Compact Superconducting RF Accelerators

Snowmass 21: Contribution *August 25, 2020*

Charles Thangaraj and Thomas Kroc

IARC at Fermilab, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510 USA

Email: kroc@fnal.gov

SRF technology has been widely adopted for new Discovery Science Accelerators requiring high power beams because of its inherent wall plug power efficiency. The result is that SRF technology is now the technology of choice for many billion-dollar class science accelerators around the world (e.g. CEBAF, SNS, XFEL, LCLS-II [1], RIA, PIP-II [2],) These large science projects have driven a world-wide R&D effort to improve SRF technology over the past decades [3]. These programs are now providing results that enable the use of this technology in simple, compact, high-power industrial accelerators. These break throughs, and including many developed at Fermilab, can be applied to a new class of SRF-based industrial accelerators that are simple, reliable, and cost effective.

Compact Superconducting RF (CSRF) Accelerators have the potential to extend the application of accelerator technology to many new areas such as environmental remediation, medical device sterilization, waste treatment, and even sourcing fresh water. Successful application of accelerator technology to these areas requires continued development of many enabling technologies particularly those that increase energy efficiency. In many of these applications, energy efficiency is a major advantage over other technologies. With the increasing concern for climate change and the need for ever more powerful accelerator sources of beams, the efficiency of discovery science accelerators will become of greater importance.

IARC at Fermilab (IARC) strives to work with industrial partners to translate research and development breakthroughs in accelerator science and technology into applications for the nation's health, wealth, and security. Doing so reduces the payback time for the nation's investments in basic science research. The needs of discovery science machines provide a "market pull" that creates incentives for industry to develop and provide necessary products for HEP. Developing a second prong for the market-pull on a technology by providing the possibility of commercial applications enhances the probability of industry support of that technology. This can result in lower cost and increased availability, to the benefit of both the marketplace and HEP. Accelerators for industrial applications need to be cost effective, reliable, and have high power efficiency.

IARC has been coordinating the development of a CSRF accelerator. The success of the CSRF design rests on a foundation of breakthroughs in gun design [4], Nb_3Sn coatings [5,6], conduction cooling [7], and RF coupler development [8]. It's economic success in commercial application will be dependent on the development of improved RF sources as noted in [9].

Below we identify areas that require continued investment to sufficiently develop these technologies to the point where they can be better engaged by industry.

R&D efforts in electron guns have led to high current guns, which provide alternatives to complex photoinjectors such a field emission cathodes. Research on higher current, more robust cold-cathode

technology based on field emitters [10], would be needed to avoid the typical thermionic failure along with a focus on increasing the lifetime for such alternative technologies.

Breakthroughs in thin-film coating such as Nb_3Sn has shown excellent progress which simplifies the cryogenic complexity of superconducting accelerators [6, 7, 11, 12]. Development of a reproducible cavity coating process that can be transferred to industry requires research on the Nb_3Sn coating properties and defects, development of coating infrastructure including high temperature vacuum ovens, and funds for sufficient cavity throughput such that a robust process can be developed in a timely way.

Magnetrons were developed pre-World War II for radar applications. However, even today they remain the most efficient source for the generation of RF power in the hundreds of MHz to few GHz frequency range. Driving an SRF-cavity based accelerator will require more precise controls and better spectral purity of the RF output. Existing magnetron systems demonstrate wall plug power efficiencies above 80%, a key requirement for accelerators that can serve in industrial settings. Investigation of injection locked magnetrons at frequencies such as 1.3 GHz and other efforts to develop a high-power CW RF source at JLab is underdevelopment, continued efforts on building a magnetron sources that can work with a superconducting machine is an important need.

High power RF couplers for SRF cavities are offered by industry (e.g., CPI and Thales). However, there is both science and art involved in their design and manufacture. Continued development is required to simplify the design and manufacture of low-loss couplers that is critical for high-power machines [8].

The energy efficiencies of the CSRF design can be looped back into the design of discovery science accelerators in order to reduce their energy requirements. This requires continued development of the foundational technologies noted above. In addition, attention is required for ancillary systems that support the technologies noted. An example of an ancillary system is DC power supply. High power RF sources need efficient lower cost DC voltage sources to ensure that total system efficiencies remain high.

Most of the existing commercial and industrial accelerator applications grew from decades-old accelerator technology. However, the accelerators of tomorrow, using recent advances developed for HEP, promise many new opportunities. While pre-modern accelerator technology has deeply penetrated existing markets, SRF technology creates new markets altogether. Converting DOE's investment in science and technology into entrepreneurship and innovation will allow new industries to emerge. This promotes the long-term economic interest of the nation. IARC is a gateway that enables companies to connect with the world-class scientific and engineering capabilities.

References

[1] Ross, M. C. LCLS-II: Status, Issues, and Plans. SLAC National Accelerator Lab., Menlo Park, CA (United States), 2019.

[2] Merminga, Lia. "PIP-II: A DOE International Project for Powering Discoveries in High Energy Physics." APS 2019 (2019):

[3] Padamsee, Hasan. "50 years of success for SRF accelerators—a review." Superconductor Science and Technology 30.5 (2017)

[4] P. Murcek et al., Modified SRF Photoinjector for the ELBE at HZDR, 15th International Conference on RF Superconductivity, 7/25-29/2011, Chicago, USA.

[5] S Posen *et al* 2019 *Proceedings of 19th Int. Conf. of RF Superconductivity* (Dresden Germany). (https://doi.org/10.18429/JACoW-SRF2019-THFUB1)

[6] Posen, S., et al. "Advances in Nb3Sn superconducting radiofrequency cavities towards first practical accelerator applications." arXiv preprint arXiv:2008.00599 (2020).

[7] R C Dhuley *et al* 2020 *Supercond. Sci. Technol.* **33** 06LT01. (https://doi.org/10.1088/1361-6668/ab82f0)

[8] Kazakov, S. "How to Eliminate a Copper Coating and to Increase an Average Power of Main Coupler." TUPO009, Proceedings of SRF (2011).

[9] https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF7-002.pdf

[10] Mihalcea, D., et al. "Measurement of Ampère-class pulsed electron beams via field emission from carbon-nanotube cathodes in a radiofrequency gun." Applied Physics Letters 107.3 (2015)

[11] Ciovati, Gianluigi, et al. "Multi-metallic conduction cooled superconducting radio-frequency cavity with high thermal stability." Superconductor Science and Technology 33.7 (2020)

[12] Stilin, Neil, et al. "Stable CW Operation of Nb_3Sn SRF Cavity at 10 MV/m using Conduction Cooling." arXiv preprint arXiv:2002.11755 (2020).