JLAB-TN-24-043

Jefferson Lab

Business Plan for a Domestic Supply of Superconducting Radiofrequency Cavities

JANUARY 2025

Prepared for the U.S. Department of Energy
under Contract DE-AC05-06OR23177

AUTHORS

GIANLUIGI CIOVATI
Senior Scientist, Thomas Jefferson National Accelerator Facility
Newport News, VA 23606

MARLA SCHUCHMAN
Chief Innovation Officer, Thomas Jefferson National Accelerator Facility
Newport News, VA 23606

WILLIAM DONALDSON
Professor, Luter School of Business, Christopher Newport University
Newport News, VA 23606

ALEX MUROKH
Chief Executive Officer
RadiaBeam Technologies, LLC
Santa Monica, CA 90404

MILES NAUGHTON, Program Manager
ATI Specialty Alloys & Components
Albany, OR 97321

DWIGHT OSHA
Engineer, C. F. Roark Welding & Engineering Co., Inc.
Brownsburg, IN 46112

DREW PACKARD
Scientist, General Atomics
San Diego, CA 92121

JOHN RATHKE
Engineering Consultant and Owner, JW Rathke Engineering Services
Centerport, NY 11721
Fmr. Co-President & Chief Engineer, Advanced Energy Systems, Inc.
Medford, NY 11763

ALAN TODD
Engineering consultant and owner, AMMTodd Consulting
Princeton Junction, NJ 08550
Fmr. Director, Chief Scientist & Co-President, Advanced Energy Systems, Inc.
Medford, NY 11763

CONTENTS

1 ACRONYMS

ADS	Accelerator Driven System
AES	Advanced Energy Systems
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ATLAS	Argonne Tandem Linear Accelerator System
BCP	Buffered Chemical Polishing
BNL	Brookhaven National Laboratory
CAFe2	China Accelerator Facility for super-heavy Elements
CAGR	Compound annual growth rate
CAMINO	Center for Advanced Manufacturing and Innovation
CAPEX	Capital expenditures
CBMM	Companhia Brasileira de Metalurgia e Mineração
CEBAF	Continuous Electron Beam Accelerator Facility
CEPC	Circular Electron Positron Collider
CERN	European Center for Nuclear Research
CESR	Cornell Electron Storage Ring
CFF	Cavity Fabrication Facility
CHESS	Cornell High Energy Synchrotron Source
CiADS	Chinese initiative Accelerator Driven Subcritical System
CIEMAT	Centre for Energy, Environmental and Technological Research
CNC	Computer numerical control
COI	Center of Innovation
CPFF	Cost plus fixed fee
CRADA	Cooperative Research and Development Agreement
CRMF	Cryomodule Repair and Maintenance Facility
CSNS	Chinese Spallation Neutron Source
CW	Continuous wave
DALS	Dalian Advanced Light Source
DESY	German Electron Synchrotron
DICP	Dalian Institute of Chemical Physics
DOD	Department of Defense
DOE	Department of Energy
DQW	Double quarter wave
DSR	Double spoke resonator
EB	Electron beam
EDM	Electro-discharge machining
EIC	Electron Ion Collider

ELL	Elliptical
EP	Electropolishing
ERL	Energy recovery linac
EUV	Extreme ultraviolet
EUVL	Extreme ultraviolet lithography
FAR	Federal Acquisition Regulation
FCC	Future circular collider
FEL	Free electron laser
FFP	Firm fixed price
FNAL	Fermi National Accelerator Laboratory
FRIB	Facility for Rare Isotope Beams
FTE	Full-time employee
GA	General Atomics
GDE	Global Design Effort
HERT	Beijing HE-Racing Technology
HIAF	High Intensity heavy-ion Accelerator Facility
HPR	High pressure rinse
HWR	Half-wave resonator
HZDR	Helmholtz-Zentrum Dresden-Rossendorf
IARC	Illinois Applied Research Center
IASF	Institute of Advanced Science Facilities
IBS	Institute for Basic Science
IFMIF-DONES	International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source
IHEP	Institute of High Energy Physics
IJCL	Irène Joliot Curie Laboratory
ILC	International Linear Collider
IMP	Institute of Modern Physics
INFN	Italy’s National Institute of Nuclear Physics
IP-SAFE	Isotope Pharmaceutical Production Platform based on Superconducting Accelerator Facility for Effective therapy
ITER	International Thermonuclear Experimental Reactor
ITN	International Technology Network
JLAB	Jefferson Lab
KEK	Japan National Laboratory for High Energy Physics
Linac	Linear accelerator
LCLS	Linac Coherent Light Source
LHC	Large Hadron Collider
MDF	Manufacturing Demonstration Facility
MHI	Mitsubishi Heavy Industries
MSU	Michigan State University

MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NGC	Northrop Grumman Corporation
NSF	National Science Foundation
NSLS	National Synchrotron Light Source
OPEX	Operational expenditures
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OSTEC	Ningxia Orient Superconductor Technology Company
OTIC	Ningxia Orient Tantalum Industry Company
PERLE	Powerful ERL for Experiment
PIP	Proton Improvement Plan
PKU	Peking University
QWR	Quarter-wave resonator
RAON	Rare isotope Accelerator complex for ON-line experiment
RDD&D	Research, Design, Development & Demonstration
RF	Radiofrequency
RFD	Radiofrequency dipole
RHIC	Relativistic Heavy Ion Collider
RI	Research Instruments
RRR	Residual resistivity ratio
S^3FEL	Shenzhen Superconducting Soft X-ray Free Electron Laser
SARI	Shanghai Advanced Research Institute
SBIR	Small Business Innovation Research
SCK-CEN	Belgian Nuclear Research Centre
SDI	Strategic Defense Initiative
SHINE	Shanghai high-repetition-rate XFEL and extreme light facility
SINAP	Shanghai Institute of Applied Physics
SLAC	Stanford Linear Accelerator Center
SMART	Source of Medical Radioisotopes
SNS	Spallation Neutron Source
SPP	Strategic Partnership Project
SRF	Superconducting radiofrequency
SSR	Single-spoke resonator
TDR	Technical Design Report
TRL	Technology Readiness Level
TIG	Tungsten inert gas
USGS	United States Geological Survey
XFEL	X-ray free-electron laser
ZRI	Zanon Research & Innovation

2 EXECUTIVE SUMMARY

Superconducting radiofrequency (SRF) cavities are critical components of modern particle accelerators. The industrialization of SRF technology in the U.S. has a long history, with several companies becoming interested in the technology in the past 30 years. However, there is currently no U.S. manufacturer with the capability to produce fully assembled, ready-to-test SRF cavities. A majority of these companies have either left the field or shut their doors. As a result, government-sponsored SRF accelerator projects in the U.S. largely rely on European vendors for the cavity supply. This presents not only a supply chain risk for scientific use cases, but also severely limits the commercialization of accelerator-based technologies. SRF accelerators have a range of strategic applications, including environmental remediation, semiconductor lithography, medical isotope production, and irradiation/sterilization. The nurturing of a domestic SRF industry is critical to maintaining U.S. economic competitiveness.

There are two vendors in Europe, Research Instruments in Germany and Zanon Research & Innovation in Italy, that have the capabilities to produce fully assembled, ready-to-test SRF cavities. From 2019 to 2021, it is estimated that the value of foreign-supplied SRF cavities to the U.S. was $100M. China has made huge investments in SRF technology over the past decade, which resulted in establishing seven full-scale facilities for the processing and testing of SRF cavities and cryomodules. The Chinese government has also successfully nurtured three industrial vendors within China. China has numerous SRF-based electron and hadron accelerator projects either planned or under construction, particularly light-sources based on free-electron lasers. When these projects are completed in the next 2-3 years, China will have the world's greatest number of SRF installations, and it will be fully self-sufficient with respect to SRF technology manufacturing.

A key supply chain factor to enable a resilient domestic SRF Industry is the stable procurement of high-purity niobium (Nb) sheet metal from U.S. vendors. Brazil is the world's largest producer of raw niobium, accounting for ~90% of global production. The worldwide production of high-purity niobium sheets is essentially handled by three companies. China has prioritized an internal supply chain required for the standard cavity fabrication technology and is home to Ningxia OTIC. Only one U.S. vendor, ATI Specialty Alloys & Components, is a longstanding source of high-purity Nb sheets, however it struggles to compete against Ningxia’s pricing. ATI’s other priorities, such as maintaining production capacity for different-grade niobium and other metals, notably for the superconducting industry, result in long lead times and higher costs for buyers. Further narrowing the market, the vendors in Europe are no longer producing high-purity Nb sheets due to competition with the Chinese vendor. At present there is only one other vendor worldwide that can supply the high-purity Nb sheets required for cavity fabrication. This vendor is located in Japan.

With regard to the manufacture of SRF cavities, Roark Welding & Engineering is the only vendor in the U.S. that has facilities and expertise to fabricate SRF cavities, however they do not have surface treatment and clean-room assembly capabilities. Advanced Energy Systems (AES) and Niowave had been developed as domestic SRF cavity vendors as part of an R&D effort for the International Linear Collider (ILC) project between 2006 and 2014. AES developed most of the capabilities for both fabrication and surface treatment of SRF cavities. The cavities they produced achieved the ILC performance specifications, which are the most challenging of any SRF accelerator project ever proposed. Without an industrial SRF market to keep them afloat, apart from Government-funded accelerator projects, AES and Niowave saw cavity contracts being awarded to the foreign vendors who could compete on cost and win bids due to procurement policies. As a consequence, AES ceased operations in 2016. Niowave pivoted to a different business altogether, the manufacture of medical isotopes. A historical account of AES is included in this report to provide valuable lessons learned.

Estimated worldwide demand of SRF cavities shows a two-fold increase in average annual production over the next five years when compared to the previous 10 years. The vast majority of this demand – 70% – is for projects in China. Should construction of the ILC be approved to start in ~2029, it will require another two- to three-fold increase in annual volume production. Applications other than government-sponsored research accelerators exist but have not been widely demonstrated, such as environmental remediation and sterilization/irradiation. One potentially large market is extreme ultraviolet lithography for semiconductor manufacturing, estimated to be $1B by 2030. At least one U.S. company has formed to pursue this application but may need to rely on foreign suppliers for SRF cavities. China also aims to build an accelerator for extreme ultraviolet lithography (EUVL). Securing a domestic SRF cavity supply would be consistent with U.S. Government policy to boost domestic research and manufacturing of semiconductors and environmental infrastructure via the CHIPS and Science Act and the Bipartisan Infrastructure Law. Another application of SRF accelerators that may experience a significant market demand within the next five years is the production of medical isotopes, with an estimated SRF cavity value of ~$50M by 2030.

For a U.S. vendor to compete with the SRF markets in Asia or Europe, it would need to bring disruptive fabrication and/or processing technologies resulting in significantly better performance and/or lower cost. This underscores the importance of investment into sustained, long-term domestic SRF R&D. One example of the fruitful outcome of U.S. investment in SRF R&D is the development of conduction-cooled SRF cavities based on Nb_3Sn. Should this technology mature over the next two to three years, it can enable compact, efficient, high-power electron accelerators for a range of industrial applications. Likely fields of use for this technology are in medical device sterilization, phytosanitary treatment and wastewater remediation. Combined, the estimated SRF cavity market reaches ~$20M/year by 2030 for these applications. However, laboratories in China are catching up very fast on this new technology: they have already assembled and demonstrated a conduction-cooled SRF accelerator.

Insights gathered from regular meetings among the project team members, an industry survey, a full-day workshop, and during one-on-one follow-up interviews with experts have been consolidated into recommendations validated by the project team and other participants. Adopting the following recommendations will lead to a sustainable, robust and competitive domestic SRF cavity industry:

1. **Sustain U.S. capabilities:** The most important aspect to ensure long-term, viable domestic suppliers of SRF cavities is for large projects to structure the procurements such that there is a set aside quantity from U.S. vendors and for national laboratories to coordinate an annual order of domestic SRF cavities, for smaller R&D projects, in order to smooth out the demand curve for SRF cavities.
2. **Establish R&D partnerships facility:** At least one SRF science and technology manufacturing center of excellence should be established. Ideally, this is located outside of a national laboratory, however it is managed by a national laboratory, modeled after the Oak Ridge Manufacturing Demonstration Facility. In this industrial third space, national laboratories and industry can effectively and efficiently collaborate on SRF R&D projects, leading to more

successful technology transfer opportunities. Past attempts to achieve these objectives through facilities inside national laboratories' campuses have not been successful in the U.S. nor in Japan.

3. **Support industrial ramp-up:** The estimated total capital investment of equipment for fabrication, treatment and clean-room assembly of SRF cavities is ~\$15M. Two SRF cavity production facilities should be established at two industrial companies in the U.S., to be operated and maintained by the companies. Procurement of the facilities and equipment can be jointly accomplished by industry and the Government through a series of smaller investments in the prospective vendor or industrial consortia. The ramping up of capacity will establish production capability while demonstrating the ability to produce a quality cavity. Support from national laboratories to facilitate knowledge transfer is important at this stage.
4. **Supply chain security:** Given the increased worldwide demand for various grades of Nb and Nb alloys for other applications, there is an opportunity to support domestic refineries to synergistically add capability for high-purity Nb. These could be incentivized by stock-piling high-purity Nb sheets through minimum annual orders. While Nb is on the 2022 U.S. Geological Survey list of minerals critical to the U.S. economy and national defense, it would be beneficial for Nb to be listed in the Department of Energy (DOE) Critical Materials List as well.
5. **Prioritize workforce development:** The development of a skilled workforce related to SRF technology should be fostered by establishing apprenticeship programs between trade schools and/or community colleges and national labs. "In-residence" programs would enable national lab scientific and engineering staff to work on projects at industrial companies, and vice versa.
6. **Dedicated funding for SRF:** Long-term funding programs dedicated to R&D in SRF science and technology should be established, similar to the Conductor Development Program for superconducting magnets.
7. **Elevate SRF to a critical and emerging technology:** The awareness of the strategic technological and economic impact of SRF technology should be raised through an accelerator technology forum, engaging industry, national laboratories and government agencies.
8. **Encourage formation of an SRF association:** The national laboratories and universities with facilities and expertise in SRF science and technology should be encouraged to establish a "National SRF Council" or similar association to advance the field in a coherent, consistent and efficient way in tandem with industry and academia. Such a Council could be the entity that coordinates the annual need of SRF cavities by each laboratory or university.
9. **Streamline procurement:** Strategic procurement policies aimed at standardization, simplification of processes and leveraging financial support mechanisms should be enacted.

In conclusion, the industrialization of SRF technology is quickly approaching an inflection point over the next five years with the potential opening of large industrial markets for SRF accelerators for industrial applications. At present, no U.S. vendor is well-positioned to take advantage of this market opportunity, and urgent action is needed to establish SRF cavity vendors that can compete with foreign suppliers. This action should be in the framework of a nationwide strategy for industrialization of SRF technology. Lessons learned from past efforts can chart the path to reviving and reinvigorating domestic industrialization of SRF technology. While the SRF cavity market may never mature to a beachhead market, developing a domestic industry is strategically important for the future of science and technology R&D in the U.S. Maintaining the status quo with respect to SRF cavity procurement and the supply chain will likely result in China becoming the dominant worldwide supplier of SRF cavities. This has already occurred with the supply of the high-purity Nb sheets required for cavity fabrication. It would be prudent to enact near-term policy reform and increase funding to ensure sustained U.S. economic competitiveness for this fundamental technology.

3 INTRODUCTION

OVERVIEW

Superconducting radiofrequency (SRF) cavities are essential components of modern particle accelerators. The standard material used for the fabrication of SRF cavities is high-purity, fine-grain Nb sheets, with thickness in the range of 2.8 to 4.2 mm. The cavities' shape and size depend largely on the operating frequency of the accelerator and the type of particles being accelerated. The target beam energy of the accelerator determines the number of cavities required.

Currently, SRF technology is primarily found at scientific laboratories for basic science research, and within limited industrial partnerships focused on R&D of adjacent SRF components through Small Business Innovation Research (SBIR) grants and other DOE-funded efforts aimed at components and subsystems up to technology readiness level (TRL) 4. A commercially viable SRF accelerator system is not yet available for purchase from a domestic vendor, however several applications of compact SRF accelerators are under exploration.

United States research, development, demonstration and deployment (RDD&D) efforts on SRF technology commercialization are funded through other vehicles as well, such as the Accelerate Innovations in Emerging Technologies grant from 2023, and sprinkled throughout the national labs via Cooperative Research and Development Agreements (CRADAs) and Strategic Partnership Projects (SPPs). The largest basic research SRF accelerator facilities in the U.S. are the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (Jefferson Lab), the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory, the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), the upgrade to the Linac Coherent Light Source (LCLS-II) at SLAC National Accelerator Laboratory, and the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU). These accelerators serve different fundamental research purposes, such as nuclear physics, condensed-matter physics, and biology.

It was recently recognized in a DOE report that high-purity Nb material and SRF cavities represent a significant risk to the supply chain for scientific facilities [1]. DOE Order 436.1A, "Departmental Sustainability," requirements state that DOE elements must "Diversify and prioritize the use of domestic supply chains" and "Invest in small and disadvantaged businesses to support American jobs" [2]. A recent data call issued by DOE to national laboratories and FRIB about suppliers of key components for particle accelerators revealed that SRF cavities had the second-highest value, estimated at ~$149M, about 70% of which was awarded to foreign suppliers [3]. Research Instruments (RI) GmbH in Germany and Zanon Research & Innovation (ZRI) Srl in Italy are the major suppliers of SRF cavities worldwide. Both vendors began fabricating SRF cavities in the 1990s, with the scientific and technical support from national laboratories in Germany (DESY) and in Italy (INFN).

The project team recognizes that, within the broader accelerator ecosystem, the U.S. is already nearly 100% dependent on foreign vendors in the production of the light source magneto-optics, insertion devices, solid state modulators and power systems, ultrafast and ultra-high peak power lasers, x-ray optics, and many other enabling technologies.

The collaboration between government laboratories and industry in Europe facilitated a strong, trusting relationship aimed at constantly improving the quality of SRF cavities. In the absence of large-scale production for accelerator projects, the European laboratories still relied on the industrial partners to build prototypes or small-series productions of SRF cavities. This approach provided vendors with “stable” demand while allowing companies to retain skilled personnel. Even under such conditions, both vendors relied on diversified production to remain profitable over the years.

The largest accelerator project to be built with SRF technology to date is the European X-ray Free-Electron Laser Facility (E-XFEL), which was commissioned at DESY in 2017. E-XFEL required the fabrication, surface processing and testing of ∼800, 1.3 GHz, nine-cell cavities [4, 5, 6]. Research Instruments and Ettore Zanon, now ZRI, were awarded contracts to fabricate those cavities. The funding included upgrades to their infrastructure to be able to handle the production volume and to meet the cavity technical specifications. The expertise and facilities acquired through the E-XFEL project has allowed these vendors to be considered the most experienced vendors for subsequent SRF cavity tenders worldwide.

SRF INDUSTRY IN THE U.S. AND OVERSEAS

The U.S. became involved in SRF technology in the early 1980s, around the same time as in Europe, with the fabrication of prototype cavities for the CEBAF accelerator. Over the past two decades, a handful of companies capable of manufacturing SRF cavities have been founded in the U.S., including Niowave, Advanced Energy Systems (AES) and C.F. Roark Welding & Engineering. Roark is the only U.S. company to have been awarded a large (>100) SRF cavity production contract, the contract being for the FRIB project. However, Roark does not maintain facilities to carry out surface processing or clean-room assemblies, required steps in post-fabrication to prepare SRF cavities for installation. Recently, Niowave pivoted its business model to focus on medical isotope production. AES had been involved with the fabrication of 1.3 GHz, nine-cell cavity prototypes for the International Linear Collider (ILC) project, which requires cavities to achieve a higher cryogenic RF performance than any other accelerator project. The cavities produced by AES met those stringent specifications after the surface treatments and testing done at national laboratories, and AES earned recognition as an “ILC-qualified” vendor in 2010. However, in 2016, AES ceased operations, leaving no U.S. vendor capable of production from bulk metal to a fully treated cavity, ready for testing. Further details about the evolution of these domestic SRF industry players, and other factors contributing to the U.S. vendor landscape, are offered in Section 4. A detailed description of the industrialization of SRF technology can be found in Ref. [7].

Overseas, Japan has been involved with SRF technology for many decades. There, the industrial production of SRF cavities dates back to the late 1980s with the fabrication of 508-MHz, five-cell cavities by Mitsubishi Heavy Industries, Ltd. (MHI) for the TRISTAN accelerator at Japan’s National Laboratory for High Energy Physics (KEK). Whereas two other companies, Hitachi and Toshiba, also produced some 1.3 GHz, nine-cell cavities during the ILC R&D phase in ∼2015, MHI had been the longstanding go-to SRF cavity manufacturer in Japan [8]. In preparation for the ILC accelerator project, hosted in Japan, KEK and the Japanese government determined a strategic approach to consolidate ILC-related SRF cavity manufacture within two new centers at KEK dedicated to the full cycle of fabrication, processing and testing of SRF cavities as well as cryomodule assembly and testing. The Cavity Fabrication Facility (CFF) at KEK contains all the necessary infrastructure to manufacture SRF cavities. It is intended to be a shared resource with industrial partners to develop cost-effective cavity fabrication methods for large-scale production [9]. The Center of Innovation (COI) building at KEK has the chemistry, clean-room, cryogenic and RF facilities to process SRF cavities, test them in liquid He, assemble them into cryomodules, and perform the high-power cryogenic RF testing of cavities in cryomodules [10]. It is intended as a facility open to industrial partners for R&D or production of SRF cavities and cryomodules. Due to delays of the ILC project, both of these facilities are now primarily utilized by staff within the KEK laboratory.

CHINESE NATIONAL INVESTMENT

China has had a longstanding interest in SRF technology, starting with researchers in Beijing at Peking University (PKU) and the Institute of High Energy Physics (IHEP) [11]. SRF activities had been the domain of laboratories and universities until ~2015, when SRF cavity production started at Ningxia Orient Superconductor Technology Co., Ltd (OSTEC). OSTEC is linked to Ningxia Orient Tantalum Industry Co. (OTIC), a large-scale supplier of tantalum and niobium products. Within the past decade, a tremendous expansion of SRF activities has taken place in China. A primary driver is the Shanghai high repetition rate XFEL and extreme light facility (SHINE), which requires the production of ~600, 1.3 GHz, nine-cell cavities [12]. In preparation for this large-scale production, two additional Chinese domestic cavity vendors have been strategically developed via investments in fabrication facilities for prototype cavities: Beijing HE-Racing Technology Co., Ltd. (HERT) and ChaoGao Zhuang Scientific Technology Co., Ltd. The development of each vendor was carried out in close collaboration with nearby laboratories and universities, such as PKU, IHEP, Shanghai Advanced Research Institute (SARI) and Harbin Institute of Technology. HERT is a spinoff from the IHEP machine shop. The initial cavity contract for SHINE was awarded to four vendors, HERT and OSTEC in China, and RI and ZRI in Europe. The facilities required for processing and assembly of all cavities produced in China were established at another company, Wuxi Creative Technologies Co., Ltd.

