Nb$_3$Sn – PRESENT STATUS AND POTENTIAL AS AN ALTERNATIVE SRF MATERIAL*

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Abstract

Nb$_3$Sn is a material that has the potential to have a transformative impact on SRF linacs. Due to its large critical temperature of approximately 18 K, Nb$_3$Sn cavities can have far smaller surface resistances at a given temperature than standard Nb cavities. This could significantly reduce the costs for infrastructure and power in cryoplants for large CW linacs. In addition, the predicted superheating field of Nb$_3$Sn is approximately double that of Nb, potentially doubling the maximum energy gradient. This would significantly decrease the size and cost of high energy linacs. In this work, we present recent progress in research and development for this promising material.

INTRODUCTION

Niobium is an excellent SRF material, and relatively easy to fabricate particle accelerator cavities with, but it has significant limitations. Let us consider two applications relevant to the linac community. The first is low duty factor, high energy SRF linacs, which require many cavities operating at high accelerating gradients E_{acc}. For example, the ILC design calls for approximately 16,000 cavities in a 31 km linac [1]. The maximum gradient of a state-of-the-art cavity has an accompanying peak surface magnetic field B_{pk} close to the superheating field B_{sh} of niobium, a fundamental limit. The only way to reach significantly higher gradients—and thereby decrease the number of cavities needed in such an SRF linac—is to use an alternative material with a larger B_{sh} than niobium.

The second application to consider is high duty factor (or CW), medium energy linacs, such as LCLS II. The BCS surface resistance R_{BCS} scales with the cavity temperature T and the material's critical temperature T_c approximately as

$$R_{BCS} \sim e^{-T_c/T} \tag{1}$$

so these these machines generally operate near 2 K to keep the surface resistance R_s manageable. However, the high duty factor means that the dynamic load is quite large, necessitating the use of large cryogenic plants, which cost on the order of 100 million USD and require megawatts of power to operate. Because the heat dissipated by a cavity scales as $P_{diss} \sim R_s E_{acc}^2$, the cost optimum energy gradient tends to be relatively small, well below the B_{sh} limit [2, 3]. An alternative material with a smaller R_{BCS} at a given temperature than niobium could increase the cost optimum E_{acc}, allowing fewer cavities to be used. Alternatively, it could

allow the cavities to be operated at a higher temperature, simplifying the cryoplant, reducing its capital cost and its power requirements.

Nb$_3$Sn, an alternative SRF material, is predicted to have a B_{sh} of ~400 mT [4], approximately twice that of niobium. At B_{pk}=400 mT, an ILC-style cavity would reach $E_{acc} \approx 100$ MV/m, compared to the maximum field for a niobium cavity, ~50 MV/m. The T_c of Nb$_3$Sn, 18 K, is also about twice that of niobium, which means that (taking into account the exponential dependence of R_s on T_c shown in Eqn. 1) it has a far smaller R_{BCS} at a given temperature. The comparison of different preparations in Table 1 shows that even with the preparation methods recently developed for very high Q_0 niobium surfaces (the quality factor Q_0 is determined by a global average of the surface resistance given by G/R_s, where G is a geometry-dependent constant), Nb$_3$Sn with small R_{res} has approximately the same Q_0 at 4.2 K as niobium has at 2 K, but the cryogenic efficiency is approximately 3.6 times higher at 4.2 K [5] and the cryoplant can be simpler without having to support subatmospheric helium. These dramatic increases in both B_{sh} and Q_0 at a given temperature illustrate the potential of Nb$_3$Sn to improve SRF linacs.

Table 1: Approximate Q_0 for 1.3 GHz TeSLA or 1.5 GHz CEBAF Cavities Prepared in Different Ways If Residual Resistance Is Small (for description of N-doping, see [6])

Preparation	Max Q_0, 4.2 K	Max Q_0, 2 K
Nb, EP+120 C bake	6×10^8	2×10^{10}
Nb, EP/bake/HF rinse	6×10^8	3×10^{10}
Nb, N-doped	6×10^8	$4 - 8 \times 10^{10}$
Nb$_3$Sn, vapor diffusion	6×10^{10}	$> 10^{11}$

On a smaller scale, Nb$_3$Sn cavities could be used in low energy industrial applications. In these situations, it may not be cost-effective to have a supply of superfluid liquid helium to keep Nb cavities in the $Q_0 \sim 10^{10}$ regime. The higher T_c of Nb$_3$Sn would allow low-loss operation with atmospheric liquid helium at 4.2 K or perhaps gas or supercritical helium at higher temperatures. This could have applications in flue gas and wastewater treatment, isotope production, and border security.

