

# FIRST CAVITY RESULTS FROM THE CORNELL SRF GROUP'S Nb<sub>3</sub>Sn PROGRAM\*

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## Abstract

Breakthrough performance levels were achieved for a 1.3 GHz single cell cavity that was fabricated, coated with Nb<sub>3</sub>Sn, and tested at Cornell. Unlike previous Nb<sub>3</sub>Sn cavities, this cavity showed minimal  $R_s$ -increase up to medium fields. This disproves speculation that the  $R_s$ -increase 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  $\sim 55$  mT, apparently due to a defect, so additional treatment may increase the maximum gradient to even higher fields. At 4.2 K, at  $\sim 12$  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

Superconducting Radio-Frequency (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  $R_s$  close to the ideal BCS value at operating temperatures, and they reach maximum surface magnetic fields close to the superheating field  $B_{sh}$ . 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<sub>3</sub>Sn is one of the most promising alternative SRF materials. Because it has a high critical temperature  $T_c$  of  $\sim 18$  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  $\sim 400$  mT depending on the material parameters used for the calculation. This makes the material ideal also for high energy linacs: it would allow Nb<sub>3</sub>Sn 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<sub>3</sub>Sn coatings via vapor diffusion, which produced

\* Work supported by NSF Career award PHY-0841213, DOE award ER41628, and the Alfred P. Sloan Foundation.

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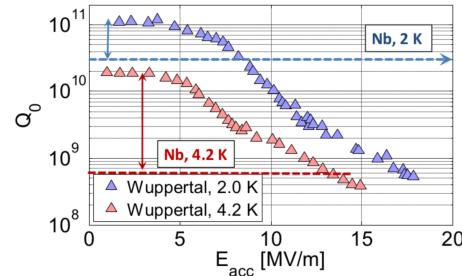


Figure 1:  $Q$  vs  $E$  curves at 2 K and 4.2 K for one of the best Nb<sub>3</sub>Sn cavities produced by U. Wuppertal [2]. The approximate values for a Nb cavity are shown for comparison.

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 increase in surface resistance with increasing field (this effect is called  $Q$ -slope, for the shape of the graph of quality factor  $Q$  versus accelerating gradient  $E_{acc}$ ). The  $Q_0$  vs  $E_{acc}$  curve of one of the best cavities produced by University of Wuppertal and tested at JLab is shown in Fig. 1 [2].

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<sub>3</sub>Sn. 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<sub>3</sub>Sn [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  $\xi$  can decrease it. Other alternative materials also tend to have relatively small  $\xi$ , so the possibility 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<sub>3</sub>Sn SRF cavities. In 2009, Nb<sub>3</sub>Sn development at Cornell began with the design, fabrication, and commissioning of a small coating chamber for samples. After establishing the capability to repeatedly produce Nb<sub>3</sub>Sn 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

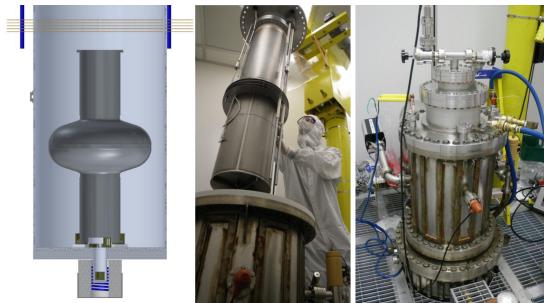


Figure 2: Cross-section of coating chamber (left), coating chamber being lowered into furnace (center), and UHV furnace with chamber inside (right).



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

Fig. 2. The first cavity coated showed unusually high  $R_s$  in RF testing, which was attributed to problems with the niobium cavity substrate. The performance of the second cavity coated will be presented here.

## RF MEASUREMENTS

ERL1-4, a 1.3 GHz Cornell ERL-shaped (similar to TESLA shape) single cell cavity, was coated with Nb<sub>3</sub>Sn via thermal vapor diffusion. Visually, the Nb<sub>3</sub>Sn 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 a high pressure rinse (HPR) before mounting to a vertical test stand for cryogenic performance test. Before insertion to the dewar, the outside cavity surface was covered with an array of temperature sensors (temperature map) to obtain information about the loss distribution. 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 resistance dominates over

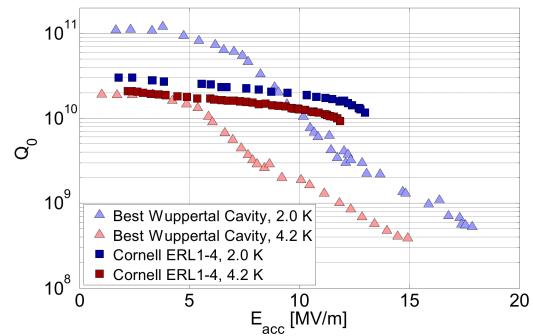


Figure 4:  $Q$  vs  $E$  curve from the new Cornell Nb<sub>3</sub>Sn cavity, showing a small residual resistance at low fields and a large improvement in  $Q_0$  at usable gradients over one of the best U. Wuppertal cavities. Uncertainty in  $Q$  and  $E$  is approximately 10%.

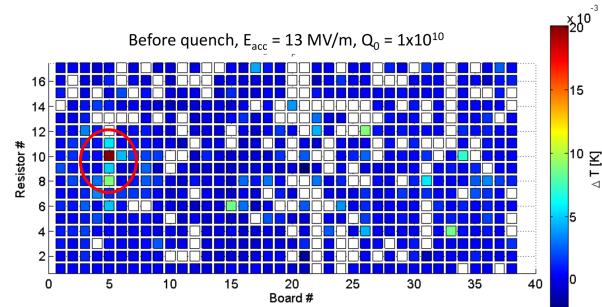


Figure 5: Temperature maps (which show the heating of the outer cavity surface relative to the helium bath) before quench, close to the quench field (top) and after the first quench (bottom). The region of strong localized heating is circled. Notice the difference in scale between the top and bottom.

