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Nb_3Sn AT FERMILAB: EXPLORING PERFORMANCE*

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Abstract

Fermilab's Nb3Sn coating program produced its first 1.3 GHz single cell cavities in early 2017 and since then has explored the performance of Nb_3Sn on a wide variety of cavity substrates and performed microscopic studies down to atomic resolution. We show that the latest films produced at Fermilab have extremely small surface roughness and unusually small thickness and grain size. We briefly discuss studies of defects to avoid in Nb_3Sn films. We show results from studies of a number of practical considerations for Nb_3Sn cavities, including frequencies <1 GHz, processing multipacting, and using a cold tuner on a cavity. Finally, we present results of the first 1.3 GHz 9-cell cavity coated with Nb_3Sn.

PROGRESS IN Nb_3Sn FILM QUALITY

Nb_3Sn is a very promising material for SRF applications, and there has been significant development in the material over the last decade [1]. However, accelerator cavities have been consistently found to be limited to gradients of at most 17-18 MV/m in CW operation [1]. At TTC 2019 in Vancouver, the Nb_3Sn team at Fermilab showed that we had made a Nb_3Sn cavity that reached 22.5 MV/m, a new record CW accelerating gradient for Nb_3Sn (25% increase) [2] (shown in Fig. 1). Since TTC, we have repeated the coating as closely as we could and found there are some major differences in appearance, surface roughness, grain size, and thickness compared to typical Nb_3Sn films.

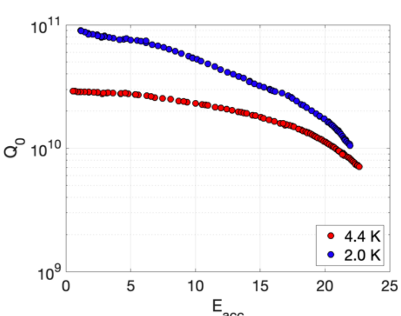

Figure 1: Q vs E curves at 4.4 K and 2.0 K for Fermilab Nb_3Sn-coated cavity CBMM-D, showing a record CW accelerating gradient for Nb_3Sn.

Appearance

Nb_3Sn films are typically matte in appearance, but the recent Fermilab films are shiny/lustrous, as shown in Fig. 2.

Figure 2: Typical Nb_3Sn coating (left) and new Fermilab coating on CBMM-D (right), which reached 22.5 MV/m.

Surface Roughness

Surface roughness was measured using a Keyence laser confocal microscope. Figure 3 shows example profiles from an electropolished niobium sample before coating, a coating typical of previous Fermilab Nb_3Sn, and a new shiny Fermilab Nb_3Sn-coated sample. Table 1 compares roughness measurements over the 30x30 micron areas of the profiles in Fig. 3. Figure 4 compares several line profiles measured in each of the samples. The surface roughness of the shiny films is found to be much smaller than that of the previous typical films, much closer to that of the niobium EP sample.

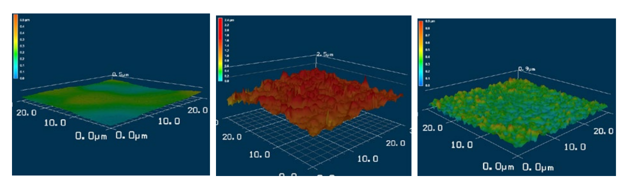

Figure 3: comparison of surface roughness of 3 samples: EP'd niobium sample before coating (left), a coating typical of previous matte Nb_3Sn (middle), and a new shiny Fermilab Nb_3Sn-coated sample (right).

Table 1: Roughness Measurements

	R_a [nm]	R_q [nm]
Nb EP	40	48
Typical Nb_3Sn	130	174
Shiny Nb_3Sn with new FNAL coating parameters	63	81

Grain Size

The grain size of the newer films was found to be significantly smaller than that of previous films. One of the shiny coatings was measured to have grain size 0.7±0.2 μm. A sample with coating typical of the previous typical matte Nb_3Sn was found to have grain size 1.2±0.5 μm. The previous coatings also were found to have a much wider spread of grain sizes.

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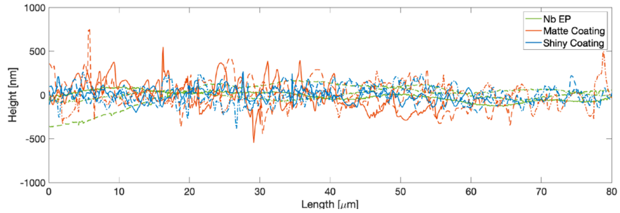

Figure 4: Line profiles of the 3 samples showing many more sharp peaks for the matte coating.

