RF TEST RESULTS OF THE FIRST Nb_3Sn CAVITIES COATED AT CORNELL*

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Abstract

Breakthrough performance levels were achieved for a 1.3 GHz single cell cavity that was fabricated, coated with Nb_3Sn, and tested at Cornell. Unlike previous Nb_3Sn cavities, this cavity showed minimal Q-slope up to medium fields. This disproves speculation that the Q-slope in previous cavities was caused by vortex dissipation for $B > B_{c1}$, as surface fields far higher than the measured B_{c1} for this cavity were reached. At 2 K, quench occurred at ~55 mT, apparently due to a defect, so additional treatment may increase the maximum gradient to even higher fields. At 4.2 K, at ~12 MV/m, the cavity achieved $Q_0{\sim}1{\times}10^{10}$, approximately 20 times higher than niobium at this temperature. This makes it the first accelerator cavity made with an alternative superconductor to far outperform niobium at useable gradients.

INTRODUCTION

SRF researchers have been highly effective at finding preparation methods that suppress performance-limiting effects in niobium particle accelerator cavities. Now cavities are regularly produced that operate very close to the fundamental limits of niobium: they have surface resistances R_s very close to the ideal BCS value at operating temperatures, and they reach maximum surface magnetic fields very close to the superheating field B_{sh}. To continue to keep up with continually increasing demands of future SRF facilities, researchers have begun a significant effort to develop alternative materials to niobium, materials with smaller R_s and/or larger predicted B_{sh}.

Nb_3Sn is one of the most promising alternative SRF materials. Because it has a high critical temperature T_c of ~18 K, compared to 9.2 K for niobium, its R_{BCS} at a given temperature is much smaller. This makes the material ideal for continuous wave (CW) linacs: benefits include a smaller and simpler cryogenic plant, the possibility of 4.2 K operation (no superfluid; atmospheric operation), and higher cost-optimum accelerating gradients in CW operation. Its predicted B_{sh} is nearly twice that of Nb, up to ~400 mT depending on the material parameters used for the calculation. This makes the material ideal also for high energy linacs: it would allow Nb_3Sn cavities to operate at higher accelerating gradients than Nb cavities, and therefore fewer cavities would be required.

In the seventies, Siemens AG developed a method to fabricate Nb_3Sn coatings via vapor diffusion, which produced excellent RF results [1]. The University of Wuppertal applied this coating mechanism to particle accelerator cavities, achieving very small R_s at low fields, but their cavities showed a strong Q-slope. The Q vs E curve of one of the best cavities produced by University of Wuppertal and tested at JLab is shown in Fig. 1 [2].

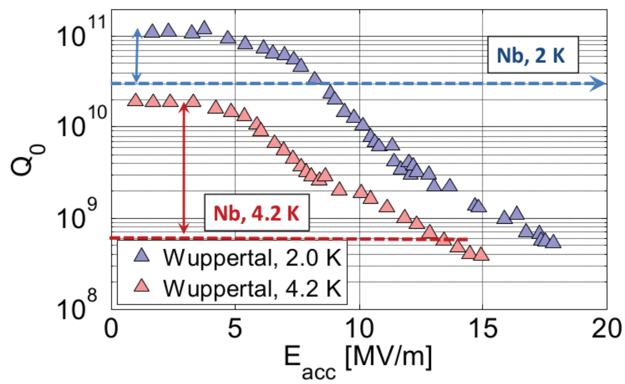

Figure 1: Q vs E curves at 2 K and 4.2 K for one of the best Nb_3Sn cavities produced by U. Wuppertal [2]. The approximate values for a Nb cavity are shown for comparison.

Various causes for the Q-slope were suggested, such as intergrain losses, imperfect stoichiometry [3], and dissipation due to vortex penetration beginning at the lower critical field B_{c1} [4]. As a result, it has been unclear whether or not this Q-slope behavior is fundamental to Nb_3Sn. In a recent historical review, Kneisel called finding the answer to this question and determining the origin of the Q-slope "the next important steps" for Nb_3Sn [5]. More importantly, if vortex penetration at B_{c1} were unavoidable, then bulk alternative SRF materials in general—which tend to have relatively small B_{c1} values—would be severely limited in the fields they could reach without strong dissipation. There is an energy barrier to vortex penetration, which for an ideal surface prevents strong vortex dissipation up to the superheating field B_{sh} [6], but small defects with size on the order of the coherence length ξ can decrease it. Other alternative materials also tend to have relatively small ξ, so the possiblity of vortex penetration above B_{c1} has been a serious concern.

