in terms of shale vs. clean formation fractions. Currently, ~6-16 Ci Am-Be sources are used to estimate the neutron porosity that allows delineation of gas and complements the natural GR data in identifying shale, especially in wells where natural GR are ambiguous. Electrical techniques are used to delineate oil from water and quantify oil saturation. Acoustic and NMR techniques that provide two important complimentary formation properties, rock anisotropy and fluid type, respectively, have also been used for porosity. NMR techniques can also provide a permeability indicator.

In more complex formations, for example in unconventional reservoirs such as shale oil or gas, where mineralogical information may be needed, D-T-generator-based (n-gamma) inelastic-*cum*-capture spectroscopy techniques which provide a more complete mineralogy are beginning to replace Am-Be-based (n-gamma) capture-only spectroscopy techniques currently used. [Pemper-2006; Radtke-2012]

In order to determine the formation characterization parameters, a suite of connected devices (denoted as a tool-string) is lowered down hole, either post-drilling with a cable called *wireline* and data recorded as the tool string is moved up-hole typically at about 1800 ft./hr., or during drilling with devices housed in the drill collar to perform the measurements in the logging-while-drilling (LWD*)* mode. The cable in wireline is used to transmit data up hole. In LWD, mud pulses are used to transmit some critical data up hole in a low bandwidth for an initial evaluation with data also stored in tool memory for a later, a more detailed analysis after the tool has been brought out of the hole.

Well logging tools often navigate harsh geological and physical conditions. The temperature can range from 75-500^{o}F, pressures from 200 psia to over 30,000 psia at the tool housing, and vibrations of 1000 G in LWD. [Badruzzaman-2015]

E-1.2. Alternatives to Radionuclide-based Techniques and Tools

Radionuclide-based tools pose security and safety risks. Thus, alternative nonnuclear and nuclear-based techniques have been proposed and some have been marketed by the industry. [Ellis-2007; Flanagan-1991; Evans-2000; Reichel-2012] In addition, the National Research Council of the National Academy of Sciences in its 2008 report to Congress recommended that Am-Be sources used in well logging be replaced by either D-T generators or ^{252}Cf sources. [NAS-2008] The Council did not make similar recommendations for the ^{137}Cs density tool source due to its lower risk category [IAEA-2003] and having no obvious electronic replacement. A recent study noted challenges of electronic radiation sources and a fairly detailed survey of the tested alternatives, both non-nuclear and nuclear-based and their associated performance was provided in a recent NNSA-supported Scoping Study. [Gilchrest-2011; Badruzzaman-2015]

E-1.2.1. Tested Alternatives: The 2015 Scoping Study assessed the proposed alternatives to radioisotope-based logging techniques. The major conclusions were as follows:

E-1.2.1.1.Non-nuclear techniques:

While acoustic and NMR techniques provide important complimentary parameter, neither is considered at replacement as detailed by Badruzzaman (2015) and summarized below.

The porosity error with the two non-nuclear techniques, acoustic and NMR, were greater than with nuclear techniques (2-4 pu and 2 pu respectively.)

Acoustic techniques would not work in unconsolidated sand due to sound velocity limitations. Many of world’s important reservoirs are such reservoirs. Nuclear-based techniques would be fine.

NMR techniques do not suffice in very low porosity formations, in micro pores, or in the presence of paramagnetic material. Only nuclear techniques would be effective in these formations. Micro pores are important in unconventional reservoirs and paramagnetic materials are present in several key formations.

While acoustic tools can be logged at the standard wireline logging speeds of 1800 ft./hr. (or higher) in open hole wireline logging, NMR techniques at ~240 ft./hr. is unacceptably low. This arises from the inherent slow rate of polarization incompatible with the wireline logging speed. This is not an issue in LWD where the rate of penetration is much lower than wireline logging speed.

NMR cannot provide lithology information while acoustic can provide only limited lithology information. Only nuclear-based techniques can provide clear lithological information. Lithology impacts interpretation of other key parameters and helps place and construct wells for safe operation.

Neither NMR nor acoustic can provide mineralogy information; only nuclear-based methods can. Mineralogy is important in unconventional resource evaluation.

E-1.2.1.2. Tested Generator-based Neutron and Density Alternatives: Tools with two concepts have been marketed.

D-T generator based neutron porosity:[23] Two such tools have been marketed one for both wireline logging and the other LWD, but by the same major logging company. [Flanagan-1991; Evans-2000] Other major companies have done the research but have not marketed such tools due to economic considerations.[24] The LWD tool has performed well but due to the borehole environment issues the wireline tool has been challenged. D-T neutrons are have higher energy and thus lower porosity

---

[23] D-T generators are not new to well logging. D-T generator-based tools have been used, since the mid-1960's, in cased-hole logging tools designed for reservoir *monitoring* to locate and quantify remaining hydrocarbons utilizing temporal n-gamma capture counts and/or n-gamma inelastic energy spectra. [Ellis-2007]

[24] Allen Gilchrist, retired Chief Scientist at Baker Hughes in commenting on a draft of the present report.

sensitivity than Am-Be neutrons. These lead to a greater impact on wireline data, especially in complex geometries[25]. [Badruzzaman-2005; Badruzzaman-2019]

Inelastic (n-gamma) density (INGD): The technique uses inelastic GRs from interaction of high-energy neutrons from a D-T source. It was implemented in an LWD tool. [Evans-2000; Reichel-2012] Reichel reported density errors of ±0.025 gm/cc in clean formations and ±0.045 gm/cc in shales. These are way over the error of ±0.01 gm/cc that the ^{137}Cs source density tool provide; the actual errors in the field were often greater. [Badruzzaman-2014] Thus, the resulting porosity errors would, in general, be unacceptably high. The INGD relies on coupled neutron-photon physics i.e., it is impacted by the neutron interactions vs. the pure photon physics utilized in ^{137}Cs density tools.[26] [Badruzzaman-2014][27]

Clearly, none of the techniques marketed can generally provide an appropriate replacement for the key parameters that radioisotope-based techniques measure, mainly due to their physics limitations.

E-1.2.2 Novel Generator-based Tool Concepts

Since the publication of the LLNL study [Badruzzaman-2015] two developments have taken place on accelerator-based tools for well logging. One is an experimental low-energy (~300 keV) x-ray density tool with a potential to replace ^{137}Cs source tools for density. [Simon-2018] The other is work on non-D-T neutron porosity concepts. Two D-D generator neutron tools have been tested, one in Ukraine and the other in the US for shallow reservoirs. [Jurczyk-2018] A comprehensive modeling study investigated the response of neutrons from D-D and D-^{7}Li fusion generators, and a (α-Be) dense plasma focus (DPF) accelerator for their potential to replace Am-Be sources for neutron porosity. [Badruzzaman-2019] All are tritium-free generators. The x-ray density tool follows the 3.5 MeV LINAC x-ray density tool in the 1980's (King-1987) which had shown promise in field tests but was never marketed due a number of remaining challenges. The new x-ray tool is smaller and simpler and shows greater promise but still faces a number of issues such as its application in the much harsher LWD conditions.

The neutron generators assessed would perform based on their energy spectrum depicted in Figures E.1(a) and E.1(b) and their neutron yields relative to those of an Am-Be source.

---

[25] Neutron porosity from D-T generator, could be good enough for log interpretation with a density measurement and real lithology (full spectroscopy), and other measurements, according to Bradley Roscoe, retired Nuclear R&D Manager of Schlumberger-Doll Research, in commenting on an early version of the report. However, note the need for additional measurements to achieve this. Besides, field experience indicates that this may not always work.

[26] This reflects the fact that here one starts with 14-MeV neutrons and their interactions determine the inelastic gamma production and hence the resultant density, in fact a pseudo-porosity. There are three aspects to this as discussed in the cited reference: softening of the neutron spectra with addition of hydrogenous fluids as the fluid-filled porosity increases, reduction of oxygen concentration as solid material is reduced, and capture correction. None of these arise with a purely photon source such as ^{137}Cs or the x-ray source.

[27] The technique had first originated in cased-hole applications in the 1990's as a density indicator in old wells which did not have modern log data [Wilson-1995; Badruzzaman-1998; Odom-1999; Neuman-1999] and thus was not intended as a quantitative measure of density.

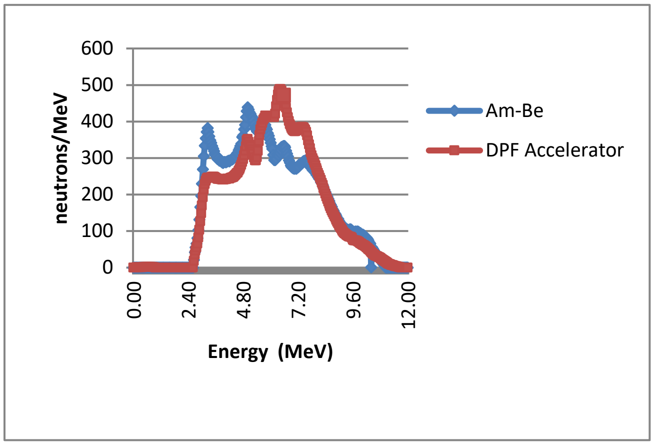


Figure E.1 (a). Am-Be vs. DPF accelerator neutron spectra from theory. [Schmidt-2012]

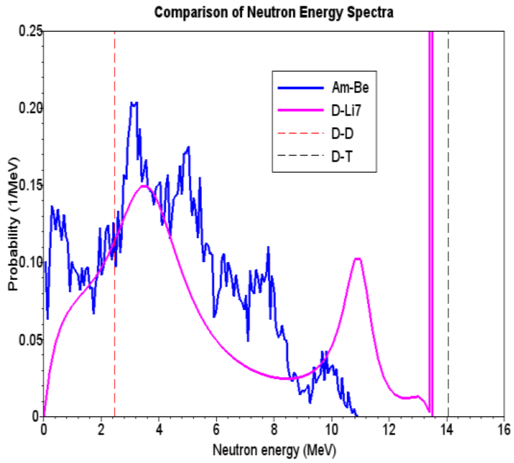


Figure E.1 (b). Neutron spectra $^{7}Li(d,n)^{9}Be$, D-D, D-T and ^{241}Am-Be. (Adopted from Badruzzaman-2015)

D-D with lower energy neutrons would show greater porosity sensitivity, D-^{7}Li with a similar spectrum will exhibit a similar porosity response, and the (α-Be) DPF with a near-identical spectrum will exhibit an almost identical porosity response. However, due to the 50-fold lower nominal neutron yield of D-D and D-^{7}Li generators, their logging speeds would be unacceptably slow. The neutron yield from (α-Be) DPF is likely to be similar but actually designing such a generator for logging tools would be a very long-term effort.

E-1.3. Advances in Associated Technologies

In addition to tests of generators in well logging noted above, the past three decades have seen use of advanced detectors to extract more information and use of three-dimensional radiation transport simulation to minimize design time and optimize field tests.

E-1.3.1.Detectors

While neutron detection still relies on ^{3}He, photon detectors have experienced significant developments beyond the traditional NaI(Tl) crystals, initially in cased-hole applications (for saturation monitoring) and later in open-hole applications. Bismuth Germanium Oxide (BGO) crystals are used in Am-Be-based spectroscopy tools [Herron-1996; Galford-2009], GSO crystals in a density tool [Eyl-1994], and $LaBr_3$ in an n-gamma spectroscopy tool. [Radtke-2012] Table E.1 displays key performance parameters of scintillators used for downhole spectroscopy to determine mineralogy.

***Table E.1.** Selected performance parameters of scintillators used for downhole spectroscopy (NaI, BGO and $LaBr_3$ parameters are adopted from Adopted from Radtke-2012 and GSO parameters from Roscoe-1992)*

Property	**NaI(Tl)**	**BGO**	**GSO**	**$LaBr_3$: Ce**
Density (g/cm^{3})	3.67	7.13	6.71	5.29
Effective atomic number	50.8	75.2	59	46.9
Primary decay time (ns)	230	300	60	25
Light yield (photons/keV)	43	8.2	18	61

$LaBr_3$ with 25 ns decay has a five-fold faster count rate than NaI and 10-fold than BGO, with no spectral distortion at high count rates. BGO crystals show significantly greater light yield degradation as the logging temperature rise. The light yield from $LaBr_3$ remains almost unchanged over the entire range of logging temperatures (up to 150ºC). [Radtke-2012] However, $LaBr_3$ cannot be used for natural GR logging due the activity originating in the crystal (from ^{138}La) that would result in a photon energy line almost identical to that from the potassium in the rock.

Recently, YAP (Yttrium Aluminum Perovskite: YAlO3) crystals, have been introduced in new cased-hole well logging tool. [Rose-2015] The YAP with very small thermal and epithermal neutron capture cross sections and no capture neutron background allows for obtaining a measure of the fast neutron cross-section. YAP showed no degradation at high temperature, and is non-hygroscopic. In time such scintillators will likely be utilized in open-hole logging tools in the future. However, most advanced scintillators are still limited to 175ºC. Thus, several well logging tool designers utilize Geiger Muller tubes in their natural GR devices for LWD up to 200ºC. [Mickael-2002; Parker-2016]

E-1.3.2. Computational Techniques - Tool Design and Assessment:

Full three-dimensional radiation transport techniques first introduced in the early 1980's to model the response of nuclear logging tools on a significant scale [Ullo-1986; Badruzzaman-1991] expanded rapidly in the 1990's to allow full tool design utilizing Monte Carlo techniques to reduce the need for multiple builds. This reduced the design cycle time for the major logging companies from 10 years to 1-2 years. [Badruzzaman-2005] The technique was recently utilized to augment the calibration in spectroscopy tools. [Pemper-2006; Inanc-2009; Radtke-2012] Several operators (oil companies) adopted simulation to assess new tools, *a priori*, in complex well-bore and formation conditions difficult to calibrate in the laboratory, to minimize the need for expensive field tests. [Day-1990; Badruzzaman-2002; Zett-2012] The Los Alamos Monte Carlo code, MCNP [LANL 2003/2008], became the simulation code of choice in the industry.[28]

Monte Carlo simulation of n-gamma spectroscopy tools can be particularly slow since they often require tracking of secondary radiation. Also, without suitable cross-section libraries for such interactions one can arrive at wrong predictions of key parameters. [Badruzzaman-2002]

In the above applications, often users had to develop their own 'patches' in MCNP for tallies and detector response functions suitable for their tools. Visualization in MCNP is limited. Thus, further work is needed to make modeling more readily useable especially as tools with novel generator-detector concepts are developed or deployed.

