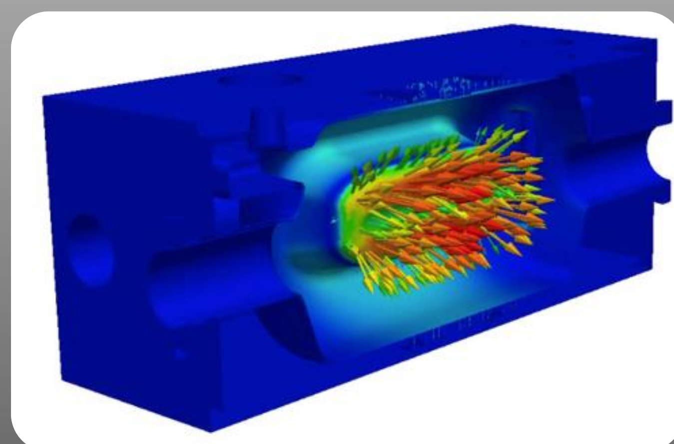
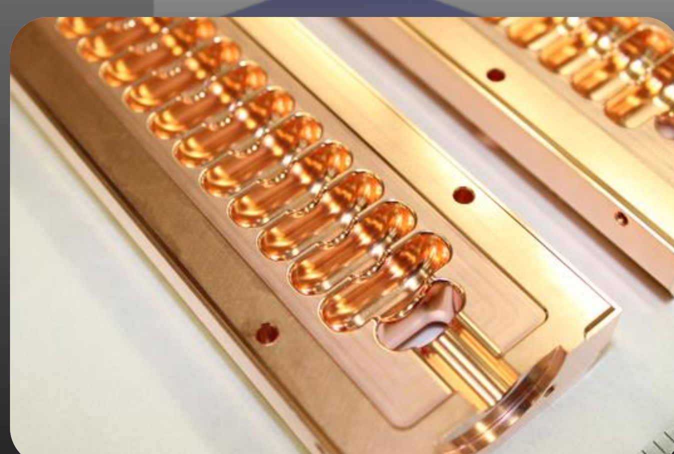
U.S. DEPARTMENT OF ENERGY | Office of Science

Radiofrequency Accelerator R&D Strategy Report

DOE HEP General Accelerator R&D RF Research Roadmap Workshop

March 8–9, 2017





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1 Introduction and Executive Summary

Over a two-day period, March 8-9, 2017 the Office of High Energy Physics convened a workshop in Gaithersburg, MD to seek community input on development of a radiofrequency (RF) research ten-year roadmap to guide the General Accelerator Research and Development Program (GARD). As described in the charge, the roadmap should reflect the Particle Physics Project Prioritization Panel strategy and the subsequent HEPAP Accelerator Subpanel recommendations. The charge for the workshop can be found in Appendix A.

At the workshop, proponents of superconducting radiofrequency technology (SRF) and normal conducting radiofrequency technology (NCRF), along with invited university and laboratory experts, critically discussed opportunities, gaps, and requirements relevant to the development of a roadmap. The roadmap workshop was preceded by preparatory workshops at SLAC on NCRF and Fermilab on SRF.

The first day of the workshop featured summaries of the two preparatory workshops and presentations of independent roadmaps for NCRF and SRF. Community proponents presented roadmaps with an overarching focus on improving the cost-capability of accelerators by improving structure gradient and efficiency, RF source power and efficiency, and auxiliary systems. Talks on the status of modeling, international efforts, potential NCRF/SRF synergies as well as synergies beyond HEP, and laboratory needs were also presented. The second day of the workshop began with presentations on the university role, user needs, and test facilities at SLAC and FNAL.

The balance and majority of the second day was devoted to review and integration of the two roadmaps and discussion of the report timeline, outline, and content. There was unanimous endorsement of the roadmap elements. The agenda for the workshop can be found in Appendix B and a list of participants in Appendix C.

As shown in Fig. 1, the decadal integrated roadmap has two main components, advancement of RF structures and advancement of the RF sources powering and auxiliary systems surrounding the structures. The overarching goal is to dramatically improve performance and cost by an order of magnitude or more. The ten-year time scale for the roadmap ensures improved performance and cost for future accelerators and upgrades now under consideration. In the past, only SRF was associated with cryogenic operation, but new results suggest NCRF structures operated at cryogenic temperatures hold promise. This blurring of the operating regime for structures has been graphically illustrated in Figure 1by positioning SRF at the “cool” end of a notional temperature gradient and NCRF at the “warm” end.

Themes or cross-cuts for cryogenic or warm RF structure R&D, include understanding basic physics and processes and exploring new shapes, materials, and operating regimes. The two SRF research sub-tracks focus on improving cavity quality factor, Q, and gradient. High-Q SRF R&D will investigate the physics of surface resistance and magnetic flux losses, explore doping, and examine new materials. High gradient SRF R&D will investigate fundamental limits, new materials, high frequency structures, and new structure shapes. The NCRF structure R&D will explore advanced topologies, advanced materials and manufacturing, and new temperature and frequency operating regimes.

Improvement in the capability and cost profile of RF accelerating structures requires commensurate progress in RF sources and auxiliary systems. The RF source roadmap will explore discrete architectures, distributed architectures, and energy recovery concepts to reach high perveance while operating at lower voltage and higher efficiency. R&D will also be required on couplers, higher order mode dampers, and frequency tuners. Other auxiliary systems requiring attention include high repetition brightness electron sources, polarized electron/positron emitters, and RF controls.

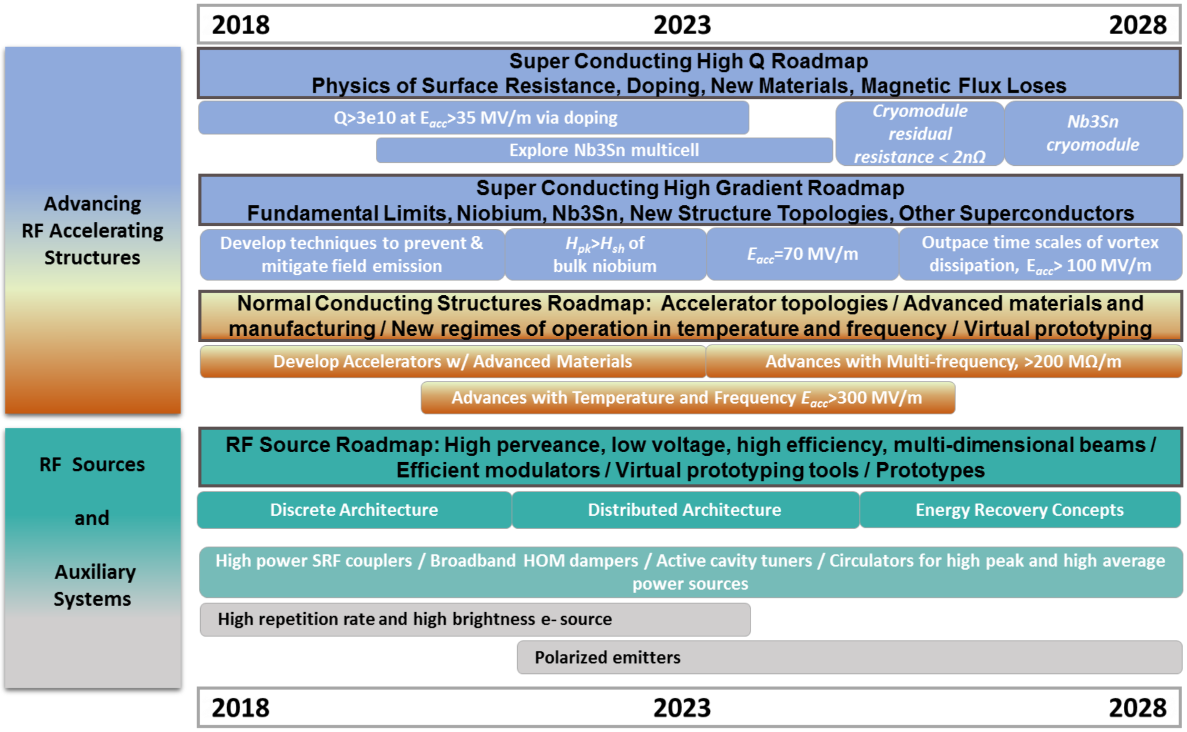

Figure 1: Ten-year integrated GARD-RF roadmap with a focus on improving accelerating structures and RF sources and auxiliary systems.

This roadmap recognizes that the NCRF and SRF accelerator communities are fundamentally synergistic, from sources to cavity geometries, and progress in each field can build from the other. RF technology can maximize its impact, reach and resources by collaborating beyond HEP and rapidly transitioning technology to the commercial sectors which are reliant on RF. RF accelerator technology will continue to be competitive for future large scale accelerator facilities.

2 RF Accelerator Technology for HEP

Radio Frequency (RF) technology is a cornerstone for many future particle accelerators including those needed for fundamental High Energy Physics (HEP). RF technology is technically ready for accelerators of any energy, including multi-TeV energies; but, based on current technology, the practical limits to RF accelerator performance are set by budgetary and footprint constraints. This technological maturity means that further improvement in quality factor, Q, cavity gradients, and shunt impedance directly translate into higher energy reach and intensity. Building the next generation of HEP accelerators would require efforts on a much larger scale than has been previously achieved. While current technology can be used for these machines, advancing the technology is necessary to make the new facilities "affordable" [1], to improve their performance, and to enable upgrades.

The HEP accelerators under consideration are the International Linear Collider (ILC) [2], CLIC [69], a future multi-TeV *e+e-* collider, future circular colliders FCC-ee, FCC-hh, FCC-he, HE-LHC at CERN [3], CEPC/SppC in China [4], and options for upgrading the Fermilab accelerating complex to a beam power over 2.4 MW, called PIP-III [5]. All these future machines would greatly benefit from the advances in RF R&D focused on delivering higher accelerating gradients and quality factors, higher shunt impedance structures, more efficient and lower cost sources, and auxiliary technologies. Some examples described below, showcase the benefits from technology improvements occurring within the next decade.

As noted in the P5 report, our Nation's flagship HEP program in the next decade will be the LBNF – DUNE neutrino project scheduled for beam in 2025. PIP-III, an upgrade of the Fermilab accelerator complex, will initially increase proton beam power to 2.4 MW and eventually reach 5 MW on target for DUNE. PIP-III will receive a >0.8 GeV beam from the PIP-II SRF linac. The two conceptual options for PIP-III under consideration are an SRF linac or a Rapidly Cycling Synchrotron (RCS) with an NCRF system. Both approaches will benefit from RF research and development. The present scenario for the SRF option envisages a 3-GeV CW-compatible SRF linac operating at 650 MHz followed up by a 6-8 GeV pulsed SRF linac operating at 1.3 GHz. Higher Q cavities would provide significant operational cost savings and, in combination with higher gradients, would result in either capital cost savings or higher beam energy. The PIP II SRF linac could also inject into a new RCS capable of delivering 8 GeV beam to the downstream MI. Challenges for the new RCS include high beam current requirements and the cost of the NCRF system. A simple enhanced design based on present cavities does not seem to be feasible as the required power and gradients are likely four to six times greater than present systems. The RCS option is also critically dependent on a rapidly-tunable NCRF system capable of accelerating 4 to 6 amps of beam. Currently, the PIP-II project is expected to be complete in FY25-FY26. If the PIP-III project starts at about the same time, research results within next seven to eight years would be most beneficial for the project.

Several staging options are under consideration for the ILC [6], with the first stage a 250-GeV Higgs factory. This machine would benefit from cost reduction R&D. If the ILC tunnel is built for a full collider (500 GeV with the state of the art SRF technology), the beam energy reach of the second stage will be determined by the SRF technological progress in higher gradients and quality factors in the next decade under the GARD-SRF R&D. Alternatively, NCRF proposals such as CLIC benefit from advances in RF sources and high gradient structures. Potential breakthroughs could make even a multi-TeV *e+e-* linear collider "affordable" in the future.

The last example is the proposed circular *e+e-* collider FCC-ee at CERN. This machine (as well as a similar CEPC proposed in China) will feature a large CW SRF accelerating system delivering ~100 MW of RF power to beams. High Q and high gradient SRF cavities operating at 400 or 800 MHz (650 MHz for CEPC) would permit construction of smaller installations at lower capital and operational costs. A timeline for the FCC-ee [3] has the first physics run in 2035. Thus, the next ten years will be extremely important for developing SRF technology for this collider.

Fig. 2 summarizes the alignment of GARD-RF R&D milestones with HEP facilities on the horizon. The highlighted progress in SRF and NCRF cavity performance would improve the affordability of even a multi-TeV collider.