Cornell University is now leading the program for new R&D efforts on Nb_3Sn SRF cavities. In 2009, Nb_3Sn development at Cornell began with the design, fabrication,

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and commissioning of a small coating chamber for samples. After establishing the capability to repeatably produce Nb_3Sn films of sufficiently high quality for cavity RF surfaces [7], Cornell researchers began work on a large coating chamber for single cell 1.3 GHz cavities, shown in Fig. 2. The first cavity coated showed unusually high R_s in one half cell during RF testing (determined by temperature mapping). The poorly performing half cell continued to show excess losses even after removing the coating and repeating the coating cycle with the cavity upside down (different orientations during cooldown were also attempted). The poor performance was therefore attributed to problems with the niobium half cell substrate. The performance of the second cavity coated at Cornell will be presented here.

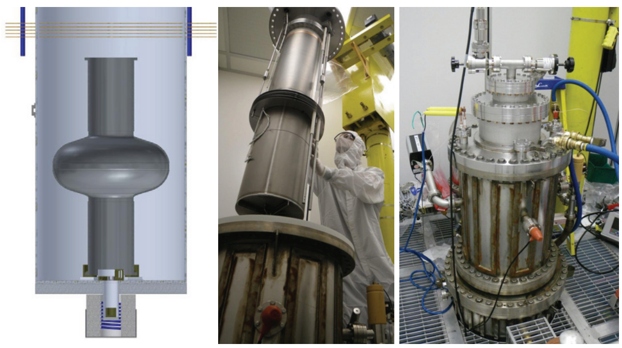

Figure 2: Cross-section of coating chamber (left), coating chamber being lowered into furnace (center), and UHV furnace with chamber inside (right).

RF MEASUREMENTS

ERL1-4, a 1.3 GHz Cornell ERL-shaped (similar to TESLA shape) single cell cavity, was coated with Nb_3Sn via thermal vapor diffusion. Visually, the Nb_3Sn surface is a darker gray than niobium, and it is matte rather than shiny, as shown in Fig. 3. After the coating process it was treated with only an HPR before mounting to a vertical test stand for cryogenic performance test. The cavity was cooled at a very slow rate, $\gtrsim 6$ min/K, as specified by Wuppertal researchers, to reduce trapped flux due to thermocurrents [2].

The Q vs E curve of ERL1-4 is shown in Fig. 4, along with that of the Wuppertal cavity from Fig. 1 for comparison. Overall, the performance is excellent. Unlike the cavities produced by Wuppertal, it does not show a strong reduction in Q_0 above 5 MV/m. At 4.2 K, at medium fields the Q_0 is up to approximately 10 times higher than that of the Wuppertal cavity, and approximately 20 times higher than a niobium cavity. At 2 K, the Q_0 is only slightly higher, indicating that residual resitance dominates over BCS, with very low R_{res} value of $\sim$9 nΩ, similar to most Wuppertal cavities [2]. Above 9 MV/m, due to its relatively flat Q_0, ERL1-4 has a higher Q_0 than even this exceptional Wuppertal cavity at 2 K.

The cavity was first tested at 4.2 K, and no hard limit

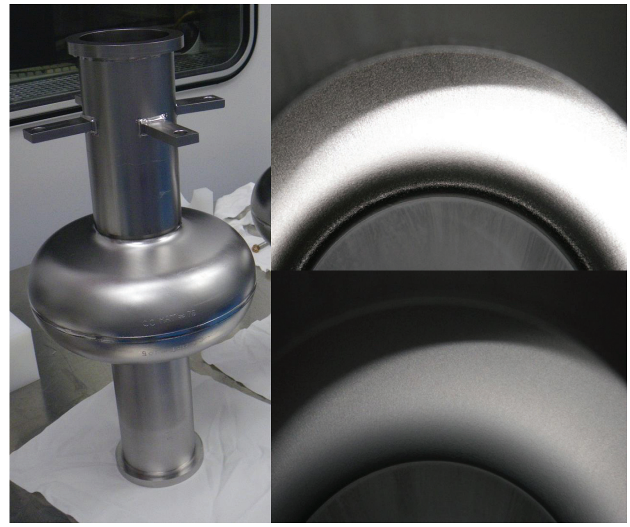

Figure 3: Coated cavity (left); view looking down into cavity before (top right) and after coating (bottom right).