E-2. NDT of Structures-Basis and Technology

E-2.1. Application Basis

NDT of structure discussed in this report is performed using a variety of techniques, including gamma radiography, x-ray radiography, ultrasonic, electrical, die-penetrant, and magnetic techniques. Gamma radiography is the primary method. Ultrasonic techniques complement these techniques and x-ray techniques, not quite as versatile as gamma radiography, are in an early stage of application. Details of

---

[28] Modeling capabilities have benefited large companies, small/medium companies often do not have access to them.

various NDT methods can be found in Section V of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. [ASME-2017][29]

E-2.2. Gamma Radiography

This technique measures the density (more specifically, the electron density) of the material and is commonly utilized to examine welds and structural cement in many industrial settings. Unlike well logging, gamma radiography is a transmission experiment, with gamma emitting radioisotope source is placed on one side and gamma-ray detector on the other of the object being imaged. So, access to both sides of the object is needed. The ‘detector’ could be a film or storage phosphor plate or direct conversion digital detector plate. Table E.2 lists the attributes of isotopes and associated devices used in gamma radiography.

Table E.2. *Gamma Radiography: Isotopes and Applications*

Isotope	**Half-life**	**Decay mode**	**Activity in Radiography device**	**Gamma-ray energy**	**Application**	**Device weight/dimensions**
^{192}Ir	73.8 days	Beta emission (96%); electron capture (4%)	20-200Ci commonly 100 Ci	206-612 keV Average: ~370 keV	< 6 cm Pipes; welds	Up to ~50 lbs. 13in. x 8in. x 9 in. Smaller lighter devices may be used to hold lower activity sources
^{75}Se	120 days	Electron capture	4-120Ci commonly 80 Ci	60-401 keV Average: ~215 keV	<3.5 cm	Up to ~42 lbs. Smaller lighter devices may be used to hold lower activity sources
^{60}Co	5.27 yrs.	Beta decay	60-300 Ci	1.173 MeV and 1.332 MeV Average: 1.22 MeV	Over 14 cm thick materials (Large structures: building, bridges)	700 lbs. and above
^{169}Yb	32 days	Electron capture	5-15 Ci	63- 308 keV	Thin metals ~1.5 cm (5-30 mm)	May use Ir-192 projectors

^{192}Ir and ^{60}Co devices are commonly used in the US while ^{75}Se is more commonly used in Europe. The interpreter studies the intensity variation to determine where material defects exist, such as voids, porosity, cracks and corrosion.

Gamma radiography is usable in extreme operating conditions (extreme cold, for example), remote locations, and tight spaces where technologies requiring large amounts of steady power or volume are not

---

[29] NDT is used in a number of other related applications. One example is the inspection for localized corrosion under insulations in plants; such corrosion can pose major safety and economic challenges. A variety of techniques are utilized. These include the radionuclide-based and x-ray techniques discussed in this report, infra-red techniques to detect damp spots, Am-Be based neutron back-scatter techniques to detect wet insulations in pipes and vessels. [Twomey-1996] The neutron backscatter technique utilizes the same Am-Be-based hydrogen-index measuring physics principles that well logging techniques utilize, but usually with a much smaller activity of the source.

practical. These include remote oil pipelines, open-water drilling platforms or lay barges, tightly packed volumes, inaccessible to larger bulky equipment such as refineries or other complex processing plants.

Power generation and petrochemical sectors make up about nearly half of all gamma radiography use, with the remainder spread across automotive, infrastructure, manufacturing, aerospace, and other applications. [Shilton-2017] In gamma radiography little surface preparation is needed prior to inspection of the material and often little or no calibration is needed and the interpretation of images is relatively straightforward. Gamma radiography can be used in remote locations without access to reliable power. It can be used in inaccessible places, where bulky or heavy devices cannot be inserted for radiography.

Table E.2 (above) notes the various energies of the gamma sources. The average energy determines the penetration depth while the dose rate and source-to-detector distance determine the shot time needed to generate a quality image. In addition to the energy, note the quality of a radiograph in its ability to show a flaw also depends on several other factors such as set-up, detector type/class (film or solid-state panel), source to film distance, object to film distance and the film processing. [Hayward-2006]

<u>*An operational example*</u>:

Figure E.2 depicts an example of taking radiography shots at definite intervals and lists some of the key operating conditions (weather, height). Typically, a shot set-up may take 10-15 minutes to position the detector and camera or a guide tube and collimator if a projector is used, while the shot itself (when the source is exposed) may take just a few seconds to a few minutes before the source is retracted to a safe position inside the device. The radiographer can then safely move on to set-up the next weld.

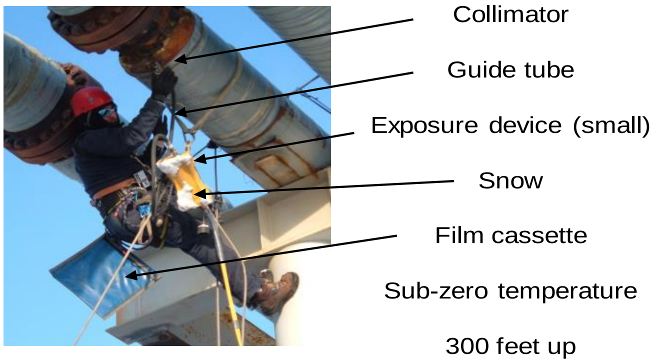


Figure E.2. *An Operational Example of Radiography of Welds. (Image credit: M. Shilton, 2017[30])*

E-2.3. Tested Alternatives to Gamma Radiography for NDT of Structures

x-ray-based radiography techniques and ultrasonic imaging that have been developed are often mentioned as alternatives to gamma radiography. Both require a reliable power supply. Ultrasonic techniques are complementary rather than replacement. Current x-ray devices can still be too large to probe small spaces that gamma ray cameras can access. Hence, a compact x-ray system would be needed. Design specs are described later. We discuss the current state of both x-ray and ultrasonic techniques next.

---

[30] M. Shilton, “Gamma Radiodgraphy”, presented to the DHS/DOE-NNSA Alternative Technologies Working Group on behalf of the International Source Suppliers and Producers Association (ISSPA), May 2017.

E-2.3.1.x-ray radiography

Early units originating in medical applications provided x-rays in the range of 120-150 kV, which however, was not sufficient for many industrial imaging applications that require seeing through a variety of metals. Modern x-ray tubes can be 400-450 kV and LINACs have been developed to produce MeV range x-rays. Both fixed and portable units now exist. The fixed units are usually large. x-ray units with energies much above 200 keV range are much larger and less portable than ^{192}Ir or ^{75}Se devices operating in that energy range. Some progress has been made in designing pipeline crawlers with x-ray sources to image empty pipes only. However, crawlers cannot go everywhere such as around tight corners or past flanges and many pipe diameters are just too small. One extreme example would be the inability of x-ray devices to access the thousands of pipes that may arise in a nuclear submarine. [Shilton-2017]

A 5-MeV electron LINAC-based radiography device was proposed. [Audutore-2005] It required 1-kW power, which would be difficult to deliver in remote locations. Recently, a micro-LINAC was reported claiming to be relatively light-weight and thus potentially a low-cost replacement for radiography sources. [RadiaBeam-2019] The device has two pieces, a power supply and a compact radiation head. The latter weighs about 40 lbs. The micro-LINAC would produce higher energy x-rays than an x-ray tube, more along the energies of ^{192}Ir gamma rays. However, these devices would require field-testing and may not lend themselves to ease of use that isotopic gamma radiography gamma cameras provide.

Similar to gamma radiography, x-ray radiography requires little surface preparation prior to inspection of the material. However, as in gamma radiography, a radiation exclusion zone needs to be set up during operation.

E-2.3.2. Ultrasonic Techniques

Here a high-frequency sound wave is sent through a transducer and propagated through the material to be probed. Radiography techniques measure the mass or density while ultrasonic techniques detect discontinuities. Thus, ultrasonic techniques are better at detecting narrow defects aligned with the sound wave, and delamination or cracks oblique to the sound wave while radiography techniques are better at detecting shallow surface defects, porosity, or wall thickness. Thus, in general, ultrasonic imaging for NDT is more of a complementary technique. [Roux-2005]

In ultrasonic operation, no radiation exclusion zone needs to be set up during testing, unlike in gamma-radiography and x-ray radiography when no additional safety steps are needed.

E-3. Security Challenges of Small Sealed Sources

Despite regulatory requirements and use protocols, both ^{137}Cs and Am-Be sources in well logging and gamma sources used in NDT of structures can pose safety and security risks, as illustrated by several source incidents. [NRC-2006; Badruzzaman-2009; Johnson-2014]

^{137}Cs logging sources are Category 3 sources according to the IAEA safety risk categorization while the Am-Be sources are generally high Category 3 sources while earlier sources are Category 2. [IAEA-2003] A logging truck often transports multiple sources and a conglomeration of lower category sources in a certain configuration can be in a higher risk category. Half-lives of radiography sources are shorter than those of logging sources and thus associated long-term environmental hazards with these radioisotopes are less. However, in view of their activity noted in Table E-2, these sources are well above the Category 2 threshold.

Security risk primarily arises from their small size, ready mobility, and use, often in unstable regions of the world, making them vulnerable to diversion for use in radiological dispersal devices (RDD). Several source incidents such as stolen or lost sources, terrorist attacks on logging trucks, etc., have been reported over the years. [Johnson-2014] According to an IAEA study, gamma-radiography has had a challenging risk profile. [IAEA-1999][31]

E-4. Desired Performance Criteria, Roadblocks and Economic Analysis-Well Logging

Source risks have propelled the discussion of replacing small sealed sources in industrial applications. However, to be replacement the proposed alternatives have to be able to meet certain technical and economic criteria. We noted previously that non-nuclear logging and radiography techniques provide complementary but not replacement quality measurements. We also noted that tested nuclear-based alternatives have not performed acceptably except in the case of the D-T generator n-gamma spectroscopy for mineralogy.

In this subsection we discuss the performance criteria required, roadblocks to transitioning, potential financial and/or application benefits if the accelerator technology meets the criteria, and specifications for the accelerator and detector components of the systems desired.

E-4.1 Desired Performance Attributes-Well Logging

Table E.3 combines the information from the NNSA Scoping Study [Badruzzaman-2015] and the BRN Workshop discussions in a composite form to indicate the desired accelerator/generator attributes. It also identifies a number of additional performance attributes that need enhancement of new research.

Table E.3. *Desired Attributes: Accelerator/Generator, Data, Interpretation and Regulatory Requirements (Sources: LLNL-TR-679101 and Information gathered during Workshop)*

Accelerator/generator: Radioactivity-free	Neutron/Photon: energy /yield	• Neutron: > 2 MeV: Am-Be equivalent (15 Ci) or better: • 2-4 10^7 n/s initially to 10^9 n/s longer term • Photon: < 1 MeV, 10^{10}-10^{11}/sec initially; 10^{11}-10^{12} /sec longer term
	Generator operation mode	• Neutron: pulsed for D-T to take full advantage-Duty factor 10%-50%, few µs pulse width (typically), sub-µs fall-off time for advanced measurements; 1-ns pulsing or associated-particle detection for time-of-flight. Will need theoretical assessment. • Photon: CW; will require 20% or higher duty cycle to simplify acquisition and reduce development cost
	Reliability and Diagnostics, including AI	• Highly desired. – Critical. Generator failure will be catastrophic in many cases.
	Directionality	• Neutron: Yes, in longer term • Photon: Yes, with collimation
Tolerances	Temperature	• 150ºC - 175ºC (under normal operating conditions.); up to 200ºC in some LWD applications
	Pressure	• As a subassembly, no extreme high pressure ratings needed.

---

[31] In addition, in 2006 a ^{137}Cs source in a logging tool stuck downhole was breached during its retrieval process with radioactive drilling mud reaching the surface. This resulted in an expensive clean-up, imposition of a long-term monitoring program by the State, and recommendations for enhanced protocols to prevent such an occurrence. [NRC-2006; Badruzzaman-2009]

	Shock	• LWD: 1000G, 1 ms half sine, 1000 shocks per axis • Wireline: 40G, 11 ms 20 shock per X/Y axis and 40 shocks z axis
	Vibration	• LWD: Random vibration 5 to 500 Hz, 20 g rms, X, Y and Z axis, 4 hours per axis • Wireline: Random vibration 5 to 500 Hz, 7.5 g rms, X, Y, and Z axis, 2 hours per axis
	Power requirements	• < 50 -500 watts wireline (5-50 watts desirable LWD). •
	Operation	• 500-1000 hours initially; > 2000 hours longer term.
	Heat removal	• no active cooling
	Tool size	• Length: < 12 ft. up to 6 ft. more for generator and electronics • Diameter: Varied- 3.5 in. -1.7 in. • Weight: n/a
	Telemetry	• Defined by the end user
Data, Calibration, Interpretation	Data acquisition	• Neutron: Energy-dependent in longer term • n-gamma spectra: Tens of nanoseconds in longer term- would allow recording of pure inelastic counts without the need for capture subtraction
	Calibration	• Unchanged. All safety issues must be resolved a priori; can be handled using current facilities (by integrated service companies)
	Accuracy	• Density porosity: 1 pu • Neutron porosity: 1.5 pu
	Additional interpretation	• Neutron: Imaging such as API • Improved density imaging of geology
	Interpretation complexity	• No issue if spectrum similar to Am-Be • Corrections required for wellbore and formation variability, in-situ interpretation and iteration required during acquisition. Typically done by end-user or client.
	Post-processing requirements?	• Real-time output, but also ability to post-process, especially if multiple parameters and combination with other tools if needed.
	Radiation transport simulation and visualization	• Faster simulation and real-time visualization that currently possible with such codes as MCNP.
Operational Risk/Cost	• Stuck tool incidents: Loss of generator, well abandonment and associated cost. Lower risk during rig-floor operations compared to chemical sources. Enables remote operations of the rig.	
Generator / Detector Cost	• Neutron: $100,000-200,000 purchase cost- affordable by major logging companies • Density: $200,000 purchase cost – affordable by major logging companies. Detector cost could also be high and together the concept may become prohibitively expensive. • Design, calibration, and deployment cost would be additional and estimating total cost would be complicated- See comment in the text. • Should not be unaffordable to small service companies- they supply 70% of US logging units- need support for affordability to make transition. Major logging companies have technological and financial ability to develop accelerator-based technologies.	
Design to deployment time frame	• 3-10 years. For more advanced concepts such as API, a longer time-frame may be OK.	

Regulatory	• Relief on regulatory regime: Currently, regulations for life cycle handling requirements, storage, shipment, abandonment of D-T generators are the same as those of radionuclide sources. Thus, the regulatory regime does not recognize difference between D-T generators and chemical sources. These, and abandonment rules, unless differentiated, offer no benefit to customer transiting to accelerators. • The above needs to be revisited for other generator types.

From the Table the following are to be noted:

1. *Accelerator/generator type*: Ideally and ultimately, radioactivity-free.

2. *Particle yield:* Initially, the desired neutron generator and photon generator yield would be similar to those for radioactive source tools. In the longer run, achieving the higher yield desired would allow a faster logging and better quality data, especially, in spectroscopic measurements.

