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A PLAN TO REVITALIZE THE DOMESTIC SUPERCONDUCTING RADIO-FREQUENCY INDUSTRY*

G. Ciovati[†1], M. Schuchman, Jefferson Lab, Newport News, VA, USA
W. Donaldson, Christopher Newport University, Newport News, VA, USA
A. Murokh, RadiaBeam Technologies, Santa Monica, CA, USA
M. Naughton, ATI Specialty Alloys & Components, Albany, OR, USA
D. Osha, C. F. Roark Welding & Engineering Co., Brownsburg, IN, USA
D. Packard, General Atomics, San Diego, CA, USA
J. Rathke, TechSource, Los Alamos, NM, USA
A. Todd, AMMTodd Consulting, Princeton Junction, NJ, USA
[1]also at Center for Accelerator Science, Old Dominion University, Norfolk, VA, USA

Abstract

Superconducting radio-frequency (SRF) cavities are essential building blocks of modern particle accelerators for scientific research, and they offer unique capabilities that could be transformative for commercial applications. Growth of the domestic SRF industry in North America has faced several challenges over the past decades, as most of the international demand for cavities was supplied by European vendors. This contribution provides a brief review of the domestic industrial vendor space, an outlook of the global demand for SRF cavities and an outline of the challenges leading to this supply chain deficiency. One of the main challenges towards establishing a robust domestic SRF industry has been the large uncertainty in the demand. Meanwhile, research and development activities to raise technical readiness of SRF accelerators for industrial use have continued and several potential markets are emerging that may offer a consistent and growing demand for SRF cavities. Finally, reasons and means of establishing and sustaining competitive domestic suppliers are described.

INTRODUCTION

Superconducting radio-frequency (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. 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.

A detailed description of the industrialization of SRF technology can be found in Ref. [1]. 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. vendor capable of producing fully assembled, ready-to-test SRF cavities. As a result, government-sponsored SRF accelerator projects in the U.S. rely on European vendors for the cavity supply.

A 1-year project was carried out to review the history of domestic SRF industrial production, to identify new potential market opportunities for the SRF technology and to outline a business plan for establishing a robust, domestic industry supporting SRF technology demonstration and deployment. Information was gathered through:

- An extensive literature review.
- Bi-weekly meetings among the authors.
- A survey distributed to scientists, engineers, industry professionals, lab operations, procurement, and technology transfer professionals.
- A 1-day workshop held at Jefferson Lab on March 2024.
- Discovery and follow-up interviews conducted after the workshop.

This contribution represents a shortened version of a more extensive report which was submitted to the Department of Energy in January 2025 [2].

EVOLUTION OF DOMESTIC SRF INDUSTRY

Niobium Sheet Production

Currently, the two major suppliers of high-purity Nb sheets for SRF cavity production are Ningxia Orient Tantalum Industry Co. (OTIC), in China, and Tokyo Denkai in Japan. 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. Supply chain issues related to the high-purity Nb sheets for SRF cavity fabrication were clearly identified in a recent DOE report [3].

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† gciovati@jlab.org

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SRF Industry

The U.S. industry 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., with the largest push for industrialization occurring between 2007 and 2012. The industrialization effort was funded through the initial R&D phase for the International Linear Collider (ILC) project. Approximately 100 1.3 GHz, nine-cell cavities were manufactured in the U.S. during that time frame by three vendors: Niowave, Advanced Energy Systems (AES) and C.F. Roark Welding & Engineering. Roark is the only U.S. company to has been awarded a large (>100) SRF cavity fabrication contract, for the FRIB project. However, Roark does not maintain facilities to carry out any surface processing or clean-room assembly of complete cavities, which are required steps prior to the cryogenic RF testing at laboratories. In 2016 Niowave successfully pivoted its business model to focus on medical isotope production, using an SRF linac they built in-house. AES built-up over time all the required infrastructure for cavity fabrication, processing and clean-room assembly. AES was also able to produce complete cryomodules, as they did for the NSLS-II project at Brookhaven National Lab. The cavities for ILC require achieving the highest cryogenic high-power RF performance than any other SRF accelerator project and the cavities produced by AES met those stringent specifications. As a result, AES earned recognition as an “ILC-qualified” vendor in 2010 [4]. In spite of this success, the volume production at AES over the years remained low. The abrupt cancellation of a large contract with the U.S. Navy and loosing the bid for the production of ∼ 340 1.3 GHz nine-cell cavities for the LCLS-II project at SLAC forced AES to cease operations in 2016, leaving no U.S. vendor capable of production from bulk metal to a fully treated cavity, ready for testing. The history of AES, described in detail in Ref. [2], is particularly telling of the challenges faced by the domestic SRF industry.

A recent white paper describes in great detail the major barriers to expand the domestic industrial participation in the construction of U.S. accelerator facilities [5]. From a business perspective, the capital investment is one of the most challenging barriers to overcome for a new domestic vendor: a company would not be inclined to invest the estimated \$16M required to set up a cavity fabrication and processing facility without confidence in the anticipated production volume over the following years.

