Supply Chain Risk Mitigation for Scientific Facilities and Tools

Report from the November 2021 Roundtable

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. Department of Energy
Office of Science Supply Chain Roundtable

November 2, 9, and 16, 2021

About the Roundtable

In November 2021, the U.S. Department of Energy (DOE) Office of Science (SC) convened a roundtable on "Supply Chain Risk Mitigation for Scientific Facilities and Tools" to gather information about current supply chain challenges in key technology areas unique to SC or critical to its mission. The roundtable brought together technical, project management, and procurement experts from DOE national laboratories, industry, academia, and other government agencies. Panelists explored opportunities, possible partnerships, and mechanisms to strengthen the domestic supply chain for critical SC technologies.

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Cover images: See Appendix E, p. 55.

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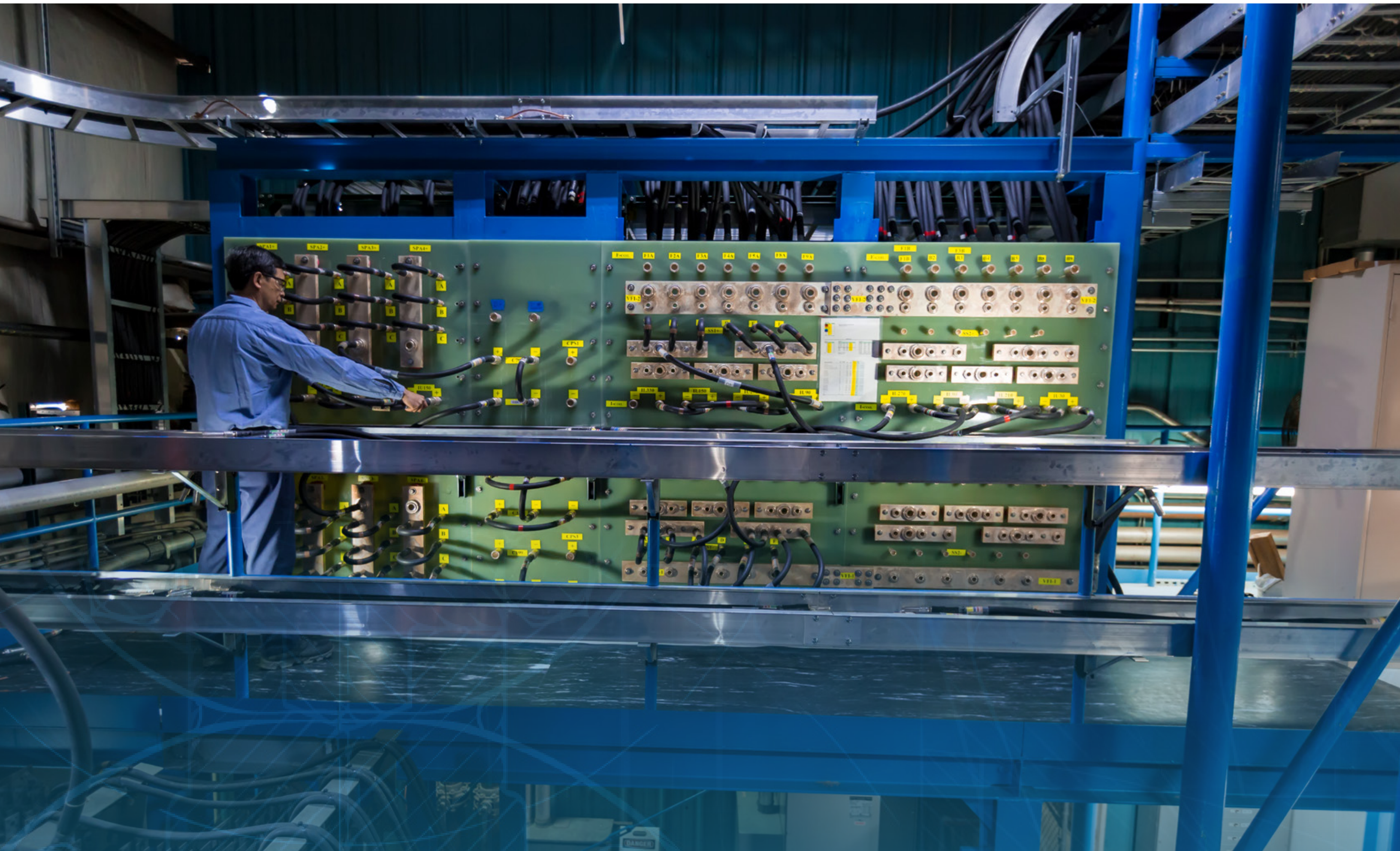


EXECUTIVE SUMMARY

Executive Summary

New research instrumentation catalyzes discovery and knowledge growth and thus is a cornerstone for advancing science. Because of the specialized research within the U.S. Department of Energy's (DOE) Office of Science (SC), instrument systems may need to operate in unique environments and are often designed and built by the scientific community. The nuclear and particle physics communities have operated like this for a century, and now the materials science and biological research communities increasingly are operating this way as well. Procurement and supply chain challenges can hinder the development of new scientific tools and the operation of existing facilities (see Appendix A, p. 46), in turn diminishing scientific discovery.

To consider these issues, SC convened a roundtable on "Supply Chain Risk Mitigation for Scientific Facilities and Tools" to gather information about current supply chain risks in key technology areas unique to SC or critical to its mission (see Appendix B, p. 48). Roundtable participants were asked to explore opportunities, possible partnerships, and mechanisms to strengthen the domestic supply chain for these technology areas.

The roundtable was timely amid an increased emphasis across the federal government in strengthening domestic supply chains to help U.S. businesses compete in strategic industries and help America's workers thrive. On January 25, 2021, President Biden issued Executive Order (EO) 14005, "Ensuring the Future is Made in All of America by All of America's Workers." This EO reinforced America's commitment to current "Buy American Act" policies, which give preference to the acquisition of goods, products, and materials produced in the U.S. by American workers. Subsequently, on February 24, 2021, the Biden administration issued EO 14017, "America's Supply Chains"—further requesting agencies to review requisite supply chain risks and identify challenges related to obtaining highly sought-after products.

Five roundtable panels were formed, composed of experts in the SC enterprise from universities, DOE national laboratories, and industry (see Appendices C and D, beginning on p. 51). The roundtable considered four technology areas: (1) Accelerator Systems; (2) Detector Systems; (3) Instrument and Target Systems; and (4) Specialty Materials, Machining, and Manufacturing, which included aspects of high-performance computing. Members from a fifth panel on Crosscutting Issues were embedded in each technical panel. All panels identified common supply chain challenges across SC endeavors and addressed procurement and business issues. Some of the identified supply chain challenges include:

- Limited U.S. or international vendors and suppliers.
- Difficulty attracting funding as well as talent to develop low-volume or high-risk commodities, such as high-purity diamonds, magnet components, beryllium components, and superconductors.
- Long lead times, production delays, or quality-control issues due to over-subscribed resources.
- Lack of a robust framework and resources to facilitate more effective partnerships among DOE national laboratories, industry, and academia.

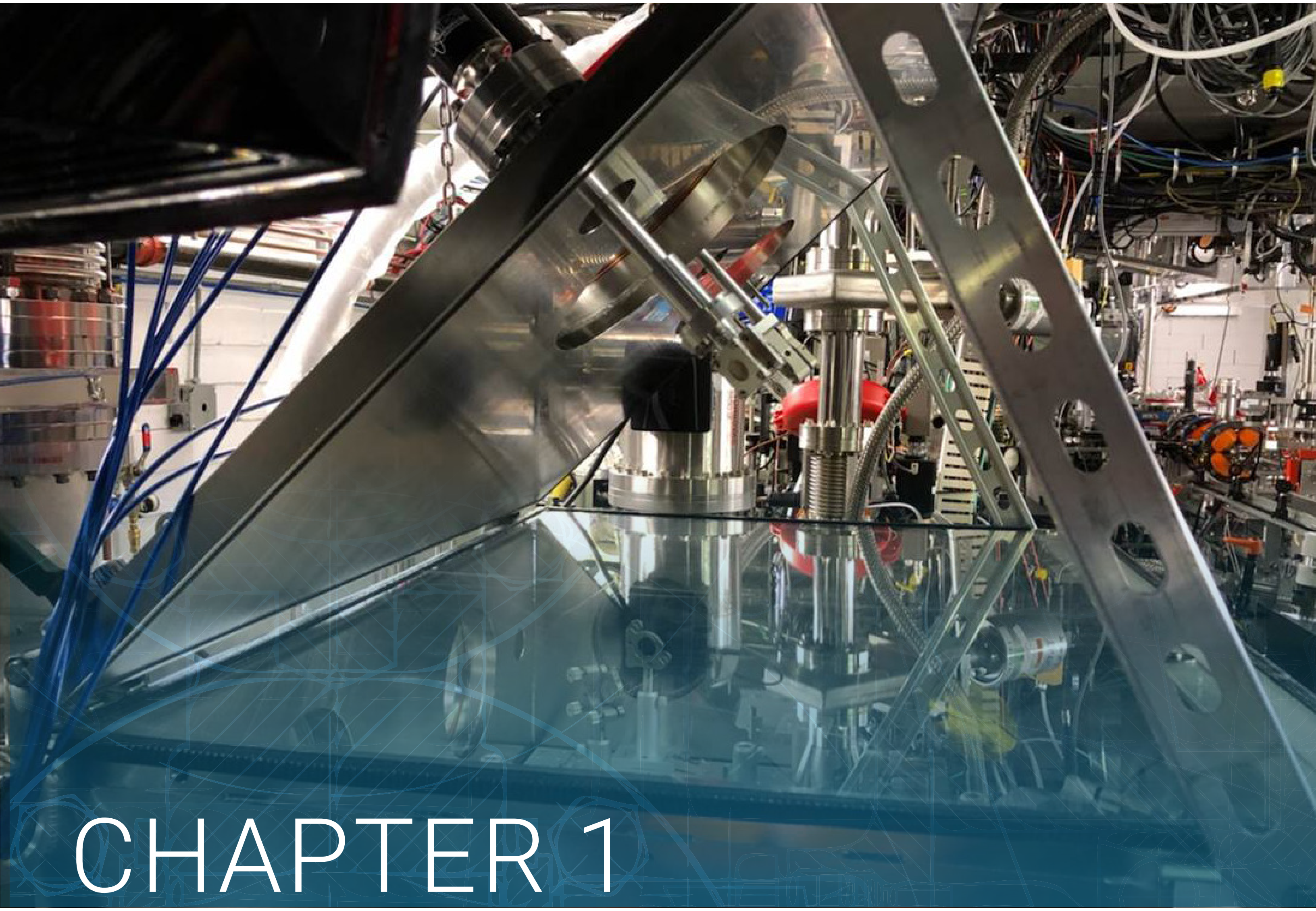
These challenges lead to high-risk procurements on projects, lengthy development cycles, and reinvention, as knowledge is often lost during the long time between major projects. Adding to this risk, many material supply chains originate in or traverse China, Russia, and other high-risk countries.

Several factors may impede domestic vendors from entering markets relevant to key SC technologies. For example, comparatively high U.S. labor costs may affect these vendors' ability to compete, along with a lack of access to proprietary technologies held outside the U.S. In some areas, foreign government research investment or investment in public-private partnerships drives the capture of technologies and ownership of a particular global supply chain for economic or strategic advantage, further hampering domestic entry into a market sector.

The panels not only identified supply chain risks, they also considered ways to mitigate them. A key near-term opportunity is the improvement of communications across the SC enterprise to identify needs and coordinate risk mitigation strategies. At a high level, a strategic research and development (R&D) ecosystem could support a continuum of activity, from basic R&D at the national laboratories to technology deployment into the marketplace. Programs could be tailored to better facilitate early interaction and collaboration with potential vendors who then could address technology and resource needs at scale. For all SC enterprise sectors—from science programs to suppliers and manufacturers—another challenge has been the availability of a skilled scientific and technical workforce that is sufficiently fluent to drive and adapt to evolving technologies. To meet this need, the national laboratories could intensify and broaden opportunities to attract and train people to participate in the development, production, and delivery of materials and technologies at scale.

Roundtable participants identified several additional opportunities that could yield near-, mid-, and long-term benefits. Holding recurring procurement conferences and establishing a database of foreign and domestic vendors—both focused on information exchange—are activities that could be implemented within the next 2 years. In the midterm, lab core capabilities for fabricating and assembling critical scientific equipment could be assessed to inform decisions about which key components, technologies, or expertise should be maintained at the national laboratories. In addition, cross-laboratory supply chain forecasting in the midterm would improve supply chain visibility and identify critical future demand, aiding the timely development of mitigation strategies at DOE, laboratory, and project levels. In the long term, SC supply chains would benefit from efforts to identify critical components for aggressive, well-funded R&D programs at the national laboratories; establish consortia opportunities with major commercial firms; consider cross-laboratory purchasing agreements; and institute a career development program at the national laboratories.

The roundtable's work is a preliminary step in surveying the landscape of supply chain risks facing the SC enterprise, particularly with respect to domestic or strategic supply chains. Going forward, supply chain considerations could be included as a factor in planning for future SC facilities.



CHAPTER 1

INTRODUCTION

Introduction

On January 25, 2021, President Biden issued Executive Order 14005, "Ensuring the Future is Made in All of America by All of America's Workers." This EO reinforced America's commitment to current "Buy American Act" policies, which give preference to the acquisition of goods, products, and materials produced in the U.S. by American workers. Subsequently, on February 24, 2021, the Biden administration issued EO 14017, "America's Supply Chains"—further requesting agencies to review requisite supply chain risks and identify challenges related to obtaining highly sought-after products. With increasing emphasis on domestic supply chains across the U.S. government, the DOE Office of Science's (SC) Office of the Deputy Director for Science Programs, in collaboration with SC programs, chartered the roundtable, "Supply Chain Risk Mitigation for Scientific Facilities and Tools." SC convened the roundtable to gather information about current supply chain risks in key technology areas and to explore opportunities, partnerships, and mechanisms to strengthen the domestic supply chain.

The roundtable included panel discussions and plenary sessions focused on technology areas unique to SC or that play a critical role in its mission. The roundtable charter outlined six questions related to understanding the state of the domestic supply and opportunities for reducing supply chain risk:

1. Which materials, components, or systems present a supply chain risk (sole source or foreign source) for achieving the SC mission?
2. What are the risks (low, medium, high) and impacts (low, medium, high) for each identified vulnerability and the current provider or source?
3. What discrepancies currently exist between DOE user facility needs and existing market capabilities?
4. Where do vendors see specific market failures that prevent a viable business model for supporting DOE needs?
5. Where would federal intervention be a prudent and cost-effective way to address supply chain risks for DOE facilities?
6. What partnering mechanisms would be most effective at supporting a long-term supplier base?

Five panel topics were identified that cover the breadth of the SC program: (1) Accelerator Systems; (2) Detector Systems; (3) Instrument and Target Systems; (4) Specialty Materials, Machining, and Manufacturing; and (5) Crosscutting Issues (see Ch. 2, Panel Perspectives, p. 3). Participants with technical, project management, and procurement backgrounds were chosen as panel leads. Panels were composed of individuals from across the national laboratory complex as well as participants from industry, academia, and other government agencies.

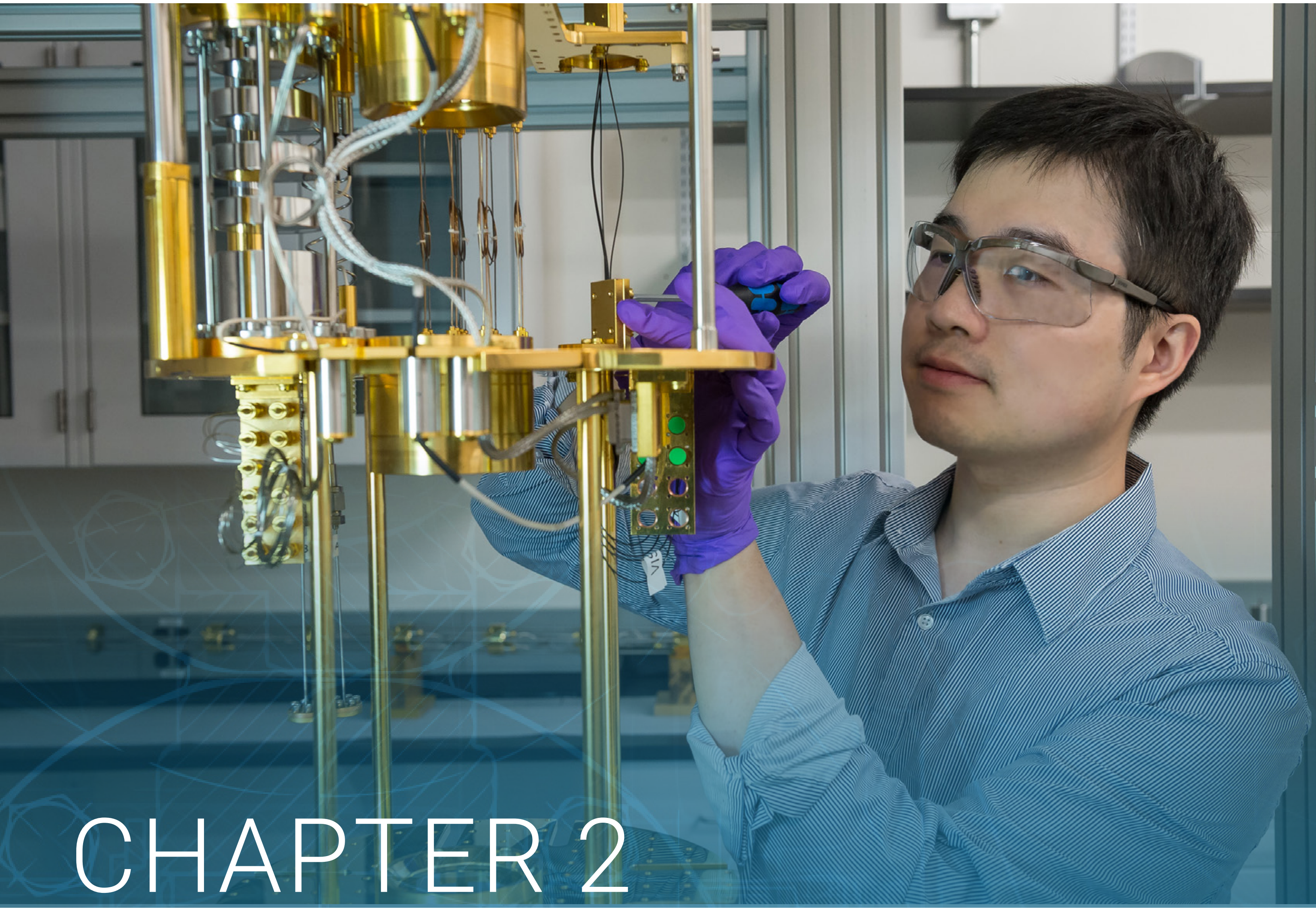
Panels 1, 2, 3, and 4 surveyed existing markets; conducted gap assessments related to domestic and foreign vendors; and identified opportunities for reducing supply chain risks and improving supply chains in the near-, mid-, and long terms. Panel 5 explored crosscutting issues related to the other four panels within the realms of business impediments, "Buy American" policies, and procurement. The panels also conducted an outreach effort that included surveying and collecting supply chain risk data from technical experts, peer groups, and industry. The data was used as source material for panel presentations and this report. Supply chain issues in the areas of materials, components, and systems, along with discussions of representative technologies, are summarized in Ch. 3, Illustrative Technologies, p. 12.

In addition to identifying supply chain challenges, the panels sought strategies and opportunities to mitigate attendant risks. These discussions are summarized in Ch. 4, Reducing Supply Chain Risk, p. 37, and include identification of opportunities in the near- (0 to 2 years), mid- (2 to 5 years), and long terms (5 to 10 years).

Also included throughout this report are several sidebars that provide concrete examples of the supply chain issues explored by the roundtable:

- Size Matters, p. 19
- Source of Last Resort, p. 21
- Sunsetting Technologies, p. 31
- Ecosystem Cultivation, p. 39
- Aligning the Starts, p. 42

The general principles within these examples are broadly applicable to SC supply chain challenges.



CHAPTER 2

PANEL PERSPECTIVES

Panel Perspectives

2.1 Accelerator Systems–Panel 1

Particle accelerators are used in numerous applications advancing scientific and technological innovation, especially in the areas of discovery science, medical therapy, industrial processing, and national security. However, access to specialty materials, components, and skills essential for the development and construction of particle accelerators—collectively described as accelerator systems—is often a bottleneck, limiting opportunities for improvement and growth. Examples include (1) limited U.S. or international vendors and suppliers; (2) difficulty in attracting resources to develop low-volume or high-risk commodities; (3) long lead times, production delays, or quality-control issues due to over-subscribed resources; and (4) the lack of an effective framework and resources to partner DOE national laboratories more effectively with industry and academia.

Supply chain issues and limitation of industrial partners emerge in all areas that are state-of-the art or cutting edge. An underlying issue is that U.S. companies typically can't sustain high-tech developments due to limited applicability to more than one specific project. While accelerator projects typically are large in scale, with total project costs on the order of $500 million to $2 billion, they are often one-of-a-kind instruments optimized to address a particular science case and thus not likely candidates for commercialization.

Nevertheless, there are common themes among accelerator science project needs. One could imagine successful models of large-scale R&D engineering firms with specialized capabilities and a large scientific portfolio, as demonstrated by international suppliers such as RI and Danphysik. The U.S. has not been proactive in engaging companies supporting the accelerator systems market. Stronger involvement by DOE national laboratories and university laboratories might be necessary going forward. The supply chain works well in areas where national and university laboratories carry product-development risks and provide expertise to further develop industrial processes while industry handles more general tasks such as machining, specialty welding, and assemblies.

Panel 1 surveyed accelerator and related projects and accelerator R&D programs at Lawrence Berkeley National Laboratory including the Advanced Light Source (ALS) and ALS-Upgrade, Linac Coherent Light Source-II (LCLS-II) and High Energy Physics program projects; Berkeley Lab Laser Accelerator; magnet development program; superconducting research groups; and accelerator low-level control and instrumentation groups. The panel also reached out to technical representatives who work directly with procurement and suppliers during contract execution.

At Thomas Jefferson National Accelerator Facility (Jefferson Lab), scientific and technical personnel met to discuss supply chain concerns that limit construction or necessary research for developing (polarized) electron injectors. The meeting captured technologies in the areas of vacuum (nonevaporable getter pumps and coatings, all-metal gate valves, ion pumps), high voltage (insulators, cables, power supplies), and high-polarization photocathodes (see Fig. 2.1, p. 5).

2.2 Detector Systems–Panel 2

Transformative scientific discovery is driven by technology innovation. To reveal fundamental physics principles that govern nature, advanced instrumentation is required. Detector systems are the tools that capture information and serve as windows to this underlying science. As such, they are central to all SC experimental science. The assessment of detector systems is structured around three themes: sensors, detector system components, and support capabilities.

