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# DEVELOPMENT OF $Nb_3Sn$ COATINGS FOR SUPERCONDUCTING RF CAVITIES AT FERMILAB*

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*Abstract*

$Nb_3Sn$ is a promising alternative material for superconducting RF cavities, with proven high quality factors at medium fields and predictions for increased superheating field as well. In this contribution, we describe the latest results from the Fermilab $Nb_3Sn$ SRF program. Early experiments have been focused on single cell 1.3 GHz cavities. We briefly review efforts to bring the parameters used in the coating process into a range where they produce uniform surfaces without regions showing signs of excess tin or thin/uncoated areas. We then present the latest cavity results, after modifications to the coating recipe based on feedback from film appearance and RF performance. These results show high $Q_0$ at medium fields and a maximum field of ~18 MV/m.

## COATING DEVELOPMENT

Niobium has been the traditional material for SRF cavities, but new materials offer the potential for high quality factors ($Q_0$) at higher temperature to take advantage of higher cryogenic efficiency. $Nb_3Sn$ is a new SRF material which already showed promise in pioneering research (e.g. [1] and [2]), and has had significant progress recently after the research was revived at Cornell University [3].

At Fermilab, a $Nb_3Sn$ SRF program recently began, and the first cavities were coated in 2017. The early program has focused on achieving strong performance in single cell cavities, so that similarly strong performance can be achieved after scaling up to the multicell and low frequency cavities that the 20” diameter coating chamber was designed to accommodate.

Cavities are coated via the vapor diffusion process. The furnace raises the cavity temperature to ~1100 C, and a heater raises the tin source even higher to evaporate tin. Excess or deficit of tin can be quickly apparent after coating. Several parameters have been found to impact important observables in the coating process such as evaporation rate, total tin transferred from the crucible, presence of non-uniformities over the surface of the cavity, and presence of poorly or overly coated regions (see Fig. 1). Some key parameters have been found to be:

- Crucible diameter (see Fig. 2)
- Heater power
- Coating time
- Annealing time

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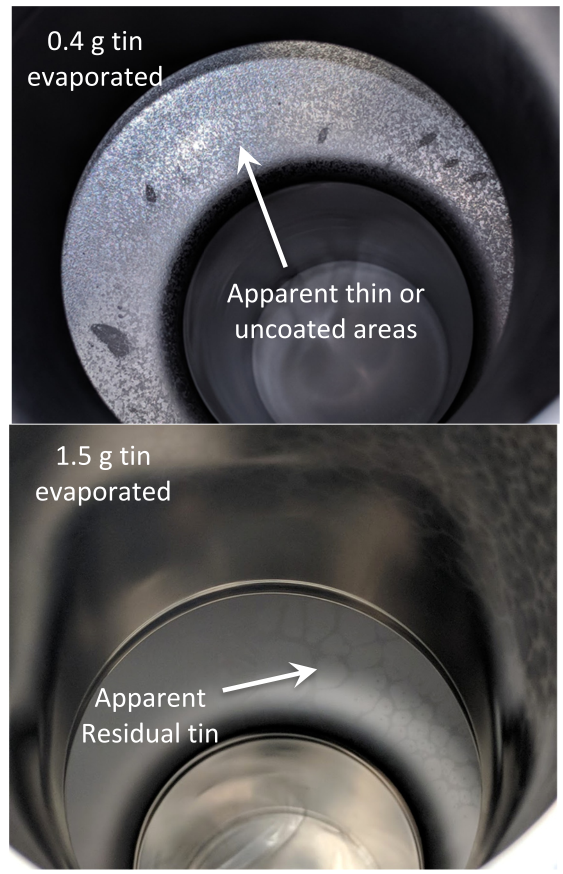


Figure 1: Cavity coatings with apparent regions of excessive or deficient tin. Note the total amount of tin evaporated in both cases, which was strongly impacted by the parameters noted in the text.

Figure 2: Four different tungsten crucible sizes.

Several 1.3 GHz single cell cavity coatings were carried out, and a strong correlation was observed between surface appearance and RF performance. For example, a cavity with apparent residual tin on the surface showed low $Q_0$ at 4.4 K, and hysteresis at 2.0 K (<$T_C$ of tin ~3.7 K), roughly consistent with $H_c$ of tin ~0.03 T. The Q vs E curves at 2.0 K and 4.4 K are shown in Fig. 3.

