

Key directions for research and development of superconducting radio frequency cavities

ABSTRACT

Radio frequency superconductivity is a cornerstone technology for many future HEP particle accelerators and experiments from colliders to proton drivers for neutrino facilities to searches for dark matter. While the performance of superconducting RF (SRF) cavities has improved significantly over the last decades, and the SRF technology has enabled new applications, the proposed HEP facilities and experiments pose new challenges. To address these challenges, the field continues to generate new ideas and there seems to be a vast room for improvements. In this paper we discuss the key research directions that are aligned with and address the future HEP needs.

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1 Executive summary

Over the last decades, the superconducting radio frequency (SRF) technology has made tremendous progress and is nowadays a critical technology for many high energy physics (HEP) accelerators and experiments [1, 2, 3]. In the near future, SRF linac PIP-II will provide H^- beam to drive LBNF/DUNE experiment at Fermilab, SRF crab cavities will chirp the proton bunches at the ATLAS and CMS detectors of HL-LHC to boost the collider's luminosity. Further down the road, the SRF technology will be crucial for the success of a future Higgs factory, being either SRF linear collider option, such as ILC and HELEN, or circular collider option, such as FCC-ee and CEPC. Recently demonstrated excellent performance of SRF cavities in quantum regime (single-photon operation at millikelvin temperatures) enables new set of experiments in dark matter searches and new avenues for building quantum computers, which would be very beneficial for the HEP field. The new applications of the SRF technologies pose new challenges that must be addressed via a dedicated SRF R&D program. There is still a vast room for improvements and many new ideas to explore.

A roadmap of SRF R&D for the decade starting in 2018 [4] was developed under the framework of the DOE GARD (General Accelerator R&D) program. The roadmap was developed by a team of leading researchers in the field from various national labs and universities, both domestic and international. It provides a community-directed guidance and reflects the most promising research directions for advances that enable future experimental high energy physics programs. In this contributed paper, we lay out a framework for key SRF R&D directions, which are largely aligned with and extend beyond the GARD roadmap.

Among the key directions that we consider in this paper are:

- studies to push performance niobium and improve our understanding of RF losses and ultimate quench fields via experimental and theoretical investigations;
- developing methods for nano-engineering the niobium surface layer and tailoring it for specific applications;
- investigations of new SRF materials beyond niobium via advanced deposition techniques and bringing these materials to practical applications;
- developing advanced cavity geometries to push accelerating gradients of bulk niobium cavities to ~ 70 MV/m and pursuing R&D on companion RF technologies to mitigate field emission, provide precise resonance control, etc.;
- research on application of SRF technology to dark sector searches.

Strategic investments in these SRF R&D areas would open opportunities to build new, more efficient, compact, and cost-effective HEP accelerators and enable new types of experiments. To realize these opportunities, we ask Snowmass 2021 for a strong recommendation to increase investment in the SRF research and technology development.

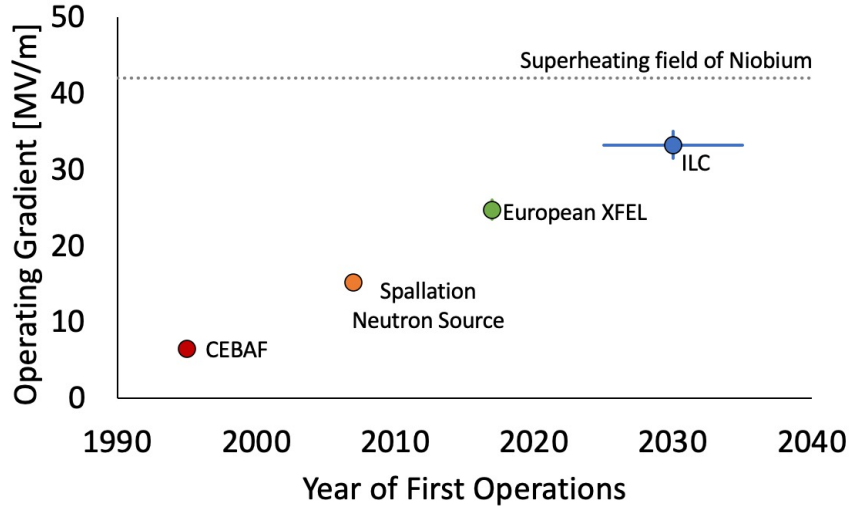


Figure 1: Progress with time in SRF R&D leading to higher operating gradients for large SRF accelerators.

