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NEXT-GENERATION Nb_3Sn SUPERCONDUCTING RF CAVITIES*

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Abstract

Nb_3Sn currently is the most promising alternative material for next-generation, higher-performance SRF cavities. Significant recent progress has been made in further increasing efficiency, maximum field, and demonstrating readiness for first applications in actual accelerators. This paper will present an overview of worldwide recent progress in making this material a viable option for future accelerators.

INTRODUCTION

The use of superconducting RF (SRF) cavities was once considered outlandish. Today, modern facilities use niobium (Nb) SRF cavities, however the future of both scientific research and industrial accelerators would greatly benefit or would be possible only if a superconducting material that supports higher performance exceeding the material limitations of Nb for use in SRF cavities can be found.

Why Nb_3Sn?

Niobium has served us well for years, so why is Nb_3Sn a better choice? First we must understand several figures of merit by which we judge an SRF cavity.

First and foremost is the accelerating gradient, E_{acc}. This determines the amount of energy that a cavity can deliver to a beam per length, typically reported in MV/m. The ultimate limit on the accelerating gradient is directly proportional to the superheating field, H_{SH}, of the superconducting material used.

The BCS surface resistance is another important factor in cavity performance defined by

$$R_{bcs} = f^2 e^{-const*T_c/T} .$$

The total surface resistance that determines the cavity's quality factor, Q_0, is made up of the BCS resistance and the residual resistance. By increasing the critical temperature, the BCS resistance decreases allowing us to achieve a higher Q_0.

The quality factor, $Q_0 = \frac{G}{R}$, is a figure which describes the cavity's efficiency, where G is the cavity's geometry factor. The quality factor plays a roll in determining the cooling power needed, and is also related to the cavity's resonant frequency. The dissipated power, P_{diss}, depends on Q_0 and is defined by

$$P_{diss} = \frac{V^2}{\frac{R}{Q} Q_0} ,$$

where V is the accelerating voltage and $\frac{R}{Q}$ is the is a factor describing how effectively power can be delivered to a beam.

Finally, the cooling power, $P_{AC,Cooling}$, depends on the AC wall power needed to do one watt's worth of cooling in your system and Q_0. The cooling power is defined by

$$P_{AC,Cooling} = COP^{-1} \cdot P_{diss} ,$$

where P_{diss} is as defined above and COP is the coefficient of performance for the system in W/W, as seen in Fig. 1.

Nb_3Sn is predicted to outperform Nb in a number of significant ways. First, the quality factors at 4.2 K of Nb_3Sn are predicted to be even higher that of pure Nb at 2 K as seen in Fig. 2 where the Q_0 is visibly much higher for Nb_3Sn than for Nb at SRF operating temperatures [1]. This means that we could, in principle, operate Nb_3Sn cavities at 4 K

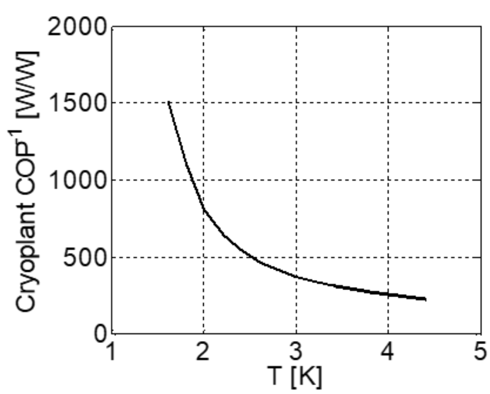

Figure 1: The cooling power, which is in watts of AC wall power needed to remove one watt of power from the cryogenic system, is much higher for low temperatures [2, 3].

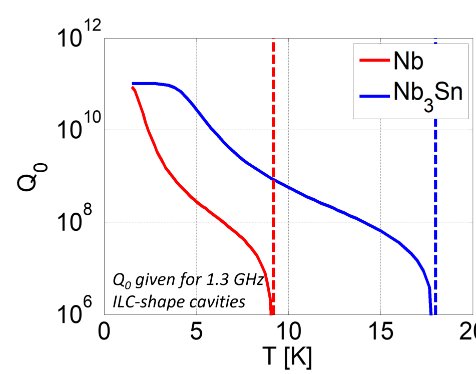

Figure 2: Q_0 versus temperature. At 4.2 K, Nb_3Sn significantly outperforms pure Nb. This figure shows that a 1.3 GHz Nb_3Sn cavity could efficiently operate at 4.2 K rather than 2 K, which is the typical operation temperature for Nb cavities

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efficiently. Operating at a higher temperature, in turn, reduces $P_{AC,Cooling}$. A higher operating temperature would also allow for a higher operating frequency according to [1] given that

$$R_{BCS} \propto f^2 e^{-const*T_c/T} \quad .$$

A higher operating RF frequency would allow for compact Nb_3Sn SRF cavity applications.

