Next Generation SRF accelerators based on Nb_3Sn

U. Pudasaini, C.E. Reece, **R.A. Rimmer**, A-M. Valente-Feliciano, JLab,
E. Barzi, G. Eremeev, FNAL.

In the last 30 years superconducting radio frequency (SRF) technology based on niobium has become the mainstay of discovery class machines such as CEBAF, LEP-II, Super KEK-B and LHC and 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 sub-atmospheric liquid helium cryogenics has kept this technology within reach only of national labs and a few major universities. Recent developments e.g. in surface modification by addition of controlled impurities and heat treatments, have improved the overall efficiency of such systems, extending their usefulness incrementally. On the other hand new materials such as niobium-tin (Nb_3Sn) have the potential to be transformative, offering order of magnitude improvement in operating efficiency, and a theoretical pathway to ~100 MV/m gradient, causing us to re-think the capabilities of SRF accelerators and the methods of producing them.

First considered more than 30 years ago the early promise of Nb_3Sn was thwarted by experimental results showing a persistent Q-slope (increase in surface resistance with gradient) that caused the technology to fall out of favor [1]. Recent results using similar Sn vapor diffusion processes but modern techniques and cleanliness however show that this phenomenon is not fundamental to the material but rather process-induced and therefore amenable to improvement [2-4]. These results have sparked renewed interest in the material, encouraged more detailed analysis of the loss mechanisms and inspired alternative approaches to the production of the SRF surface layer including thin-film deposition, electro-chemical application, and atomic layer deposition [5]. All these options merit further investigation and development.

Recently demonstrated gradients exceeding 20 MV/m make this technology already attractive for CW applications including storage rings colliders such as EIC, FCC and CEPC, CW linacs and ERL's. Operation with Q's ~ 10^{10} at 4K will also reduce the capital and operating costs of these systems considerably.

To maximize the impact of this new capability we believe intensive continued R&D is needed to pursue the following opportunities:

1. **Extract the maximum performance from Sn vapor diffusion Nb_3Sn technology**. Thermal reaction of tin vapor on the surface of bulk Nb, as proposed 30 years ago, is clearly now established as the front-runner in the race to displace conventional Nb technology [2-4]. This method has been the main one funded by U.S. agencies until now. The near term priority is to continue improving the consistency and quality of the surface layer on real cavities with the goal of early adoption for practical CW accelerators. R&D efforts need to be continued to optimize the coating technology to produce conformal coatings on practical accelerator structures of arbitrary geometry, and to reproduce demonstrated best R&D single-cell cavity performance on them, bringing it closer to accelerator application. Research continues to understand the contributing process dynamics that grow quality Nb_3Sn grains on Nb [6, 7]. An important milestone on this regard will be beam acceleration with actual all-Nb_3Sn cavities. An extensive

R&D effort is merited to identify the potential technical challenges toward the practical deployment of such cryomodules, such as tuning limitations because of the brittleness of the material. Continued improvement in material quality and consistency is expected to also improve high field performance, eventually also surpassing bulk Nb at the gradient frontier in pulsed linacs.

2. **Exploit recent advances in thin film technology for Nb_3Sn**. Recent advances in thin film technology such as energetic condensation enable the possibility of high quality engineered films with unique properties. Sequential or co-deposition of niobium and tin with the optimal stoichiometry may offer an attractive alternative to the bulk thermal reaction method. This opens up the possibilities for using alternative substrates e.g. with better thermal properties, and for creating multilayered structures. While this technology is in the early phase of development, it benefits from a great deal of prior experience with other metallic films and holds much promise. Several approaches are in development for SRF applications and have already produced encouraging results with the production of films exhibiting a crack-free surface, dense morphology and critical temperatures (T_c) above 17 K :
-Direct current magnetron sputtering of sequential deposition of Nb and Sn layer with post-reaction via annealing to form the A15 phase [8-10].
-Direct current magnetron sputtering with a stoichiometric target of Nb_3Sn on copper [11-12].
-Direct Nb_3Sn deposition using two separate targets in a co-sputtering setup leads to phase formation at substrate temperature lower than diffusion temperatures and post-reaction is not necessary [13].
-Energetic condensation via HiPIMS is also envisioned and would benefit from increased funding in the USA.

3. **Electro-chemical application.** In this method, the superconducting Nb_3Sn is obtained by electrodeposition from aqueous solutions of Sn and Cu intermediate layers onto Nb substrates, followed by post-reaction [14-16]. This work has been funded at a very small level through a DOE US-Japan collaboration grant. In 2019, the technology was transferred from FNAL to KEK, which continued development with a Japanese company AKITA KAGAKU Co., Ltd. In Japan this work is progressing through a collaborative research framework between KEK and this company. Early results are promising and this method should be strongly supported also in the USA.

4. **Atomic layer Deposition.** This is potentially the most precise process for producing uniform and conformal films with the optimum stoichiometry [5]. Films are produced layer by layer with tightly constrained morphology and chemical properties, even on high aspect ratio substrates. The challenge in this case is developing the pre-cursor gasses compatible with Nb and precise conditions for optimal coating. Once achieved however this is a very attractive process for coating real complex cavity shapes, including HOM ports and power

couplers [17, 18]. This fundamental development should be strongly supported, followed by scale up and testing on real structures.

While such breakthroughs will transform the landscape for discovery science, perhaps equally importantly the propagation of these improvements and cost reductions into other fields such as medical, environmental, industrial, energy, and security applications will greatly expand the societal benefits of our work.

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