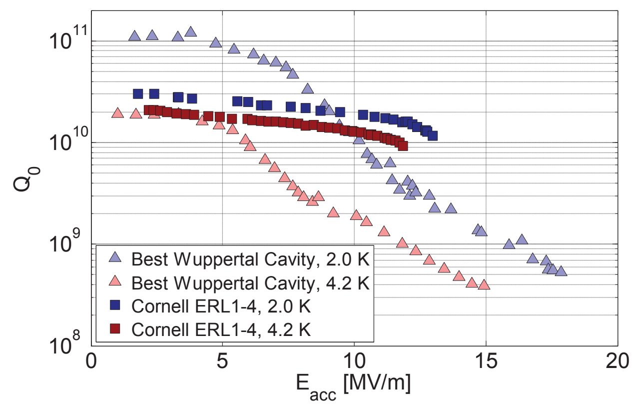

Figure 4: Q vs E curve from the new Cornell Nb_3Sn cavity, showing a small residual resistance at low fields and a large improvement in Q_0 at usable gradients over one of the best U. Wuppertal cavities. Uncertainty in Q and E is approximately 10%.

was reached, but at the highest fields shown, there were indications that the cavity might quench soon: a sharp drop in Q_0 (reminiscent of Q-switch) on the order of 10%. To avoid quench—which traps flux at the quench site and requires a new slow cooldown for additional testing without Q_0 reduction—the 4.2 K test was stopped and the cavity was cooled to 2 K. At 2 K, the limitation was quench at approximately 55 mT, which was again preceeded by a sharp drop in Q_0, as well as pre-heating on the temperature map. The pre-heating was highly localized, as shown in Fig. 5. After quench, the same area showed further increased heating, which is consistent with this being the quench location: locally the temperature spikes to near or above T_c during quench, then cools rapidly back to the helium temperature, trapping lossy flux due to thermocurrents. Our

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observations suggest that the limitation is a defect that becomes normal conducting when the Q_0 drop occurs, and triggers thermal breakdown at slightly higher fields. The dominance of this spot on the temperature map shows that this is a local problem—a defect—not a global problem with Nb_3Sn. Furthermore, though it was accompanied by a large decrease in Q_0, the Wuppertal cavity reached significantly higher CW fields than ERL1-4, so the limitation cannot be attributed to a fundamental problem with Nb_3Sn.

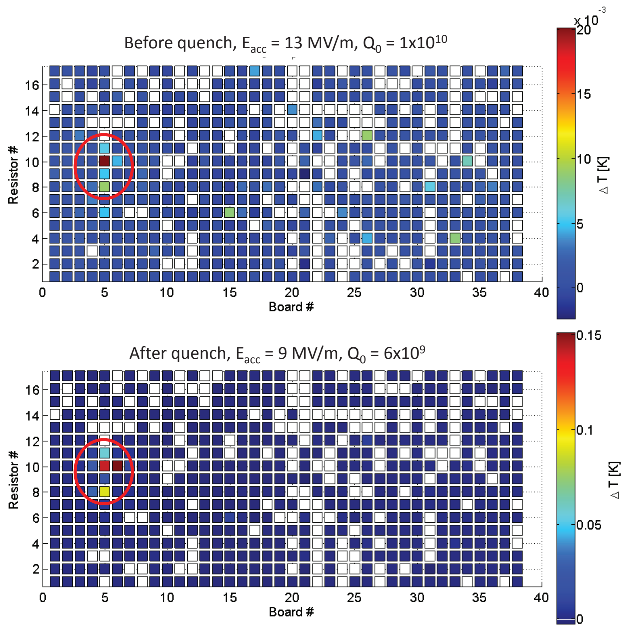

Figure 5: Temperature maps (which show the heating of the outer cavity surface relative to the helium bath) before quench, close to the quench field (top) and after the first quench (bottom). The region of strong localized heating is circled. Notice the difference in scale between the top and bottom.

Q_0 was measured as a function of temperature, as shown in the left side of Fig. 6. There was no sign of Q_0 change near the T_c of niobium, 9.2 K, indicating excellent Nb_3Sn coverage of the surface. The high-temperature range is highlighted in the inset, from which a T_c of 18.0 ± 0.1 K is measured. Q_0 was converted to an estimated average surface resistance via $R_s = G/Q_0$, where G is the geometry constant of the cavity. The resulting R_s vs T data was fit using a polymorphic BCS analysis [8]. The fit is shown in the right side of Fig. 6, and the fit parameters and derived values are summarized in Table 1. Δ/k_BT_c and B_c are in good agreement with literature values.

Table 1 lists the material parameters obtained from the $R_s(T)$ fit, together with additional parameters calculated from the fit parameters using Ginzburg-Landau theory. The so obtained B_{c1} value agrees well with a B_{c1} measurement performed with μ-SR by A. Grassellino et al [9] on a Nb_3Sn witness sample produced by Cornell. Figure 7

