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NEXT GENERATION SRF CAVITIES AT CORNELL UNIVERSITY*

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Abstract

Our goal is to develop new materials and protocols for the growth and preparation of thin-film and layered superconductors for next generation SRF cavities with higher performance for future accelerators. We are working primarily with Nb_3Sn to achieve this goal, as well as other materials which aim to optimize the RF field penetration layer of the cavity. This contribution gives an update on our most recent Nb_3Sn simulations and cavity test results. A deeper insight into RF loss distribution and dynamics during cavity testing is gained using a new global high-speed temperature mapping system (T-Map).

INTRODUCTION

Nb_3Sn is well acknowledged as a promising material for the improvement of superconducting radio-frequency (SRF) cavity performance [1]. Its critical temperature of 18 K is nearly double that of Nb's, which is only 9.2 K, making for lower losses during operation. Additionally, the superheating field of Nb_3Sn is ~425 mT compared to ~220 mT for pure Nb [2], meaning that much higher accelerating gradients are achievable with the theoretical potential to reach 90 MV/m [3, 4]. Improvements to the SRF community's understanding of Nb_3Sn and how to optimize it's usage continues to be a priority for the SRF community. Many labs, including Cornell, Fermi Lab, Jefferson Lab, and KEK have continuing research and development projects focusing on Nb_3Sn [5–7].

Our goal is to develop new protocols for the growth and preparation of thin-film and layered superconductors for next generation SRF cavities with higher performance for future accelerators. We present here our latest work on Nb_3Sn cavities produced using a vapor diffusion based coating process. Achieving higher accelerating gradients and/or a lower RF dissipation would have a ripple effect of advancements in other fields from fundamental particle physics to medical accelerators to food sterilization.

THE CORNELL HIGH SPEED GLOBAL TEMPERATURE MAPPING SYSTEM

Cornell uses the a high-speed global temperature mapping system (T-Map) to see in real time what temperature fluctuations are occurring on the surface of a cavity during RF testing. This system uses over 600 Allen-Bradley carbon resistors to monitor local temperatures at a resolution on the order of 100 μK at helium bath temperatures of 2 K. The high-speed DAQ electronics developed for this system are able to read all of the sensors simultaneously at a maximum sample rate of 50k samples/s [8, 9].

The T-Map is used to take short exposure snapshots and dynamic long exposures of heating events that the cavity experiences during RF testing. These can capture when a cavity ceases superconductivity (quenches), giving us insight into where and why the cavity is heating up. We are interested in better understanding quench mechanisms so that they can be resolved and higher fields achieved. Nb_3Sn cavity performance is still well below the theoretical limit. An example of such a quench is shown in Fig. 1, where the initial limiting mechanism is multipacting.

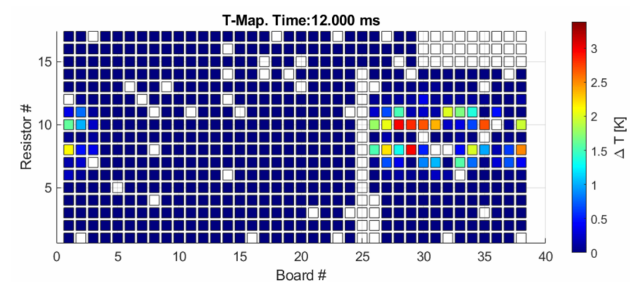

Figure 1: Example of a suspected multipactor quench captured on the T-Map.

Later in the same test, the same cavity that produced the multipacting in Fig. 1 changed to a quench caused by a defect on the RF surface of the cavity as seen in Fig. 2 caused by a defect on the RF surface of the cavity. We were interested in better understanding what the T-Map was seeing, so we turned to simulations to see if we could create a reliable model.

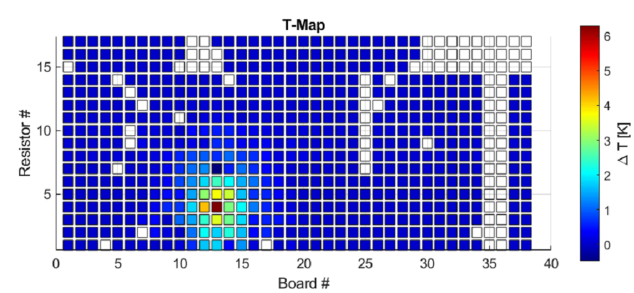

Figure 2: Example of a quench due to a surface defect captured on the T-Map.

THERMAL SIMULATIONS

In order to better understand the quench mechanisms shown by T-Map studies, thermal models of the Nb_3Sn film and Nb substrate were done using a simulation of a Nb_3Sn–Nb substrate – Nb_3Sn layered surface, as shown in

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Fig. 3. The simulation uses an over-relaxation method to solve for thermal equilibrium [2].