3. *Power requirement:* Higher power input would be required to overcome the low nominal neutron yield of D-D and D-^{7}Li generator to obtain statistically meaningful counts and thus acceptable logging speed. [Badruzzaman-2019]

4. *Neutron detectors:* ^{3}He detectors for neutrons record total counts. If neutron spectra can be discriminated into fast, epithermal and thermal, additional information such as pure hydrogen index not affected by thermal absorbers can be determined.

5. *Photon detectors:* Section E-1.4.1.noted the use of advanced scintillators in well logging. However, currently, all gamma detectors in these tools usually record the secondary gamma rays in two stages, first total (inelastic and capture) gamma counts versus energy during neutron burst (10-40 microseconds) and then capture gamma counts vs. time after the source is turned off. One then utilizes complex capture corrections to extract the inelastic gamma counts from the total counts. As was seen in a recent paper by Monte Carlo modeling, if photon detectors can acquire sufficient energy-dependent data in tens of nanoseconds during the burst, it will likely be possible to delineate the inelastic counts with little or no capture correction. [Badruzzaman-2014]

6. *Reliability and diagnostics:* Electronic radiation generators can fail and such failure can be catastrophic in well logging application due to the expense of rig time in a place such as off-shore, where rig times often are $1 million/day. Wells may cost several million dollars and inability to acquire quality data would add to the rig-time cost. Thus, it is essential that a capability be developed and installed to predict accelerator or accelerator component failure before it happens, to allow a quick corrective action in order to finish the job. These PHM systems can include the use of AI, machine learning or other such methods.

7. *Neutron imaging:* Currently, only density images of rock beds are constructed using data from the ^{137}Cs density tools and those too are somewhat rudimentary. Neutron imaging with associated particle imaging can open up new areas of down-hole investigation. Two specific possibilities of this are discussed next.

    a. Directional information using alpha-imaging: This will be done with an API neutron generator that has a built-in alpha detector to detect the alpha particle associated with its neutron counterpart; they fly off in opposite directions. Alpha detection allows determination of the direction of the outgoing “tagged” neutron resulting in an “electronically collimated” cone of neutrons (in contrast to the isotropic distribution in a normal D-T neutron generator). When the tagged neutrons cause a gamma-producing reaction in the formation, time-of-flight (ToF) coincidence is used between the detected gamma and the alpha particle to determine the location where the reaction occurred (i.e., depth information) and the detected characteristic gamma is used to obtain elemental information. One then obtains a composition depth profile or image of the region probed by the cone of neutrons.

Directional information can possibly be used for well integrity assessments over the lifecycle of a well and this is a critical need in light of the 2015 Alsio Canyon failure.

Currently, API measurement is an extremely slow process (30 minutes in some homeland security applications). This would require a generator with an order of magnitude higher neutron output with a very small spot size to improve imaging resolution. But this would result in very high power densities on the target. So trade-offs would be needed. In addition to imaging, the neutron – alpha coincidence with API can also provide better signal to noise in some scenarios. However, significant challenges would arise, for example, following 10^7 or 10^8 neutrons, associated particles, and coincidence gamma rays each second.

b. <u>In-situ rock and fluid imaging with secondary gamma rays</u>: The concept of visualization of fluid flow and characterization of porous media by neutron radiography has been around for a long time. [Jasti-1992; de Beer-2006] The concept is predicated on the contrast between the thermal neutron absorption cross-section of rocks and hydrogenous liquids (sandstone is transparent, water and oil are opaque). de Beer and Middleton (2006) demonstrated in the laboratory that they can get a good estimate of the effective porosity, an important parameter in well logging. Badruzzaman (2005) using results of similar experiments by geologists at University of California, Davis that imaged the water-flow, speculated if the permeability of rocks can be determined from temporal snapshots as the front moves through the rock.

   The sources of neutrons were nuclear reactors in the above-noted rock and fluid imaging. Clearly, in down-hole measurements, a compact neutron generator with a high flux would have to be the alternative. Major innovations in neutron imaging technology will be required in such applications, however.

   Availability of neutron imaging techniques would encourage adoption of alternative technologies. However, extensive theoretical studies would need to be conducted in order to assess the potential of neutron imaging technologies in a well logging setting.

8. *<u>Simulation and Visualization</u>*: As noted previously significant challenges still exist in using radiation transport simulation, especially for spectroscopy. These challenges warrant faster computers, better particle tracking algorithms, and more complete cross-section libraries, especially if API processing is required simultaneously with tracking of secondary photons. In addition, a full dynamic visualization of the radiation transport would be particularly useful in the process.

9. *<u>Cost</u>*: Table E-3 lists only generator purchase cost and notes that other elements such as novel detectors that may be needed, and the design, calibration, and deployment may make it prohibitively expensive. Estimating the cost of transition from radioisotope-based logging tools to generator-based tools would be complicated and will depend on the company. Data on cost is usually company-confidential, further compounding such estimates. The impact of cost is discussed further in the section titled, 'Roadblocks,' elsewhere in the present Appendix.

10. *Regulatory impact*: Accelerator-based technology would cost more, especially in R&D phase but could reduce operational and regulatory risks. Although the D-T generator cannot be used as RDD's, there still remain some regulatory constraints in using them, mainly related to their dual-use nature, and presence of tritium. The regulatory environment would then need to be assessed in regards to the emerging technologies such as x-ray sources, D-D, DPF, or D-^{7}Li generators.

E-4.2. Roadblocks to Transition to Alternatives:

As noted in [Badruzzaman-2015], cost will be a primary roadblock in developing and transiting to alternatives, even with perfect technical attributes and usable technology. This arises from the complex mix of industry entities that exists in terms of their size, their associated financial and technical, and their respective business drivers. Many small companies are 'mom-and-pop' shops with limited technologies and reliance on third-party vendors for their tools and would need support on technology and funding.[32] They cater to on-shore oil companies operating in conditions that do not need complex technologies such as NMR or n-gamma spectroscopy. An x-ray density tools would be also complex and expensive for them. Economic challenges have limited the development of generator-based neutron porosity tools to only one major logging company). Thus, both technical and financial needs of a diverse industry will have to be accounted for as we search for compact accelerators for well logging.

The issue of technical and funding support for small/medium logging companies to help them transition was discussed in LLNL-TR-679101 where government support was recommended on both aspects. [Badruzzaman-2015] The mechanism of SBIR-funding that led to design and testing of a D-D generator neutron porosity tool for non-petroleum application by a start-up-like company that develops neutron generators [Jurczyk-2018] is unlikely to work for existing small/medium logging companies in view of their business structure and commitments.

While availability of technological and financial support would be an incentive for small/medium logging companies to consider alternatives to radionuclide-based logging tools, additional information likely from generator-based tools will be attractive for all logging companies and their users. The discussion of neutron imaging illustrated this.

E-4.3. Commercial/economic/strategic Value for Replacement:

Logging sources pose operational and security risks. One key operational risk is a tool getting stuck down-hole. Both retrieval, and well-abandonment, that is necessary if the source cannot be retrieved, can be very expensive; a well may have cost several million dollars to drill.

Security risks associated with radioactive sources result in stricter regulations, enforcement, more controlled transport, especially across international borders, or even between jurisdictions in a given country and thus adding to operating costs. Any source incident, even one without security implications but requiring clean-up and decontamination, can be very expensive. [Badruzzaman-2009] This may prompt calls for abandoning source use in well logging.

However, as noted previously in the present report, radionuclide-based logging tools are critically important. This was illustrated in Section 3.2 by the potential financial impact of 1-pu or larger porosity uncertainty on US oil reserves. Thus, a compact accelerator photon source,

preferably mono-energetic or at least with an average energy close to that of the 662 keV of the ^{137}Cs gamma rays (GR) would be very desirable for US strategic position in petroleum resources.

---

[32] In the US they supply nearly 70% of the logging units; a logging unit is a logging truck or a skid.

E-4.4. Existing market/economic Driver for Replacement Technology

Radionuclide-based logging techniques are fit-for-purpose technology for most applications, providing information worth trillions of dollars. However, an RDD incident would be devastating. Accelerator-based technology could significantly reduce these risks. Further, these new techniques could supply additional information, as noted elsewhere in the report. However, they will still have to be replacement quality for in standard applications, in terms of accuracy, reliability, and compatibility with legacy data, etc. Thus, tradeoffs would have to be examined.

E-5. Performance Criteria and Economic Analysis: Accelerators for NDT of Structures

We noted in the discussion of current state of technologies for NDT of structures that ultrasonic techniques are complementary and current x-ray devices can still be too large to probe small spaces that gamma ray cameras can access. Thus, compact x-ray generators with appropriate energy levels and a reliable power source would be essential if a significant replacement of gamma radiography cameras is desired. We briefly discuss these next.

E-5.1. Performance Criteria and Design Requirements

x-ray devices can offer radiography information similar to that from gamma radiography, but current x-ray machines proposed for the application are still inadequate for replacing gamma radiography devices. x-ray machines would require design of a miniaturized (4 in. diameter, 9 in. long), lightweight (<50 lbs.), power efficient device that can access crawl spaces that may be only a few inches. The device will have to survive in extreme temperatures (well below freezing and often above 100°F). The power supply has to be extremely reliable for a power failure can be catastrophic. Also, power requirements such as that for the 1-kW, 5-MeV LINAC device designed for radiography [Audutore-2005] and noted previously in the report would be impractical. From the energy of the GRs, noted in Table E.2, it can be seen that the electronic source should be a ~350 keV average energy device (1 MeV endpoint Bremsstrahlung, if a LINAC). Radiation emission from radioactive sources is very constant, short and medium term (notwithstanding decay). Electronic sources would have to match such high emission stability.

E-5.2. Commercial/economic/strategic Value of Replacement

The cost of gamma radiography devices will vary depending on the source and needs of the user. Public data on cost is hard to come by. It is believed that costs start at about $20,000.The maintenance and operations costs for these systems, including radiological safety and security costs are generally low. However, an RDD incident will be financially ruinous for the industry. Thus, their replacement is of interest. The National Research Council in its 2008 report to Congress noted that portable accelerator-based x-ray systems can be in the range of $200,000 and ultrasonic systems typically range from $50,000 to $100,000. [NAS-2008] However, the cost has likely changed since the report was issued. The maintenance and operational costs of these alternatives are higher than gamma radiography systems. The x-ray-based system will likely be subject to radiation protection practices that gamma radiography cameras have to follow. However, if a suitable compact, low-power x-ray system can be developed, these costs may be acceptable, provided the x-ray technology fits the bill technically, and the consequences of a potential RRD incident are factored in.

E-6. Technical Gaps: Well Logging and NDT of Structures

The desired technical attributes in Table E.3 identified a number of technical gaps between the current state of the art in various aspects of accelerator and associated technologies to advance use of accelerator technology compared to specifications in Charge Question 3. We review a selective set of these in this subsection.

E-6.1. Materials and Sources

Accelerator-based replacements for compact sealed neutron sources: All fusion generators adapted for well logging will likely meet the for factor requirements noted in Table E.3. It is not clear if a DPF will meet the criteria. Only D-T generators would meet the desired generator yields of order 10^7 to 10^8 neutrons per second initially, and higher in the future; current generation of D-D and D-^{7}Li would fall short. However, the latter generators are of interest to several potential users in view of the presence of tritium in D-T and its dual-use potential of the D-T source, and their greater porosity sensitivity than that of D-T neutrons.

On the other hand, in view of high energy neutrons, a D-T generator-based (n-gamma) spectroscopy tool would perform much better than Am-Be source or other neutron generators being considered. [Radtke-2012] However, statistical uncertainty of the spectral data can be high. Consequently, the near-term technology gap is suitable D-D sources for well logging, and to some extent, even higher yield D-T sources. In the longer term, D-^{7}Li generators can be of interest due to the proximity of their and spectra to Am-Be spectrum and the resultant porosity response noted in Section E-1.4. In addition, its 13.3 MeV line that arises in the D-^{7}Li spectrum, could possibly be used for neutron-induced gamma-ray spectrometry. Lithium is a problematic target as noted previously. More study is needed to understand the relative advantages/ disadvantages of D-^{7}Li over the standard D-D and D-T reactions, and if a lithium target can be hardened.

In the case of both D-D and D-^{7}Li, neutron yield has to be increased.

To truly replicate an Am-Be neutron spectrum with an accelerator, one would have to accelerate helium into a beryllium target. The (α-Be) DPF noted in Section E-1.4 showed a great potential for obtaining a porosity response almost identical to the Am-Be response. However, the cross sections associated with this reaction are negligible below almost 2 MeV. Thus, making a 2 MeV accelerator in such a small space is a technical grand challenge.

Even if above were possible, multiple generators in a single device, one for neutron porosity, a second for density, and a third possibly for spectroscopy, would greatly increase the reliability risk of generator-based devices. This would enhance the need for incorporating PHM techniques recommended for generator-based devices. However, as noted by [Badruzzaman-2019], a single generator D-T tool that can provide porosity and spectroscopy may be preferable if its tritium issues can be assuaged.

Financial and technological challenges of small/medium logging companies were discussed previously. Also, generators emitting neutrons with spectra different from Am-Be may force re-calibration of their measurements by logging companies, imposing a particular burden on small/medium companies.

On a longer-term basis, the well logging industry would also love to have the ability for time-of-flight measurements in well environments (Section E-4.1). One route to achieve this is with an extremely short neutron pulses (~1 ns). This is far more of a technological challenge than a longer pulse or CW source, in light of the small space and power requirements; the extremely short pulse requirement can likely only be met with a laser-based source. Laser-based neutron sources tend to be much larger than other available technologies and are lower TRL.

Accelerator-based replacements for compact sealed gamma ray sources: The technical gaps for gamma ray sources and ultra-compact sources for radiography based on compact accelerators fall into three main areas, which are the (1) size and weight of most present accelerators and their RF electronic drivers (in particular the diameter), (2) the poor conversion efficiency between the power in the accelerated electron beam and production of x-rays (or gamma-energy-level x-rays) from simple bremsstrahlung emission from slamming the electrons into a dense metal target, and (3) the adverse operating conditions, in particular ambient temperature and the lack of active cooling. For the demanding application, all three of these technology gaps must be simultaneously narrowed, in ways that could ultimately be made cost-competitive with isotope-based sources.

With regards to size and weight, the most common accelerators in S-band and C-band are too large in diameter (due to wavelength-dictated transverse size of the accelerating structure). Similar dimensional issues with transverse size arise at these lower frequencies with the typical klystron-based RF electronics. While smaller X-band accelerator structures and novel klystron-like sources have potential [Smirnov-2018] to meet some of the sizing requirements, accelerators and their RF electronics operating at even higher frequencies (> 20 GHz) would offer the prospect of even smaller diameter and shorter configurations. A major related technological gap is the difficulty in manufacturing accelerating structures and RF source circuits with the dimensional tolerances demanded by the higher frequencies in a way that remains economical.