2 Introduction: SRF cavity performance frontier

Superconducting radio frequency (SRF) cavities are a critical technology for several frontiers of experimental high energy physics. SRF cavities make up the vast majority of the PIP-II linac, which will drive LBNF/DUNE [5]; SRF cavities provide energy to the beams of the LHC, and they will also provide crabbing at the interaction regions to boost luminosity of the HL-LHC [6]; SRF cavities would provide energy for beams in the next generation of proposed Higgs factories, including ILC [7, 8, 9], FCC-ee [10], and CEPC [11]. In addition, SRF cavities are being explored not only for particle beam acceleration but for detection in the next generation of dark sector searches [12, 13, 14, 15] as well as for quantum computing, which could be extremely beneficial for HEP applications [16, 17]. To continue enabling future high energy physics experiments, research and development on SRF cavities is crucial. Continued improvements in cavity performance make new scientific applications feasible when they would have otherwise been either un-achievable or too expensive.

Fig. 1 gives some examples of how SRF R&D can enable experimental physics. It plots operating gradient of large-scale SRF linear accelerators (order of hundreds of SRF cavities) versus year of first operations. It shows how as progress was made in SRF R&D to increase accelerating gradient – through years of efforts to ameliorate degradation mechanisms such as multipacting, thermal breakdown, and field emission [18, 19, 20] – the new capabilities would bring into reach new accelerator-based experimental programs in nuclear physics, basic energy sciences, and high energy physics.

Fig. 1 includes ILC, based on gradient targets from the TDR [7, 8]. In a Snowmass 2021 submission [9], there is a discussion of how the baseline gradient could be increased, including significant increases for upgrades to ILC as R&D progress continues to be made.

The figure does not show other relevant ways in which R&D has improved cavity performance, such as improvements in Q_0 (e.g., the factor of ~ 3 improvement in Q_0 provided by nitrogen doping has been an enabling factor in the LCLS-II X-ray FEL project [21, 22]; and Q_0 values $> 3 \cdot 10^{11}$ at temperatures 1.4 K have been achieved by medium temperature baking [23]). These and new advances in the near future would be crucial for new proposals, e.g., HELEN collider [24].

A roadmap of SRF R&D for the decade starting in 2018 was developed under the framework of the DOE GARD (General Accelerator R&D) program. The roadmap was developed by a team of leading researchers in the field from various national labs and universities, both domestic and international. The GARD roadmap for SRF R&D provides community-directed guidance, based on best planning from the exercise in 2017, and reflects the most promising research directions for advances that enable future experimental high energy physics programs. Fig. 2 shows two summary tables from the road-mapping exercise [4]. Recently, the 2020 update of the European Strategy for Particle Physics [25] emphasized the importance of accelerator R&D. The followed up effort on developing a roadmap for European accelerator R&D culminated in a report, which includes a roadmap for high-gradient RF structures and systems [26]. The European roadmap covers SRF cavity topics similar to the GARD roadmap and hence there is a lot of synergy and opportunities for collaboration between the U.S. and European laboratories and universities.

In this contributed paper, we outline our views on key future research directions, which largely continue to align with the GARD roadmap. This includes studies pushing the performance of niobium, including doping, multi-step heat treatment, flux expulsion and flux losses; it includes new materials such as Nb₃Sn as well as layered structures; it also includes fundamental studies of the physics of RF surface resistance and penetration of flux into superconductors at high fields. Further, the paper discusses advanced SRF cavity shapes, use of SRF cavities for dark sector searches, and other key R&D directions. The goal is to highlight the importance of the SRF cavity technology for future HEP accelerators and experiments and provide an update to the GARD roadmap.