Additionally, the superheating field of Nb_3Sn is predicted to be nearly double that of pure Nb [4]. This allows for a higher accelerating gradient, predicted to go as high as ~100 MV/m.

Nb_3Sn Cavity Fabrication

Armed with an understanding of Nb_3Sn's material properties, we must now consider the all important question of how to actually *use* it. Nb_3Sn is quite brittle and cannot be machined into a cavity shape. Currently, the preferred method of Nb_3Sn cavity fabrication is thermal vapor diffusion [5].

The Nb cavity base is placed in a furnace with a tin source, which is then pumped down to vacuum and heated. This causes the tin to sublimate, creating an "atmosphere" of tin. The tin in this "atmosphere" is then able to nucleate onto the surface of the Nb cavity and diffuse into it, creating a Nb_3Sn film. The thickness of this film can be controlled with reasonable precision by adjusting the amount of time spent in the furnace.

Back in the early 2010s, Cornell was the first to show this high quality of Nb_3Sn cavity performance [6], as seen in Fig. 3. This breakthrough resurrected the SRF community's interest in Nb_3Sn, leading to an international research effort.

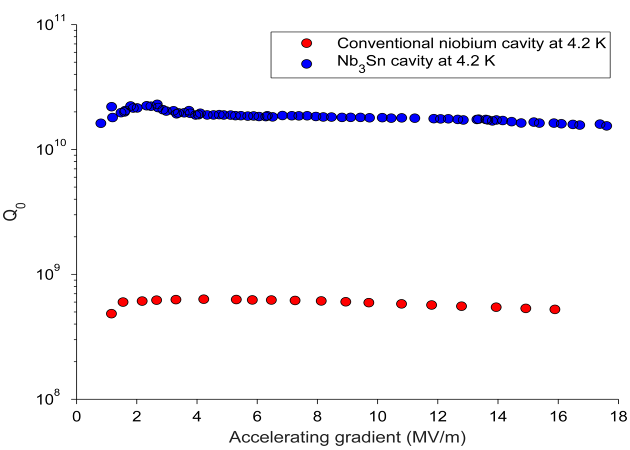

Figure 3: RF data comparing the early Nb_3Sn work done at Cornell to Nb cavity RF data.

UPCOMING FACILITIES

As Nb_3Sn grows as a field, more and more facilities from around the world join the Nb_3Sn family's research effort including Cornell, Fermilab [7], and Jefferson Lab [8, 9].

KEK has recently joined the growing list of Nb_3Sn research facilities. The recent highlights of the upgrades made to the KEK facility include upgrades to their cleanroom facilities. These infrastructure upgrades will allow them to improve their cavity performance by ensuring a cleaner RF surface during assembly [10].

RESEARCH AND DEVELOPMENT

Nb_3Sn as a material has not yet reached it's theoretical potential in most areas. It has a theoretical maximum accelerating field of ~100 MV/m and a theoretical Q_0 of ~6×10^{10} at 4.2 K. There is a significant worldwide effort to understand what is currently limiting the performance of Nb_3Sn from a number of different angles.

Better Films for Increased E_{acc} and Q_0

Improving the quality of the Nb_3Sn films that we grow is a focus of the SRF community. Adjusting various aspects of the surface preparation and growth process has allowed the us to continuously improve the performance of Nb_3Sn.

Surface roughness is believed to be one of the limiting factors on Nb_3Sn performance, and as such, there is a significant effort across institutions to improve this factor. Using thinner films is one way to reduce the surface roughness, which by extension reduces sources of early quenching. Fermilab has produced a cavity with a smoother and thinner film and the RF results showed that it is capable of exceeding 20 MV/m at 4.4 K [7] as seen in Fig. 4. Jefferson Lab is also working on a thinner film cavity, with a film thickness of 1 µm and a finer Nb_3Sn grain size [8, 9]. This cavity has been producing promising results and we are looking forward to the future of this work.