Development of an experimental x-ray density tool was noted in Section E-1.4. The present method of producing gamma-ray like energies or conventional x-rays from an electron accelerator is simply to hit a dense metal target with the accelerated electron beam. This has extremely low conversion efficiency, of order 5-7%. This in turn demands a much higher accelerator power with its concurrent demands on size, weight, and input electrical power. Note that the remainder of the beam energy is lost as waste heat, which cannot be recycled to reduce the input power burden. Target heating also presents a cooling problem. In addition, the resulting spectra are very broad and do not resemble those of traditional ^{137}Cs sources or other particularly well-known radioisotopes. However, for compact x-ray radiography, a bremsstrahlung spectrum might be acceptable, but the poor efficiency remains a serious problem that must be overcome with new ideas.

The adverse operating conditions of very high ambient temperature and pressure (especially for well logging), and the prospect of rough handling and shock, put demands on the mechanical robustness of the accelerating structure, electron gun, and all portions of the RF sources that are beyond traditional technology, in particular with the constraints of size and the need to avoid active cooling. The poor existing conversion efficiency of electrons to photons exacerbates the thermal management problem.

An alternative method of producing gamma rays in a compact package, such as by triggering induced nuclear reactions in a target from lower energy particle beams from electrostatic accelerators [Chen-2013], is presently an immature technology. It cannot produce the needed gamma ray flux rates for nearly all the applications of interest. Although this method of gamma ray production shares some technological aspects with neutron generators, the gamma-producing reactions are less-well investigated, less efficient, and the beam requirements are different and more demanding. The requirements for the compact generation and insulation of ultra-high voltages (>300 kV) is largely beyond the capabilities of present technology. Electromagnetic MeV particle acceleration has demonstrated the technique, but the conventional systems are massive requiring fixed installations, although a recent advance in low-power, compact (~1.5 m long) radio-frequency quadrupole 4 MeV linear accelerator has been demonstrated that is field transportable in a van.[33]

---

[33] Jurczyk, B., IPAC 2019 Invited Talk

E-6.2. Detectors

Detector R&D: Non-destructive probing of structures and well logging applications present an interesting set of challenges for detectors. In particular, the applications require operation in harsh environmental conditions as well as being able to withstand activities up to 300 Ci, in the case of NDT of structures. Moreover, the both applications require and gamma detectors and well logging also requires neutron detectors. Historically, neutron detection has been limited to ^{3}He gas detectors, for neutron signatures and primarily NaI for photon detection. As illustrated in Table E.1, gamma-ray detectors have undergone significant improvements due to development of high-density, high-efficiency crystals in well logging. Less R&D has been devoted to neutrons detectors, partially due to harsh conditions of well drilling. One particularly important area of research is would be robust neutron imaging systems as noted in Section E-4.1.

Imaging with neutrons: Localization of neutrons improves the measured signal-to-background reducing the sampling time and refining the accuracy of porosity analysis. Various fast and thermal neutrons detectors can be used for imaging in general; however, the harsh environmental conditions associated with well logging limits the choice to a few. In particular, these detectors have to withstand temperatures up to 200^{o}C, making various scintillators difficult to be used for imaging with neutrons. Alternatives to ^{3}He detectors include scintillators based on ^{6}Li neutron capture reaction. GS20 is a commercially available glass scintillator with density of about 2.5 g/cm3. While its thermal neutron detection efficiency is an order of magnitude higher than ^{3}He, it suffers from photon signals due to inability to discriminate between the two particles. Pulse shape discrimination, a technique that allows to differentiate between photon and neutron induced signals in the detector based on time structure of the signal, would allow for various scintillators capable of operating in high-temperature high-vibration environments to detect neutrons and perform gamma spectroscopy simultaneously.

Enhancement of photon detection with scintillators: Ideally, photon detectors must have high density (for photon conversion efficiency), high light yield (for better energy spectroscopy), fast timing (for time characteristics of the reactions when paired with a pulsed source). Section E-1.4.1, noted advanced detectors with several these characteristics allowing them to potentially replace the traditional NaI scintillator. However, as noted in Table E.3, better timing resolution than 25 ns that $LaBr_3$ provides would be highly desirable. Also, $LaBr_3$ is radioactive; a radioactivity-free crystal would be needed for use in natural GR logging.

E-6.3. Engineering

As noted in Section E-4, one would need the following for the two applications discussed.

Well Logging: Most gaps can be identified from requirements noted in Table E.3. We note a few key items.

- <500 W power supply; 500-1000 hours operation initially, 2000 hours
- SWaP for accelerator-based photon and neutron sources
- No active cooling
- High operational reliability in downhole environment (temperature, pressure, shock, vibration)
- High-temperature, rugged detectors
- Fast, high-temperature electronics (FPGAs, processors, memory)
- High-temperature HV generator components (HVHT diodes, resistors, capacitors)
- D-T generator with negligible tritium leakage
- Small form-factor (α-Be) DPF in the long run

Radiography for NDT of Structures

- SWaP
- Portable ruggedness for in-field radiographic NDT
- NDT operations in temperature extremes (freezing to >100F)
- Reliable power supply for NDT
- Long lifetime

E-6.4. Diagnostic and Computational Capabilities

These would include the following:

- Reliability and diagnostics, including ML/AI – Fault detection and machine protection prediction.

- Predictive Health Monitoring (PHM) – System diagnostics must be in place to independently assess the status, functionality, performance of the generator/detector/analysis systems. Engineers and operators may be remotely located with respect to the probe site, and may be monitoring multiple sites simultaneously. The PHM technology will have to compatible with the desired attributes of accelerator/generator, detection, and interpretation attributes listed in Table E.3. Generator operation would incorporate pulsed modes for neutrons (DF 10-50%; 1 ns pulses for ToF) and Photons (CW, need DF >20% to simplify acquisition and reduce development costs). Development for timing, triggering and synchronization of data with generator will be needed. Specific systems needed are

  - ➢ DAQ, monitoring and control, fault detection and machine protection functions that locally reside on remote generator/detector heads.
    - o Environmentally hardened integrated circuits for real-time logic, memory, and communications (few GHz)
  - ➢ Integrated sensors and communications channels to provide diagnostic data for PHM.
  - ➢ Integrated triggering and synchronization systems at sub-ns-scale.
  - ➢ Differentiate neural net ML with real-time, on-board AI to separate fast decision making logic from slower training and retraining algorithms, and communication channels. Develop FPGA or GPU ML/AI algorithms for performance evaluation, machine state monitoring, fault detection/machine protection.
  - ➢ High level controls and human-machine interfaces to interact with (pseudo-)autonomous probe systems.
  - ➢ Develop improved computational models based on advanced radiation and particle tracking with full cross-section data libraries.
    - o Develop dynamic visualization tools for real-time data analysis
    - o Develop advanced ML/AI systems for decision making, HMI

- Computational needs: These would include faster computation time Monte Carlo simulation capability, improved particle tracking algorithms, and more complete cross-section libraries, full dynamic visualization of radiation transport, coupled to machine learning and AI techniques for data analysis, decision-making, and operator alerting. The cross-section libraries must to allow spectroscopy and API simulations.

E-6.5. High Gradient Accelerators

Advanced compact high gradient accelerators are ultra-compact sources but the associated drivers and their power supplies can still be large foot-print devices that require more space and resources to operate.

If the accelerator and radiation generation portion (the head) can be made compact enough with the drive power (laser or THz) being fed through some tethering structure, then even for the very limited space down well bores long distances underground or NDT of deep confined spaces such as inspection of interior of extended pipe structures, these advanced accelerators could still be a potential candidate for this application. However, these accelerators are also still limited in their ability to produce high average current beams. High repetition rate laser drivers are still being developed for laser-driven advanced accelerators. High repetition beam-driven sources are available for PWFA and SWFA but making them compact and portable is still awaiting development. Average power, efficiency, and size tend to be common limitations when considering the systems level. Nevertheless, several accelerator technologies relevant to this application, both for compactness and the gamma ray generation, are discussed below, even though the TRLs are very low at the system level.

LWFA DLA and THz accelerators for penetrating and endoscopic accelerators: The size of conventional MeV-class x-ray sources limits their capability to be constructed at the end of a tether and be fed into a well bore or pipe for this application. On the other hand, fiber feed of laser power to small (few cm) LWFA and DLA accelerator heads and fiber/waveguide feed of THz power to small THz accelerators, where a 1-10 MeV bremsstrahlung spectrum is generated, may offer an alternative, with fiber/waveguide tethers providing the power. The head has no, or almost no, moving parts, and could be expendable. Fiber can be of ~10 or more meter length to allow accelerator head to be positioned around or inside objects: upper limit not at this time clear. Laser driver required is modest, at mJ class, and in COTS form is ~600 lb, but there is a development path to ≤200 lb.

Compact accelerators could also be built with advanced high gradient accelerators like DLA/THz accelerators. This would require development of MeV sources at cm to mm scale for these laser-structure based accelerators. Such accelerators and systems at present are at somewhat early TRLs but substantially more advanced than other advanced approaches because they can use existing laser drivers. Testing may be realistic in the 5 year time frame.

LWFA/SWFA/PWFA/DLA and THz accelerators for high resolution mono-energetic gamma source: Compact mono-energetic gamma sources offer greatly improved performance and reduced dose to this application, whether it is for well logging and confined space NDT of structures like pipe inspection, or NDT of structures with larger sizes like buildings and bridges. This can open the ability to penetrate and resolve very dense objects, for example, resolving missing fuel assemblies in a very thick nuclear fuel storage cask has been simulated. The compact accelerator for the electron beam can be a LWFA or DLA using laser drivers or a THz accelerator using THz driver.

For well logging and NDT pipe inspection, a mono-energetic gamma source, at the head of the boring or inspection device, can be envisioned from the scattering of a laser beam from a narrow divergence, mono-energetic electron beam also generated by the same laser beam sent down the bore or pipe to produce mono-energetic gammas. If the confined space restriction is relieved for NDT of larger size targets, the scattering laser can be a different laser than the accelerator drive laser and can be brought to the accelerator using other optical means without a fiber tether. These useful characteristics require further development to improve the gamma ray flux generation and collimation to increase the brightness of the radiation beam. For example, long wavelength lasers could be used to reduce the divergence, e.g., 10 µm scatter laser gives gammas at 0.6 MeV with divergence of ~2 mrad, i.e., 10 cm spot size (CA head diameter) at 50 m.

Accessing these benefits requires development of mono-energetic sources with narrow divergence and small emission spot size, which is a good fit to high gradient advanced accelerator concepts and in particular laser-plasma (LWFA), laser-structure based (DLA), and THz accelerators. Such accelerators and systems are presently at early TRLs. This is also an area where the high rep-rate SWFA accelerators can be used for high speed examination of objects. Recent work on a compact collinear wakefield accelerator module has shown the promise to operate at near 1 MHz repetition rates. For high energy, this requires the development of SRF based beam drivers to power the SWFA structures and development of the structure capable of handling the heat load. These accelerators would be most suitable for medium future (10 years) development in this application.

Appendix G. Supplemental Background and Reference Technical Information on Accelerators

This appendix provides some additional information on the operating principles of various types of conventional particle accelerators, as well as a some examples of existing compact accelerators for medical and security applications. It also provides detailed supplemental information on a number of present electron beam linear accelerator structures. In addition, existing RF source technology is described. The appendix concludes with a very brief summary of the conventional method of x-ray generation from electron beams produced by accelerators. Together, the material in this appendix serves as a reference on present accelerator source technology, and the specific technology examples act as a point of departure for further advancements explored during the workshop.

Summary of Accelerator Configurations

The types, sizes, operating principles, and capabilities of accelerator systems in use today span an enormous parameter space, ranging from tabletop instruments for routine laboratory sample characterization all the way up to huge (27 km in diameter) multi-national facilities for fundamental particle physics research. Similarly, energy scales for the accelerated particles can range from ~100 eV to 100s of TeV. The general broad classes of accelerators are electrostatic LINACs, RF LINACs, cyclotrons, betatrons, microtrons, rhodotrons, and synchrotrons; note that this list is not inclusive of every type of accelerator in use. The following paragraphs provide simplified descriptions.

Electrostatic LINACs use only a static DC gradient in electric potential or unipolar pulsed gradient to accelerate particles. They are limited to relatively low energies (typically a few 100 keV) by insulation breakdown considerations (both internal and external), and further hampered by the typical need to operate the particle source components in a high voltage “floating deck” with respect to the rest of the machine, which complicates control and results in additional bulky corona shielding and insulation. Nevertheless, electrostatic acceleration is routinely used in conventional x-ray tubes for medical, industrial, and security applications, and furthermore, electrostatic systems are often used to provide source particles for conversion to neutrons in compact neutron sources.

RF LINACs use a series of cylindrical or discoid-like cavities arranged longitudinally in a periodic fashion relative to the desired axis of acceleration. The axis of symmetry of each cavity is collinear with the acceleration axis. When an RF electric field energizes the ensemble of cavities, high axial electric fields are generated in the throat of each cavity, and these fields oscillate sinusoidally. By appropriate design, the oscillations in each cavity are properly synchronized in space and time so that a bunched particle beam gets successively accelerated downstream as is passes through the throat of each cavity, building total energy. RF LINACs are the mainstay of electron accelerators for medical and security applications, with energies of 6 MeV and 10 MeV being the most common for compact units, and much higher energies are used in large national-lab style institutions. Note that the term “RF” is generic and also applies to microwave or mm-wave frequencies. RF LINACs can also be used to accelerate protons or other heavy charged particles, usually as part of a larger system. A completely different type of RF linear accelerator used for protons or charged nuclei is the radio frequency quadrupole (RFQ). In and RFQ, a set of 4 sectoral electrodes, separated by 90 degrees in azimuth, protrude inward from the circumference of the accelerating tunnel towards the beam and extend downstream over the length of the tunnel. The innermost edges of the electrodes that surround the beam have a sinuous profile vs the axial position, with the undulations on adjacent electrodes 180 degrees spatially out of phase from each other. These complex shaped electrodes create RF electric fields that simultaneously focus the beam, enhance its bunching, and provide axial acceleration downstream when energized by an RF source. Beam energies produced by typical RFQs range from 0.05 – 3 MeV.

Cyclotrons are one of the earliest-invented types of high energy particle accelerator, and in its original form consists of a central particle source and a pair of D-shaped hollow semicircular disk cavities (Dees) with a gap between them, with the whole apparatus immersed in a strong magnetic field perpendicular to the plane of the Dees. The Dees are energized with an RF field, and particles get accelerated across the gap between the Dees. Due to the magnetic field, the particle bunch executes circular orbits inside the hollow part of the Dees, and with proper design, arrive again at the gap at a time synchronized to the RF field to cause further acceleration. As acceleration sequentially occurs with each gap crossing, the orbit radius increases, until the beam is extracted near the outer periphery. Cyclotrons are usually used for medium energy (60 - 400 MeV) protons or other heavier ions. A significant disadvantage of conventional cyclotrons is the weight and size of the magnet, often being over 100 tons. A new development is that of the compact cyclotron, based on superconducting magnet technology. Such systems often use a variety of Dee configurations, including a single 180 degree Dee, multiple 90 degree Dees, or multiple spiral sector Dees.