3 Nano-engineering the Nb surface layer for high Q and high gradient

Superconducting properties of niobium cavities – surface resistance and breakdown magnetic field – depend on the state of material in the first few tens of nanometers of the RF surface of the cavities. For example, the penetration depth of a clean niobium is about 40 nm. Only relatively recently the techniques have been developed to systematically change the surface properties and study the effects of the changes, e.g., using HF rinse [27]. The ultimate goal of the experimental studies – in parallel with developing theoretical concepts and models [28] – is to come up with methods for nano-engineering the surface layer to control its properties for optimal, project-dependent SRF performance. Such “tailored surface” methods would offer prospects for a dramatic reduction of accelerator footprint, construction costs, and operation costs, broadening the range of applications. The cavity performance is one of the

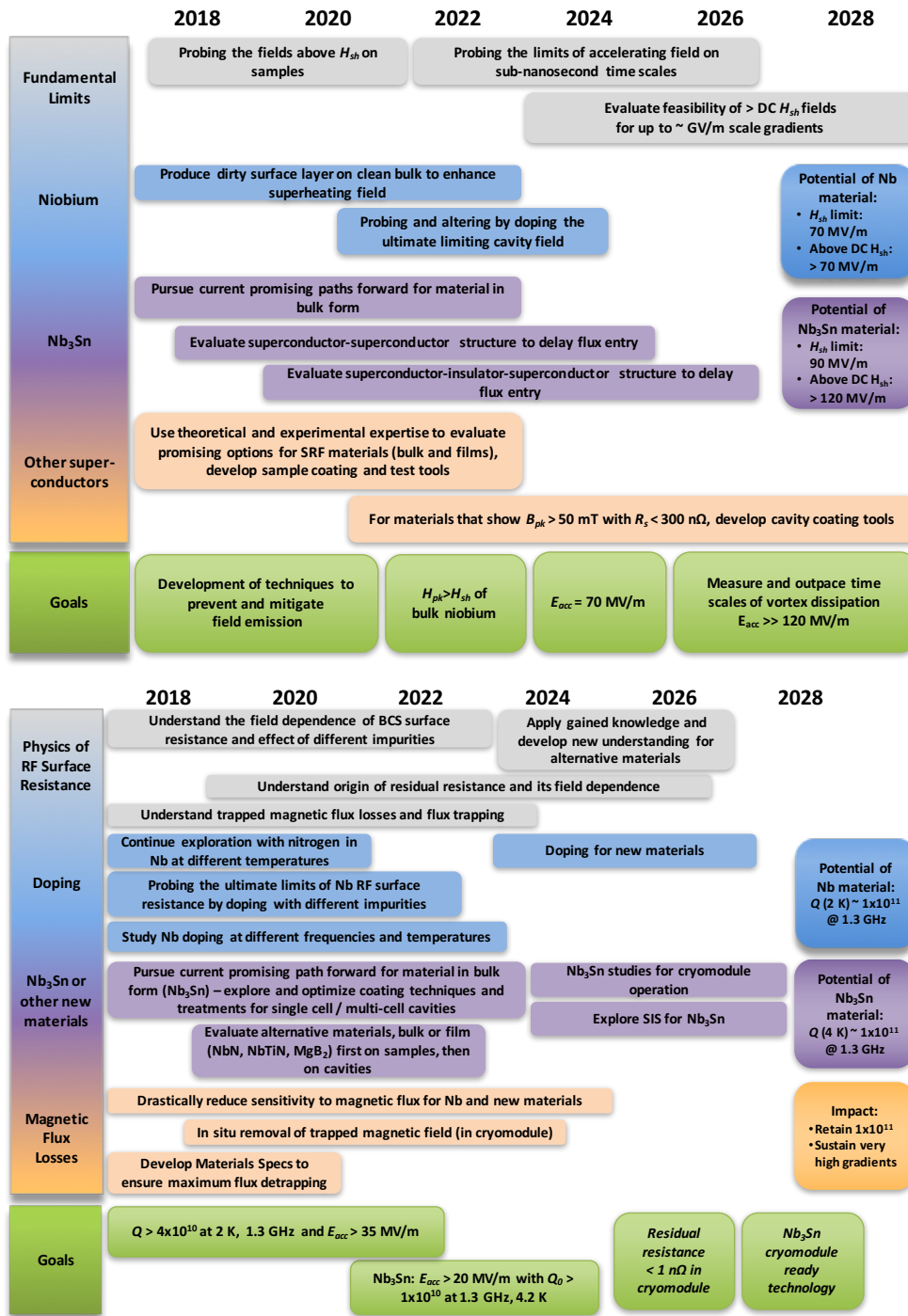


Figure 2: Tables showing proposed directions over a decade of research and development towards pushing the accelerating gradients (top) and Q_0 (bottom) of SRF cavities (from [4]).

main cost driver for SRF accelerators.