Almost all scientific detectors employ sensors to convert signals into electronically recordable information. Because of the specialized nature of SC research, instrument systems may need to operate in unique environments often designed and built by the scientific community. The nuclear and particle physics communities have operated like this for a century, and now the materials science and biological research communities are as well. In particle physics, the cost of a detector system can be high, but it is often a one-of-a-kind instrument, limiting opportunities for direct commercialization. The same increasingly holds true for large user facilities, such as light and neutron sources, where dedicated beamline instruments provide unique capabilities through custom instrumentation. While there have been significant technology spinoffs, SC detector systems inherently constitute a niche application and are not market drivers. In other fields, detectors can be less

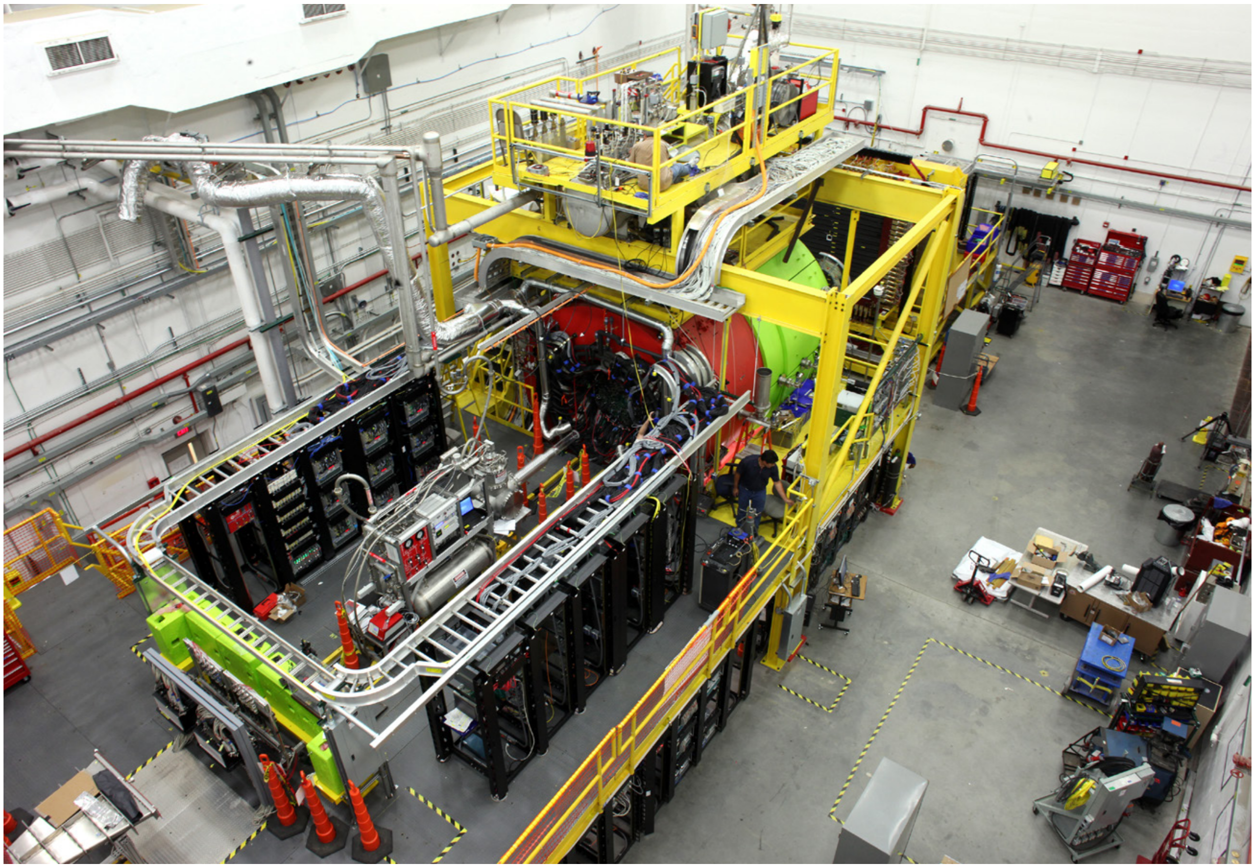


Fig. 2.1. Experimental Hall D at the Continuous Electron Beam Accelerator Facility is dedicated to the operation of a large-acceptance detector for experiments with a broadband, linearly polarized photon beam produced by ~12 GeV electrons. [Courtesy Thomas Jefferson National Accelerator Facility]

expensive and more ubiquitous, thus offering more commercialization opportunities even though initial designs are generally conceived in the academic community (see Fig. 2.2, p. 6).

In addition to the sensor itself, detector systems require other components [e.g., electronics, lasers, optical elements, microwave or radiofrequency (RF) components, and shielding] to process the collected data and store it in a digital format.

To validate the designs and ensure their proper operation, various support capabilities tailored to the detector technology at hand are needed. These might include cryogenic refrigeration or suitable testing facilities such as low-background environments or high-radiation sources.

Data produced by all SC detectors require significant computational resources for data processing and analysis. However, the topic of computation was outside the scope of this supply chain evaluation. In addition, limited access to highly skilled workforce exacerbates supply chain issues, but this was also outside the scope of this study.

SC has many projects under construction that require highly specialized detectors that are currently unavailable but are needed to fully exploit the scientific potential of future facilities spanning the full breadth of SC. The LCLS-II and HE upgrades will provide unprecedented brilliance of X-ray beams, which current detector technologies cannot handle. Upgrades to the ALS and the Advanced Photon Source (APS) are equally demanding. The Spallation Neutron Source (SNS) is constructing the Second Target Station with eight new beamlines requiring dedicated instruments. The Facility for Rare Isotope Beams (FRIB) is being completed, and detector systems

Fig. 2.2. The enormous NOvA far detector in Ash River, Minnesota, sits in the path of Fermi National Accelerator Laboratory's intense neutrino beam and captures particle interactions. Researchers use this data to better understand how the subatomic world works. [Courtesy Fermilab]

to fully exploit the physics potential of this facility are still under construction. Detector technologies for the Electron Ion Collider are quite demanding for this unique facility and still must be further developed and refined to realize its full physics potential. SC's High Energy Physics (HEP) program has launched the Deep Underground Neutrino Experiment and the Stage 4 Cosmic Microwave Background Experiment, both of which employ cryogenic technologies at unprecedented scales. The Material Plasma Exposure eXperiment is a next-generation linear plasma device to study how plasmas interact long term with the components of future fusion reactors. Ultra-trace analytical measurements are required for conducting special classes of science experiments and for supporting national and international nuclear safeguards, security, nonproliferation, verification, and forensics missions. In addition, SC runs five Nanoscale Science Research Centers (NSRCs), each requiring cutting-edge technology developments. All of these unique facilities have dedicated instruments that need to break technological barriers to fully realize their scientific potential, illustrating the huge scope of need for highly specialized detector systems (see Fig. 2.3, p. 7).

To assess the need, detector experts supported by SC's Biological and Environmental Research, Basic Energy Sciences, Fusion Energy Sciences, High Energy Physics, and Nuclear Physics programs were polled for input on a wide range of detector technologies. A key issue in assessing the supply chain for detector systems is the limited number of vendors. Either there are no U.S. vendors able to meet the demanding scientific specifications, or there are only a few vendors worldwide. The main barriers identified for industrial development of detector systems are long lead times for technology development, high start-up costs, a limited market with no steady stream of procurements, and high nonrecurring engineering costs for small volumes.

Fig. 2.3. At the National Synchrotron Light Source II, scientists use a technique called inelastic X-ray scattering to study the inner dynamics of materials and condensed matter. To achieve its extremely high energy resolution, the Soft Inelastic X-ray Scattering (SIX) beamline's detector is positioned at the end of a long arm, which allows scientists to study samples from multiple angles. [Courtesy Brookhaven National Laboratory]

2.3 Instrument and Target Systems—Panel 3

New research instrumentation catalyzes discovery and knowledge growth and thus is crucial for advancing science. Procurement and supply chain difficulties hamper the development of new scientific tools and the operation of existing facilities and consequently impede scientific discovery. Among the many scientific instruments important to SC, Panel 3 focused on Instruments and Target Systems including (but not limited to):

- High-end analytical equipment, (e.g., electron microscopes at DOE NSRCs)
- Laboratory-based X-ray sources, X-ray microscopes, and X-ray spectrometers
- Cryogenic systems that provide, for example, ultralow temperatures for quantum computing applications
- X-ray and neutron optics as well as other specialty components used to guide photons and neutrons through beamlines to endstations at DOE synchrotron sources (ALS, APS, National Synchrotron Light Source-II, LCLS, Stanford Synchrotron Radiation Lightsource) and neutron sources (SNS, High Flux Isotope Reactor)
- Technology for ultrahigh-power lasers (e.g., those operated and maintained by facilities that are part of LaserNetUS)
- Target technology used at HEP target facilities, spallation neutron sources, and radioactive ion beam facilities
- Robotics and components for remote sample handling

Scientific instruments are typically integrated with computers to improve and simplify control and to streamline data collection, processing, and analysis. The panel's assessment therefore includes the needs and supply chain issues associated with scientific software and software frameworks.

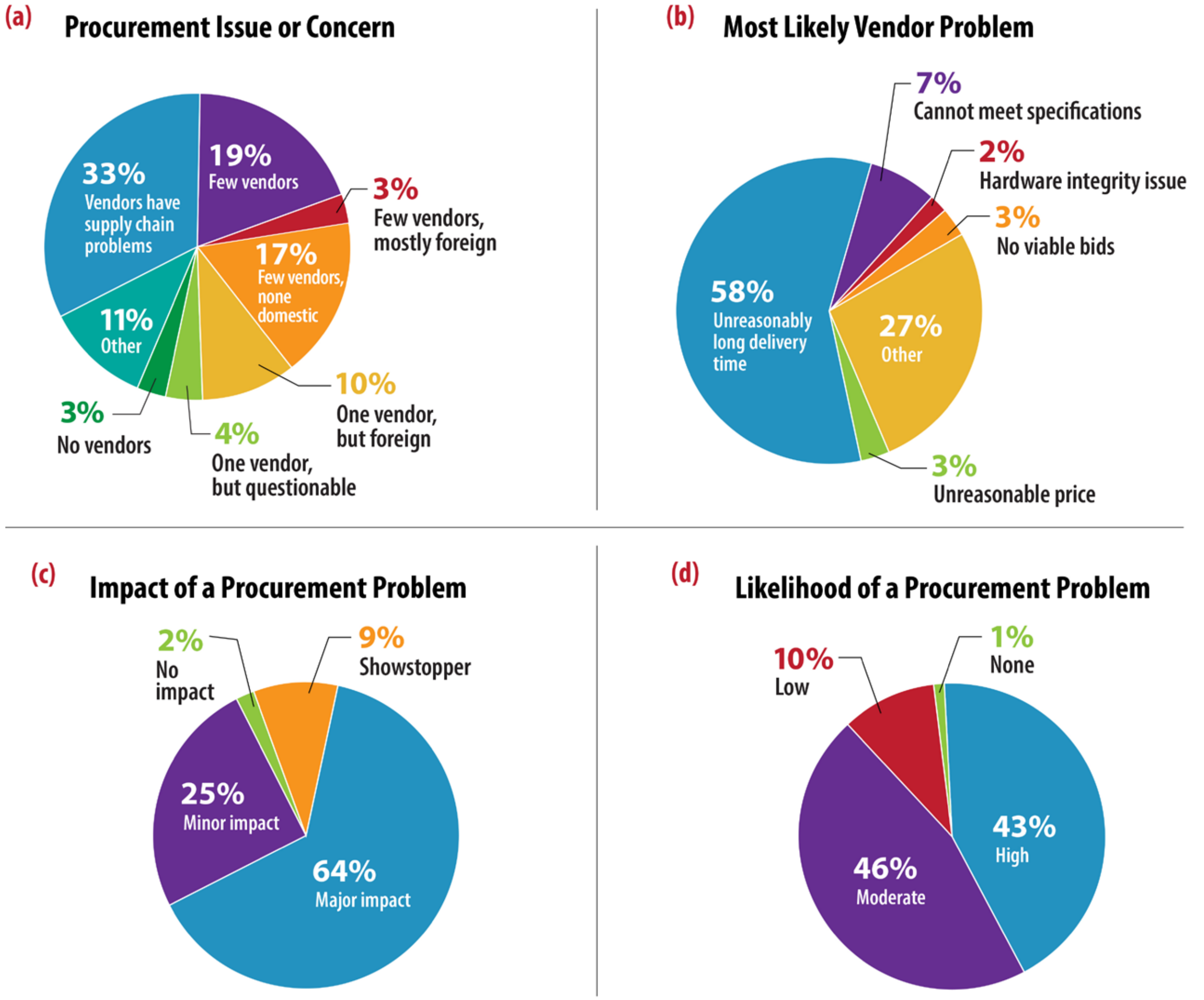


Fig. 2.4. Summary of the approximately 180 components identified as experiencing procurement challenges. Graphics show **(a)** the procurement issue or concern, **(b)** most likely vendor problem, and **(c, d)** impact and likelihood of the procurement problem.

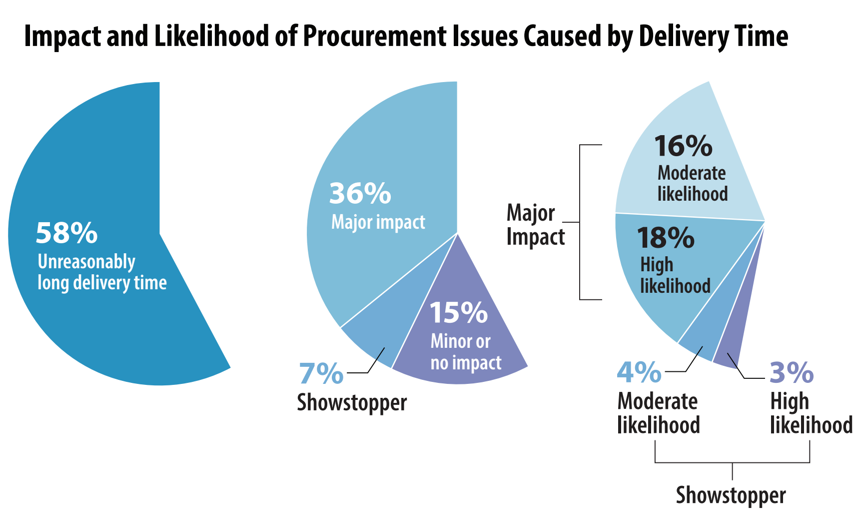


Fig. 2.5. Overview of the impact and likelihood of procurement issues caused by unreasonably long delivery times.

Panel members reached out to more than 70 experts in the research community with the request to provide feedback on procurements. Of interest were procurements that occurred within the last 2 years or were currently underway and for which some degree of procurement difficulty occurred even if the item was ultimately successfully received and deployed.

A brief summary of the survey results (see Figs. 2.4 and 2.5, p. 8) suggests that the scientific community participating in this outreach is experiencing supply chain problems and that they expect these challenges to impede the progress of scientific research.

2.4 Specialty Materials, Machining, and Manufacturing—Panel 4

Panel 4 examined the following critical materials and components as part of roundtable efforts to gather information about current supply chain risks, opportunities, possible partnerships, and mechanisms to strengthen the domestic supply chain with regard to the SC mission:

- Highly radiation-tolerant materials
- Magnet materials
- Niobium
- Rare earth materials
- Optics
- High-performance computing (HPC)
- High-temperature superconductor (HTS) materials
- High-purity diamonds
- Other specialty materials and manufacturing

Experts with experience in these materials, their fabrication, and in supply chains for specific material spaces were selected from across the national laboratories, universities, and industry. The experts utilized their knowledge and networks to gather information on supply chain challenges and opportunities. Community outreach requests were sent to 170 individuals, resulting in approximately 15 group responses representing the input of nearly 50 people. Information from across the various areas was then reviewed by the panel and discussed in a series of sessions to identify crosscutting trends and opportunities across the materials and manufacturing spaces.

In surveying the current state of the domestic supply chain for specialty materials, manufacturing, and machining, high-risk and high-impact items were identified in each of the materials and fabrication categories. For highly radiation-tolerant materials, there are several significant challenges including the capacity of the domestic supply chain to develop and supply these materials and a lack of U.S. facilities to carry out time-efficient methods for long-term neutron exposure to aid in material selection for SC programs. Magnet materials have similar issues: lack of domestic supply chains, long lead times, and the need for significant R&D to develop items such as high-current leads and high-current power supplies for specialized magnet designs used in experimental programs. These challenges are also applicable to other programs across DOE and other federal agencies.

Many materials supply chains come completely from foreign nations, including some countries with strained U.S. relationships. For example, most of the world's niobium comes from one mine in Brazil owned by CBMM and partially by the Chinese government. High-purity niobium is produced by only a few vendors worldwide (two in the U.S. and two significant ones in China). Rare earth materials face similar challenges to niobium, with no domestic suppliers. All pure rare earth elements are sourced from China and Russia. High-purity diamonds have comparable supply chain issues with the additional problem of an extremely small market with few suppliers. The two best suppliers are in Russia, with one developing in Japan. High-temperature superconducting materials are emerging as a critical component for the compact fusion community, and compact fusion companies are buying up the world's supply of HTS materials to make their demonstration prototypes. There is an extremely limited supply of HTS materials in the U.S. with only one U.S. manufacturer of yttrium barium copper oxide tapes, which is owned by a Japanese company, and one U.S. manufacturer of bismuth strontium calcium copper oxide tapes. A major scale-up of the HTS industry will be required if compact fusion technology is successful. Similar problems exist for other specialty materials.

For optics, the market is very large, and DOE's needs are a very small subset. Like many technology components, the market is rapidly moving to China. Many companies are experiencing rising labor costs and a lack of trained personnel, which drive costs up, create manufacturing issues, and impact component availability.

High-performance computing is being significantly impacted by vendor delays, resulting in extremely long delivery times. HPC is challenged by the offshoring of microelectronics manufacturing, which creates the risk of increasing costs and introducing manufacturing issues.

Installation of current systems is greatly affected by parts availability.

Several highly specialized materials components do not have a large enough market to be sustained over large SC projects, and they require significant R&D (i.e., diamonds, magnet components, beryllium beam pipes, and superconductors). This leads to high-risk procurements, long development cycles, and repeated relearning of core technical knowledge due to long time intervals between major projects. Many material supply chains depend on China, Russia, and other high-risk countries.

2.5 Crosscutting Issues—Panel 5

The Crosscutting Issues panel was tasked with identifying risks and opportunities spanning multiple technological areas in the domestic supply chain serving SC missions.

The panel was composed of members with diverse backgrounds and expertise from multiple organizations within the DOE complex, universities, and industry. Each member participated in one of the four technology panels where they contributed to the development of risks and opportunities and identified supply chain issues impacting multiple technology areas. They then reported to Panel 5 what they had learned for further discussion and development.

Several crosscutting themes emerged during discussions and in the survey responses. These themes represent risks or impediments in leveraging the domestic supply chain in support of the DOE SC mission. These crosscutting issues have been organized into the following categories:

- Domestic supply chain constraints
- DOE project funding and acquisition constraints
- DOE national laboratory collaboration and coordination

2.5.1 Domestic Supply Chain Constraints

One risk area that impacts multiple technical areas is when no domestic supplier exists to meet DOE demand. For example, many of the raw materials required for fabrication of scientific equipment are mined predominately or exclusively outside the U.S., including stainless steel (316/316LN), niobium, high-purity diamonds, and rare earth materials. Several risks were identified for items that can be sourced only from a foreign supplier; these risks include higher costs due to customs, duties, tariffs, and currency exchange rate fluctuation. Furthermore, there are concerns about initiating subcontracts with foreign vendors located in countries which the U.S. government has designated as "potentially high-risk," such as China and Russia.

For specialized materials, there is insufficient U.S. market demand to support private-firm investment in the required infrastructure to enter the market. In addition, there is insufficient follow-on work for vendors to rely on to help defray the infrastructure cost if a first job is won. Another risk related to the sporadic nature of procurements is that vendors can experience a loss of core technical knowledge due to turnover of experienced personnel, making it difficult to maintain a competitive position in the market.

Other impediments to domestic vendors entering the manufacturing segment in these areas include an inability to be competitive in the market due to comparatively high U.S. labor costs, lack of access to proprietary technologies held outside the U.S., and a lack of effective partnerships such as the European Consortia model. Many of the critical components procured for DOE projects are initiated via "Best-Value Tradeoff" solicitations. Best Value Tradeoff source selection is a strategy that provides for the evaluation of both technical factors and costs to determine which proposal offers the overall best combination of both. In these solicitations, awards to higher-cost proposals may be made if the respective technical superiority of those proposals are such that the additional cost is justified. The superior technical capability of foreign suppliers is often due to foreign governmental subsidies provided to foreign vendors. Foreign vendors are also often recipients of foreign government infrastructure investments, which enable development of proprietary technologies. These proprietary technologies can later result in market entry barriers for U.S. firms. Such government investments allow foreign vendors to submit pricing that undercuts U.S. competition. As a result, foreign vendors are often selected as the "best value" due to both higher technical capability and more competitive pricing, even after the applicable Buy American factors are applied. Thus, even in the cases where domestic suppliers exist, they are often not awarded U.S. contracts or subcontracts. Furthermore, due to foreign government restrictions, U.S. vendors are frequently prevented from participating in scientific projects abroad, further limiting their ability to gain technical expertise and market capitalization.

2.5.2 DOE Project Funding and Acquisition Constraints

A significant portion of engagement with vendors is conducted through the DOE national laboratories. Practices at the national laboratories and DOE policies and procedures to which the labs must adhere, may contribute to missed opportunities for domestic procurement. Examples include:

- Incomplete inventories within each laboratory and an inability to share inventory information across laboratories limit opportunities for joint purchases.
- Lack of warehousing capabilities and rigid funding rules limit ability to purchase larger orders (safety stock).
- No experience or limited ability for national laboratories to absorb risks disincentivizes or prevents potential suppliers from participating in solicitations or causes vendors to inflate proposal prices to mitigate against potential risks and profit losses.
- Just-in-time delivery and individual project funding cycles prevent the ability to take advantage of multiproject or even cross-laboratory bulk purchases. Each DOE project has separate critical decision timelines and thus is not authorized to execute procurements outside that cycle.

2.5.3 DOE Laboratory Collaboration and Coordination

There are barriers to collaboration and coordination among DOE national laboratories, which are Federally Funded Research and Development Centers operated by organizations under sponsoring agreements known as management and operating contracts. The nature of national laboratory engagement with industry can serve to exacerbate some of the risks and issues noted in this section. These include:

- Lack of coordination or sharing among lab procurement departments regarding supply chain issues, strategies, and lessons learned.
- No efficient way for laboratories to share information about qualified vendors, which is especially unfortunate when one lab invests effort to develop a vendor.
- Insufficient forward planning limits industry’s ability to plan for sales in the future.
- Limited ability or experience of national laboratories to act as a final assembly, integrator, or general contractor—assuming risks unknown to individual vendors (for which vendors submit a “no bid” or respond with noncompetitive bids).

CHAPTER 3

ILLUSTRATIVE TECHNOLOGIES

Illustrative Technologies

Technologies and assessments described in this chapter are based on extensive outreach of the panels to their communities. While these technologies may not fully represent the entire scope of potential SC supply chain issues, they illustrate the types of technologies needed and the landscape of supply sources—both domestic and foreign.

3.1 Materials and Processing

This section outlines materials and processing issues noted by the roundtable as being both important to the accomplishment of SC missions and potentially difficult to obtain due to a variety of supply chain challenges.

3.1.1 Niobium

Across the panels, niobium (Nb) was a significant topic of discussion and concern. It is utilized in superconducting technologies, including RF accelerating structures, superconducting wire in magnets, and in detectors. The challenges with Nb typify some supply chain issues common across SC applications.