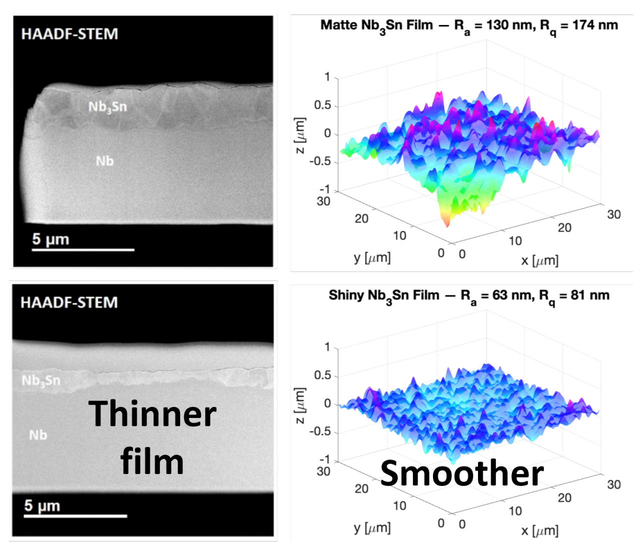

Figure 4: STEM images and 3D surface maps for the Fermilab thin and smooth coating [7].

Cornell University also has a thin film cavity which had two significant changes made to the standard coating recipe. First, the coating was shortened to produce a thinner film. The typical film thickness for a Nb_3Sn cavity from Cornell is around 3 µm, however this thinner film is half that at 1.5 µm.

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Second, the availability of Sn during the initial phase of the coating process was increased.

A second reason to pursue thinner films is that the Nb substrate onto which the film is grown is able to thermally stabilize the Nb_3Sn layer. This was shown in calculations done by our lab [1] and can be seen in Fig. 5. Simulations with different Nb_3Sn layer thicknesses showed that the thinner the layer, the more efficiently the Nb substrate could thermally stabilize itin the presence of small normal-conducting surface defects. As can be seen in Fig. 6, halving the thickness nearly doubles the quench field. This would in principle allow for the cavity to reach higher accelerating gradients.

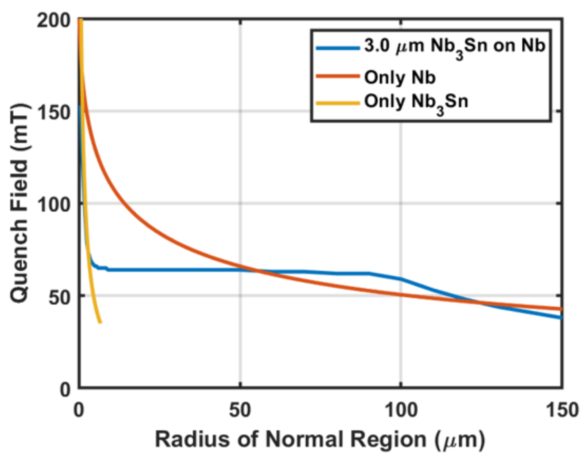

Figure 5: Thermal simulations showing how the Nb substrate is able to stabilize the Nb_3Sn film allowing it to survive to higher fields before reaching cavity quench [1].

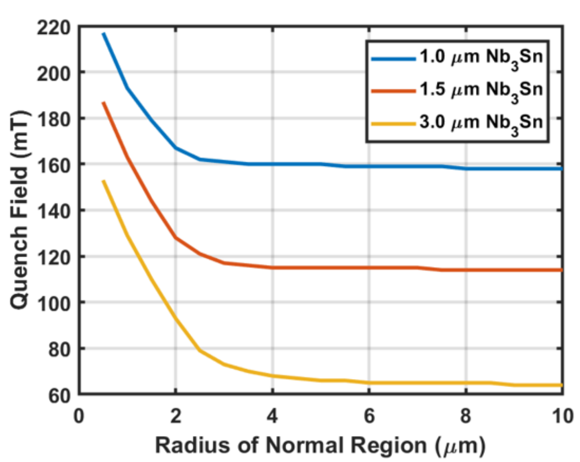

Figure 6: Simulation showing the maximum quench fields that can be supported at different thicknesses of Nb_3Sn as a function of normal conducting region radius [1].

Increasing the Sn supply during the film growth process allowed us to address a problem we had been seeing with the BCS resistance data. A typical BCS resistance for a Cornell Nb_3Sn 1.3 GHz ILC cavity versus inverse temperature data set is shown in Fig. 7. One would expect the data to be linear for a pure material [1], however this one appears to be two linear functions summed together. We predicted that this was due to tin depletion. Tin depleted Nb-Sn species typically have far worse RF performance than pure Nb_3Sn due to their very low critical temperatures, and so their impact on the cavity's properties could be significant and detrimental [1].