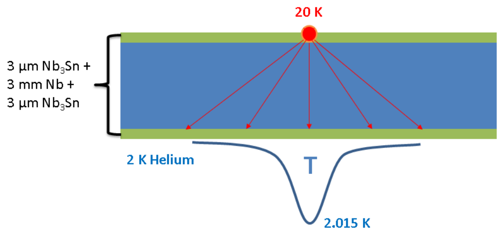

Figure 3: Diagram of a simulated point heat-source. The material has three layers – Nb_3Sn on the vacuum surface, Nb substrate, and then Nb_3Sn on the outside of the cavity.

Nb_3Sn is known to be more thermally unstable than pure Nb [2], so it is more susceptible to premature quench due to heating from small defects (Fig. 4). Fortunately, these simulations also revealed that a Nb substrate can stabilize a Nb_3Sn film, preventing a normal conducting region in the film from growing to the critical size to cause a quench by conducting heat away more quickly. The flat region below 100 μm agrees with experimental data, putting the quench field of a typical 1.3 GHz Nb_3Sn cavity at approximately 60 – 70 mT, which has a film thickness of ~3 μm [2].

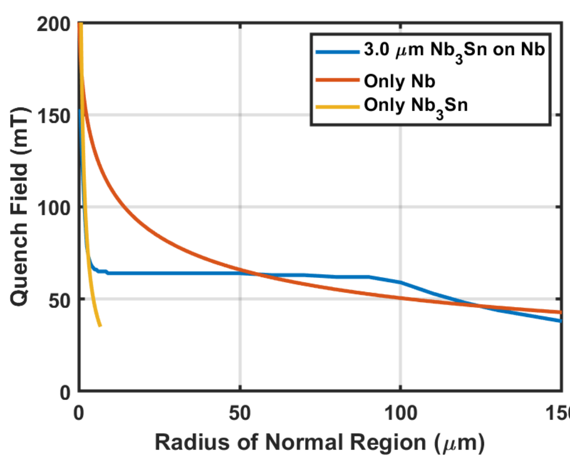

Figure 4: Quench fields of various materials as a function of the radius of the normal conducting region from thermal modelling.

The next question to consider was how to use this result to improve cavity performance. The conclusion we came to was that a thinner film would be more stable as confirmed by simulations summarized in Fig. 5. As previously mentioned, Nb_3Sn cavities produced at Cornell have a film thickness of ~3 μm. If a cavity with a film thickness of ~1 μm were produced, it would have the potential to more than double the quench field.

To produce such a thin film while retaining uniform thickness would be challenging. Patchy thin regions would cause issues where the RF field would penetrate through the Nb_3Sn layer and see the Nb-Nb_3Sn interface, which is typically tin-depleted. Tin-depletion causes strong RF dissipation, which is less than ideal. Creating a thinner Nb_3Sn film must be balanced with its need for uniform thickness.

Motivated by these results, the next step was to create a cavity with a thinner Nb_3Sn layer. A coating profile that produced a Nb_3Sn film of ~1.5 μm was tested on a Nb 1.3 GHz ILC-shape single-cell cavity. The cavity was subsequently tested several times, however both the first and second tests were limited to 14 MV/m and 17 MV/m respectively by field emission. This is not believed to be the ultimate limit of the cavity, as these quenches appeared to be due to contamination and not material qualities.

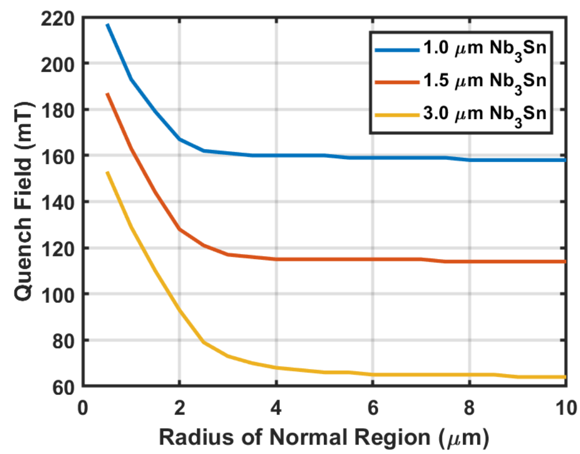

Figure 5: Quench field of various thicknesses of Nb_3Sn films on a Nb substrate vs. the radius of the normal conducting region from thermal modelling.

ELIMINATION OF THE SECOND BCS RESISTANCE GAP

Another area of interest for Nb_3Sn cavity performance came from observing the behavior of the BCS resistance, which is the temperature dependent part of the surface resistance. We would expect that the relationship between the BCS resistance and the inverse temperature to be linearly related in a data set like the one shown in Fig. 6. The data from a standard coating Nb_3Sn cavity instead shows a curved shape with higher than ideal resistances, especially below ~4.5 K where the operating range for the cavity is.

The predicted cause is that the coating contained a mixture of Nb_3Sn and forms of tin-depleted $Nb-Sn$, where the ratio of tin to niobium is not exactly 3 to 1. Tin-depleted $Nb-Sn$ species have worse superconducting properties than stoichiometric Nb_3Sn, exhibiting both higher BCS resistances and lower critical temperatures [2]. The presence of these tin-depleted $Nb-Sn$ species would negatively affect cavity performance.