- Nb is not particularly scarce. Globally, production levels approach 100,000 tons per year.
- Roughly 90% of global production is utilized for manufacture of high-grade structural steel and superalloys.
- To be used for superconductors, Nb must be especially high purity, which requires special processing.
- The low residual resistivity ratio sheet is used for fabrication of superconducting cavities. It has particularly stringent purity requirements.
- Much of the production of superconducting wire is focused on commercial magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) magnets and thus does not satisfy the full range of SC needs.

Taken together, these factors illustrate the issues of (1) very small volume requirements (as a fraction of the world supply) and (2) the specialized processing requirements for other materials and technologies explored by the panels. Nb-based technologies are vital to the SC mission but are a very small potential market share on a global scale. They are either produced by boutique operations or through some form of government support. High-purity Nb suitable for the needs of SC missions is not produced domestically.

Superconductors

Many superconducting particle accelerators are based on the low-temperature superconductors niobium-titanium (Nb-Ti) and niobium-tin (Nb_3Sn). Government-funded projects represent most of the market for accelerator-grade strands. Because these strands are different from the conductors used for commercial MRI and NMR magnets, suppliers for the MRI market may not be able, or find it cost effective, to supply strands for particle accelerators or similar big science projects. (see Fig. 3.1, p. 14).

Superconductor manufacturers for commercial markets find it difficult to justify the recurring expense of maintaining R&D activities and manufacturing capabilities (e.g., factory footprints and supply chains) for accelerator products that may be sold only infrequently or at relatively low volume.

The market for superconductors for accelerators goes through boom-and-bust cycles as major government projects begin and end. In recent decades, there have been industry consolidations shortly after procurements finish for major government projects. Two examples from past decades are the Large Hadron Collider and ITER. The evolution of the sources of supply as well as the growing dominance of Nb-Ti conductor in commercial applications has undercut the profitability of producing Nb_3Sn conductor, posing a major challenge to maintaining a viable accelerator technology business in low-temperature superconductors.

Round-Wire Superconductors

Superconducting round wires used in most scientific facilities include long-mature products based on Nb-Ti alloy, mature and innovative forms of conductors based on Nb_3Sn, and emerging products based on bismuth strontium calcium copper oxide (Bi-2212) and magnesium diboride (MgB_2). These are round, multifilamentary composite conductors typically twisted and cabled and thus distinct from 2G high-temperature superconductor tape conductors. Twisting and cabling facilitates reduction of losses during magnet charging or discharging,

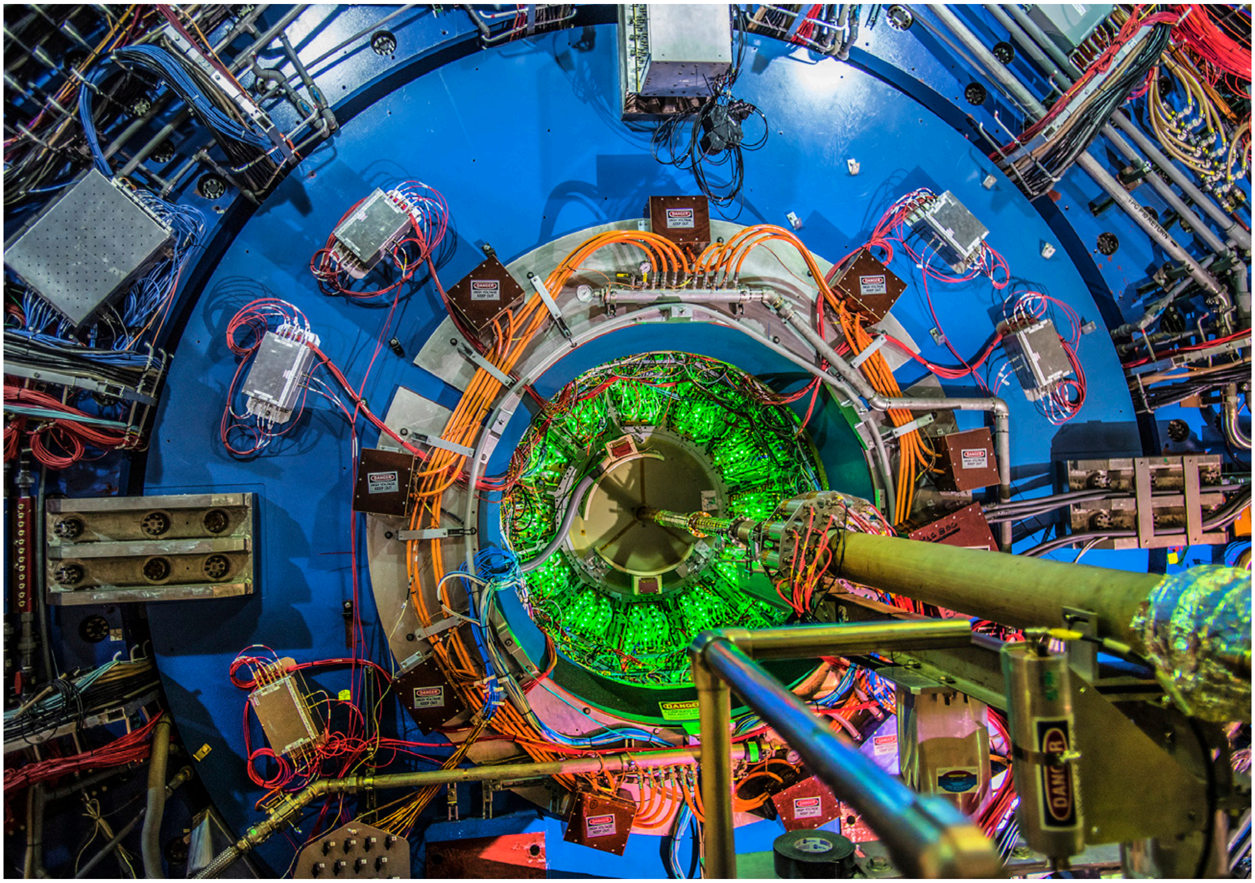


Fig. 3.1. The Solenoidal Tracker (STAR) is a detector that specializes in tracking the thousands of particles produced by each ion collision at the Relativistic Heavy Ion Collider (RHIC). Weighing 1,200 tons and as large as a house, STAR is a massive detector. It is used to search for signatures of the form of matter that RHIC was designed to create and study: quark-gluon plasma. STAR is also used to investigate the behavior of matter at high densities by making measurements over a wide range of beam energies. [Courtesy Brookhaven National Laboratory]

and cables provide options for reducing inductance. Filaments reduce field errors and magnetization.

Magnet conductors traverse three generations of product maturity:

- Commodity-rate Nb-Ti manufacturing is driven by the medical imaging magnet industry at a production equivalent to the amount of strand needed for a significant science facility each year (200 to 1,000 tons).
- Premium Nb_3Sn manufacturing at 10 to 50 tons annually is driven by cutting-edge magnet markets (e.g., NMR systems for chemistry) and frontier scientific facilities (e.g., ITER and the upgraded Large Hadron Collider). Regulatory and other market factors have not driven Nb_3Sn manufacturing for medical imaging at any significant scale; a change in regulatory policy could disrupt the present manufacturing status.
- Specialty manufacturing is at <1 ton for emerging Bi-2212 and MgB_2. Future NMR systems, particle accelerators in the 2030 to 2050 era, and other very high field magnets (>20 T and likely 30 to 50 T) are enabled by Bi-2212 and rare earth barium copper oxide (REBCO). MgB_2 and Bi-2212 provide access to niche applications at 20 K.

Nb_3Sn is presently the conductor receiving the most attention, with Nb-Ti being a commodity product. Bruker OST is completing delivery of 30 tons of conductor for the High-Luminosity Large Hadron Collider Upgrade Project. Research programs to develop accelerator magnets with 12 to 15 ton fields are underway, and they require significant amounts of conductor. A future particle accelerator of 100 TeV scale could require 9,000 tons of Nb_3Sn conductor. A power plant demonstration scale of the ITER tokamak could also require several thousand tons of conductor. Other envisioned science facilities could drive demand for magnets and hundreds of tons of conductor.

Magnet conductors in this category all rely on manufacturing processes generally like those used for other types of conductors but are necessarily highly specialized for superconducting materials. Similarly, cabling relies upon technology from electricity products but can be highly specialized for certain magnet applications (e.g., Rutherford cables for accelerator magnets).

Magnet conductors and magnet windings incorporate several ancillary material supply chain needs:

- The superconducting material itself:
  - Nb-Ti alloy and Nb-wrought products from Nb ingot manufacturing
  - Nb sheet for wrapping Nb-Ti rods and filaments
  - Specialty high-purity copper and tin
  - Other raw materials as well-controlled powders
- Insulation (e-glass, s-glass from fiber-optic industry, Formvar film insulation)
- Epoxies and composites
- Ceramics
- Structural material (mostly advanced stainless steels and titanium alloy)
- Reaction furnaces with clean environments. Nb_3Sn, Bi-2212, and MgB_2 conductors are often wound into the coil shape and then reacted in a furnace to optimize superconducting properties. Boiloff from liquid argon and high-vacuum environments is typical.

Domestic manufacturers of Nb-Ti and Nb_3Sn conductors include:

- Bruker OST (New Jersey), a subsidiary of Bruker EAS (Massachusetts). Bruker OST is the only vendor currently qualified to deliver product for advanced particle accelerators.
- Luvata (Connecticut), a subsidiary of Mitsubishi Materials
- Three companies at the small-business scale

Worldwide manufacturers with significant capacity include:

- JASTEC (Japan)
- Hitachi, Ltd. (Japan)
- Furukawa Electric Co. Ltd. (Japan)
- Western Superconducting Technologies (China)
- Bruker EAS (Germany)
- Luvata (Finland)
- TVEL Fuel Company (Russia)

Manufacturing of Nb_3Sn conductors is threatened by loss of profit margins from Nb-Ti manufacturing and inconsistent demand. For many manufacturers, Nb_3Sn wire is a shoulder project that is difficult or impossible to sustain as a single product. Market forces associated with the manufacturing of conductors for medical magnets have forced consolidation since about 2005.

Emergence of Bi-2212 and MgB_2 conductors also requires valley-of-death transitions from research scale to industrial production.

Conductor development occurs over 30-year cycles, with about a decade of innovation and manufacturing advances, followed by a decade of adoption, and an additional one to two decades of maturity, saturation, and consolidation. Nb-Ti conductors rose in the 1980s and led to large science projects and the growth of the medical imaging industry in the 1990s and early 2000s, with saturation and consolidation after that time. Nb_3Sn was advanced by significant public-private cooperative investments between about 1995 and 2010, with emergence into advanced science facilities described above and NMR magnets thereafter. Forms of Bi-2212 suitable for very high field magnets began emerging around 2009, and initial magnets emerged in 2020.

3.1.2 High-Temperature Superconductor Materials

High-temperature superconducting (HTS) tape (REBCO) is used in electricity applications and some magnet applications, particularly fusion and applications at or above 20 K. REBCO tape applications also apply to very high field magnets (>20 T and some >30 T) operated at 4 K for scientific facilities.

Despite a few companies attempting to secure funding and develop HTS materials in the U.S. during the past 5 years, there is currently limited domestic capability to provide HTS tape. The single domestic source producing tape is SuperPower in New York, but it is owned by a Japanese conglomerate (Furukawa) and does not have capacity to deliver quantities sufficient to construct large-scale facilities. There is also no domestic capability to perform tests on these materials under high magnetic fields outside of select universities, the National High Magnetic Field Laboratory, and Commonwealth Fusion Systems. Previous high-field testing had to be done in New Zealand (Rogers Research Institute).

Known and qualified suppliers:

- SuperPower / Furukawa (U.S. subsidiary of Furukawa Electric Co. LTD., Japan)
- S-Innovations (Russia) / SuperOx Japan (Japan)
- SuNAM (Korea)
- Shanghai Creative Superconducting Technologies (China)

Emerging suppliers:

- Fujikura Ltd. (Japan)
- THEVA (Germany)
- AMPeers (Texas, research scale)
- American Superconductor (U.S., positioned as an electricity system supplier and not a supplier of 2G HTS conductor)

HTS will be a key enabler of all markets where magnets are a core technology including medical equipment, transportation, wind turbines, fusion, and electric aircraft. Potential tipping points exist where system economics drive power-density requirements above that achievable by permanent magnets and magnetized iron. When HTS magnets for fusion or other industries are regularly produced, a steady and profitable market could be facilitated, as was seen during the emergence of the medical imaging magnet industry when the first particle accelerators were built.

3.1.3 Rare Earth Elements

Permanent magnets and specialty alloys suitable for high-performance, customized, and permanent magnet components for accelerators are critical resources for ion sources, clearing magnets, and undulators. Limited capabilities in these areas also limit industrially available high-performance specialty permanent magnet structures (e.g., undulators, insertion devices, and permanent accelerator components).

The supply chain for rare earth elements has been a topic of U.S. national and economic security for more than a decade. China has achieved supply domination over the past 25 years. This has become a greater concern as technology growth continues to rely on rare earth elements for functionality. These elements are vital for a wide range of components across broad market segments including batteries, catalysts, lasers, detectors, magnets, motors, and optical devices.

The rare earth market is primarily driven by the permanent magnet market, which globally is expected to grow from $34.4 billion in 2021 to $54.1 billion by 2026. This increase in demand will result in greater quantities of all rare earth elements; however, none of these other elements have sufficiently large markets to allow for a stable rare earth supply chain. It is estimated that magnetic rare earths (neodymium, praseodymium, dysprosium, and terbium) will represent 90% of the total economic value for the rare earth market. This estimate presents a unique vulnerability for scientific applications that rely on other rare earth elements, as they will not necessarily be profit centers for building robust and resilient supply chains.

For scientific purposes, many applications depend on sourcing high-purity oxides and other salts, metals, and alloys. Purity requirements for oxides and salts are usually specified with respect to the other rare earth elements; whereas with metals and alloys, interstitial impurities such as oxygen, carbon, and nitrogen are more troublesome.

There are limited specialty alloy manufacturing and limited high-performance magnet companies in the U.S. market. Typical suppliers are Hitachi Metals Neomaterial, Ltd. (formerly NEOMAX; Japan), Shin-Etsu (Japan), Neorem Magnets (Finland), and Vacuumschmelze (Germany). For most customized permanent magnet structures (built to specifications), non-U.S. companies are leading the market [e.g., Hitachi Metals Neomaterial, Ltd. (Japan), Kyma (Italy), Danfysik (Denmark), Bilfinger Noell GmbH (Germany)]. While foreign suppliers for these materials are readily available (with substantial lead times) under normal market conditions, any disruption in supply chain through external events such as the COVID pandemic can delay U.S. accelerator projects.

Significant DOE activities addressing the rare earth element supply chain are primarily focused on the permanent magnet supply chain for clean energy technologies. In 2013, the DOE Office of Energy Efficiency and Renewable Energy (EERE), through its Advanced Manufacturing Office (AMO), established the Critical Materials Institute (CMI) to develop innovative solutions along the supply chain for permanent magnets. CMI conducts early-stage research focused on improved beneficiation, enhanced separations, new applications for overmined rare earths, metal productions, and permanent magnet fabrication.

CMI applies the three DOE strategic approaches of diversify supplies, develop substitutes, and reuse and recycle to mitigate the risks of supply chain disruptions. CMI, as a public-private partnership, has established an innovation ecosystem around rare earth mining and processing that can be leveraged to establish domestic supply chains for specialized scientific components and applications.

In 2015, the DOE Office of Fossil Energy and Carbon Management (FECM) supported programs to evaluate the technical feasibility of recovering rare earth elements from coal and coal byproducts. These programs are directed at establishing demonstration- and pilot-scale facilities.

During this same period, Advanced Research Projects Agency–Energy (ARPA-E) established programs to look specifically at downstream activities focused on magnet discovery and magnet processing. In the past 18 to 24 months, DOE and the U.S. Department of Defense have ramped up additional activities to address scientific challenges, from fundamental research on separation science of rare earths supported by SC Basic Energy Sciences to mid-technology readiness level activities supported by EERE AMO and FECM.

3.1.4 Highly Radiation-Tolerant Materials: XM-19 (Nitronic 50) / Fusion Structural Steels

XM-19 is a highly alloyed austenitic stainless steel, which is also known by the trade names Nitronic 50 and Fermonic 50 (from AK Steel Holding Corp. and Langley Alloys, respectively). These materials typically are in the range of chromium content (20.50 to 23.50%), increased molybdenum content (1.5 to 3.0%) and raised levels of nitrogen (0.20 to 0.40%). They exhibit very good corrosion resistance and are used in applications where 316 stainless is regarded as having marginal performance. They also have nearly twice the yield strength of 304 and 316 stainless steels.

There are existing markets for these materials in heat exchangers, pumps, nuclear fission fuel containers, and other similar equipment. Materials of this sort possibly could be used as the main structural material for HTS magnets. In some applications, such as fusion devices, specific alloys may need to be developed and produced. There are two primary U.S.-based suppliers for XM-19: ATI and G.O. Carlson. The leading supplier of this material is ArcelorMittal in the United Kingdom.

Currently, structural components are machined from plate stock or forgings, which results in high-cost machined components with long lead times. Innovations in additive manufacturing or machining will be required to improve efficiency, increase material yields, reduce cost, and shorten lead times. No existing capability exists globally for effective additive manufacturing using XM-19 material.

3.1.5 Highly Radiation-Tolerant Materials: Accelerator Targetry and Particle Beam Intercepting Materials

Accelerator targetry (e.g., targets, windows, and dumps) is a niche application and cannot drive the market for needed specialty materials. Currently, the selection of available materials is typically based upon physics performance and limited data from nuclear materials experience (when available). There has been some modest R&D success to identify microstructures and alternative alloys to improve radiation damage and physics performance for future facilities, but this R&D will not pay off unless developed materials are shown to benefit the larger market.

Identified vulnerabilities in the current supply chain for these specialty materials include (1) single or few suppliers or vendors, (2) no domestic sources for certain materials, and (3) consistency of microstructures and composition of available materials for some radiation-tolerant materials applications that are inadequate.

Currently used materials include:

- **Fine-grain graphite.** No domestic vendors, inadequate consistency of microstructure
- **Beryllium (AlBeMet).** One supplier (domestic: Materion), machining vendors scarce (although better in U.S.), dual-use export control
- **Titanium alloys.** No significant domestic vendor, inadequate consistency of microstructure between heats
- **Austenitic stainless steels.** Especially seamless, stainless steel tubes, and low-cobalt
- **Tungsten.** No significant domestic vendor
- **Inconel.** General pandemic-related supply chain delays
- **5,000 to 6,000 aluminum alloys.** General pandemic-related supply chain delays

Future potential accelerator targetry materials:

- **Radiation and thermal shock–tolerant materials.** Ongoing research is developing more radiation and thermal shock–tolerant materials
- **Custom graphite**. "Doping" with higher density materials
- **Nano-crystalline titanium alloys.** Only developmental quantities
- **High-entropy alloys**. Only developmental quantities, 3D printing technology is currently the vendor-preferred production method
- **Glassy carbon.** No significant domestic vendor
- Many other examples in nuclear materials and high-power targetry communities

Development and testing of new materials for high-radiation environments will require testing facilities for high-dose, high-volume, and accelerated radiation damage. These could serve the accelerator targetry, fusion, and fission communities.

3.1.6 Specialty Semiconductor Processing

From an SC point of view, electronics for detector systems are mostly designed by the research community. Very often, this activity entails the use of application-specific integrated circuits (ASICs) designed by the research community and fabricated in a commercial foundry. The global supply chain challenges associated with reduced foundry capability due to COVID-19 are well known and impact the SC mission. While there are some domestic integrated circuit foundries, the majority—including the most advanced—are outside the U.S. The same processing techniques used to make integrated circuits are also used for several kinds of semiconductor sensors [e.g., diode arrays for particle tracking, charge-coupled devices, and complementary metal oxide semiconductor (CMOS) sensors for imaging]. In addition to the foundry pressures described in this report, these sorts of specialty processes are often low volume, and almost none are carried out in the U.S., including none in the U.S. for the advanced nodes (see sidebar, Size Matters, p. 19).

Other very specialized needs in semiconductor materials also serve the SC mission. High-polarization gallium arsenide (GaAs) photocathodes were pioneered in the U.S., Japan, and Russia. But, it wasn't until researchers at SLAC National Accelerator Laboratory (SLAC) teamed with commercial vendors via the Small Business Innovation Research / Small Business Technology Transfer (SBIR/STTR) program that reliable sources of high-polarization photocathode materials became commercially available in the early 2000s. SLAC first teamed with SPIRE Semiconductor (formerly Bandwidth Semiconductor) and then with SVT Associates to develop the strained-superlattice photocathode, which now represents the benchmark for success. However, without sufficient demand, SVT Associates stopped selling these photocathodes, and they have been commercially unavailable since the mid-2000s. The lack of an industrial application makes it difficult to attract industry to this market, which has not been profitable. Operating and maintaining a dedicated thin film–growth facility capable of growing superlattice photocathodes based on GaAs/gallium arsenide phosphide have large costs in terms of initial investment, personnel training, and maintenance—likely requiring annual revenue of $1 to $2 million. While initially the SBIR/STTR program helped commercialize the technology, it had an unintended consequence. Successful vendors leave due to low market demand, and new vendors cannot be funded to reproduce the same successful product.

3.1.7 Specialty Components for Neutron Facilities and High-Power Targetry Systems

Science performed at neutron facilities, HEP target facilities, and radioactive ion beam facilities relies on highly specified and technical instruments and solutions. These resources often require materials, expertise, or capabilities beyond those readily available commercially.

Many of these items are one-of-a-kind or variations of a technology that has been customized for a particular application. As such, facilities depend on a small subset of specialized companies. In some cases, few or no domestic suppliers exist, which puts pressure on pricing and lead times of critical components and services. In general, these cases can be divided into four categories: specialty materials, specialty manufacturing processes, specialty expertise, and precision or complex manufacturing. For each category, supply chain risks for DOE SC facilities have been identified and are described below.

Specialty Materials

Materials that illustrate the challenges in sourcing materials for these applications include:

- **Cadmium.** This element has useful properties as a neutron absorber. While cadmium itself is not particularly rare or difficult to obtain, its classification as one of the eight Recovery and Conservation

Size Matters

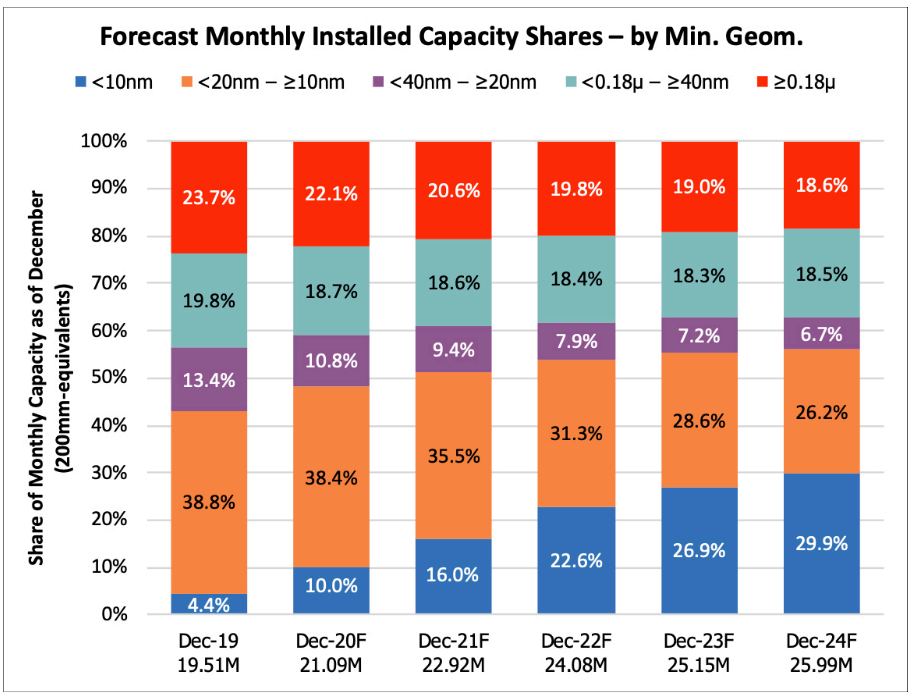
Chip Size and Technology Maturity Influence Production and Availability for Science Applications

Global supply chain disruptions in integrated circuits (chips) have been well-documented but are influenced by subtleties related to a chip's feature size and technological maturity. Foundery fabrication facilities are designed to produce chips at a given lithographic feature size, a factor that determines where the chip is produced. The most advanced chips used in detector systems, with sub10 nm features such as high-end field programmable gate arrays (FPGAs), are currently fabricated exclusively overseas.