Film Thickness

The thickness of the films was measured via cross sections extracted in a focused ion beam tool at Northwestern University. The shiny films were found to have substantially smaller thickness compared to the new matte films, approximately 1 μm (see Fig. 5), compared to 2-3 μm for typical matte films [1].

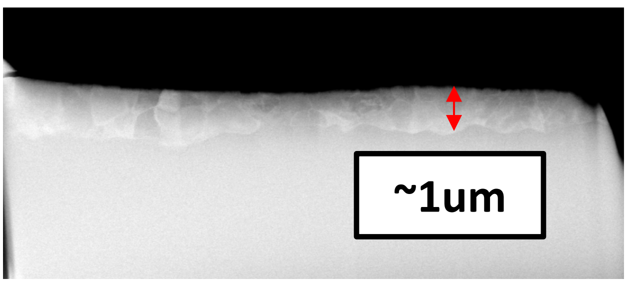

Figure 5: Measuring thickness of Nb_3Sn films via a cross section extracted using a focused ion beam tool at Northwestern University.

Possible Effect on Quench

The smaller film thickness may help to improve maximum field for thermal reasons. Nb_3Sn has poor thermal conductivity, and the thinner films may help to reduce overheating.

The smaller surface roughness may help to improve the maximum field for magnetic reasons. Smoother films have less field enhancement.

Some previous observations suggest that quenching in Fermilab Nb3Sn films is magnetic rather than thermal. An example is shown in Fig. 6, in which a Nb_3Sn film traps a large amount of field in the quench spot leading to significantly increased dissipation (ΔT>1 K measured on T-map), and yet the quench field remains the same after quench. If overheating were the cause of quench in this case, one would expect a lower quench field. As a result, the more likely canidate for improved quench field seems to be the improved surface roughness rather than the smaller thickness.

We include another quick note about quench. The cavity from TTC that reached 22.5 MV/m was retested with T-map. This cavity had an unusual heating pattern after quench. Nb_3Sn cavities tend to trap flux in the quench region, presumably due to thermocurrents. Figure 7 shows the unusual T-map pattern after quench, compared to the T-map before quench. There is a band of heating all around the equator. The explanation is currently unknown, though it is interesting that the location corresponds to where multipacting is expected to occur in the 1.3 GHz cell. Additional testing including attempts to process possible multipacting are planned in the future.

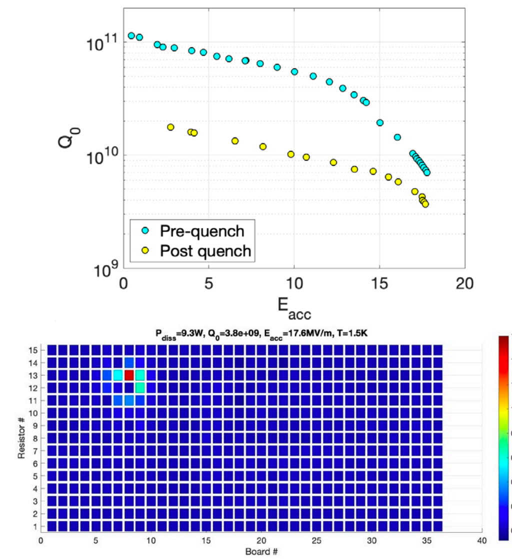

Figure 6: Q vs E curve for a Nb3Sn cavity at Fermilab before and after the first quench (top) and T-map after quench (bottom). The similar quench field after the first quench (which results in >1 K heating at the quench spot) suggests that the quench is not thermal.

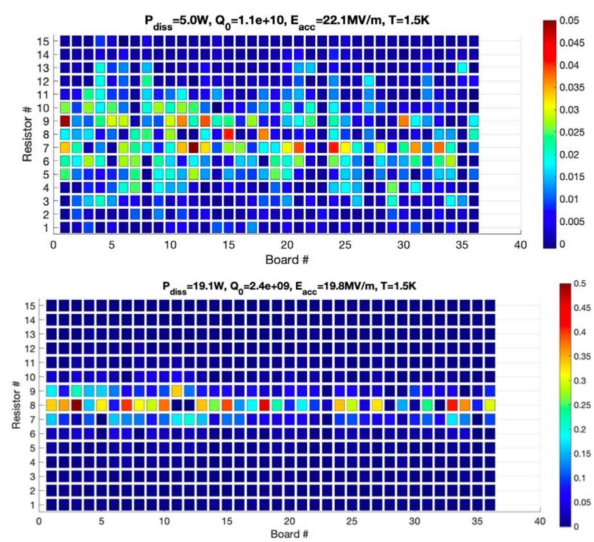

Figure 7: T-maps of CBMM-D before (top) and after (bottom) quench. Note the difference in color scale.