3 Superconducting RF Structures Roadmap and Milestones

The performance of SRF cavities depends strongly upon the properties of superconducting material in the first tens of nanometers of the inner cavity surface [7-9]. Recent and future improvements in the SRF technology aim at nano-engineering the surface layer and controlling its properties to optimize the SRF performance. This "tailored surface" approach offers prospects for a dramatic reduction of accelerator footprint, construction costs, and operation costs, broadening the range of applications. Cavity performance has clearly emerged as the main cost driver for SRF accelerators.

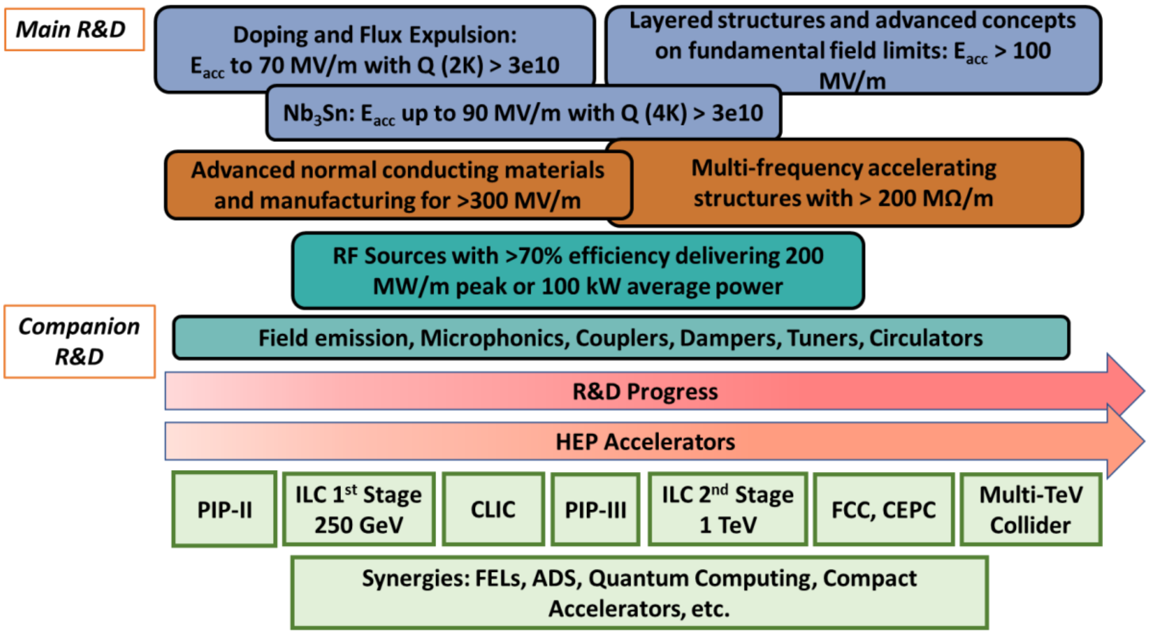

Figure 2: GARD-RF R&D alignment with future HEP particle accelerators.

The GARD SRF program will pursue the fundamental science underpinning performance and the most promising transformational R&D directions. The two main research thrusts are the *High Q Frontier* and the *High Gradient Frontier*. Below we discuss high priority topics for each thrust as well as the facilities and tools required to pursue the research and development. There are many research elements common to both thrusts and these are enumerated and discussed in detail.

3.1 High Q Frontier

The cavity quality factor, Q, is possibly the most important parameter for SRF based accelerators. The resonant Q of an accelerating structure varies inversely with resistive wall losses, driving the cost of SRF machines because of the cryogenic load, thus the emphasis on high-Q SRF surfaces. Higher Q allows longer RF pulse lengths, up to the CW regime, and therefore higher luminosity and brightness of the accelerated beams, which, in turn, can extend the physics reach.

Recent progress in SRF experimental and theoretical research includes a dramatic increase in achievable quality factors and deeper understanding of the mechanisms in play, particularly for a) the development of new surface treatments resulting in very high-Q via nitrogen doping [10-18]; and b) achievement of very high Q under real accelerator conditions via efficient magnetic flux expulsion (fast cooling and low flux pinning) [20-24]. These advances have been confirmed at laboratories worldwide and transferred to industry. They have found recent practical demonstration in the first LCLS-II cryomodules that have reached two times the previous state of the art Q on an accelerator scale unit with an average $Q \sim 3 \cdot 10^{10}$ at 2 K, 1.3 GHz, 16 MV/m [18]. This corresponds to a mean surface resistance of less than 10 nΩ.

Despite having reached very high thresholds, there are still ample opportunities for improvement in quality factors of niobium SRF cavities. Continued exploration of doping with nitrogen at lower temperatures [19] and recent theories of the reverse *Q(H)* slope and superheating field [33,34] offer new pathways to even higher Q at very high accelerating gradients. Exploration of the effect of nitrogen and other impurities on the surface resistance, RF breakdown fields, and superconducting density of states in Nb will be crucial for further potential breakthroughs in Q and field gradients. Studies of applicability to cavities of different frequencies have only just begun. New materials will be also evaluated.

The progress on the impact and management of trapped flux has been tremendous in the past few years, from the discovery of the manipulation of flux trapping via cooling to the understanding of trapped flux sensitivity for different surface treatments (as a function of mean free path). These are topics of extreme importance for both niobium and new materials. The abatement of trapped flux losses are being further pursued, as it has repercussions not only on Q but potentially also on achievable SRF cavity gradients.

The ten-year plan and milestones for the high Q thrust are presented in Fig. 3. The Q roadmap includes the following main directions:

- Continue exploration of the effect of interstitial impurities on bulk Nb surface resistance;
- Study the effect of doping on Q of cavities at different frequencies in the range of 650 MHz to 3.9 GHz;
- Develop fundamental understanding of the reverse field dependence of the BCS surface resistance and devise experiments towards validation of different theories;
- Develop understanding of mechanisms of trapping magnetic vortices and their contribution to the RF losses, and devise experiments towards validation of models;
- Develop understanding of 'intrinsic' residual resistance and its field dependence;
- Ameliorate trapped vortices via innovative ideas: advanced magnetic shielding concepts, in situ flux removal, determine material properties/preparation for minimal pinning strength, etc.;
- Develop Nb_3Sn coating on single and multi-cell cavities of different frequencies;
- Investigate feasibility of other materials for high Q.

3.2 High Gradient Frontier

The ten-year plan and milestones for the high gradient thrust are presented in Fig. 4. This R&D plan will include research into fundamental questions; layered structures and advanced vortex dynamics concepts; new materials, films, and multilayers; development of Nb_3Sn as a practical SRF material; field emission mitigation; microphonics and Lorentz force detuning compensation R&D; and novel SRF cavity shapes.

An outstanding question concerns the *fundamental* limit of the accelerating gradient in SRF cavities. Based on the current understanding, vortex entry at a DC superheating field limits the maximum achievable accelerating field. However, except for a few indirect experimental indications, there is no unambiguous experimental or theoretical proof that the DC superheating field is the limiting factor at GHz frequencies relevant to many SRF linacs. Therefore, it is crucial to develop a theory of a dynamic superheating field $H_{sh}(\omega,T)$ taking into account the complex kinetics of quasiparticles in superconductors under strong RF fields to show whether $H_{sh}(\omega,T)$ can indeed exceed the DC H_{sh} and, if so, to what extend $H_{sh}(\omega,T)$ can be further increased by impurities and RF frequency.

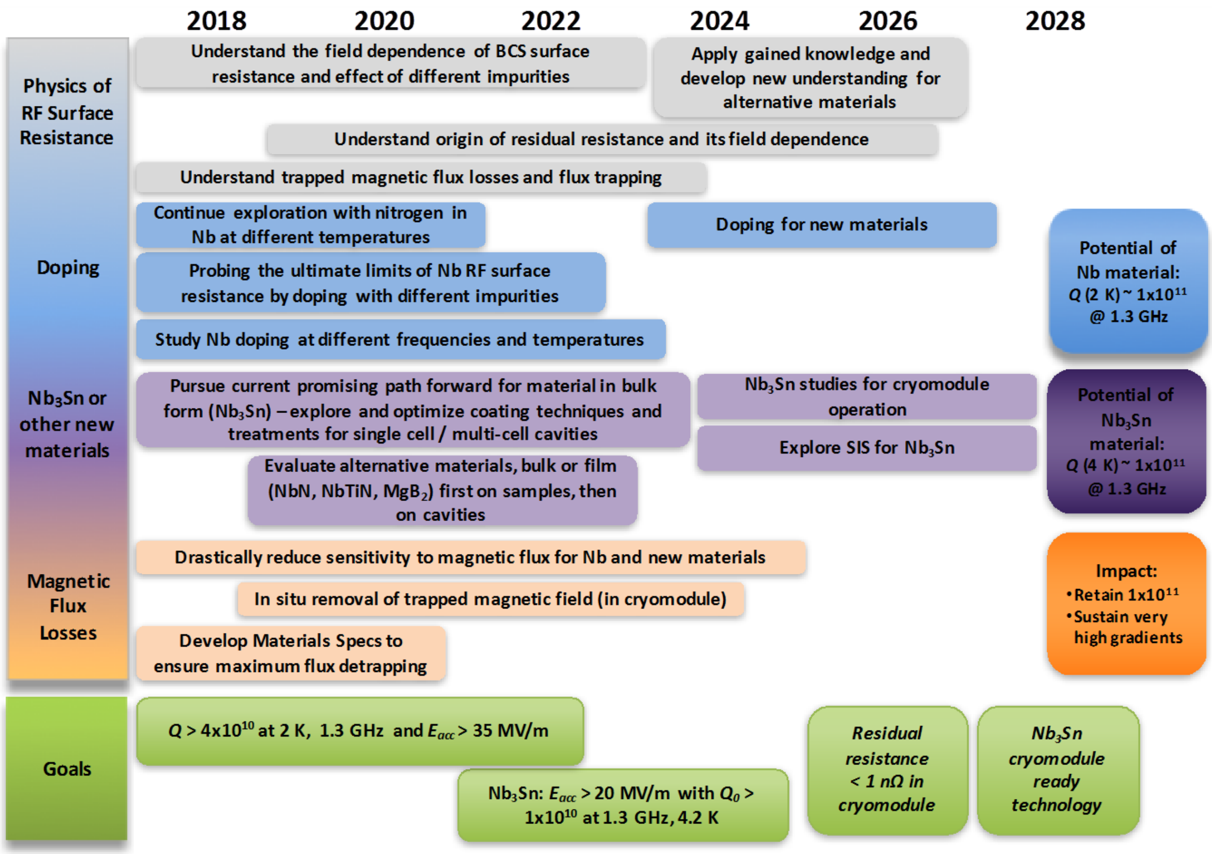

Figure 3: Ten-year roadmap and milestones for the high Q SRF frontier.

Extensive experimental investigations are needed to establish the maximum achievable RF field for a given material. For bulk niobium, which is by far the most advanced SRF material to date, the achievable gradient in CW operation is currently limited by a localized quench and not a global transition, indicating that the fundamental limit has not yet been reached. Local surface quench fields at $T << T_c$ already exceed the DC lower critical field $H_{c1} \sim$ 160-170 mT of Nb, and the theoretical limit is believed to be at least as high as a DC superheating field $H_{sh} \sim$ 240 mT (corresponding to an accelerating gradient $E_{acc} \sim$ 56 MV/m for a TESLA-shaped structure), at which the Meissner state becomes unstable with respect to avalanche vortex penetration. However, the SRF breakdown field may be increased relative to current estimates if the dynamic superheating field exceeds the DC H_{sh}.

The limit of the RF fields at the surface of the bulk niobium cavity are not yet fully understood. In particular, whether the field can be maintained in excess of the DC H_{sh}, and, if so, to what field strength is achievable [25]. Superconductivity in a dissipative vortex state persists up to the upper critical field $H_{c2} \sim$ 400 mT, which would correspond to $E_{acc} \sim$ 100 MV/m, whereas superconductivity in the surface layer of Nb ceases to exist at $H_{c3} \sim$ 1.3 T for standard ILC type surface preparation, translating into $E_{acc} \sim$ 300 MV/m if quenching of superconductivity could be avoided before then. However, SRF technology relies crucially on the exponentially small surface resistance in the vortex-free Meissner state, while the maximum field gradients are determined by the dynamics of breakdown of this state during the RF periods of ~1 ns, as the field is swept from the full negative to the positive amplitude range. A complete analysis of initial vortex nucleation, motion, and dissipation when the RF field amplitude exceeds the DC H_{sh} has not been done. This fundamental problem must be addressed both theoretically and experimentally to establish the ultimate SRF field gradients.