DOE Office of Science goals generally require detector systems that have both these cutting-edge, commercially produced chips as well as researcher-designed chips. Because of high development costs, researcher-designed chips are in larger, more mature nodes (i.e., they have feature sizes larger than 10 nm). These chips are like those used by the automotive industry or for other consumer purposes and thus are subject to the same supply chain shortages. Most researcher-designed chips are fabricated in Taiwan, Europe, or other parts of the world. Expanding scientists' access to domestic mature nodes can improve supply chain resilience for these technologies.

Takeaways

- *The feature size of an integrated circuit determines where it can be made.*
- *The market for mature technologies (larger feature sizes) dwarfs the market for custom science applications, limiting foundry access.*
- *High-end specialty devices, such as FPGAs, are not produced in domestic advanced foundries.*



Capacity for leading-edge (<10 nm) integrated circuit processes is expected to become the largest portion of monthly installed capacity across the industry beginning in 2024. As shown in the graph, <10 nm capacity accounted for 10% of the industry's total water capacity at the end of 2020 and is forecasted to rise Above 20% for the first time in 2022 and then increase to 30% of worldwide capacity in 2024. [Courtesy IC Insights]

Act (RCRA) hazardous metals discourages many companies from working with it.

- **Beryllium (Be).** This element is useful in many nuclear applications as a neutron reflector. Materion, based in the U.S., is the only supplier of Be components for this purpose. The only other known supplier is ULBA, located in Kazakhstan. ULBA is not able to produce the larger ingots used in facilities such as the Spallation Neutron Source (SNS) and the High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL).

  Facilities at Fermilab use brazed-Be windows, Neutrinos at the Main Injector (NuMI) horn–Be crosshairs (manufactured using electrical discharge machining) for beam-based alignment, Be target tube and fins for the Booster Neutrino Beam (BNB) horn, electron beam welded–Be windows to aluminum, brazed-Be rods for beam-based alignment, and thick Be windows for lithium lens fabrication. (These are pulsed-focusing devices used in the Antiproton Source target hall and now used in the Muon g-2 target hall at Fermilab.) Beryllium is also used in X-ray facilities in small quantities for focusing lenses and exit windows (from vacuum to ambient pressure).

- **Boron-10.** This material, with its strong neutron absorption properties, is used in applications such as neutron choppers and beamline apertures. 3M is the only domestic supplier of Boron-10 in the configurations used for these applications. The company has been able to meet the needs of the facilities examined, although there have been long lead times.
- **Boron-aluminum alloys.** These alloys are used in certain types of neutron detectors. Currently, there are no known suppliers for this material.

In general, the markets for products and services for neutron facilities and high-power targetry systems described above are specialized and limited to neutron facilities or nuclear applications. There are many markets for cadmium. However, its use in thick coatings or machined shapes is generally limited to neutron decouplers or neutron absorbers in neutron facility reflector plugs, instrument beamlines, and fission reactors.

Beryllium is a common reflector material in spallation- and fission-based neutron facilities. There are other applications where Be is useful as a lightweight metal with desirable properties (e.g., various aerospace applications).

Specialty Manufacturing Processes

Specialty material applications processing is either unique or very low volume. Examples include:

- **Cadmium thermal spray coating.** In this process, cadmium is applied in thick layers (~1.5 mm) in some critical applications. Most notably, cadmium is used on SNS' neutron moderators and as a neutron decoupler on the inner reflector plug, which is at the center of the facility and affects many beamlines. Tennessee Metalizing is the only known supplier that is capable and willing to apply this coating. Cadmium's classification as a RCRA hazardous metal discourages otherwise capable companies from applying this coating. Other application methods are being investigated, but a suitable alternate process or supplier has yet to be identified.
- **Cadmium machining.** This capability is also needed to achieve the precise and complex shapes used at the SNS. No capable and willing vendors have been found for this work. As such, ORNL has developed its own in-house capabilities to cover this need (see sidebar, Source of Last Resort, p. 21).
- **Electron beam (EB) welding.** This capability is used extensively in the manufacture of neutron facility equipment. Several suppliers of varying capabilities exist for this work. There are two qualified suppliers for EB welding of SNS mercury targets, neutron moderators, and reflector plugs: C.F. Roark (Indiana) and PTR-Precision Technologies (Connecticut). While these companies are currently meeting demand, there have been delays and other issues due to reliance on a few aging welding machines used for this work. Identifying additional suppliers may be possible; however, qualification of new vendors for certain work is difficult and costly. Materion has generally been the only vendor that can EB weld Be to 5000 series aluminum used for Fermilab's NuMI target downstream window assembly. Not many vendors want to EB weld Be, as their beam-welding chambers and workers require special procedures and monitoring for Be and declared Be workers.
- **Beryllium Machining.** Working with Be carries certain health risks that require specialty equipment

Source of Last Resort

Finding Solutions to Technology Needs When Nobody Wants Your Work

Favorable neutron-absorption properties make cadmium a useful material in various nuclear applications. One such use is as a neutron decoupler on the inner reflector plug (IRP) at Oak Ridge National Laboratory's (ORNL) Spallation Neutron Source (SNS). The decoupler helps select neutron energies and shape the neutron pulse used by various instruments. SNS is fabricating the next IRP (IRP-3), which has large surfaces coated with cadmium for this purpose. The thick cadmium coating (1.4 mm in thickness) is applied to the IRP's aluminum surfaces using a metal arc spray technique and then machined to a precise thickness.

In recent years, the adverse health effects from inhalation of cadmium dust and fumes have become more apparent. While previous IRPs were machined commercially, many companies have exited this business because of the recognized dangers associated with cadmium processing. As a result, no qualified vendors are willing to machine large, intricate cadmium parts such as those needed for the IRP. To meet the need for precisely machined cadmium, SNS and ORNL's Facilities and Operations (F&O) directorate partnered to build a facility that can safely machine cadmium parts.

Takeaways

- *Some technologies critical for the Office of Science will be unattractive to industry due to low volumes, high investment costs, or significant (and expensive-to-mitigate) hazards.*
- *The Office of Science may need to invest in and maintain the required resources to assure mission success.*

The cadmium facility consists of a large horizontal milling center (Haas model EC-1600ZT outfitted with a Haas model HRT 600 rotary table) with five axis capabilities. Operated by the F&O directorate, the facility is monitored by ORNL Environmental Health and Safety staff and has several levels of protection to ensure safe operation. These protective measures include custom enclosures, ventilation, and monitoring systems as well as all the proper work procedures for safely handling cadmium. Although the facility was constructed specifically for machining SNS IRPs, it is capable of machining a large range of cadmium part sizes and types for customers at ORNL and other DOE facilities.

Machining cadmium for the Inner Reflector Plug at the Spallation Neutron Source. [Courtesy Oak Ridge National Laboratory] and processes for machining. Cost is typically very high, and deliveries are long. Several specialty companies exist that provide this service, including Peregrine Corporation, WessDel, and General Dynamics. Despite having several suppliers, high costs and long deliveries are normal for this service.

- **Large-diameter turning capabilities for thin-walled precision structures (e.g., aluminum for NuMI and BNB focusing horns).** This work requires machine size capacity, but more importantly knowledge of progressive machining and vacuum fixturing to support thin-wall structures (requiring precision vacuum-capable mandrels and tooling). These efforts have resulted in a short list of U.S. vendors.
- **Large-component electroless nickel plating.** This plating is used by Fermilab on focusing horn inner conductors to provide enhanced fatigue life and minimize corrosion. A prior vendor in Illinois (Krel Laboratories) has gone out of business. A new machine shop has been identified on the East Coast.
- **Friction stir welding.** This capability has been used for fabrication of horn aluminum bus conductors. A limited vendor base exists for working on low-volume, complicated-to-fixture shapes while minimizing distortion and maintaining tight quality control.
- **Fabrication of large diameter (>1m) ceramic isolation rings.** These rings are expected to be made by a vendor in Japan. There is no domestic supplier.

Precision or Complex Manufacturing

There are many applications where specialty or complex manufacturing is needed. In general, the availability of capable companies is not an issue. However, a significant upfront investment by both the customer and the supplier is needed to reach a point where they can become reliable and profitable suppliers. A lack of commitment from both parties is a hinderance in expanding the supplier pool for certain needs. Examples from the panel discussions include:

- **Mercury targets and reflector plugs.** These plugs used by neutron facilities have presented significant challenges with respect to finding reliable suppliers for these complex, precision, and highly specified components at the heart of the facilities. In the case of SNS, one reliable partner exists, Metalex, which is the result of many years of mutual collaboration. Efforts to engage additional suppliers have met with limited success, hampered mainly by the significant upfront investment needed to develop a supplier's capabilities and processes necessary for these components.
- **Neutron moderators.** These are pressure vessels that require precision machining of complex shapes, specialty welding processes, qualification to various codes and standards, and use of materials atypical of code-compliant pressure vessels. As such, facilities have struggled to identify reliable suppliers capable of fabricating moderators. Currently these are produced with heavy involvement by the customer—utilizing multiple suppliers for specific operations. The result is high cost and long delivery times.

3.1.8 Specialty Materials and Processing

This section provides examples of specialty materials and processing that may be derived from large-scale commercial products that have been tailored to SC applications (in addition to the neutron and targetry systems, just described) and are needed in comparatively small quantities. The specialized nature of these examples inhibits investment to meet the niche needs and therefore presents challenges in the execution of SC mission–driven equipment and facilities.

Copper

- **Copper plating.** This plating, primarily deposited onto stainless steel, is required in components needed in nearly all DOE accelerator facilities, including in most RF power couplers and many beamline components. Copper and plating suitable for many accelerator applications is available from A.J. Tuck Company (Connecticut) but with limited production capability. SLAC has been able to produce high-purity copper coatings, but this capability may be negatively impacted by recent retirements. A second domestic copper plater, especially one with more robust production capabilities, is needed for risk mitigation.
- **Oxygen-free high-conductivity copper.** This material is used for the fabrication of warm RF cavities. It is not produced in the U.S.

Non-Evaporable Getter

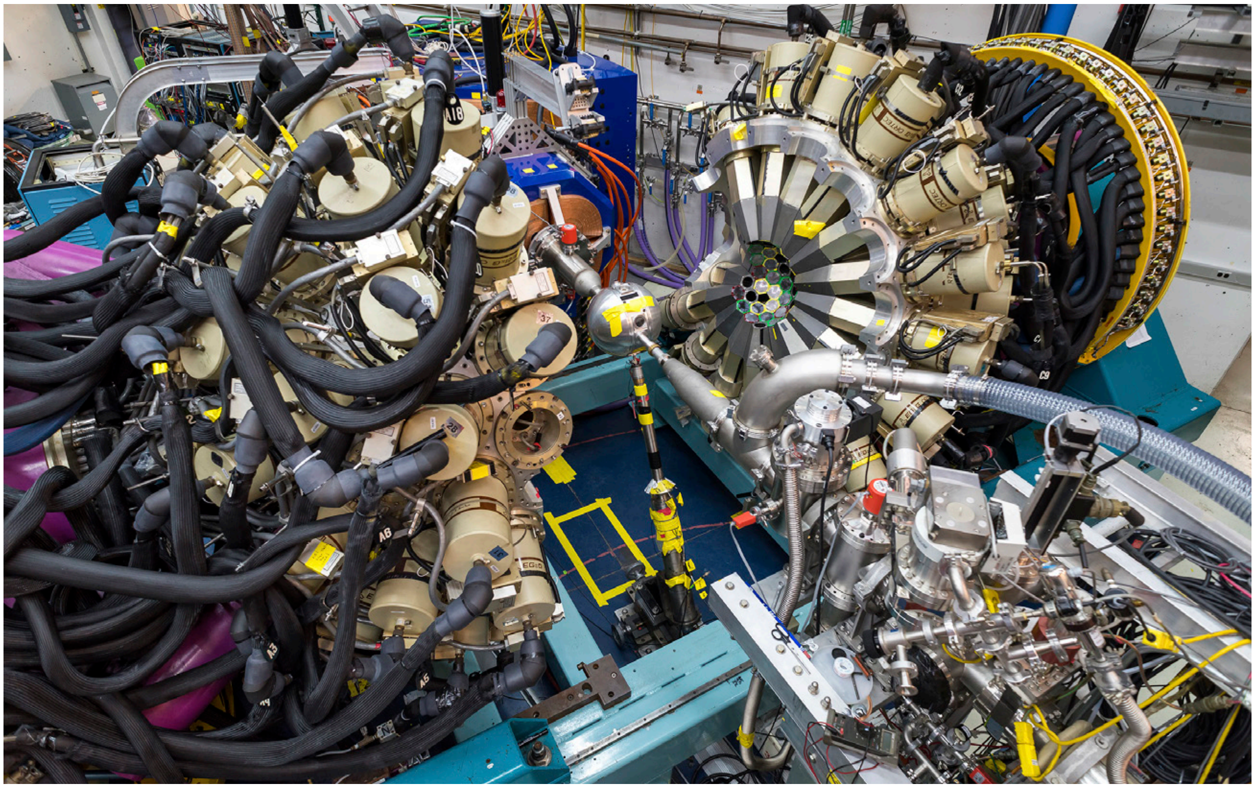


Fig. 3.2. The Gammasphere is a gamma-ray detector array at the Argonne Tandem-Linac Accelerator System (ATLAS). The two hemispheres, which can host up to 110 high-purity germanium detectors, are moved apart to provide access to the target chamber and show the entrance to the Argonne Gas-Filled Analyzer (AGFA). The combination of Gammasphere and AGFA was built to provide the world's highest detection efficiency for gamma-ray spectroscopy of the heaviest elements. [Courtesy Argonne National Laboratory]

Non-evaporable getter (NEG) is a small-market, high-risk, low-profit application that has discouraged U.S. suppliers from entering the market. Lack of domestic vendors makes development of advanced products and applications difficult.

- **NEG-coated vacuum chambers.** Suppliers of these vacuum chambers are limited with none in the U.S. Standard NEG-coated chambers can be procured from European companies including FMB (Germany) and SAES Getters (Italy). Special geometries are typically coated at national laboratories.
- **NEG pumps.** Higher-quality (lower-dust) versions of NEG pumps are essential for use near high-gradient components (DC gun, RF cavity). These formulations remain under patent protection and are available only from SAES, although U.S. companies such as Gamma Vacuum (Minnesota) produce getter-ion combination pumps with an older NEG formulation.

Specialty Sensor Materials

- **Crystals and scintillators**. These are often critical sensing materials to determine the characteristics of processes under study (see Fig. 3.2, this page). Crystal growth has migrated overseas with very few domestic vendors remaining. There is a highly qualified domestic vendor for production of scintillating material for neutrons, but the main production for this component has also moved overseas.
- **Specialty sensor materials (e.g., scintillating crystals or compound semiconductor sensors).** These materials often require significant process development to create a scalable product, which is also true for specialized sensor fabrication processes. Similar to semiconductor sensors, there

are limited opportunities in the U.S. to support and sustain these activities, absent a commercial driver. This trend will continue without intervention. Medical imaging is an example of a commercial driver for sensor technologies borne from the SC missions, but the synergies tend to be minimal, since successful technologies are then acquired by industry.

X-Ray Diffraction–Grade Diamond Crystals

The roundtable surveyed the supply chain of diamond crystals for X-ray optics applications (X-ray diffraction–grade). In this report, only X-ray diffraction grade monocrystalline diamonds are addressed featuring flawless crystal structure. They are produced via high-pressure, high-temperature (HPHT) technology. There are other types of diamond crystals (electronic grade, polycrystalline), produced via chemical vapor deposition technology, which have a better supply chain but are not X-ray diffraction grade.

Diffraction-grade diamond crystals are important X-ray optical components critical for the realization and operation of next-generation, accelerator-based X-ray sources at DOE national laboratories. These include X-ray free-electron lasers (at SLAC) and diffraction-limited storage ring X-ray sources at Argonne National Laboratory, Brookhaven National Laboratory, and Lawrence Berkeley National Laboratory. These materials also are used in precision X-ray beam monitors as part of beam characterization (position, intensity, imaging).

Although critical for DOE facilities, these materials represent a relatively narrow-band application, with market value of a few million dollars per year. The small market does not stimulate manufacturers. Currently, there is no U.S. manufacturer of X-ray–diffraction grade HPHT diamond crystals. The main suppliers of X-ray–diffraction grade diamonds in the past decade were two companies from Russia. There is a third supplier in Japan, but the quality of its product is low. DOE laboratories can no longer purchase diamond crystals from Russia due to geopolitical issues.

Low-Background Materials

Low-background radiation detection has been a focus in SC searches for dark matter and neutrinoless double beta decay. In addition, there is a broad range of U.S. government organizations that use low-background detectors for studies of fate and transport in the environment (e.g., age dating). These communities rely on low-radioactivity materials for detectors, detector enclosures, and shielding. Three highly specialized materials used are electroformed copper, low-radioactivity lead, and low-radioactivity underground argon.

The U.S. supply chain for these materials has dwindled or disappeared entirely, largely, due to environmental and health concerns and the associated regulatory environment, which has rendered U.S. refining and manufacturing of these materials cost-prohibitive.

- **Low-radioactivity lead**. Production of this material was historically available from the Doe Run facilities in Missouri, including mining of ore, which is low in natural radioactivity, and smelting to produce finished products such as lead bricks. Doe Run no longer smelts lead domestically. The only supplier with sufficiently low radioactivity is in Europe. As such, costs for both materials and the much higher shipping have escalated.
- **Electroformed copper.** Achieving the required low radioactivity for copper involves starting from the purest commercially available electrorefined copper and further refining using electroplating methods. This process, developed in the DOE laboratory system over the past 30+ years, addresses both material production and the ability to assay it (quality assurance). There is currently no domestic ultrahigh-purity copper ingot provider. The copper required for the scientific instruments is currently supplied by the SC projects themselves.
- **Underground argon.** This material is obtained through a collaborative effort between the Urania project and the Kinder Morgan Doe Canyon facility located in Colorado, which operates an underground carbon dioxide source. The Urania facility is an argon extraction and purification plant capable of extracting 250 kg/day of underground argon and is funded by the Italian Institute for Nuclear Physics (INFN). It is built by a contracted vendor following specifications established by the Urania project team and is composed of scientists from the experiments that require the underground argon.
- **Beryllium**. This element has a long history of use in SC as a low-mass, low-scattering material in physics experiments and as a thin window material in accelerators and light sources. Beryllium production and manufacturing has a long-standing single U.S. supplier (Materion, formerly Brush Wellman Electrofusion, located in Ohio). Beryllium is also discussed in the context of target materials.

Legacy Manufacturing Methods

The DOE SC community relies on several fabrication techniques that are being replaced by modern manufacturing. Legacy fabrication methods (e.g., EB welding and friction stir welding) are rapidly becoming difficult to source in the U.S. and may soon become obsolete. This is largely due to the rapid progress made in additive manufacturing, which allows for direct production of complex geometries as single parts with no filler materials. Unfortunately, additive manufacturing is not viable in the foreseeable future for specialty materials described elsewhere in this report such as niobium, electroformed copper, and some of the specialty target materials.

3.2 Components

The scientific enterprise has, by its very nature, become much more interdisciplinary. Bringing together the required expertise is more difficult and costly. As an example, the study of quantum systems at ultralow temperatures requires both fundamental knowledge about the sensors and considerable cryogenic engineering expertise. Also, if the system is read out through an ASIC, electronics design expertise is needed in an advanced node at cryogenic temperatures. Collected data is processed through high-speed field programmable gate array (FPGA) systems for offline storage where high-level software applications analyze the data.

Systems such as these have been developed within the national laboratories and efforts made to transfer the technologies to industry. Due to the rapid technological advances made over the last 2 decades, the cost for keeping up with technology has become prohibitive for many smaller manufacturers. Industry has consolidated or, in several cases, the expertise has become extinct in the U.S. As these fields and markets evolve, the commercial world is drawn to serve the most profitable markets, and from this perspective, SC research programs become a niche market.

This section describes selected components that have proven (or are anticipated) to be difficult to obtain due to supply chain issues. For the purposes of this report, components can be regarded as materials processed into finished articles that would not be functional as stand-alones without integration into systems.

3.2.1 Niobium Cavities

Cavities from purified niobium are the core component for DOE HEP/NP/BES superconducting accelerators (see Fig. 3.3, this page). The development of new cavity structures (e.g., crab cavity, balloon cavity) and next-generation niobium tin–coated cavities also depends on availability of niobium cavities. The current cost for quality prototype cavities in small quantities from European vendors is high and negatively impacts R&D, such as that supported by ongoing SBIR projects. The U.S. annual market is driven by the DOE laboratories for larger projects and is variable year to year, but it is on the order of 100 cavities per year.

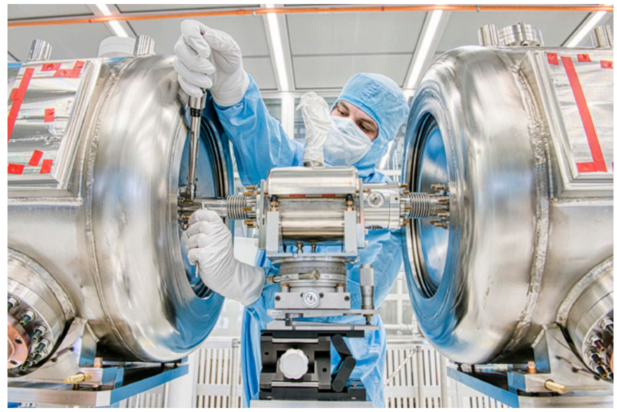


Fig. 3.3. A technician works on a 325-megahertz spoke resonator cavity string in one of the cleanrooms at Fermi National Accelerator Laboratory. The device is part an accelerator upgrade project that will improve the lab's accelerator complex and the beam it provides to experiments. [Courtesy Fermilab]

Finished niobium cavities processed, cleaned, and suitable for installation into DOE accelerators are available for purchase from RI (Germany) and Zanon (Italy). A former U.S. supplier of high-quality cavities, Advanced Energy Systems, is no longer in business. C.F. Roark (Indiana) has the capability to fabricate cavities, but its cavities require final processing and cleaning at national laboratories. Key individual cavity fabrication steps, including EB welding (Sciaky, Jefferson Lab) and hydroforming (Stuecklen), are available in U.S. industry and at DOE laboratories.