DEFECTS TO AVOID IN Nb_3Sn COATINGS

As part of the development of Nb_3Sn at Fermilab, several defects have been studied. These defects are not observed in most coatings. However, there are several cases in which they were observed and correlated with poor performance in cavities.

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The first is thin regions. In a collaboration between Fermilab and Cornell the first 1.3 GHz Nb_3Sn cavity coated at Cornell was re-tested with T-map and then coupons were cut from its surface. This cavity had strong Q-slope degradation. In this study it was found in the low Q regions of the cavity spots that had very thin coatings, on the scale of just about one penetration depth. For more details, see [3]. A collaborative study between Northwestern and Fermilab took these studies further, exploring the influence of relative grain orientation between the film and the substrate in these regions [4]. Recent studies at Fermilab with a 9-cell sample host showed a strong correlation with tin flux. In these studies, it was observed that thin regions tend to form when tin flux is low [5].

The second type of defects studied is tin segregation at grain boundaries. Witness samples coated with cavities with Q-slope analyzed by TEM and APT show segregation of tin in grain boundaries in regions with size ~ξ [6,7].

Both these types of defects appear to be avoidable, as neither are observed in samples from cavities with strong performance.

PROGRESS IN DEMONSTRATING PRACTICALITY OF Nb_3Sn CAVITIES

As researchers begin to seriously consider Nb_3Sn SRF cavities for accelerator applications, there arise practical considerations that must be better understood. Recently, we evaluated some of these important concerns in a series of experiments that go beyond standard vertical test of single cell 1.3 GHz cavities.

Can We Successfully Coat at Frequencies <1 GHz?

At TTC 2019, we showed results of our first coating of a 650 MHz single cell cavity [2]. This frequency of cavity is under evaluation as part of the Fermilab compact Nb_3Sn SRF accelerator program [8]. At TTC 2019, the results were a very good start, but recent results significantly improved. The same cavity had its coating removed, and then it was recoated but with very similar parameters as to the coating of CBMM-D from Fig. 1, resulting in a similar shiny film, as shown in Fig. 8. The results of the new coating are compared to the previous coating in Fig. 9.

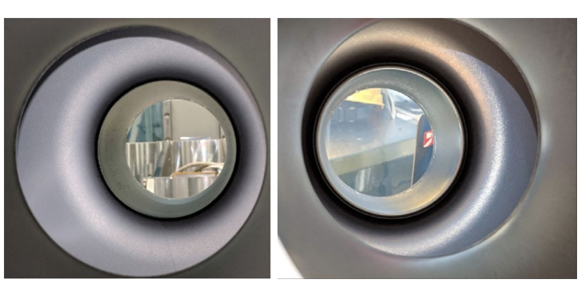

Figure 8: Pictures of the Nb3Sn coatings of the 650 MHz cavity B9AS-AES-002 from the first coating (left) with matte appearance and the second coating (right) with shiny appearance.

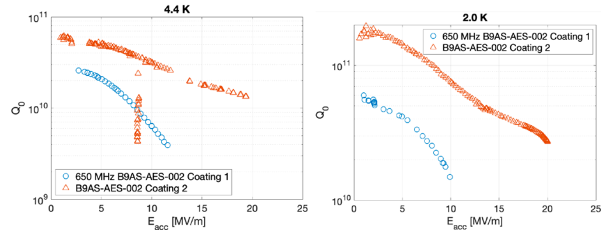

Figure 9: Q vs E curves at 4.4 K and 2.0 K for the 650 MHz cavity B9AS-AES-002 from the first coating and improved performance from the second coating. In the first coating, the gradient was power limited. In the second coating, the cavity quenched at both temperatures.

The results show that it is very possible to achieve strong performance with Nb_3Sn at 650 MHz. The dissipated power at 10 MV/m is just 1.1 watts, showing strong potential for cryocooler-based accelerator applications. It also gives a second case of a maximum gradient exceeding the 17-18 MV/m limit observed previously.