After many years of development, state-of-the-art niobium cavities can now achieve high-Q_0 operation close to B_{sh}. Achieving this with Nb$_3$Sn will be the ultimate goal of R&D into this alternative material, to which comparatively little effort has been dedicated to date. This paper will present recent progress towards this goal.

HISTORY AND RECENT PROGRESS

Pioneering work into developing Nb_3Sn for SRF applications was performed in the 1970s to 1990s by Siemens AG [7], Kernforschungzentrum Karlsruhe [8], University of Wuppertal [9], Cornell University [10], Jefferson Lab [11], CERN [12], and SLAC [13]. Researchers at University of Wuppertal developed a Nb_3Sn coating recipe based on vapor diffusion that reliably achieved extremely high quality factors on 1.5 GHz Nb_3Sn-coated accelerator cavities at low fields, as shown in Fig. 1 [14]. However, they consistently observed a strong Q-slope, starting at about 5 MV/m, where the quality factor decreases as E_{acc} is increased. In the cavity shown in the figure, no field emission or quench was observed. The cause for the Q-slope was unclear.
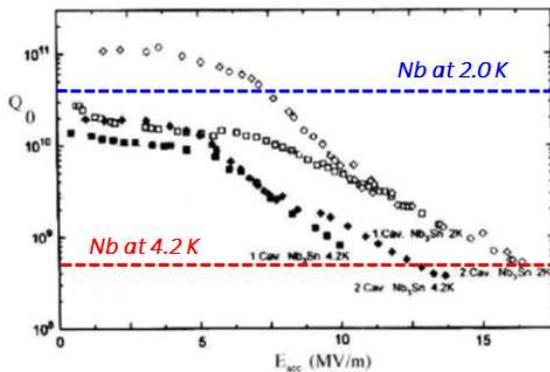
Figure 1: Q vs E curves from some of the best Nb_3Sn cavities coated at Wuppertal [14], compared to approximate Q_0 values of niobium at the measured temperatures.

Wuppertal researchers investigated the RF performance on small samples, observing that they could delay the onset of RF instability to higher peak magnetic fields by tweaking their coating process to increase the grain size [15]. They made preliminary attempts to anneal full Nb_3Sn cavities to increase the grain size, but they did not develop a recipe to produce high quality films with increased grain size before the research ended [11].

In 2009, researchers at Cornell University began development on a Nb_3Sn coating chamber. After gaining experience in coating small samples [16], the system was upgraded to accommodate single cell 1.3 GHz niobium cavities [17]. Three cavities have been coated in the chamber, two having had buffered chemical polish (BCP) as the chemistry before coating, and one having had electropolishing (EP). The second BCP cavity was coated and tested many times in order to establish the repeatability of the process and in order to try different preparations.

For the first cavity coated at Cornell, the Wuppertal recipe was closely followed. A strong Q-slope was observed, as shown in Fig. 2, similar to that consistently observed in the Wuppertal cavities. There was also an unusually high residual resistance R_{res}, which was concluded to be caused by problems with one of the niobium substrate half-cells, based on temperature maps.

For the second cavity, an annealing step was developed to grow the Nb_3Sn grains in an effort to suppress the Q-slope. Coated substrates were baked in the UHV furnace at 1100 C for several hours after the original Wuppertal recipe called for it to be shut down. SEM/EDX of samples confirmed that this process grows grains by a factor of approximately 2 while maintaining the desired stoichiometry (see Fig. 3).

After applying this modified recipe to the cavity, it showed no strong Q-slope, reaching fields of approximately 13 MV/m at 2 K before quench occurred, as shown in Fig. 2. The top of Fig. 4 contrasts this extremely high Q performance with that of niobium and the curve from Fig. 1, all at 4.2 K. To make an equivalent comparison of this cavity operating at 4.2 K to a niobium cavity operating at 2 K, in the bottom of Fig. 4, the Q_0 at 4.2 K is multiplied by the previously mentioned estimate of the ratio of the efficiency of a 4.2 K cryoplant relative to that of a 2 K cryoplant, a factor of 3.6.

After quench, the quality factor decreased by approximately an order of magnitude, and it could only be recovered by thermal cycling above T_c. No field emission was observed, and the quench field was not increased by repeated quenching. Temperature mapping showed that the quench occurred in a localized area in the high magnetic field region. If this were a niobium cavity, it would be suspected that this region held a performance-limiting defect, and material removal might be used to try to remove it.

The usual processes of BCP and EP would remove too much material (the Nb_3Sn layer is only a few microns thick), so the only possibility was light removal. The first light material removal process attempted was five cycles of HF rinsing, in which the cavity was immersed in hydrofluoric acid for 2 minutes to remove the oxide, then immersed in water for 5 minutes to regrow the oxide. Five cycles is expected to remove 30-50 nm of material. The desired outcome of this process would be an increase in maximum E_{acc}, Q_0, or both. However, as Fig. 5 shows, this resulted in a strong increase in Q-slope. SEM analysis of HF-rinsed samples found sub-micron scale structures on the surface which may be the source of degradation. See [18] for details.