3.2.2 High-Performance Superconducting Magnets and Subassemblies

High-performance superconducting magnets and conductors have been and will continue to be critical components for large accelerator projects for the foreseeable future (e.g., Jefferson Lab 12 GeV Upgrade project of the Continuous Electron Beam Accelerator Facility, High-Luminosity Large Hadron Collider Accelerator Upgrade

Fig. 3.4. Magnet measurement technician Gentillo Curescu works with an array of magnets for the Advanced Photon Source Upgrade construction project. A total of 1,321 magnets will be installed during the upgrade. [Courtesy Argonne National Laboratory]

Project, FRIB, Advanced Photon Source Upgrade, and the future Electron-Ion Collider). These magnets and superconductors are the cause of many challenges encountered in project execution. Similar to undulator and specialty permanent magnet structures, the high-performance superconducting magnet structures are built mostly in national laboratories or academic labs, such as Michigan State University, through collaborations with partner laboratories (see Fig. 3.4, this page). There are limited suppliers for "standard" items in the U.S., and there is a more active magnets industry in Europe. This industry is likely to accelerate with ambitious European magnet development programs being started under the oversight of the CERN Council and Laboratory Directors Group.

Developing any superconducting magnet technology is impossible without a cheap, reliable, and reproducible supply of conductor, which is a composite structure significantly more complex than a length of copper wire. New magnet technologies are being actively developed, including high-temperature superconductors (HTS) capable of higher fields, yet development of these conductors is confronted with a valley of death. The emerging market opportunity for rare earth barium copper oxide (REBCO) HTS is particularly large, due to its ability to achieve 3–7 T magnetic fields at 50 K comparable to present Nb-Ti magnets. HTS are also important to rising accelerator and fusion applications toward the 20 T level.

Many other less-obvious materials and systems can pose supply chain challenges and need to be considered as part of the ecosystem that supports the manufacture and delivery of high-performance magnet systems. Some recent examples include:

- **Low-cobalt stainless steel**. Procurement of material for manufacturing of spare ITER magnet components using low-cobalt stainless steel requires long lead times (>12 months).
- **Radiation-resistant resins and composites**. Commonly used as electrically insulating components, cyanate-ester resins, for example, are more suited for high-radiation environments; but most vendors do not customarily provide cyanate-ester resin composites. An R&D program is usually recommended to develop them.
- **Low-sulphur and low-phosphorus cutting fluids**. ITER has extremely stringent requirements for the level of sulphur and phosphorus present in

cutting fluids used for cooling and lubrication during machining operations. Cutting fluids with this specification can be extremely difficult to source on the open market. Furthermore, the use of these fluids usually means that some manufacturing development is required by the machining vendor to requalify the cutting process using the new fluid—resulting in additional expense and longer lead times.

- **High-current leads (>10 kA).** Current leads >10 kA usually require an R&D program.
- **High-stability magnet power supplies for driven (nonpersistent) magnets.** Typically, better than 10 ppm/hr are not available off-the-shelf and need development by vendors.
- **High-current, high-voltage power supplies.** Generally, >2000 A, >500 V are not available off-the-shelf and need development by vendors.

Existing markets for these items are generally small and restricted to R&D activities, usually at experimental facilities at national laboratories and in similar international organizations.

The items listed above are not commonly available off-the-shelf, and discussions with both domestic and international vendors, especially over the last 2 to 3 years, indicate that the vendors will have to put in some development work (sometimes a significant amount) to achieve the required specifications. This cost is usually passed on to the customer unless there is a potential for repeat orders in the near future.

For the radiation-resistant resins and composites, the whole manufacturing and testing process (including the irradiation process) can be very protracted, especially if access to irradiation facilities is not readily available.

3.2.3 Optics

Optics (e.g., mirrors, lenses) covers a large area known as photonics that also includes metrology devices for measuring light/lasers, lasers themselves, and experimental setups containing light and lasers (see Fig. 3.5, this page). Many DOE facilities use these components in conjunction with linac and synchrotron sources for experiments in fundamental physics. While the immediate supply chain risk is moderate, the impact of a major disruption or foreign supply dominating the market could prove critical.

Many industries use photonics/optics and related supplies (e.g., communications, auto, aerospace, research, military, lighting, and quantum). For example, the new SLAC PetaWatt laser facility will require several components that are classically supplied by photonics manufacturers: optical tables, mirrors/lenses, laser crystals, optical fiber, optical metrology, rare earth fiber, labor, and pump lasers.

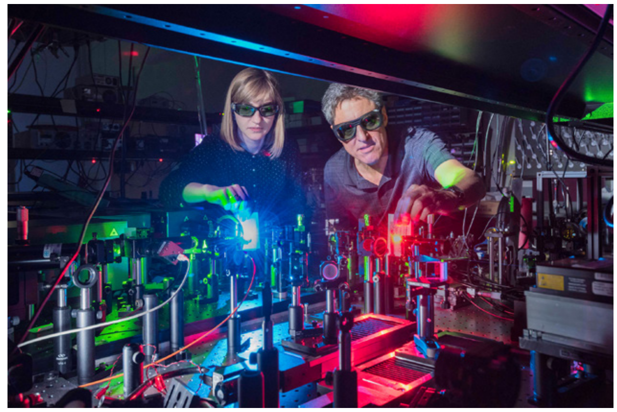


Fig. 3.5. Sandia National Laboratories postdoctoral appointee Polina Vabishchevich (left) and Center for Integrated Nanotechnologies senior scientist Igal Brener (right) work in a laser lab to make a metamaterial that mixes two lasers to produce 11 colors ranging from the near infrared to ultraviolet. [Courtesy Sandia National Laboratories]

The two major areas of need for the DOE supply chain are (1) standard components produced by companies and (2) more-difficult specialized optics, lasers, and metrology systems necessary to support new and existing DOE facilities.

The domestic supply chain is slowly slipping to other countries for materials and manufacturing due to the availability of cheap labor. The main risk is the supply going to high-risk countries such as China. Currently, photonics has a good supply chain that mainly suffers from the lack of skilled labor. Many companies are experiencing rising labor costs and lack of trained personnel, which is driving up costs and lead times of most components needed by DOE programs. As a result, mostly small struggling businesses are the main DOE suppliers for specialized photonics. This challenge may not represent a major supply chain issue, but it could delay DOE programs.

3.2.4 X-Ray Optics

X-ray optics is a grouping of several highly specialized niche products essential to the operation of

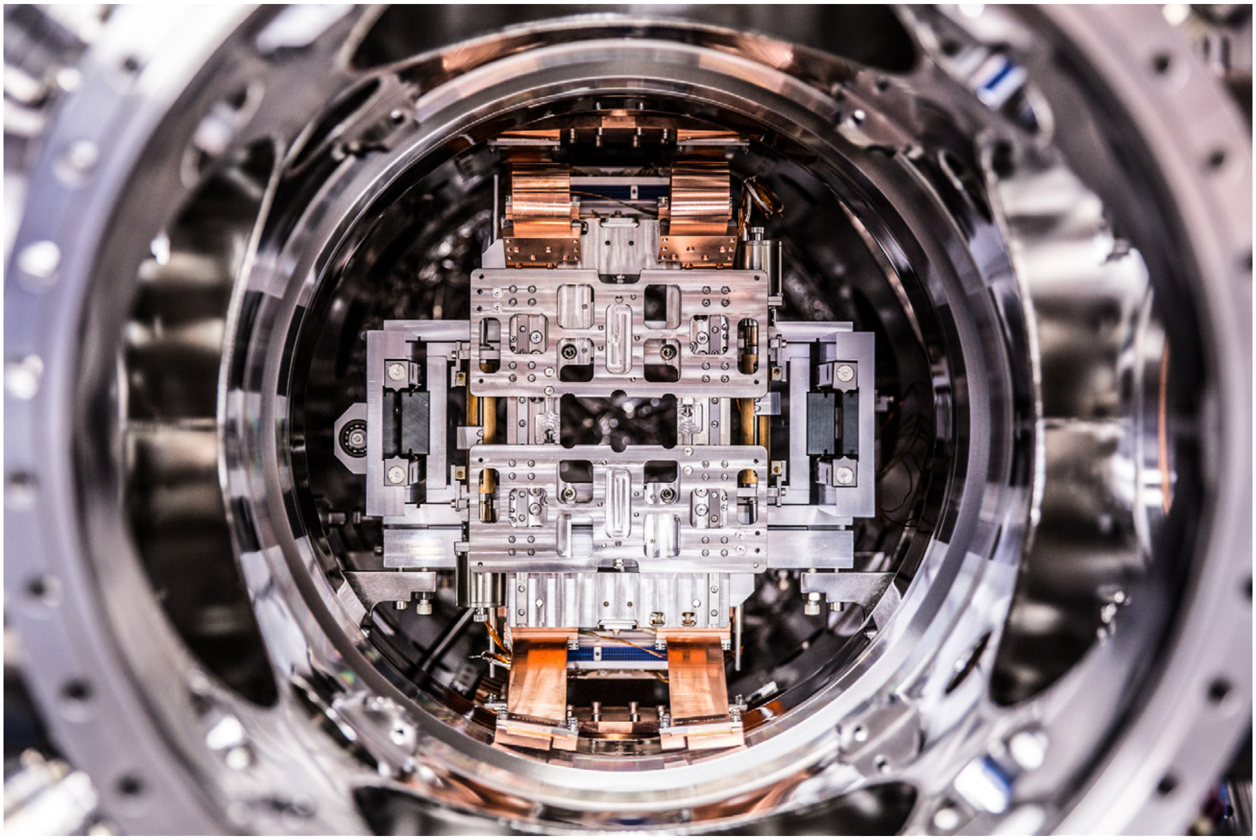


Fig. 3.6. The LAMP multipurpose endstation was designed to be deployed at the Linac Coherent Light Source soft X-ray atomic, molecular, and optical science instrument. LAMP supports a wide array of experiments including imaging, spectroscopy, and multi-beam experiments. [Courtesy SLAC National Accelerator Laboratory]

short-wavelength synchrotron and free-electron laser light sources operating at extreme ultraviolet, soft X-ray, and hard X-ray photon energies. As light source technology advances, the performance requirements for optical elements and systems increase. In most cases, these elements are uniquely specified for their application with little potential for standardization. Relatively small numbers of mission-critical parts are required each year to meet the demand. DOE SC light sources share similar, overlapping needs. Without access to the highest quality elements, U.S. light sources could not maintain competitiveness with international peers (see Fig. 3.6, this page).

Included in this category are superpolished X-ray mirrors, other figured X-ray mirrors, specialized mirror coatings, blazed gratings, compound refractive lenses, monochromator crystals, zone plates, X-ray adaptive optics, multilayer Laue lenses, and X-ray diamond screens. For most of these, a small number of vendors has emerged to serve the community. With major investments in effort, metrology tools, fabrication technology, and expertise, these vendors' fabrication limits largely define or constrain the scope of what is possible. Limited market size and the extreme challenge of fabrication at the cutting edge are viewed as significant impediments to new companies entering the market.

For several classes of X-ray optics, there are no suitable domestic vendors for highest-quality products. Domestic, boutique fabrication shops offer components that are suitable for some applications but not at the technological forefront. Existing domestic market leaders in closely related fields often will not bid on small, precise X-ray optics jobs. In areas where there are no suitable vendors to supply X-ray optics, national laboratories have had to develop the means and ability to fabricate components to meet program needs. Despite their success in several areas, these programs are small, expensive to maintain, and not easily scalable. They are also threatened by funding constraints, reprioritization of facility programs, and the retirement or departure of key staff.

Light sources supported by DOE's Basic Energy Sciences program have similar overlapping needs, yet in any category described in the previous section, the total number of parts required per year is low (tens of elements). Worldwide demand for components is a small multiple of that. As light sources are upgraded and funding is allocated for new beamlines to replace outdated predecessors, demand for the most advanced X-ray optical components will likely increase. However, demand will never reach mass-production levels and so until there is standardization among beamline designs, most individual elements will continue to be uniquely specified for their application, lowering the opportunity for spares, redundancy, and economies of scale.

3.2.5 Specialized Laser Systems and Components

The following examples illustrate the difficulties today in procuring specialized laser components for laboratory laser systems:

- **Optical parametric chirped-pulse amplifier (OPCPA) high-average-power lasers**. These cutting-edge lasers are based on a fairly new platform. As such, there are few suppliers (Class 5, Light Conversion, AMPHOS), and none are in the U.S. Because the technology is new, not much is known about the reliability of the lasers, which puts applications (e.g., at SLAC) at risk.
- **High-energy ultrafast lasers and pump lasers**. These are provided by foreign vendors (Thales, Amplitude) and are known to exhibit hardware integrity issues. While domestic companies previously provided these lasers, owing to strong investment in Europe and Asia, they have either stopped building leading-edge systems or have been acquired by overseas companies. High-performance deformable laser optics and pulse shapers can be supplied only by a few foreign vendors (Fastlite, Imagine Optic, Phasics), enabled by strong investment in Europe and Asia.
- **Single-mode fiber amplifiers for ultrafast lasers**. These lasers have been offered by Thorlabs and other vendors, but they are mainly purposed for continuous or long-pulse laser systems. Their polarization extinction does not meet the needs of high-energy ultrashort pulse laser systems. New qualified products would greatly facilitate ultrafast fiber laser R&D, as those amplifiers are in demand but currently must be custom made at national laboratories.
- **Large-mode-area fiber laser amplifier modules.** Foreign vendor NKT Photonics offers low-integration modules based on photonic-crystal fibers, but the domestic vendor, Optical Engines, can offer higher-integration modules based on other large-mode-area fibers, which fit the needs of large-scale ultrafast fiber laser arrays. However, the single-vendor case increases the risk of product performance and cost.

Most specialized lasers, optical components, and high-power/intensity laser systems are purchased for individual researcher use at universities and for fundamental research. The recent creation of DOE-sponsored networks of facilities, such as LaserNetUS, will increase the demand for these components. For specialized laser components described above, market gaps arise from the limited number of vendors, mostly foreign. This leads to very long procurement delays in an often noncompetitive market.

3.2.6 Specialty Neutron Instrumentation

These instruments and the expertise required to produce them are specific to neutron sources. They have much in common with other SC instrumentation needs, since they are very specialized and have a limited, largely foreign, vendor community.

- **Helium-3 neutron detectors.** These detectors are used extensively on instruments for neutron sciences. There is only one supplier of this technology, Reuter-Stokes.
- **Instrument Heusler analyzers, monochromators, and crystal arrays.** These technologies and equipment are used extensively in neutron instruments. There are no domestic suppliers and two foreign suppliers: CEA Saclay and Laboratoire Léon Brillouin.
- **Neutron choppers, chopper discs, and velocity selectors.** There are no domestic suppliers for these technologies used extensively on neutron instruments. There are two foreign suppliers: Airbus Defence and Space GmbH and Mirrotron Ltd.

3.2.7 Imaging Sensors and Electronics

Many detector systems depend on the efficient detection of photons over a very broad wavelength range.

Cosmological surveys depend on high-quality imaging sensors for which there is only one vendor worldwide. Nearly all vacuum photodetection has migrated overseas. This exposes a large swath of SC research to single-point criticalities. Semiconductor-based photodetectors do not fare much better. While there are many vendors, they are mostly foreign. Only in the area of superconducting photodetectors does the U.S. retain its edge because of NIST, a world-leader in this technology.

Quite a few sensor industries have left the U.S., including photodetectors, crystal growers, gaseous detectors for tracking and imaging, and silicon-based X-ray detectors. For many SC science projects, a large fraction of the key components come from overseas suppliers. The irony is that many of these technologies were invented in the U.S. The €4.6 trillion annual global electronics industry (2019) is driven by market forces disconnected from SC needs, and SC is a miniscule share of that market. Delays are already being experienced, and mitigation strategies will be needed. Besides impacting production, the design environment is also under stress. The U.S. pioneered multiproject wafers where many designs were pooled together. For decades, this capability was organized in the U.S. by MOSIS but this capability has now been supplanted by Europractice.

Semiconductor and related image sensors are more niche products than integrated circuits, and SC's market influence can be more significant. However, there is global consolidation and very little remaining domestic capability. In most cases, these are technologies originally developed or produced in the U.S. that could not survive commercially on only the scientific market. If volumes are small enough, production in DOE or other government laboratories may be possible. However, this scenario requires continuous facility and personnel investments, which face budgetary pressures. Some foundry capabilities still exist in the U.S. government, such as at MIT Lincoln Laboratory or Microsystems Engineering, Science, and Applications (MESA, Sandia), but these are geared toward and funded by defense applications. There are also some semiconductor detector fabrication capabilities at national laboratories (BNL, LBNL); however, these are typically more suited to research than production (see sidebar, Sunsetting Technologies, p. 31).

3.2.8 High-Voltage Components

High-voltage cables, cast receptacles, and high-voltage power supplies are available in the U.S. but from limited suppliers. Dielectric Sciences will provide cables and receptacles, but products have long lead times because of high demand and low availability of raw materials. Development of new cables and receptacles is needed to advance the next generation of high-voltage photoguns >500 kV, but the supplier is not able to engage because a sufficient skilled labor force is lacking. Glassman builds high-voltage power supplies and will develop new capabilities but with long lead times due to the significant product development required. Taken together, state-of-the-art high-voltage developments are constrained by limited suppliers with small labor force and long lead times.

Custom high-voltage insulators that are reliable and reproducible are needed for electron and ion sources. There is no known U.S. supplier. SCT (France) will do custom work but with a long lead time that throttles meaningful and timely R&D. A U.S. supplier would mitigate risk for facilities requiring timely spares and insulators when needed.

3.2.9 Cryogenic Components

Many systems today operate at ultralow temperatures. Pulse tube cryocoolers have become the standard precoolers for millikelvin refrigeration systems that are used in quantum information science, quantum sensing, and other fields. There is only one U.S. vendor (and one foreign vendor) available for these cryocoolers, with very long lead times. Nonavailability is a showstopper for many experiments. For dilution refrigerators that provide millikelvin temperatures for quantum sensing and computing, the number of vendors is limited and a single overseas vendor has a large majority of the market. The situation for a variety of other cryogenic components is not much better.

Large-scale, helium-refrigeration systems—such as those used for cooling superconducting magnets, RF cavities, and linacs in accelerators—are critical for the success of many SC missions (see Fig. 3.7, p. 32). Key components, such as turbo expanders, have no domestic sources of supply.

3.2.10 Electronics

Electronics important to DOE SC can be divided into three broad categories: (1) commercial, off-the-shelf (COTS) electronics relevant to industrial applications and scientific facilities; (2) scientific instrumentation tailored to the needs of large scientific facilities (small-market); and (3) bespoke solutions that are largely developed in-house and fit-for-purpose (e.g., to support scientific

Sunsetting Technologies

A Core Office of Science Technology Vanishing into the Commercial Sunset

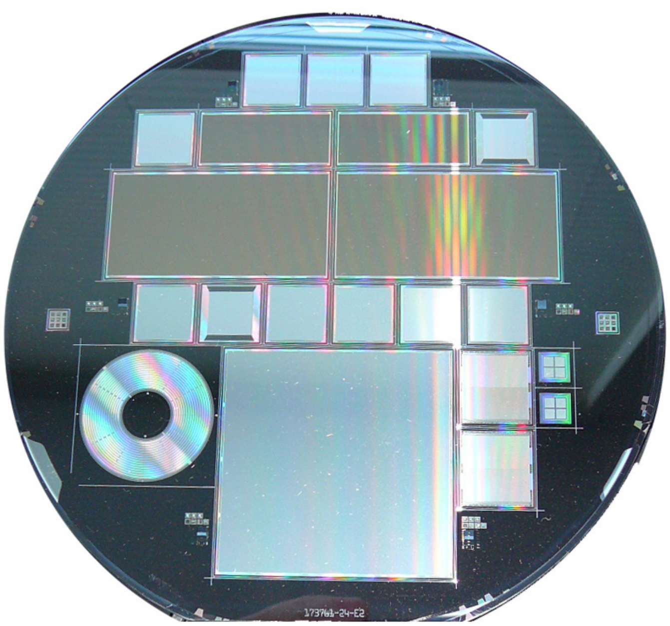
As the first electronically readable imagers, charge-coupled devices (CCDs) have been central to scientific imaging applications ranging from astronomy to X-ray and electron microscopy. Direct detection CCDs are used at most X-ray synchrotron and free-electron laser light sources. They are also prominent in cosmology (Vera C. Rubin Observatory and various telescope cameras) and even dark matter searches including OSCURA, a project to develop a 10-kg advanced design CCD experiment.

Today, CCDs have been supplanted by complementary metal oxide semiconductor (CMOS) image sensors (CIS) for most commercial applications. While CCD fabrication uses the same techniques as other CMOS circuits, the process has different optimizations than conventional logic. With the dominance of CIS, CCD foundries have dwindled. As part of industry consolidation, the few that remain have been absorbed by larger parent companies. As a result, there are few commercial CCD sources worldwide and none that currently support the combination of desired features needed for many Office of Science projects, including full-contact lithography (big sensors) on thick, high-resistivity silicon with thin entrance contacts.

CCD facility requirements are modest (unlike those for advanced CMOS), and production by national laboratories or small industries is possible but only with the funding and expertise levels that can sustain such a facility.

Takeaways

- *CCD technology is passing out of commercial use (and production).*
- *Production of this legacy technology is critical to many Office of Science projects.*
- *Alternative sources of supply will need to be developed.*



Example of a 150-mm CCD wafer with sensors for X-ray and electron microscopy. [Courtesy Lawrence Berkeley National Laboratory]

Fig. 3.7. A view inside the Facility for Rare Isotope Beams (FRIB) cryogenic plant. The vertical cold box (in blue) works together with the horizontal cold box to cool helium to 4.5 K. FRIB's beam-accelerating cryomodules contain superconducting radio frequency resonators that must operate at temperatures a few degrees above zero to be superconducting. The 4.5 K liquid helium makes the resonators superconducting. [Courtesy Facility for Rare Isotope Beams]

data acquisition and timing systems). In each instance, the challenge is largely that some amount of foreign manufacturing is involved.

The current silicon shortage and shipping delays are additional disruptors. With bespoke electronics, the issues are the same, but due to limited production runs and small supplier profit margins, quoted lead times have increased by up to fivefold (6 to 8 weeks with the possibility of premium processing increased to 40+ weeks). This presents a true risk to large upgrade projects if, for example, prototyping or manufacturing activities incur an error that results in more than one long lead time production run.

Detector systems also heavily use COTS electronics in addition to custom-designed semiconductors. While there are numerous domestic manufacturers of COTS equipment, they have the same foundry supply chain problems as bespoke electronics. Taken together, this disruption has led to (1) excessive lead times; (2) the need to design and then redesign around available components; and (3) performance degradation, when an available lower performance component must be substituted for a preferred, but unavailable, component.

COTS electronics are widely used across industries and SC facilities, but just-in-time delivery within the supply chain is straining availability and creating shortages and long lead times to fill orders. Moreover, prices have increased by as much as 40% over the past two years. Suppliers that provide niche-market scientific electronics manufactured to order in small quantities and custom designs initiated within SC facilities are at a disadvantage competing with bigger players with more buying power and potentially preferential contracts. As a result, these niche-market suppliers end up last in the queue in the current silicon shortage. This is outside the control of the U.S. market, as the suppliers are largely foreign.