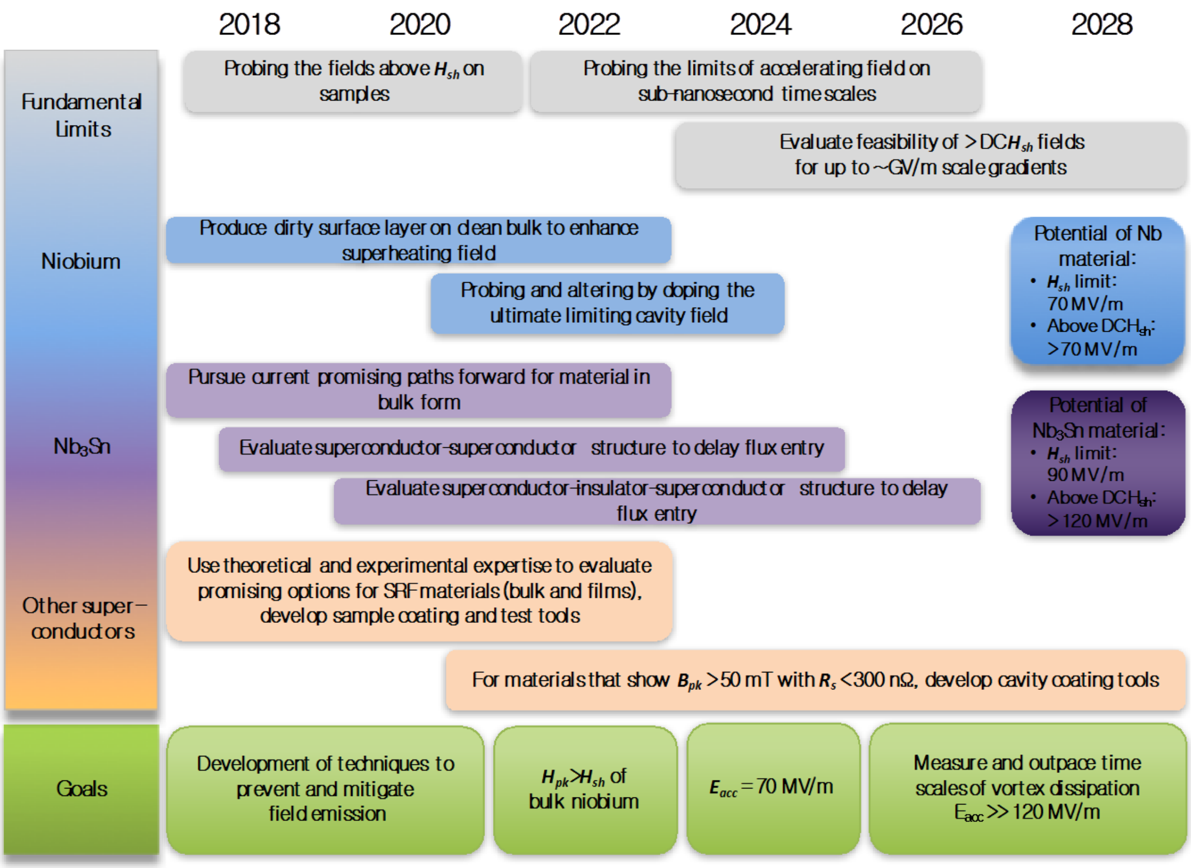

Figure 4: Ten-year roadmap and milestones for the high gradient SRF frontier.

Theoretical analysis indicates that several layered SRF surface structures can be very promising for delaying the flux penetration and preserving the Meissner state in the surface layer up to higher accelerating fields [31-36]. These surfaces are:

- "Dirty Nb" on "Clean Nb", with a potential of $E_{acc} \sim 70$ MV/m;
- "Other superconductor" on "Clean Nb", e.g. with a potential of $E_{acc} \sim 120$ MV/m for Nb_3Sn–Nb;
- "Other superconductor" – "Insulator" – "Clean Nb", e.g. with a potential of $E_{acc} \sim 120$ MV/m for Nb_3Sn–I–Nb.

Theoretical models for these layered surface structures should be developed to guide experiments toward engineering ideal surface nanostructures, first on samples and then on cavities. Another R&D direction involves theoretical understanding and experimental exploration of dynamic vortex behavior to prevent quenching in bulk Nb on sub-nanosecond timescale using techniques such as doping/flux pinning and RF pulse manipulation, for evaluation of the ultimate limitation in achievable gradients.

3.3 Common SRF Roadmap Elements

New Materials, Films, and Multilayers: The ten-year plan and milestones for the new materials research are presented in Figs. 3 and 4 as parts of the high Q and high gradient frontiers. There are many promising superconductors that could potentially achieve high accelerating gradients and high Q's: MgB_2, NbN, Nb_3Sn, other A15 superconductors (Nb_3Al, V_3Si etc.), and zinc iron pnictides. For all these materials, the potential and limitations for SRF applications bear investigation. Alternative SRF materials performing close to theoretical predictions could offer important advantages compared to traditional niobium: 1) high-Q even at temperatures well above 2 K, important for reducing costs for large-scale, high duty factor SRF accelerators and small-scale, cryocooler-based accelerators; and 2) theoretical potential for higher accelerating fields, to help enable pulsed linear accelerators with unprecedented reach into the Energy Frontier.

These materials could be used in bulk or thin film form. Thin films could bring the advantage of layered structures for a potential further boost in achievable accelerating gradients. To date, thin films, even of simple niobium material, show increased residual resistance and large medium-field Q-slope. Improved deposition methods R&D is ongoing at CERN, Jefferson, FNAL, ANL, and other laboratories. This R&D must continue so that breakthroughs in the production methods of high performing RF films can be applied directly to new materials films for high Q and high gradients.

Over the next several years, research will explore candidate superconductors and geometries that show potential based on practical and theoretical considerations. These candidates will be evaluated in RF tests on samples or simple cavity geometries to determine which to target for more intensive development. For those that demonstrate practical levels of surface resistance at relatively low fields, fabrication techniques will be scaled up for detailed evaluation. Materials manufactured in bulk versus those deposited in a thin film have the advantage of higher potential of success in terms of RF performance as at present deposited films (including Nb) are afflicted by strong Q-slopes and high residual resistances.

Development of Nb_3Sn as Practical SRF Material: Nb_3Sn bulk films show promising results, recently demonstrating high-Q for medium fields at 4.2 K in R&D cavities [26]. Recent experiments have also revealed several promising paths forward for improving the performance of this material, if appropriate surface treatments can be developed [27,28]. Studies will be performed on the coating of multiple cells to develop recipes that produce uniform, high quality films over a large surface area. Research will continue to focus on identifying and mitigating non-fundamental limitation mechanisms via a combination of advanced materials science studies and experiments on R&D-scale cavities. To demonstrate the breakthrough potential of this material for pulsed high energy applications, the goal in four to six years will be to achieve peak surface magnetic fields in pulsed mode that exceed the DC superheating field of niobium. With sufficiently defect-free coatings, theoretical predictions suggest that the superheating magnetic field limit of Nb_3Sn is approximately twice as high as niobium [29]. Extrapolation from high power pulsed RF experiments shows agreement with this prediction [30]. A suitable goal would be to achieve twice the accelerating field specification of ILC, first in single cell cavities, then in multi-cell cavities.

In parallel to bulk Nb_3Sn development, alternative manufacturing routes should be pursued via thin Nb_3Sn films on clean Nb or Superconductor-Insulator-Superconductor (S-I-S) Nb_3Sn layered structures to try to achieve the superheating field of Nb_3Sn with potential up to 90 MV/m (or even 10-20% above, up to 120 MV/m). The thin film or S-I-S avenue would not be as straightforward as simply bulk film Nb_3Sn, and would require more development to ensure good RF performance.

Field Emission Mitigation: Field emission phenomenon could be a serious impediment to achieving high gradients. Special studies will be required in parallel with high gradient research to abate field emission in vertical tests and cryomodules. Promising pathways include plasma processing, high power processing, and eventually robotic assembly. Some of these studies may be pursued outside of GARD (e.g. ILC cost reduction R&D).

Microphonics and Lorentz Force Detuning Compensation: Material science research for high acceleration gradient and high-Q should be supported by the cavity resonance control R&D and other RF ancillaries R&D [37-40]. SRF structures operating in the CW regime are susceptible to vibrations due to external excitation (microphonics). For pulsed-beam accelerators such as the ILC, compensating cavity resonant frequency detuning due to the Lorentz force (Lorentz Force Detuning or LFD) is especially important as the ratio of LFD over the cavity bandwidth is proportional to the cube of acceleration gradient. First, the reasons for vibrations (microphonics) should be determined, understood and mitigated. Second, the new cavity designs should be optimized to minimize LFD, and the cavity response to vibrations and He pressure fluctuations. Third, new active LFD and microphonics compensation algorithms should be developed along with the new tuner (fine and coarse) designs. Microphonics R&D becomes particularly important for 4.2 K operation of accelerators (e.g. for Nb_3Sn).

Novel SRF Cavity Shapes: R&D on new cavity shapes can further improve performance of SRF structures and HEP accelerators. The TESLA cavity shape [41] was developed in 1990's and has served the accelerator community well, enabling such accelerators as FLASH, European XFEL, and LCLS-II and serving as a baseline for ILC. However, several alternative elliptical cavity geometries were proposed (Ichiro, re-entrant, low-loss, low surface field) and have demonstrated accelerating gradients up to 55 MV/m on R&D cavities. These shapes can potentially provide up to ~20% higher gradients for the same peak surface magnetic field [42]. Some effort towards improving cavity shapes to reduce multipacting issues can be beneficial. Novel fabrication methods could permit the use of structures considered previously only for NCRF systems. An example is a parallel-feed accelerating structure [43]. If a robust, high-performance coating of thin-film niobium on copper is developed, such structures could potentially be more efficient for future accelerators.

Future HEP experiments require higher beam intensities and shorter synchrotron cycle times. Hence, either new accelerators will have to be built or existing ones upgraded (e.g. the Main Injector at Fermilab). Use of SRF technology would significantly reduce the number of cavities in these machines. However, the lack of fast frequency tuners prohibits the use of SRF cavities at present. Development of a new generation of fast frequency tuners for SRF cavities is proposed under the Auxiliary Systems R&D thrust. In parallel, new cavity structures will have to be designed, e.g. [44,45]. These fast-tuned SRF cavities operating at ~50 MHz would provide much higher acceleration gradients and; therefore, a smaller number of cavities and lower beamline impedance.

4 Normal Conducting RF Structures Roadmap and Milestones

Through new insights into the physics of RF breakdown at high gradients and innovations in the topologies of accelerating structures, normal conducting radiofrequency (NCRF) structures have undergone a momentous leap in accelerating gradient from around 50 MV/m to more than 200 MV/m. The goal of the normal conducting RF accelerating structure roadmap is to extend the limits of useful gradient for HEP accelerators while improving efficiency. The improved performance will be achieved with new topologies and optimized geometries for normal conducting and, synergistically, for super conducting accelerating structures.

The ten-year plan and milestones for the normal conducting RF are presented in Fig. 5. This R&D plan will explore advanced topologies, materials and manufacturing techniques; leverage the latest virtual prototyping tools; and investigate operation in new temperature and frequency regimes. The first roadmap priority is focused on implementing the best topologies with high strength materials using low cost manufacturing techniques. Then the limits of frequency and temperature will be explored to maximize gradients and efficiency. The final priority of the roadmap is to explore exotic accelerator concepts such as operation at multiple frequencies to break the quadratic scaling of power with gradient which limits efficiency. The roadmap naturally leads to the demonstration of a cost-effective accelerator facility capable of delivering a 1 GeV or more electron beam in an accelerator length of less than 10 m.

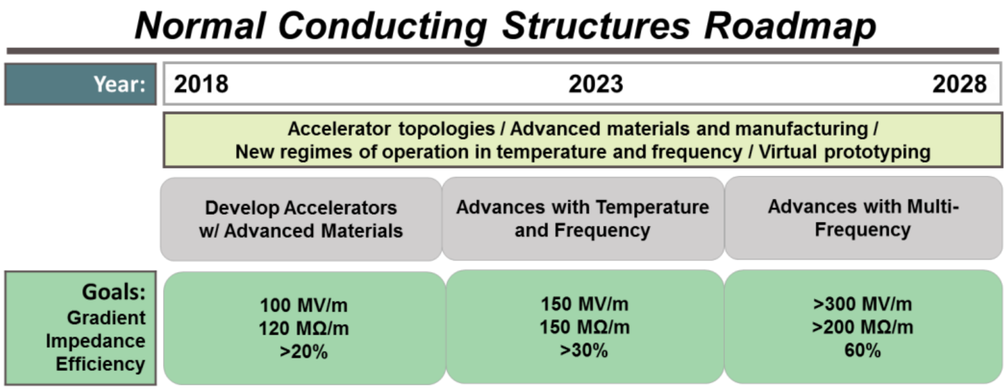

Figure 5: Ten-year roadmap and milestones for the normal conducting structures roadmap.