Can We Process Multipacting on Nb_3Sn Surfaces?

To the authors' knowledge, there is no known case of processing multipacting in a Nb3Sn cavity in CW mode. Only sample studies have been performed, which suggest that the SEY of Nb_3Sn is only slightly higher than that of Nb [9]. The 650 MHz cavity results confirm that, similar to niobium, multipacting can be processed in Nb_3Sn. In the second coating, the cavity reached a multipacting barrier at ~10 MV/m. As shown in Fig. 9, at 4.4 K, minimal effort was spent processing multipacting, and instead the RF power was raised quickly to "jump" over the multipacting, reaching 15 MV/m and then slowly recording data higher than that. Before recording data at 2.0 K, more time was spent processing multipacting, and the cavity easily spent time in the multipacting band without multipacting occurring, as shown in Fig. 9.

Can We Tune a Cold Nb_3Sn Cavity?

To operate an accelerator with multiple cavities, it is important to be able to tune them to match their frequencies. However, Nb_3Sn is a strain sensitive superconductor. For example, its critical current may be degraded on the order of tens of percent by strain on the order of several tenths of a percent [10]. As a result, Nb_3Sn wires in magnets must be pre-stressed so that they are closer to neutral loading under operating conditions. Similarly, one may be concerned about degraded superconducting properties when straining a cold cavity to tune its frequency. Might this increase BCS or residual resistance for example?

To evaluate this, we placed a tuner on a 1.3 GHz cavity under vertical test, as shown in Fig. 10. The tuner was only engaged to the cavity once it was cold. A Q vs E curve was measured at 2 K up to ~11 MV/m (the cavity had a sharp Q-slope limitation above this field). After this, the tuner was applied to the cavity and it was tuned by several kilohertz, and Q was measured at several field points. This was repeated until the cavity was tuned by 1.4 MHz. The cavity

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was then warmed to 4.4 K, Q vs E was measured, then the tuner was fully relaxed and Q vs E was measured again, as shown in Fig. 11. At both 2.0 K and 4.4 K, no change in Q_0 was observed beyond measurement uncertainty. It therefore appears that there was minimal effect on residual or BCS resistance. Comparing the tuning range of ~1.4 MHz to the tuning range typically used in SRF cryomodule of several hundred kHz, it looks like it should be very possible to tune a cold Nb_3Sn cavity. For more information on the tuner in vertical test, see [11].

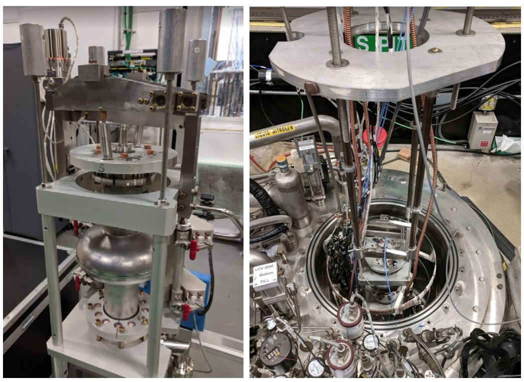

Figure 10: Setup for vertical test with tuner.

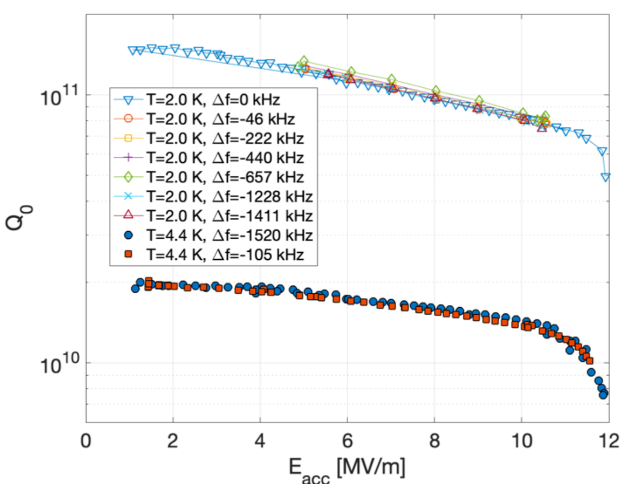

Figure 11: Results from vertical test with tuner show no effect on Q vs E at 2.0 K or 4.4 K from tuning up to 1.4 MHz.