Approved by China in 2023, the Shenzhen Superconducting Soft-X-Ray Free Electron Laser (S^3FEL) will require the production of ~300, 1.3 GHz, nine-cell cavities [13]. Additionally, the Dalian Advanced Light Source (DALS) is an extreme ultraviolet (EUV) FEL, proposed as an upgrade of the normal-conducting Dalian Coherent Light Source in Dalian, and it will require the production of ~100, 1.3 GHz, nine-cell

Figure 1. List of light sources operating, under construction and planned in China, based on SRF technology [14]. The grayed-out items are light-sources based on normal-conducting technology.

cavities. Figure 1 shows a map of the nine light-source facilities that are operating, under construction, or planned in China, based on SRF technology [14]. The grayed-out facilities are those based on normal-conducting RF technology. For comparison, a total of six accelerator-based light sources are in the U.S.: the Advanced Light Source at Lawrence Berkeley National Laboratory, the upgraded Advanced Photon Source at Argonne National Laboratory, the Cornell High Energy Synchrotron Source (CHESS) at Cornell University, the National Synchrotron Light Source-II (NSLS-II) at Brookhaven National Lab and the LCLS-II at SLAC National Lab. Only three of those (CHESS, NSLS-II, and LCLS-II) are based on SRF technology. The High-Energy upgrade project for LCLS-II is currently underway, but there are no new SRF-based light sources planned in the U.S. at present.

The number of SRF-based hadron accelerators in China in operation or under construction is equally impressive [15]:

- The China Accelerator Facility for super-heavy Elements (CAFe2) at the Institute of Modern Physics (IMP) for nuclear and astrophysics research.
- The upgrade to the China Spallation Neutron Source (CSNS-II) at IHEP.
- The High Intensity heavy-ion Accelerator Facility (HIAF) at IMP, to produce radioactive beams for nuclear, plasma and atomic physics research.
- The Chinese initiative Accelerator Driven Subcritical System (CiADS) at IMP, for energy generation and nuclear waste transmutation.
- The Isotope Pharmaceutical Production Platform based on Superconducting Accelerator Facility for Effective therapy (IP-SAFE) at IMP in Lanzhou for medical isotope production.

More large-scale SRF-based projects are being pursued or planned for in China, such as the Circular Electron Positron Collider [16]. Considering only the SHINE and S^3FEL projects, China will have the largest quantity of SRF cavities installed in an accelerator compared to any other country by ~2027. A majority of the cavity production is expected to come from homegrown vendors in China.

The extraordinary development of SRF accelerators in China has been accompanied by an increasing number of government institutions establishing new full-scale SRF infrastructures for R&D and production of SRF cavities and cryomodules. For example, the Platform of Advanced Photon Source Technology R&D, with a cost of ~$70M, began operating at IHEP in Beijing in 2021, and the Southern Advanced Photon Source – Test Platform, with a cost of ~$84M, started operations in 2022 in Guangdong [14]. These new facilities add to the ones already existing at PKU, IHEP, IMP in Lanzhou, and the Shanghai Institute of Applied Physics (SINAP) in Shanghai. An additional facility for the surface treatment of SRF cavities for SARI was also set up at an industrial company site, Wuxi Creative Technologies Co., Ltd., in Wuxi.

In the U.S., five institutions have full-scale SRF facilities for cavity processing and testing: Jefferson Lab in Newport News, Virginia; Michigan State University in Lansing, Michigan; Cornell University in Ithaca, New York; Argonne National Laboratory in Argonne, Illinois; and Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois.[1] Limited SRF cavity processing facilities are in place at ORNL/SNS, mainly to support cryomodules repair. A Cryomodule Repair and Maintenance Facility (CRMF) is planned to be built at SLAC, also with limited SRF cavity processing facilities.

---

[1] Fermilab uses the surface treatment facilities at Argonne for most of its cavity production projects.

A CRITICAL MATERIAL - NIOBIUM

As mentioned above, the vast majority of SRF cavities are built from high-purity, fine-grain bulk Nb sheets. Niobium is most commonly used in the form of ferroniobium for steel production and it has applications in several industrial sectors, such as for nuclear reactors, superconducting magnets and aerospace. These applications require lower-purity "reactor-grade" material, or the Nb is alloyed with other metals. A significant increase in Nb demand has come in recent years, from applications in the defense industry and the growing worldwide aerospace industry [17].

Niobium is consumed mostly in the form of ferroniobium by the steel industry and as niobium alloys and metal by the aerospace industry. Data from the U.S. Geological Survey for 2023 indicate a world mine production of 83,000 tons, with estimated reserves sufficient for the next >200 years at the current rate of extraction [18]. The U.S. imported 9,400 tons, 66% from Brazil and 26% from Canada. Of U.S. niobium material imports, 72% was ferroniobium, 18% was niobium metal, 9% was niobium oxide, and 1% was niobium ores and concentrates. The production of Nb ingots typically starts from niobium oxide and niobium powders. The cost of a high-purity Nb ingot is ~\$175/kg, and the cost of the finished sheet is ~\$1,500/kg. One of the specifications commonly used to purchase Nb sheets is the requirement for the tantalum content to be less than 500 wt.ppm. The pyrochlore mineral in Companhia Brasileira de Metalurgia e Mineração's (CBMM's) mines in Brazil has a Ta content of ~1500 wt.ppm, and since this is acceptable for all other Nb uses, no further reduction of the ore is done by the vendor. The electron-beam melting process does not reduce the Ta concentration in Nb, therefore the Nb used for the high-purity Nb sheets is often produced starting from columbite ore, which has naturally lower Ta content. However, this mineral is much less prevalent than pyrochlore, contributing to the higher cost of the Nb used for SRF cavity production. Studies have shown that the requirement on the Ta concentration could be relaxed [19], which may increase the availability of the starting Nb ingots, if a revision of the Ta requirement will be adopted by the wider SRF community.

CBMM is the largest producer of raw Nb material and ingots worldwide. The high-purity requirements for SRF, coupled with stringent quality control requirements throughout the Nb sheets' fabrication, results in extended production cycles [20]. Only two vendors worldwide, Ningxia OTIC in China and Tokyo-Denkai in Japan sell Nb sheets that meet requirements. In the U.S., ATI Specialty Alloys & Components is a longstanding producer of high-purity Nb sheets. Increased competition from international sources, as well as increases in non-high-purity niobium and niobium-titanium demand related to superconducting industries, result in this U.S. vendor being priced out of the SRF Nb supplier competition, with unattractive lead times further straining its ability to provide high-purity Nb to U.S. projects. In the past, Fansteel and Cabot in the U.S. were suppliers of high-purity Nb in the 1990s, but they have both ceased operation. W.C. Heraeus, GmbH, in Germany and Plansee in Austria were also vendors of high-purity Nb sheets, but they no longer produce them. Supply chain issues related to the high-purity Nb sheets for SRF cavity fabrication were clearly identified in a recent DOE report [1].

In addition to using bulk Nb, SRF cavities have also been produced by depositing a thin film, 1-2 microns thick, of Nb onto the inner surface of a cavity made of copper, typically by sputtering. This method has several advantages compared to bulk Nb, though the RF performance of thin Nb film is well below what can be obtained with bulk Nb. The Nb/Cu technology was transferred to three industrial suppliers in Europe (Ansaldo in Italy, CERCA in France and RI in Germany, formerly ACCEL), which produced a total of more than 200, 352 MHz, four-cell cavities for the upgrade of the Large Electron Positron collider at CERN in the 1990s [21]. No accelerator has been built in the U.S. based on this technology yet.

APPLICATIONS OF SRF TECHNOLOGY

Nearly all of the accelerators utilizing SRF technology are for basic research applications. The project team is aware of only one exception, a superconducting linac operated by Niowave for medical isotope production [22]. Recently, there has been a growing interest toward possible industrial applications of SRF accelerators, such as: EUV photolithography for semiconductor manufacturing, accelerator-driven systems (ADS) for transmutation of nuclear waste and energy production, medical isotope production, medical sterilization, phytosanitary treatment, and environmental remediation.

Accelerators for EUV lithography and ADS require a beam energy of ∼1 GeV, therefore requiring on the order of 100 multicell SRF cavities relying on the current Nb-based SRF technology [23, 24]. A liquid-helium cryoplant would be the most efficient way to cool the cavities for such an accelerator. Accelerators for most of the other industrial applications require a more modest beam energy, on the order of 10 MeV. Additionally, a low operating cost and competitive suppliers of components are essential enabling factors for industry to adopt SRF technology. The large capital expense and operation of helium liquefiers/refrigerators represents a significant barrier to industrializing SRF technology.

Recent R&D activities in the U.S. showed the feasibility of producing SRF cavities with a Nb_3Sn thin-film formed on the inner surface of bulk Nb cavities, cooled by conduction using commercial cryocoolers and operating at useful accelerating gradients of ∼10 MV/m [25, 26, 27]. Increasing the technology readiness level of this innovation could open up new, sustainable markets for SRF cavities [28]. Rapid progress on this technology has been made in China as well, and it was recently announced that a compact, conduction-cooled SRF accelerator demo built at IMP in Lanzhou was able to accelerate an electron beam with an average current of 60 mA up to ∼1.6 MeV [29]. Additionally, the Innovation Fostering in Accelerator Science and Technology project in Europe, with funding of ∼$20M over four years, also has a thematic area aiming at implementing novel societal applications of accelerators [30].

BUILDING THE CASE FOR INCREASED INVESTMENT

The aim of this report is to outline a business plan for establishing a robust, domestic industry supporting SRF technology demonstration and deployment. The result of a one-year project, this report represents a highly coordinated effort among key SRF researchers, business owners, industry experts, and other stakeholders from the DOE and the national labs. The core project team consisted of nine individuals from a range of backgrounds. The project team held biweekly meetings to discuss key elements of sustaining a U.S. industrial market for SRF. The group prepared a survey and a one-day workshop to solicit and collect the information that is condensed in this report. Section 4 of the report presents a historical evolution of the SRF industry in the U.S. along with the biggest barriers to its development. Section 5 provides an outlook for the potential markets for SRF cavities. Section 6 presents the results of the survey. A roadmap to establish a competitive and viable SRF cavity industry in the U.S. is discussed in Section 7. Finally, recommendations on how to implement a business plan are provided in Section 8. The one-day workshop was held March 22, 2024, at Jefferson Lab, and the agenda and list of participants are provided in Appendices 1 and 2, respectively. Several discovery and follow-up interviews were conducted after the workshop, and those are listed in Appendix 3. A table with the market research data used for Section 5 is provided in Appendix 4. Appendix 5 provides information about the spoke selection criteria for the C4 partnering model discussed in Section 7.

4 EVOLUTION OF DOMESTIC SRF INDUSTRY AND RELATED COMPONENTS

THE INDUSTRY OF HIGH-PURITY NIOBIUM SHEET PRODUCTION

The production of high-purity Nb sheets typically used for the fabrication of SRF cavities begins with a Nb ingot that has been remelted multiple times in an electron-beam melting vacuum furnace. Afterward, the ingot is press-forged into slabs; the surface is mechanically ground, hot-rolled to an intermediate plate, mechanically polished, and chemically etched. The Nb is then cold-rolled to finished sheet, cut, annealed, and polished [31]. The estimated material waste from the initial ingot to the final sheets is ~45% [32]. This production method is common to all high-purity Nb sheet manufacturers. An alternative production method involving direct slicing into discs of a high-purity Nb ingot offers much reduced material waste, and SRF cavities made from this material have been fabricated by many laboratories throughout the world with success [33, 34]. The material purity is typically defined by the value of the residual resistivity ratio (RRR).

Fansteel Metals, Inc., was a U.S. manufacturer of specialty metals, including niobium, that was active in the production of niobium sheets of increased purity in the 1980s, as demanded by the SRF cavity technology at the time, but ceased operation in the specialty-metals business in 1989. Cabot Corporation was another U.S. company that produced high-purity Nb sheets for a brief period of time in the 1980s [35]. The company continued to produce reactor-grade (Nb purity up to 99.95%) Nb products throughout the years, until 2011 when its Nb and Ta production was sold to Global Advanced Metal.

ATI Specialty Alloys & Components has been producing high-purity niobium for accelerator applications since the mid-1980s and collaborated with Jefferson Lab in the establishment of the specification for RRR-grade niobium for CEBAF, the first largescale application of SRF technology. Formerly known as Teledyne Wah Chang, it was one of the two Nb sheet suppliers for the CEBAF project, the other being W.C. Heraeus in Germany [36]. In 1996, Teledyne Wah Chang became ATI Wah Chang, and in 2014 ATI changed its name to ATI Specialty Alloys & Components. Following this initial development in the ’80s, ATI produced more than 50 tons of RRR > 300 niobium products, supporting many domestic (e.g., Fermilab, SLAC) and global projects (e.g., Institute for Rare Isotope Science Korea) until the early 2010s [37]. Between 2010 and 2020, ATI saw reduced production, an average of 3 tons annually for various projects. This decline continued into the 2020s due to a combination of factors: cyclicality of project demand, an increase in price competition from China (Ningxia), as well as competing resource needs for the production of niobium and niobium-titanium products in the superconducting magnet industry, a significantly larger and more stable market. Today, ATI still manufactures high-RRR niobium products, most recently for Fermilab’s PIP-II project, however the company competes against Chinese sources for both domestic and international demand. Additionally, the high cost of material limits the amount of inventory that can be carried through the supply chain and distribution channels, making mill minimums a barrier to small orders and developments. Recent manufacturing improvements, including capacity investments and the development of “medium-grain” forged billet-slice technology, aim to maintain ATI’s competitiveness in the Nb marketplace [38].

FACILITY REQUIREMENTS FOR SRF CAVITY FABRICATION AND SURFACE TREATMENT

The fabrication of bulk Nb cavities requires a number of facilities, some of which are highly specialized and require significant capital investment. Gathered from know-how and experience of the project team, the information in Table 1 shows a list of such equipment along with the estimated cost, sized to fabricate SRF cavities up to 50 cm in diameter and up to 1.5 m in length.

Equipment such as computer numerical control (CNC) lathes and milling machines, wire electro-discharge machining (EDM), water-jet cutter, and hydraulic presses are fairly conventional equipment found in machine shops. However, the RF equipment and fume hoods for chemical etching of components are more specialized. The electron-beam (EB) welding machine is the item with the highest capital expense and requires highly skilled, specialized operators. EB welding is used for the fabrication of components in many industrial sectors, but those mostly require small-size EB welding machines [39], unlike the large welds of SRF cavities and components. Tungsten inert-gas welding is also used for welding of the helium vessel around the cavity and may also be considered an essential tool for a facility involved with SRF cavity fabrication. Reviews of cavity fabrication and surface preparation methods can be found in Refs. [40, 41]. It is recommended that all the facilities listed in Table 1 should be co-located for an efficient and sustainable production workflow. The total estimated capital cost for the equipment listed in Table 1 is $4.3M.

The standard surface treatment of SRF cavities requires the use of the facilities listed in Table 2, along with the estimated capital cost. These facilities should also be co-located. Some of the equipment in Tables 1 and 2 overlap, therefore if a vendor was capable of doing both cavity fabrication, surface preparation and assembly, it would be sufficient to have one of each type of equipment. The equipment for cleaning and chemical etching is larger for a cavity processing facility than in a cavity fabrication facility. The total estimated capital cost for the equipment listed in Table 2 is $11M.

Table 1. List and estimated cost of equipment required for the fabrication of SRF cavities.

Production Equipment	Estimated cost ($k)
EB welding machine	2,800
Wire EDM	250
Water-jet cutter	250
Coordinate measuring machine	200
CNC lathe	150
Ultrasonic tank	150
RF measuring fixtures and Vector Network Analyzer	150
200 ton Hydraulic press	130
CNC milling machine	100
Chemical fume hood	50
Portable ISO 5 clean-room (10 ft x 8 ft x 8 ft)	40
Ultra-pure water system with 8 gal/min capacity	10
TIG welding machine	10

Table 2. List and estimated cost of equipment required for the surface treatment and assembly of SRF cavities.

Surface Treatment Equipment	Estimated cost ($k)
3000 ft^2 ISO 4 clean-room	2,000
Electropolishing cabinet	2,000
High-vacuum 1200 °C annealing furnace	1,600
Buffered chemical polishing cabinet	1,500
High-pressure water rinsing cabinet	1,500
Ultrapure water system with 60 gal/min capacity	1,500
High-pressure diaphragm pump	240
Bench tuning machine	200
Ultrasonic tank	150
RF measuring fixtures and Vector Network Analyzer	150
Chemical fume hood	100
Helium leak detector	25
Turbo-molecular vacuum pump cart	15

The maintenance and operating cost of the facilities for SRF cavity fabrication are ~50 k$/year, and they are ~1 M$/year in procurement and ~4 FTE for the SRF cavity treatment and assembly, based on the expertise within the project team.

HISTORY OF THE DOMESTIC SRF INDUSTRY

The transfer of SRF technology and know-how to U.S. companies dates back to the late 1980s, during the prototyping phase for the construction of CEBAF at Jefferson Lab, which was the largest SRF-based accelerator project at that time. The Naval Nuclear Fuel Division within Babcock & Wilcox produced four 1.5 GHz, five-cell cavities with the support of Jefferson Lab (which was then named CEBAF) and Cornell University [42]. The cavities exceeded the project performance specifications. Another large U.S. company, TRW, Inc. [43], participated in the CEBAF cavity prototyping phase by producing two five-cell cavities, which also met the project's specifications. However, the contract for entire production, requiring 360 cavities, was awarded to Interatom, Germany. It is worth noting that "although CEBAF had indicated that it would prefer to deal with two cavity manufacturers, the substantial additional cost of doing so was not justified" [44]. Babcock & Wilcox protested the decision with the General Accounting Office, and the procurement contract was halted for some time [44]. It is also worth noting that the need to have co-located facilities and a venue for sustained knowledge transfer (in this case, a team of engineers and technical staff went to Cornell University to learn the cavity fabrication procedures) were valuable lessons already understood as early as 1987 [45].

The next most significant opportunity to transfer SRF cavity technology to industry came during the "S0" Global Design Effort (GDE) R&D of the ILC, active between 2007 and 2012 [46]. Approximately 100 1.3 GHz, nine-cell cavities were manufactured in the U.S. during that time frame by three vendors: Niowave, Inc., Advanced Energy Systems (AES), and Roark.

Niowave

Niowave, Inc., was established in 2005 as a spinoff from the National Superconducting Cyclotron Lab at MSU. It built up the SRF fabrication infrastructure mainly through grants from the DOE SBIR program and benefited from the expertise in SRF technology at MSU, located ~5 miles from the company. The company did not acquire an EB welding machine and relied on Sciaky, Inc., for the welding of cavity components. Niowave produced different types of cavities for BNL, Fermilab, Jefferson Lab, Old Dominion University, and CERN until ~2017, when it successfully transitioned on setting up and operating an SRF electron linac to produce medical isotopes [47, 48, 49]. Figure 2 shows some of the cavities built by Niowave.

Figure 2. Example of SRF cavities manufactured by Niowave: subassembly and completed 400 MHz, LHC Hi-Lumi DQW cavity (left) and 704 MHz, five-cell cavity for the Relativistic Heavy Ion Collider at BNL (right). Image courtesy of Niowave, Inc.

Roark


Figure 3. Example of SRF cavities manufactured by Roark: subassembly and completed 325 MHz, PIP-II SSR1 cavity (top), spoke and completed 322 MHz, FRIB HWR cavity (bottom).

Roark's SRF cavity work began in 2006 with the fabrication of a prototype 325-MHz single spoke resonator (SSR) cavity for Fermilab. Roark was chosen based on its metal-forming capabilities and EB welding experience. As part of the ILC R&D effort, 14 1.3 GHz, nine-cell cavities were also built by Roark between 2010-2012, as well as 10 SSR cavities for Fermilab. Niowave was subcontracted by Roark to do RF frequency measurements of the cavity parts. Roark began a relationship with MSU in 2010 to manufacture subassemblies needed for prototyping a 322 MHz, β=0.53, half-wave resonator (HWR) cavity. This work led to the development, pre-production, and production of all the 322 MHz HWR cavities for the FRIB project at MSU, between 2015 and 2019. A total of 239 HWR cavities were manufactured by Roark, representing the largest volume production of SRF cavities ever made in the U.S. For this project, Roark also acquired the knowledge and equipment for RF frequency measurements of subcomponents, with guidance from MSU scientists and engineers. The cavities for FRIB were delivered welded into their titanium helium tanks, ready for final processing. The cavities' surface treatment, assembly, and cryogenic RF testing was done at MSU, and they exceeded the project's performance specifications. Notably, the relatively close proximity of Roark to both Fermilab (∼200 miles) and MSU (∼270 miles) aided in the transfer of the SRF cavity fabrication technology to the company.

At the completion of the work for FRIB, Roark manufactured two 644 MHz, five-cell cavities as part of the R&D toward a possible future upgrade of FRIB. Roark has competed unsuccessfully for other large domestic (LCLS-II and SSR cavities for PIP-II) and international (E-XFEL) SRF cavity production contracts. A major obstacle to effectively competing with the European vendors is Roark's absence of surface treatment and clean-room facilities. Figure 3 shows examples of SRF cavities manufactured by Roark, and Figure 4 shows the quantity of cavities built by Roark over the years.

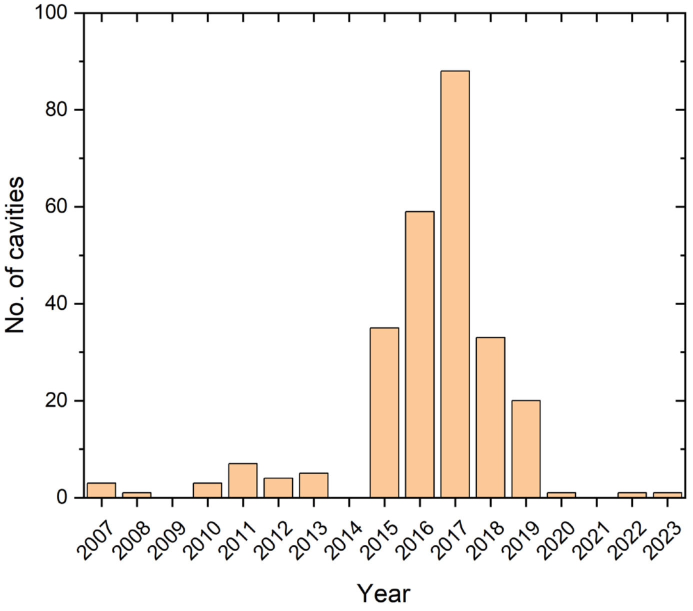


Figure 4. Quantity of SRF cavities manufactured by Roark over the years.