Because of collaborations established to answer fundamental questions about the limits of high gradient acceleration, the past decade has seen remarkable progress in NCRF accelerator technology. Foundational research in applied electrodynamics and materials science has led to the discovery of the basic physics mechanisms behind high gradient vacuum RF breakdown phenomena [54] and has significantly improved the capability-cost curve of charged particle acceleration systems. New linear accelerator topologies enable the use of novel geometries and materials to enhance gradients while reducing manufacturing costs. The reduction in cost comes, in part, from reducing manufacturing complexity and part count. At the same time, these new designs dramatically improve the RF-to-beam efficiency; hence, the system cost, including RF source, decreases. At X-band this has resulted in an increase in loaded accelerating gradient from 50 MV/m to 200 MV/m while doubling the structure's shunt impedance (or efficiency of establishing the accelerating gradient).

The roadmap explores many new, promising avenues. New accelerator structure topologies such as the distributed coupling accelerator structure [55] or photonic band gap structures [68] have great potential. Hard copper and hard copper alloys as a base material for accelerator structures support significantly higher gradient operation [49]. New manufacturing techniques (split structure technology) lower the cost of fabrication due to the great reduction in the number of fabricated parts [48]. Operation of the normal conducting accelerator structures at cryogenic temperatures achieve much higher gradients [53]. Multi-frequency multi-mode linac configurations and accelerating structures operating in the mm-wave range [46, 47] offer interesting possibilities. These possibilities will benefit from a continuation of a basic science R&D approach, which led to these discoveries.

While recent developments pave the way for high gradient structure operations, improvements in efficiency and cost, in addition to performance, will extend the energy reach, beam quality, and compactness of future accelerators. The accelerator structures research program must satisfy multiple requirements besides high gradient operation at statistically low breakdown rates, including structures with the capability of accelerating ~10 MW of beam power with high RF-to-beam efficiency, sufficient detuning and damping to suppress multi-bunch instabilities with reasonable alignment tolerances, appropriately large apertures to mitigate short range wakefields, while minimizing production and processing costs. The design of the accelerator structures must balance conflicting requirements, such as: 1) reduced RF-to-beam efficiency when operating at high gradients; 2) increased processing costs to achieve high operating gradients; 3) reduced RF-to-beam efficiency and reduced achievable gradients with larger apertures; 4) higher beam loading leading to stronger coupling of higher order modes, requiring sophisticated damping features that are expensive and typically reduce achievable gradients.

Several recent discoveries indicate possible new directions for future accelerators. The distributed coupling approach has made RF-to-beam efficiency of higher than 60% feasible. New, “hard” copper alloys allow reliable operation at gradients well above 100 MV/m at reduced RF processing cost. Multi-frequency structures break the historical scaling law dictating that the required operating power is proportional to the square of the gradient. Operation with normal conducting structures at cryogenic temperature allows gradients well above 200 MV/m at lower peak RF power and as a result, high RF-to-beam efficiencies. However, this comes with the expense of infrastructure and refrigeration required for the cryogenic system. Higher frequency operation could allow even higher gradients with increased shunt impedance and higher efficiency. Operation at these high gradients becomes cost effective only if appropriate RF sources are developed, which must be reflected in the RF accelerator roadmap discussed below.

One of the most important metrics for the accelerator structure is the RF-to-beam efficiency at a given gradient. A reasonable near-term goal would be an RF-to-beam efficiency of 60% at 100 MV/m. In addition, by utilizing new manufacturing techniques and automated tuning of structures on the assembly line, the goal to decrease the cost to mass produce accelerating structures to less than $10k/m is achievable. The structure must also mitigate both long- and short-range wakefields through damping and detuning, and satisfy the following requirements: 1) provide sufficient damping of the higher order modes to ensure stable beam propagation; 2) be compatible with new manufacturing techniques and the use of hard copper.

With these opportunities to improve the gradient and cost-capability tradeoffs, the research program for the next decade has five specific goals:

- Design new, simple-to-fabricate hard copper structures with integrated damping.
- Demonstrate wakefield suppression in these novel structures.
- Determine the impact of frequency and temperature on the high gradient limit.
- Develop better understanding of the tradeoffs in operating frequency and temperature.
- Demonstrate multi-frequency accelerating structures.

By the end of the decadal roadmap, these targets will lead to accelerating gradients greater than 300 MV/m, shunt impedance greater than 200 MΩ/m, RF-to-beam efficiency of 60%.

The proposed research program will naturally lead to the selection of preferred frequencies and temperatures for the accelerating structures, development of application-ready structures, and demonstration of their operation. The choice of frequency and operating temperature requires the simultaneous development of cost-effective, efficient RF sources. The long-term goal is demonstration of a cost-effective accelerator facility capable of delivering a >1 GeV electron beam in an accelerator length of less than 10 m. The decadal goal of achieving 300 MV/m gradients in accelerating structures enables a holistic optimization of this accelerator including the RF source for cost-capability. As source performance improves, operation at even higher gradients and beam energies becomes a reality.

High gradient cavities impact not only linear accelerators, but also circular designs such as rapid cycling synchrotrons (RCS) used for accelerating hadrons. An essential feature of the rapidly tunable types of cavities is that they require precise control over their resonance as beam is accelerated. The technology developed for the first generation accelerators has not changed significantly in the past 50 years or more. The cavity design for the FNAL Booster, MI and the BNL Booster and AGS as well as many others has been very successful and dependable. However, as we move on to the energy frontier (and even the intensity frontier – when considering cost/maintenance) the limitations for these tunable wide band cavities become a limiting factor in any future RCS.

Another area of RF R&D is in developing non-tunable low-Q RF cavities. The broad-band cavity technology developed during 1980's using ferrite [70] were widely adopted for FNAL, BNL, CERN accelerators. However, these RF systems have very low accelerating field gradients and are very lossy. The cost of cavities and operating systems represent a significant cost to future circular accelerators or RF upgrades to existing installations. Over the years, high-permeability soft magnetic alloys such as finemet, metglas and other amorphous types of materials have become available and proved to be useful in developing higher gradient broad band RF cavities [71]. Cavities built with these new types of material have high potential to enhance the performance of RCS ring accelerators. Smaller footprint, higher voltage cavities tunable over a large frequency range (>10 MHz) at double the cavity voltage and lower cost per cavity can be achieved by exploring improvements in ferrite/garnet materials, heat transfer materials, eddy current mitigation, feasible reparability and rapid tuners; and applying innovative solutions developed for high gradient accelerating structures in cavity geometry, topology and fabrication.

There is much synergy between NCRF HF and VHF tunable and VHF to S-band 'fixed' frequency RF structure research and development. The overlap can be significant in simulations and material research. However, some areas of research are unique such as ferrite/garnet development and cavity cooling and control. There is also significant material activation and degradation in cavity materials such as ceramic windows and attached power drive systems.

These concepts are broadly applicable and extend beyond normal conducting accelerators. Distributed coupling or multi-frequency structures may lead to SRF structures with reduced peak surface magnetic fields and increased acceleration gradients. New manufacturing techniques combined with development of thin film superconductors on copper may improve SRF capabilities. These new design topologies with high RF-to-beam efficiency may also benefit proton accelerator designs for PIP-II and PIP-III and lead to substantial savings in cryogenic power.

5 Advanced RF Source Roadmap and Milestones

High gradient operation, with increased peak power demands, necessitates a focus on high-efficiency accelerator systems, comprising both the accelerating structure and RF sources, and cost effective RF power generation. When pushing high gradient or intensity limits, RF sources become the leading cost driver for normal conducting accelerators and a significant cost driver for superconducting accelerators. Only with innovative concepts for designing and building RF sources will dramatic reduction in cost and increased efficiency be achieved.

The ten-year plan and milestones for the RF source roadmap are presented in Fig. 6. This R&D plan must apply a systems or holistic vision to developing RF sources, exploring new regimes of operation for electron beams at high perveance and low voltage; develop efficient modulators; employ rapid virtual prototyping and low cost prototyping; and explore innovative energy recovery concepts. The first roadmap priority is to explore discrete architectures with power combining. Concepts for distributed RF sources employing multi-dimensional beams and structures come to fruition resulting dramatic cost reductions by the middle of the decade. The latter stage of the roadmap addresses beam and RF energy recovery concepts, which will allow sources to transcend conventional limits on efficiency.

RF sources are presently a significant limitation for both pulsed and CW accelerators in terms of cost per peak and average watt, but they have not been a focus of intensive R&D efforts. These limitations are particularly pronounced when we envision future accelerators with high beam loading, high gradients, and higher frequencies. RF source technology with increased efficiency and lower capital costs must be

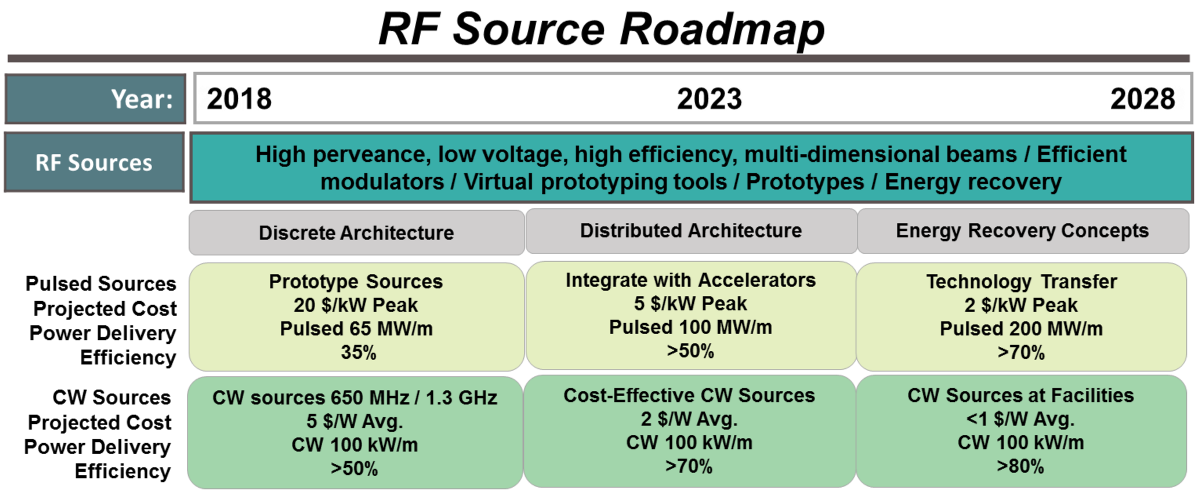

Figure 6: Ten-year roadmap and milestones for the RF source roadmap.

developed. Key physical limitations must be identified and high fidelity and fast simulations developed for virtual prototyping. Simulations can significantly reduce the time required from concept to implementation. Cost models are needed to provide production scale input to accelerator optimization. Development costs can be reduced by focusing on lower power demonstrations that are strongly synergistic with other applications and the commercial sector. Devices operating at low voltage and high efficiency, while at the same time producing the high peak and/or average power for high gradient and high intensity operation, are needed. High efficiency is essential to reduce the wall-plug power consumption for future large scale facilities such as colliders, PIP-II, PIP-III, and, possibly, at current installations such as the LCLS.

Long pulse and CW accelerators will require sources, with high amplitude and phase stability, to operate with high efficiency, even when output power decreases. RF source cost remains an important consideration for these accelerators, dramatic reduction to less than 1$ per W for high average power sources will benefit future high intensity machines.

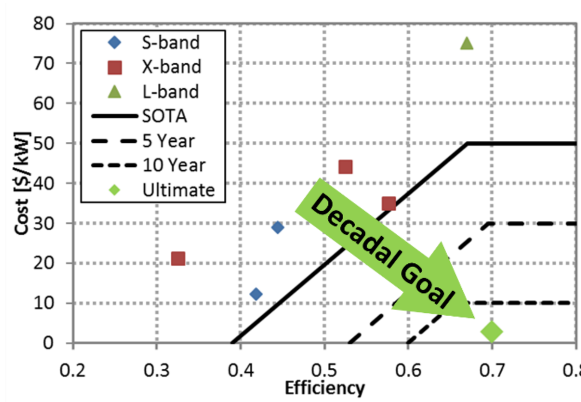

Figure 7: RF source cost including modulators in $ per peak kW vs. efficiency for mature source technologies.