3.2.11 Software

For software, two categories of concern are COTS and bespoke scientific software frameworks and applications of interest to SC facilities. In the COTS category, the major issue is cost where monopolies have emerged, such as Red Hat Enterprise Linux, which has become the industry standard. Licensing fees for such software become a significant burden when deploying thousands of computer hosts in a modern scientific facility to cover the needs of the controls and data acquisition and analysis systems.

Domestic and foreign laboratories operating complex scientific facilities collaborate with private firms to co-develop operations control and data-handling frameworks (e.g., EPICS, BlueSky, PyDM, and CS-Studio) as well as data-analysis software frameworks. These are generally based on open-source standard platforms and libraries tailored to the needs of the scientific community and individual facilities. The absence of consistent funding to support maintenance and extension of these systems is the primary challenge to maintaining state-of-the-art capabilities in software to support the best possible science at SC facilities.

COTS solutions are widely used industry standards, and availability is not an issue, but costs may be prohibitive at the scale necessary to support the increasing demands on computing by scientific facilities. Scientific software frameworks often suffer from inconsistent funding (dependent on major projects or upgrades, but they are often the first scope to be removed when budgets are exceeded). Also of concern is the continuity of talent as industry is willing to pay 2 to 3 times the total compensation for experienced developers. A significant upfront investment is required to train scientific software developers capable of making meaningful contributions to national laboratory programs.

The development of scientific software and frameworks is crucial to enable control and automation of scientific equipment and for secure remote access to facilities. The use of analysis pipelines and processes in addition to the analyzed data will increase the reliability and reproducibility of data processing. Moreover, new scientific software and software frameworks will help enable guided experiments that rely on on-the-fly or even real-time data analysis and comparisons with theory and simulations. Adaptive and fully autonomous or self-driven experiments combining automated experiments with artificial intelligence and machine learning will also require the development of new scientific software tools.

3.3 Systems

This section provides some illustrations of systems described by members of the roundtable as being difficult to obtain due to supply chain issues. For the purposes of this report, systems are an assembly of components that might actually be subsystems integrated into a larger system to form an instrument, or they may be a stand-alone instrument. In many cases, they illustrate how multiple threads of a weak or nonexistent supply chain threaten progress in a number of strategic areas significant to accomplishing the DOE SC mission.

3.3.1 Cryomodules

Complete cryomodules built around high-performance superconducting cavities are assembled in the U.S. at national laboratories and universities. Fermilab and Jefferson Lab have advanced production capabilities for assembly of cryomodules. There is, however, no significant U.S. industrial capability for production of complete cryomodules (see Fig. 3.8, this page).

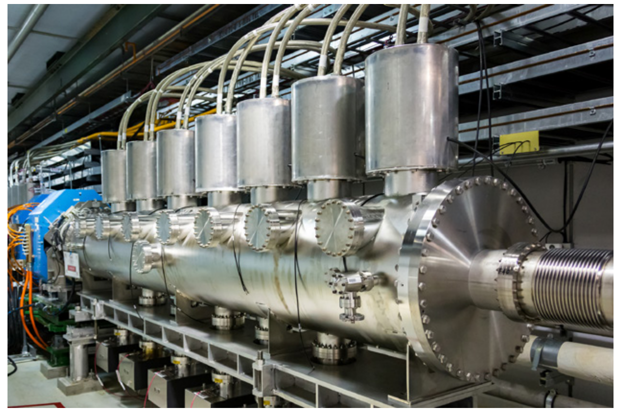


Fig. 3.8. Linear accelerator (linac) for the Spallation Neutron Source, which accelerates ions to very high energies. The linac is a superposition of normal conducting and superconducting radio-frequency cavities that accelerate the beam and a magnetic lattice that provides focusing and steering. [Courtesy Oak Ridge National Laboratory]

3.3.2 Normal Conducting Radiofrequency Technology

Normal conducting radiofrequency (RF) technology, such as conventional linacs, has been the driving force for radiation applications in medicine and industry. The leading U.S. company in medical linacs is Siemens (formerly the Varian Company in California). There are many other companies with similar capabilities in Europe and Asia.

While numerous specialized companies can conduct many subprocesses (e.g., linac design and fabrication, fabrication of RF structures, and brazing and assembly of copper structures), there is lack of adequate full-system capability in industry. At the same time, maintaining national laboratory capability has become increasingly difficult due to a lack of strong R&D support, which has impeded development and transfer of technology to industry, exacerbating vendor and supply issues.

3.3.3 High-Power Lasers

High-power lasers are important drivers for accelerator injectors, cooling, and advanced accelerator concepts, such as plasma wakefields that are being developed for next-generation systems. While the U.S. retains leading laboratory expertise, commercial suppliers are few and are now located outside the U.S. for high-energy laser systems, ultrafast spatial/temporal/spectral diagnostics, and beam-delivery systems including active feedback and stabilization. This has been driven by strong European and Asian investment at the billion-dollar scale in laser facilities, development, and coordination.

High-repetition-rate (>1 kHz), high-power lasers are the next step to transition from research to applications of advanced accelerator technologies and other applications (e.g., ultrafast laser surface processing). The U.S. retains significant leadership in high-repetition-rate systems, but supply chains are not well developed. As in magnets, new technologies are confronted with a valley-of-death issue in technical development. For example, in ultrafast fiber laser systems, there are few vendors for either single-mode preamplifiers or large-mode-area fiber amplifiers. Development of new, qualified products for fiber amplifiers, pulse manipulation, and integration is needed. The same applies to other advanced laser technologies such as high-efficiency materials [e.g., thulium-doped yttrium lithium fluoride (Tm:YLF) crystals, ytterbium-doped yttrium aluminum garnet (Yb:YAG)] and pump lasers for these. European and Asian nations are investing strongly, including through the Fraunhofer Institutes, to develop and industrialize these technologies. Developing the U.S. supply chain is important to both advanced particle accelerators and industrial laser surface processing with broad importance for energy storage and carbon management.

High-power laser systems were pioneered in the U.S., and most vendors were located here until the early 2000s. In the last decade, Europe and Asia have seen a large and rapid investment in high-power laser technology, along with the construction of major facilities. This is unparalleled in the U.S., and the resulting waning U.S. leadership and available supply chain in this field have been well documented in several recent reports, including the National Academies' report, *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light* (2018), and the U.S. research community response to that report, the *Brightest Light Initiative Workshop Report* (2019).

There are challenges in bringing new products to market that meet accelerator needs. Development of new technologies requires investment over many years, which, like in the magnet area, is difficult without external support from stakeholders such as DOE. Challenges due to market size have also limited investment and supply. Market size can, in part, be addressed by strategies such as high-repetition-rate fiber combination, which uses larger numbers of smaller lasers rather than single large systems. These have higher unit count, and the high-repetition-rate systems may also have greater overlap with industrial needs. The ability to pay nonrecurring engineering costs to bring new products to market is important.

3.3.4 Active Feedback Controls, Accelerator Instrumentation, Low-Level Radiofrequency Systems

Active feedback controls, specialized accelerator instrumentation, and low-level RF systems leveraging artificial intelligence, machine learning, and field-programmable gate arrays (FPGAs) are important to both improve accelerator and laser control as well as to extend performance. Suppliers of integrated systems are few and are largely in Europe. This is an emerging area in which dedicated investment could be useful.

3.3.5 Electron Microscopes

Electron microscopes (EMs) have become a staple in every research lab, with universities even having several basic EMs and national laboratories and some universities having advanced EMs. There are few EM vendors, and most are based in other countries. JEOL and Hitachi are based in Japan, and FEI (now part of Thermo Fisher Scientific) is based in the Netherlands. Nion Company is based in Washington state and makes specialized microscopes that are dedicated to scanning transmission electron microscopy under ultrahigh vacuum. Such specialized EMs are not essential for many user facilities and most laboratories training graduate students and postdocs. Microscopes are therefore often acquired from vendors outside the U.S.

3.3.6 Instruments and Systems Enabling Quantum Computing

Instrumentation and technologies to support quantum computing applications—referred to here as "quantum industry"—are quickly becoming of paramount importance. Today, the quantum industry depends on vendors specializing in supplying instruments and components for research applications. Measurement instrumentation, materials-growth instrumentation, cryogenics, lasers, and electronics are examples of the supporting technologies on which the quantum industry is dependent. Nearly all these fields are advanced by small niche research-oriented companies, national laboratories, and university laboratories.

The existing supply chain for quantum technologies is like many other scientific markets in that it lacks redundancy and robustness and, in some cases, has no domestic suppliers. There exists a heavy reliance on foreign suppliers today and some foreign sole-source suppliers. What is unique about the quantum supply chain is that it represents the foundation of a future industry that is expected to be larger than today's semiconductor market and carries special national security threats. Building a robust, agile, and scalable quantum supply chain now is imperative for U.S. leadership in the increasingly competitive emerging technology landscape. Provided here are some examples of quantum supply chain vulnerabilities that exist today.

- **Dilution refrigerators.** The number of vendors for dilution refrigerators is very limited, and most are overseas. This is a technology area where deep cryogenic expertise is required to be successful, and much of the world's legacy cryogenic expertise exists in foreign nations because the U.S. has invested very little into this area of science. About 70 to 80% of the world's dilution refrigerators come from one supplier, Bluefors in Finland. Further, dilution refrigerators are needed for quantum computing, as industrial products have not yet been developed. Many industry needs are not met with current solutions (e.g., scalability, higher throughput, reliability, serviceability, redundancy, and modularity).

- **Pulse-tube cryocoolers.** Every dilution refrigerator relies on at least one cryocooler and often multiple cryocoolers for larger systems. There is only one U.S. supplier for pulse tube cryocoolers and one foreign supplier. The U.S. supplier lacks significant development capabilities because it is a relatively small company serving primarily the research markets. Rare earth materials are necessary for every cryocooler to function. Holmium copper 2 ($HoCu_2$) is sourced from China and Russia. Processing of this material is necessary to produce tiny spheres appropriate for cryogen flow and heat transfer performance. There is one primary supplier in Japan, and it is unknown where the processing step occurs, but it is thought to also be processed in China due to significant cost savings. If so, there is potentially a double dependency on $HoCu_2$ on China and Russia for both the material and as the processing step. One supplier in the U.S. has attempted to perform the processing of $HoCu_2$ but has not yet reached adequate quality.
- **Compressor assembly.** Every cryocooler requires a compressor assembly, which depends on a scroll compressor that can compress helium gas. This is a specialty item that has been modified from the commercial refrigeration industry. There is currently only one supplier in Japan. The sole U.S. supplier stopped making this product due to a lack of profitability. This is now a sole-source supply chain issue that could stop production of cryocoolers, dilution refrigerators, and quantum computers.
- **Cryogenic electronics.** Products such as low-noise cryogenic amplifiers, quantum-limited amplifiers, high-density cryogenic signal transmission, and cryogenic passive components (e.g., isolators and circulators) represent a category of electronics that is currently being reinvented. None of the existing components were designed for use at cryogenic temperatures. They need to be miniaturized with new design constraints (e.g., low-temperature conductance, thermal conductivity, thermalization time, superconducting materials, local heating, and extremely low power generation). The existing supply chain and U.S. investment in these components are limited, while foreign nations are investing heavily in these areas. There are many new European start-ups in cryogenic electronic hardware but almost none in the U.S.

The commercial markets for many scientific instruments are small. Some are too small to support a sustainable business. Others may be large enough to support a business, but the infrastructure and development costs needed to get initial technology developed are too large for an investment payoff in a reasonable timeframe. Technologies within the quantum supply chain are similar to many scientific instrument markets in that the current markets are relatively small and require significant customization to a variety of customers to be successful. Profitable businesses can be built and sustained, but this often requires a unique approach and creative start-up financing. Many of these businesses become "lifestyle businesses" for the owner. This creates a common situation where the business dies with the owner or dissolves after the owner loses interest because the business lacks consistent cash flow, processes, documentation of procedures, documentation of intellectual property, and many of the things that make a business valuable and sustainable. These small businesses are critical to scientific progress, and in the case of the quantum supply chain, are critical to the development of quantum applications such as quantum computing. They are critical to the pace of innovation in quantum technologies. If such businesses disappeared, progress would stop. Conversely, if the U.S. quantum supply chain were given significant investment, U.S. progress in quantum technologies would accelerate.

What is unique about the quantum supply chain is that the industry is on the cusp of a tremendous scaling up as quantum computing is beginning to demonstrate capabilities beyond classical computing. However, hardware in the quantum supply chain is stuck because the relatively small markets today don't warrant significant investment, and the risk of investing in tomorrow's quantum scaleup has an uncertain timeframe.

3.3.7 High-Performance Computing

DOE is an international leader in high-performance computing (HPC), often fielding the most powerful and

Fig. 3.9. The newly built central energy plant serves power and cooling to the high-performance computing systems of the Oak Ridge Leadership Computing Facility, including the soon-to-be launched Frontier supercomputer. [Courtesy Oak Ridge National Laboratory]

complex HPC systems in the world. This capability is critical to maintaining U.S. leadership in science and technology, as well as for national security. DOE National Nuclear Security Administration is a partner with SC in this area. The National Science Foundation and other agencies (e.g., NOAA and NASA), also use large-scale HPC to further their missions.

Supply chain issues in HPC are largely driven by vendor supply chain problems and are resulting in unreasonably long delivery times. Large, first-of-their-kind, world-class HPC systems are provided by vendors that are sometimes called integrators because they integrate various components into an HPC system, including processors; coprocessors; accelerators; memory; data storage systems; and custom high-speed, low-latency networks, most of which are provided by other vendors. But these vendors are more than just integrators of microelectronic and other components provided by others, they add unique, highly sophisticated technical value like:

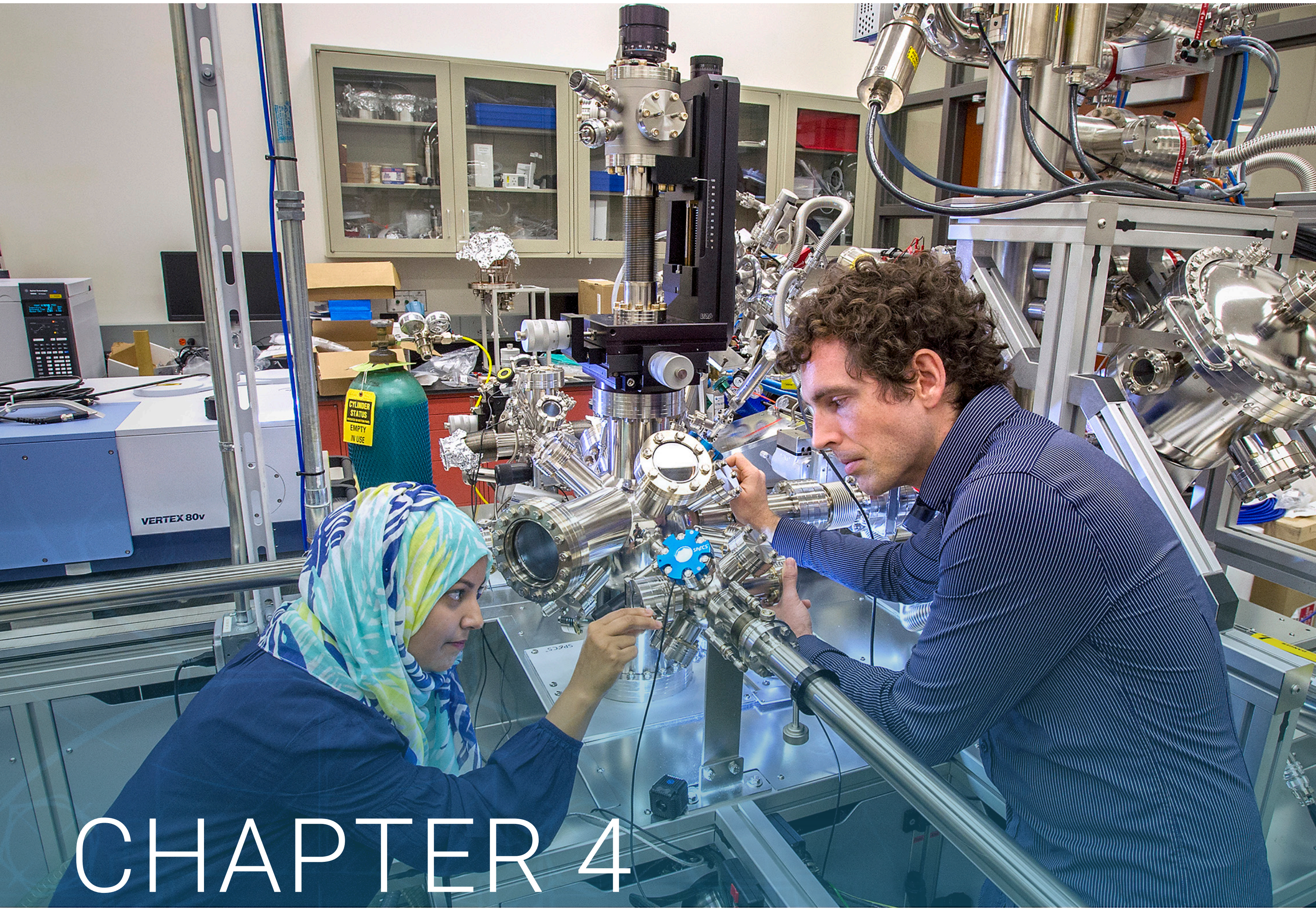
- Custom high-speed, low-latency network interconnects (a critical technology)
- Custom racking, electrical management, liquid cooling, packaging, resilience features (see Fig. 3.9, this page)
- Custom blades (motherboards)
- Custom system management software
- Custom network management software (switching, congestion management, routing optimization)
- Custom user environments, programming tools, software libraries

There are few domestic vendors with the ability to build and support such systems at the scale required to maintain U.S. leadership in HPC, and there is a risk of losing some of those. There are also a limited number of vendors and competing technologies for major system components like the high-speed network (e.g., vendor custom, Intel Omni-Path, Mellanox InfiniBand) and high-performance file systems (e.g., Lustre, IBM GPFS, BeeGFS).

In addition to the risk of having few domestic system providers, HPC is critically susceptible to supply chain problems with microelectronics—the materials needed to make them, manufacturing (which is often done in other countries), and delivery issues.

Governmental agencies drive the market for HPC systems at the cutting edge of technology and scale for systems that meet U.S. science and technology needs. While large data centers exist in the commercial sector, they are typically architected to address different computational problems (e.g., for Facebook or Google) and cannot accommodate the full breadth of U.S. science and engineering needs. Other countries (e.g., Japan, China) are actively competing to build the most powerful HPC systems to assume leadership in this area. As described above, these high-end HPC systems rely critically on the availability of components to construct the systems.

Programs like the Exascale Computing Project's PathForward initiative and its predecessors can help prepare the U.S. industry for advanced HPC system procurements and generally improve U.S. competitiveness in the worldwide computing market. Anything that increases the world supply of component parts (e.g., semiconductors and other electronic components) will help ensure timely delivery of procured systems.



CHAPTER 4

REDUCING SUPPLY CHAIN RISKS

Reducing Supply Chain Risks

From roundtable deliberations, several possible opportunities emerged, which potentially could mitigate many of the supply chain risks identified by the technical panels. These opportunities are organized in terms of the timeframe for which they may yield benefits.

4.1 Common Themes

Across the technologies considered by the roundtable, several themes represent risks throughout the SC enterprise. They include coordination of information, support for strategic R&D and vendor cultivation, and workforce development.

4.1.1 Coordination of Information

The information gathering undertaken by the panels illustrated that enhanced communication among stakeholders (i.e., SC, the laboratories, and potential vendors) could provide a better assessment of risk exposure and potential avenues for mitigation.

The current coordination of information regarding resource requirements across the laboratories is somewhat informal. It is often driven by personal networks or, in some instances, strategic collaborations on a specific project. To the extent that laboratories are funded by common program offices, they may share an awareness of common needs, but understandably the focus of a particular laboratory is on serving the needs of its community and not on the interests and needs of the broader laboratory community. Similarly, information regarding procurements and potential vendors is compartmentalized and held at the laboratory level.

A more holistic perspective—at least at a high level that factors in the needs across SC and communicates them to the laboratories and other potential stakeholders—may help reveal capabilities or opportunities that might otherwise be missed. Longer-term program roadmaps could be useful tools in the context of understanding and developing the necessary supply chains. A roadmap might also serve as a projection of the acquisition schedule and likely funding for a particular material or technology that could help potential domestic vendors assess the viability of entering (or perhaps not exiting) a market sector (see sidebar, Ecosystem Cultivation, p. 39).

Where commercial entry to source a need seems unlikely, coordination of capabilities across laboratories and other DOE resources or government agencies might help address supply chain risks more efficiently than individual laboratories duplicating effort or capability.

There are barriers to be addressed in understanding which information can be shared, as the laboratories are operated by different contractors and interactions with potential vendors are sometimes within the framework of nondisclosure agreements and other legal constraints.

4.1.2 Strategic Investment

During the roundtable deliberations, much was made specifically about Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) programs and limitations in scaling up to the delivery of material needed by SC. This largely arises from familiarity with the programs and the challenges encountered in executing work under their boundary conditions. Reporting requirements are significant, support levels are modest, and the duration is limited. Many participants felt these were barriers to supporting the level of R&D needed to meet even very specific near-term requirements. Nonetheless, the SBIR/STTR programs are a potential resource to cultivate domestic sources of critical components and systems.

At a high level, a strategic R&D ecosystem could support basic research and development activity at the national laboratories. Programs could be tailored to support early interaction and collaboration with potential vendors who could then develop and supply at scale the materials or technologies needed by SC. This approach might require a different framework than is available to SBIR and STTR programs, and development timelines might be longer, potentially requiring significant investment.

Efforts are needed not only to engage potential vendors in developing a supply chain for needed technologies and materials, but also to manage their risk exposure for these activities. Encouraging commercial interest will require reducing investment risks for vendors and demonstrating to them that time invested in developing a capability will ultimately be profitable. Even if relatively small, the business volume supporting SC needs could

Ecosystem Cultivation

Fostering Collaboration and Capability Sharing Among Researchers, DOE Labs, and Private Industry

The U.S. Department of Energy Office of Science has a long history of sponsoring multilaboratory collaborations as part of complex projects whose scope is beyond the capabilities of any single institution to deliver. Across the Office of Science ecosystem, successful examples—including the Spallation Neutron Source, Linac Coherent Light Source-II, and U.S. ITER project—illustrate the critical role partnerships play in filling capability gaps. In these cases, partner laboratories typically share responsibilities within their areas of expertise to mitigate risk and leverage existing relationships with a limited number of specialized vendors.

In addition to these partnerships, the Office of Science has created successful multi-institutional networks that not only foster collaboration among facilities and their researchers and users, but also engage and welcome private-sector partners. One such network is LaserNetUS, which the DOE Fusion Energy Sciences program established in August 2018 to enable U.S. scientific leadership in laser-driven, high-energy-density, and high-field optical sciences. LaserNetUS carries out this mission by:

1. Advancing the frontiers of laser-science research.
2. Providing students and scientists with broad access to unique facilities and enabling technologies.
3. Fostering collaboration among researchers and networks from around the world.

Since its inception, LaserNetUS has awarded more than 80 experimental runs across 10 facilities and has hosted over 400 users from more than 120 institutions, including 90 graduate students from the U.S. and Canada. The network, which is working to establish a common diagnostic program, has already enabled new science by using, for example, the diagnostic or optical capabilities from one facility to run experiments using the drivers at another facility. The sharing of capabilities or components among facilities will be key to sustained LaserNetUS operation.