Advanced Energy Systems

Some of the SRF cavities built by AES are shown in Figure 5. Advanced Energy Systems began as an advanced development group in 1975 under that name in the research department at Grumman Aerospace Corp., working on development of fusion energy. Beginning ~1984, AES began branching out into particle accelerator technology and by 1987 was a major company working on Neutral Particle Beam systems for the Strategic Defense Initiative (SDI). As SDI waned in the early 1990s, AES focused efforts on emerging accelerator technologies including free-electron lasers (FEL). In late 1994, Northrop took over Grumman to become Northrop Grumman Corporation (NGC). At about the same time, AES worked with Jefferson Lab on the 1 kW infrared FEL energy recovery linac (ERL) project and later on the 10 kW upgrade. During this period, AES began exploring the fabrication of SRF cavities and cryomodules. At the same time, a major SRF accelerator was being pursued by Los Alamos National Laboratory for the production of tritium. The 700 MHz single-cell and five-cell prototype cavities were built by AES initially while still part of NGC. In 1998, AES spun out from NGC and completed the fabrication of those cavities, with very good test results.

In addition to accelerators, AES was also a member of the EUV LLC group pursuing semiconductor lithography. During that time, AES patented a new technology, unrelated to SRF, to produce EUV light.

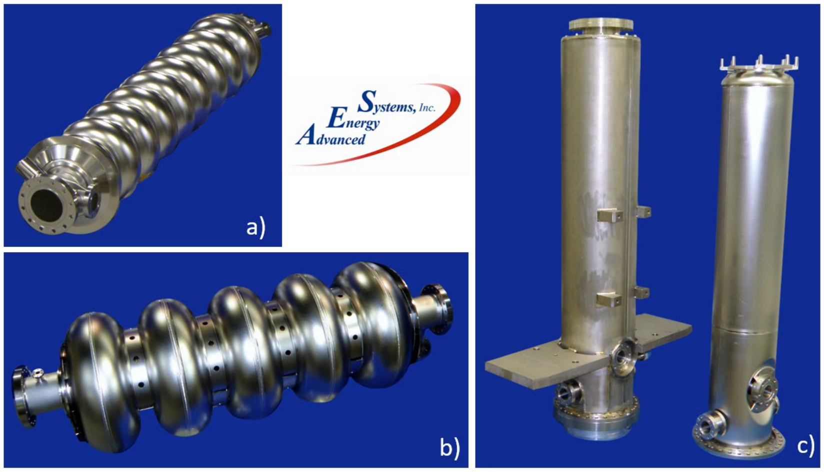


Figure 5. Example of SRF cavities manufactured by AES: (a) nine-cell, 1.3 GHz ILC cavity, (b) five-cell $\beta = 0.9$, 650 MHz PIP-II cavity, (c) 80.5 MHz, $\beta = 0.041$ FRIB QWR cavity with and without helium tank.

AES continued to grow its SRF manufacturing capabilities through contracts with Argonne National Laboratory (ANL) and with the U.S. Navy. While pursuing the adoption of innovative methods, AES became the sole supplier for forming and machining niobium components for ANL. Novel tooling and techniques such as hydroforming proved particularly advantageous in manufacturing complex shapes for quarter-wave, half-wave, and spoke resonators.

For the U.S. Navy, AES was a key industrial partner for the design and manufacturing of components for the high-power FEL. AES successfully designed and built a complete FEL injector cryomodule comprising three single-cell cavities operating at 748 MHz plus one single-cell cavity operating at 2.245 GHz. It also included high-power, continuous-wave (CW) power couplers designed by AES.

In the 2004-2005 timeframe, Fermilab engaged with AES for the fabrication of nine-cell, 1.3 GHz cavities for the ILC-GDE R&D [50]. At the time, the AES manufacturing process utilized an outside vendor for EB welding. When building more than three or four cavities at a time, the logistics of outsourcing EB welding became too cumbersome. Fermilab pressed AES to buy its own EB welding machine based upon the numbers of cavities they were envisioning. In 2006, AES purchased a large, refurbished EB welding machine and, over the course of the next few years, AES became the only U.S. company qualified for ILC production by delivering a series of cavities with outstanding performance [51]. The cavity processing, assembly, and cryogenic RF testing were all done by Jefferson Lab and Fermilab.

In 2006, BNL offered to have the buffered chemical polishing (BCP) and high-pressure rinse (HPR) equipment, required for the cavities' processing and cleaning, installed at AES. The agreement was for AES to provide the facility and to operate and maintain the systems. AES would also be allowed to use the systems for their other work on the promise that BNL would be given top priority when it had a need. At the time, given the plans BNL had for SRF activities, ERL's, and ongoing cavity manufacturing, the arrangement seemed good for both parties. Only as time went on, and cavity production from BNL fell short of earlier expectations, did it become clear that the processing facility, though a valuable tool to AES, was a net loser due to the carrying cost.

Over the period from 2007 to 2012, AES produced 69 SRF cavities but, as can be seen in Figure 6, the quantities per year fluctuated greatly. Furthermore, while many of the cavities were 1.3 GHz nine-cells where production was well understood, many of the other cavities were new and novel designs such as the 650 MHz five-cell cavities for PIP-II and the traveling-wave prototypes with waveguide feedback for Euclid Techlabs. These cavities proved very challenging to build, and because they were all fixed-price delivery contracts, they resulted in substantial losses for the company. In 2010, AES won a competitive contract from Fermilab to design and build a state-of-the-art electropolishing system and laboratory. The system was collaboratively designed to incorporate the best features learned at labs worldwide. It was installed and operated at AES, while Fermilab maintained ownership. The contract provided for ongoing maintenance costs, whereas AES provided the facility.

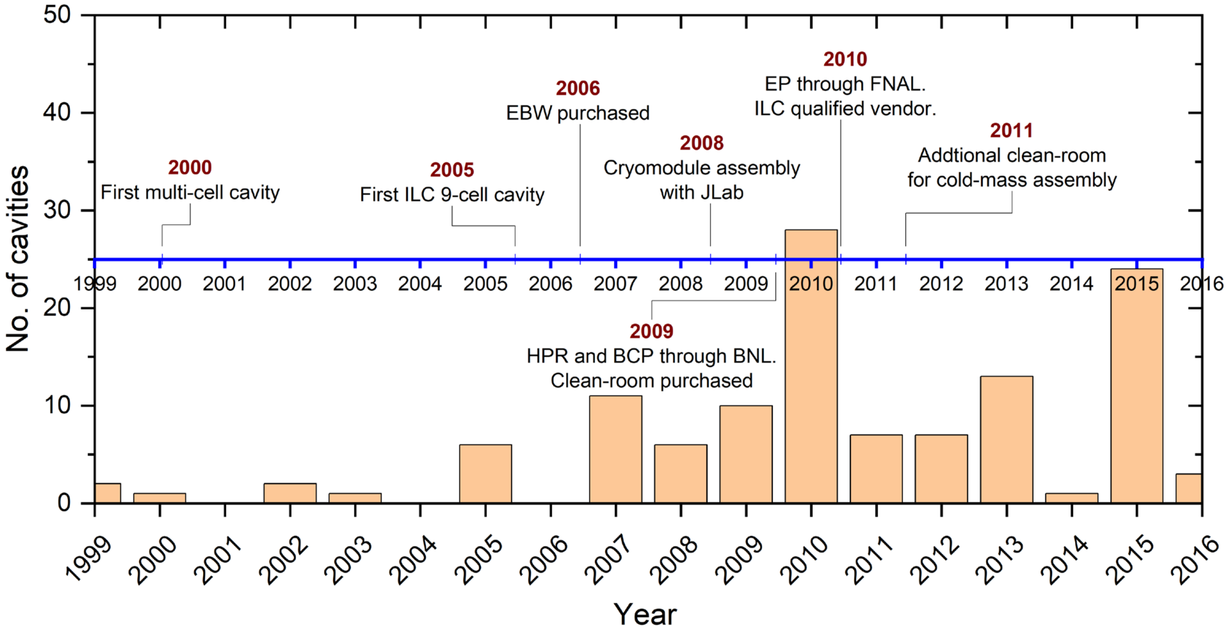


Figure 6. Quantity of SRF cavities manufactured by AES and major milestones over the years, until it ceased operation. The graph does not include formed and machined parts and subassemblies for 32 cavities for ANL.

One of the most significant, challenging contracts for AES was an order for two complete cryomodules and one extra SRF cavity for the NSLS-II Light Source at BNL. AES bid on this project very aggressively, knowing that the competition, RI, had already built several of the Cornell Electron Storage Ring (CESR)-B cryomodules that were the basis for this design. It was a firm-fixed-price delivery contract with the added complication of a substantial redesign to comply with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. The redesign effort was extremely difficult to estimate beforehand, adding serious risk to the project. While carrying out this contract, it was clear that the budget would be overrun. Adding further strain to the company, another major contract for the U.S. Navy Free Electron Laser demonstrator was abruptly canceled. The sudden loss of business drove AES labor rates up. Faced with growing overruns on NSLS-II, AES was forced to renegotiate the NSLS-II contract with BNL. The renegotiations largely involved reexamining earlier requests for budget adjustment that had been previously denied. Upon review, they were accepted, providing some relief in a delicate situation. BNL also agreed to purchase tooling and fixtures that had been property of AES. These adjustments allowed AES to complete the project and deliver in time to meet program goals. In 2013, AES was awarded a contract from FRIB for the design and fabrication of 19, β = 0.041 quarter-wave resonators (QWRs), providing further relief. The cavities were delivered on schedule in 2015 and had excellent cavity performance, after the surface treatments were carried out at MSU. At that point in time, AES was bidding on two opportunities. First was a new bid to FRIB to build 113, β = 0.085 QWRs; that contract was awarded to the Italian company Zanon.

The other opportunity of 2015 was the fabrication, processing, and assembly of ~340, 1.3 GHz, nine-cell cavities for the LCLS-II project at SLAC. For this large contract, AES teamed with General Atomics (GA) as the prime contractor. RI and Zanon had recently completed delivery of large production runs of very similar cavities for the European XFEL. The European Union (EU) had not allowed any U.S. bidders for that contract, and it supplied RI and Zanon with substantial amounts of equipment that was now available for the LCLS-II. In the end, the GA/AES proposal was not competitive on price, and the awards were made to RI and Zanon.

AES had made one last-ditch effort, requesting that DOE hold back 24 to 36 cavities as a small business set-aside. An agreement was made with Cornell University to use its new high-temperature vacuum furnace, which was the only equipment necessary for the cavity processing that was not on AES's site. At these quantities, AES could produce the cavities using its existing facilities with no need for capital purchases and therefore could offer the cavities at the same unit cost as the Europeans. AES was informed by DOE that it had followed all federal acquisition regulation (FAR) regulations for procurement and there would be no further consideration of the awards. AES had runway for one more year. In the spring of 2016, it became clear AES needed to close operations and liquidate all assets. Over the course of six months, an orderly shutdown of operations took place. The EP system was returned to Fermilab, the HPR system was returned to BNL and the BCP cabinet was sent to Jefferson Lab. AES' relationship with ANL, Fermilab, and Jefferson Lab lasted until AES ceased operations. The company's final contract was the complete manufacturing, design, and fabrication of the 1.4 GHz, higher-harmonic cavities for the upgrade of the Advanced Photon Source at ANL.

LESSONS LEARNED FROM LCLS-II

The LCLS-II cavity production was one of the largest procurement of cavities for a U.S. project since the start of acquisitions and fabrication for CEBAF in the 1990s. Although the LCLS-II cavity production was ultimately very successful, the following considerations are worth noting:

1. Processing LCLS-II cavities required applying a novel "nitrogen doping" treatment, which was developed jointly by Fermilab, Jefferson Lab and Cornell University, through R&D funding from

DOE [52]. However, as a result of the cavity contract award, this new technology was transferred only to European companies, none in the U.S. [53].

2. Issues during the cavity production at one of the two vendors required scientists and engineers, rotating among the partner labs, to be present at the vendor for oversight for about one week each month over the two-year-long production. The possibility of extended overseas travel should be considered during the selection of a cavity vendor.
3. The extra cost that might have resulted from awarding a small fraction of the entire cavity production to a U.S. vendor, which was valued at over $30M, should be balanced with the economic and technological impact resulting from the potential loss of a well-qualified domestic U.S. vendor, as was the case with AES.

A high-energy upgrade of LCLS-II is currently ongoing, requiring the production of ~200 additional, 1.3 GHz, nine-cell cavities, and a single contract was awarded to RI in 2020 for that work.

BARRIERS TO A DOMESTIC SRF INDUSTRY

During the 2022 Snowmass gathering, SRF industry players and researchers discussed impediments to establishing a robust domestic SRF industry. A recent white paper resulting from that meeting describes in great detail the major barriers to expand the domestic industrial participation in the construction of U.S. accelerator facilities [54]. These barriers can be summarized as follows:

1. The lengthy rules and regulations imposed by Government contracts result in a high overhead to the vendors.
2. Vendors are often not included in the engineering design phase and are handed a long list of requirements.
3. Industry should be involved in prototype development not through firm-fixed-price contracts but through cost-plus-fixed-fee (CPFF) contracts, which allow companies to better manage changes and growth of scope.
4. Technology transfer between labs and industry is often done in terms of offering lab-developed intellectual property (IP) to industry. The focus should be shifted to “knowledge transfer,” meaning direct engagement of industry with lab personnel through contract supervision, collaboration, and consulting arrangements.
5. Difficulty to attract angel or venture capital investors as the business return is both highly volatile and unspectacular. It requires a hockey stick business plan to secure such investments.
6. Lack of consistency in contracting policy within the DOE laboratories. Some have a very collaborative approach to contracting while others have an aggressively adversarial approach.

From a business perspective, perhaps item 5 is the most challenging on the list: A company would not be inclined to invest the millions of dollars required to set up a cavity fabrication and processing facility without confidence in the anticipated production volume over the next few years.

THE EVOLUTION OF THE EUROPEAN MODEL

Research Instruments in Germany is considered the de facto prime industrial supplier of SRF technology [55]. The company started in the 1960s as Interatom, GmbH, owned by Siemens AG, as a supplier of specialized equipment for nuclear technology. The company’s involvement with accelerator technology started in the 1970s with the manufacturing of ultrahigh-vacuum chambers and copper cavities [56], and it began working on RF superconductivity in the late 1970s. After an acquisition in 1994, the company became ACCEL Instruments. Throughout the years, ACCEL Instruments produced cavities for many SRF accelerator projects worldwide. From 2007-2009, the company became a subsidiary of Varian Medical Systems and was eventually acquired by Bruker Energy & Supercon Technologies, Inc., a subsidiary of Bruker Corporation. At this point, the company rebranded again and became Research Instruments.

Through a decades-long collaboration with the DESY laboratory in Germany, the company strengthened its expertise and capabilities in SRF technology. Besides cavity fabrication, the company was active in SRF R&D projects in collaboration with European laboratories and universities since the 1980s [57]. The company was involved during the prototyping phase of the five-cell cavities for CEBAF [58], supported by the University of Wuppertal, and was awarded the contract for the manufacture all the 360 cavities. Early on, the company had the opportunity to develop expertise required for the design and fabrication of a complete SRF cryomodule the 1990s, via a contract from Japan [7]. In 1999, RI was able to transfer some Cornell University technology for the design and fabrication of an SRF cryomodule for high-current storage rings. The company produced and sold these cryomodules for several accelerator projects worldwide.

RI has developed into a complete vendor of accelerator technology, capable of designing and delivering fully assembled SRF cryomodules and normal-conducting accelerators. Prior to 2009, most of its cavity production was limited to fabrication. However, a contract for 429 cavities for the European XFEL project provided the necessary capital and resources to expand surface treatment and assembly capabilities. After this contract, RI was able to provide fully assembled cavities, ready for cryogenic testing. One contributing factor in RI's maturation is that some equipment was loaned from DESY to build capacity at the company. In recent years, RI has continued its growth, in part due to diversifying its production to include tools and components for EUV lithography machines [59]. RI is also a supplier of key components for the International Thermonuclear Experimental Reactor (ITER), which is a large-scale, international nuclear fusion reactor under construction in France.

Zanon Research and Innovation in Italy is the other major worldwide supplier of SRF cavities. It started as Ettore Zanon, S.p.A, a company founded in 1919 that began working with European research institutes in the 1980s, producing the vacuum vessels for SRF cryomodules. The company began fabricating SRF cavities in the 1990s for the ALPI-PIAVE accelerator for Italy's National Institute of Nuclear Physics (INFN) and 1.3 GHz cavities for DESY [60]. Since then, Zanon has continued producing cavities for projects at DESY and INFN, as well as for other laboratories in France and the U.S. The largest production project it worked on was the fabrication, treatment, and assembly of 420, 1.3 GHz, nine-cell cavities for the European XFEL project, between 2011 and 2018. This contract allowed Zanon to install all the facilities for the surface treatment and clean assembly of the cavity, with some of the equipment for RF measurement and tuning provided by DESY. Zanon also produced 94, β=0.085 QWRs for FRIB between 2015 and 2017.

In 2020, the part of the company working on accelerator components became Zanon Research & Innovation and was acquired by SIMIC, S.p.A, an Italian company with experience in the engineering and manufacturing of critical components for scientific research, fusion energy, nuclear, and oil & gas.

Some important features of the European model of industrial economic policy have contributed to the successful long-term industrialization of SRF technology. These factors, which have not occurred at the same level with any industrial vendor in the U.S., include:

1. The establishment of a long-term, trusted relationship between RI and Zanon and the government laboratories in their respective countries.
2. The companies' management has long-term interest in SRF technology because they are either former researchers or invested in contributing to critical fundamental science efforts.
3. The fabrication and, in many cases, the surface treatment of prototype or small-quantity R&D cavities was done in collaboration with industry and government.
4. The decision to procure the cavities for the E-XFEL project, the world's largest SRF accelerator project to date, within Europe rather than abroad.

There have been other European companies besides RI and ZRI, such as Dornier in Germany, CERCA in France, and Ansaldo in Italy, which had been SRF suppliers, however they are no longer involved in the technology. CERCA and Ansaldo were involved with the manufacturing and surface treatment of the cavities for the upgrade of the Large Electron Positron collider at CERN in the 1990s [21]. However, the management perspective after the project concluded was that the SRF opportunity was too small, and the company abandoned the business line. Dornier only manufactured a few prototype cavities, and the company's management was also not interested in the SRF business [61]. The close relationship of RI to its home country facilitated continuous technical improvements and quality control, and provided vendors with sufficient business to remain viable during the time gap between larger production projects. Industrialization of SRF technology in China appears to be following this model as well.

5 MARKET OUTLOOK AND APPLICATIONS OF SRF TECHNOLOGY

In order to perform an analysis of the SRF industrial market, the project team and workshop participants first addressed the supply chain. Beginning with the source metal, bulk niobium, the quantities needed for various upcoming SRF projects was estimated. The group then turned its attention to the various applications of SRF accelerators, which may provide a steady or high-growth market pull for both the raw material and the technology components.

CAVITY VOLUME ANALYSIS

It was noted in Ref. [7] that the approximate total number of cavities produced worldwide between the 1980s and 2010 was ~2,500, corresponding to an average of ~100 cavities per year. This represents a fairly low volume, which certainly contributed to the challenge of sustaining more than one or two vendors of SRF cavities worldwide. However, the average number of cavities per year has nearly doubled over the past 13 years, as more SRF accelerator research facilities are being built. Table 3 lists the major current and upcoming accelerator projects for basic research requiring the procurement of SRF cavities, along with the estimated start of the cavity procurement, years to fulfill, number of cavities for each project, and amount of high-purity niobium needed.

The largest basic research accelerator requiring SRF cavities is the proposed International Linear Collider: such a project requiring ~16,000, 1.3 GHz, nine-cell cavities would be a game-changer in the industrialization of the SRF technology, as contributions from vendors from all continents likely would be needed. However, the future of the project is quite uncertain. The technical design report (TDR) was released in 2014, following six years of R&D as part of the “Global Design Effort” [62]. An addendum to the TDR was published in 2017, proposing a staged approach to the project, with the initial center-of-mass energy reduced to 250 GeV, “ILC-250,” instead of 500 GeV, reducing the number of cavities needed to ~8,000 [63]. A global collaboration program, named ILC Technology Network (ITN), focusing on accelerator R&D with SRF cavities being among the topics, was started in 2023 with an expected three-year duration. DOE and its national laboratories have decided to be “observers” and not officially join the ITN.

The sum of all SRF cavities needed for accelerator projects over the next ~6 years is about half of the cavities needed for the ILC: If approved, the construction of the ILC would be a game-changer to broaden the industrialization of the SRF technology. Excluding the cavities for ILC, Figure 7 shows the fraction of SRF cavities required by country over the next six years, without those for the Future Circular Collider (FCC), which is another large-scale project with a very uncertain future. The graph shows how China is poised to dominate the SRF market. The establishment in China of three cavity vendors, as well as the presence of a high-purity Nb sheet manufacturer which already dominates the market, shows the clear intent of China to be completely self-sufficient with the SRF technology within the next few years.

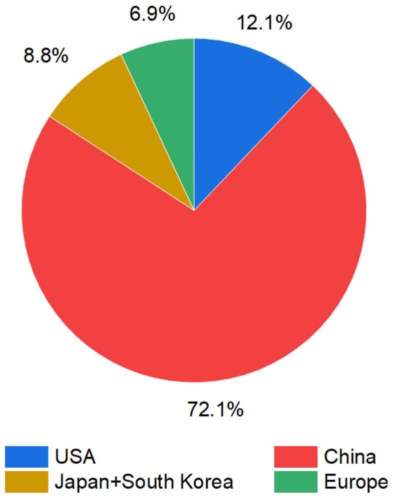


Figure 7. Fraction of cavities needed for research accelerator projects over the next six years, by region.

Table 3. Ongoing and future research accelerator projects requiring SRF cavities. The number of cavities, start and length of procurement, and quantity of high-purity Nb material required are estimates. ELL: Elliptical; RFD: Radiofrequency Dipole; DQW: Double Quarter Wave; DSR: Double-Spoke Resonator.