In pulsed applications, lower voltage simplifies the modulator design, eliminating oil tanks and perhaps the pulse forming network. Such a modulator could be agile with variable pulse length and less expensive. The systems would be more efficient and reliable, and have broader appeal and applicability. Figure 7 shows the cost per peak kW and efficiency for a variety of mature sources produced commercially and by national laboratories. A decadal breakthrough in source cost and efficiency, 2$/peak-kW and 70% efficiency, would dramatically change the landscape for accelerators.

Several concepts for new RF sources have been developed during the last few decades. High efficiency can be achieved in devices with high voltage and low current, i.e. devices with low space charge [58]. This is true for all types of sources, whether a klystron, magnetron, gyrotron, magnicon, etc. Creating efficient, high-power devices at higher frequency, where the device shrinks in size as the square of the wavelength [63] is even more difficult. New cathodes producing higher current densities, simplifying beam transport, have been developed, but need to be reliably integrated in RF sources [68]. Concepts with other resonance mechanisms, such as gyrotrons and free electron masers, can use overmoded structures to overcome this limitation. Sheet beam klystrons have been developed, which stretch the dimensions of the device in one plane [62]. Multi-beam devices have also been built, but only in implementations where all the beams are collected in one single-mode cavity [57, 59]. A combination of ideas related to overmoding, gyro-devices [64] and multiple beams have also been developed. These devices still suffer from various technical shortcomings, such as low efficiency due to mode competition in overmoded devices or increased mechanical difficulties with single-mode devices. In the case of unusual beam configurations such as sheet beam devices, guiding the beam becomes a significant problem. Despite these opportunities, achieving high power without using high voltage remains an open question and R&D is required.

Innovative concepts are needed to reduce cost, but only initial steps have been taken. Recent efforts have started to push new concepts in discrete and distributed architectures. Discrete architectures aim to implement modular low-voltage high-efficiency RF sources that exploit the favorable cost-scaling of low-voltage operation and volume manufacturing, with power combining to achieve the goals of an extremely high power device. These take advantage of new techniques to combine many RF sources to achieve the high peak RF power. Examples include cascaded magnetrons [56] and modular array multi-beam klystrons (MA-MBK) [60].

Discrete architectures using solid-state sources are cost-competitive at lower frequencies and modest power. Efficiencies can be higher than 80% at low frequencies for the modules. Combiner losses are important and must be minimized. LCLS-II will be the first large scale SRF linac to use solid-state amplifiers, one per cavity. This also simplifies the RF distribution system compared to a large centralized RF source. The solid-state systems can also be fault tolerant and hot-swappable to contribute to improved availability.

A natural extension to the discrete combining concept are RF sources with continuously distributed architectures. Distributed architectures continuously merge discrete elements to share costly infrastructure such as the vacuum, electron beam and cavities. In these devices, the electron beam naturally expands under space charge forces, and hence it does not require magnetic focusing to guide it. Both bunching the beam and extracting power become simpler and the device can have high current and low voltage. Two geometries are naturally suitable for this: circular cylindrical structures and spherical structures, where diodes are constructed from two concentric cylinders or hemispherical shells, and would not need magnetic guidance (neglecting the end effects).

Distributed architectures enable transverse bunching [51]; utilized in magnicons and gyrocons. To date, development has been limited to high-voltage, high-power, low-frequency devices. These devices may be able to operate with low voltages and high peak power through compact power combining. This new class of devices is referred to as distributed bunching frequency multiplier tubes (DBFM), because the input frequency is a sub-harmonic of the output frequency [52]. At low voltages, novel topologies for the guidance and extraction circuits can employ permanent magnets and produce rather compact high power devices.

Energy recovery is another way to improve the overall system performance of the RF source. Typically, less than half the wall-plug power consumed for beam acceleration couples energy to the beam. Recovering the lost energy can dramatically improve the overall system efficiency. The most commonly adopted approach is a depressed collector for the spent electron beam, but this is challenging at high voltage. Low voltage sources or new approaches [61] to recovering energy would have a dramatic impact on the cost-capability of RF sources for pulsed and CW accelerators.

The time required to develop these concepts would be prohibitive without virtual prototyping tools; i.e., simulation tools and algorithms. Low-voltage RF devices that strive to achieve high power and high efficiency operate in a rather challenging simulation regime. Space charge effects are important; image currents and charges cannot be neglected; the beam dynamics cannot be considered as highly relativistic; the detailed shapes of the interaction regions must be considered accurately; and because of the high efficiency, all solutions must be self-consistent. Tools must also permit fast design optimization; it is not enough to simulate the system in a few days, even if faithfully predicting its performance. Fundamentally new algorithms, capable of leveraging modern computing, are needed.

6 Auxiliary Systems Roadmap and Milestones

Accelerators have many components besides the main linac, and the limitations of critical components define the operational regime and cost of any accelerator. Significant improvements in electron sources, high repetition rate positron sources, fast cavity tuners, HOM couplers, high power couplers, circulators, and RF controls could all have major impacts by opening new operational regimes. Furthermore, there is significant technological overlap between R&D for accelerating structures and RF sources and for auxiliary systems, for example, electron sources are required for both accelerators and for their RF sources, likewise, accelerator structures are required for both injectors and linacs. Very likely, R&D in these areas will cross-pollinate. The impact of auxiliary systems on accelerator performance and cost as well as the technological overlap, suggest that the GARD-RF roadmap should encompass auxiliary systems.

The ten-year plan and milestones for the auxiliary systems roadmap are presented in Fig. 8. Throughout the next decade, work will continue on couplers, dampers, and circulators. During the half decade, particle source development will focus on injector brightness, followed in the second half by implementation of polarized emitters in those injectors.

Electron Sources: For accelerators with significant challenges handling short and long range wakefields, an attractive approach to operation of the electron source would be to fill every RF bucket during the RF pulse and tailor the charge per bucket to a slowly rising profile. This reduces the bunch charge impacting short range wakefields, and could eliminate the need for long range wakefield damping. Detuning could reduce the long range (multi-bunch) transverse wakes to acceptable limits. For colliders, such a bunch train would require a damping ring well beyond the state of the art of current designs, or an injector capable of producing sufficiently low emittance without a damping ring. This

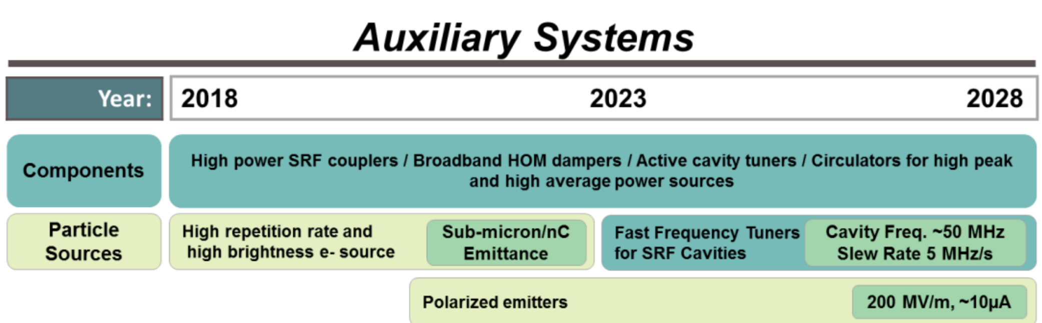

Figure 8: Ten-year roadmap and milestones for the auxiliary systems roadmap.

would have a dramatic impact on the main linac, reducing its cost and achieving much higher RF-to-beam efficiency.

Next generation cryogenic photoinjectors [50] have the potential to produce extremely high brightness beams. Essential studies for such photoinjectors aimed at demonstration of >250 MV/m are necessary and will have significant synergy with accelerator structure and RF R&D, including optimization of the accelerating structures and system optimization (RF frequency, temperature, gradient). Current collider designs require a damping ring to reduce the emittance of the electron beam. This ring would not be needed if there were polarized electron emitters which could operate in an RF gun and produce low emittances with sufficient charge and current.

Higher-Order Mode damping: Higher-Order Mode (HOM) damping is increasingly important as accelerator performance pushes ever higher in current, brightness and energy. Beam break-up in linacs, rings and ERLs has been well studied and the thresholds for instabilities can be confidently predicted. SRF structures tend to apply HOM damping to the cavity ends. NCRF structures tend to use porting and apertures in the cells to remove HOMs at the source, but these apertures can lead to surface field enhancements. Cross-fertilization between these options may be beneficial. Both communities need reliable supplies of affordable, repeatable, HOM absorbing materials.

Circulators: The rapid advancement of high gradient accelerators necessitates significant enhancement in the surrounding RF network. High power circulators (tens of MW) are often a limiting factor in the operational performance of these systems due to their inherently low power handling, poor frequency scaling and high cost. Achieving these operational goals at low cost requires a significant deviation from the nominal circulator embodiment and expanded research into more advanced concepts including heavily over-moded grytropic media with distributed Poynting flux, parametric excitation of periodic structures, thin film ferromagnetics and spin wave suppression within the bulk materials.

Power couplers: Input couplers or fundamental power couplers (FPC's in SRF parlance) are an essential part of the operating accelerator, but can be expensive and can impact reliability. SRF power couplers can cost as much as the cavity and are complex and vulnerable components. NCRF power couplers must handle extremely high peak power and can be weak points in breakdown and reliability. Multipacting and DC charging at the ceramic windows have been mitigated by low SEY surface coatings. Advances in ceramic technology such as the ability to provide bulk DC conductivity without increased RF losses could be very useful in advancing this field. Advanced simulation tools can aid in designing more reliable couplers.

Fast Frequency Tuners for SRF Cavities: Future HEP experiments require higher proton beam intensities and shorter cycle times of synchrotrons. Developing a new generation of fast frequency tuners for SRF cavities would allow for their implementation and the potential for higher acceleration gradient. To develop external tuners for superconducting RF cavities, we will explore options such as faster mechanical tuners; new low-loss ferrites [65] and ferroelectrics [66], which can operate at high gradient; or novel concepts in electromagnetic tuners [67].

High Precision RF Controls: Recent development and success in high-Q SRF cavity development provides potential for much higher efficiency in energy transfer from RF to beam, namely less RF power for a given accelerating gradient plus significant savings in required cryogenic power. In order to take advantage of high-Q SRF cavities, the very narrow cavity resonances must be precisely measured and controlled to match the external RF power source. Frequency detuning from microphonics (typically controlled by Piezo tuners) and Lorentz force detuning (for pulsed beam accelerators) must be compensated through advanced low-level RF (LLRF) control system. Application of field programmable gated arrays-based digital LLRF control systems, pioneered at Berkeley Lab, has been successfully implemented through multi-US-national-lab collaborations on accelerators, such as the Spallation Neutron Source SRF linac, the Fermi@Elettra linac, and many circular storage rings and is currently the technology of choice for the LCLS-II SRF linac under construction. High beam quality in such sophisticated accelerators can only be achieved by precisely controlling the RF accelerating amplitude and phase with active resonant control of the RF structures. Timing and synchronization of beams with RF and possibly laser systems are critical in a modern accelerator complex. Continued R&D is needed to further advance LLRF technology to meet ever increasing high Q SRF development and sophisticated control requirements in modern accelerators and colliders.

7 Synergies

The GARD-RF roadmap is strengthened by synergies between the SRF and NCRF technologies, supports science and technology missions beyond HEP, and offers opportunity for partnership with the private sector. SRF and NCRF synergies exist with respect to surface physics, design and materials, and fabrication methods. Federal agencies beyond HEP will benefit from and inform GARD-RF R&D. Synergistic applications in other Office of Science missions include injectors and accelerators for BES and NP. Other federal stakeholders include DOE-NNSA and DHS-DNDO, both seeking compact, efficient accelerator-based x-ray sources and DOD regarding advanced RF source technology. Opportunities in the commercial section are medical accelerators offering therapy with x-rays and particle beams and compact light sources for university and commercial customers. All sectors benefit from cross-cutting R&D, shared facilities, and mutually supportive scientific investigation. Given an era of constrained resources, the GARD-RF roadmap should exploit synergies to make the best use of available resources and facilities.

7.1 SRF/NCRF Synergies

Physics of the cavity surface: For both SRF and NCRF, cavity or material sample experiments are necessary to develop a fundamental understanding of the physics at the nanometer to micrometer near-surface level. Defect and impurity content of the material can play a crucial role in limiting the achievable accelerating gradients of SRF and NCRF structures.

Design and materials: Both SRF and NCRF accelerators are fundamentally limited by practically achievable electric and magnetic surface fields. Certainly, design lessons can be transferred in both directions. Cavity shape optimizations for highest field, highest efficiency, and highest current are different. SRF and NCRF face a common enemy of field emission due to high surface electric fields and can benefit from mutual understanding of geometric effects, surface processing and clean assembly techniques. When these are sufficiently controlled, the limitation shifts to the magnetic field, from heating to quench in the case of SRF to breakdown in the case of NCRF.