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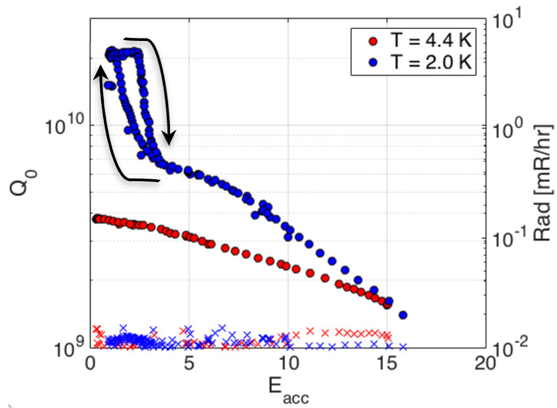


Figure 3: RF measurement of the cavity with apparent residual tin from Fig. 2 (bottom). Note the hysteresis at 2 K appears to be consistent with residual tin on the surface.

## RECENT RESULTS

To date, the best performance of a $Nb_3Sn$ cavity at Fermilab has been achieved with the smallest diameter crucible tested, with the heater at maximum power (crucible temperature ~1200 C). The cavity was anodized prior to coating, as advocated by Siemens in the 1970s [4] and recently revived by Cornell [5]. The cavity surface, shown in Fig. 4, visually was highly uniform, showing the matte dark gray typical of $Nb_3Sn$. Both half-cells showed similar appearance.

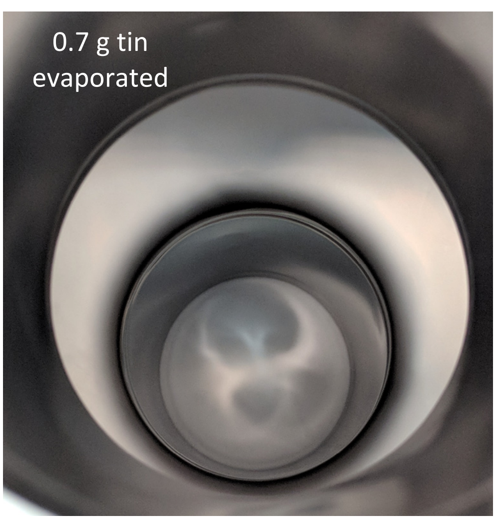


Figure 4: Cavity coating after coating parameter development with no apparent non-uniformities

The cavity was cooled slowly and uniformly through the critical temperature to avoid generating thermocurrents [6]. The cooldown is shown in Fig. 5, including signals from 4 thermometers at various locations and 4 fluxgate magne-tometers, 3 of which were equally spaced the equator, and one located on the frame. $Q_L$ vs T obtained with a network analyzer is also shown in Fig. 5, with transition very close to the expected $T_c \sim 18$ K.

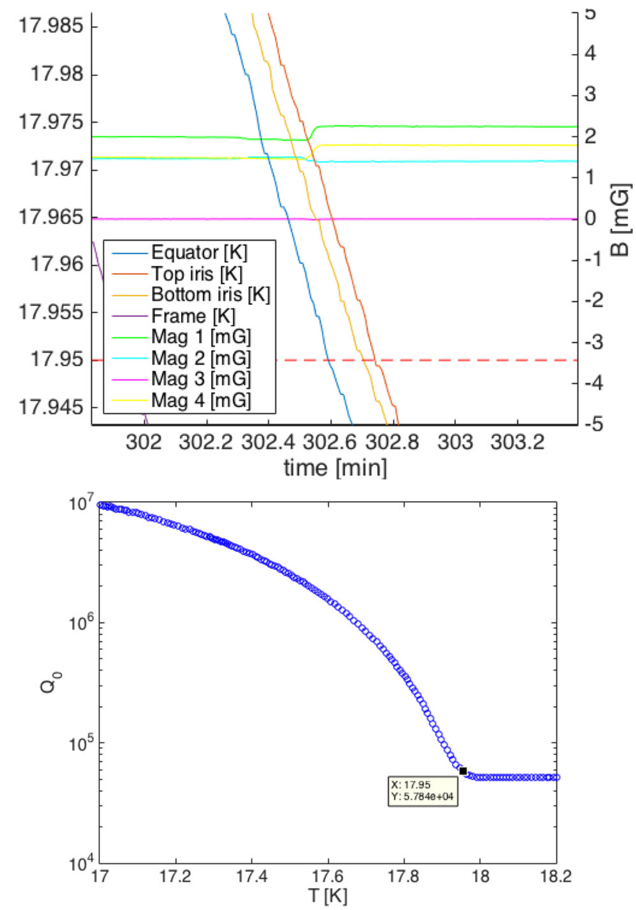


Figure 5: Cooldown through of the cavity, including temperature and magnetic field at the transition and $Q_L$ vs T measured with a network analyser.