Project name	Leading institute	Cavity type	Country	No. of cavities	Start of cavity procurement	Yrs. to fulfill	Q.ty of Nb (ton)
SHINE	SARI	9-cell, 1.3 GHz and 3.9 GHz ELL	China	616	2023	3	22
Hi-Lumi LHC	CERN	400.8 MHz RFD and DQW	Europe	22	2023	3	2.5
PIP-II	Fermilab	162.5 MHz HWR, 325 MHz SSR, 5-cell 650 MHz ELL	US	153	2023	2	20
CiADS	IMP	162.5 MHz HWR 325 MHz DSR 6-cell and 5-cell 650 MHz ELL	China	150	2023	3	20
HIAF	IMP	81.25 MHz QWR, 162.5 MHz HWR	China	100	2023	2	10
CSNS-II	IHEP	324 MHZ DSR, 648 MHz ELL	China	50	2024	2	5
EIC	BNL	1- and 5-cell 591 MHz ELL 5-cell 1773 MHz, ELL, 197 MHz QWR, 197 MHz RFD, 394 MHz RFD	US	62	2024	3	10
PERLE	IJCLab	5-cell 801.58 MHz ELL	France	20	2024	5	1.4
ILC pre-lab	Multi	9-cell 1.3 GHz ELL	US/Europe/Asia	24	2024	1	1
RAON	IBS	325 MHz SSR	South Korea	219	2025	3	10
CEBAF C75/C100	JLAB	5-cell 1497 MHz ELL	US	32	2025	4	0.6
IFMIF-DONES	CIEMAT	175 MHz HWR	Spain	56	2025	3	4
IP-SAFE	IMP	162.5 MHz and 325 MHz HWR	China	60	2025	1	4
S^{3}FEL	IASF	9-cell 1.3 GHz and 3.9 GHz ELL	China	224	2026	2	8
DALS	DICP	9-cell 1.3 GHz and 3.9 GHz ELL	China	100	2026	1	8
CEPC	IHEP	9-cell 1.3 GHz ELL, 2-cell 650 MHz ELL	China	500	2026	5	18
MYRRHA	SCK-CEN	5-cell 704.4 MHz, ELL	Belgium	72	2027	5	7
FRIB 400	MSU	5-cell, 644 MHz, ELL	US	55	2028	3	6
ILC-250	KEK	9-cell 1.3 GHz ELL	Japan	8000	2029	6	340
FCC	CERN	1- and 2-cell 400 MHz ELL Nb/Cu, 5-cell 800 MHz ELL	Switzerland	1500	2032	8	110

Figure 8 shows the average annual rate for the global SRF cavity production, showing the increasing demand from basic-science research accelerators over the years, with a steep increase projected in the next decade if the ILC project will be approved. If one considers an average cost of $250k for a fully-processed SRF cavity, including material cost, the value of the global SRF cavity market for research accelerators in 2030 can be estimated at ~$100M, without ILC, and ~$430M if the production for ILC starts in 2029. Of course, SRF cavity production at a vendor, within the time periods considered in Fig. 8, can be quite uneven, depending on which contracts may be awarded and the duration of the procurement.

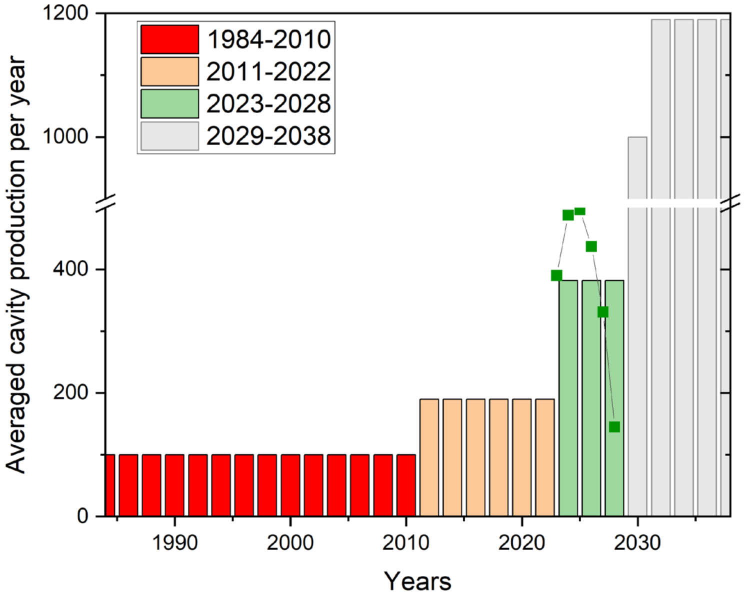


Figure 8. Averaged global cavity production per year, including for both ILC and FCC starting in 2030. The squares refer to the estimated cavity production per year between 2023 and 2028. The average value between 1984-2010 is taken from Ref. [7].

EARLY ADOPTION MARKET PROJECTIONS

Additional growth opportunities for the SRF cavity market are represented by the potential for industrial uses of the SRF accelerator technology. A review of the prospect for industrial applications of SRF technology can be found in Ref. [64]. The project team identified six potential early adopter markets for SRF technology:

1. EUV lithography
2. ADS systems for nuclear waste transmutation
3. Medical isotope production
4. Medical sterilization
5. Phytosanitary treatment
6. Wastewater treatment

When conducting the market research, the focus on SRF cavity production was highlighted, rather than the production of complete cryomodules. While full cryomodules represent a potentially larger market, it is the innermost cavity that forms the core SRF technology component of the system. Looking at a range of projections, the team narrowed on the 2030 time horizon to make estimates about the SRF cavity market for each application area. While accelerator-driven systems are a substantial and attractive market for energy production, the R&D in this space is still too early to mature as a market by 2030. The project team estimates the ADS market emerging only in 2040 or later. National security priorities and nuclear proliferation issues may make it a priority for future U.S. Government investments, thus accelerating the market adoption timeline.

Our Approach

To carry out the analysis, the team captured various estimates with both top-down and bottom-up approaches. Bottom-up estimates were drawn from the input of workshop participants, knowledge within the project team, and specific market expertise, while the top-down estimates worked with information available online and through market research firms. The team evaluated the online information and eliminated outliers related to initial and final market projection sizes and compound annual growth rate (CAGR). The data from the different sources that produced the average values are tabulated in Appendix 4. To ensure complete and unbiased analysis of the markets, full reports on EUV lithography (EUVL) [65] and medical device sterilization [66] were procured from a third-party market research firm. All market analyses are global; only publications from 2022 to 2024 were considered.

To establish the top-down projections, the project team first determined how much of a given market segment could use accelerator technology, captured in Table 4 as the Accessible Market. The team estimated what percentage of the application could be attributed to an SRF accelerator component itself and not other infrastructure, labeled as the Accelerator Fraction. To account for only the SRF cavity portion of an accelerator, the team estimated that 10% of the cost could be attributed to the cavities, based on the team's knowledge of accelerator science projects. To address market penetration and adoption, the team determined a reasonable SRF entry year and then projected the market CAGR to 2030. The resulting market projections for each application are shown in Table 4.

Table 4. Top-down global market projections available on the internet from reputable market research firms.

	EUVL	Wastewater	Phytosanitary	Sterilization	Isotopes	ADS
CAGR	21.50%	6.40%	5.40%	6.30%	8.20%	3.00%
Start Year	2023	2023	2023	2023	2023	2022
End Year	2030	2030	2030	2030	2030	2030
Start Value	$9.7B	$317.3B	$0.417B	$8.576B	$6.234B	$59.62B
End Value	$36.8B	$490.2B	$0.605B	$13.11B	$10.814B	$75.232B
Accelerator Fraction	56%	5%	15%	15%	15%	15%
SRF Cavity Fraction	10%	10%	10%	10%	10%	10%
Accessible Market	50%	0.50%	15%	3%	30%	75%
SRF Entry Year	2026	2027	2027	2027	2028	2035
SRF Market by 2030	**$1.030B**	**$12.3M**	**$1.4M**	**$4.9M**	**$48.7M**	N/A

For the bottom-up estimates, the team collected input from the March 2024 workshop. Together, the group estimated the number of cavities required for each accelerator, the number of cavities per cryomodule, and the number of cryomodules per installation for each application. For the EUVL application, the group determined a "unit" to consist of two accelerators and three spare cryomodules, providing critical uptime and redundancy. For an installation at a wastewater treatment plant or phytosanitary treatment plant, the group allocated two accelerators, to allow for both the high uptime and/or double-sided irradiation. Units for all other applications consist of a single accelerator. A $250k cost for a fully dressed cavity, including material cost, was considered to be a reasonable assumption in most cases. The exceptions are $200k for an EUVL cavity because of production-level savings and $150k for the smaller isotope production cavities. These inputs for all considered applications are collected in

Table 5. Using the market entry date, the project team adjusted the production rates to match the data provided at the workshop in a manner the group felt reasonable from a supply chain standpoint and assumed acceptance of accelerator technology. These results are tabulated in Table 6. Our intent is to establish consistency between the top-down and bottom-up approaches. Our assumptions are validated when comparing the 2030 SRF market costs between Tables 4 and 6. Figure 9 shows plots of the estimated number of units and SRF cavity market value in the 2025-2030 timeframe. Further analyses by individual application are described in the sections that follow.

Table 5. Estimated cost of the SRF cavities for each system unit for different industrial applications.

	EUVL	**Wastewater**	**Phytosanitary**	**Sterilization**	**Isotopes**	**ADS**
SRF Technology	Nb, 1.3 GHz, 9-cell	Nb_3Sn, 915 MHz, 5-cell	Nb_3Sn, 915 MHz, 5-cell	Nb_3Sn, 915 MHz, 5-cell	Nb, 1.3 GHz, 2-cell	Nb, multiple cavity types
Accelerator Energy (MeV)	1,000	8	8	8	75	1,000
Cavities/Accelerator	80	1	1	1	35	140
Cavities/Cryomodule	8	1	1	1	5	4
Cryomodule/Unit	23	2	2	1	7	35
Cavity Cost ($k)	200	250	250	250	150	250
SRF Cost/Unit ($k)	36,800	500	500	250	5,250	35,000

Table 6. Bottom-up market projection based on workshop participants' expertise. ADS is not included because it is anticipated that procurement for would not begin before 2030.

Year		**EUVL**	**Wastewater**	**Phytosanitary**	**Sterilization**	**Isotopes**
2025	No. Units	0.5	0	0	0	0
	Cavity market ($M)	18.4	0	0	0	0
2026	No. Units	1	0	0	0	0
	Cavity market ($M)	36.8	0	0	0	0
2027	No. Units	2	1	1	2	0
	Cavity market ($M)	73.6	0.5	0.5	0.5	0
2028	No. Units	6	3	3	4	4
	Cavity market ($M)	220.8	1.5	1.5	1	21
2029	No. Units	14	10	4	8	8
	Cavity market ($M)	515.2	5	2	2	42
2030	No. Units	28	24	6	16	10
	Cavity market ($M)	1,030.4	12	3	4	52.5

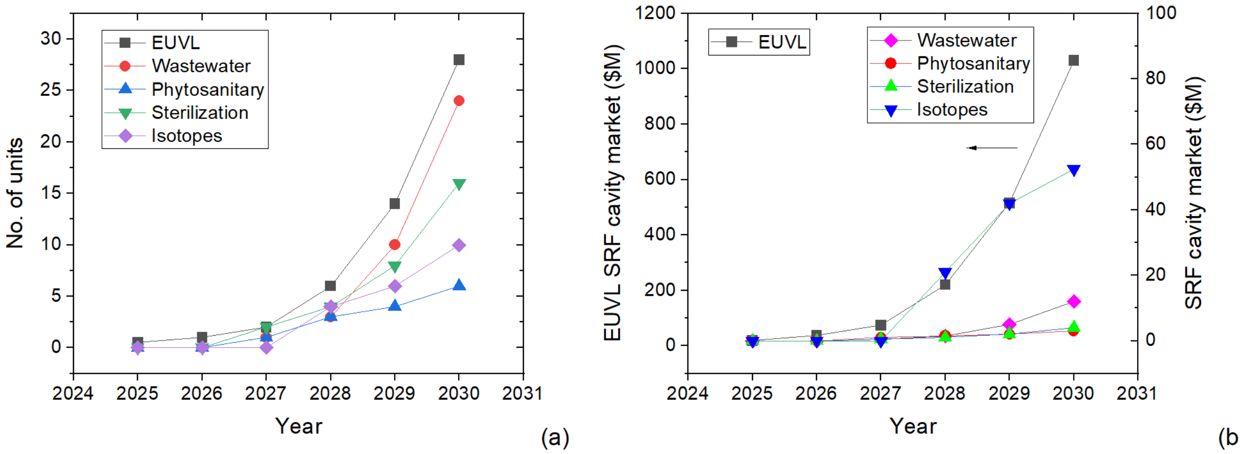


Figure 9. (a) Estimated number of SRF system units and (b) estimated SRF cavity market value for different industrial applications.

EUV LITHOGRAPHY

The largest potential industrial SRF cavity market is EUVL. In 2014-15, ASML briefly engaged with Jefferson Lab and AES around the idea to use free-electron laser technology as a more efficient EUV light source than throughput-constrained Trumpf CO_2 lasers hitting tin droplets to produce the EUV radiation. ASML ultimately decided to concentrate on the tin droplet technology. FEL technology opens the possibility of going to smaller feature sizes (nodes), which are impossible with the present Trumpf sources. Presently, the U.S. company xLight is pursuing the EUV-FEL approach and has announced plans to build a demonstration system in the next few years [67]. Efforts on developing the SRF-based EUV-FEL technology are also ongoing at laboratories in China and Japan [68, 69]. ASML is the only ~$350M per copy EUVL stepper[2] supplier today.

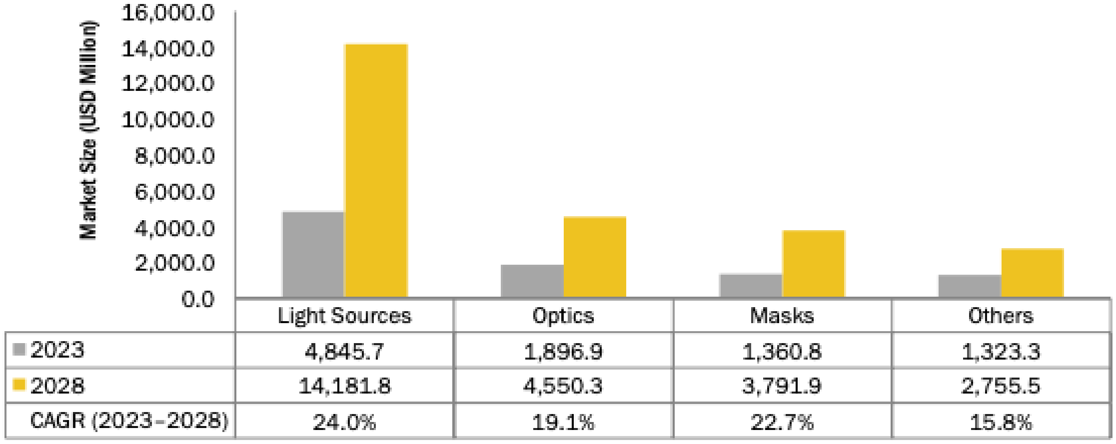
A semiconductor foundry today costs many billions of dollars and contains many steppers, only some of which use EUVL for the critical layers. Foundries require an astonishing >99% uptime 24/7. An FEL light source is proposed to supply about eight steppers and requires two FEL systems so that one is always on hot standby to ensure stepper availability and, in case of an FEL failure, to ensure the loss in production is minimal. We estimate that two FELs replace eight CO_2 lasers for an available light source cost of $368M. In assessing the market, the team assigned 56% of the EUV stepper cost to the light source, as indicated in Figure 10. The light source dominates the device cost despite the need for complex optics, masks and other high-tech components. Current wafers cost >$100k and are rapidly growing in cost and complexity. They have to be discarded if the exposure step is interrupted, thus each FEL dropout would cost almost $1M. The team assumed there will be a high market penetration of 50% due to the upgrade and power advantages of an EUV-FEL system finding early adopters across the entire industry, with an SRF fraction of the systems at 10% of the addressable market. These assumptions yield a projected SRF market of $1B translating to approximately 28 units sales by 2030.

While the SRF cavity market potential is huge, it is unlikely that ASML would consider ordering critical production cavities from a U.S. neophyte manufacturer by 2030 instead of established vendors such as

---

[2] A "stepper" in semiconductor manufacturing is a specialized piece of equipment used in the photolithography process, where it projects a circuit pattern from a mask onto a silicon wafer

ZRI and RI. Hence, the market entry gap for a domestic vendor is only likely to expand unless there is significant federally developed IP and technology transfer involved.



	Light Sources	Optics	Masks	Others
■ 2023	4,845.7	1,896.9	1,360.8	1,323.3
🟨 2028	14,181.8	4,550.3	3,791.9	2,755.5
CAGR (2023-2028)	24.0%	19.1%	22.7%	15.8%

Note: Others include metrology tools, sensors, and subassembly components.

Figure 10. Global forecast for the EUVL market segmented by components, showing the dominance of the EUV light source in an EUVL stepper cost. The figure is taken from Ref. [65].

ACCELERATOR DRIVEN SYSTEMS

ADS demonstrator projects are most advanced in China and in Belgium, although designs are being developed in several other countries worldwide [70]. ADS devices are very early TRL and thus not perceived as a promising market for the investor community. No third-party market projections exist, and it would be a valuable exercise to conduct a technoeconomic analysis for ADS systems based on SRF technology. The project team did look at the overall growth of the nuclear energy market. The market is very significant but unlikely to be a factor in any near-term prospects for an onshore SRF cavity manufacturer. The team estimated a 2030 nuclear energy market to reach $75B and continue to rise as global demand for carbon-free energy increases. ADS systems could capture a significant portion of this market because of increased safety as a subcritical nuclear technology, as well as their ability to reduce both their own nuclear waste products and the stores of existing nuclear waste via transmutation.

The team assumes a market penetration of 75%, with the accelerator fraction 15% of the reactor cost, and the SRF fraction of the accelerator at 10%. However, there is no projected SRF market by the 2030 time horizon due to the immaturity of the technology. By the time of likely maturation and adoption in the 2040 time range, the market will be many hundreds of million dollars.

MEDICAL ISOTOPES

The medical isotope application is the second-largest potential SRF cavity market. Today, the isotopes are mostly produced in aging nuclear fission reactors and using cyclotrons. One challenge to an SRF approach is the existing methods, including other competitive accelerator technologies already on the market, which may be difficult to displace. Together with EUV-FEL and ADS, this is an application space where operators are likely to tolerate the costs and reliability concerns of operating a 2 Kelvin SRF plant. Recently, ASML in collaboration with Demcon, IRE, and HZDR-Dresden initiated the SMART (source of medical radioisotopes) project, which proposed to use the ASML FEL technology for the production of metastable ^{99}Mo that decays to the ^{99m}Tc used in a very large number of medical diagnostic procedures worldwide [71]. However, in 2023, like with its EUV-FEL project, ASML also discontinued the SRF accelerator effort. Niowave has targeted this market with its distinct SRF approach. Conventional room-temperature accelerators are also under consideration. The Canadian Light Source (CLS) produces medical isotopes with its injector.

The project team assumes that the SRF technology selected will be two cell, 1.3 GHz, as was chosen for the SMART project, to produce 75 MeV from 35 cavities [72]. In this case, with shorter cavities, the estimated cost for each fully dressed cavity is $150K. The workshop participants estimated a production rate of 10 systems per annum by 2029-2030 due to the competing production technologies. The group assumed a larger accessible market at 30%, due to the criticality of isotope production with several key nuclear reactors scheduled for decommissioning and the cyclotrons having some undesirable properties. The accelerator and SRF fractions are again 15% and 10%, respectively. These assumptions yield a projected 2030 SRF market of $52M requiring about 14 units sales in 2030.

MEDICAL DEVICE STERILIZATION

The remaining three markets (medical device sterilization, phytosanitary treatment and wastewater treatment) require the maturation of conduction-cooled, Nb_3Sn technology to be competitive in these environments that are highly sensitive to capital expenditures (CAPEX) and operational expenditures (OPEX). Hence the market insertion date has been delayed until 2027, and this may be optimistic. The workshop participants suggested 12 systems per year by the end of the decade with the possibility of a big uptick to replace conventional cobalt radiation systems that have disposal and nonproliferation issues. The medical device sterilization market also has existing entrenched technologies such as steam/heat, filtration, and chemical processes that would need to be displaced and/or replaced.

This is the second application for which the team acquired a third-party market evaluation. From the report, a key point is that the 2029 ionization radiation market fraction was projected to be 16% with a much higher CAGR value of 9.2% compared to the average for the sector, as shown in Figure 11 [66]. Further, it notes that electron-beam sterilization has the greatest utility and is a quickly maturing technology with an ability to impact a significant section of the market. The replacement of cobalt radiation devices is specifically called out as likely to happen sooner rather than later. By 2030, the market may be larger than predicted.

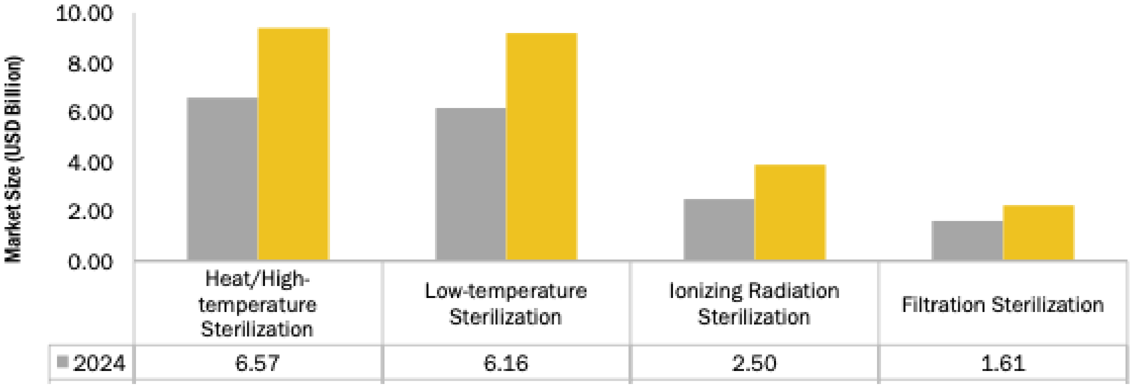


Figure 11. Global forecast for the medical sterilization equipment market segmented by technology, showing the market share and strong relative projected growth of the ionizing radiation sector. The figure is taken from Ref. [66].