A similar approach could be extended to provide solutions to common supply chain challenges, such as building capability and resilience through information sharing and improved networking across multiple projects or facilities. Collaboration among facilities develops mutual understanding and common requirements, which may aid market development. Such networks also facilitate growth of a broad scientific user base, helping expand the size of a field, which is a key driver of market response, particularly overseas investment. In addition, the ability to loan or transfer assets to support multiple facilities could mitigate the urgency of supply chain issues and facilitate concentration of orders. Moreover, this understanding could be used to pool procurements for added leverage, which would require funding coordination.

Takeaways

- *Collaboration and information sharing are key components of DOE Office of Science activities.*
- *A similar approach to LaserNetUS could enhance supply chain capabilities and resilience.*

Scientists set up an experiment at Lawrence Livermore National Laboratory's Jupiter Laser Facility, a member of LaserNetUS. [Courtesy Lawrence Livermore National Laboratory] be attractive to vendors if it proves stable, reliable, or at least predictable.

In some instances, SC facilities rely on manufacturing processes that are becoming obsolete and unprofitable in the general market. Reducing risk to the SC enterprise may require acquiring these capabilities or supporting their maintenance within the DOE complex.

SC also relies in many instances on materials processing that is not generally required in the larger market (for example high-purity materials). Sometimes these materials are not produced domestically due to the cost of producing relatively small quantities in an environmentally responsible manner. In such cases, where feasible, stockpiling and recycling of material might be considered, as well as reaching out to other government agencies to seek sound methods for their domestic supply in the quantities needed for SC missions.

4.1.3 Workforce Development

Workforce development, both in SC laboratories and for the potential vendors, arose in many areas as a concern. A great deal of information, particularly on specialty technologies, is based on institutional knowledge, which is lost as experts leave the workforce. Systematic development of specialty workforce members has not been part of the investment in supply chain stabilization or development.

For all SC enterprise sectors—from science programs to suppliers and manufacturers—another challenge has been the availability of a skilled scientific and technical workforce that is sufficiently fluent to drive and adapt to evolving technologies. People filling these roles are part of the supply chain and deserve attention and investment in that context to reduce supply chain risk overall. In this sense, the special opportunities and needs of the laboratories can serve as both a magnet and training ground for people to gain and improve their skills. Through these interactions, workers can participate in development of the needed materials and technologies as well as their production and delivery at scale.

4.2 Opportunities for Reducing Supply Chain Risk

The committee identified several possible opportunities that could mitigate many of the supply chain risks identified by the technical panels. These opportunities are organized in terms of the timeframe for which they may be implemented: Near term (0 to 2 years), mid term (2 to 5 years), and long term (>5 years).

4.2.1 Near-Term Opportunities (0 to 2 Years)

The following opportunities represent those requiring the lowest investment in resources and could yield benefits within the next 2 years.

DOE Laboratory Procurement Collaboration and Training

The DOE complex has an established Integrated Contractor Purchasing Team (ICPT) that is a collaboration among DOE and its Management & Operations sites to award strategic agreements that result in lower total cost of ownership for DOE contractors through reduced prices and streamlined procurement processes.

A possible solution to improve procurement collaboration is to expand the role of the ICPT to include recurring (semi-annual or quarterly) procurement conferences where designated procurement leads from each DOE national laboratory, including ICPT members, can share procurement challenges, mitigation strategies, best practices, and lessons learned. A logical follow-on would be to institute a DOE procurement leadership training program, which would consolidate and organize procurement best practices across the complex. The curriculum could include case studies of past procurements. Encouraging procurement collaboration and advanced education opportunities will enable each organization to continually elevate their respective procurement knowledge and capabilities and raise the level of expertise across the complex.

Vendor Database

The committee discussed the benefits of an SC-wide database of foreign and domestic vendors, including vendor capabilities, a list of successfully completed contracts, and technical and procurement contacts. The database would track vendors' performance on recent DOE contracts, and a rating system could be utilized to rank vendors based on their past performance. Each laboratory could access the database to search for potential vendors for upcoming requirements. In the long term, the tool could be used as a method to motivate vendor performance (e.g., quality, schedule, and cost).

Developing Partnerships with Vendors

DOE SC facilities require highly complex components and systems often sold only in low volumes or as one-offs, and ordering patterns are irregular and hard to predict. The following initiatives could address the supply chain issues in the near term:

- Developing partnerships with potential vendors to create interest and capabilities to supply components and services
- Increasing risk sharing with these vendors, for example through implementing time and materials contracts rather than fixed-price contracts, which tend to discourage vendors from entering proposals or cause vendors to build in high costs to cover hard-to-estimate risks
- Considering bundling common needs across DOE facilities to make finding solutions more appealing to suppliers
- Utilizing conferences and workshops with industry participation and other means of outreach to potential vendors to highlight DOE SC needs and opportunities for collaborations to vendors
- Providing anticipated DOE-wide, near-term, and long-term demand information on specific components to vendors, which might help their business decisions and engagement with DOE facilities, in addition to helping them chart a course for technological advancement
- Simplifying the bid and procurement process to encourage vendors interested in working with DOE national laboratories

Sufficient Support for Essential Software Developments at National Laboratories

To reduce supply chain risk for scientific software, sufficient funding is essential for the development of scientific software and software frameworks as part of DOE projects and facility operations. Special instrumentation requires extensive, bespoke solutions in both control and data acquisition and analysis. The coordination of scientific software development across institutions and potentially even internationally will ensure the best use of resources as well as compatibility and synergies between solutions. Training and retaining software engineers who have an in-depth understanding of the underlying science and establishing a well-defined career path for scientific software engineers will be important since the competition for talent in this domain is high.

4.2.2 Mid-Term Opportunities (2 to 5 Years)

The following opportunities require a greater investment in resources than those described above and could yield benefits in the next 2 to 5 years.

Centers of Excellence

Centers of Excellence could be developed by identifying core capabilities at each DOE laboratory for fabrication and assembly of critical scientific equipment. A coordinated “make or buy” decision would identify which components should be fabricated or assembled within the DOE complex and those that should be procured from industry. Multiple Centers of Excellence could be designated for critical components and assemblies as incubators for maintaining expertise and to provide alternative solutions to items for which there is limited or no qualified commercial suppliers.

Shared Inventory

An SC-wide inventory management system could offer the potential for reduced waste, sharing of common equipment, and cost savings. The database could include critical components, materials, and equipment at each laboratory. This inventory could then be used to identify excess equipment, which may be utilized by other laboratories within the lab complex.

Resiliency

Government procurement decisions could include scoring for resiliency to ensure supply and quality while also demonstrating systematic risk management. To improve anticipatory and operational resiliency, national laboratories and university computational capabilities could be leveraged to strengthen public and private modeling and simulation of operational risk and the ability to adapt.

Competitiveness Analysis

A competitiveness analysis could be performed to understand if specific industries, materials, or supply chain steps should receive government support to maintain or build a domestic capability. This type of analysis would identify unacceptable risk and the impact and effectiveness of policy steps.

Cross-Laboratory Supply Chain Forecasting

Domestic manufacturing and supply chain limitations need to be understood and quantified, including beyond first-tier suppliers. Connecting improved supply chain visibility and identification of critical future demand lays the foundation for development of mitigation strategies at the DOE, laboratory, and project levels.

Aligning the Starts

Launching a Small Business for Scientific Instrumentation in the U.S. Today

Often overshadowed by commercial titans, small entrepreneurial niche suppliers contribute significantly to the success of DOE Office of Science missions by providing critical technology and expertise. Although launching any small business is challenging (most fail within a year of start-up), new businesses that are highly technical and specialized are especially challenged. Markets can be small, highly variable, and, in some cases, vulnerable to emerging technological developments.

In the examples of Montana Instruments and Inprentus, the entrepreneurs had the advantage of being deeply versed in their respective technologies, and they recognized unique opportunities to meet very specialized market needs. Instead of "waiting for the stars to align," these entrepreneurs aligned the starts of their business to carve out and fill specialized niches.

Takeaways

- *Technically experienced people founded two start-ups by recognizing unmet needs and in those, a business opportunity.*
- *Both examples highlight the need for engagement to provide products the market needs and wants.*
- *Neither firm sought SBIR support, perceiving it as unduly limiting their business development.*

Montana Instruments

Montana Instruments is a contemporary example of a successful scientific supply chain company born of entrepreneurial spirit, private capital initial investment, and business mentorship. The company manufactures high-precision electrical, optical, and cryogenic products for quantum computing, quantum education, quantum networking, and quantum materials research. Nearly 1,000 of its cryogenic platforms are used by commercial system engineers and quantum scientists in universities and research centers around the world. Examples like Montana Instruments illustrate that opportunities for U.S. companies to launch and then grow to become best in class are as possible today as ever before.

Luke Mauritsen, founder of Montana Instruments, had experience developing cryogenic technologies for defense applications under Small Business Innovation Research (SBIR) and other government contracts. Recognizing many of the challenges of experiments at low temperatures, he set about re-inventing the optical cryostat.

Montana Instruments CryoAdvance™ turnkey cryogenic system for quantum materials and device characterization. [Courtesy Montana Instruments]

Mauritsen connected with a mentor, an owner of a scientific instrument company, who wanted to invest in his new product idea. Montana Instruments did not seek SBIR funding because the funding profile (amount and award duration) and the intellectual property rights and

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Supporting and Expanding U.S. Small Business Ecosystems for Scientific Components and Systems

DOE facilities utilize components for scientific applications supplied by small businesses, for example, X-ray gratings, sample holders, and sample environments for X-ray and neutron beamlines. The demand for these components is comparatively consistent over time, and while the product specifications are constantly evolving, vendors interested in further developing their products can address this demand (see sidebar, Aligning the Starts, this page). To support and expand the ability of the U.S. small business ecosystem to supply these components and systems, the following steps could be taken:

- Assist domestic suppliers to improve their product specifications to meet DOE SC needs through partnerships with DOE national laboratories or

Continued from previous page

obligations did not meet business and investor needs. Instead, with modest start-up funding of $400,000 and investor mentorship, Montana Instruments began working with potential customers to discuss their needs and understand their diverse challenges at low temperatures. These discussions led to an exciting new design, and the idea of “Cold Science Made Simple” was born, freeing scientists to think about what to do with their experiments when they were cold, not about how to get them cold.

After 2 years of working with customers and delivering this novel technology, news about the product and product support spread, and sales grew fourfold. Montana Instruments has continued its growth trajectory and successfully created a high-end cryogenic systems market.

Inprentus

X-ray gratings for synchrotron and free-electron laser light sources make spectroscopy possible, driving these facilities’ fundamental scientific capabilities. However, the worldwide market for gratings is highly specialized, relatively low volume, and challenged by tight manufacturing tolerances and custom designs. When the 2011 Fukushima earthquake permanently knocked out the leading Japanese gratings vendor, the opportunity arose to make the supply chain more robust. Enter Inprentus, founded by Peter Abbamonte, a University of Illinois professor and former beamline scientist at Brookhaven National Laboratory.

Selection of X-ray gratings fabricated by Inprentus in the U.S. [Courtesy Inprentus]

With leftover project funding and a green light from the National Science Foundation, Abbamonte co-developed a novel grating-writing technology and built it into a venture-backed company that is now a leading gratings manufacturer. Inprentus supplies X-ray facilities worldwide and is branching into other markets. Located in Champaign, Illinois, the company has access to a highly qualified, technical workforce. Bucking the traditional model of building unique ruling engines for each type of grating and reliance on expert senior craftsmen, Inprentus developed a scalable manufacturing platform with tools that can be assembled from commercially available components and operated by trained staff.

According to Inprentus Vice President Marty Dugan, “The most important missing element for continued technological advancement is engagement.” Although leading X-ray facilities have overlapping and similar needs, the coordination and planning required to enable vendors to meet future demands do not yet exist. A working group that includes facilities, vendors, scientists, and beamline designers could chart a roadmap for technological development and work together. For example, standardization among grating substrate form-factors and other aspects could improve yield and delivery times.

targeted investments in fabrication tools, R&D, and expertise.

- Support expert staff at national laboratories working on problems and questions related to mission needs that are strongly affected by supply chain problems.
- Strategically target projects at the national laboratories that could be spun-off into private ventures.
- Help transition scientific staff into spin-offs as is common at European scientific facilities.

4.2.3 Long-Term Opportunities (5 to 10 Years)

The following opportunities will likely have the greatest long-term benefits to the domestic supply chain. Due to their complexity, they will require further development, possible significant investment in funds or resources, and could yield benefits in 5 to 10 years.

Critical Component R&D Technology Transfer

In conjunction with the supply chain forecasting described above, results could be utilized to identify critical components for aggressive and well-funded R&D programs at the national laboratories. Efforts could be focused on developing and maintaining state-of-the-art capabilities for eventual transfer to industry partners for production. Continued R&D funding beyond the point of technology transfer will enable suppliers' sustainment and further market capitalization.

DOE and Industry Collaboration

Consortia opportunities could be developed with major commercial firms. In addition, potential spin-off technologies, which offer commercial opportunities to encourage industry investment, could be identified and leveraged through these collaborations. DOE and the national laboratories could coordinate with industry leaders to transfer the technology. A government-academic-industry partnership could explore models of collaborations among laboratories, universities, and industry partners where investments and risks are shared appropriately to develop market solutions.

Other countries have strong and successful government-industry partnerships. They focus on developing key technologies that are vital for the future of the national scientific enterprise and on enabling the commercial exploitation of this work by business and industry. In that capacity, they play a central role in the innovation process and often pioneer or catalyze groundbreaking developments and promote scientific excellence. These partnerships represent a mutual, highly beneficial relationship employing innovation to bridge the gap between basic research and manufacturing, creating new spin-off companies, and drawing on extensive know-how to help scientific and industrial partners excel. Examples of such partnerships are the Fraunhofer Gesellschaft in Germany, CEA-Leti in France, and IMEC in Belgium. Basic funding for these partnerships is provided by the government, but the majority of revenue is earned through contract work, either for government, government-sponsored projects, or from industry.

Cross-Laboratory Purchasing Agreements

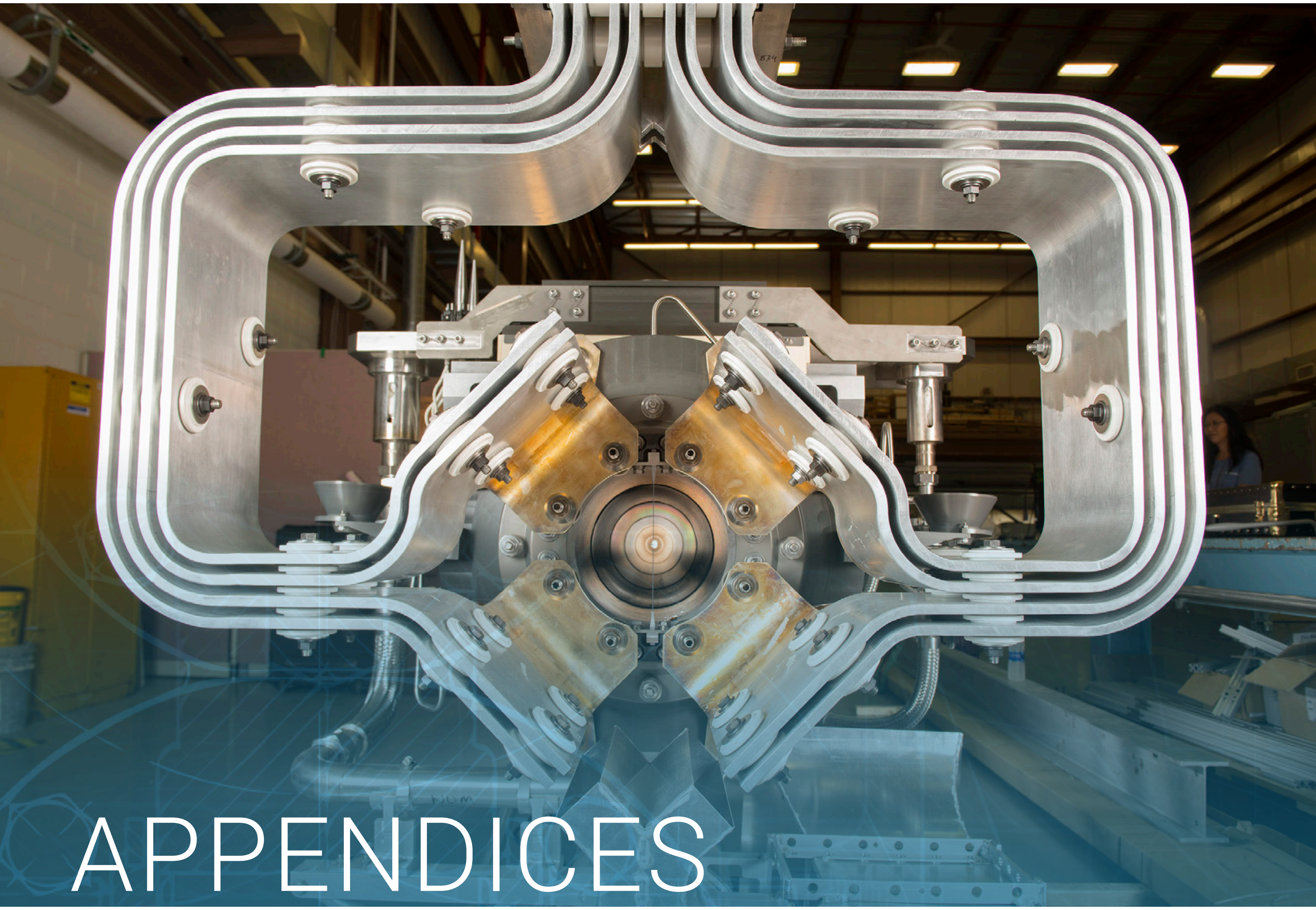
Partnering mechanisms could be instituted between DOE laboratories that would be most effective at supporting a long-term supplier base. Long-term supply chain demands could be identified throughout the complex, as described above. The timing of purchases for identical items could be coordinated to create bulk subcontract and purchasing agreements to supply items to multiple laboratories.

DOE Laboratory Career Development Program

An opportunity exists to initiate an SC-wide career development program to identify career opportunities for critical, hard-to-retain skill sets needed within the laboratory complex to mitigate against the loss of technical experts to the commercial industry. This program could also address the laboratories' ability to hire qualified candidates. The program could re-evaluate salary and benefits packages in comparison to industry to become more competitive and attract highly skilled applicants.

Partnerships with Private Investors to Develop Emerging Markets

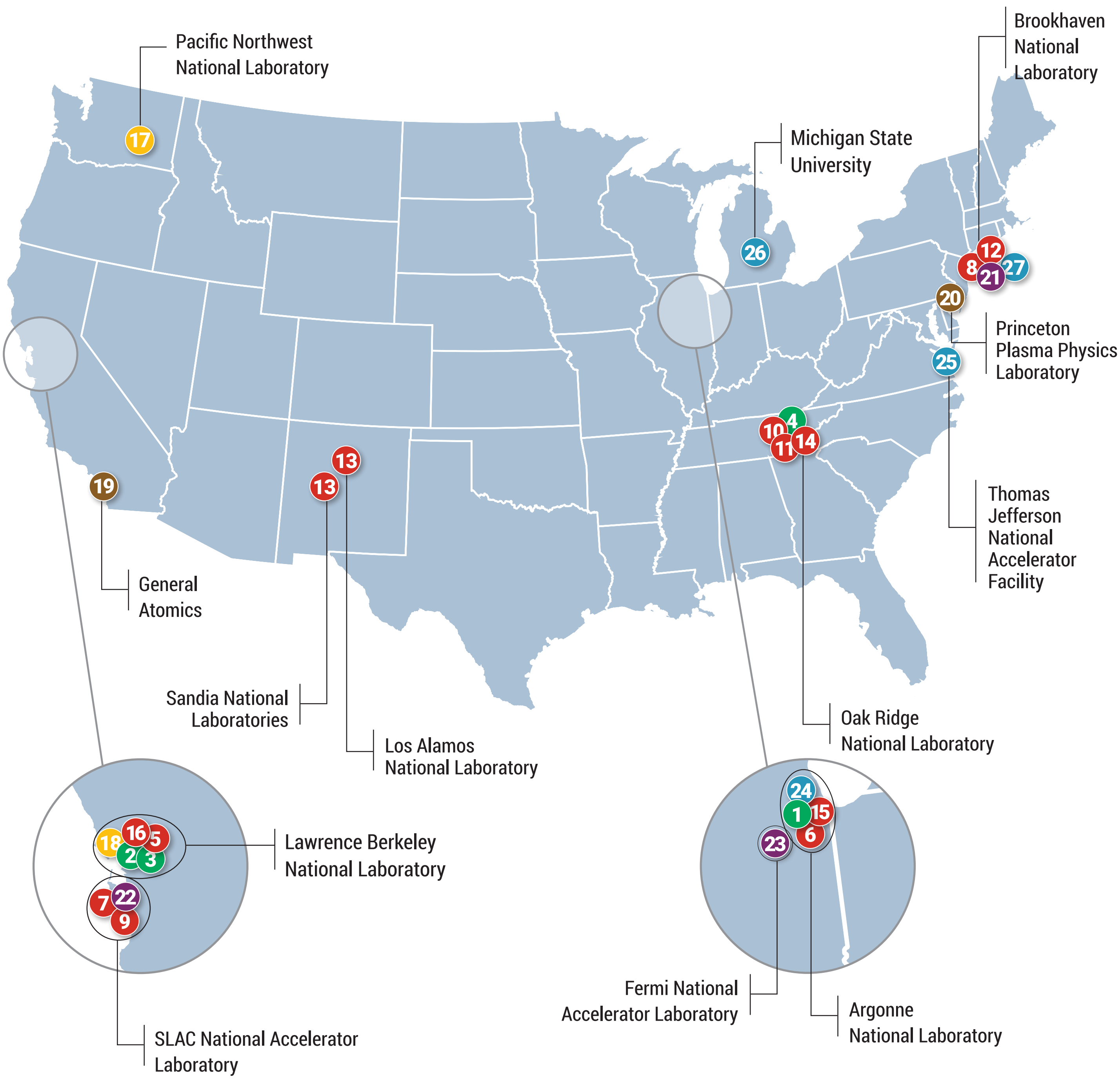
There are some areas within the scientific facilities and tools supply chain where a small market exists and is anticipated to grow substantially, but a reliable domestic supply chain has not been developed. One promising way to build the domestic supply chain could be through formalized public-private partnerships where public entities invest in the development of those supply chains in important emerging scientific areas.