SRF INDUSTRY OVERSEAS

The European Model

W.C. Heraeus, GmbH, in Germany and Plansee in Austria had been suppliers of high-purity Nb sheets in Europe for many years, however they are no longer involved with Nb production.

Research Instruments (RI) in Germany and Zanon Research & Innovation (ZRI) in Italy are the major worldwide suppliers of SRF technology. Both companies have been involved in the technology for several decades and have experienced buyouts and reorganizations over their long history. Considerable expertise and facilities have been acquired by both companies through the contracts for the fabrication and processing of more than 400 1.3 GHz 9-cell cavities which were awarded to each vendor for the construction of the European X-ray Free-Electron Laser facility (E-XFEL) in Germany [6–8]. The E-XFEL is the largest accelerator project to be built with SRF technology to date.

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:

- The establishment of a long-term, trusted relationship between RI and ZRI and the government laboratories in their respective countries.
- 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.
- The fabrication and, in many cases, the surface treatment of prototype or small-quantity R&D cavities was done through contracts from government laboratories to industry.
- The decision to procure the cavities for the E-XFEL project 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 for European projects, however they are no longer involved in the technology since many years.

Chinese National Investment

SRF activities in China had been the domain of laboratories and universities until ∼2015, when SRF cavity production started at Ningxia Orient Superconductor Technology Co., Ltd (OSTEC). Within the past decade, a tremendous expansion of SRF activities has taken place in China. Large-scale projects such as SHINE [9], S3FEL [10] and DALS upgrade require the production of hundreds of 1.3 GHz, 9-cell cavities. The number of SRF-based hadron accelerators in China in operation or under construction is equally impressive [11]. In preparation for this large-scale productions, 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. The facilities required for processing and assembly of all cavi-

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ties produced in China were established at another company, Wuxi Creative Technologies Co., Ltd.

More large-scale SRF-based projects are being pursued or planned for in China, such as the Circular Electron Positron Collider. Considering only the SHINE and S3FEL projects, China will have the largest quantity of SRF cavities installed in an accelerator compared to any other country by ~ 2027.

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.

MARKET OUTLOOK AND APPLICATIONS OF SRF TECHNOLOGY

It was noted in Ref. [1] that the approximate total number of cavities produced worldwide between the 1980s and 2010 was ~ 2500, corresponding to an average of ~ 100 cavities per year. 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. An estimate of the number of cavities and amount of high-purity Nb required by ongoing and upcoming SRF accelerator projects worldwide between 2023 and 2028 resulted in close to an average of 400 cavities and 25 ton of Nb per year. However, ~ 72% of this production is for projects in China, which has essentially already become self-sufficient on all aspects of the SRF technology. If approved, future large-scale projects such as ILC and FCC would be game-changers in terms of the number of cavities and Nb required and their construction may begin in the 2030s. 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 can be estimated at ~$100M, without ILC, and ~$430M if the production for ILC starts in 2029.

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. [12]. The following were identified as potential early adopter markets for SRF technology: extreme ultra-violet lithography (EUVL), accelerator-driven systems (ADS) for nuclear waste transmutation, medical isotope production, medical device sterilization, phytosanitary treatment and wastewater treatment.

When conducting the market research, the focus on SRF cavity production was highlighted, rather than the production of complete cryomodules. Projections were made up to 2030. While ADS 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.

The assumptions and methodology to carry out the market analysis are described in details in Ref. [2]. Figure 1 shows the estimated number of SRF ”units” for each application and the estimated value. 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. For the EUVL application, a “unit” consists of a total of 184 cavities for two 1 GeV linear 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 8 MeV accelerators, each with one SRF cavity, to allow for both the high uptime and/or double-sided irradiation. Units for all other applications consist of a single accelerator. A single-cavity, 8 MeV accelerator could be used for medical device sterilization and a 35 cavities, 75 MeV linear accelerator was considered for medical isotopes production.

Whereas the accelerators for EUVL, ADS and isotopes production would still rely on cavities cooled by liquid He, those for all other applications would rely on the emerging conduction-cooled SRF technology [13–18].

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 EUVL 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.

ACTION PLAN

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:

- Be able to handle swings in procurement from “big science” projects.
- Be ready to deliver goods for small projects.
- Be able to ramp up quickly for large projects.

The information gathered through the project suggests that adopting the following recommendations will lead to a sustainable, robust and competitive domestic SRF cavity industry:

- 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 procurement 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

