Snowmass 2021 Letter of Interest

Nb_3Sn Superconducting Radiofrequency Cavities

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Introduction

Superconducting radiofrequency (SRF) cavities are extremely efficient devices for generating large electromagnetic fields, which often makes them the technology of choice for transferring energy to beams in modern particle accelerators. Major high energy physics facilities that are based on SRF accelerators include LBNF/DUNE [1], LHC [2], HL-LHC [3], and EIC [x], as well as the proposed next generation Higgs factories ILC [4], FCC-ee [5], and CepC [6]. Normal conducting (NCRF) and SRF cavities can both reach accelerating gradients on the order of 10s of MV/m. The key advantage that superconducting cavities have is their high quality factor Q_0, which gives them orders of magnitude smaller heat dissipation, allowing them to operate with high duty factor at high fields (e.g. constantly running vs requiring short pulses) and to greatly reduce the amount of overhead from RF power supplies that would be dissipated in the cavity walls.

SRF cavities have been around for about 50 years [7], and all SRF accelerators in use today use niobium as the material in the RF surface. Niobium has been the material of choice because it has good superconducting properties (e.g. high critical temperature ~9.2 K), and, as an element, is easy to fabricate with good stoichiometric uniformity over a large ~1 m^2 surface. Over years of development, new cavity treatments have led to continued improvement in Nb cavity performance. For example, the maximum accelerating gradient of Nb cavities has reached as high as ~50 MV/m [8, 9], which is very close to the predicted ultimate limit set by the superheating field of the superconductor [10, 11, 12].

While research continues on improving niobium cavity performance, research effort is also being dedicated in parallel to next-generation SRF cavity materials which have the potential to significantly outperform Nb and thus replace Nb as the prime SRF material. The current most promising and most advanced next-generation material is Nb_3Sn [13]. We are therefore expressing here a strong recommendation for increasing support of Nb_3Sn SRF research and technology development.

Medium term motivation: High Q at high T

Nb_3Sn has a critical temperature of ~18 K, about twice that of niobium, allowing it to achieve a high $Q_0>10^{10}$ at ~2x higher operating temperatures than Nb. Changing the operating temperature from typical 2.0 K for Nb to 4.4 K for Nb_3Sn while maintaining intrinsic quality factors in the 10^{10} to 10^{11} range would slash energy consumption and thus cryogenic operating costs by as much as an order of magnitude, and would substantially decrease infrastructure costs for the cryogenic plant.

This would be a considerable advantage for high duty factor HEP accelerators, such as FCC-ee [5]. For a linear collider (ILC) Higgs Factory and Top Factory upgrade, high-Q, high-temperature Nb_3Sn could enable increasing the RF pulse length as well as the repetition rate of the pulses, thereby greatly increasing luminosity. For smaller applications, Nb_3Sn SRF also opens up the possibility for turn-key operation with cryocoolers instead of complex liquid helium cryogenic plants, which is already being explored for small scale and industrial accelerator applications [14, 15, 16].

Long term motivation: Potential for high gradient operation

Nb_3Sn also has a predicted superheating field that is twice as high as niobium [12], which could allow for a similar increase in the maximum accelerating field, up to 100 MV/m. This would be an enormous advantage for high energy linac applications such as an energy upgrade for the ILC to multi-TeV (see also separate LOI on ILC high-energy upgrade [17]).

Additional motivation: Dark sector searches

SRF cavities are also being explored not as a means of accelerating particles but as a means for detecting them in the next generation of dark sector searches [18, 19, 20]. Nb_3Sn could have a distinct advantage for these searches due to its ability to remain superconducting in large magnetic fields, which would be important for example for axion haloscopes.

Current landscape for Nb_3Sn R&D

In the U.S, the Department of Energy started funding Nb_3Sn R&D initially at Cornell University, followed by programs at Jefferson Lab and Fermilab [13]. Stimulated by the Nb_3Sn SRF progress at these laboratories with first proof-of-principle demonstrations of superior performance, worldwide interest in Nb_3Sn SRF has greatly increased recently, and new Nb_3Sn R&D efforts have started at labs and in industry, *e.g.* at CERN, IMP, ULVAC/KEK, NHMFL/Florida State University/University of Texas–Arlington, Peking University, STFC, ODU, and Ultramet [21-29].

Nb_3Sn cavity performance has not reached its ultimate performance potential discussed above yet, but it has been making substantial progress over the past years. Using as a metric the maximum accelerating gradient with $Q_0>10^{10}$ at 4.4 K, cavities have increased from ~5 MV/m in the 1990s [29] to ~13 MV/m in 2014 [30], to ~18 MV/m in 2015 [31], to ~24 MV/m in 2020 [32]. This has come with corresponding improvements in understanding of the materials science and fabrication methods for the Nb_3Sn coatings [33-40].

Recommendation for continued investment in Nb_3Sn

Superconducting RF is a key technology for future HEP accelerators. With continued investment into Nb_3Sn SRF cavity R&D, next-generation cavities based on Nb_3Sn will become a reality with performance specifications highly beneficial for HEP applications, enabling higher luminosity, higher energy, and facilitating energy sustainable science.

Conclusions

The unique advantages of Nb_3Sn cavities make them an exciting prospect for future HEP experiments. They already achieve high Q_0 at 4.4 K at accelerating gradients that are useful for high duty factor applications, including first demonstrations in large, accelerator-scale structures [32, 35]. With continued progress, they have the potential to further reduce cryogenic losses and also to eventually outperform current state-of-the-art niobium in energy gain by a significant margin for high energy linear accelerator applications. Investigations that are already underway will reveal how useful they could be in dark sector searches requiring a high magnetic field. In a future Snowmass 2021 contributed paper, we will expand on the state-of-the-art for Nb_3Sn SRF cavities, and ask the Snowmass community to strongly endorse continued investment into Nb_3Sn SRF cavity R&D.

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