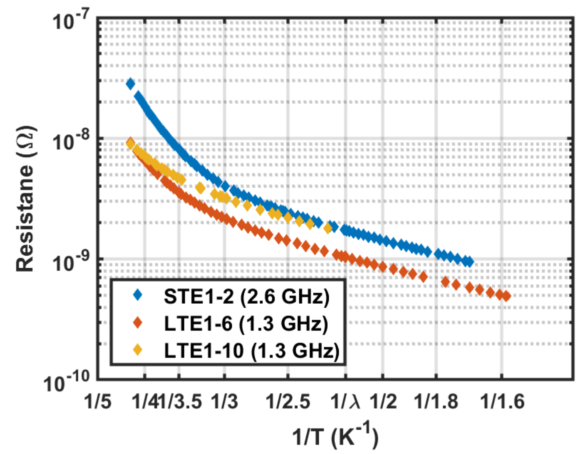

Figure 7: BCS resistance versus inverse temperature data for several typical Cornell ILC shaped Nb_3Sn cavities of various frequencies [1].

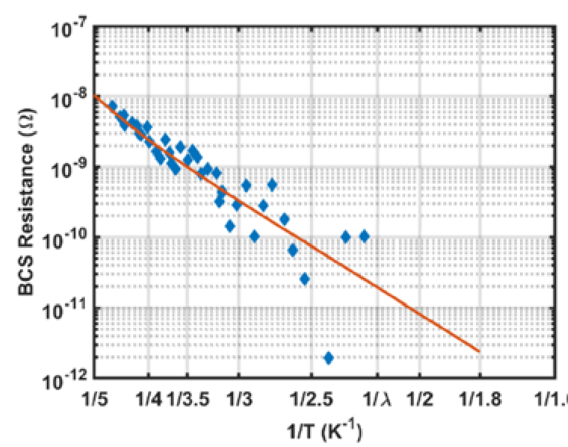

Figure 8: BCS resistance versus inverse temperature data for the Cornell thin film cavity which is a 1.3 GHz ILC shaped Nb_3Sn cavity baked with higher Sn availability and a 1.5 µm thick film [1].

As one can see in Fig. 8, the BCS resistance versus inverse temperature data for the cavity with the high Sn availability is quite linear, indicating a purer material. In addition to this, the BCS resistance on the new cavity was also significantly lower coming in at 3.35 nΩ compared to a typical cavity from Cornell which has a BCS resistance of ~8 nΩ [1].

RF data for this cavity is shown in Fig. 9. Unfortunately, a quench due to field emission occurred at 17 MV/m. We do not believe that this is the ultimate limit of the cavity and hope to push the accelerating gradient further in upcoming

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tests. Those with a discerning eye may have noticed that the quality factor is not very good for this test. While the BCS resistance was lowered, the total surface resistance for this cavity was higher. This could have been due to a poor thermal gradient while cooling down causing trapped flux, or other surface defect issues.

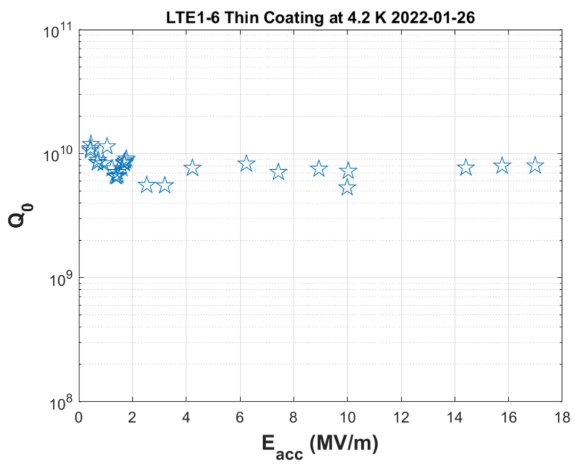

Figure 9: Q_0 versus E_{acc} for the Cornell thin film cavity. Quench occured at approximately 17 MV/m.

Nucleation Study

Another angle from which Cornell is approaching improving Nb_3Sn films is by investigating the affect that various chemical rinses have on Sn nucleation. The study began by rinsing Nb samples of approximately 1 cm^2 in chemicals of varying pH. The samples are then baked in the furnace up to the nucleation phase at which point they are removed and examined using a scanning electron microscope (SEM). The SEM images are analyzed with considerations for the average nearest neighbor distance and the density of Sn nucleation sites. Early results are showing a difference between low and high pH samples. The low pH samples have a more uniform distribution of nucleation sites. More detailed information is available in [11].