For this sterilization application, the SRF technology will likely be a single 8 MeV, 4 kelvin cryomodule. The team assumed the same $250k cost per cavity and that the market ramps up to 16 units by 2030, to include a few cobalt-source replacements. However, given the alternate technologies that are and will continue to be in play in this market, and given that the purchasers are very risk-averse and cost-sensitive, the team only assumed a 2.5% market accessibility with the usual 15% and 10% accelerator and SRF fractions. Note that 2.5% is calculated as 15% of the projected 16% ionization sterilization market, but there still will be a need to displace the standard room-temperature copper accelerators and cobalt sources used today. These assumptions yield a projected 2030 SRF market of $4-5M requiring about 16 unit sales in 2030.

PHYTOSANITARY TREATMENT

The market research for this application is difficult to assess and evaluate due to widely varying reports available. Most of the 2030 market projections are less than or around $1B, however one study projected upwards of $309B. In the end, the team excluded this outlier report and used the average of the others. Because of similarity to the medical sterilization systems, which we do address in some detail and both of which are single cryomodule/cavity 8 MeV, Nb_3Sn, conduction-cooled devices, the team has decided not emphasize this niche application. Despite that, phytosanitary treatment may be a very near-term and significant application of SRF technology, particularly as food quality, preservation and safety issues become increasing important due to challenges in global agriculture supply chains.

These assumptions yield a projected 2030 SRF market of $4-5M requiring about 16 unit sales in 2030. As noted, there is strong upside should this application becomes a critical food security issue across the world.

WASTEWATER TREATMENT

The application of SRF technology in wastewater treatment presents an enormous opportunity, on the order of $500B by 2030. The industry itself is extremely risk-averse and cost-competitive with many entrenched technologies. Market penetration would require competitiveness on operating or CAPEX costs, and could be achieved with Nb_3Sn conduction-cooled technology. The project team anticipates two units per system, perhaps for double-sided irradiation, depending on the configuration in the treatment plant. Under consideration is a single cryomodule/cavity 8 MeV, Nb_3Sn conduction-cooled device for each of the environmental applications to include wastewater treatment. Related markets not specifically called out include environmental remediation and effluent from industrial sites.

In this market, the team assumes the usual 10% SRF fraction but a much lower accelerator fraction, 5% due to the large size of wastewater treatment plants and the tiny relative footprint of accelerator systems. To accommodate the risk-averse and cost-competitive nature of this market, the team assumed only a 0.5% market penetration by 2030 since first adopters will be few and far between.

These assumptions yield a projected 2030 SRF market of $12M requiring about 24 unit sales in 2030. Over a longer time-horizon, it is expected that the environmental market for SRF accelerator technology will grow to a large market, but it will likely take a long time to become fully adopted.

MARKET ANALYSIS SUMMARY

While any market assessment is highly subjective and based on highly variable inputs, the project team made every effort to assemble the best available market data with contributing knowledge from experts across many industries, as well as third-party sources as referenced. There is quite a bit of variation in anticipated unit sales for each application. To bound the uncertainties when predicting future markets, the team recommends a ±25% deviation from the numbers given, to account for the highly variable inputs.

There are other serious considerations as well for any new market entry. Specific to SRF technology: Will a domestic U.S. SRF supply chain be in place to support the numbers projected? Will domestic U.S. vendors be encouraged to try and enter the marketplace given the existing foreign competition and the track history of the DOE & the U.S. Government to support domestic vendors?

The potential markets are enormous, both near-term and far-term, and cannot be ignored. The total bottom line is that there is a combined ~$1.1B market for SRF cavity production in 2030. This is a very attractive number, but it is completely dominated by the EUV-FEL market, which for multiple reasons may not be penetrable by an onshore vendor at this point. Without EUV-FEL, the market is $67.2M. This is not inconsequential, but more than an order of magnitude down from the total quoted market. If we take out the second-highest projected market, medical isotope production at $48.7M in 2030, then the opportunities for development of domestic vendors becomes even more questionable because the remaining market is not particularly compelling. However, when combined with other business lines, a domestic vendor capable of playing in the SRF technology space may see significant benefits from diversifying its operations to include opportunities in the SRF application spaces described above.

6 SURVEY RESULTS

An anonymous, 10-question survey to gather input on this project's topic was prepared and deployed on February 13, 2024. The survey was open until March 1, 2024. During this period, a broad range of perspectives were collected from scientists, engineers, industry professionals, lab operations and procurement, and technology transfer professionals. The invitation to participate in the survey was sent to 152 potential respondents, which can be broadly categorized as 1) scientists/engineers working in Government laboratories or universities (~40% of invited participants), 2) scientists, engineers and businesspeople working in private companies (~38% of invited participants) and 3) program managers, tech-transfer, and procurement officers from government agencies (~22% of invited participants).

Sixty-seven complete responses were received, corresponding to a 44% participation rate. "Feeling"-type responses were input according to a Likert scale [73]. As an example, a response item that allowed choosing among "very likely", "likely", "unlikely", "very unlikely", "no opinion" was assigned a numerical rating given by: $(N_{\text{very\_likely}}*4+N_{\text{likely}}*3+N_{\text{unlikely}}*2+N_{\text{very\_unlikely}})/N_{\text{TOT}}$, where N_{xyz} is the number of respondents that had the selected feeling and N_{TOT} is the total number of respondents.

The opportunity to elaborate on survey questions was provided with a comment box under each question. Additionally, respondents were asked whether they were interested in a follow-up interview on the project's topic. The following provides a summary of the responses and comments to each of the survey questions.

Question 1: Of the following applications, which do you feel are most likely to adopt SRF technology?

According to the respondents, the top three most likely applications of SRF technology are "basic science research applications," "isotope production," and "extreme ultraviolet photolithograghy," as shown in Figure 12. The first item is related to large-scale, government-funded particle accelerators, where the niobium-based SRF technology is already the technology of choice. The EUV application

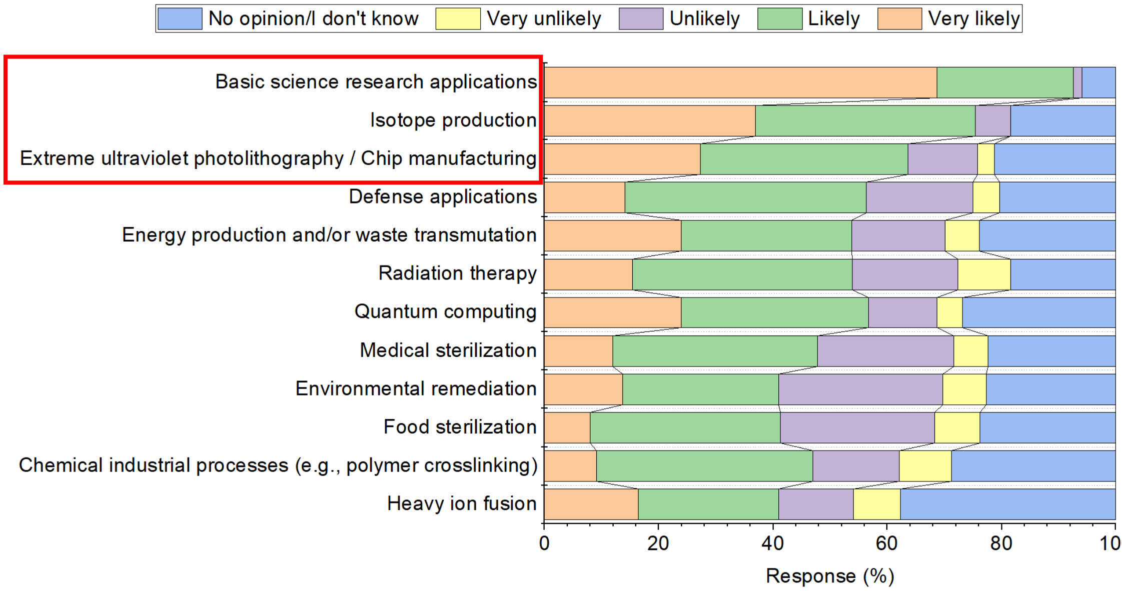


Figure 12. List of items in the response to the first question, ordered from the most to least likely. The top three most likely applications are inside the red box.

requires an electron accelerator with a relatively high energy, which would most likely rely on the conventional niobium-based SRF technology. Accelerators for isotope production require more moderate energy, and there is an existing one based on the niobium-based SRF technology, but future ones may adopt the cryogen-free Nb_3Sn SRF technology.

Question 2: Consider a shared public-private facility for SRF cavity fabrication and processing. Which of the following features are the most important?

The respondents felt that quality assurance/quality control; the presence of a skilled local workforce; and streamlined site access, training, and safety procedures to be the most important features of a public-private SRF cavity fabrication and processing facility. The ranked answers to this question are shown in Figure 13.

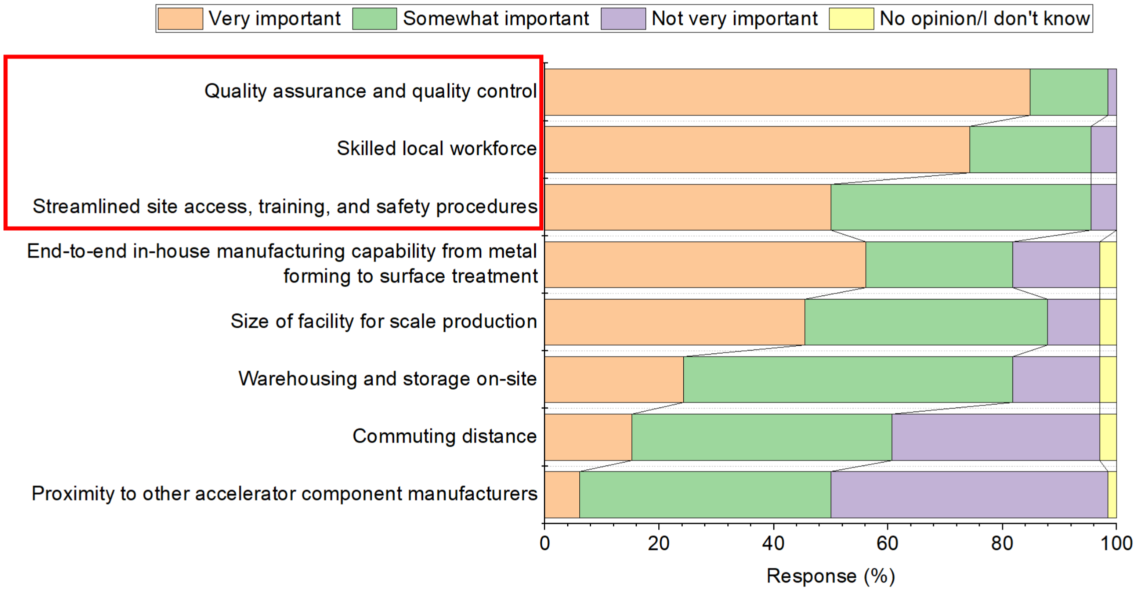


Figure 13. List of items in the response to the second question, listed from the most to the least important. The top three most likely applications are highlighted by the red box.

Question 3: Consider the business entity structure for a public-private facility for domestic SRF cavity production. Which of the following structures is preferable to you?

Figure 14 shows a chart with the percentage of votes for each response item. The respondents had the option to choose up to three response items. “Federally supported facilities and/or equipment at an industrial partner’s site” was the preferred option, with ~60% of the votes. An industrial user accessing facilities already established at DOE national laboratories or on university campuses was the second-most voted option, with ~50% of the votes. Three options below the top two received nearly the same, ~30% of the votes.

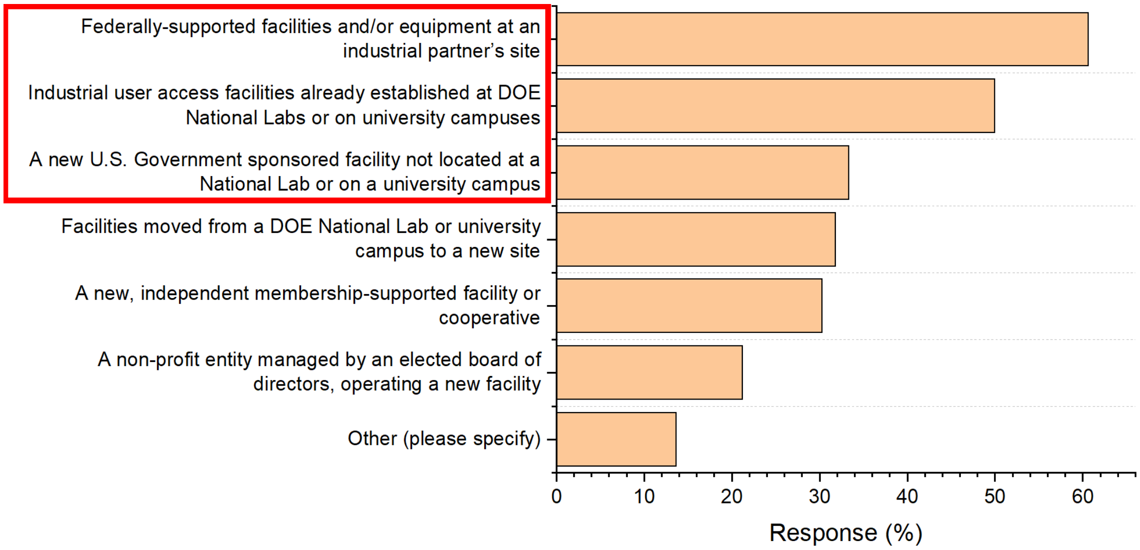


Figure 14. List of items in the response to the third question, listed from the most to the least voted. The top three most voted responses are highlighted by the red box.

Question 4: Considering proximity and capacity, how many facilities do you think should be established to support U.S. domestic SRF cavity production?

The majority of respondents clearly indicated that two SRF cavity production facilities should be established in the U.S., as shown in Figure 15.

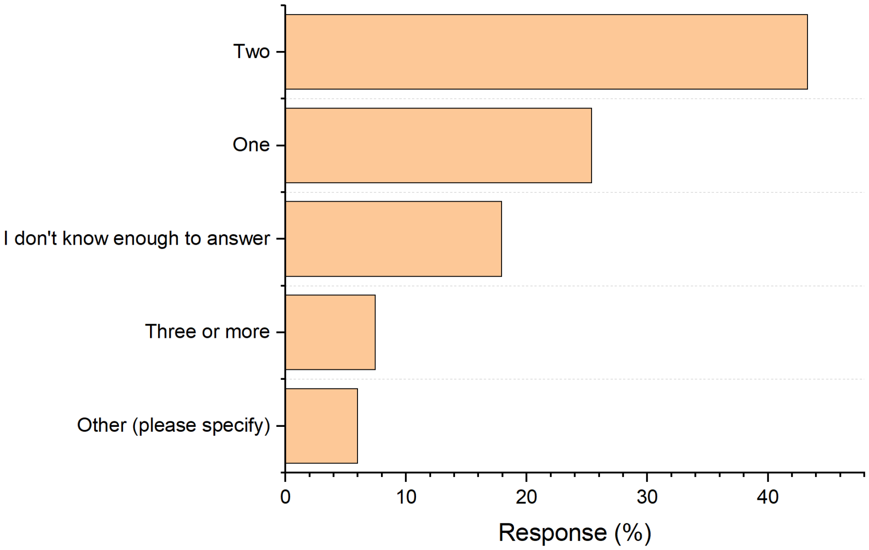


Figure 15. A chart with the percentage of votes for each response item. There was strong response toward having two facilities established in the U.S. to support domestic SRF cavity production.

Question 5: Of the following barriers to sustaining a U.S. domestic SRF industry, which do you feel are the most challenging to overcome?

The initial capital investment required to manufacture and process SRF cavities and cryomodules was considered the most challenging barrier toward sustaining a domestic SRF industry, as shown in Figure 16. Additional significant challenges were:

- The complexity of rules and regulations of government contracts.
- The need for a niche talent, which primarily resides at national labs.
- The difficulty to attract angel or venture capital investors.

The response to Questions 5 resulted in a good number of comments, left by 18% of the respondents, which can be summarized as follows:

- Explore alternative markets: Investigate applications with broader appeal, such as technologies requiring lower Nb purity, which have larger potential markets.
- Seek synergies with existing nuclear energy and superconductor wire supply chains.
- Implement a “Manhattan Project”-style initiative to establish technical standards and attract industrial players.
- Offer low-risk, high-reward opportunities to incentivize private investment and development.
- Address procurement issues: streamline procurement procedures and encourage collaboration between labs and industry.
- Focus on commercialization: Identify and promote broader industrial applications of SRF technology to create a sustainable market.

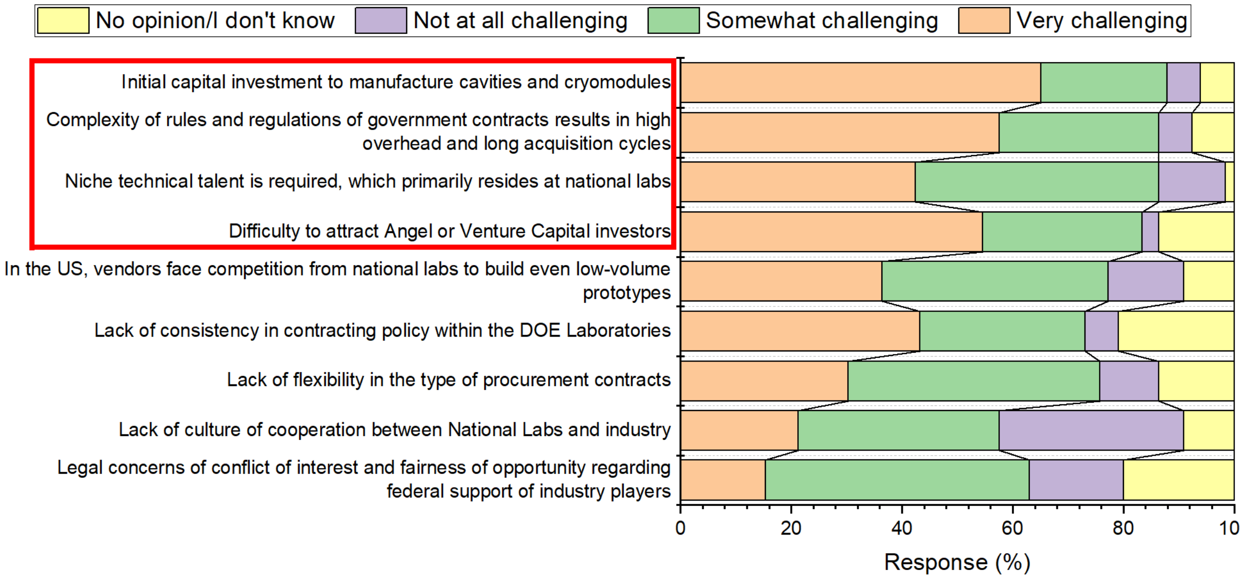


Figure 16. List of items in the response to the fifth question, listed from the most to the least challenging. The top four most challenging barriers are highlighted by the red box.

Discussions during the workshop highlighted the issue that all the DOE labs procure differently. The cycle times are different, as are review schedules/thresholds, and the site officials for each individual lab have different requirements for procurements of SRF cavities.

Question 6: Which of the following would have the most impact in assuring a reliable domestic supply of high-purity Niobium sheets, used for SRF cavity fabrication?

The responses that were considered most impactful were to increase the demand for high-purity Nb and to build and maintain a Nb inventory through a guaranteed minimum annual purchase from domestic Nb vendors. The ranked responses to this question are shown in Figure 17.

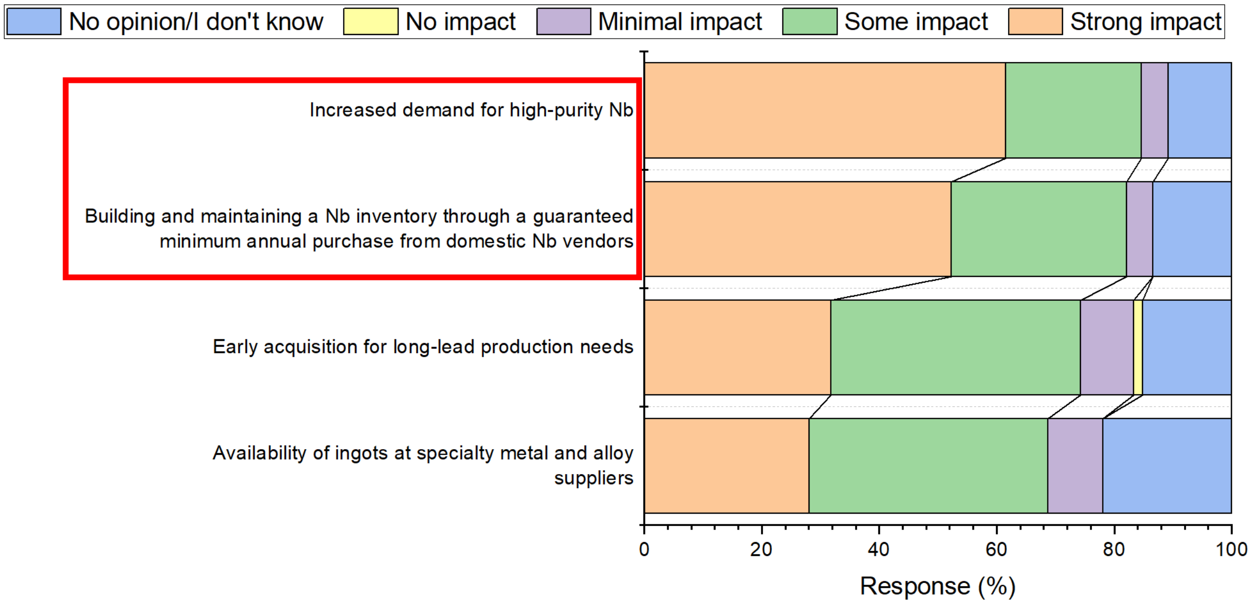


Figure 17. List of items in the response to the sixth question, listed from the most to the least impactful. The top two most impactful options are highlighted by the red box.

Question 7: Should a U.S. government-funded SRF accelerator project require SRF cavities to be produced domestically, even if the cost of the project may be higher than if purchasing from overseas vendors?

Whereas 63% of the respondents answered “Yes” and 37% answered “No,” the answer to this question inspired the largest number of comments, written by about one-third of the respondents. While the comments acknowledge the potential benefits of domestic resonator production, concerns regarding cost, schedule delays, and quality issues need to be addressed. The comments can also be summarized as:

- The focus should be on fostering a competitive domestic industry through incentives and strategic partnerships.
- Quality and performance must remain paramount, with open competition considered unless national security concerns dictate otherwise.
- A cost-benefit analysis is crucial to determine whether the additional cost that may result from supporting domestic SRF vendors is justified.