Improving Q factors of niobium cavities at medium gradients (16–25 MV/m) is a key R&D area for future CW and high duty factor HEP accelerators, such as circular e^+e^- colliders FCC-ee [10] and CEPC [11], a CW SRF linac for PIP-II upgrade [29], etc. This key area is synergistic with rapid progress over the past 5–10 year in developing nitrogen doping technology [21] for SRF-based free electron lasers, specifically LCLS-II and LCLS-II-HE. The most recent nitrogen doped 1.3 GHz cavities for LCLS-II-HE demonstrate an average Q of 3.6×10^{10} at 23 MV/m [30]. Presently, it looks like the most promising path to even higher quality factors would come from mid-temperature ($\sim 300^\circ\text{C}$) baking of SRF cavities in vacuum, which dissolves the natural oxide and other surface layers into the bulk of niobium [23], with demonstrated $Q = 5 \times 10^{10}$ at 30 MV/m. While the Q factor drops after exposure to air and High-Pressure Rinsing with ultra-pure deionized water (HPR), the cavities still demonstrate quite good performance with Q in the range of $3.5 - 4.4 \times 10^{10}$ at gradients between 16–24 MV/m [31]. This is still a very promising and active R&D area. The name of the game in improving Q is improving the cavity surface resistance. While some progress was made, the main open questions remain as it was highlighted in [4]:

- Continue exploration of the effect of interstitial impurities on bulk Nb surface resistance;
- Develop fundamental understanding of the reverse field dependence of the BCS surface resistance and devise experiments towards validation of different theories;
- Develop understanding of mechanisms of trapping magnetic vortices and their contribution to the RF losses, and devise experiments towards validation of models;
- Develop understanding of 'intrinsic' residual resistance and its field dependence;
- Ameliorate trapped vortices via innovative ideas: advanced magnetic shielding concepts, in situ flux removal, determine material properties/preparation for minimal pinning strength, etc.

Pushing toward higher gradients while improving cavity quality factors is related to investigating fundamental electromagnetic field limit in SRF cavities. There was some recent empirical progress. Two low-temperature surface treatment recipes demonstrated accelerating gradients higher than the standard ILC treatment. First, the nitrogen infusion [32] process demonstrated gradients of 40–45 MV/m in 1.3 GHz TESLA-shaped cavities. Second, near 50 MV/m have been achieved with a 75/120°C two-step bake with cold electropolishing treatment [33, 34], which is a more robust recipe than infusion. However, there still no good theoretical model explaining what the dynamic superheating field $H_{sh}(\omega, T)$ is [28]. It is very important to continue theoretical and experimental research to establish the ultimate SRF field of niobium.

4 Nb₃Sn as practical Nb material

Nb₃Sn superconductor has potential of reaching fields approximately twice as high as niobium, or $E_{acc} \sim 100$ MV/m [35]. Extrapolation from high power pulsed RF experiments is in agreement with this prediction [36]. In CW regime, Nb₃Sn deposited on bulk niobium cavities show promising results [37], reaching high $Q \sim 10^{10}$ even at temperatures ~ 4 K. So far, R&D cavities demonstrated accelerating gradients up to 24 MV/m in single-cell cavities and 15 MV/m in 9-cell TESLA-shape cavities [38]. Such gradients might already be useful for small-scale accelerators. In addition, Nb₃Sn SRF cavities could have an advantage for dark matter searches due to the material ability to remain superconducting in large magnetic fields thus outperforming copper cavities that are used in such experiments so far. For example, initial results are quite promising, demonstrating Q_0 of $\sim 5 \times 10^5$ in DC magnetic field of 6 T at 4.2 K for a special shape cavity [39].