Alternative Growth Methods

While thermal vapor diffusion has thus far been the most successful method of growing Nb_3Sn films, there are other ways to create a Nb_3Sn cavity. Cornell is currently exploring two alternative methods – electroplating and chemical vapor deposition. More information about Cornell's electroplating effort is available in [12–14].

The chemical vapor deposition (CVD) furnace at Cornell is nearing the end of the commissioning phase, and early results are expected this coming Fall. The CVD furnace works by using a carrier gas, Ar, to carry the precursors, $NbCl_5$ and $SnCl_2$, through a plasma RF generator that breaks the molecules up into their components before they get to the coating chamber. There, the Nb and Sn combine to form the Nb_3Sn film and the excess Cl combines with H_2 to be removed as a waste product [15].

APPLICATIONS

In order for Nb_3Sn to be used practically in an accelerator, the coating process needs to be scaled up from a single cell test cavity to a multicell cavity. Efforts on this are underway at both Fermilab and Jefferson lab. At Jefferson lab, they are working on a Nb_3Sn 5-cell which they hope to beam test in their UTIF this coming year, and has shown good performance in vertical tests [16]. Fermilab's 9-cell Nb_3Sn coated cavity has been able to produce gradients of ~15 MV/m and a Q_0 of 9×10^9 [7] as seen in Fig. 10. These values are approaching those of a single cell Nb_3Sn cavity and are practical for use in a first application outside of research and development.

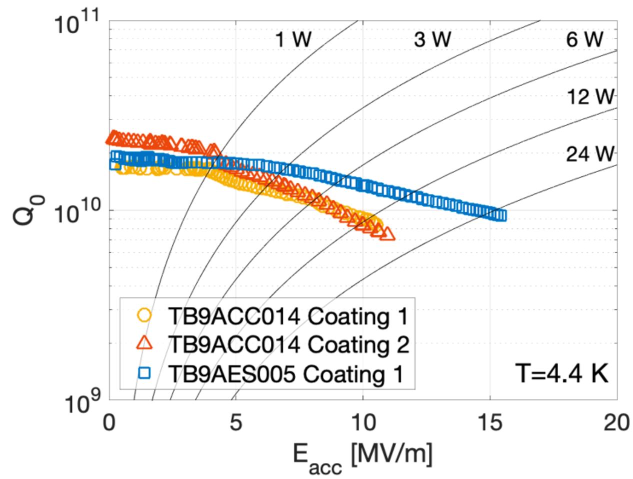

Figure 10: The Fermilab Nb_3Sn 9-cell cavity RF data [7].

In addition to multicell cavities, there are many efforts across institutions from around the world toward practical compact turn-key cryomodules based on Nb_3Sn cavities, which are further discussed in [17]. An example of Cornell's compact cryomodule is show in Fig. 11.

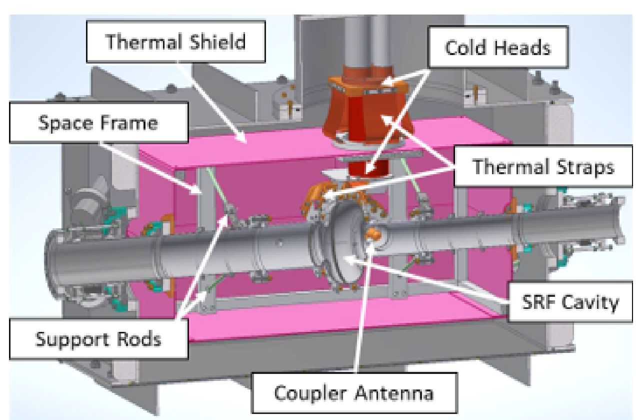

Figure 11: Schematic of the Cornell Compact Turn-Key Cryostat [17].

Outside of direct accelerator applications, Fermilab is working on Nb_3Sn cavities for the axion dark matter search.

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These will be used in the scanning device that searches the skies for dark matter [18].

CONCLUSION

Progress on Nb_3Sn research continues to march forward. As more and more coating facilities join the Nb_3Sn family, more and more advancements are made in fundamental Nb_3Sn research. The results of this research and development effort are newly emerging applications, including promising early results for multicell coating techniques and compact turn-key cryostat systems that require less power and fewer experts to operate [17]. Right now is a very exciting time for Nb_3Sn research as we see the results of our effort start to go out into the world.

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