Question 8: What type of incentives should the U.S. government establish to support domestic SRF cavity production?

Figure 18 shows a chart with the percentage of votes for each possible response. Respondents were allowed to choose multiple responses. Adding the SRF technology to the White House Critical and Emerging Technologies list was the response that received most votes. Tax incentives and guaranteed minimum annual order of SRF cavities also received more than 50% of the votes. Answering this question also prompted a good number of comments, left by about one-quarter of the respondents. The comments emphasize the need for a multipronged approach to strengthening the domestic SRF industry, such as:

- Focus should be placed on fostering innovation and moving beyond outdated production methods.
- Long-term federal investment in cutting-edge technology and workforce development is critical.
- Strategic procurement practices, such as "Buy American" initiatives and targeted funding allocations, can provide temporary support.
- Establish a well-defined strategy for accelerated (near-term) development with clear metrics and accountability and commit to succeed.

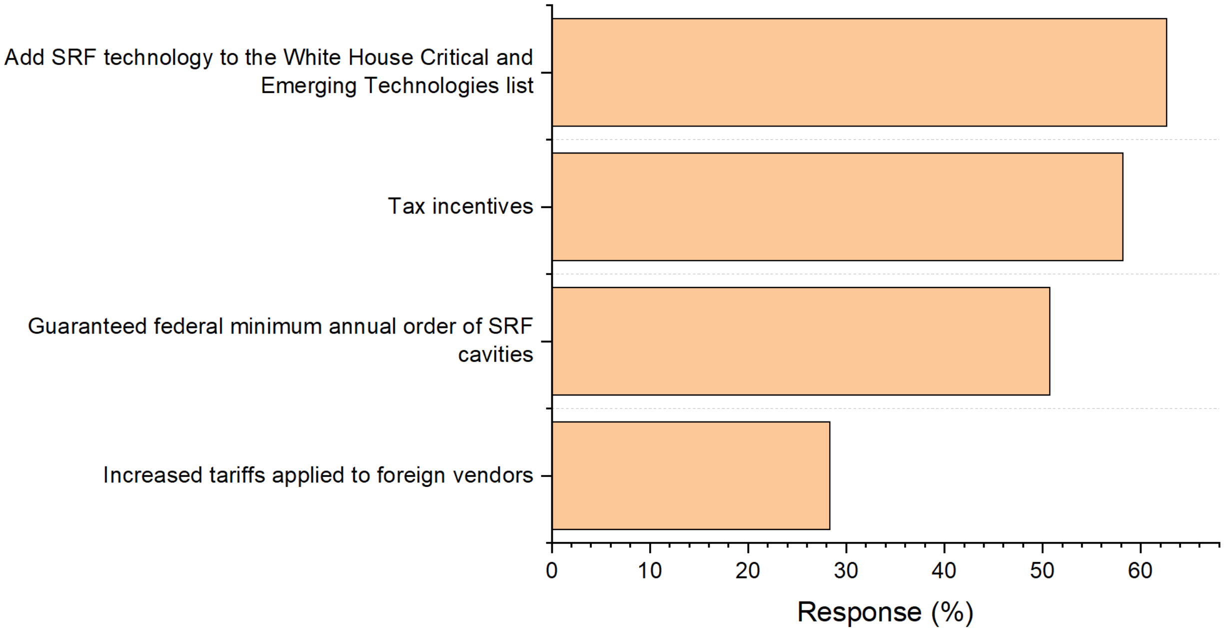


Figure 18. Percentage of votes for each possible response to question number eight.

Question 9: Should a uniform procurement policy regulating the acquisition of SRF cavities, within FAR-based contracts, be established among all U.S. national laboratories?

The answer to this question was overwhelmingly “Yes,” with 77% of the votes.

Question 10: Which of the following do you think would result in a significant improvement in the national labs/universities' procurement process for SRF cavities?

Figure 19 shows a chart with the percentage of votes for each possible response. Respondents were allowed to choose multiple responses. A simplification of the Terms and Conditions clauses was voted as the most significant improvement in the procurement process. DOE soliciting feedback from vendors about their experience in dealing with procurements from national labs/universities was also considered to be a valuable mechanism to improve the procurement experience. Improvement in the communication among the national labs/universities procurement team and technical representatives was also seen as beneficial by more than half of the respondents.

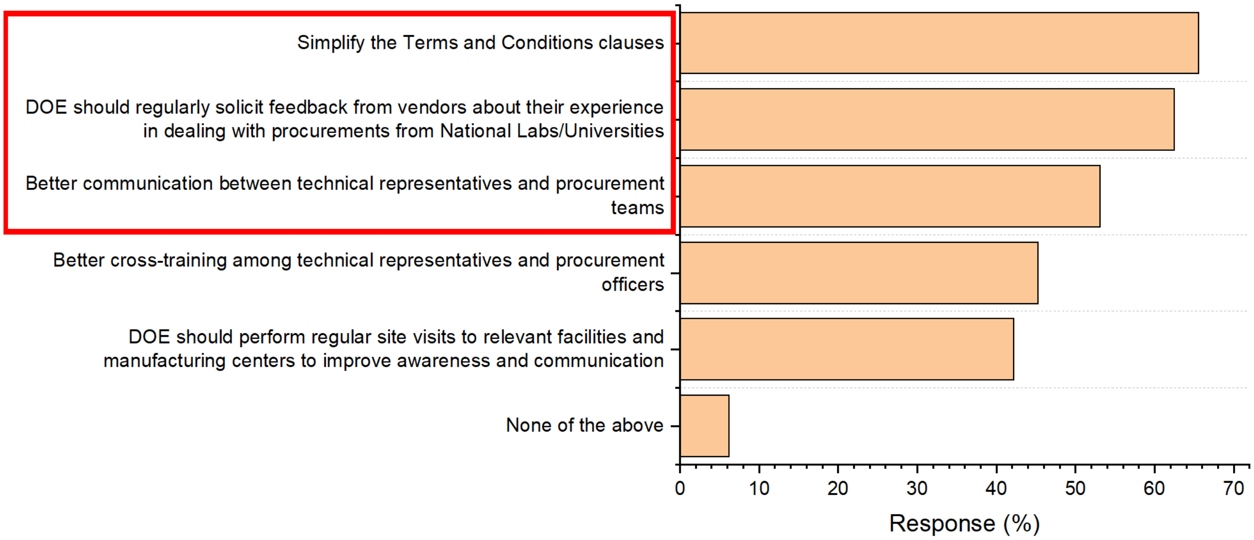


Figure 19. Percentage of votes for each possible response to the last question. The top three most voted responses are highlighted by the red box.

7 ROADMAP

Robust domestic production of SRF cavities cannot be decoupled from the larger SRF technology landscape. Only when investments are made across the full value chain, and when adoption of SRF technology reaches a sustainable volume depending on each application area, will the cavity production itself be a sustainable business line for industrial players.

As it was discussed in Section 4, establishing a facility to fabricate and perform the surface treatment and assembly of SRF cavities at the same level as the European manufacturers requires an equipment capital investment of the order of $16M. Based on existing facilities, the estimated footprint of a building that hosts all of the required equipment is of the order of 25,000 sq.ft. To further understand the limiting factors for bulk Nb production, a full market analysis on ingot production and sheet production would need to be performed. The capital cost of such a Nb production facility would be much larger than the manufacture of cavities alone.

It is key to the long-term establishment of a domestic SRF industry that it has both sustainable revenue and market-independent cash reserves. It should also:

1. Be able to handle swings in procurement from "big science" projects.
2. Be ready to deliver goods for small projects.
3. Be able to ramp up quickly for large projects.

The team has evaluated various potential approaches to establish a resilient and competitive domestic SRF industry that can address the above constraints. The project team has also reviewed federal agencies' models, such as the National Science Foundation's Industry-University Cooperative Research Centers (NSF IUCRC), and Consolidated Nuclear Security, LLC [74, 75]. Additionally, the team discussed previously active public-private partnerships such as EUV LLC [76] and SEMATECH [77] to look for insights into potential business models for an SRF industry consortium. Both EUV LLC and SEMATECH were large consortia with many member institutions; the SRF industry simply does not have as many mature, vested entities at this time to justify creating such a consortium.

NSF IUCRCs initially appeared to be a compelling example from an agency focused on R&D. The IUCRC model is "design to help corporate partners and government agencies connect directly and efficiently with university researchers …" At its core, each IUCRC is a membership consortium where industry pays a fee to collectively determine projects of interest, gaining access to precompetitive R&D and helping shape the research vector. The IUCRCs are supported by NSF at first, but must be able to operate independently by the end of the award. Ultimately, this model was removed from consideration due to the extremely narrow focus area of SRF cavity manufacture, and the importance of a sustained federal investment due to inconsistent SRF cavity demand. In this model, a dedicated and sustainable R&D consortium would be financially difficult to maintain without regular investment from the federal sponsor.

The project team narrowed potential business models to three facilities with certain common elements. In each of these elements is a need for continued federal investment, whether through capital expenses and large procurements, or in the management and operations of the facility itself. As previously discussed, the primary driver for continued federal investment is the nonlinear market demand for SRF cavities. Should the potential applications proliferate in the marketplace, this may result in a reduced need for federal investment as new economies of scale are realized for SRF cavity fabrication. The three models are detailed below:

1. A new industrial user facility managed by a DOE national lab
2. Federally funded facility at a company site
3. Industrial user access to an existing facility at a DOE national lab

INDUSTRIAL USER FACILITY MANAGED BY A DOE NATIONAL LAB

This approach involves establishing a federally funded industrial user facility for SRF cavity fabrication, surface treatment, and assembly close to, but outside the perimeter of, a DOE national lab or accelerator facility. The national lab manages the facility, and industrial users can apply to access and use it. Standard partnership mechanisms such as User Agreements, CRADAs and SPPs would be the vehicles through which industrial users can access the resources of the facility, both technical experts and equipment. An advantage of establishing the facility outside of a lab's campus is the streamlined access requirements, and less disruption to mission-critical operations on campus.

The Manufacturing Demonstration Facility (MDF), managed by Oak Ridge National Laboratory, is a prime example of this approach [78]. The hosting laboratory provides the base funding and staff to operate the facility. Private companies can apply to access the equipment and collaborate with the laboratory staff by submitting a short proposal for review. After selection, a simplified CRADA is signed and work can be scheduled, without affecting work in other parts of the laboratory. If the company wants to engage with the laboratory's equipment and personnel to work on a product or process that is already proprietary to the company, it will pay a fee to the laboratory to receive the services, and work will be carried out under an SPP. A company may also have the option of installing its own equipment at the facility in order to receive support from the lab's staff to develop a new process or product related to that equipment. The MDF was established in 2012 and has been very successful in improving partnerships' efficiency and promoting innovation and technology transfer. The MDF facility is being adapted via a "hub and spoke" model at the Center for Advanced Manufacturing and Innovation (CAMINO) at Sandia National Laboratories, funded in part by a DOE Office of Technology Transitions award, "C4 Partnering," under the Technology Commercialization Fund [79]. This C4 Partnering project has a goal to establish more MDF-like spokes at other national labs. Several labs are involved in that project and exploring spokes at their respective locations.

This option is very attractive from the point of view of technology maturation, commercialization, and industry-led development of new SRF cavities. It also has the following benefits:

1. It provides an opportunity for national lab personnel to work alongside industry personnel, favoring rapid and effective transfer of technology to maintain U.S. competitiveness.
2. It provides vertical control over an entire process, including the equipment.
3. It provides for an efficient use of the facilities, which can be used to carry out lab-directed R&D projects as well as small-scale industrial production and the rapid prototyping needs of the lab.

A major challenge of this model pertaining to SRF cavity manufacture is in the case where a company would like to access the facilities for a large-scale production effort. In this situation, it may be difficult to coordinate access to the facility by other companies, or lab personnel involved in lab-directed R&D as there is a potential to consume the facility's resources for the duration of the production. It would also be important that the governance body that selects the proposals represents the broader domestic SRF scientific community, not just that of the hosting laboratory.

FEDERALLY FUNDED FACILITY AT A COMPANY SITE

This approach involves setting up an SRF cavity production facility, with the funds for the capital equipment provided by federal and/or local government. This approach was followed to some degree at AES, as discussed in Section 4, as the company was able to acquire the BCP and EP cabinets through contracts from BNL and Fermilab, respectively. This approach also reflects elements of the “European model” and may provide the lowest risk to a company interested in entering the SRF business. There are examples of this approach being applied successfully for DOE and DOD projects. For example, General Atomics (GA) was awarded in 2011 a contract from ORNL to manufacture the Central Solenoid for the ITER project. GA constructed a new building for the project, the General Atomics Magnet Technology Center, and all of the equipment required for the manufacturing of the solenoid was procured through the contract [80, 81]. Similarly, it is not uncommon for DOD to release open calls to industry to establish new manufacturing facilities to produce specialized military components. Under this approach, the company would be considered a federal government prime contractor.

Challenges with this approach are:

1. If the volume of production is too low, it becomes too expensive to maintain the equipment. This was the situation at AES.
2. There should be a way to allow the company to use the equipment to produce SRF cavities for customers other than the Federal government.
3. There are workforce considerations if the company fails or decides to exit the SRF cavity production business. Investments in staff training will remain in the company, unless those individuals move to other professional engagements.

INDUSTRIAL USER ACCESS TO EXISTING FACILITY AT A DOE NATIONAL LAB

This approach relates to providing access to SRF cavity fabrication, processing and assembly facilities already existing at a DOE national lab in order to fulfill a cavity production contract. This approach requires the least upfront capital investment by either the federal government or the private sector, however it has significant challenges from the point of view of establishing a competitive domestic SRF industry:

1. It will be difficult to prioritize public versus private use of the facilities.
2. It will be difficult to determine responsibilities with respect to equipment maintenance over the duration of a cavity production.
3. There may be reduced efficiency because of possible delays with respect to access to the labs’ site.
4. Increased overhead and longer schedules may result due to complying with the lab’s safety and access policies.

An example of this approach in the U.S. is the Illinois Accelerator Research Center (IARC) at Fermilab, which was established as a space for industrial partners with access to experts at the lab. The CFF at KEK in Japan is a similar example but, in both cases, there hasn't been significant interest by industry to engage and access the facilities on the labs’ sites.

8 RECOMMENDATIONS

SRF technology is projected to grow significantly over the next five years, and for the first time in the history of the technology, there are several near-term prospective applications for industrial accelerators. As RI is the only company in the world that is able to produce complete, turnkey SRF cryomodules, it is well positioned to be the dominant player in the market. Companies in China are rapidly advancing toward similar capabilities. As a result of the team's efforts over the prior year, the project team has developed the following recommendations.

The project team strongly recommends that two domestic industry production facilities with overlapping capabilities are established to fabricate, perform surface treatments of, and assemble SRF cavities. The facilities should be open to allow companies to use the facilities to produce SRF cavities for any customer. The facilities should be operated by private sector companies that are responsible for the maintenance and operation of the equipment. Having two domestic vendors, instead of one, will assure some continuity in the technology within the U.S., if one of the vendors were to change their business model or need to react to other market dynamics out of their control.

At least one SRF R&D facility, modeled after the Oak Ridge MDF, should be established in close proximity to a national lab campus. This facility would be managed by a national lab and would be a space where industry and lab personnel can work together to advance the technology, through R&D projects and prototyping. Such an off-campus facility is necessary to reduce the barriers to industry participation because of complexities in access restrictions and fluid availability of equipment as well as the time needed to establish new cooperative agreements with national labs.

In order to ensure the long-term success of a domestic SRF industry:

- A minimal viability production volume threshold should be defined. A 10-year public sector guarantee of the minimum production volume should be established. If the market provides enough orders to meet the threshold, the public sector guarantee is not activated. This could be evaluated on an annual basis.
- Public sector guarantees could be used to raise venture capital or funding to establish a production line.
- The need for the public sector to guarantee the minimum production volume can be re-evaluated at a regular cadence, for example every five to 10 years.

The procurement for any U.S.-based SRF accelerator project should be structured to have a minimum mandatory quota of the domestic SRF cavity production to be awarded to a U.S. vendor that has demonstrated adequate technical expertise. This strategy is implicitly implemented in Asia and Europe. Past examples of the negative consequences of not adopting this strategy were given by the entire cavity productions for both CEBAF and LCLS-II/-HE being awarded to foreign vendors. Even though the projects were indeed successful, a domestic SRF industry was a casualty.

The supply chain of Nb sheets could be strengthened by providing a minimum annual order of Nb sheets to U.S. vendors, allowing stockpiling of the material. Examples for authorization of similar actions can be found within the framework of the 2024 National Defense Authorization Act, through the National Defense Stockpile Transaction Fund, aiming at increasing the domestic processing of critical minerals. Niobium is one of the 50 minerals considered to be critical to the U.S. economy and national defense

[82]. Given the importance of niobium and its alloys to superconducting wire manufacturing, besides SRF cavities, it would be auspicial for niobium to be added on the DOE's Critical Materials list [83], because both superconducting magnets and cavities are the essential components needed for many current and future particle accelerators at the DOE national laboratories. It would also be beneficial to gather more information on the potential for domestic Nb sheets supply, in order to understand what are the current industrial capabilities with respect to electron-beam melting furnaces, which could be used to produce Nb ingots, as well as the equipment for the forging, rolling, and annealing to turn ingots into sheets. This may help determine the need for a possible investment into small-scale facilities at several companies that could better accommodate the much lower demand of Nb sheets for SRF cavities, compared to the much larger demand for Nb for other superconducting applications.

Raising awareness of the strategic importance of the SRF technology for the present and future scientific and economic leadership of the U.S. should be a priority of the SRF businesses. This could result in the SRF technology being added to the White House Critical and Emerging Technologies list.

Whereas programs to increase the engineering and scientific workforce in SRF technology are in place, more opportunities to increase the technical, skilled-labor workforce should be created. This is not specific to SRF technology but applies in general to practical accelerator technology. To strengthen the pipeline for talent and succession planning, technical workforce opportunities should take the form of apprenticeship programs at trade schools and/or community colleges in partnership with national labs, in which lab experts teach hands-on classes in basic vacuum, radiofrequency, and other accelerator technologies.

It would be beneficial to have long-term funding for R&D in SRF science and technology, similar to the Conductor Development Program, which was established in 1999 for R&D in superconducting cables for magnets and which led to the successful development of high-field Nb_3Sn and Bi-2212 conductors [84, 85]. The most supportive funding period for SRF R&D in the U.S. was during the ILC-GDE effort between 2006-2014. DOE funding to establish adequate SRF capabilities at national labs in preparation for ILC was ~\$19M/year between 2006-2014. During the same time period, a total of ~\$18M was provided by DOE for cavity and cryomodule components contracts to industry and ~\$12M in support of the ILC-GDE R&D efforts at national labs [86]. The ILC-GDE R&D in the U.S. represented a focused, coordinated effort to both industrialize and mature SRF technology. Many of the industrial applications that could benefit from SRF technology rely on the development of Nb_3Sn conduction-cooled cavities. Whereas this effort started in the U.S. [25-28], China made enormous progress in just a few years. Without adequate and sustained funding to U.S. institutions, China may be the first to commercialize the technology. For example, being able to deposit a high-performance SRF Nb_3Sn film on a copper or aluminum substrate would be a significant scientific and technological breakthrough for SRF-based industrial accelerators. R&D is also needed in the following areas to reduce the SRF cavity production cost, potentially providing a competitive advantage to the U.S. industry:

- More efficient and/or alternative Nb sheet production methods
- Streamlined and/or novel surface treatments
- Efficient and advanced manufacturing methods

Funding for these focus areas may overlap with the Advanced Materials & Manufacturing Technologies Office within DOE, and an intra-program office collaboration would be beneficial.

The national laboratories and universities with expertise in SRF science and technology should be encouraged to form a “National SRF Council” aiming at the following:

1. Define a national strategy for R&D in SRF.
2. Define a national strategy for the acquisition of the minimum volume threshold of SRF cavities and Nb sheets or ingots.
3. Create uniformity and/or standards in the requirements for Nb material for SRF cavities.
4. Create uniformity in the procurement approach for SRF cavities.
5. Create uniformity in the way technical packages for the procurement of SRF cavities are produced.
6. Serve as a technical advisory board on domestic SRF accelerator projects.

Whereas the vast majority of the government contracts are issued as “firm fixed price” (FFP), other contracting options, such as CPFF should be encouraged to share some of the risks involved in low-volume fabrication of prototypes. An example of how this can be helpful is represented by a contract that Northrop Grumman had with BNL to build the RHIC dipoles and quadrupoles. That contract began as CPFF for the manufacturing planning, producibility analysis, and production of the first ∼10% of the magnets. This was followed by an FFP phase to complete the production. The arrangement worked extremely well and resulted in a superior product at a good price. During the CPFF phase, more than 300 engineering change orders were approved that would have never progressed under FFP rules and would have incurred significant financial risk to the vendor.

Standardizing procurement processes across DOE labs can streamline operations, reduce cycle times, and provide clarity to vendors. Lengthy Terms and Conditions required for vendors to sift through and understand seem daunting to small businesses and tend to make the small business wary of working with DOE. Simplifying these documents or providing resources to help small businesses navigate them could encourage more participation from these vendors. Offsetting the costs associated with preparing offers could alleviate the burden on vendors, especially small businesses. Allowing sole source procurement for domestic vendors can expedite the process and encourage diverse responses from startups and smaller domestic companies. This approach is similar to how DOD handles critical items, ensuring rapid acquisition time to meet the national security needs. Increasing the Buy American percentage for SRF cavities could provide a competitive edge to domestic startups by favoring local production over foreign suppliers.

Together, the recommendations listed above can facilitate a highly nimble and prolific SRF industry ecosystem for the United States. Figure 20 provides a pictorial representation of the proposed ecosystem for a robust domestic SRF cavity production.

The history of the domestic SRF industry shows that vendors who are fully committed to the technology can achieve the same level of quality and schedule as the European vendors. Key elements and examples of successful transfer of the SRF technology to industry for small and large projects exist and should be held up as examples to replicate [87, 6].