Can We Successfully Coat an Accelerator-Style Structure?

An extremely important and difficult step in evaluating whether Nb_3Sn cavities are ready for practical applications is scaling up from R&D structures like 1.3 GHz single cell cavities to the kind of structures more typically used in accelerators. Likely the SRF structure with the most cavities in use or planned today is the 1.3 GHz 9-cell cavity (e.g. EXFEL, LCLS-II, SHINE, ILC, and many more). Showing a performance that would be usable in an accelerator with this structure was chosen a key milestone for the Fermilab Nb_3Sn program.

To prepare for the coating, a 9-cell sample host cavity was made out of a cavity with a manufacturing error. Its NbTi parts were removed by machining and holes were added at each equator and each inner iris to hold witness samples. The cavity was used to develop the coating parameters for a 9-cell cavity to achieve good uniformity. Details of these studies are presented in [5].

After the sample-host studies were completed, a real 9-cell ILC cavity, TB9ACC014, was coated, including all its features that are difficult for coating (e.g. HOM cans and F-hooks, NbTi flanges and conical end-dishes). Pictures of the coated cavity are shown in Fig. 12.

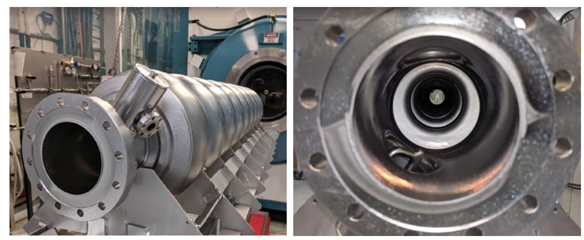

Figure 12: TB9ACC014 after coating with Nb_3Sn.

The cavity was vertically tested at 4.4 K and <1.5 K, as shown in Figs. 13 and 14. The cavity quenched at a maximum gradient of 10.5 MV/m, with a $Q_0 > 8x10^9$ at 4.4 K. In addition to having a high Q_0 at 4.4 K at useful accelerating gradients, this cavity sets a record for accelerating voltage in a Nb_3Sn cavity ~10 MV. The result shows that it is now possible to produce accelerator-style Nb_3Sn cavities with performance that is useful for applications.

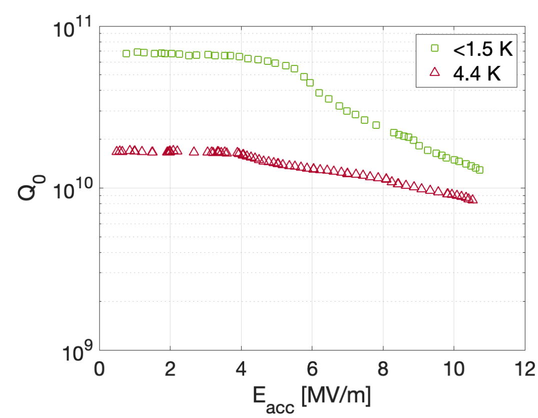

Figure 13: Q vs E curves measured at 4.4 K and <1.5 K for the first ever Nb_3Sn-coated 9-cell cavity.

The measurements in Fig. 13 were performed in liquid helium. Additional measurements were performed in helium gas. The reported temperatures are approximate, as the dissipation caused a dissipation-dependent increase of the outer surface temperature during the measurement of the curve. The curves measured at 6.2 ± 0.3 K, 5.8 ± 0.3 K, and 5.3 ± 0.2 K were administratively limited to avoid quench. The curves measured at 4.7 ± 0.2 K, 4.4 K, and <1.5 K were limited by quench.

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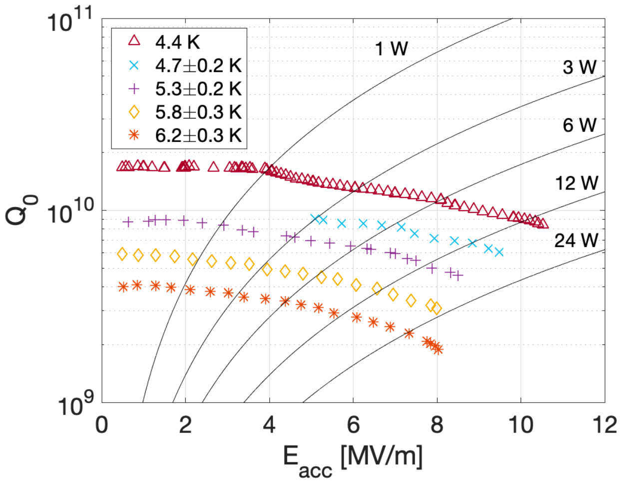

Figure 14: Comparison of the 4.4 K Q vs E curve of the 9-cell cavity to curves measured at higher temperatures in helium gas. Dissipated power curves are plotted as well.

