Letter of Interest- Snowmass 2021

The necessity of a basic materials research community for the accelerated development of SRF materials.

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SRF accelerators are the technology of choice for producing high quality, high energy beams in the energy range of tens to hundreds of GeV, which is an essential high energy physics (HEP) science driver for "big science" projects. In the coming decades, there are several US and international projects proposed, such as the ILC[1], LCLS-II-HE[2], FCC[3], [4] , and CEPC[5], which will benefit from developments in the current technology. The workhorse material for SRF accelerators has been high purity bulk Nb which has been developed for the past 50 years[6]. In the last 20 years, project-driven advances have led the community to significantly improve SRF Nb cavity performances with the development of surface preparation and heat treatment procedures, and clear identification of physical metallurgy issues that limit the performance such as the hydride problem [7]–[10]. Within the past decade, modification of the surface chemistry by diffusion of N [11], [12], Ti [13], and C [14] into Nb, and understanding the influence Nb surface composition has provided pathways to further the Nb technology. More recently, there have also been demonstrations that a high accelerating gradient $E_{acc} > 45$ MV/m with low losses or high-quality factor Q_0[15] can be achieved. These remarkable values of E_{acc} correspond to the ultimate achievable breakdown magnetic fields of H~200 mT in Nb. However, the ability to consistently achieve higher gradients at high Q in Nb requires a fundamental understanding of the relationship between the final Nb surface and the processing steps from Nb ingot to the operational cavity. Control over-processing and structure starts at the ingot and must be maintained all the way to the final cavity. Yet, the various processing requirements often lie behind empirical recipes and carefully guarded trade knowledge.

Newer materials with higher T_c beyond Nb (T_c = 9.2 K) and material strategies that involve multilayer structures [16]–[18] are already on the horizon. The most promising superconductor among them is Nb_3Sn, with recent results for an Nb_3Sn layer on Nb, indicating that gradients over 20 MV/m at 4.2 K is now possible[19] with theoretical limits of over 100 MV/m. Other superconducting materials such as MgB_2, V_3Si, and iron-pnictides are being considered as they offer economic high-temperature options but need sustained development and evaluation of microwave and rf properties. All of these materials are brittle granular intermetallics, and the success of any rf strategy depends on the details of transport across grain boundaries. There are several exciting results on an R&D level, and their evolution into the state-of-the-art accelerator technology processes require careful metrology, specification control, and modeling capabilities to obtain predictive and consistent material level performances for next-generation accelerators. The recent advances in SRF cavity performance show that a sustained investment in SRF materials can be expected to provide actual dividends for future accelerators.

Below we summarize three significant opportunities that would enable further development of better SRF materials:

1. **Fundamental materials R&D for Nb**
   The development of processes for consistent and predictable performance in Nb SRF cavities and to go beyond state-of-the-art requires an understanding of the physical metallurgy aspects involved during Nb processing, forming, heat treatment, and cavity processing. These studies are

also relevant to understand solving issues with current SRF cavity technology regarding flux trapping and expulsion. Much of this work can be performed economically and quickly by using small samples and then confirmed on cavities. Material based modeling needs investment and can provide predictive capabilities. To obtain predictive performances in Nb accelerators, physics-based material models need implementation, for example, the prediction of microstructure after processing and heat treatment given the initial microstructure. The results of this work can provide recommendations for sheet vendors for better initial sheet specifications in addition to cavity fabrication optimization. A well-developed model could be a predictive tool to inform initial material selection or evaluation. These models are well developed in both the automobile industry for steel, beverage can industry for Aluminum, and for materials for nuclear applications and have occurred due to close academic-national lab collaborations[20], [21]. Such a template would lead to the development of a long-term base workforce that stays active.

2. **Moving beyond Nb**
   Beyond Nb, the next generation of SRF materials with higher T_c and lower cost will be much more complex, and the development of these materials will need R&D specific to microstructure and microchemistry and their impact on SRF properties. Grain boundaries must be transparent to rf current, yet the details of grain boundaries are complex and require the most advanced instruments available to materials science to elucidate. High-risk, high reward technologies along with fundamental R&D studies would also benefit from the development of coupon scale, 25-100 mm diameter RF testing systems that are easily accessible for small scale studies to open up research opportunities in these areas to a broader community.

3. **Sustaining broad-based research collaborations**
   The complex issues that will need to be solved to move the materials science forward will require the support of a wide variety of expertise and technology. The development of a base workforce to support the advanced SRF materials initiative and its application will also be essential to sustain this effort. An excellent model to follow for such an interaction could be the Low-Temperature Superconductor Workshop (LTSW), which has had a significant impact on the magnet development community by bringing together, industry, universities, and national laboratories in a collective effort to improve the performance of superconducting wire for accelerator and fusion applications. The plans for future accelerators could provide the thrust for more comprehensive community activity. A strong recommendation is to reinvigorate the US SRF Materials workshop that could offer a potential avenue to bring together experts from various walks.

This letter of interest supports the efforts of the DOE-GARD program in enabling significant developments in recent years. The community has benefited from the improved understanding provided by fundamental material R&D done on Nb. The LOI promotes building a strong collaborative research community that will provide immediate and long-term support to the SRF community and the development of the next generation of SRF cavities.

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