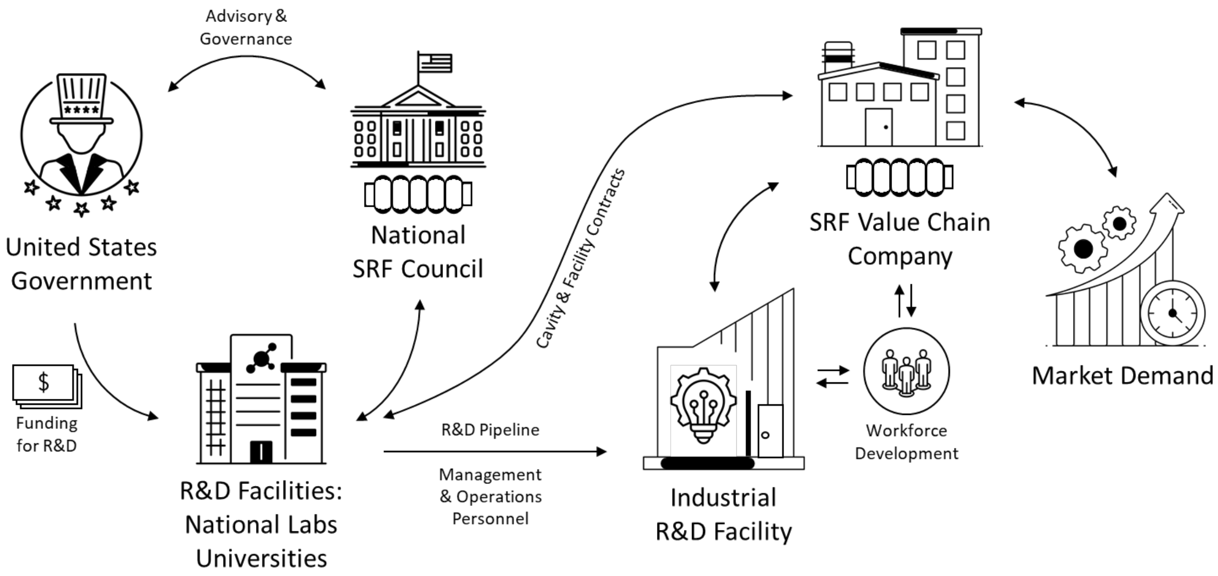


Figure 20. Graphic representation of the proposed ecosystem to develop a robust domestic supply of SRF cavities.[3]

It should also be recognized that vertical integration may be beneficial for companies entering the SRF technology market, from SRF cavities to cryomodules, to complete accelerators, in order to add value and be competitive with RI. Regarding the national labs that already have the full spectrum of SRF production capabilities, it should also be recognized that some degree of "cultural change" is required. National labs have an important role to play in sustaining and nurturing a domestic SRF industry, and in fact, this should be a priority as part of their mission, even with respect to the development of prototypes. This is also one of the features of the "European model" for SRF industrialization. However, the team recognizes that smaller laboratories and universities already have the equipment and facilities to fabricate and process SRF cavities, yet they often do not have sufficient procurement budgets to contract small-volume or prototypes production to industry. This has the effect of making it appear more cost-effective for in-house fabrication of cavities. In-house fabrication of prototype cavities for projects within a lab does not violate FAR's policy with respect to research and development contracting [88]. On the other hand, situations where a laboratory or university enters an agreement with another lab or university to fabricate SRF cavities, instead of procuring them from industry, may require proper justification and an approval from DOE.

General considerations that apply broadly to accelerator technology include:

- It is auspicial to foster a strong domestic accelerator technology consortium, in addition to an SRF council, such as the one in China in support of the CEPC project [89], or in Japan in support of ILC [90], in order to leverage existing resources and expertise. The Superconducting Particle Accelerator Forum of the Americas, initially called the Linear Collider Forum of America, was a nonprofit organization in the U.S. promoting participation of domestic industry in domestic, federally funded particle accelerators. It started in late 2005, shortly after the announcement that the ILC was going to be based on SRF technology, and was active until 2015 [91]. It is recognized that this is easier to establish in the presence of a large-scale accelerator project

---

[3] Credits: icons sourced from Brickclay, iconcheese, P Thanga Vignesh, Made by Made, iconfield, Eko Purnomo on thenounproject.com

than in small-scale projects. Such a consortium should be supported regardless of the future planned project size, to maintain a domestic body capable of strategic planning and addressing concerns in real time.

- It would be beneficial to establish ways for lab personnel to participate in technologically challenging projects at a company, and vice versa for industry personnel. A way to facilitate this could be establishing a program similar to the Grant Opportunities for Academic Liaison with Industry at NSF [92].

In closing, SRF technology is approaching an inflection point. Breakthroughs can initiate the first beachhead industrial accelerator market within the next five years. This adds fuel to the worldwide increased pace of new SRF accelerator projects for scientific research. If the U.S. does not have a competitive SRF industry developed by then, it will remain dependent on foreign vendors and fall farther behind on related R&D outcomes. With the remarkable rise in the development and industrialization of SRF technology in China over the past few years, it is likely that China can take the dominant position in this technology.

The required investments outlined in this report are significant but well within the capacity of the technology sector of the U.S. economy. A competitive and robust SRF industry could be established in the U.S. within the next five years if a coordinated and financially supported plan is initiated, without delay.

9 ACKNOWLEDGEMENTS

We would like to thank the survey and workshop participants for providing expert opinions and insights that informed our recommendations. We would like to thank Anthony DeTrane, Abigail Bunting, undergraduate students of the Luter School of Business at Christopher Newport University, for helping to prepare the workshop, and Justin Klingenberger and Jenah Parman of Jefferson Lab's Research and Technology Partnerships Office for helping with the market analysis. We would like to thank Mitch Laney and Jessie Tenbusch of Jefferson Lab's Procurement Department for facilitating a focused group discussion on procurement practices and challenges. We would like to thank Phil Denny of Jefferson Lab's SRF Operations Department for providing the cost estimates for some of the equipment used for the processing of SRF cavities. We would also like to thank Matthew Cahill of Jefferson Lab's Science Communications department for careful proofreading of this report. We would like to thank Carlo Pagani of INFN-Milan and Richard Stanek of Fermilab for providing valuable information related to the European model and to the funding for SRF activities in the U.S. during the ILC-GDE R&D period, respectively. This report is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Accelerator R&D and Production under contract DE-AC05-06OR23177.

10 REFERENCES

[1] U.S. DOE, “Supply Chain Risk Mitigation for Scientific Facilities and Tools: Report from the November 2021 Roundtable,” U.S. Department of Energy Office of Science, May 2022. doi: 10.2172/1863553

[2] U.S. DOE, “Departmental Sustainability,” order DOE O 436.1A, April 2023. Order O 436.1A

[3] U.S. DOE, FY 2021 AS&T Supplier Data Call to DOE labs, ASnTDataCallOnePage.pdf

[4] W. Singer, J. Iversen, A. Matheisen, H. Weise, and P. Michelato, “The Challenge and Realization of the Cavity Production and Treatment in Industry for the European XFEL,” in *Proc. SRF'13*, Paris, France, Sep. 2013, paper MOIOA03, pp. 18-23. MOIOA03.pdf

[5] H. Weise, “How To Produce 100 Superconducting Modules for the European XFEL in Collaboration and with Industry,” in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 1923-1928. doi:10.18429/JACoW-IPAC2014-WEIB03

[6] A. Matheisen, J. Iversen, A. Schmidt, W. Singer, P. Michelato, and L. Monaco, “Strategy of Technology Transfer of EXFEL Preparation Technology to Industry,” in *Proc. SRF'13*, Paris, France, Sep. 2013, paper MOP039, pp. 197-200. MOP039.pdf

[7] M. Peiniger, M. Pekeler and H. Vogel, “Industrialization of superconducting RF accelerator technology,” *Rev. Accel. Sci. Technol.* **5**, 265 (2012). DOI: 10.1142/S1793626812300101

[8] H. Hitomi, H. Hara, F. Inoue, K. Kanaoka, K. Sennyu, and T. Yanagisawa, “Fabrication of Superconducting RF Cavity at MHI,” in *Proc. ERL'11*, Tsukuba, Japan, Oct. 2011, paper WG3002, pp. 83-86. WG3002.pdf

[9] T. Saeki *et al*., “Studies of Fabrication Procedure of 9-cell SRF Cavity for ILC Mass-production at KEK,” in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2528-2530. doi:10.18429/JACoW-IPAC2014-WEPRI025

[10] T. Saeki and H. Hayano, “Fabrication of TESLA-shape 9-cell Cavities at KEK for Studies on Mass-Production in Collaboration with Industries,” in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 31-33. doi:10.18429/JACoW-IPAC2015-MOBB2

[11] J. E. Chen and K. Zhao, “The growth of SRF in China,” in *Proc. SRF'07*, Beijing, China, Oct. 2007, paper MO101, pp. 1-5. MO101.pdf

[12] J. F. Chen, “Status of SRF Activities for SHINE,” presented at the *SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper MOIXA01, unpublished. moixa01_talk.pdf

[13] W. Q. Zhang, “Shenzhen Superconducting Soft X-ray Free Electron Laser(S3FEL),” presented at the *SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper TUCAA01, unpublished. tucaa01_talk.pdf

[14] P. Zhang, “Overview of SRF projects for Synchrotron Light Sources in China,” presented at the *TESLA Technology Collaboration Meeting*, Fermilab, IL, USA, Dec. 2023. TTC2023-SyncLS-in-China-PeiZhang-final.pdf

[15] Y. He, “Recent Status of SRF Projects for Hadron Accelerators in China,” presented at the *TESLA Technology Collaboration Meeting*, Fermilab, IL, USA, Dec. 2023. TTC2023He.pdf

[16] Circular Electron Positron Collider Technical Design Report, Institute for High Energy Physics, Beijing, China, 2023, http://cepc.ihep.ac.cn/

[17] G. L. Torres, L. Delgado López, R. C. Berg, and H. Ziemer, “Hypersonic Hegemony: Niobium and the Western Hemisphere’s Role in the U.S.-China Power Struggle,” Center for Strategic and International Studies, Mar. 2024, webpage

[18] National Minerals Information Center, *U.S. Geological Survey Mineral Commodity Summaries 2024 Data Release (ver. 2.0, March 2024)* U.S. Geological Survey, 2024. DOI: 10.5066/P144BA54

[19] P. Kneisel *et al*., "Influence of Ta Content in High Purity Niobium on Cavity Performance," in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper TPPT075, pp. 3955-3957. TPPT075.pdf

[20] W. Singer, A. Brinkmann, D. Proch, and X. Singer, "Quality requirements and control of high purity niobium for superconducting RF cavities," *Physica C* **386**, 379–384 (2003). DOI: 10.1016/S0921-4534(02)02208-6

[21] E. Chiaveri *et al*., "Analysis and Results of the Industrial Production of the Superconducting Nb/Cu Cavities for the LEP2 Project," in *Proc. PAC'95*, Dallas, TX, USA, May 1995, paper FAE11, pp. 1509-1511. DOI: 10.1109/PAC.1995.505267

[22] T. L. Grimm *et al*., "Commercial Superconducting Electron Linac for Radioisotope Production," DOE-NP SBIR Phase II Project DE-SC0007520 Final Technical Report, Niowave, Inc., East Lansing, MI, USA. DOI: 10.2172/1209691

[23] C. Pagani, E. L Saldin, E. A. Schneidmiller, M. V. Yurkov, "Design considerations of 10 kW-scale, extreme ultraviolet SASE FEL for lithography," *Nucl. Instrum. Methods Phys. Res. Sec. A* **475**, 391 (2001). Doi: 10.1016/S0168-9002(01)01546-7

[24] A. H. Abderrahim *et al*., "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production," Technical Report FERMILAB-FN-0907-DI, Sept. 2010. Doi: 10.2172/1847382

[25] R. C. Dhuley *et al*. "Development of a cryocooler conduction-cooled 650 MHz SRF cavity operating at ~10 MV/m cw accelerating gradient," *IOP Conf. Ser.: Mater. Sci. Eng*. **1240**, 012147 (2022). DOI: 10.1088/1757-899X/1240/1/012147

[26] G. Ciovati *et al*., "Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators," *Phys. Rev. Accel. Beams* **26**, 044701 (2023). DOI: 10.1103/PhysRevAccelBeams.26.044701

[27] N. A. Stilin *et al*., "RF and thermal studies on conduction cooled Nb_3Sn SRF cavity," *Eng. Res. Express* **5**, 025078 (2023). DOI: 10.1088/2631-8695/acdd51

[28] R. D. Kephart *et al*., "SRF, Compact Accelerators for Industry & Society," in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper FRBA03, pp. 1467-1473. FRBA03.pdf

[29] Z. Yang *et al*., "Stable Acceleration of a LHe-Free Nb_3Sn demo SRF e-linac," *Supercond. Sci. Technol.* **38**, 015009 (2025). DOI: 10.1088/1361-6668/ad9998

[30] Innovation Fostering in Accelerator Science and Technology, https://ifast-project.eu/about

[31] M. Hörmann, "Production of high thermal conductivity niobium on a technical scale for high-frequency superconductivity," *J. Less Comm. Metals* **139**, 1-14 (1988). DOI: 10.1016/0022-5088(88)90324-4

[32] K. Saito, F. Furuta, and H. Umezawa, "Multi-wire Slicing of Large Grain Ingot Material," in *Proc. SRF'09*, Berlin, Germany, Sep. 2009, paper THOAAU05, pp. 467-472. THOAAU05.pdf

[33] P. Kneisel *et al*., "Review of ingot niobium as a material for superconducting radiofrequency accelerating cavities," *Nucl. Instrum. Methods Phys. Res. Sec. A* **774**, 133 (2015). DOI: 10.1016/j.nima.2014.11.083

[34] W. Singer *et al*., "Development of large grain cavities," *Phys. Rev. ST Accel. Beams* **16**, 012003 (2013). DOI: 10.1103/PhysRevSTAB.16.012003

[35] P. Kumar, "High purity niobium for superconducting applications," *J. Less Comm. Metals* **139**, 149-158 (1988). DOI: 10.1016/0022-5088(88)90337-2

[36] D. B. Smathers, "Production scale niobium ingots for r.f. cavity applications," *J. Less Comm. Metals* **139**, 61-66 (1988). DOI: 10.1016/0022-5088(88)90329-3

[37] R. A. Graham, "RRR Niobium Manufacturing Experience," *AIP Conf. Proc*. **927**, 191–199 (2007). DOI: 10.1063/1.2770692

[38] G. Myneni *et al.*, “Medium grain niobium SRF cavity production technology for science frontiers and accelerator applications,” *JINST* **18**, T04005 (2023). DOI: 10.1088/1748-0221/18/04/T04005

[39] Electron beam welding applications, https://www.ptreb.com/electron-beam-welding-applications accessed August 16, 2024

[40] W. Singer, “Fabrication of elliptical SRF cavities,” *Supercond. Sci. Technol*. **30**, 033001 (2017). DOI: 10.1088/1361-6668/30/3/033001

[41] M. J. Kelly and T. Reid, “Surface processing for bulk niobium superconducting radio frequency cavities,” *Supercond. Sci. Technol.* **30**, 043001 (2017). DOI: 10.1088/1361-6668/aa569a

[42] S. Loer, J. Cirillo, E. Connor, H. Padamsee, P. Weller, and W. Wong, “Test Results on a CEBAF/Cornell Prototype Superconducting Cavity Fabricated by TRW,” in *Proc. PAC'87*, Washington D.C., USA, Mar. 1987, pp. 1951-1954. PAC1987_1951.pdf

[43] TRW Inc., https://en.wikipedia.org/wiki/TRW_Inc., accessed August 16, 2024.

[44] R. Sundelin *et al*., “RF Superconductivity at CEBAF,” in *Proc. SRF'89*, Tsukuba, Japan, Aug. 1989, paper SRF89A01, pp. 1-18. SRF89A01.pdf

[45] M. Hiller, W. Bensiek, J. Dateo, and W. Pruitt, “CEBAF Cavity Fabrication - a Successful Technology Transfer,” in *Proc. LINAC'88*, Williamsburg, VA, USA, Oct. 1988, paper WE3-29, pp. 379-381. WE3-29.pdf

[46] A. Yamamoto, “Global R&D Effort for the ILC Linac Technology”, in Proc. EPAC'08, Genoa, Italy, Jun. 2008, paper MOYBGM01, pp. 12-16.

[47] C. H. Boulware, J. Diemer, T. L. Grimm, M. Zamiara, “High-Power Two-Pass Superconducting Electron Linac for Medical Radioisotope Production,” presented at the *21th Int. Conf. RF Supercond. (SRF'23)*, Grand Rapids, MI, USA, Jun. 2023, paper FRIYA02, unpublished. friya02_talk.pdf

[48] NNSA awards $13 million to promote U.S. production of critical medical isotope, https://www.energy.gov/nnsa/articles/nnsa-awards-13-million-promote-us-production-critical-medical-isotope-0, accessed August 16, 2024.

[49] Michigan Economic Development Corporation press release, April 11, 2023, https://www.michiganbusiness.org/press-releases/2023/04/niowave-expansion/, accessed August 16, 2024.

[50] A. J. Favale, M. D. Cole, E. Peterson, and J. Rathke, “Fabrication of ILC Prototype Cavities at Advanced Energy Systems, Inc.,” in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper MOPD002, pp. 448-450. MOPD002.pdf

[51] R. L. Geng *et al*., “Qualification of the Second Batch Production 9-Cell Cavities Manufactured by AES and Validation of the First US Industrial Cavity Vendor for ILC,” in *Proc. SRF'11*, Chicago, IL, USA, Jul. 2011, paper TUPO028, pp. 433-435. TUPO028.pdf

[52] M. Liepe *et al*., “The Joint High Q_0 R&D Program for LCLS-II”, in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2627-2630. DOI: 10.18429/JACoW-IPAC2014-WEPRI062

[53] D. Gonnella *et al*., "Industrialization of the nitrogen-doping preparation for SRF cavities for LCLS-II," *Nucl. Instrum. Methods Phys. Res. A* **883**, 143-150 (2018). DOI: 10.1016/j.nima.2017.11.047

[54] A. M. M. Todd *et al*., “Nurturing the Industrial Accelerator Technology Base in the US,” arXiv:2203.10377 [physics.acc-ph]. DOI: 10.48550/arXiv.2203.10377

[55] Research Instruments, GmbH, https://research-instruments.de/en/about-us/our-history, accessed August 16, 2024.

---

[56] H. U. Klein, “Case history of commercialization of accelerator technology: Interatom GmbH,” in *Proc. of CERN Accelerator School: General Accelerator Physics*, Aarhus, Denmark, 15-26 September 1986, pp. 332-337. CERN-87-10.pdf

[57] U. Klein, M. Peiniger, and H. Vogel, “RF Superconductivity at Interatom,” in *Proc. SRF'89*, Tsukuba, Japan, Aug. 1989, paper SRF89G08, pp. 507-527. SRF89G08.pdf

[58] U. Klein, A. Palussek, M. Peiniger, H. Piel, and H. Vogel, “Fabrication and Test of Superconducting RF Cavities for CEBAF,” in *Proc. EPAC'88*, Rome, Italy, Jun. 1988, pp. 1309-1312. EPAC1988_1309.PDF

[59] M. Pekeler, “From science requirements to applications in industry,” presented at the *3rd I.FAST Annual Meeting*, Paris, France, April 16-19, 2024. 2024-03-17-IFAST-Pekeler.pdf

[60] Zanon Research & Innovation, Srl, https://www.zanonresearch.com/about-us/, accessed September 5, 2024.

[61] Carlo Pagani, INFN Milan, private communication, September 2024.

[62] C. Adolphsen *et al.*, "The International Linear Collider Technical Design Report - Volume 3: Accelerator," ILC-REPORT-2013-040, June 2013, https://linearcollider.org/technical-design-report/

[63] L. Evans and S. Michizono, “The International Linear Collider Machine Staging Report 2017,” arXiv:1711.00568 [physics.acc-ph]. DOI: 10.48550/arXiv.1711.00568

[64] A. Todd, “Prospects for Accelerator Technology,” *Rev. Accel. Sci. Technol*. **4**, 235-255 (2011). DOI: 10.1142/S1793626811000604

[65] MarketandMarkets™ “Extreme Ultraviolet (EUV) Lithography Market – Global Forecast to 2028,” Report Code SE 6398, July 2023. www.marketsandmarkets.com

[66] MarketandMarkets™ “Sterilization Equipment Market – Global Forecast to 2029,” Report Code MD 2149, April 2024. www.marketsandmarkets.com

[67] https://www.xlight.com/, accessed September 12, 2024.

[68] Peng Li, Ming Li, Dai Wu, Zheng Zhou, Chun Tang, “Development Strategy of Free Electron Laser Technology in China,” *Strategic Study of Chinese Academy of Engineering*, **22**(3), 35–41 (2020). DOI: 10.15302/J-SSCAE-2020.03.006

[69] N. Nakamura *et al.*, “High-power EUV free-electron laser for future lithography,” *Jpn. J. Appl. Phys*. **62**, SG0809 (2023). DOI: 10.35848/1347-4065/acc18c

[70] B. Yee-Rendon, “Overview of ADS Projects in the World,” in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 310-313. DOI: 10.18429/JACoW-LINAC2022-TU2AA01

[71] Fast electrons accelerate the production of medical isotopes, https://physicsworld.com/a/fast-electrons-accelerate-the-production-of-medical-isotopes/, accessed August 16, 2024.

[72] J. M. Krämer *et al.*, “LightHouse - A Superconducting LINAC for Producing Medical Isotopes,” in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 35-37. DOI: 10.18429/JACoW-LINAC2022-MOPOGE04

[73] Likert scale, https://en.wikipedia.org/wiki/Likert_scale, accessed August 16, 2024.

[74] National Science Foundation Industry–University Cooperative Research Centers, https://iucrc.nsf.gov/about/, accessed September 12, 2024.

[75] Consolidated National Security, LLC, https://cns-llc.us/about, accessed September 12, 2024.

[76] S. Wurm, “The EUV LLC: An Historical Perspective,” in *EUV Lithography*, edited by V. Bakshi (SPIE Press, 2nd edition, 2018), Chapter 2. ISBN: 9781510616783

[77] SEMATECH, https://en.wikipedia.org/wiki/SEMATECH, accessed September 12, 2024.

[78] Manufacturing Demonstration Facility, https://www.ornl.gov/content/manufacturing-demonstration-facility, accessed August 16, 2024.

[79] The C4 Partnering Model, Sandia National Laboratories, https://www.sandia.gov/c4/, accessed September 12, 2024.