Betatrons and microtrons are circular motion accelerators, typically for electrons, that are closely related to the cyclotron magnet geometry. A betatron employs a relatively slow sinusoidal time varying magnetic field (instead of a static one) that creates, via Faraday’s law, a circular electric field in the plane perpendicular to the magnetic axis. During the appropriate quarter cycle of the magnetic field, electrons are injected and the circular electric field accelerates electrons continuously in circular orbits of increasing radius as they gain energy, and they are extracted near the outer circumference before the sign of the induced circular electric field reverses. High energy units (> 300 MeV) have been built, but magnet weight is several hundred tons. However, lower energy betatrons (7 – 20 MeV) for industrial or medical applications are more compact, and portable 7 MeV units have been used for onsite structural x-ray imaging. A microtron combines some aspects of an RF LINAC with a cyclotron magnet geometry. In the most compact units, a single accelerating cavity is used to repetitively accelerate the same electron bunch. This is made possible by an applied magnetic field, which bends the bunch back around to the accelerating cavity for another boost. As energy is gained, the orbits become larger, but with proper design, the cyclic reentry into the cavity can be preserved, with final particle extraction occurring as the outer circumference is approached. A variant (racetrack aka. “Mainz” microtron) employing a short multi-cavity RF LINAC and a pair of D-shaped bending zones with magnetic field on either end, with appropriate drift tubes in between, has been used to obtain energies above 1 GeV. However, much more compact microtrons have been made for 10 – 30 MeV energies, with magnet pole dimeters of 50-100 cm. Magnet weight is still a significant issue for non-superconducting systems.

Rhodotrons are a type of re-circulating electron accelerator that employ an RF cavity, typically a coaxial geometry supporting a RF electric field between the inner and outer cylindrical conductors. An electron bunch enters the cavity mid-plane along a radial path and gets accelerated inward by the RF electric field. It passes through holes in the inner conductor, shielding it from RF fields as it passes through, and during this time the RF field reverses so that when passing radially outward though the coaxial gap on the opposite side it gets further accelerated outward. External to the cavity, the beam bunch is turned around by bending magnets to radially re-enter the cavity along a different azimuthal position around the circumference. The timing of the bending and re-entry path length is such that the re-entering electron bunch again experiences a radially inward acceleration from the cavity RF field. This process is repeated by multiple series of bending magnets, radial beam paths, and azimuthal cavity entry angles until the desired beam energy is reached; at this time the beam is extracted rather than re-directed further into the cavity. Thus, the overall beam path resembles a multi-leaf clover pattern. Rhodotrons typically have cavity diameters of order of 1-2 meters (overall size is larger, due to the external bending magnets and beam tunnels). Typical final beam energies are 1-20 MeV, with the higher energies obtained with up to 10 passes through the cavity. Rhodotrons have found their greatest application in sterilization applications for food, medical equipment, and mail.

A synchrotron is an accelerator type that uses a circular loop geometry for the beam tunnel and variable strength bending magnets and a sequence of accelerating cavities as part of the circular loop. As the particle bunches gain energy, the magnetic field strength is continuously increased to keep the particle trajectories within the loop. Although the synchrotron is the main type of particle accelerator used for physics research, such as at Fermilab or CERN, more modest synchrotrons have been used in proton medical treatment facilities such as at Loma Linda or for use in powering coherent x-ray and gamma ray sources for materials research. These are obviously large user facilities and are not suitable for consideration as compact accelerators. However, compact systems of the superconducting magnet synchrocyclotron type, which are a hybrid between aspects of the synchrotron's energy- and time-dependent beam-steering methods and the basic geometrical configuration of a superconducting cyclotron, have been shown to be highly promising.

Examples of Existing Compact Accelerators

When specifically considering the issue of relatively compact accelerators for medicine and security applications, most of the standard and new commercial products have focused on small electron LINACs, compact superconducting magnet cyclotrons (and the related compact superconducting magnet synchrocyclotron), and electrostatic accelerators also maintaining a significant role for neutron sources and other ultra-compact (but low flux) systems. Research engineering efforts at a lower TRL have also concentrated on these same basic accelerator configurations, with the goals of further compactness and overall system simplification. Table G.1 summarizes some key features of compact accelerator configurations, including some recent research demonstrations.

Table G.1. *Properties and Capabilities of Compact Accelerator Systems*

commercial

< TRL 4

Type	**Application**	**RF Freq.**	**Energy**	**Avg. Beam Current**	**Pulse width, PRF**	**Weight and Dimen. (m)**	**Additional Properties**	**Ref #**
e-LINAC / x-ray	Medical Oncology	2.998 GHz	6, 10, 25 MeV (other values avail.)	Not published	5 μs 180 pps typ.	8200 kg [§] (5.0 L x 2.3 W x 2.5 H) [§]	45 kW wall power cost ~1.5 – 2 M$	[Varian-2014] [Varian-2011] [Burke-2009]
e-LINAC / x-ray	Medical Oncology	2.856 GHz	6, 10, 18 MeV (other values avail.)	Not published		8300 kg [§] (5.8 L x 4.0 W x 2.6 H) [§]	45 kW wall power cost ~2.5 M$	[Elekta-2017] [Elekta-2013] [Narayanasamy-2016] AEP-2019
e-LINAC	Medical Oncology	(X-band)	6, 9, 12 MeV	Not published		1395 kg [and] (2.2 L x 1.1 W x 2.8 H) [and]	2 kW wall power cost ~1.4 M$	[Interop-2019]. [Wootton-2017]

e-LINAC for x-ray	Civil / Chemical Engineering Radiography	9.3 GHz	3.95 MeV	80 μA	4 μs 200 pps	386 kg § (1.0 L x 1.0 W x 0.5 H) §		[Uesaka -2013]
e-LINAC for x-ray	Security scanning	2.856 GHz	3.5 MeV	100 μA	5 μs 200 pps	(1.5 L x 0.7 W x 0.5 H)*		[Welsch -2018]
e-LINAC	Industrial / sterilization	2.856 GHz	10 MeV	2.5 mA	13.5 μs 700 pps	(5. 0 L x 0.75 W x 1.0 H)*		[Kamino -1996]
e-LINAC for x-ray	Cargo inspection, NDT	(X-band)	6, 9 MeV	Not published	0.5 μs 500 pps	1950 kg[and] (0.9 L x 0.76 W x 1.07 H)[and]	16 kW wall power	[Radiabeam-2016a]
e-LINAC for x-ray	Radioisotope replacement source	Not published	2 MeV	55 μA	4 μs 250 pps	20 kg* (0.95 L x 0.2 W x 0.35 H)*	4.8 kW wall power	Radiabeam-2016b]
SC magnet proton cyclotron	Medical isotope prod.	68 MHz	12.5 MeV	25 μA	Cont. bunched beam	2300 kg * (0.9 Dia x 1.9 H)*	35 kW wall power, cost ~1.5 M$	[Wu-2016] [Smirnov-2016]
SC magnet proton cyclotron	Medical isotope prod.	60 MHz	8.5 MeV	10 μA	Cont. bunched beam	1200 kg * (0.8 Dia x 0.7 H)*		[Smirnov-2016]
SC magnet synchro-cyclotron	Proton therapy	90-133 MHz	250 MeV	40-100 nA	~40 μs 500-1000 Hz	17000 kg * (1.8 Dia x 1.6 H)*	Cost ~25-30 M$	[Smirnov-2016] Zwart-2016]
Electrostatic Accelerator	Endoscopic brachytherapy (miniature x-ray tube)	DC	50 kV	0.5 mA	DC	~100 kg (0.5 L x 0.5 W x 1.5 H)		[Ramachandran -2017]
Electrostatic Accelerator	Skin brachytherap	DC	100 kV	10 mA	DC	~100 kg		[Ramachandran -2017]

	y (miniature x-ray tube)					(0.5 L x 0.5 W x 1.5 H)		
D or p linac	Active interrogation, isotope generation, p injection		1-5 MeV	10-50 μA	5-500 μs	350 kg, 34” W x 88” L x 62” H	4-6 kW wall power	[Star-fire – 2019]

§ Entire system (accelerator and support equipment, including integral shielding but not external vault)

* Accelerator only (no support equipment included; shielding not included)

and Accelerator head or Treatment head including shielding (no other support equipment included)

¤ Total time-averaged current (averaging interval includes both pulse on and pulse off regions of repetitive modulation). Typical value for compact medical e-LINAC is ~100 μA.

Accelerator Structures – Supplemental Information and Present Examples

The discussion in this section concentrates on electron RF LINACs. Key issues are the acceleration gradient, which gives how much energy is imparted to the electrons per unit length of accelerator, and the RF power requirement to produce this gradient, which depends on the ohmic quality factor (Q) of the cavities and the shunt impedance (coupling of cavity fields to beam). The structure also has to be made with very smooth internal surfaces to avoid electrical breakdown at the desired acceleration gradient. Another key parameter is the operating frequency of the structure. Since the physical cavity sizes and overall length of the structure are related to the electromagnetic wavelength, increasing the operating frequency leads to more compact accelerators and higher accelerating gradients for a given desired output energy. However, higher frequency also demands a more accurately manufactured accelerating structure and more stringent overall alignment. At lower microwave frequencies, there is ample evidence that the maximum allowable gradient (before breakdown) gets larger as the frequency increases, which is a favorable behavior for achieving compactness. However, as one pushes higher in frequency towards and into the mm-wave regime, this trend might not continue indefinitely, and at some point in frequency there is expected to exist a maximum achievable gradient.

The most typical commercial compact electron LINAC structures are operated at a narrow design frequency (due to the high Q of the structure) within either S-band (2-4 GHz), C-band (4-8 GHz), or some in X-band (8-12 GHz). Ku-band (12-18 GHz) and higher frequency structures tend to be experimental in nature. Some typical accelerating structure parameters are shown in Table G.2. Note that these lengths are the multi-cavity accelerating structure only and do not include the electron gun, the pre-bunching injector, nor a target to convert the electrons to x-rays. The dimensions also do not include the RF sources and associated power electronics. The typical cost of the accelerating structure for a medical LINAC in S-band to X-band is of order $200,000. [McDermott-2018]

TABLE G.2. *Key Parameters for Compact Electron Beam LINAC Structures*

🟩 *commercial* 🟨 *< TRL 4*

Type	**length**	**frequency**	**Q**	**Shunt impedance**	**Beam Energy and Peak RF Drive Power**	**Beam Current***	**Ref.#**
S-band	15 cm	2.856 GHz	14,500	90 MΩ/m	2 MeV at 2 MW	500 mA	[AET-2018]
S-band	40 cm	2.856 GHz	14,500	130 MΩ/m	6 MeV at 2.5 MW	100 mA	[AET-2018]
S-band	70 cm	2.856 GHz	14,200	60 MΩ/m	10 MeV at 5 MW	150 mA	[AET-2018]

S-band	42 cm	2.998 GHz	15,000	87 MΩ/m	6 MeV at 2.6 MW		[Krishnan-2009]
C-band	25 cm	5.712 GHz	13,000	80 MΩ/m	10 MeV at 12 MW	100 mA	[AET-2018]
C-band	90 cm	5.712 GHz	11,000	70 MΩ/m	10 MeV at 4 MW	100 mA	[AET-2018]
X-band	25 cm	9.400 GHz	8,500	70 MΩ/m	1 MeV at 0.25 MW	150 mA	[AET-2018]
X-band	50 cm	11.99 GHz	6,400	93 MΩ/m	28 MeV at 5 MW		[Diomede-2018]
X-band	100 cm	11.99 GHz	6,800	122 MΩ/m	9 MeV at 2 MW	158 mA	[Jang-2018]
X-band	30 cm	9.300 GHz		90 MΩ/m	6 MeV at 2 MW	30 mA	[Shin-2018]

* Average current during RF pulse on interval

One can see from the table that the more compact (shorter length) structures at a given frequency require considerably higher peak RF power than their longer counterparts. Once can also notice that a shorter structure length is possible for a given energy by using a higher frequency. All of these structures in the table are made from oxygen-free high conductivity (OFHC) copper. The large RF peak power requirements for creating the specified acceleration gradient are a direct consequence of the electrical conduction (ohmic) losses in the copper cavities (note that beam loading is responsible for only a fraction of the total losses). Accordingly, the power required by LINACs can be dramatically reduced by using cryogenic superconducting cavities. By raising the Q values to at least 10^6, or more desirably towards 10^8, the power can be reduced by factors of 100 to 10^4 or more for the same acceleration gradient vs. a room temperature accelerator.

RF Sources – Summary and Present Examples

The vast majority of present-day RF sources for accelerators are vacuum electronic devices. These devices include klystron amplifiers and magnetron oscillators for powering most electron LINACs at microwave frequencies, while for the highest operating frequencies (towards the mm-wave regime), research accelerators have been powered using gyro-devices. For rhodotrons, RFQs, or compact cyclotrons, which operate at lower frequencies well below the microwave bands, the most commonly used vacuum electronic RF sources are based on power tetrode or triode tubes. Some recent commercial cyclotrons have used conventional solid-state transistors and conventional power combining, which is reasonably achieved due to the lower frequency. However, researchers in compact electron LINACs operating at microwave frequencies are also beginning to examine the application of new types of high-performance microwave transistors based on wide-bandgap semiconductors in conjunction with spatially-distributed power combining. A comparison of the typical properties of RF source technologies relevant to compact accelerators is provided in Table G.3. For further technical background, see “RF Sources – Principles of Operation and Supplemental Information” later in this appendix.

TABLE G.3. *Comparison of RF Source Technologies for Accelerators*

regular *TRL < 4*

Type	Frequency	Peak RF Output Power	Voltage	Peak Current	η	Pulse width	Repetition Rate	Weight*	Primary Length* or Vol.	Ref #
Klystron	11.99 GHz	6 MW	152 kV	96 A	37%	5 µs	400 Hz	150 kg	1.0 m	[Jang-2018]
Klystron	2.856 GHz	5 MW	125 kV	91 A	44%	16 µs	440 Hz			[Kutsaev-2015]
Klystron	2.856 GHz	6 MW	140 kV	95 A	45%	1 µs	10 Hz	480 kg	0.96 m	[Min-2019]
MB Klystron	1.3 GHz	10 MW	110 kV	130 A	70%	1.5 ms	10 Hz		2.5 m	[Hemmatalizadeh-2014]
Magnetron	3.0 GHz	3.1 MW	46 kV	110 A	60%	4.5 µs	220 Hz	18 kg	0.36 m	[NJR-2018]
Magnetron	5.7 GHz	2.5 MW	50 kV	110 A	45%	4 µs	250 Hz	16 kg	0.3 m	[CPI-2015]
Magnetron	9.3 GHz	250 kW	25 kV	30 A	33%	2 µs	280 Hz	8 kg	0.3 m	[Uesaka-2013]
Magnetron	9.3 GHz	1.5 MW	35 kV	88 A	49%	4 µs	200 Hz	18 kg	0.35 m	[Uesaka-2013]
Gyrotron	27 GHz	2 MW	100 kV	50 A	40%	400 µs	10 Hz	~140 kg	~0.7 m	[Bondarenko-2014]
Power RF Transistor Array	68 MHz	6 kW power combined	< 100 V		65%	CW	CW		0.3 m^3 total	[Wu-2016]
GaN HEMTs	5.5 GHz	500 W ea.	50 V	20 A	60%	100 µs max.	(10% duty)	~10 g ea.	0.024 m	[Nguyen-2018] [Lewellen-2018]

* Includes magnet, if applicable. HV power supplies, HV modulators, and any magnet supply not included.