While dark current is certainly involved in NCRF breakdown dynamics, recent studies have shown that long term breakdown rates scale most closely with the magnetic field and depend strongly on the electrical, thermal and mechanical properties of the material. Recent results show that cryogenically cooled copper or alloys may yield significant improvements.

In SRF, in the absence of limiting field emission, quench occurs when the local magnetic field exceeds a critical threshold that is material and temperature dependent. This can be degraded by surface imperfections and contaminants. SRF production processes acknowledge the importance of ultra-clean preparation and assembly techniques. Clean and smooth starting surfaces in copper cavities may condition faster, which can be an important factor in a project timeline.

For both SRF and NCRF cavity production:

- Detailed understanding of the geometrical effects in design and fabrication can lead to useful reductions in peak surface electric and magnetic fields.
- Improved understanding of material properties and performance in real operating environments can lead to significant advances in usable gradient.
- Advances in materials and processes may produce dramatic impacts in other arenas such as RF guns and compact accelerators for industry, academia, medicine, security, etc.

As examples of synergy, recent developments in NCRF cavity design such as the distributed coupling scheme and dual frequency designs may have benefits for SRF structures. SRF experience in minimizing surface magnetic field may benefit NCRF.

Novel fabrication methods: Both SRF and NCRF communities have well-established fabrication methodologies, partly because of conservatism and partly due to investments in specific facilities and equipment. Project scale production has typically involved scaling of these processes with only minor changes. Alternative ideas for cavity fabrication exist, such as transversely segmented copper structures or seamless hydroformed SRF structures, that could lead to fabrication cost reduction. Early industry involvement in the design process may have significant benefit in reducing production costs down the road. Emerging fabrication technologies such as additive manufacturing may find applications in both sectors. Both warm and cold communities could benefit from cross-fertilization of ideas, from "disruptive" fabrication technologies, and from early involvement of industry in the design process. Designs may need to be adapted to realize the potential of new or efficient industrial production techniques. This requires a whole-system cost-benefit trade study to be performed.

7.2 RF Accelerator Technology Synergies within the Office of Science and DOE

SRF technology finds wide use at facilities for nuclear physics experiments (e.g. ATLAS at ANL, FRIB at MSU, RHIC at BNL), spallation neutron sources (SNS at ORNL, ESS in Sweden), storage ring and linac-based X-ray light sources (LCLS-II at SLAC, NSLS-II at BNL, European XFEL in Germany), and others. Thus, any advances in SRF technology developed for HEP are synergistic with a broad spectrum of applications and could immediately be put to practical use.

Brighter beams, compared to existing injectors, can be produced by utilizing advances in RF accelerator technology for photoinjectors and accelerators with high gradient operation. This research has immediate impact on BES, in the form of an ultra-high brightness source for hard X-ray FELs and in ultrafast electron diffraction/microscopy sources dramatically pushing performance limits with extreme low emittance at low operating charge.

High-power accelerators require beams with high duty factors. That calls for continuous-wave (CW) RF accelerating fields to be applied on charged particle beams. Traditionally CW acceleration has been considered to be the province of costly superconducting RF, but normal conducting CW structures have a clear advantage and proven to be very successful in applications such as the CW NCRF RFQ for PIP-II injector, the CW NCRF photo-cathode gun cavity for the Advanced Photo-Injector Experiment (APEX) and the photo-cathode gun cavity for LCLS-II. In general, the design of CW NCRF structures has two main challenges: proper design of structures that produce required high accelerating fields to control the beam quality, and good thermal management design to minimize the temperature rise and mechanical stress produced by RF heating in the structure. R&D on new CW NCRF structure/cavity design and novel thermal management approaches can further improve the performance of CW NCRF structures and accelerators for HEP, BES and NP.

Within the HEP mission, wakefield accelerators could be employed as drive beams for RF structures that produce high peak powers at desired frequencies to explore scaling of gradient with frequency. Electron beams from wakefield accelerators, can be employed as drive beams to excite short range wakes. Facilities that can produce witness bunches can also allow for probing the long range wakefield and emittance dilution.

7.3 RF Accelerator Technology Synergies with Federal Sponsors and Industry

The selection and implementation of accelerator technology for future accelerators will require innovations that reduce cost and increase capability for prototypes; and an accurate assessment of cost for the large-scale production of these systems. Commoditization employing optimized manufacturing techniques and tooling will be required to achieve the cost-scaling. Enormous potential exists for technology transfer to occur, reinvigorating the commercial RF sector with tremendous societal impact in areas such as security and medical applications.

A broad range of applications rely on RF accelerator technology and research. Examples include light sources, ultrafast electron diffraction, medical linacs, and x-ray sources for cargo inspection. RF accelerator technology has played an enabling role for many commercial market applications. Normal conducting accelerators are used to produce MeV electron beams which produce x-rays for both medical therapy and security and screening applications, and multi-MeV proton and ion beams which hold distinct therapeutic advantages.

The RF sources used by these accelerators are high power, short pulse klystrons or magnetrons. High power, short pulse klystrons have also found widespread adoption for use in radar applications. RF source technology developed by DOE at SLAC was recently transferred to commercial vendors for production of high peak power S-band and X-band klystrons. While the performance of RF sources and RF accelerator technology has steadily improved through the investment in research and development, the adoption of new technology in the commercial sector has effectively remained unchanged. Perhaps more shockingly the manufacturing techniques have also widely remained unchanged limiting productivity and driving up costs.

For example, x-ray sources for security and cargo screening applications are based on decades old designs that are costly and inefficient. This is recognized by this community with ongoing efforts funded through the NNSA and DNDO. Exemplary efforts funded through HEP Accelerator Stewardship efforts such as the GREEN-RF program are pairing the NCRF research and industrial community to rapidly commercialize technology that is having an immediate impact on product lines. A concerted effort to rapidly transfer technology to the commercial sector should be maintained and encouraged to leverage modern tooling and commoditization to climb the learning curve and yield cost savings.

8 Facilities

The long-term health of the field requires sustainable testing facilities for future accelerator technologies and for training scientists and engineers. Both SRF and NCRF require significant multi-disciplinary teams and facilities. These facilities require long-term vision and continual re-investment to support DOE missions and remain internationally competitive. Since construction of new test facilities in the immediate future will be resource constrained, maximizing the utilization of and re-tasking existing facilities to leverage previous investment will be paramount.

Many facilities and processes are unique to SRF or NCRF**,** some are common. As an example of a common facility, facilities involving material science and surface analytical tools crucial for pushing SRF performance towards higher gradients and Q, will be useful for NCRF investigations. Likewise, the GARD-RF research program would benefit from the construction of a new joint SLAC-FNAL test facility for testing both SRF and NCRF accelerator structures with different topologies. The short pulse test facility could be constructed based on cryogenic RF test facilities at FNAL with the RF infrastructure developed and constructed at SLAC.

Beam test facilities such as NLCTA at SLAC and FAST at FNAL are vital to prove new technologies are ready for deployment. Cryogenic or structure testing alone cannot adequately demonstrate next-generation accelerator capabilities without including beam loading and other effects. Demonstrating a complete "vertical slice" of any new technology, including RF source, distribution, controls and instrumentation, structures, and auxiliary systems will be essential before construction of major new facilities. An important capability gap is the lack of a high-current test bed for new structures and systems to allow verification of HOM damping, and beam loading compensation.

8.1 SRF Facilities

While infrastructure underpinning SRF R&D is well-established at national laboratories and universities, new research directions require new facilities or upgrading the existing ones. As the technology evolves, these facilities need upgrade and new investments to stay at the frontier of SRF cavity performance. SRF facilities are in high demand and will continue to be utilized by existing and future projects and programs within and outside HEP, such as PIP-II, LCLS-II, MaRIE, FRIB, and SNS. Figure 9 is a cross-reference matrix of SRF R&D areas and facility types, highlighting the facility utilization.

Fermilab hosts state of the art HEP SRF test facilities (FermiCARD) consisting of an SRF Cavity processing facility (chemical and furnace treatments); cleanroom assembly facility (including high pressure water rinsing); coating systems (e.g. Nb_3Sn, thin films); material science laboratory (advanced instruments for material studies, bulk and surface); multiple vertical and horizontal cryogenic cavity test stands; cryomodule test stands; and test stands for ancillary components.

Well-established SRF facilities include cryomodule test facilities at Fermilab (CMTS1 for tests without beam and FAST for testing with beam). ILC-style cryomodules can be equipped with cavities subjected to new treatment procedures or made from new materials. Such cryomodules could also use ancillaries of advanced designs. CBETA (Cornell-BNL ERL Test Accelerator), under construction at Cornell, and CMTF at Fermilab could be used for testing a 650-MHz cryomodule to validate high Q performance of lower frequency cryomodules and new HOM damping schemes. This is relevant for PIP-III, FCC-ee and CEPC, future hadron colliders, future electron-ion collider, and many other accelerators.

New facilities could include small specialized test stands for advanced SRF R&D; test stands for ancillary components to provide capabilities beyond what is available now; facilities to validate R&D concepts in cryomodules without and with beam (the latter could be utilized synergistically for other applications). Here is a partial list of new equipment and facilities that could be considered for testing/validating new SRF concepts:

- The future quantum computing testbed facility at Fermilab can be used to study SRF cavity performance at very low temperatures and very low gradients. This might help to improve understanding of fundamental SRF physics.
- An atomic layer deposition (ALD) facility would be crucial for R&D on nano-engineering S-I-S SRF surfaces. The existing ALD setups at ANL are critical for initial studies, but have limited capabilities.

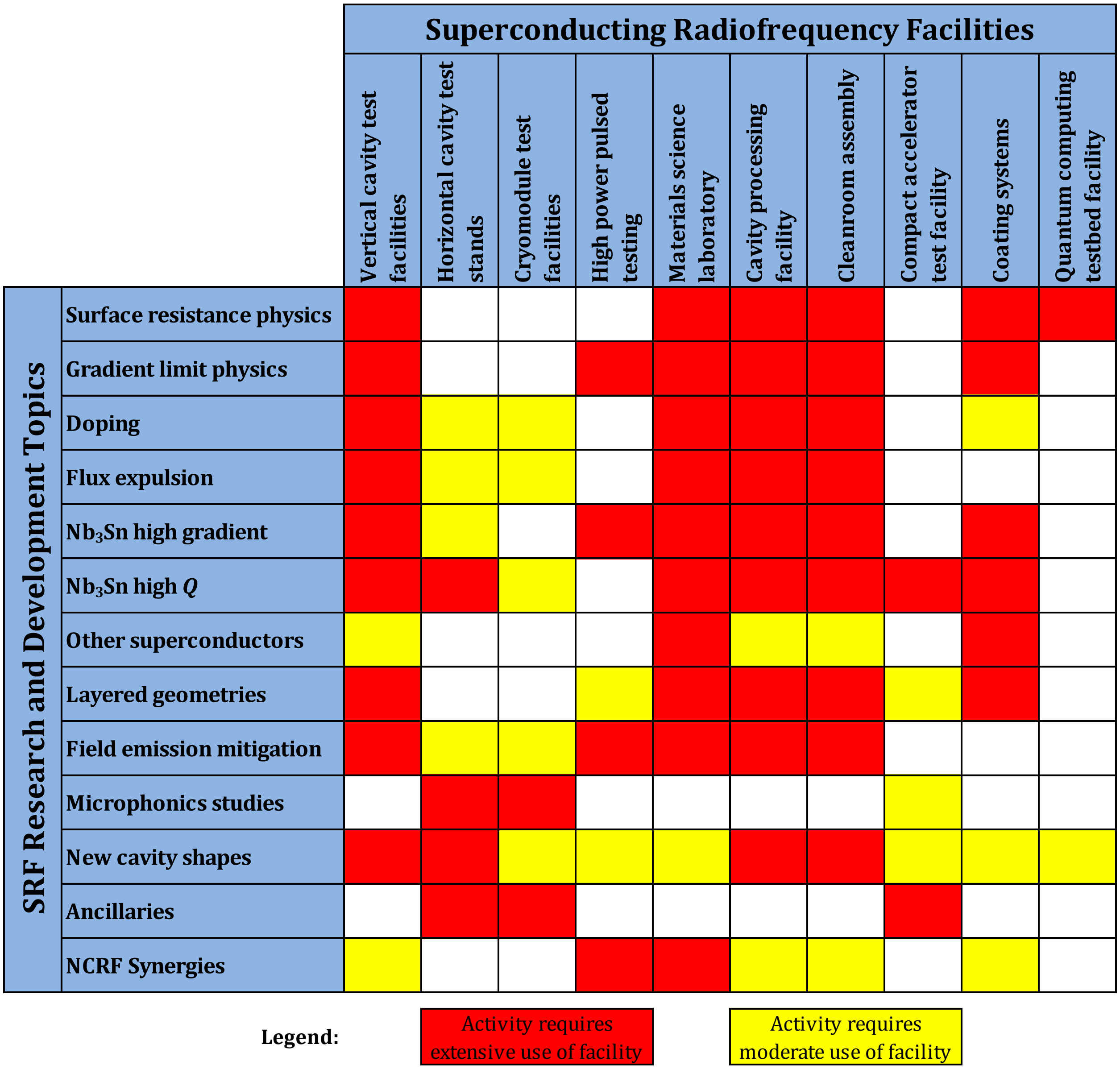

Figure 9: Facility utilization for SRF R&D.