For accelerator-based HEP applications, further developments are necessary. Circular e^+e^- colliders FCC-ee [10], CEPC [11] and other CW/high duty factor accelerators (e.g., a CW SRF linac for PIP-II upgrade [29]) would require medium gradient (in the range 15–25 MV/m), high efficiency cavities. Pulsed linacs for an energy upgrade of ILC [9] or for HELEN collider [24] would need very high gradient cavities of ≥ 80 MV/m that would still maintain high efficiency.

Due to relatively short coherence length ~ 3 –4 nm, approximately an order of magnitude smaller than niobium, the Nb₃Sn cavity performance is more sensitive to surface defect. There are experimental results indicating that indeed this is the case [36, 40]. As the post-coating surface treatments are not well developed yet, more R&D efforts in this area are in order. In parallel to bulk Nb₃Sn film R&D, alternative manufacturing routes should be pursued as well. For example, thin Nb₃Sn films on clean Nb or Superconductor-Insulator-Superconductor (S-I-S) Nb₃Sn layered structures should be studied to try to achieve the superheating field of Nb₃Sn. These efforts would require more development to ensure good RF performance. A white paper [37] outlines the current status of the Nb₃Sn research and proposed R&D directions in more details.

5 Other materials beyond bulk Nb

Superconductors other than bulk niobium have been used in non-RF applications for many years, see for example [41]. However, it is still very difficult to apply those to SRF cavities due to extremely high sensitivity of surface resistance to the quality of deposited films. At present, the only material close to become practical for SRF cavities is Nb₃Sn, discussed in the previous section.

Technology of depositing thin films of niobium on copper (Nb/Cu) has been used in accelerators that do not require high gradients and can operate at 4.5 K (that is at low RF frequency), such as LEP2, LHC, and Hie-ISOLDE at CERN, ALPI at INFN-LNL (Italy), SOLEIL (France). Although exhibiting very high Q at low field, sputtered Nb on Cu cavities have been plagued with steep increase of RF losses at medium to high gradients. Recent

R&D efforts to develop advanced coating methods have produced some encouraging results (see references in [42]), but further efforts are needed to scale up the processes and firmly establish the good baseline performance of SRF cavities.

Alternative superconducting materials with higher critical field and critical temperature can potentially surpass the intrinsic limits of niobium. Among the advantages the new materials might offer are i) high Q at temperatures above 2 K for higher efficiency and lower cost of large-scale facilities and small scale cryocooler-based accelerators, and ii) higher accelerating gradients for reaching higher beam energies in more compact accelerators.

Among the alternative materials that are still being evaluated are A15 superconductors other than Nb₃Sn (Nb₃Al, V₃Si, ...), Mg₂B, pnictides, etc. [43]. All these materials require development of deposition techniques on a suitable SRF cavity substrate, e.g., copper or niobium. Deposition methods such as sputtering, energetic condensation and atomic layer deposition (ALD) are being explored. Thin films could also bring the advantage of layered structures (e.g., superconductor-insulator-superconductor, or SIS) for a potential to further boost achievable accelerating gradients. R&D to improve deposition methods must continue so that the most promising techniques are selected, and alternative superconductors with practical levels of surface resistance are applied to SRF cavities for performance evaluation in a reasonable time frame.

6 Advanced SRF cavity shapes

For an e^+e^- linear collider, the 1.3 GHz TESLA cavity [44], along with other aspects of SRF technology, was developed in the 1990's. While the cavity has an optimized geometry and served the community well enabling several small and large accelerators (the prime examples are European XFEL [45] and LCLS-II/LCLS-II-HE) [46, 47], there is room for improvement of the geometry to reduce the ratio of surface magnetic field H_{pk} , which is fundamentally limited by the field at which superconductivity breaks down, to accelerating gradient E_{acc} . A reduction of H_{pk}/E_{acc} by 10–20% can be achieved. Several advanced cavity geometries have been proposed over the years: Re-entrant [48, 49], Low-Loss [50], ICHIRO [51], and Low Surface Field (LSF) [52]. Many single cell R&D cavities of these geometries were built and tested with the standard ILC surface treatment, demonstrating gradients well above 50 MV/m. Combining one of these cavity geometries with the most advanced surface treatments, such as two-step low-temperature bake, one can expect improving gradients up to 60 MV/m in 9-cell standing wave structures. However, very limited efforts have been devoted to multi-cell cavities so far. More funding for R&D in this area could provide rapid progress in a short time. More details on the advanced cavity shapes can be found in [24] and references therein. An advanced cavity shape could be used for an energy upgrade of ILC [9] or for a more compact Higgs factory HELEN [24].