As far as the choice between klystrons and magnetrons at microwave frequencies, generally speaking klystrons are preferred when peak powers of 5 MW or higher are needed, and magnetrons are more typically used at lower power levels. Magnetrons are significantly smaller and weigh less than klystrons, which gives magnetrons an important role for the purposes of achieving a compact accelerator. They are also considerably less expensive, typically about $35,000 for a C-band magnetron at the several MW level, vs. $75,000 to $100,000 for a klystron with marginally more power (5 MW). For solid-state devices, individual components are inexpensive (e.g., $320 for a LDMOS (lateral double-diffused MOS) transistor at 108 MHz with 1000 W output power CW [Ampleon-2016]; or $1,250 for a GaN HEMT at 5.5 GHz with 475 W peak output power at 10% duty [Wolfspeed-2017]), but typically dozens to hundreds of devices must be power-combined with sophisticated feed networks (or emerging spatially distributed concepts) to reach the required total power levels. Some approximate SWAP and cost metrics of the various source technologies are listed in Table G.4.

Table G.4. *Approximate RF Source Metrics Related to Weight, Volume, and Cost**

Type	**Band**	**Peak Power/Weight**	**Peak Power/Volume**	**Peak Power/Cost**	**Multiplier for Average Power**
klystron	S-band	12.5 W/g	50 W/cm^3	68 W/$	0.007
klystron	X-band	40 W/g	84 W/cm^3	60 W/$	0.002
magnetron	S-band	172 W/g	790 W/cm^3	88 W/$	0.001
magnetron	X-band	83 W/g	400 W/cm^3	42 W/$	0.001
LDMOS transistor	10-100 MHz	47 W/g	324 W/cm^3	3.1 W/$	1.0
GaN HEMT	C-band	48 W/g	225 W/cm^3	0.38 W/$	0.1

* Computed metrics include the weight, volume, and cost of any required magnet along with the vacuum electronic device. Power supplies and cooling are not included for either vacuum or solid-state devices. Solid-state power combiner not included.

It is also important to point out that the vast majority of vacuum electronic and many solid-state RF sources for accelerator use are operated in a low-duty factor pulsed mode to keep the average RF and dissipated power to manageable limits, both in the RF source itself and in the accelerating structure. Accordingly, with pulsed RF operation, the output beam of the accelerator consists of a series of macro-pulses corresponding to the portion of time that the RF source is energized, and during these "on" portions the accelerator is producing micro-bunches of accelerated high energy particles spaced in time as dictated by the period of the RF source frequency. Hence, for the RF sources, one has to consider the combination of peak RF output power, RF pulse width, and pulse repetition rate.

RF Sources – Principles of Operation and Supplemental Information

Klystrons amplify microwaves from a sinusoidal low power signal source to the 100's of kW to 10's of MW peak power levels needed by the accelerator structure to produce the desired accelerating gradient. Klystrons use a linearly streaming electron beam from an electron gun that passes through a sequence of RF resonant cavities along the length of the beam, separated by cylindrical beam tunnels that are cutoff to the RF frequency to be amplified. A signal source applied to the input resonant cavity of the klystron creates oscillating electric fields that velocity-modulate the electron beam. As the beam subsequently passes into the downstream field-free drift tube, the imparted differential velocities cause ballistic bunching of the beam. Subsequent passive resonant ("buncher") cavities and interconnecting drift tubes along the beam path act to sharpen the bunches on the modulated beam to contain a high amount of RF current at the operating frequency (each buncher cavity adds about 20 dB of gain). Finally, the strongly bunched beam enters an output resonant cavity of the correct frequency detuning and at the appropriate phasing to excite strong electromagnetic fields in the cavity, in such a way as to slow down the average kinetic energy of the beam and convert this energy into RF power, which is extracted from the output cavity via a coupling iris and through a vacuum window (and the spent beam gets collected downstream). In some sense, the klystron acts as the opposite of a particle accelerator; the klystron converts a modest kinetic energy, high current DC electron beam into RF energy, while an accelerator converts RF energy into an extremely high energy, low average current bunched beam. Because klystrons are amplifiers that can be amplitude- and phase-controlled, they are readily power-combined, most typically by powering successive portions of an accelerator by additional klystrons and properly phasing their signals to ensure synchronism.

Klystrons, like accelerator structures, have characteristic sizes that are inversely proportional to the operating frequency, due to the wavelength-based scaling of resonant cavity dimensions and drift tube lengths. Hence low frequency klystrons tend to be quite large, and source compactness can be improved by using higher frequency klystrons. However, the power handling capability (both for peak and average power) in klystrons scales as $f^{-5/2}$, so there is a tradeoff that has to be optimized between the accelerator structure size and its power requirements and the klystron power production capability and the size or number of klystrons. Klystrons also require an axial magnetic field (permanent magnet or electromagnet) over the majority of their length to confine its electron beam, which adds a significant amount of weight and size. Another way to achieve higher power in klystrons for a given physical size restriction is to use multiple-beam or sheet-beam klystrons, which are more experimental but offer SWAP advantages, including with respect to the magnet.

Another type of RF source is the magnetron oscillator. Magnetrons consist of central electron source (cathode), surrounded by an annular cylindrical anode which has its inner surface slotted periodically in azimuth (or has lollipop-like slot and cavity periodic structure). A magnetic field oriented perpendicular to the plane of the cathode-to-anode annular gap forces emitted electrons to spiral around in the gap at a azimuthal speed synchronous to the propagation of electromagnetic waves around the slotted inner surface (slow wave structure) of the anode. Feedback between the waves, the bunching of the azimuthally streaming electrons in response to the waves, and the outward motion of the electron orbits and their change in potential energy acts to convert the energy of the beam into RF power, which is extracted though an aperture/window or coaxial feedthrough in the anode. The overall size of the magnetron interaction structure is considerably smaller than that of klystron. Furthermore, although magnetrons, like klystrons, need a magnetic field, the volume of the RF interaction region needing magnetization in magnetrons is at least a factor of 10 less that in klystrons, and the required field strength is lower, so magnetrons have considerable advantages in lighter weight. Magnetrons are oscillators, and they build up their RF from spontaneous low-level noise in the slow wave structure. This makes it difficult to power combine them, although there has been continuing research on ways to phase lock them by seeding with low-level RF. For compact accelerators this is less of an issue since often a single magnetron can provide sufficient power.

Klystrons and magnetrons attain their highest power capabilities at frequencies in S-band, C-band, and X-band. For power production at higher frequencies, one can consider the gyrotron family of devices, including the gyrotron oscillator and the gyro-klystron amplifier. In gyro-devices, the electron beam pursues a helix-like motion including both downstream linear motion and transverse rotational motion in the guiding magnetic field. The energy extraction mechanism is though rotational bunching via the cyclotron resonance maser mechanism, in which the relativistic velocity variation of mass affects the cyclotron frequency of the spiraling electrons (faster electrons slow down in rotational phase and slower electrons speed up in rotational phase). The direct proportionality relation between the magnetic field value and the cyclotron frequency allows the magnetic field to have a strong selective effect on the operating frequency. The control effect of the magnetic field allows the use of higher order mode (and hence oversized) cavities, as well as interaction with fast wave electromagnetic modes in the cavities, making the cavity dimensions at a given frequency much larger than possible with conventional devices. As a consequence in gyro-devices much higher average and peak power production is possible due to improved thermal management and lower field strengths in relation to breakdown.

For the lower frequency operation of compact cyclotrons, which are typically operating at frequencies of 60 MHz up to 110 MHz, with peak Dee voltages from 20 kV up to 130 kV, the RF source of choice is the power tetrode or triode. Similarly, rhodotrons and RFQs, which typically employ frequencies of a few 100 MHz, typically utilize tetrodes and triodes as their RF sources. These conventional gridded tubes are used in FM broadcast radio and VHF television, and increasing the total power can be achieved by paralleling tubes with matching networks to ensure even power contributions. The relatively low frequency allows lumped element helical inductors and discrete capacitors, or relatively large transmission line stubs, simplifying the matching and balancing. Some recent commercial highly compact systems have used conventional solid-state transistors and standard power combining. This is comparatively straightforward at the lower frequencies used in cyclotrons, but considerable RF design is needed to transform the lower voltage, high current waveforms of the transistors to the very high voltage, low-current fields that energize the Dees.

Finally, there have been dramatic advances over the last 15 years in the power production capabilities of wide-bandgap solid-state microwave transistors, in particular silicon carbide metal-semiconductor field effect transistors (MESFETs) and gallium nitride HEMTs. The wide bandgap of the parent semiconductors, the mechanism and density of charge control in the gated channels (and the lack of a thin oxide gate insulator as in power metal-oxide-semiconductor MOSFETs), the high thermal conductivity, and high saturation velocities in the semiconductor channels allow combinations of much higher voltage, current, and high speed operation compared to silicon devices. Within a given transistor package, the multi-finger design layout allows large total gate periphery devices to be fabricated, essentially a form of on-chip power combining. Nevertheless, the power outputs of such integrated amplifiers are orders of magnitude lower than the power capabilities of vacuum electronic devices. However, the physical sizes of the solid-state amplifiers are vastly smaller, so in fact the power density (volumetric and by weight) of individual solid state devices in the S-band to X-band can be competitive or even exceed those of vacuum electronics. An interesting concept of a distributed solid-state driven accelerator is presently under experimental development. In this strategy, multiple transistors are distributed around individual accelerator cavities (typically around the azimuthal perimeter, connected in such a way as to power-combine to mutually drive that individual cavity. Likewise, this topology is repeated for each downstream accelerator cavity. This distributed powering organization (spatial power combining) for solid state amplifiers applied to accelerators is unique and bears no relationship to the typical corporate feed connected to a single high power RF source. The solid-state approach effectively combines the powering electronics and the accelerator structure into a single, compact unit. While still in its earliest stages of development, it appears particularly promising for future compact accelerators.

Electron to x-ray Converters – Existing Technology

In many medical and security applications of electron accelerators, the ultimate goal of the accelerator is the production of intense, collimated x-rays. [Permatasari-2019; Jimenez-2017; Wang-2017] This is accomplished by directing the beam into metallic target and producing x-rays by a combination of Bremsstrahlung (radiation from rapidly decelerating the incident electrons within the target) and from electronic excitations of inner shell electrons of the target atoms. The typical “treatment head” of a medical LINAC [McDermott-2018] consists of a moderate thickness tungsten target disk, surrounded at the edges by a water-cooled copper supporting structure. Typically only 5 to 7% of the incident energy is converted to x-rays (although at beam energies above 10 MeV the levels can reach 12% or slightly more); in any case, the majority of the deposited beam energy becomes waste heat, requiring thermal management and resulting in a low overall efficiency. Other materials used in targets have included tungsten-rhenium alloys, tantalum, or a layer of tungsten or tantalum bonded to a layer of copper, depending on the thermo-mechanical design tradeoffs and desired x-ray spectrum (and sometimes beryllium filters out bleed-through electrons [Juntong-2016]). Bremsstrahlung x-ray spectra are very broadband and are concentrated towards the lower energies relative to the beam energy. For incident electron beam energies above 6 MeV, which is typical for accelerator-based systems, the emitted x-ray spectrum peaks at 0.5-1.5 MeV, with a slow falloff tail towards higher energies (with cutoff at incident energy). Higher incident electron energies do not markedly change the peak position, but the tail towards higher energies is extended, and conversion at any given energy and the overall spectrally-integrated flux are significantly increased. A general rule of thumb is that the mean energy of Bremsstrahlung is approximately 1/3 of the energy of the incident beam.

In medical accelerators, following the target is a diverging funnel-shaped or jaw-like dense metal collimation section (narrow apex by target, wide end downstream), which absorbs x-rays emitted at sharp angles. The emitted x-ray beam is more intense on-axis, so in many systems a flattening filter (FF, typically tungsten, steel, or other dense material) is used to progressively absorb the more central x-rays to create a much more uniform transverse distribution. This has the negative effect of significantly reducing the total integrated x-ray intensity (therefore requiring a larger accelerator for the same dose), so FF-free (FFF) designs involve computer-guided scanning of the stronger but non-uniform x-ray beam to deliver a more spatially uniform dose (and in some newest systems, intensity modulation). Finally, an important part of the system is a secondary MLC, which is a sideways-stacked array of transversely sliding dense metal leaves that can be opened up like a series of pocket doors to define a complex shaped 2D aperture for the x-rays, to direct the radiation and spare normal tissue. Such collimators are heavy and complex and can be potentially simplified with intelligent 3D scanning systems.

It should be noted that for security applications, some of the requirements on the x-ray source uniformity associated with medical applications can be heavily relaxed and/or more readily replaced by active scanning, sophisticated spatial-temporal resolving detectors, etc. Finally, for some uses like electron-beam sterilization and electron-beam radiotherapy, the electron beam is used directly and only passes through a thin metal scattering foil/window, saving much weight, and improving the dose delivery efficiency for those compatible applications requiring minimal penetration depth.

Methodology for Creating a Master Dose Rate Curve for Broadband Bremsstrahlung for Dense Targets that are of Optimized Thickness[34]

The general presumed form of the equation, at distance r downstream from target and on axis ($\theta = 0$ degrees) is

$$\dot{D} = \frac{I_b f(E_b)}{r^2} Y_o(E_b) \qquad (1)$$

where $\dot{D}$ is the spectrally-integrated dose rate in Gy/s, I_b is the beam current, and E_b is the electron beam energy. The function $Y_o(E_b)$ is the x-ray yield (fractional conversion efficiency of beam energy to total spectrally integrated energy in x-rays) as a function of incoming beam energy, assuming that the target is of optimal thickness (hence the “o” subscript) for the particular beam energy. This function can range from 0 for no conversion to unity for 100% conversion. Data for the more general x-ray yield $Y(E_b, d)$, where d is the target thickness, can be found in the literature for experiments done on various target materials and thicknesses. In that case one finds Y_o by looking at Y (at the given E_b) for the various values of d and choosing d to maximize Y. More conveniently, optimized data sets that directly give $Y_o(E_b)$ are also available for some situations. For the dense materials tungsten, tantalum, and molybdenum, which are common refractory high energy target materials, the $Y_o(E_b)$ curves (that take into account the respective optimized target thickness for the given material and beam energy) are quite similar to each other. This is highly useful for creating a master dose curve that would apply with reasonable accuracy to all the common dense target materials under optimized conditions.