In an attempt to mitigate these effects, tin availability was increased earlier in the coating process. This was done as part of the same cavity coating process as the thin film

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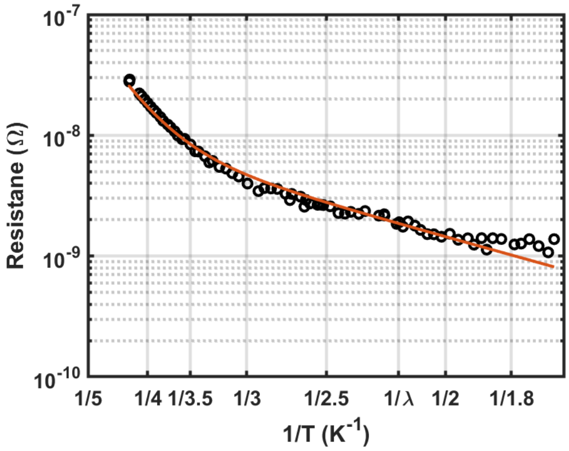

Figure 6: Measured BCS resistance vs. inverse temperature for a 1.3 GHz cavity with a typical Nb_3Sn coating scheme with a best fit line.

cavity discussed above. The resulting coating exhibited a far more linear fit in the logarithmic BCS resistance vs. inverse temperature data as shown in Fig. 7. Up to the noise level of $10^{-9}\,\Omega$, the data has a linear behavior, implying that the increased tin availability during the coating process dramatically reduced the presence of tin-depleted regions. Additionally, the values of the BCS resistance were much lower, implying a potential for higher performance. This reduction in BCS resistance is a direct result of decreasing tin-depleted $Nb-Sn$ species present, which have far poorer superconducting properties as discussed above. A standard Nb_3Sn cavity produced by Cornell has a BCS surface resistance of ~8 nΩ at 4.2 K, however this new coating has a surface resistance of ~3.5 nΩ at 4.2 K.

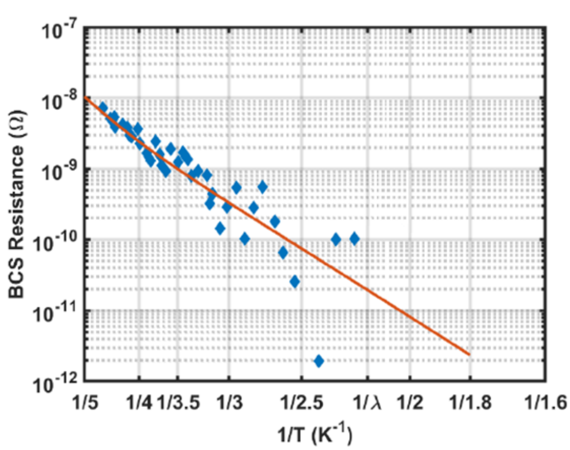

Figure 7: Measured BCS resistance vs. inverse temperature of a high tin-availability Nb_3Sn 1.3 GHz cavity with a best fit line.

FUTURE WORK

As previously mentioned, the thin-film cavity that utilized the new coating process discussed above quenched early due to contamination on previous tests. The intention is to re-test it this summer. Our lab also continues to work on improving Nb_3Sn growth in other ways [10]. We are also exploring new geometries, like the reentrant cavity, whose Nb_3Sn coating is shown in Fig. 8.

Additional work being done by Cornell's SRF group in the near future includes the use of other novel materials for SRF cavities.

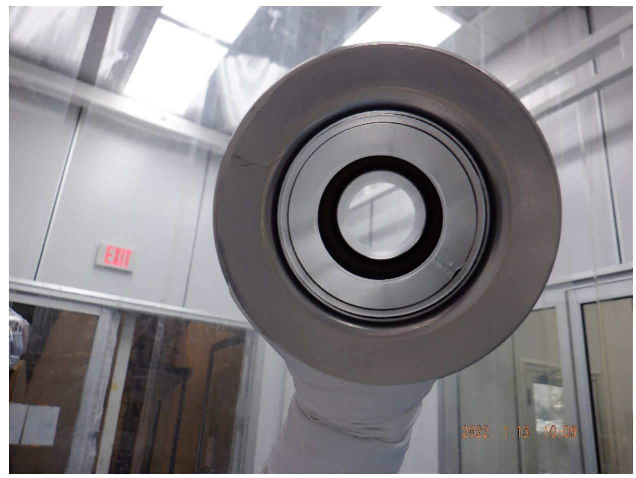

Figure 8: Nb_3Sn coating on the LR1-3 reentrant cavity.

CONCLUSION

The preliminary results of working with improved vapor deposition based Nb_3Sn coatings are very promising. The increase in tin availability during the coating process has reduced the BCS surface resistance via decreasing the other $Nb-Sn$ species typically present. This, combined with a thinner coating, is predicted to increase the quality factor and accelerating gradient, and a proof of principle cavity awaits retesting.

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