- New cleanroom facility at FNAL to house a high-pressure water rinse test stand to support R&D to increase throughput and explore new ideas to abate field emission at very high accelerating gradients. Promising ideas include dry ice cleaning and robotic assembly.
- Existing facilities for MgB_2 coating are not suitable for SRF cavities. Developing a new apparatus large enough to accommodate 1.3 GHz cavities is very desirable.
- High power pulsed klystron test stand at Fermilab Vertical Test Facility to provide very short RF pulses for probing the ultimate gradient limits of SRF cavities. If equipped with an S-band klystron, this test stand can be synergistically used to test NCRF cavities at low temperatures in collaboration with SLAC.

A test facility for compact SRF accelerators based on Nb_3Sn technology at Fermilab would be a base for developing high-power accelerators for industry while serving as a test bed for R&D on new technologies such as conduction cooling of SRF cavities with cryocoolers, high-efficiency RF power sources. Nb_3Sn applied to frequencies higher than 3.9 GHz could then be put into a "miniaturized" proof of principle cryomodule for demonstration of moving towards table top compact accelerators for universities, industry and medicine.

SRF sample host cavity at Jefferson/ODU and SLAC, similar to the CERN quadrupole resonator, or Cornell TE cavity are vaulable for quick evaluation of RF performance of films of niobium or new materials.

8.2 NCRF Facilities

NCRF facilities are necessary to demonstrate integration of an accelerator system based on high-gradient RF structures and advanced RF power sources. Most facilities are largely established, but will require maintenance and upgrade as the GARD-RF program progresses. These facilities are described below and a facility utilization matrix for NCRF is shown in Fig. 10.

A world-class fabrication and testing facility, Advanced Prototyping & Fabrication (APF), is co-located with both engineering and design at SLAC. Nearly every part of high-power RF sources and high-gradient accelerating structures can be fabricated at the lab. There is multi-decade corporate knowledge of all high-power RF components, including material specification and control, ultra-high vacuum, and high voltage design and fabrication. Facilities include CNC and five manual lathes, two CNC and four manual w/CNC controls milling machines, five hydrogen retort and one cold wall furnace, and three vacuum furnaces. Also, there are four thin film sputter and evaporative coating chambers for the application of special coatings such as Ti on ceramic insulators to inhibit charge buildup and prevent voltage breakdown and multipactor. Facilities for diffusion bonding or electroforming metallic structures are also available. Finally, there are seven vacuum bake-out stations with a double-bell furnace/vacuum pumping system.

The Test Lab at SLAC provides high-power RF and associated facilities for R&D activities such as high gradient breakdown research, electron gun development, and testing of RF components. Thirteen pulse

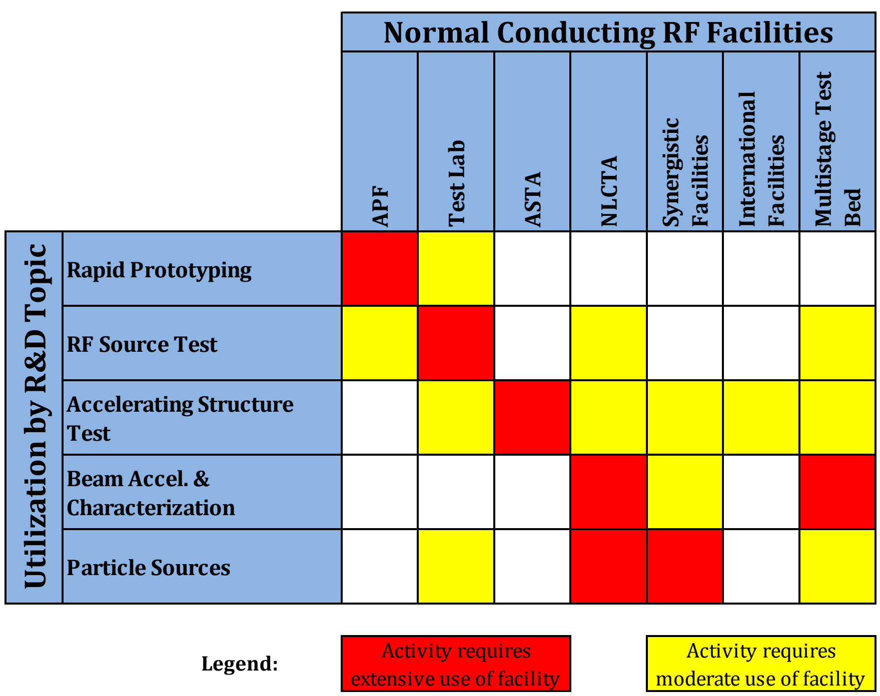

Figure 10: NCRF facility utilization matrix for decadal roadmap.

power test stands, with 150 MW peak power capability and transformers that can exceed 400 kV; and two test stands with several megawatts continuous waveform at roughly 100 kV DC are available.

The Accelerator Structure Test Area (ASTA) at SLAC is a specialized research laboratory, adjacent to the Test Lab, designed specifically for hosting high gradient experiments capable of generating significant radiation. ASTA is equipped to provide diagnostic access to a suit of accelerating structures including both room temperature and cryogenic structures and standalone cavities.

The Next Linear Collider Test Area/X-band Test Area (NLCTA/XTA) is a comprehensive and available accelerator and laser user facility at SLAC, with all the necessary, power, water, RF, and ES&H protocols that houses two 60-120 MeV linacs. The accelerator cave is 50 m long, and offers ample space and shielding for high power beam demonstrations. The accelerator infrastructure includes both S and X band RF sources (Klystron/Modulators) powering accelerators and injector guns, all with the diagnostics, test beamlines and equipment necessary to fully characterize novel accelerator concepts, performance and beams.

The Synergistic Facilities for auxiliary systems are actively engaged in research into new photocathodes (BNL, LANL, Cornell, LBL APEX), polarized e- source development (BNL, Jefferson), and cryogenic normal conducting RF photo injectors (UCLA, SLAC, INFN). Finally, International Facilities pursuing high gradient research around the world include NEXTF at KEK, Xbox at CERN, and C-band at INFN-LNFA.

Moving forward, a Multistage Test Bed for accelerator development should be designed and constructed with the goal of developing an experimental platform to study emittance preservation in accelerator topology and validating RF and beam transport modeling tools. The design of the multi-stage test bed must maintain close contact with advanced RF sources, structures, and auxiliary systems developments to assess projected performance and cost in these systems to guide parametric goals for the conceptual design. In turn, this design effort will provide guidance to the component thrusts to focus direction. A multi-stage NCRF test bed should be commissioned within 10 years and will provide the following information to inform a subsequent down-select of competing technologies:

- Evaluation of NCRF technology ability to preserve beam emittance
- Mechanical fabrication and alignment tolerance requirements
- NCRF accelerator capital and operating cost model validation
- Initial quantification of engineering fabrication issues
- Initial quantification of lifetime, fault, and reliability issues

The lowest cost option will likely be to repurpose an existing accelerator test facility (bunker, conventional and safety infrastructures). The effort will leverage synergies with related RF technologies, other Federal missions, and additional research and commercial applications, with the aim of identifying and pursuing possible sponsors to cost share and play a critical role in the development of this technology from component level to multi-stage prototypes. A multi-stage prototype accelerator would have many potential synergies with compact light sources (FEL, coherent ICS), MaRIE, as a test platform for “auxiliary” NCRF LC technologies (e.g. high brightness injector), pursuing high-brightness injectors for BES and for testing RF component technologies for SRF.

9 Modeling and Simulation

As endorsed in the HEP P5 Report, virtual prototyping of accelerator components is possible on a larger scale with high performance computing (HPC) combined with new algorithms. This has been noted in the HEP Accelerator R&D Subpanel Report: "Advances in simulations, as well as in computational capabilities, raise the exciting possibility of making a coherent set of comprehensive numerical tools available to enable virtual prototyping of accelerator components as well as virtual end-to-end accelerator modeling of beam dynamics."

The state of the art for RF modeling and simulation on HPC resources has transformed the design and optimization of particle accelerators on computers to a level of realism that wholly reflects all the complexities pertaining to a system. The development of computational methods for high fidelity modeling of complex geometries that includes multi-physics simulation capabilities in electromagnetic, thermal, mechanical effects for accelerator design, as well as integration of these tools with beam dynamics and radiation codes provides a unique HPC accelerator modeling toolset to achieve an optimized design at reduced costs and to address machine issues for its operational reliability. The simulation tools for virtual prototyping can be applied to particle accelerators using normal conducting or superconducting RF accelerator technologies, and thus they serve to support all HEP RF accelerator development. The R&D thrusts in support of GARD-RF research roadmap in virtual prototyping are shown in Fig. 11 and described below.

Advancing multi-physics modeling and simulation capabilities: The computing capabilities of massively parallel simulation software enable RF design of novel accelerator structures, which leads to the invention of new types of structures and cost effective manufacturing. The development of electromagnetic-thermal solvers enables accurate calculation of cryogenic heat load in superconducting RF cavities, providing critical evaluation of cryoplant capacity requirements. The development of electromagnetic-mechanical solvers facilitates the evaluation of cavity response to RF gradient and fluctuation and mechanical vibrations. The combination of HPC with these multi-physics modeling capabilities provides a unique simulation environment that is not readily available from commercial software packages. Future development in electromagnetics includes new nonlinear eigensolvers for calculating RF mode damping and algorithms for modeling frequency-dependent dielectric and ferrite materials. The development of a time domain thermal solver aims to model thermal stress arising from superconducting RF cavity cool down process. The implementation of a time domain mechanical solver provides a modeling capability for broadband mechanical pulse propagation, which can directly simulate microphonics by determining the RF response to the realistic machine operation environment.

Developing integrated modeling tools for accelerator system simulation: The parallel accelerator codes developed for RF modeling, beam dynamics studies, and particle-matter interactions can be combined to provide unique coherent numerical tools for modeling accelerator systems and machine protection. The integration of RF and beam dynamics codes combines high accuracy calculation of three dimensional fields in beamline components with beam dynamics optimization to enable end-to-end simulation and virtual machine analysis. Integrating RF and plasma codes provides a realistic modeling capability to investigate the mechanism of plasma processing for commissioning cavities to reach high

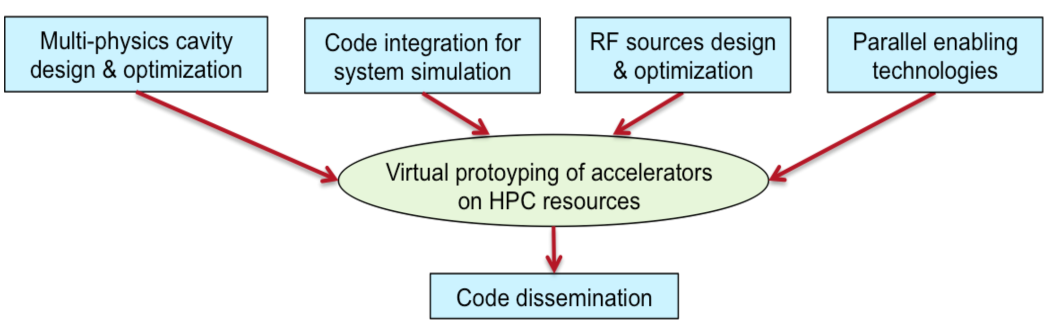

Figure 11: R&D thrusts in RF modeling and simulation for virtual prototyping of accelerators.

gradient. The integration of RF with particle-matter interaction codes enables the evaluation of radiation safety and instrumentation protection for reliable machine operation due to background electrons originated inside an accelerator cavity. The future R&D effort focuses on automatic operation through function calls in the integrated codes to produce a tightly coupled single tool, which bypasses the present time-consuming, error-prone procedure of manual operation on the separate codes. The development of these coherent modeling tools requires implementation of numerical algorithms for proper treatment of in-memory data transfer between codes and handling of geometry at different computational domains.