---

[34] J.P. Calame, Naval Research Laboratory, (2019).

Besides the yield effect, the remainder of the overall variation of dose rate vs. electron beam energy is embodied in the function $f(E_b)$. At the simplest, $f(E_b)$ would just be directly proportional to E_b, i.e., of the form aE_b, where a is a constant. In the dose rate formula this type of functionality would represent the simple product of the yield factor with the beam energy. However, there are other effects of importance, including the tendency of the angular spread of the emitted x-rays to become smaller (more collimated in the forward direction) with higher energies, which makes the overall variation of $f(E_b)$ more rapid than just linear. Furthermore, the dose rate associated with a given power flux of x-rays depends on the spectral shape of the emitted total Bremsstrahlung, and this spectral shape changes with incoming electron beam energy in a way that also gives more effective dosing at higher values of E_b. Overall, then, $f(E_b)$ is faster than linear, with a power law of the form

$$f(E_b) = \hat{A}(E_b)^{\beta} \qquad (2)$$

being most useful, with $\hat{A}$ being a constant and the exponent β typically in the range $1 \leq \beta \leq 2$.

The functional form of the dose rate equation (1) is directly proportional to beam current, as expected. The inverse-square proportionality to distance r is from simple beam divergence. Accordingly, care must be taken to keep r considerably larger than the spot size, the target thickness, and other characteristic dimensions in the source optics that cause departures from ordinary divergence. This applies for both the values of r used in experiments to provide data for the dose rate curve fitting process, and to any application of the resulting dose rate formula for predictive purposes.

To begin the process of defining the functions in (1), consider first the x-ray yield term. Using data from a variety of literature sources, the plot of $Y_o(E_b)$ shown in Figure G.1 was assembled. It includes data for primarily W and Mo targets, with some Ta target data, with each data point implicitly having the target thickness optimized for electron beam energy and material type. The primary references used for the data in the plot are from classic studies and more recent investigations. [Tsechanski-2016; Berger-1970; NAP-2008; Meissner-2000; IIA-2011] The data is limited to below 60 MeV electron beam energy. For exceptionally high energies beyond the range of the plot, the yield is known to ultimately asymptote towards unity (100% conversion). However, for the purposes of deriving a dose formula, the present interest is an empirical fit to the data in Figure G.1 in the E_b < 60 MeV regime, so the extremely high energy regime is not relevant. The data in Figure G.1 is well-described by an exponential fit of the form

$$Y_o(E_b) = Y_{om}(1 - \exp(-E_b/E_0)) \qquad (3)$$

with Y_{om} = 0.496 (i.e., 49.6%) and E_0 = 22.0 MeV. This fit is plotted by the curve in Figure G.1, and the correlation coefficient is 0.985.

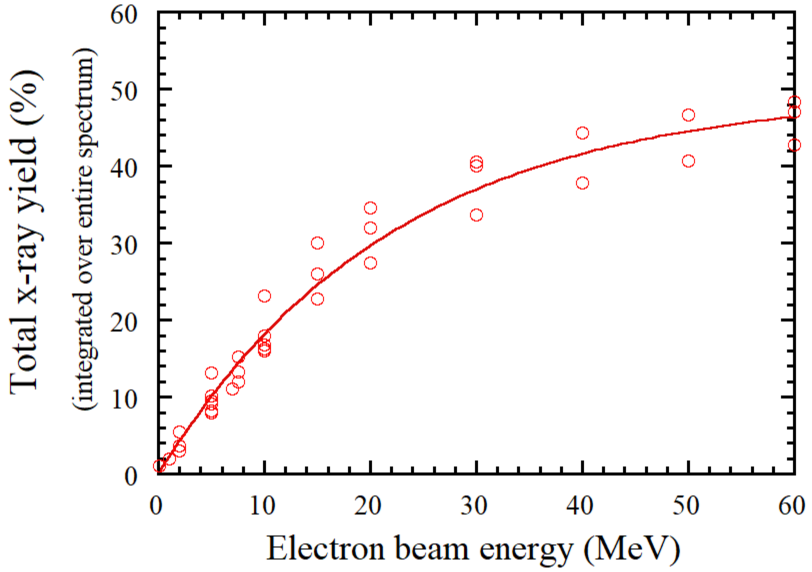


***Figure G.1**. Spectrally integrated Bremsstrahlung yield $Y_o(E_b)$ expressed in%, based on data (circles) for various optimized thickness W, Mo, and Ta targets. The curve fit with the exponential functional form is shown by the line.*

With the behavior of $Y_o(E_b)$established, to complete the dose formula (1), the function $f(E_b)$ needs to be determined by comparison to other experimental data that provides measured dose rates as functions of E_b, I_b, and r. Note that with the power-law from of (2), the constant Y_{om} from (3) can be combined with the constant $\hat{A}$ from (2) to give a new constant A. Thus the dose rate formula for fitting to experimental dose rate data is

$$\dot{D} = \frac{AI_b(E_b)^\beta}{r^2}(1 - \exp(-E_b/E_0)) \qquad (4)$$

Since E_0 is already known from the fit of Figure G.1, only A and β remain to be determined. Data on dose rate was assembled from a number of sources. [Takada-2013; Kosako-2010; Hodges-2018; Buaphad-2017; IAEA-1979] The measured data is presented in Grays per second (Gy/s) in Table G.5 below. To create a dataset that will be a function of beam energy only, the dose rate is divided by the beam current and multiplied by r^2 to give the quantity $\dot{D}r^2/I_b$, which is the dose rate at 1 m distance from the target per μA of beam current. This normalized data is listed in the rightmost column of the table and is plotted as a function of beam energy in Fig 2 using the symbols.

***Table G.5.** Experimental dose rate data for downstream, on-axis Bremsstrahlung from optimized targets.*

Electron Beam Energy (MeV)	**Average Beam Current (μA)**	**Distance from Target (m)**	**Dose Rate (Gy/s)**	**Normalized Dose Rate at 1 m (Gy/s μA)**
0.95000	36.000	1.0000	0.00083300	2.3139e-05
1.0000	1.0000 *	1.0000	5.0000e-05 *	5.0000e-05
3.9500	80.000	1.0000	0.033300	0.00041625
6.0000	55.000	1.0000	0.11670	0.0021218
9.0000	111.00	1.0000	0.50000	0.0045045
10.000	1.0000 *	1.0000	0.0080000 *	0.0080000

18.000	1.0000 *	0.50000	0.094000 *	0.023500
18.000	1.0000 *	0.50000	0.056600 *	0.014150
18.000	1.0000 *	0.50000	0.20900 *	0.052250
28.000	1.0000 *	0.50000	0.094300 *	0.023575
28.000	1.0000 *	0.50000	0.16800 *	0.042000
28.000	1.0000 *	0.50000	0.21000 *	0.052500
35. 000	1100.0	1.0000	111.00	0.10091
38.000	1.0000 *	0.50000	0.47000 *	0.11750
38.000	1.0000 *	0.50000	0.31400 *	0.078500
38.000	1.0000 *	0.50000	0.16000 *	0.040000

* Original data had accumulated dose in Gy/C (Grays per Coulomb), which were converted to Gy/s for a reference **1** μA of beam current by dividing Gy/C figure by 10^6

To determine A and β, given that the quantity E_0 has already been determined to be 22.0 MeV, one further divides the normalized dose rate $\dot{D}r^2/I_b$ by $(1-\exp(-E_b/E_0))$ to get the following equation for the fitting process, which is a simple power law on the right hand side.

$$\frac{\dot{D}r^2}{I_b(1-\exp(-E_b/E_0))} = A(E_b)^{\beta} \qquad (5)$$

The results of the power-law fitting (by means of a log-log transformation) yield $A = 8.65\times10^{-4}$ and $\beta = 1.31$. The fitted overall variation of $\dot{D}r^2/I_b$ vs. E_b is shown by the red curve in Figure G.2. The correlation coefficient is 0.85.

The fitted dose rate formula is therefore

$$\dot{D} = (\,8.65\times10^{-4}\,)\frac{I_b(E_b)^{1.31}}{r^2}(1-\exp(-E_b/22.\ 0)) \qquad (6)$$

where $\dot{D}$ is the spectrally integrated dose rate in Gy/s, I_b is the average beam current in μA, E_b is the beam energy in MeV, and r is the distance from the target in m.

To validate the dose rate formula, it was compared to several additional sources of measured data. These include a well-known Sandia report [Sandia-1985] providing dose rate data at 1 and 10 MeV for various optimized Ta and Ta/C targets (and yield data at other beam energies), and also a well-respected review paper on medical LINACs [Karzmark-1973] that contained dose rate data from many studies. An

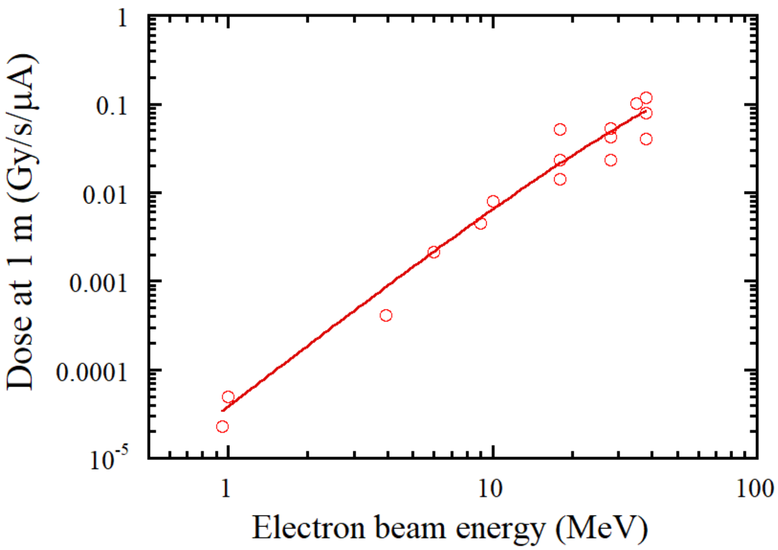


Figure G.2. *Spectrally integrated dose rate for Bremsstrahlung from optimized thickness targets as a function of electron beam energy, at a distance of 1 m on-axis downstream from the target. The symbols are the data points previously listed in Table G.5 and the curve is the fitted dose rate formula given by (6).*

additional comparison point of calibrated dose rate data, which was 45 Gy/min (0.75 Gy/s) at 1 m using a 130 μA and 10 MeV electron beam, was also obtained from Stanford University Oncology. [Stanford-2019] The comparison between the dose rate formula of (6) and these various additional validation data points is plotted in Figure G.3.

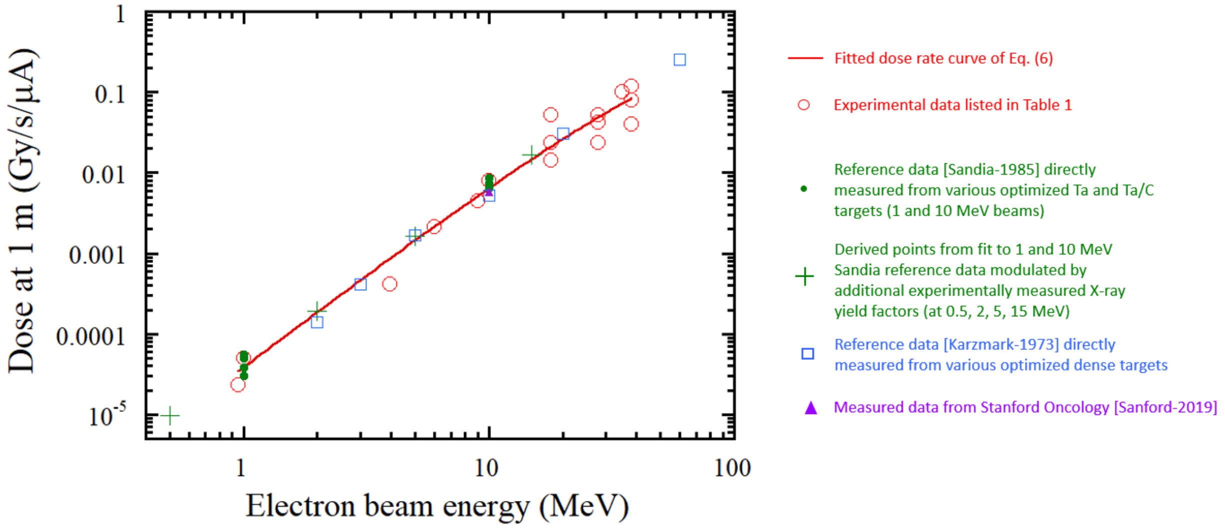


Figure G.3. *Comparison between dose rate curve of (6), shown by the red line, with additional validation data (green, blue, purple symbols). The original source data is retained and shown by the red circles.*

The excellent agreement between the dose rate curve and the additional experimentally measured data provided in Figure G.3 provides excellent confirmation of the quality of the formula (6) and its predictive capability for optimized targets. The confirmed range of direct validity of the formula is $1 \leq E_b \leq 60$ MeV, although it can likely be used down to 0.5 MeV. Extrapolation to higher energies beyond 60 MeV is strongly discouraged.

Additional References for Appendix G

The following references for Appendix G did not previously appear in the any of the reference lists for chapters 3-5, so they are provided here.

[AEP-2019] AEP LINAC. 2019. *Product Brochure (LINAC Magnetrons)*.

[AET-2018] AET Inc. 2018. *Compact Linear Accelerators Brochure*.

[Ampleon-2016] Ampleon USA, Inc. 2016. *Product Datasheet BLF578 Power LDMOS Transistor*.

[Berger-1970] Berger M. J. and Seltzer S. M. 1970. “Bremsstrahlung and Photoneutrons from Thick Tungsten and Tantalum Targets,” *Physical Review C* **2**, 621.

[Bondarenko-2014] Bondarenko, T. V., Y .D. Kliuchevskaia, S. M. Polozov, and V. I. Rashchikov. 2014. “The Base Parameters of the Compact 27 GHz Electron LINAC for Medical Application,” *Proceedings of the IPAC2014*, **2189**.

[Buaphad-2017] Buaphad P., Y. Kim, K. Song, H. Park, S. Cha, Y. Joo, B. Lee, and S. Ryu. 2017. “Developments of Various Low Energy RF Accelerators at KAERI and RTX,” *Proceedings of the 21st International Conference on Accelerators and Beam Utilization (ICABU17)*.

