SRF for future accelerators

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Accelerator technology continues to evolve, driven by the experimenters' insatiable desire for ever-higher energy and more powerful beams. This has also enabled great societal benefits through the development of synchrotron light sources, particle beam therapies, neutron and x-ray imaging, industrial applications, etc. In the last 30 years SRF has been a transformative technology, enhancing the reach and efficiency of discovery class machines such as CEBAF, LEP-II, Super KEK-B and LHC and enabling ultra-bright and intense X-ray and neutron sources such as the European XFEL, LCLS-II, SNS and ESS. However the cost and complexity of SRF based on bulk Nb and liquid helium cryogenics has kept this technology within reach only of national labs and a few major universities. To realize the full potential of SRF for future science and broader society requires further significant improvements in performance, reliability, efficiency and cost. Fortunately recent history has shown that adequately funded and well-directed R&D can make rapid progress in this still-young technology.

The required advances for future linacs, rings and ERL's may be along different axes but they have many challenges in common and progress along one axis often unlocks benefits in others. Progress in SRF relies on fundamental understanding of superconducting material properties and their limitations combined with vigorous theoretical and experimental work to improve performance. The job of the SRF system designer is to get the best overall performance out of available materials within known constraints. This optimization must adapt to progress in electric or magnetic surface field limits, surface resistance, fabrication technology and component costs.

We believe intensive continued R&D is needed to pursue the following opportunities:

1. **Extract the maximum performance from established bulk Nb technology**. This is the baseline but recent breakthroughs e.g. in surface modification by addition of controlled impurities and heat treatments, show that it is far from played out. The empirically demonstrated benefits are still not fully understood or reproducible and require improvements in theory and practice to fully exploit. Field emission is still undefeated and confident elimination of particulates and field-enhancing surface features is needed. If this is successful cavity shapes can be adapted to take advantage. Similarly elimination of magnetic field enhancing defects by improved fabrication methods would allow confident operation closer to the critical field limit.

2. **Exploit recent advances in thin film Nb on Cu technology**. Recent results showing greatly improved accelerating field and dramatically reduced Q-slope show the potential of this process for many applications. In particular high current storage ring colliders such as FCC, EIC and CEPC, where the frequency is typically lower and the gradients are modest, could benefit greatly from the cost savings and operational advantages of this technology. Further effort is needed to scale up this process and develop protocols and procedures that can be industrialized.

3. **Explore alternative materials with higher critical temperature and critical fields**. These are the prime candidates to disrupt the established bulk Nb technology. Materials such as Nb_3Sn offer order of magnitude improvements in operating efficiency, enabling so-called “green accelerators”, and a theoretical pathway to 100 MV/m gradient. Recent results show that the persistent Q-slope that caused the Siemens thermal-reaction technology to be dropped 30 years ago is not fundamental but process induced and therefore amenable to improvement. Alternative approaches such as electro-chemical, thin-film and atomic layer deposition should be fully explored. Other materials such as NbN, V_3Si, MgB_2 etc. should be evaluated. New HTS materials would be particularly interesting should any of them turn out to have favorable microwave properties.

4. **Cost reduction**. The basic bulk Nb SRF manufacturing technology has been in place for decades. Improvements such as high-pressure rinsing, electro-polishing and furnace heat treatments have been added over the years to improve performance and there has been significant scale up of industrial capacity due to projects like LEP-II, CEBAF, SNS, XFEL, LCLS-II and ESS. Extrapolating this capability another order of magnitude for ILC still leaves cost as a major limitation. Every aspect of this production chain should be critically examined and more cost-effective alternatives sought. Unnecessary cost-driving requirements in the material specifications and fabrication processes should be identified and eliminated. Unfortunately recent developments such as surface doping and its requirement for extreme flux expulsion have made the process more complex, not less. Alternative fabrication methods and cavity designs optimized for mass production should be developed. While the TESLA technology base has served the community well for many years it locks in many production inefficiencies. Clean-sheet, optimized cavity and cryomodule designs should be developed for major new projects, with a view to industrial production, with reduced parts counts, a high degree of modularity, efficient design based on clear functional requirements, less expensive materials and processes and a more automation. Developments such as ingot Nb material or thin films, seamless cavity fabrication and HF-free electro-polishing can contribute to overall cost reduction.

In support of these R&D activities continued investments are needed in R&D, production and test facilities. Given the rapid evolution of the technology and the diverse range of processes and analytic capabilities involved, frequent renewal and upgrading of infrastructure is required. Cryogenic and beam test facilities are expensive and limited in number, emphasizing the importance of collaboration and sharing of knowledge within the community. These facilities are also the training ground for future generations of SRF scientists, engineers and multi-disciplinary technical personnel. Likewise they are the hubs from which to drive tech transfer to industry, building the capabilities that will be needed for the next generation of machines. Lastly, but by no means least, the propagation of these improvements and cost reductions into other fields such as medical, environmental, industrial, energy, security and even quantum information applications will continue and expand the societal benefits of our work. The day may not be far away when these demands overtake “big science” as the drivers of the technology.