Travelling wave SRF (TW) structures offer further advantages over standing wave: substantially lower peak magnetic (H_{pk}/E_{acc}) and lower peak electric field (E_{pk}/E_{acc}) ratios, two times higher R/Q . The TW shape optimization [53] indicates that an accelerating gradient as high as 70 MV/m might be achievable. The 38% increase of the $G \cdot R/Q$ parameter

reduces the cryogenic dynamic heat load at high gradients. The higher cell-to-cell coupling of the TW mode makes the structure less sensitive to cavity detuning errors, making tuning easier, despite the larger number of cells. Also, high stability of the field distribution along the structure with respect to geometrical perturbations allows for longer accelerating structures (compared to TESLA cavities), limited by manufacturing technology.

Developing novel fabrication methods could enable the use of structures considered previously only for NCRF systems, for example a parallel-feed accelerating structure [54]. If a robust, high-performance coating of thin-film niobium (or other superconductor) on copper is developed, such structures could potentially be more efficient for future accelerators, both linear and circular.

Future HEP experiments require higher beam intensities and/or shorter synchrotron cycle times. The higher beam intensities of future circular colliders mean that the accelerating cavities should incorporate strong damping of higher order modes (HOM). While such cavities have been successfully developed and operated, see e.g., [2], new approaches are always sought to improve the performance even further. Some machines require low-frequency RF, for which quarter-wave, $\beta = 1$ resonators have been developed [55, 56, 57]. However, proton synchrotrons, either new or upgraded existing (e.g., the Main Injector at Fermilab) require fast frequency tuning during the machine cycle. The SRF technology would significantly reduce the number of cavities in these machines, thus reducing parasitic impedance due to accelerating structures, but the lack of fast frequency tuners prohibits the use of SRF cavities at present. Development of the required fast frequency tuners (we discuss the fast tuner R&D further in section 8) in parallel with new cavity structures operating at ~ 50 MHz would provide much higher acceleration gradients and; therefore, a smaller number of cavities and lower the beamline impedance.

7 SRF for dark sector searches

SRF cavities are resonators with extremely high quality factors. As such, they are of a strong interest for quantum information science. In particular, these cavities can serve as an extremely sensitive detectors of very weak signals when dark matter, new particles (e.g., dark photons or axions) or high-frequency gravitational waves convert to microwave photons [15]. 3D SRF cavities provide large volumes where the photons can be collected with high efficiency, that is the photons would have a very long lifetime due to extremely low losses in the cavity walls.

While some salient features that make SRF cavities so attractive for particle accelerators (high acceleration rate, high Q at medium and high gradients) are not relevant for most experiments discussed here, maintaining high quality factor at very low electromagnetic fields and millikelvin temperatures is of utmost importance. Experiments with 2D and 3D resonators show that the Q factor goes down at very low temperatures and electromagnetic fields. This is an indication that the two-level systems (TLS) residing inside an amorphous niobium oxide layer may play a significant role in the low-field performance [58, 59, 60]. Reducing TLS losses is an active area of research [61], but more efforts are required to find

a robust method to consistently achieve high Q in quantum regime. In addition, there is a need to achieve high Q when a cavity is in a multi-tesla magnetic field.

Traditional, TESLA-shape SRF cavities can be used as is in experiments such as Dark SRF (light shining through wall) [62]. However, many other experiments require development of special cavities and/or operating in high DC background magnetic field, which we mentioned in section 4. Examples of such cavities are a two-mode cavity [15] or a cigar-shaped cavity [39] for axion searches.