[Burke-2009] B. Burke, M. Lamey, S. Rathee, B. Murray, B. G. Fallone. 2009. “Radio Frequency Noise From Clinical Linear Accelerators,” *Physics in Medicine and Biology* **54**, 2483.

[CPI-2015] CPI-Beverly Datasheet. 2015. *VMC3109 C-Band Coaxial Pulsed Magnetron*.

[Diomede-2018] Diomede, M., D. Alesini, M. Bellaveglia, B. Buonomo, F. Cardelli, N. Catalan Lasheras, E. Chiadroni, G. Di Pirro, M. Ferrario, A. Gallo, A. Ghigo, A. Giribono, A. Grudiev, L. Piersanti, B. Spataro, C. Vaccarezza, and W. Wuensch. 2018. “Preliminary RF Design of an X-band LINAC for the EuPRAXIA@SPARC_LAB Project,” *Nuclear Instruments and Methods in Physics Research A* **909**, 243.

[Elekta-2013] Elekta, Inc. 2013. *Versa HD Delivery System, Site Planning and Design for Johns Hopkins Hospital Vault B192*.

[Elekta-2017] Elekta Inc. 2017. *Versa HD Brochure*.

[Hemmatalizadeh-2014] Hemmatalizadeh, R., D. Sardari, and N. B. Tehrani. 2014. “Electrical Engineering Aspects of Radiotherapy Accelerators,” *Romanian Reports in Physics* **66**, 39.

[Hodges-2018] Hodges M. and A. Barzilov. 2018. “Radiation Safety Aspects of LINAC Operation with Bremsstrahlung Converters,” *Accelerator Physics-Radiation Safety and Applications*, Chapter 9, Intech Open, http://dx.doi.org/10.5772/intechopen.71317

[IAEA-1979] Swanson, W. P. 1979. “Radiological safety aspects of the operation of electron linear accelerators,” *International Atomic Energy Agency*, Technical Reports Series No. 188.

[IIA-2011] International Irradiation Association. 2011. *Industrial Radiation with Electron Beams and x-rays*.

[Interop-2019] Interop, Inc. 2019. *Mobetron Product Datasheet*.

[Jang-2018] Jang, J., M. Yamamoto, and M. Uesaka. 2017. "Design of an X-band Electron Linear Accelerator Dedicated to Decentralized 99Mo/99mTc supply: From Beam Energy Selection to Yield Estimation," *Physical Review Accelerators and Beams* **20**, 104701.

[Jimenez-2017] Estepa Jimenez, J. S., M. D. Lagos, and S. A. Martinez-Ovalle. 2017. "A Monte-Carlo Study of the Photon Spectrum Due to the Different Materials used in the Construction of Flattening Filters of LINAC," *Computational and Mathematical Methods in Medicine* **2017**, 3621631.

[Juntong-2016] Juntong, N., et al. 2016. "The Optimized x-ray Target of Electron Linear Accelerator for Radiotherapy," *Proceedings of the 7th International Particle Accelerator Conference*, 1933.

[Kamino-1996] Y. Kamino. 1996. "10 MeV 25 kW industrial electron LINAC," *Proceedings of the 18th International LINAC Conference*, 836.

[Karzmark-1973] Karzmark, C. J. and N. C. Pering. 1973. "Electron Linear Accelerators for Radiation Therapy: History, Principles, and Contemporary Developments," *Physics in Medicine and Biology* **18**, 321.

[Kosako-2010] Kosako K., K. Oishi, T. Nakamura, M. Takada, K. Sato, T. Kamiyama, and Y. Kiyanagi 2010. "Angular Distribution of Bremsstrahlung from Copper and Tungsten Targets Bombarded by 18, 28, and 38 MeV Electrons," *Journal of Nuclear Science and Technology* **47**, 286.

[Krishnan-2009] Krishnan, R., A. P. Deshpande, T. S. Dixit, S. Chavan, C. S. Nainwad, S. N. Pethe, and T. T.Tiwari. 2009. "'S'-band LINAC Tube Developmental Work in SAMEER," *Proceedings of the 23rd Particle Accelerator Conference*, 4969.

[Kutsaev-2015] Kutsaev. S. V., R. Agustsson, A. Arodzero, S. Boucher, L. Faillace, J. Hartzell, and V. Ziskin. 2015. "Electron LINAC with Deep Energy Control for Adaptive Rail Cargo Inspection System," *IEEE Nuclear Science Symposium and Medical Imaging Conference*. doi:10.1109/NSSMIC.2015.7581765

[Lewellen-2018] Lewellen, J. W. 2018. "LINAC Design Elements for Spaceborne Accelerators," *9th International Particle Accelerator Conference*, 4291.

[Meissner-2000] Meissner J., M. Abs, M. R. Cleland, A. S. Herer, Y. Jongen, F. Kuntz, and A. Strasser. 2000. "x-ray Treatment at 5 MeV and Above," *Radiation Physics and Chemistry* **57**, 647.

[McDermott-2018] McDermott, P. N., and C. G. Orton. 2018. *The Physics and Technology of Radiation Therapy*, 2nd Edition. Medical Physics Publishing. Madison, WI, chapter 9.

[Min-2019] Min, S. H., O. Kwon, M. Sattorov, S. Kim, D. Hong, C. Park, B. H. Hong, I. S. Jung, I. Cho, W. T. Hwang, R. K. Barik, A. Bera, and G-S. Park. 2019. "Low-Level RF Control of a Klystron for Medical Linear Accelerator Applications," *AIP Advances* **9**, 025012.

[NAP-2008] The National Academies Press. 2008. *Radiation Source Use and Replacement*, abbreviated version, National Research Council.

[Narayanasamy-2016] Narayanasamy, G., D. Saenz, W. Cruz, C. S. Ha, N. Papanikolaou, and S. Stathakis. 2016. “Commissioning an Elekta Versa HD Linear Accelerator,” *Journal of Applied Clinical Medical Physics* **17**, 179.

[Nguyen-2018] Nguyen, D. C., C. Buechler, G. Dale, V. Dolgashev, R. Fleming, M. Holloway, E. Jongewaard, J. Lewellen, E. Nanni, J. Neilson, D. Patrick, A. Sy, and S. Tantawi. 2018. “The Path to Compact, Efficient Solid-State Transistor-Driven Accelerators,” *9th International Particle Accelerator Conference*, 520.

[NJR-2018] New Japan Radio Co. Datasheet. 2018. *M1466T S-Band Magnetron*.

[Permatasari-2019] Permatasari, I. D. A., Suharyana, R. Riyanto. 2019. “Monte-Carlo Simulation of x-ray Spectra Produced by LINAC,” *Journal of Physics: Conference Series* **1153**, 012109.

[Radiabeam-2016a] Radiabeam Systems, Inc. 2016. *MXS: Miniaturized x-ray System Product Information*.

[Radiabeam-2016b] Radiabeam Systems, Inc. 2016. *MicroLINAC Electronic NDT Isotope Replacement Product Information*.

[Ramachandran-2017] Ramachandran, P. 2017. “New Era of Electronic Brachytherapy,” *World Journal of Radiology* **9**, 148.

[Sandia-1985] Halbleib J. A., T. W. L. Sanford. 1985. “Predicted Flash x-ray Environments using Standard Converter Configurations,” *Sandia Report SAND83-2572*, Sandia National Laboratories.

[Shin-2018] Shin, S., S-H. Lee, S. Oh, D. Ha, M. Ghergherehchi, J. Chai, B-n. Lee, and M. Chae. 2018. “Measurement of Characteristic of X-band RF Cavity for 6 MeV LINAC,” *Journal of the Korean Physical Society* **72**, 818.

[Smirnov-2016] Smirnov, V. and S. Vorozhtsov. 2016. “Modern Compact Accelerators of the Cyclotron Type for Medical Applications,” *Physics of Particles and Nuclei* **47**, 863.

[Stanford-2019] Stanford University Oncology. 2019. unpublished communication.

[Starfire - 2019] Starfire Industries LLC, 2019. *nGen-400 Portable Neutron Interrogation Product Datasheet*.

[Takada-2013] Takada M., K. Kosako, K. Oishi, T. Nakamura, K. Sato, T. Kamiyana, and Y. Kiyanagi. 2013. “Angular Distributions of Absorbed Dose of Bremsstrahlung and Secondary Electrons Induced by 18-, 28-, and 38-MeV Electron Beams in Thick Targets,” *Radiation Protection Dosimetry* **153**, 369.

[Tsechanski-2016] Tsechanski A., A. F. Beilajew, J. P. Archambault, and E. Mainegra-Hing. 2016. “Electron Accelerator-Based Production of Molybdenum-99: Bremsstrahlung and Photoneutron Generation from Molybdenum vs. Tungsten,” *Nuclear Instruments and Methods in Physics Research Section B* **366**, 124.

[Uesaka-2013] Ueaska, M., M. Jin, W. Wu , K. Dobashi, T, Fujiwara, J. Kusano, N. Nakamura, M. Yamamoto, E. Tanabe, S. Ohya, Y. Hattori, and I. Miura. 2013. “Commissioning of Portable 950 keV/3.95 MeV X-band LINAC x-ray Sources for On-Site Transmission Testing,” *E-Journal of Advanced Maintenance* **5**, 2, 93.

[Varian-2011] Varian Medical Systems. 2011. *Designers' Desk Reference, High Energy CLINAC Edition*, **11**, 3.

[Varian-2014] Varian Medical Systems. 2014. *CLINAC iX Accelerator Specifications Brochure*.

[Wang-2017] Wang, J., S. Trovati, P. M. Borchard, B. W. Loo Jr., P. G. Maxim, and R. Fahrig. 2017. "Thermal Limits on MV x-ray Production by Bremsstrahlung Targets in the Context of Novel Linear Accelerators," *Medical Physics* **44**, 6610.

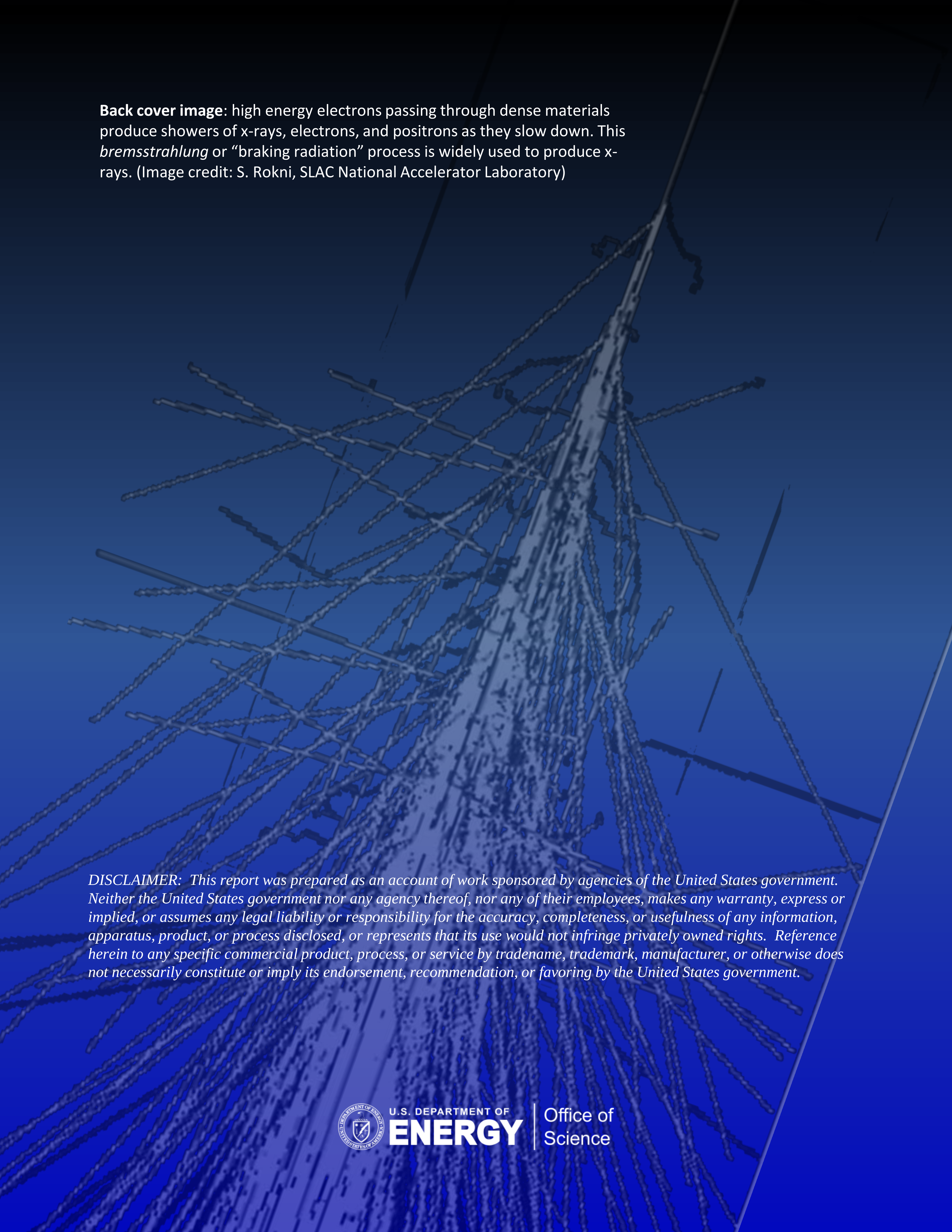
[Welsch-2018] Welsch, A. 2018. "Cockcroft Aviation Cargo Screening LINAC Achieves 3.5 MeV," *The Cockcroft Institute of Accelerator Science and Technology* press release, September 2018.

[Wolfspeed-2017] Wolfspeed/Cree, Inc. 2017. *Product Datasheet CGHV59350 GaN HEMT*.

[Wootton-2017] Wootton, L. S., J. Meyer, E. Kim, and M. Phillips. 2017. "Commissioning, Clinical Implementation, and Performance of the Mobetron 2000 for Intraoperative Radiation Therapy," *Journal of Applied Clinical Medical Physics* **18**, 230.

[Wu-2016] Wu, X. 2016. "The ION-12SC Compact Superconducting Cyclotron for Production of Medical Isotopes," *IONETIX Corp.* presentation.

[Zwart-2016] Zwart, T., J. Cooley, K. Franzen, K. Milkowski, M. Jones, M. Wagner, and S. Rosenthal. 2016. "Developing a Modern, High-Quality Proton Therapy Medical Device with a Compact Superconducting Synchrocyclotron," *AIME-SCMED*.



Back cover image: high energy electrons passing through dense materials produce showers of x-rays, electrons, and positrons as they slow down. This *bremsstrahlung* or “braking radiation” process is widely used to produce x-rays. (Image credit: S. Rokni, SLAC National Accelerator Laboratory)

U.S. DEPARTMENT OF
ENERGY
Office of
Science