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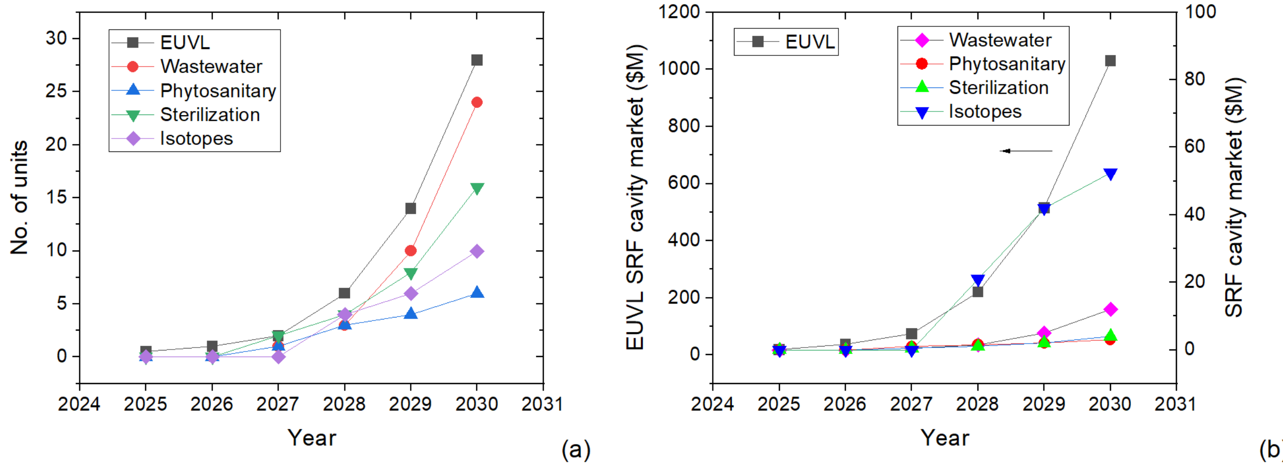

Figure 1: (a) Estimated number of SRF system units and (b) estimated SRF cavity market value for different industrial applications.

projects, in order to smooth out the demand curve for SRF cavities.

- Establish an 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.
- Support industrial ramp-up. 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 cavities with the required quality. Support from national laboratories to facilitate knowledge transfer is important at this stage.
- 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 stockpiling high-purity Nb sheets through minimum annual orders.
- 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.
- 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.
- 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.
- Facilitate the 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.
- Streamline procurement. Strategic procurement policies aimed at standardization, simplification of processes and leveraging financial support mechanisms should be enacted. Whereas the vast majority of the government contracts are issued as “firm fixed price”, other contracting options, such as ”cost plus fixed fee” should be encouraged, to share some of the risks involved in low-volume fabrication of prototypes.

Together, the recommendations listed above can facilitate a highly nimble and prolific SRF industry ecosystem for the United States. Figure 2 provides a pictorial representation of the proposed ecosystem for a robust domestic SRF cavity production.

CONCLUSIONS

The 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

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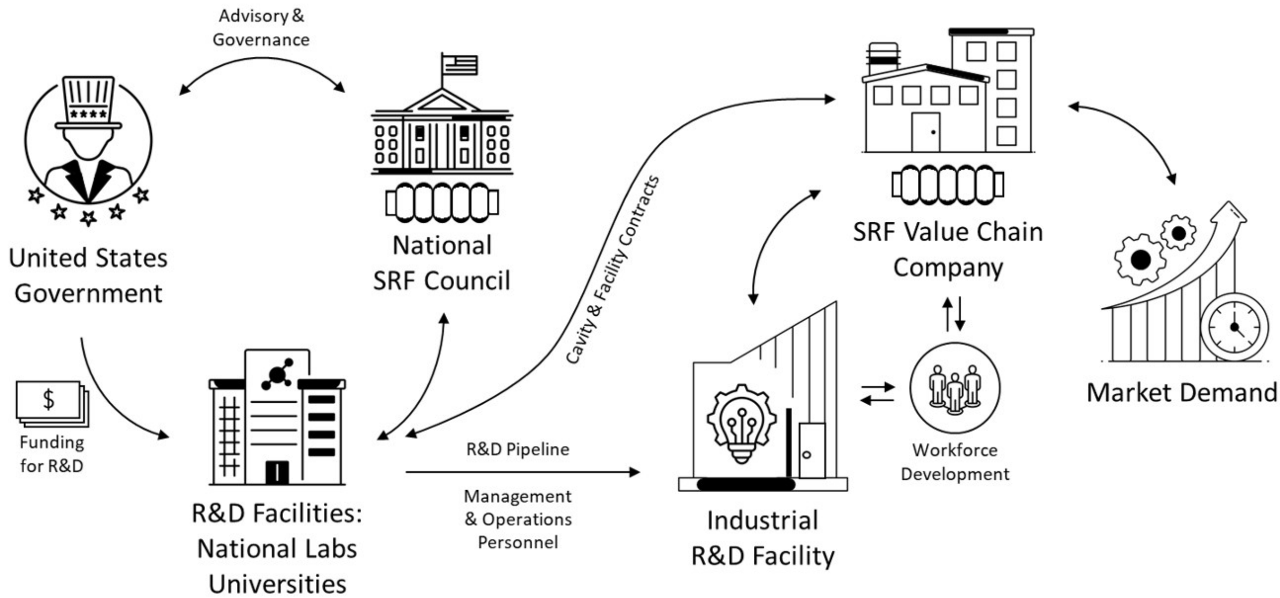

Figure 2: Graphic representation of the proposed ecosystem to develop a robust domestic supply of SRF cavities [19].

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 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. Lessons learned from past efforts can chart the path to reviving and reinvigorating domestic industrialization of SRF technology. The action plan presented in this contribution provides a possible solution to the problem.

The required investments 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.

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