APPENDICES

Appendix A

U.S. Department of Energy Office of Science User Facilities, FY 2022



Advanced Scientific Computing Research (ASCR)

1 **Argonne Leadership Computing Facility (ALCF)**
Argonne National Laboratory

2 **Energy Sciences Network (ESnet)**
Lawrence Berkeley National Laboratory

3 **National Energy Research Scientific Computing Center (NERSC)**
Lawrence Berkeley National Laboratory

4 **Oak Ridge Leadership Computing Facility (OLCF)**
Oak Ridge National Laboratory

Basic Energy Sciences (BES)

LIGHT SOURCES

5 **Advanced Light Source (ALS)**
Lawrence Berkeley National Laboratory

6 **Advanced Photon Source (APS)**
Argonne National Laboratory

7 **Linac Coherent Light Source (LCLS)**
SLAC National Accelerator Laboratory

8 **National Synchrotron Light Source II (NSLS-II)**
Brookhaven National Laboratory

9 **Stanford Synchrotron Radiation Lightsource (SSRL)**
SLAC National Accelerator Laboratory

NEUTRON SOURCES

10 **High Flux Isotope Reactor (HFIR)**
Oak Ridge National Laboratory

11 **Spallation Neutron Source (SNS)**
Oak Ridge National Laboratory

NANOSCALE SCIENCE RESEARCH CENTERS

12 **Center for Functional Nanomaterials (CFN)**
Brookhaven National Laboratory

13 **Center for Integrated Nanotechnologies (CINT)**
Sandia National Laboratories and
Los Alamos National Laboratory

14 **Center for Nanophase Materials Sciences (CNMS)**
Oak Ridge National Laboratory

15 **Center for Nanoscale Materials (CNM)**
Argonne National Laboratory

16 **The Molecular Foundry (TMF)**
Lawrence Berkeley National Laboratory

Biological and Environmental Research (BER)

Atmospheric Radiation Measurement (ARM) User Facility
Multi-Site Global Network

17 **Environmental Molecular Sciences Laboratory (EMSL)**
Pacific Northwest National Laboratory

18 **Joint Genome Institute (JGI)**
Lawrence Berkeley National Laboratory

Fusion Energy Sciences (FES)

19 **DIII-D National Fusion Facility**
General Atomics

20 **National Spherical Torus Experiment Upgrade (NSTX-U)**
Princeton Plasma Physics Laboratory

High Energy Physics (HEP)

21 **Accelerator Test Facility (ATF)**
Brookhaven National Laboratory

22 **Facility for Advanced Accelerator Experimental Tests (FACET)**
SLAC National Accelerator Laboratory

23 **Fermilab Accelerator Complex**
Fermi National Accelerator Laboratory

Nuclear Physics (NP)

24 **Argonne Tandem Linac Accelerator System (ATLAS)**
Argonne National Laboratory

25 **Continuous Electron Beam Accelerator Facility (CEBAF)**
Thomas Jefferson National Accelerator Facility

26 **Facility for Rare Isotope Beams (FRIB)**
Michigan State University

27 **Relativistic Heavy Ion Collider (RHIC)**
Brookhaven National Laboratory

Appendix B

Roundtable Charter

Chartered by: The U.S. Department of Energy (DOE) Office of Science (SC) Office of the Deputy Director for Science Programs in collaboration with DOE Office of Science Programs.

Mode: A virtual plenary kickoff followed by asynchronous virtual panel discussions and writing over two weeks supported by virtual collaboration tools. A virtual wrap-up plenary session for panels to report out and for the co-chairs to present findings.

When: Plenary kickoff – Tuesday, November 2, 12:00 p.m. – 4:00 p.m. ET

Roundtable check-in and discussion – Tuesday, November 9, 12:00 p.m. – 4:00 p.m. ET

Wrap-up plenary – Tuesday, November 16, 12:00 p.m. – 4:00 p.m. ET

Planning Team: Co-chairs, with Eric Colby, Kurt Fisher, and Natalia Melcer representing the Office of Science. A program committee of the co-chairs and panel leads would be the engine of program planning and execution.

Attendees: By invitation only, including representatives from industry (including small businesses), national laboratories, and academia with expertise in procurement and relevant technology areas.

Deliverable: A report identifying supply chain risks and opportunities for reducing supply chain risk by December 2021.

Motivation: Recent Executive Orders (EOs) emphasize domestic manufacturing and investment in domestic supply chains. EO 14005 states that the U.S. government should, whenever possible, procure goods, products, materials, and services from sources that will help American businesses compete in strategic industries and help America's workers thrive.[1] EO 14017 focuses on strengthening the resilience of America's supply chains.[2] A recent memorandum from the Office of Management and Budget describes the process that will be undertaken to reduce the need for waivers from Made in America laws.[3]

Expanding domestic capabilities for highly technical and specialized materials, equipment, and components that support the Office of Science's facilities, instruments, and experiments is critical to maintaining and fulfilling the Office of Science mission and for the national and economic security of the United States.

There is a significant and growing need for a technically proficient domestic industrial base that can provide the increasingly high technology components for Office of Science facilities, instruments, and experiments. At the same time, domestic industrial sources and expertise in critical technologies have waned. For example, reductions in federally funded long-term accelerator R&D over the past decade, coupled with marginal domestic markets for accelerator technologies, have resulted in weakening of the domestic accelerator technology production capability. Meanwhile, other countries have subsidized and invested in key technology areas over decades to establish leadership in those areas.

The Office of Science is convening this roundtable to gather information about current supply chain risks in key technology areas and to explore opportunities, possible partnerships, and mechanisms to strengthen the domestic supply chain. The roundtable is focused on technology areas that are unique to the Office of Science and/or play a critical role in achieving our mission.

[1] EO 14005 of January 25, 2021: "Ensuring the Future Is Made in All of America by All of America's Workers."
[2] EO 14017 of February 24, 2021: "America's Supply Chains."
[3] M-21-26 on June 11, 2021: "Increasing Opportunities for Domestic Sourcing and Reducing the Need for Waivers from Made in America Laws."

Roundtable Discussion Topics

Surveying the Scope of Need

Accelerator Systems (Panel 1)

- Magnets
  - Normal and superconducting, accelerator, high field, and fusion confinement
- Superconducting radiofrequency cavities
- Laser technologies
- Radiofrequency power production technologies
  - Vacuum electronic devices: klystrons, magnetrons, inductive output tubes (IOTs), triodes, gyrotrons, etc.
  - Solid state amplifiers
- Particle source technologies
- Cryoequipment/cryoplants
- Relevant software
- Relevant control systems

Detector Systems (Panel 2)

- Calorimeters
- Trackers
- Application-specific integrated circuit (ASIC) design and fabrication
- Material purity
- Data analysis
- Quantum devices
- Relevant software
- Relevant control systems

Instrument and Target Systems (Panel 3)

- High-end analytical equipment (e.g., electron microscopes—high speed, high resolution)
- Robotics/remote sample handling—laboratory instruments, light sources, isotope production
- Target technologies
- Light source end stations (beamlines)
- Laser technologies, not connected to accelerators [e.g., Office of Science programs—Fusion Energy Sciences (LaserNetUS), Basic Energy Sciences (pump-probe experiments)]
- Relevant software
- Relevant control systems

Specialty Materials, Machining, Manufacturing (Panel 4)

- Highly radiation-tolerant materials
- Magnet materials
- Silicon photonics
- Niobium
- Rare earths
- Optics
- High-performance computing

- High-temperature superconductor materials
- High-purity diamonds
- Lithography

Crosscutting Issues (Panel 5)

- Procurement
- Business impediments
- Buy American
- Risk

Exclusions

- The mission of the DOE Isotope R&D and Production (Isotope) Program is to manage the supply chain for critical radioactive and stable isotopes that are not available commercially. Thus, isotope supply chains and isotope separations and production technologies are not included in the scope of this roundtable. The committee is encouraged to note any isotopes of interest, and the DOE Isotope Program will follow up with a supply chain assessment using established processes.
- Helium

Understanding the State of the Domestic Supply

1. Which materials, components, or systems present a supply chain risk (sole source or foreign source) for achieving the Office of Science mission?
2. Identify the risk (low/medium/high) and impact (low/medium/high) for each identified vulnerability and the current provider/source.
3. What discrepancies currently exist between DOE user facility needs and existing market capabilities?
4. Where do vendors see specific market failures that prevent a viable business model for supporting DOE needs?

Opportunities for Reducing Supply Chain Risk

1. Where would federal intervention be a prudent and cost-effective way to address supply chain risks for DOE facilities?
2. What partnering mechanisms would be most effective at supporting a long-term supplier base?

Appendix C

Roundtable Agenda

Agenda times are Eastern Time Zone. Plenary and breakout sessions via Zoom.

Tuesday, November 2, 2021		
12:00 p.m. – 12:10 p.m.	Welcome/Charter	Harriet Kung, U.S. Department of Energy
12:10 p.m. – 12:30 p.m.	Microelectronics Supply Chain Risk Management Strategies at NASA	Jonathan Pellish, National Aeronautics and Space Administration
12:30 p.m. – 12:50 p.m.	Manufacturing USA and Technology Development: Strengthening U.S. Manufacturing and Supply Chains	Michael Molnar, National Institute of Standards and Technology
12:50 p.m.– 1:10 p.m.	Mars Perseverance Rover	Matthew Wallace, National Aeronautics and Space Administration
1:10 p.m. – 1:30 p.m.	Panel Discussion	Plenary Speakers
1:30 p.m. – 1:50 p.m.	Committee Discussion	Co-Chairs
1:50 p.m. – 2:00 p.m.	Break	
2:00 p.m. – 3:30 p.m.	Panel Breakouts	Panel Leads
3:30 p.m. – 4:00 p.m.	Reconvene for Discussion	Co-Chairs
4:00 p.m.	Adjourn	

Tuesday, November 9, 2021		
12:00 p.m. – 12:05 p.m.	Welcome/Opening Remarks	Co-Chairs
12:05 p.m. – 12:20 p.m.	Panel 1 Update – Accelerator Systems	Thomas Glasmacher, Michigan State University/Facility for Rare Isotope Beams Andrei Seryi, Thomas Jefferson National Accelerator Facility
12:20 p.m. – 12:35 p.m.	Panel 2 Update – Detector Systems	Marcel Demarteau, Oak Ridge National Laboratory Peter Denes, Lawrence Berkeley National Laboratory
12:35 p.m – 12:50 p.m.	Panel 3 Update – Instrument and Target Systems	Elke Arenholz, Oak Ridge National Laboratory Susana Reyes, SLAC National Accelerator Laboratory
12:50 p.m. – 1:05 p.m.	Panel 4 Update – Specialty Materials, Machining, and Manufacturing	Kathleen Amm, Brookhaven National Laboratory Allison Lung, Thomas Jefferson National Accelerator Facility

1:05 p.m. – 1:20 p.m.	Panel 5 Update – Crosscutting Issues	Jarrod Fitzpatrick, SLAC National Accelerator Laboratory Roberta Leftwich-Vann, Lawrence Berkeley National Laboratory
1:20 p.m. – 1:50 p.m.	Discussion	Co-Chairs
1:50 p.m. – 2:00 p.m.	Break	
2:00 p.m. – 3:30 p.m.	Panel Breakouts	Panel Leads
3:30 p.m. – 4:00 p.m.	Reconvene for Discussion	Co-Chairs
4:00 p.m.	Adjourn	

Tuesday, November 16, 2021		
12:00 p.m. – 12:15 p.m.	Welcome/Opening Remarks	Co-Chairs
12:15 p.m. – 12:45 p.m.	Panel 1 Report – Accelerator Systems	Thomas Glasmacher, Michigan State University/Facility for Rare Isotope Beams Andrei Seryi, Thomas Jefferson National Accelerator Facility
12:45 p.m. – 1:15 p.m.	Panel 2 Report – Detector Systems	Marcel Demarteau, Oak Ridge National Laboratory Peter Denes, Lawrence Berkeley National Laboratory
1:15 p.m. – 1:45 p.m.	Panel 3 Report – Instrument and Target Systems	Elke Arenholz, Oak Ridge National Laboratory Susana Reyes, SLAC National Accelerator Laboratory
1:45 p.m. – 2:00 p.m.	Break	
2:00 p.m. – 2:30 p.m.	Panel 4 Report – Specialty Materials, Machining, Manufacturing	Kathleen Amm, Brookhaven National Laboratory Allison Lung, Thomas Jefferson National Acceleratory Facility
2:30 p.m. – 3:00 p.m.	Panel 5 Report – Crosscutting Issues	Jarrod Fitzpatrick, SLAC National Accelerator Laboratory Roberta Leftwich-Vann, Lawrence Berkeley National Laboratory
3:00 p.m. – 4:00 p.m.	Discussion	Co-Chairs
4:00 p.m.	Adjourn	

Appendix D

Roundtable Participants

Co-Chairs

Erik Johnson
Brookhaven National Laboratory

Fulvia Pilat
Oak Ridge National Laboratory

Hekima Qualls
Princeton Plasma Physics Laboratory

Accelerator Systems (Panel 1)

Thomas Glasmacher, co-lead
Michigan State University/Facility for Rare Isotope Beams

Andrei Seryi, co-lead
Thomas Jefferson National Accelerator Facility

Monica Blank
Communications & Power Industries

Rao Ganni
Michigan State University/Facility for Rare Isotope Beams

Cameron Geddes
Lawrence Berkeley National Laboratory

Joe Grames
Thomas Jefferson National Accelerator Facility

Mike Kelly
Argonne National Laboratory

Jim Kerby
Argonne National Laboratory*

Daniela Leitner
Lawrence Berkeley National Laboratory

Michael Parizh
GE Global Research

Ted Roark
C.F. Roark Welding & Engineering Co., Inc.

James Rochford
Brookhaven National Laboratory

Marc Ross
SLAC National Accelerator Laboratory

William Tulloch
Coherent, Inc.

Katherine Wilson
Thomas Jefferson National Accelerator Facility*

Detector Systems (Panel 2)

Marcel Demarteau, co-lead
Oak Ridge National Laboratory

Peter Denes, co-lead
Lawrence Berkeley National Laboratory

Allison Bennett Irion
Argonne National Laboratory*

Rejean Boivin
General Atomics

Tim Bolton
Kansas State University

Gabriella Carini
Brookhaven National Laboratory

Nancy Hess
Pacific Northwest National Laboratory

Roberta Leftwich-Vann
Lawrence Berkeley National Laboratory*

Gregg Panning
SkyWater Technology

Thomas Shutt
SLAC National Accelerator Laboratory/Stanford University

Bernd Surrow
Temple University

Joel Ullom
National Institute of Standards and Technology

Instrument and Target Systems (Panel 3)

Elke Arenholz, co-lead
Oak Ridge National Laboratory

Susana Reyes, co-lead
Oak Ridge National Laboratory

Félicie Albert
Lawrence Livermore National Laboratory

Ilke Arslan
Argonne National Laboratory

Simon Billinge
Columbia University

Jarrod Fitzpatrick
SLAC National Accelerator Laboratory*

Daniel Flath
SLAC National Accelerator Laboratory

Kenneth Goldberg
Lawrence Berkeley National Laboratory

Kevin Lyons
Rutgers University*

Mark Lyttle
Oak Ridge National Laboratory

Luke Mauritsen
Montana Instruments

Christopher Saldana
Georgia Institute of Technology

Wenbing Yun
Sigray, Inc.

Specialty Materials, Machining, and Manufacturing (Panel 4)

Kathleen Amm, co-lead
Brookhaven National Laboratory

Allison Lung, co-lead
Thomas Jefferson National Accelerator Facility

Sterling Backus
Thorlabs, Inc.

Lance Cooley
Florida State University

Ruben Fair
Princeton Plasma Physics Laboratory

James Fast
Thomas Jefferson National Accelerator Facility

Richard Gerber
Lawrence Berkeley National Laboratory

Patrick Hurh
Fermi National Accelerator Laboratory

Andrea Jarrett
Commonwealth Fusion Systems

Thomas Lograsso
Ames Laboratory

Vito Lombardo
Fermi National Accelerator Laboratory*

Jeff Parrell
Bruker OST LLC

Nick Perry
Oak Ridge National Laboratory*

Yuri Shvyd'ko
Argonne National Laboratory

John Smith
General Atomics*

Crosscutting Issues (Panel 5)

Jarrod Fitzpatrick, co-lead
SLAC National Accelerator Laboratory

Roberta Leftwich-Vann, co-lead
Lawrence Berkeley National Laboratory

Allison Bennett Irion
Argonne National Laboratory

Jim Kerby
Argonne National Laboratory

Vito Lombardo
Fermi National Accelerator Laboratory

Kevin Lyons
Rutgers University

Nick Perry
Oak Ridge National Laboratory

John Smith
General Atomics

Katherine Wilson
Thomas Jefferson National Accelerator Facility

**Also member of the Crosscutting Issues Panel*

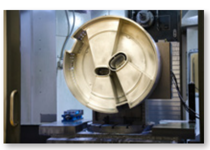
Appendix E

Select Image Credits

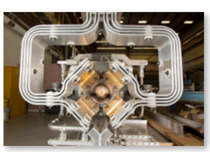
Image credits for which a caption is not already included.

Cover, p. 12. View of the inside of the NSTX-U vessel from the bottom looking upwards along the device center stack. The High Harmonic Fast Wave antenna is on the upper right, neutral beam armor on the upper left, and two concentric rows of passive plates can be seen outside the divertor plasma facing components at the very top the vessel. [Courtesy Princeton Plasma Physics Laboratory]

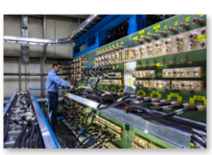
Cover. The heart of the STAR detector at Brookhaven's Relativistic Heavy Ion Collider is the Time Projection Chamber which tracks and identifies particles emerging from ion collisions. By using powerful computers to reconstruct the subatomic interactions that produce the particles emerging from each collision, the detector can, in a sense, run time backwards. This process can be compared to examining the final products coming from a factory and trying to determine what kinds of machines produced them. [Courtesy Brookhaven National Laboratory]



Cover. Cadmium machining facility at ORNL. The piece being machined in the photos is the SNS Inner Reflector Plug Moderator Housing. [Courtesy Oak Ridge National Laboratory]

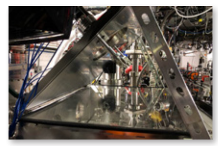


Cover, p. 45. A neutrino horn capable of handling one megawatt of particle beam is prepared at Fermilab in advance of the Deep Underground Neutrino Experiment. [Courtesy Fermilab]

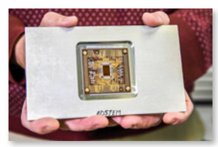


Executive Summary, back cover. A staff member makes connections between power supplies and electromagnetic coils on a "patch panel" at the DIII-D National Fusion Facility hosted by General Atomics in San Diego, California. [Courtesy General Atomics]

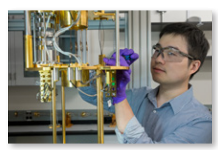
Back cover. A 9-Cell Superconducting Radio Frequency Cavity being inserted into a vacuum oven to manufacture a superconducting RF cavity for particle acceleration. [Courtesy Fermi National Accelerator Laboratory]



Back cover, p. 1. This experimental chamber at the Accelerator Test Facility (ATF) is used to study laser wakefield acceleration by harnessing ATF's unique nine-micron wavelength laser system. [Courtesy Brookhaven National Laboratory]



Back cover. Sensor for the 4D CAMERA used at the National Center for Electron Microscopy at the Molecular Foundry for phase contrast ptychographic imaging, nanoscale strain mapping, and other high-speed electron diffraction. The detector can take pictures at 100,000 frames per second. [Courtesy Lawrence Berkeley National Laboratory]



p. 3. Center for Nanoscale Materials (CNM) scientist Dafei Jin preparing for a measurement using a dilution refrigerator in the CNM Quantum Matter and Devices laboratory. [Courtesy Argonne National Laboratory]

p. 37. Scientists at the Center for Functional Nanomaterials (CFN) load a sample for *in situ* spectroscopy measurements. This state-of-the-art instrument allows for the study of chemical reactions at surfaces under elevated pressures through a combination of vibrational and photoelectron spectroscopy. [Courtesy Brookhaven National Laboratory]

Appendix F

Acronyms and Abbreviations

AGFA Argonne Gas-Filled Analyzer

ALS Advanced Light Source

AMO Advanced Manufacturing Office

APS Advanced Photon Source

ARPA-E Advanced Research Projects Agency – Energy

ASIC application-specific integrated circuit

ATLAS Argonne Tandem Linac Accelerator System

Be beryllium

BER Office of Biological and Environmental Research

BES Office of Basic Energy Sciences

Bi-2212 bismuth strontium calcium copper oxide

BNB Booster Neutrino Beamline

BNL Brookhaven National Laboratory

CBMM Companhia Brasileira de Metalurgia e Mineração

CCD charge-coupled device

CEA Commissariat à l'énergie atomique, et aux Energies Alternatives

CERN European Organization for Nuclear Research (Conseil européen pour la recherche nucléaire)

CMI Critical Materials Institute

CMOS complementary metal oxide semiconductor

COTS commercial off the shelf

COVID-19 Coronavirus disease 2019

DOE U.S. Department of Energy

EB electron beam

EERE Office of Energy Efficiency & Renewable Energy

EO Executive Order

EPICS Experimental Physics and Industrial Control System

F&O Facilities and Operations

FECM Office of Fossil Energy and Carbon Management

FEI Formerly known as Field Electron and Ion Company; merged with Thermo Fisher Scientific in 2016

FES Office of Fusion Energy Sciences

FMB Feinwerk-und Meßtechnik GmbH

Fermilab Fermi National Accelerator Laboratory

FPGA field-programmable gate array

FRIB Facility for Rare Isotope Beams

GaAs gallium arsenide

HEP Office of High Energy Physics

HFIR High Flux Isotope Reactor

$HoCu_2$ holmium copper 2

HPC high-performance computing

HPHT high pressure, high temperature

HTS high-temperature superconductor

ICPT Integrated Contractor Purchasing Team

INFN Istituto Nazionale de Fisica Nucleare

IRP3 inner reflector plug

JASTEC Japan Superconductor Technology, Inc.

JEOL Japan Electron Optics Laboratory Co., Ltd.

Jefferson Lab Thomas Jefferson National Accelerator Facility

K Kelvin

LBNL Lawrence Berkeley National Laboratory

LCLS Linac Coherent Light Source

LINAC linear accelerator

MESA Microsystems Engineering, Science, and Applications (SNL)

MgB_2 magnesium diboride

MOSIS Metal Oxide Semiconductor Implementation Service

MRI magnetic resonance imaging

NASA National Aeronautics and Space Administration

Nb	niobium
Nb-Ti	niobium titanium
Nb_3Sn	niobium tin
NEG	non-evaporable getter
NEOMAX	Trade name for Hitachi Metals, Ltd.
NIST	National Institute of Standards and Technology
NMR	nuclear magnetic resonance
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NP	Office of Nuclear Physics
NSLS-II	National Synchrotron Light Source II
NSRC	Nanoscale Science Research Center
NSTX-U	National Spherical Torus Experiment – Upgrade
NuMI	Neutrinos at the Main Injector
OPCPA	optical parametric chirped-pulse amplification
ORNL	Oak Ridge National Laboratory
RCRA	Resource Conservation and Recovery Act
REBCO	rare earth barium copper oxide (superconductor)
REE	rare earth element
R&D	research and development
RF	radiofrequency
SAES	Società Apparecchi Elettrici e Scientifici
SBIR	Small Business Innovation Research
SC	Office of Science
SCT	Société des Céramiques Techniques
SLAC	SLAC National Accelerator Laboratory
SNL	Sandia National Laboratories
SNS	Spallation Neutron Source
SSRL	Stanford Synchrotron Radiation Lightsource
STTR	Small Business Technology Transfer
T	Tesla
Tm:YLF	thulium-doped yttrium lithium fluoride
USD	U.S. Dollar
XM-19	Nitronic 50 or Fermonic 50 stainless steel
YAG	yttrium aluminum garnet
YBCO	yttrium barium copper oxide
Yb:YAG	ytterbium-doped yttrium aluminum garnet
YLF	yttrium lithium fluoride