8 Other key R&D directions

There are other research elements and companion technologies that are important for success of SRF cavities in different operating regimes. Here we mention just a few of them.

Mitigation of field emission: Imperfections of the cavity inner surface or contamination by dust particles enhance local electric field and can cause emission of electrons in cavities. This so-called field emission (FE) could be a serious impediment to achieving high gradients. To reduce the probability of appearing emitters, special care should be taken during the cavity preparation and assembly. In particular, all SRF cavities are high-pressure rinsed with ultra-pure deionized water and assembled in clean rooms of Class 100 or better. Even when using these state-of-the-art techniques, some cavities still suffer from FE. Special studies will be required in parallel with high gradient research to abate FE. A promising pathway is to develop robotic assembly of SRF cavities and cryomodules to eliminate human errors and reduce sources of possible contamination [63, 64]. This is still a nascent area and requires better funding to produce results in reasonable time. Other post-assembly in situ methods that require further development include, e.g., plasma processing [65].

Compensation of microphonic noise and Lorentz force detuning: Advances in the SRF cavity performance should be accompanied by R&D on the cavity resonance control [66, 67]. SRF cavities operating in CW regime, especially with weak beam loading like energy recovery linacs and low-beam-current proton linacs (and hence with high loaded Q 's) are susceptible to large swings of their resonant frequency due to vibrations of their walls. These vibrations are caused by external excitation from different sources and are commonly known as microphonic noise, or simply microphonics. Compensation of microphonics becomes particularly important for operations at ~ 4 K (e.g. for Nb_3Sn cavities). Liquid helium systems are inherently noisier at these temperatures than the superfluid operations at 2 K. For pulsed linacs, such as European XFEL, ILC, HELEN, compensating cavity resonant frequency detuning due to the Lorentz force (Lorentz Force Detuning or LFD) is especially important as gradients of the linac increases, as the ratio of LFD to the cavity bandwidth is proportional to the cube of the accelerating gradient. R&D efforts should focus on i) new cavity designs optimized for response to LFD and microphonics, and ii) new active LFD and microphonics compensation algorithms along with the new tuner (fine and coarse) designs.

Ferroelectric tuners: Ferroelectric ceramic materials with low loss tangent at RF frequencies [68, 69, 70] allow development of electrically controlled devices (tuners) with much

shorter switching times than those of piezo-electric mechanical tuners. Such a ferroelectric tuner, when inserted into a high-power transmission line connected to the SRF cavity, can allow to do two things: i) alter the coupling between the transmission line and the acceleration structure [71], and ii) electronically control the cavity frequency within a bandwidth needed for active compensation of microphonics. A ferroelectric tuner could eliminate the need for overcoupled fundamental power couplers, thus significantly reducing RF amplifier power. A proof-of-principle demonstration of the ferroelectric fast reactive tuner (FE-FRT) was recently accomplished at CERN [72]. Further R&D efforts are needed in this area to realize the full potential of ferroelectric devices.

9 Summary and conclusions

Superconducting radio frequency cavities have improved dramatically in performance over the last decades, thanks to dedicated R&D efforts. These improvements have enabled new scientific applications that had not previously been feasible. Even considering these significant past improvements, there is still vast room for continued improvement through additional R&D. These efforts are funding-limited, not idea-limited, and more ideas continue to be generated as more experimental advances are made. The exciting areas to explore that were discussed in this document include

- furthering our understanding of RF losses and ultimate quench fields of niobium via experimental and theoretical investigations;
- developing methods for nano-engineering the niobium surface layer and tailoring it for specific applications;
- studying new SRF materials beyond niobium via advanced deposition techniques and bringing these materials to practical applications;
- developing advanced cavity geometries to push accelerating gradients of bulk niobium cavities to ~ 70 MV/m and pursuing R&D on companion RF technologies to mitigate field emission, provide precise resonance control, etc.;
- investigating application of SRF technology to dark sector searches.

Strategic investments in these R&D areas would open opportunities to build new, more efficient, compact, and cost-effective HEP accelerators and enable new types of experiments. To make these performance improvements realizable, we ask Snowmass 2021 for a strong recommendation to increase investment in the SRF research and technology development.

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