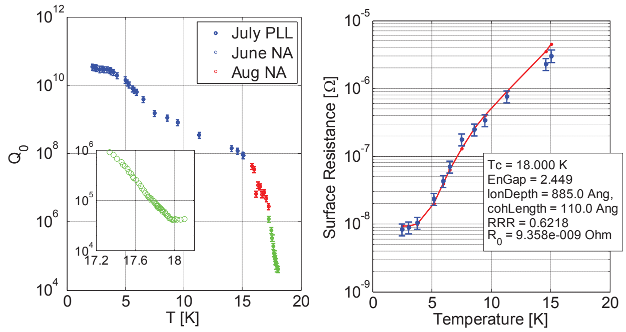

Figure 6: Q vs T measured with phase lock loop (PLL) or with network analyzer (NA) with weak coupling such that the $Q_0 \sim Q_L$ (left); R_s vs T from PLL data and polymorphic BCS fit (right).

compares B_{c1} to the Q vs B data, showing that the cavity far exceeds B_{c1} without a significant increase in surface resistance. This is important, as it shows that vortex penetration does not occur at B_{c1} for bulk films of superconductors with small coherence length. The energy barrier keeps Meissner state metastable, even with the small ξ of Nb_3Sn. The Q-slope seen in the Wuppertal cavities therefore does not represent a fundamental problem for alternative SRF materials.

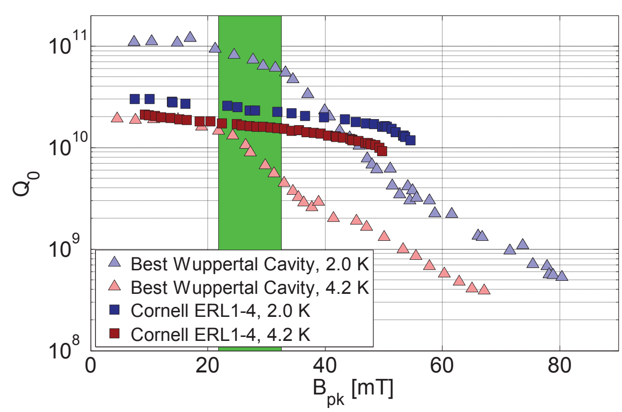

Figure 7: Q vs B curves of the Cornell and Wuppertal cavities. In green is the Cornell cavity's $B_{c1} = 27 \pm 5$ mT, which the cavity clearly exceeds without any indication of vortex dissipation.

CONCLUSIONS

Exceptional SRF performance was observed in tests of a new Nb_3Sn cavity at Cornell. At 2 K, the surface magnetic field reached 55 ± 6 mT, far exceeding $B_{c1} = 27 \pm 5$ mT without any sign of vortex penetration. This disproves spectulation that the Q-slope observed in previous Nb_3Sn cavities was an inevitable result of exceeding B_{c1}. The gradient was quench limited at a defect, and there is no indication of any fundamental mechanism that would

Table 1: Measured and Calculated Properties of the Nb_3Sn film [13]

Property	Value	Derivation
$\lambda_L(0)$ [nm]	89 ± 9	[10], 10% uncertainty assumed
$\xi_0(0)$ [nm]	7.0 ± 0.7	[10], 10% uncertainty assumed
T_c [K]	18.0 ± 0.1	observed from Q vs T
Δ/k_bT_c	2.4 ± 0.1	fit to Q vs T
l [nm]	3.7 ± 0.5	fit to Q vs T
R_{res} [nΩ]	9 ± 2	fit to Q vs T
$\lambda_{\text{eff}}(0)$ [nm]	150 ± 20	$\lambda_L\sqrt{1+\frac{\xi_0}{l}}$ [11]
$\xi_{GL}(0)$ [nm]	3.2 ± 0.2	$0.739\left[\xi_0^{-2}+\frac{0.882}{\xi_0 l}\right]^{-1/2}$ [12]
κ	47 ± 6	$\lambda_{\text{eff}}/\xi_{GL}$ [11]
$B_c(0)$ [T]	0.47 ± 0.6	$\frac{\phi_0}{2\sqrt{2}\pi\lambda_{\text{eff}}\xi_{GL}}$ [11]
$B_{c1}(0)$ [T]	0.027 ± 0.005	$B_c\frac{\ln\kappa}{\sqrt{2}\kappa}$ [11]
$B_{sh}(0)$ [T]	0.39 ± 0.05	$B_c\left(\frac{\sqrt{20}}{6}+\frac{0.5448}{\sqrt{\kappa}}\right)$ [6]

prevent future Nb_3Sn cavities from reaching even higher fields. Future research on preparation methods to achieve better Nb_3Sn surfaces can be expected to overcome non-fundamental limitations as they have in niobium, allowing fields close to B_{sh}~400 mT to be reached. Even with the current performance achieved, Nb_3Sn now becomes a promising alternative material for certain future accelerators, as at usable accelerating fields ~12 MV/m, we have shown that at 4.2 K Nb_3Sn cavities can achieve a Q_0 of 10^{10}, ~20 times higher than niobium.

ACKNOWLEDGEMENTS

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