Developing fast codes for design and analysis of RF sources: The development of new codes for design and optimization requires the correct implementation of space charge forces and rapid computations. Current particle-in-cell (PIC) codes solve the full-wave Maxwell equation, which take a long time to simulate and therefore are not suitable for design and optimization. A new approach based on a large-signal formulation can circumvent these problems. The code development starts with two-dimensional implementation, which includes the development of fast 2D mesh generator, eigensolver, static solvers and efficient particle tracking on a finite-element grid. Subsequent three-dimensional implementation can take advantage of the finite element framework established in existing parallel RF software. In addition to these RF source design codes, the development of a beam-wave analysis code for rapid determination of possible spurious oscillations for a large number of resonant modes in an entire RF source presents an efficient parallel capability to analyze the device stability.

Enabling efficient modeling and simulation on HPC resources: The collaboration in computational science is essential for the development and implementation of scalable parallel codes on DOE emerging supercomputing architectures including those at exascale. Enabling technologies in mesh adaptation and shape optimization are needed for parallel multi-physics optimization of cavity to speed up the process of virtual prototyping with fast turnaround time using less computational resources for achieving the best design of the cavity. Advanced algorithms in scalable numerical algebra are required for the efficient solutions of large linear systems representing the physics equations. Furthermore, the simulation codes need to implement relevant parallel program paradigms to enhance their parallel performance on architectures with multi-core compute nodes and with GPU's.

Dissemination of virtual prototyping toolset for community: To facilitate the accelerator community to use the virtual prototyping tools effectively on HPC resources, simulation workflows with a user-friendly GUI should be developed and documented. Detailed documentation including command syntaxes, tutorials, and demonstration of workflows for integrated RF, beam dynamics and radiation simulations should be available online. Code workshops with hands-on tutorials should be organized to facilitate the dissemination of the developed modeling toolset to the accelerator community. Proposed milestones for the R&D thrusts of RF modeling and simulation are shown in Table 1.

Year	Milestone
1 - 2	Time domain thermal and mechanical solvers for cavity design; Integration of RF and beam dynamics codes for emittance calculation; Solver components for 2D modeling of RF sources; Nonlinear eigensolvers for damping calculation; GUI for multi-physics cavity design.
3 - 4	Capability for EM mode damping calculation for all boundary conditions; Integration of RF and radiation codes as a coupled system; 2D large-signal code for RF source design; Parallel RF shape optimization tool; GUI including RF shape optimization tool
5 – 6	Coupled time domain thermal and mechanical solver for cavity design; System-level integrated RF and beam dynamics simulation; Tool for analysis of spurious oscillations in RF sources; Nonlinear eigensolvers for dispersive lossy materials; GUI for code integration
7 – 8	Capability for microphonics simulation in cryomodule systems; System-level integrated RF and radiation calculation; 3D large-signal code for RF source design; Parallel multi-physics shape optimization tool; Dissemination of RF source codes
9 - 10	Multi-physics shape optimization of large accelerator systems; End-to-end integrated simulation; Optimization procedures for RF source codes; Performance enhancement of parallel codes on emerging supercomputing platforms; GUI for multi-physics shape optimization tool

Table 1: Milestones for RF modeling and simulation R&D thrusts.

10 A Comment on the RF Workforce

Although not an element of the charge, the committee noted there is a chronic shortage of qualified scientists and engineers in RF technology. Laboratories across the world have difficulty filling RF technology related positions. As an illustrative example, there is a shortage of engineers and scientists trained to work on high-power RF. Most young engineers are educated to design and build communications devices and prefer to work in the communications industry. Stop-gap training measures, although necessary, are not effective long term solutions. The situation is becoming more acute as many highly-experienced RF scientists and engineers are retiring. The impact on RF accelerators could be severe if a systematic campaign to develop and implement a long-term plan for training and attracting next-generation RF specialists is not in place. A stable RF research and development program is a key element of such a plan.

Appendix A DOE HEP GARD RF Workshop Charge

DOE HEP GARD-RF Research Roadmap Workshop
Courtyard Hotel
204 Boardwalk Place
Gaithersburg, MD 20878
March 8-9, 2017

Dear Colleagues,

This workshop is being organized to develop a ten-year research roadmap for the DOE HEP General Accelerator R&D (GARD) RF Acceleration Technology thrust. This follows in the footstep of two previous GARD workshops, for the High Field Magnets and Advanced Accelerator Concepts research thrusts, in response to the HEPAP Accelerator R&D Subpanel Report, *"Accelerating Discovery—A Strategic Plan for Accelerator R&D in the U.S."* (The report is available online at http://science.energy.gov/~/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf). The roadmap should include clearly identified goals and milestones with metrics.

The GARD-RF Thrust covers a broad spectrum of research topics—ranging from superconducting radio frequency R&D to normal conducting RF accelerating structures, as well as RF sources. The goal of this workshop is to identify HEP mid and long term needs that support the P5 strategy and HEPAP Accelerator Subpanel recommendations, and then develop a ten-year research roadmap for the HEP GARD-RF research thrust with appropriate milestones and priority.

As you construct the roadmap, please prioritize the milestones to align with what you think are the most pressing challenges that need to be addressed to move the field forward in support of the HEP program. The roadmap should have a near-term ten-year focus but should be embedded in the long term plans for the intensity and energy frontiers articulated by the P5 roadmap.

You should consider the most sensible sequence for the following research activities:

- SRF
  - What is the most rewarding technological push? Cavity Q? Accelerating gradient? Cavity geometry? New materials? New processing techniques?
  - Are there potential benefits in going to higher frequencies? What is the cost scaling at different frequencies?
- NCRF
  - What is the practical high gradient limits?
  - How to realize such high-gradient structures?
  - What are the limiting items and weak links? Materials? Geometry? Wakefields? Efficiencies?
  - How to mitigate rf breakdown problems?
- RF Sources
  - What are the future needs in RF sources? Power? Frequency? Efficiency? Cost?
  - Are there promising new innovations and inventions available? In what kind of time scale?
- High Power RF Components

        - What, if any, are the HP RF components that need to keep up with current and future facility demands?
        - Identify these RF components; compare capabilities with desired specifications.
    - Analytical and Modeling Tools
        - Are there theoretical and analytical models available to explain and predict performance?
        - Are the modeling tools currently available adequate for the job now and going forward?
        - What are some missing features that need to be implemented in current suites of codes?
    - Synergies
        - What are the areas where synergies can be exploited across the different sub-thrusts of SRF, NCRF, RF sources, HP RF devices?
        - What synergies can the GARD program leverage off efforts in other domestic and international programs?
    - Facilities
        - What type of facilities are needed?
        - Are current test facilities adequate?
    - Applications
        - Are there any applications for the technology prior to deployment in a collider?
    - Priorities and Timeline
        - What are the relative priorities for these different R&D activities?
        - Knowing the relative priorities, what milestones and timescale are appropriate for the GARD-RF research thrust for the next decade?

In preparation for this workshop, SLAC and FNAL have each organized a preparatory workshop focusing on slightly different scope areas—with SLAC focusing on NCRF structures RF sources while FNAL on SRF-related activities. Preliminary research roadmaps are being developed at SLAC and FNAL, which will be presented and integrated at this workshop. For convenience and efficiency consideration, and for the benefit of those attending this workshop, we ask that the leaders of these preparatory workshops (Emilio Nanni and Sergey Belomestnykh) provide reading material (documents or website links) to the attendees as soon as possible prior to the workshop. This will help them prepare for discussion at the workshop.

It should be noted that this workshop is not a review of the research programs but rather a strategic formulation undertaking to generate a research roadmap with milestones, taking full advantage of potential synergies, to guide the GARD-RF activities over the next ten years.

Thank you for agreeing to participate in this workshop. Your contribution to the development of this comprehensive research roadmap—complete with a prioritized list of milestones together with justification and explanation for their selection—is very important for the success of the GARD-RF thrust and the HEP-GARD program.

Sincerely,

LK

Appendix B DOE HEP GARD RF Workshop Agenda

REVISED AGENDA

DOE-HEP GARD-RF Research Roadmap Workshop

Meeting Room: Salons A-B
Courtyard Gaithersburg
Washingtonian Center
204 Boardwalk Place
Gaithersburg, MD 20878
March 8-9, 2017

Wednesday, March 8, 2017

Time	Speaker	Title	Duration
7:30 AM	***Breakfast***	*A/V and internet connection set up*	60
8:30 AM	Jim Siegrist/Glen Crawford	Welcome and Opening Remarks	15
8:45 AM	L.K. Len	GARD Overview and Workshop Objectives	30
9:15 AM	Sami Tantawi / Emilio Nanni	NCRF preparatory workshop report	45
10:00 AM	S.Belomestnykh/A.Grassellino	SRF preparatory workshop report	45
10:45 AM	***Break***		15
11:00 AM	Sami Tantawi	High gradient structures and novel RF sources	30
11:30 AM	Cho Ng	RF modeling and simulation	30
12:00 PM	Matthias Liepe	Current state of the art in SRF R&D	30
12:30 PM	***Working Lunch***		60
1:30 PM	Alex Gurevich	High gradient SRF material/coating R&D	30
2:00 PM	Erk Jensen	International efforts on RF technology R&D	30
2:30 PM	Robert Rimmer	Potential synergy between NCRF and SRF	20
2:50 PM	Sami Tantawi / Emilio Nanni	NCRF Research Roadmap and Milestones	45
3:35 PM	***Break***		15
3:50 PM	S.Belomestnykh/A.Grassellino	SRF Research Roadmap and Milestones	45
4:35 PM	Bruce Carlsten, Wim Leemans, Lia Merminga, Sergei Nagaitsev, Robert Rimmer and Others	Group discussion: Program and laboratory RF needs and R&D status	60
5:35 PM	All	Discussion	25
6:00 PM	***Adjourn***		

Thursday, March 9, 2017

Time	Speaker	Title	Duration
7:30 AM	***Breakfast***	*A/V and internet connection set up*	60
8:30 AM	John Byrd	RF instrumentation and controls	20
8:50 AM	Richard Temkin	GARD-RF university roles	20
9:10 AM	James Rosenzweig	GARD-RF: user-need perspective	20
9:30 AM	Sergey Belomestnykh	GARD-RF test facilities@FNAL: status and availability	20
9:50 AM	Emilio Nanni	GARD-RF test facilities@SLAC: status and availability	20
10:10 AM	Jerry Blazey + All	Discussion: Research roadmap and integration plan	20
10:30 AM	***Break***		15
10:45 AM	Jerry Blazey + All	Research roadmap integration and discussion	90
12:15 PM	***Working Lunch***		60
1:15 PM	Jerry Blazey + All	Research roadmap integration and discussion	120
3:15 PM	***Break***		15
3:30 PM	Jerry Blazey + All	Research roadmap integration and discussion	60
4:30 PM	All	Finalize GARD-RF Research Roadmap	30
5:00 PM	***Adjourn***		

Appendix C DOE HEP GARD RF Workshop Participants

Participants

Sergey Belomestnykh	*Fermi National Accelerator Laboratory*
Jerry Blazey (co-chair)	*Northern Illinois University*
John Byrd	*Lawrence Berkeley National Laboratory*
Bruce Carlsten	*Los Alamos National Laboratory*
Anna Grassellino	*Fermi National Accelerator Laboratory*
Alex Gurevich	*Old Dominion University*
Erk Jensen	*CERN (European Organization for Nuclear Research)*
Andy Lankford	*University of California, Irvine*
Wim Leemans	*Lawrence Berkeley National Laboratory*
L.K. Len (co-chair)	*U.S. Department of Energy, Office of High Energy Physics*
Matthias Liepe	*Cornell University*
Lia Merminga	*SLAC National Accelerator Laboratory*
Sergei Nagaitsev	*Fermi National Accelerator Laboratory*
Emelio Nanni	*SLAC National Accelerator Laboratory*
Ali Nassiri	*Argonne National Laboratory*
Cho Ng	*SLAC National Accelerator Laboratory*
Robert Rimmer	*Thomas Jefferson National Accelerator Facility*
Jamie Rosenzweig	*University of California, Los Angeles*
Sami Tantawi	*SLAC National Accelerator Laboratory*
Richard Temkin	*Massachusetts Institute of Technology*

Observers

Jim Siegrist	*U.S. Department of Energy, Office of High Energy Physics*
Glen Crawford	*U.S. Department of Energy, Office of High Energy Physics*
Eric Colby	*U.S. Department of Energy, Office of High Energy Physics*
Ted Lavine	*U.S. Department of Energy, Office of High Energy Physics*
Simona Rolli	*U.S. Department of Energy, Office of High Energy Physics*
Manouchehr Farkhondeh	*U.S. Department of Energy, Office of Nuclear Physics*
Eliane Lessner	*U.S. Department of Energy, Office of Basic Energy Sciences*
Vyacheslav Lukin	*National Science Foundation*

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