Q vs E was measured at 4.4 K and <1.5 K up to quench, as shown in Fig. 6. 2.0 K measurement of Q vs E occurred up to 16 MV/m before quench and up to maximum field after quench. The post-quench 2.0 K data is corrected to match the lower field data to the pre-quench data.

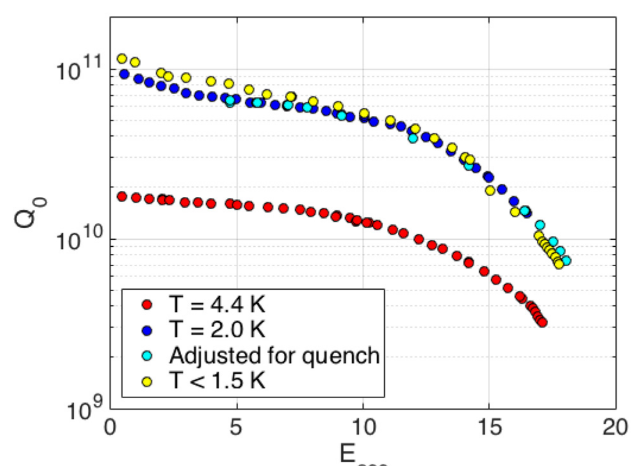


Figure 6: Q vs E data at 4.4 K, 2.0 K (including post-quench data with $Q_0$ corrected to align with pre-quench data), and <1.5 K.

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T-maps were measured at <1.5 K to localize regions of high heating (Fig. 7). Some hot spots were observed, but the heating was fairly widely distributed. Most regions showed non-linear heating in the Q-slope region.

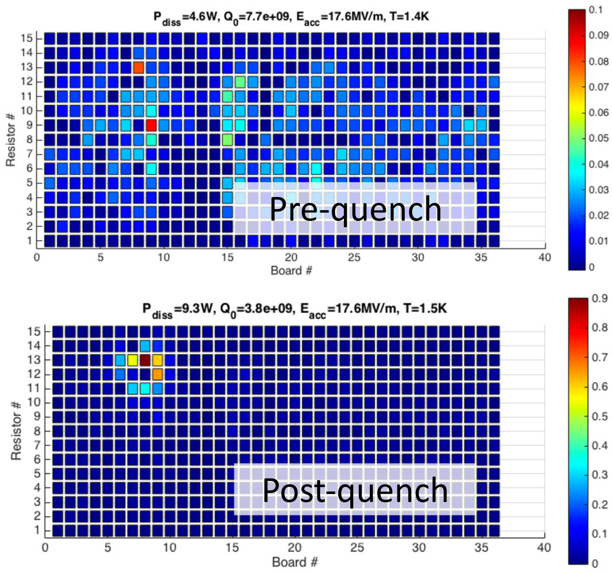


Figure 7: Temperature maps with bath temperature <1.5 K showing heating over the surface before and after quench.

## CONCLUSION

After a program to explore parameters for coating $Nb_3Sn$ cavities, a recipe was found that resulted in high quality factors up to medium fields. Near future work on single-cell cavities will focus on reproducibility, as well as systematic variation of individual parameters to further improve performance. The lessons learned will be applied to different frequency cavities (e.g. 650 MHz) and to multi-cell cavities to begin to scale up from R&D-scale cavities to application-scale cavities. Some Q-slope is still present above ~10 MV/m, but the cavity shows performance close to the highest measured for $Nb_3Sn$ accelerator cavities, and significantly improved compared to previous results from Fermilab, as well as pioneering studies at University of Wuppertal [7]. The Q vs E data is already promising for scaling up to larger cavities for industrial accelerators operating at 5-10 MV/m with ~5 watts of dynamic load per cavity at 4 K.

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