[80] J. Spitzer *et al*., "ITER Central Solenoid Module fabrication program," *2015 IEEE 26th Symposium on Fusion Engineering (SOFE)*, Austin, TX, USA, 2015, pp. 1-6. DOI: 10.1109/SOFE.2015.7482276

[81] K. Schaubel *et al*., "The ITER Central Solenoid Module final test facility," *Fusion Eng. Des*. **124**, 59-63 (2017). DOI: 10.1016/j.fusengdes.2017.05.010

[82] L. R. Rowan, "Critical Mineral Resources: National Policy and List," Congressional Research Service, Report R47982, March 2024. https://crsreports.congress.gov/product/pdf/R/R47982/

[83] *Critical Materials Assessment*, U.S. Department of Energy, July 2023. doe-critical-material-assessment_07312023.pdf

[84] R. M. Scanlan, 'Conductor development for high energy physics-plans and status of the US program," in *IEEE Trans. Appl. Supercond.*, **11** (1), 2150-2155, (2001). DOI: 10.1109/77.920283

[85] D. R. Dietderich and A. Godeke, "Nb_3Sn research and development in the USA – Wires and cables," *Cryogenics* **48**, 331-340 (2018). DOI: 10.1016/j.cryogenics.2008.05.004

[86] R. P. Stanek, Fermi National Accelerator Laboratory, private communication, September 2024.

[87] A. Favale, "The Transfer of Accelerator Technology to Industry," in *Proc. LINAC'92*, Ottawa, Canada, Aug. 1992, paper TH2-01, pp. 587-590. TH2-01.pdf

[88] Federal Acquisition Regulation, *Federally Funded Research and Development Centers*, Section 35.017(a)(2). FAR_35_017

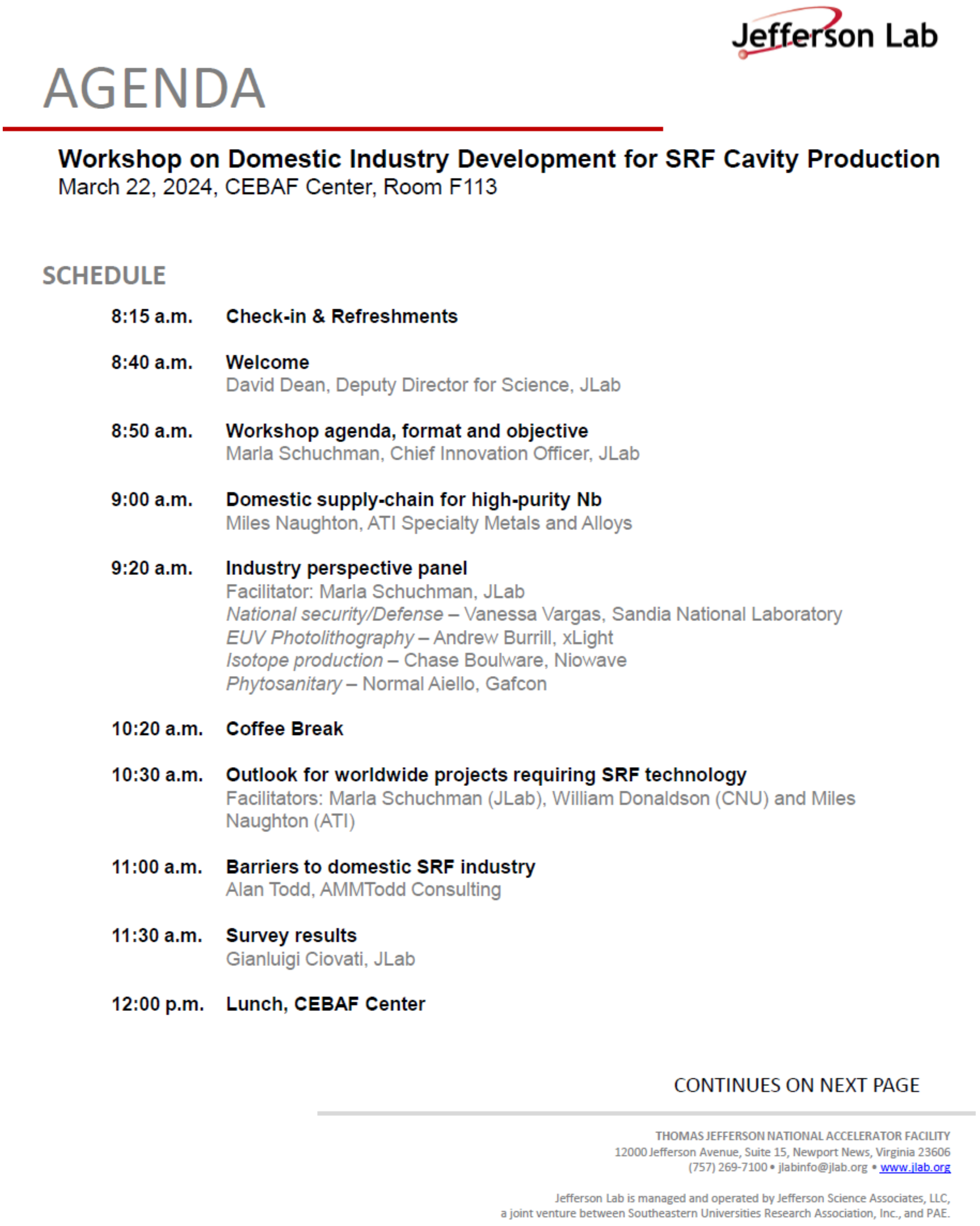
[89] J. Gao, "Introduction of CEPC Industry Promotion Consortium (CIPC)," presented at the International Workshop on Future Linear Colliders, LCWS2024, Tokyo, Japan, July 8-11, 2024. CEPC consortium.pdf

[90] Advanced Accelerator Association Promoting Science & Technology, https://aaa-sentan.org/en/, accessed August 16, 2024.

[91] Superconducting Particle Accelerator Forum of America, https://www.spafoa.org/index.htm, accessed August 16, 2024.

[92] Grant Opportunities for Academic Liaison with Industry (GOALI) Proposal, https://www.nsf.gov/eng/eec/goali.jsp, accessed August 16, 2024.

APPENDIX 1: WORKSHOP AGENDA



Jefferson Lab

AGENDA

Workshop on Domestic Industry Development for SRF Cavity Production

March 22, 2024, CEBAF Center, Room F113

SCHEDULE

8:15 a.m.	**Check-in & Refreshments**
8:40 a.m.	**Welcome** David Dean, Deputy Director for Science, JLab
8:50 a.m.	**Workshop agenda, format and objective** Marla Schuchman, Chief Innovation Officer, JLab
9:00 a.m.	**Domestic supply-chain for high-purity Nb** Miles Naughton, ATI Specialty Metals and Alloys
9:20 a.m.	**Industry perspective panel** Facilitator: Marla Schuchman, JLab *National security/Defense* – Vanessa Vargas, Sandia National Laboratory *EUV Photolithography* – Andrew Burrill, xLight *Isotope production* – Chase Boulware, Niowave *Phytosanitary* – Normal Aiello, Gafcon
10:20 a.m.	**Coffee Break**
10:30 a.m.	**Outlook for worldwide projects requiring SRF technology** Facilitators: Marla Schuchman (JLab), William Donaldson (CNU) and Miles Naughton (ATI)
11:00 a.m.	**Barriers to domestic SRF industry** Alan Todd, AMMTodd Consulting
11:30 a.m.	**Survey results** Gianluigi Ciovati, JLab
12:00 p.m.	**Lunch, CEBAF Center**

CONTINUES ON NEXT PAGE

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY
12000 Jefferson Avenue, Suite 15, Newport News, Virginia 23606
(757) 269-7100 • jlabinfo@jlab.org • www.jlab.org

Jefferson Lab is managed and operated by Jefferson Science Associates, LLC,
a joint venture between Southeastern Universities Research Association, Inc., and PAE.

Workshop on Domestic Industry Development for SRF Cavity Production

March 22, 2024, CEBAF Center, Room F113

SCHEDULE

1:00 p.m.	**Design of entity models** Facilitators: Marla Schuchman, JLab, and William Donaldson, CNU
2:00 p.m.	**Case study: ITER Central Solenoid** Drew Packard, General Atomics
2:30 p.m.	**Breakout table discussions** *Topic 1: Partnership model* – Facilitator: Marla Schuchman, JLab *Topic 2: Facility features* – Facilitator: John Rathke, JW Rathke Engineering Services *Topic 3: Regulatory, Policy and Procurement* – Facilitator: Mitch Laney, JLab
3:15 p.m.	**Coffee Break**
3:30 p.m.	**Outcomes of the workshop** Facilitator: Marla Schuchman, JLab
4:15 p.m.	**Next steps** Gianluigi Ciovati, JLab
4:30 p.m.	**End of the workshop**
6:30 p.m.	**No-host dinner at Bull Island Brewing Co.,** 758 Settlers Landing Rd, Hampton, VA 23669

APPENDIX 2: WORKSHOP LIST OF PARTICIPANTS

Workshop on Domestic Industry Development for SRF Cavity Production
March 22 , 2024
CEBAF Center, Jefferson Lab
Newport News, VA

Participants List

Aiello , Norman	Gafcon, Inc.	naiello@gafcon.com
Araujo Martinez , Aurora	RadiaBeam Technologies	araujo@radiabeam.com
Balachandran , Shreyas	JLab	shreyas@jlab.org
Boulware , Chase	Niowave, Inc.	boulware@niowaveinc.com
Bunting , Abigail	CNU	abigail.bunting.20@cnu.edu
Burrill , Andrew	xLight	andrew@xlight.com
Buttles , John	Bailey Tool	jbuttles@texaswindtower.com
Ciovati , Gianluigi	Jefferson Lab	gciovati@jlab.org
Colley , Jason	JSA	colley@jlab.org
Conway , Zachary	BNL	zconway@bnl.gov
Daly , Edward	xLight	ed@xlight.com
DeTrane , Anthony	Christopher Newport University	anthony.detrane.20@cnu.edu
Dhakal , Pashupati	Jefferson Lab	dhakal@jlab.org
Donaldson , William	Christopher Newport University	william.donaldson@cnu.edu
Fast , James	JLab	jfast@jlab.org
Geng , Rongli	Jefferson Lab	geng@jlab.org
Goldin , Mariana	JLab-RTPO	mgoldin@jlab.org
Huque , Naeem	TJNAF	huque@jlab.org
Jing , Chunguang	Euclid Techlabs	c.jing@euclidtechlabs.com
Johnson , Rolland	MUONS Inc.	rol@muonsinc.com
Laney , Mitchell	JLab Procurement	laney@jlab.org
Lawrence , Abigail	Christopher Newport University, Newport News, VA	abigail.bunting.20@cnu.edu
Marchlik , Matt	JLab	marchlik@jlab.org
Matalevich , Joseph	JLab	josephm@jlab.org
Michalski , Tim	Jefferson Lab	michalsk@jlab.org
Morello , Christopher	City of Newport News	morelloca@nnva.gov
Murokh , Alex	RadiaBeam Technologies, LLC.	murokh@radiabeam.com
Myneni , Ganapati	BSCE Systems, Inc.	ganapati@isohim.org
Narduzzi , Manuele	Fermi National Accelerator Laboratory, Batavia, IL	manuele@fnal.gov
Nassiri , Alireza	ANL	nassiri@anl.gov
Naughton , Miles	ATI Specialty Alloys & Components	miles.naughton@atimaterials.com
Neil , George	xLight	neil@jlab.org
Osha , Dwight	C.F. Roark	dosha@roarkfab.com
Packard , Drew	General Atomics	drew.packard@ga.com
Panton , Boyd	The Ohio State University	panton.7@osu.edu
Perkins , David	TJNAF	dperkins@jlab.org
Rathke , John	TechSource, Inc.	john_rathke@optonline.net
Reilly , Tony	JLab	areilly@jlab.org
Rimmer , Robert	JLab	rarimmer@jlab.org
Ross , Marc	SLAC National Accelerator Laboratory	mcrec@slac.stanford.edu
Ruber , Roger	JLab	ruber@jlab.org
Samoylich , Yuryi	Metal Technology	yuryi@mtialbany.com
Schuchman , Marla	Jefferson Lab	marla@jlab.org
Seryi , Andrei	Jefferson Lab	seryi@jlab.org
Smith , Robert	DOE-NNSA Office of Radiological Security	Robert.e.smith@nnsa.doe.gov
Sparkowich , Steven	Niobium Research	steve@niobium-research.com
Spata , Michael	Jefferson Lab	spata@jlab.org
Tenbusch , Giuseppina	Jlab	jessie@jlab.org
Thangaraj , Jayakar	Fermilab	jtobin@fnal.gov
Todd , Alan	AMMTodd Consulting	ammtodd@gmail.com
Vargas , Vanessa	Sandia National Laboratories	vnvarga@sandia.gov
Wilson , Katherine	JLab	kwilson@jlab.org

APPENDIX 3: LIST OF FOLLOW-UP INTERVIEWS

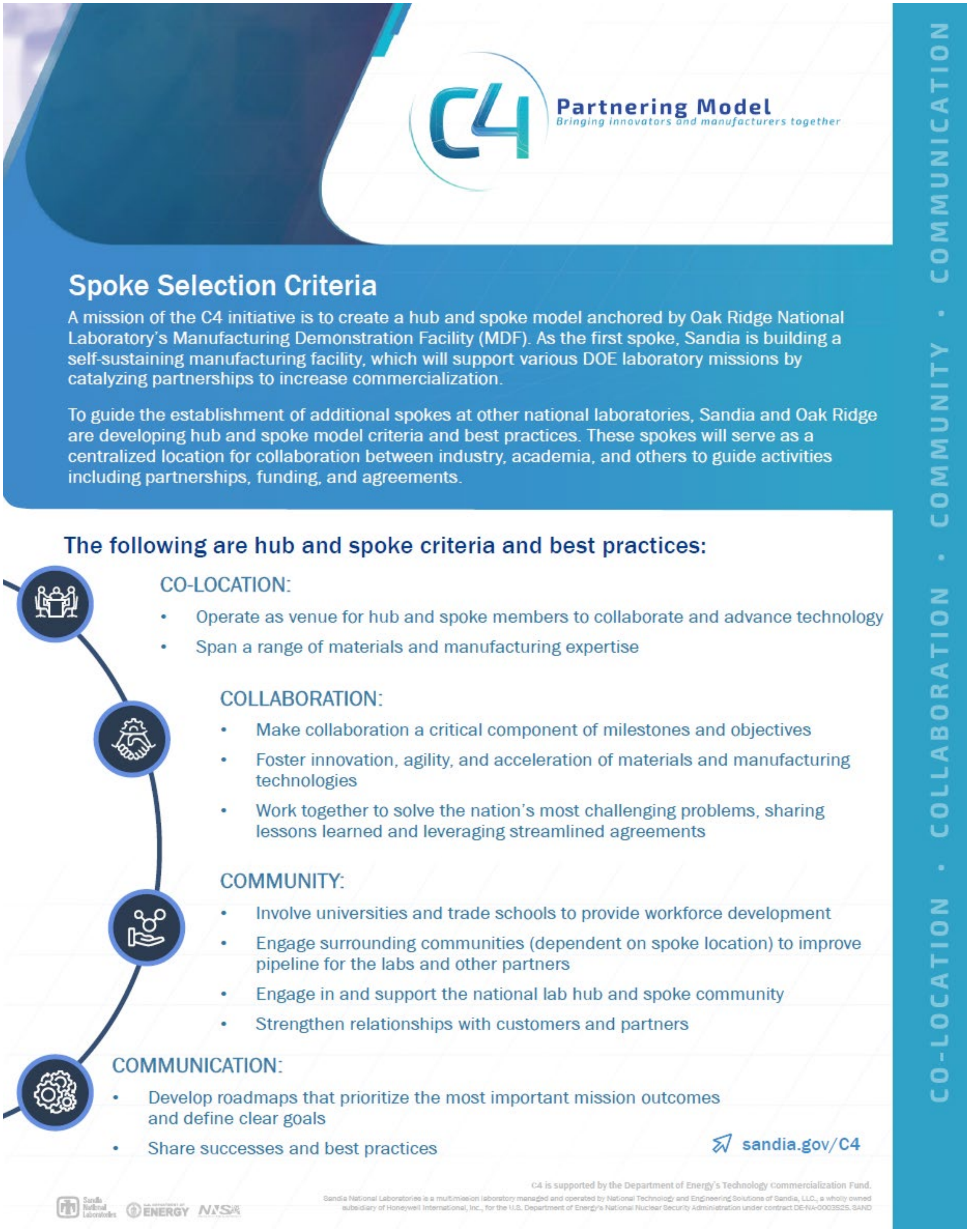
January 19, 2024: Prakash Balan, IUCRC Program Director	National Science Foundation Alexandria, VA 22314
May 7, 2024: Ganapati Rao Myneni, President & CEO	BSCE Systems, Inc. Yorktown, VA 23693
May 7, 2024: Leonardo Ristori, Principal Engineer Genfa Wu, Senior Scientist	Fermi National Accelerator Laboratory Batavia, IL 60510
May 9, 2024: Normal Aiello, Director, Specialty industrial systems	Gafcon, Inc. San Diego, CA 92131
May 13, 2024: Robert Hamm, President & CEO	R&M Technical Enterprises, Inc. Pleasanton, CA 94566
May 22, 2024: Yuryi Samoylich, Project Manager	Metal Technology, Inc. Albany, OR 97322
May 22, 2024: Marc Ross, Senior Scientist Mattia Checchin, Scientist John Hogan, Project Engineer	Stanford Linear Accelerator Center Stanford, CA 94025
June 5, 2024: Ted Roark, President	C.F. Roark Welding & Engineering Co., Inc. Brownsburg, IN 46112
July 1, 2024: Mark Honecker, President	Executive Solutions Enterprise, LLC. Chesapeake, VA 23322
July 17, 2024: Boyd Panton, Assistant Professor	The Ohio State University College of Engineering Columbus, OH 43210
August 13, 2024: Shreyas Balachandran, Scientist John Vennekate, Scientist John Buttles, Engineer	Thomas Jefferson National Accelerator Facility Newport News, VA 23606
August 20, 2024: Lance Cooley, Professor	Florida A&M University, Florida State University Director – Applied Superconductivity Center National High Magnetic Field Laboratory Tallahassee, FL 32310

APPENDIX 4: MARKET RESEARCH DATA

The following table summarizes the information found online from different market research firms on the global market for the selected applications of industrial accelerators. The greyed-out data were considered outliers and were not included in the calculation of the notional averages for each application.

	CAGR	Start Year	End Year	Starting Value ($B)	Ending Value ($B)	Report Year	Source
EUVL	21.5%	2022	2029	4.6	23.0	2022	Future Market Insights
	11.5%	2023	2029	10.3	17.8	2023	Modor Intelligence
	20.1%	2023	2031	9.4	40.6	2023	Data Bridge MR
	22.5%	2022	2032	10.2	63.2	2022	MR Future
	21.7%	2023	2030	9.3	36.8	2023	Market Digits
	21.8%	2023	2028	9.4	25.3	2023	Markets&Markets
Wastewater	6.2%	2021	2031	106.6	193.6	2022	Transparency MR
	6.5%	2022	2030	299.8	497.3	2022	Data Bridge MR
	6.3%	2022	2028	55.9	80.7	2022	Markets&Markets
	7.5%	2023	2032	323.3	619.9	2022	Fortune
	6.4%	2023	2032	328.7	574.5	2023	Precedence Research
Phytosanitary	6.0%	2023	2033	0.312	0.559	2023	Future Market Insights
	5.0%	2021	2030	199.400	309.335	2022	Coherent Market Insights
	5.2%	2019	2026	0.197	0.280	2020	Zion MR
	5.2%	2023	2030	0.194	0.276	2024	Maximize MR
	5.9%	2020	2027	5.570	8.320	2023	Verified Market Reports
Sterilization	5.7%	2022	2030	10.860	16.921	2023	Data Bridge MR
	4.8%	2023	2031	7.250	10.549	2024	Skyquest Technology
	5.5%	2021	2027	4.300	5.929	2023	Markets&Markets
	10.6%	2023	2030	7.600	15.385	2023	Grand View Research
	1.0%	2023	2033	4.010	4.430	2023	Global Data
	6.6%	2022	2030	4.900	9.285	2023	Global Market Insights
Isotopes	8.8%	2022	2032	5.100	11.854	2023	Allied MR
	8.8%	2022	2032	5.142	11.951	2023	Research Dive
	6.9%	2021	2032	0.715	1.484	2024	Business Research Insights
	8.3%	2024	2029	9.920	14.772	2024	Mordor Intelligence
ADS	2.8%	2022	2031	84.810	108.739	2023	Skyquest
	3.1%	2023	2032	34.430	45.317	2024	Straits Research
	3.8%	2018	2030	129.800	203.069	2018	BCC Research

APPENDIX 5: SPOKE SELECTION CRITERIA FOR C4 PARTNERING MODEL



C4 Partnering Model

Bringing innovators and manufacturers together

CO-LOCATION • COLLABORATION • COMMUNITY • COMMUNICATION

Spoke Selection Criteria

A mission of the C4 initiative is to create a hub and spoke model anchored by Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF). As the first spoke, Sandia is building a self-sustaining manufacturing facility, which will support various DOE laboratory missions by catalyzing partnerships to increase commercialization.

To guide the establishment of additional spokes at other national laboratories, Sandia and Oak Ridge are developing hub and spoke model criteria and best practices. These spokes will serve as a centralized location for collaboration between industry, academia, and others to guide activities including partnerships, funding, and agreements.

The following are hub and spoke criteria and best practices:

CO-LOCATION:

- Operate as venue for hub and spoke members to collaborate and advance technology
- Span a range of materials and manufacturing expertise

COLLABORATION:

- Make collaboration a critical component of milestones and objectives
- Foster innovation, agility, and acceleration of materials and manufacturing technologies
- Work together to solve the nation's most challenging problems, sharing lessons learned and leveraging streamlined agreements

COMMUNITY:

- Involve universities and trade schools to provide workforce development
- Engage surrounding communities (dependent on spoke location) to improve pipeline for the labs and other partners
- Engage in and support the national lab hub and spoke community
- Strengthen relationships with customers and partners

COMMUNICATION:

- Develop roadmaps that prioritize the most important mission outcomes and define clear goals
- Share successes and best practices

sandia.gov/C4

C4 is supported by the Department of Energy's Technology Commercialization Fund.

Future spoke development

The C4 Partnering Model is seeking to create a spoke—Sandia's Center for Advanced Manufacturing Innovation (CAMINO)—based on similar advanced manufacturing and partnership principles to ORNL's MDF. The intent of this project is to develop a foundational model which will inform future spoke development.

MDF: ORNL's Manufacturing Demonstration Facility
CAMINO: Center for Advanced Manufacturing Innovation

sandia.gov/C4

C4 is supported by the Department of Energy's Technology Commercialization Fund.