CONCLUSIONS

In this paper, we presented studies of the Nb_3Sn coatings that resulted in accelerating gradients exceeding the 17-18 MV/m range previously observed as limiting Nb_3Sn cavities. These coatings were unusually shiny, had very low surface roughness, had relatively small grain size, and were relatively thin. We discussed implications for quench field. We discussed studies of avoidable defects in Nb_3Sn films. We overviewed several experiments designed to study practical considerations for Nb_3Sn cavities, in each case, showing that Nb_3Sn was able to meet the requirements. We showed that we can coat at 650 MHz and achieve $Q_0>10^{10}$ at 20 MV/m at 4.4 K. Figure 15 shows the extremely small dissipated heat for this single cell cavity, showing strong promise for cryocooler-based compact accelerators applications (e.g. see [8]). We showed that we can process multipacting if needed. We showed that we can tune a cold cavity without degradation. And with the first ever Nb_3Sn coating of a 9-cell cavity, a record accelerating voltage was achieved for a Nb_3Sn cavity, with a Q of $8x10^9$ at 4.4 K. These results show very promising progress towards realizing the first accelerator applications of Nb_3Sn cavities.

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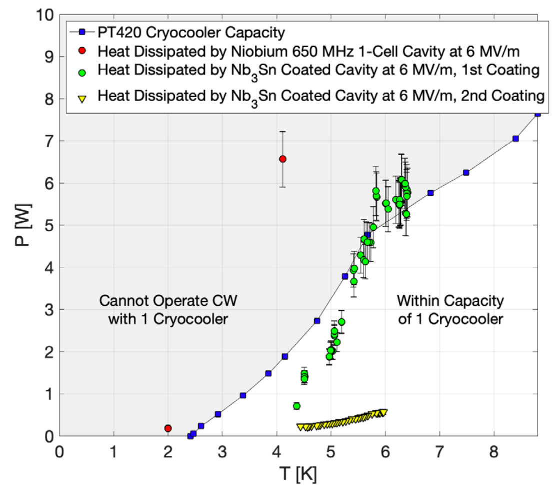

Figure 15: Dissipated power for the 650 MHz 1-cell cavity at 6 MV/m before coating, after the first coating, and after the second coating. These are compared to the capacity of a PT420 cryocooler.

REFERENCES

[1] S. Posen and D. Hall, *Supercond. Sci. Technol.* **30** 033004 (2017).

[2] S. Posen, TTC Workshop (Vancouver, Canada), WG3 Session 4 (2019).

[3] Y. Trenikhina *et al.* SuST **31** 015004 (2018).

[4] J.-Y. Lee *et al.* SuST **32** 024001 (2019).

[5] T. Spina, S. Posen, B. Tennis, and J. Lee, “The Role of Sn Sources on the Nb3Sn Coating of 9-cell Coupon Cavity”, presented at the *19th Int. Conf. RF Superconductivity (SRF'19),* Dresden, Germany, Jun.-Jul. 2019, paper MOP059, this conference.

[6] J. Lee *et al.*, “Performance-Limiting Imperfections in Nb3Sn Coatings for SRF Cavity Applications: Grain Boundary (GB) Segregations”, presented at the *19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, paper MOP008, this conference.

[7] J.-Y. Lee et al. manuscript in preparation.

[8] R. D. Kephart *et al.*, “SRF, Compact Accelerators for Industry & Society”, in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper FRBA03, pp. 1467-1473.

[9] S. Aull, T. Junginger, H. Neupert, and J. Knobloch, “Secondary Electron Yield of SRF Materials”, in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper TUPB050, pp. 686-690.

[10] A. Godeke, *Supercond. Sci. Technol.* 19 R68–80 (2006).

[11] Y. M. Pischalnikov *et al.*, “Operation of an SRF Cavity Tuner Submerged into Liquid He”, presented at the *19th Int. Conf. RF Superconductivity (SRF'19),* Dresden, Germany, Jun.-Jul. 2019, paper TUP085, this conference.