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.

Quench occurred at approximately 55 mT at 2 K, which was preceded by a sharp drop in  $Q_0$  on the order of 10%, 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, consistent with this being the quench location. Our observations suggest that the limitation is a defect that becomes normal conducting when the  $Q_0$  drop occurs, and triggers breakdown at 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<sub>3</sub>Sn.

$Q_0$  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<sub>3</sub>Sn coverage of the surface. The high-temperature range is highlighted in the inset, from which a  $T_c$  of  $18.0 \pm 0.1$  K is measured.  $Q_0$  was converted to an estimated average surface resistance via  $R_s = G/Q_0$ , where  $G$  is the geometry

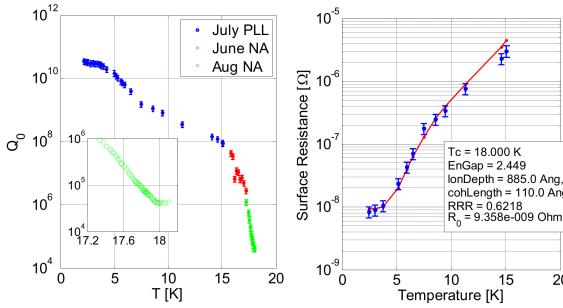


Figure 6:  $Q$  vs  $T$  measured with phase lock loop (PLL) or with network analyzer (NA) with weak coupling such that the  $Q_0 \sim Q_L$  (left);  $R_s$  vs  $T$  and BCS fit (right).

Table 1: Measured and Calculated Nb<sub>3</sub>Sn Film Properties

Property	Value
$T_c$ [K]	$18.0 \pm 0.1$
$\Delta/k_b T_c$	$2.4 \pm 0.1$
$l$ [nm]	$3.7 \pm 0.5$
$R_{\text{res}}$ [nΩ]	$9 \pm 2$
$\lambda_{\text{eff}}(0)$ [nm]	$150 \pm 20$
$\xi_{GL}(0)$ [nm]	$3.2 \pm 0.2$
$\kappa$	$47 \pm 6$
$B_c(0)$ [T]	$0.47 \pm 0.6$
$B_{c1}(0)$ [T]	$0.027 \pm 0.005$
$B_{sh}(0)$ [T]	$0.39 \pm 0.05$

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.  $\Delta/k_B T_c$  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 (see [9] for derivation of each value). The so obtained  $B_{c1}$  value agrees well with a  $B_{c1}$  measurement performed with  $\mu$ -SR by A. Grassellino et al [10] on a Nb<sub>3</sub>Sn witness sample produced by Cornell. Figure 7 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  $\xi$  of Nb<sub>3</sub>Sn. The  $Q$ -slope seen in the Wuppertal cavities therefore does not represent a fundamental problem for alternative SRF materials.

## CONCLUSIONS

Exceptional SRF performance was observed in tests of a new Nb<sub>3</sub>Sn cavity at Cornell. At 2 K, the surface magnetic field reached  $55 \pm 6$  mT, far exceeding  $B_{c1} = 27 \pm 5$  mT without any sign of vortex penetration. This dis-

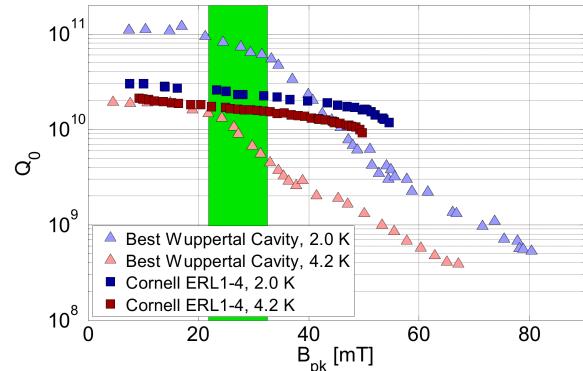


Figure 7:  $Q$  vs  $B$  curves of the Cornell and Wuppertal cavities. In green is the Cornell cavity's  $B_{c1} = 27 \pm 5$  mT, which is exceeded without indication of vortex dissipation.

proves speculation that the  $Q$ -slope observed in previous Nb<sub>3</sub>Sn 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 prevent future Nb<sub>3</sub>Sn cavities from reaching even higher fields. Future research on preparation methods to achieve better Nb<sub>3</sub>Sn surfaces can be expected to overcome non-fundamental limitations as they have in niobium, allowing fields close to  $B_{sh} \sim 400$  mT to be reached. Even with the current performance achieved, Nb<sub>3</sub>Sn now becomes a promising alternative material for certain future accelerators, as at usable accelerating fields  $\sim 12$  MV/m, we have shown that at 4.2 K Nb<sub>3</sub>Sn cavities can achieve a  $Q_0$  of  $10^{10}$ ,  $\sim 20$  times higher than niobium.

## ACKNOWLEDGEMENTS

The authors would like to express sincere thanks to summer student assistant F. Wohlfarth; A. Grassellino et al. for sample  $B_{c1}$  measurement; N. Valles for polymorphic fit program; J. Halbritter, author of the SRIMP program; P. Kneisel for excellent summary of Nb<sub>3</sub>Sn SRF history [5]; and H. Padamsee for helpful discussions.

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