Following this, the cavity was given BCP to remove the Nb_3Sn layer and coated again with the same modified recipe, with results presented in Fig. 5. Again, only modest Q-slope was observed up to fields of approximately 14 MV/m at 2 K, showing that the excellent performance is repeatable. Following this, light removal was employed. Since chemistry appears to be causing bad performances (Wuppertal researchers observed a similar degradation after oxipolishing low-R_s Nb_3Sn [19]), centrifugal barrel polishing (CBP) was employed in this round of testing. CBP is an industrial mechanical polishing technique in which an abrasive material is placed inside the cavity, and then it is rotated at high speeds. To perform a small amount of material removal, only the finest polishing step of the standard niobium recipe [20, 21] was used. Figure 6 shows the 40 nm colloidal silica with wood blocks that were put into the cavity for the 4.5 hour process. The performance degradation was even stronger

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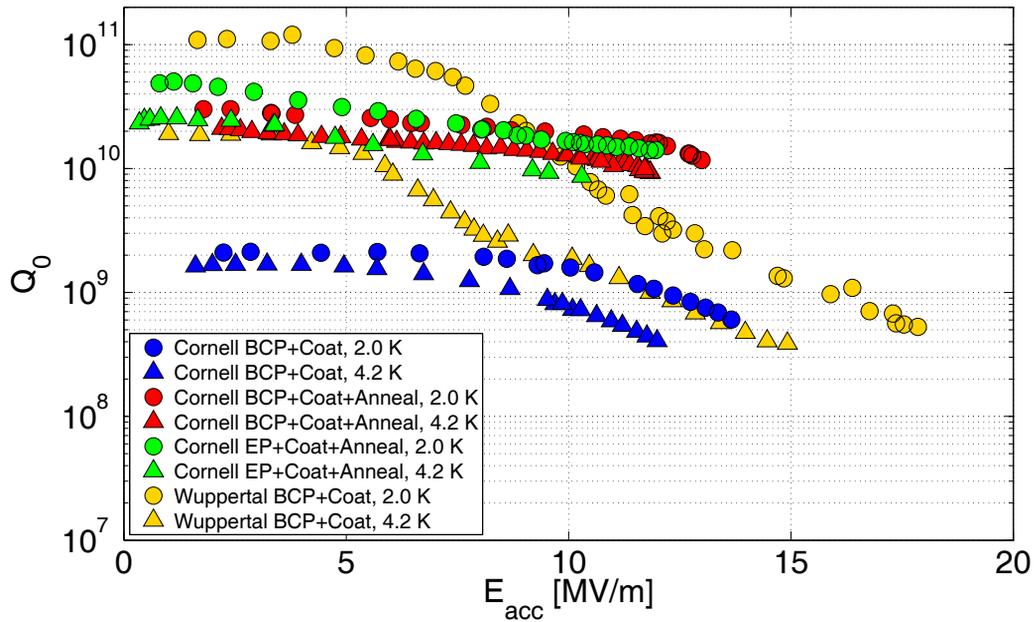
Figure 2: Q vs E curves of the three Cornell Nb_3Sn cavities (1.3 GHz) at 2 K and 4.2 K compared to one of the best Wuppertal cavities (1.5 GHz). The Cornell cavities were given a high pressure water rinse to clean the surface before each test.
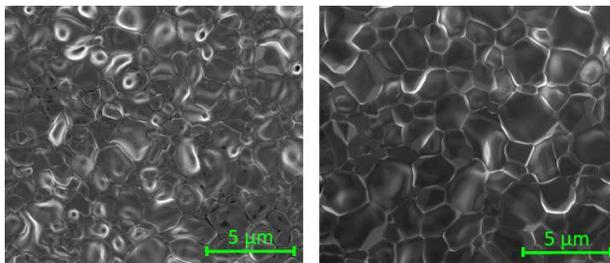
Figure 3: SEM images of witness samples coated with the basic recipe (left) and with 6 h annealing step (right). The grains are approximately twice as big when the annealing step is included.

than with HF rinse, as Fig. 5 shows. Afterwards, the cavity was left at ~120 K overnight to check for Q-disease (the formation of hydrides is known to cause degradation in Nb cavities), but none was observed, ruling hydrogen out as the cause for Q-slope.

It should be noted that it is unknown if reduction of quench-inducing defects was achieved after material removal from HF rinsing and CBP. The maximum E_{acc} in the post-removal tests was limited by available RF power to fields well below where quench occurred before removal.

The surface was reset again with BCP, then the cavity was coated again, this time with an extra long annealing time, approximately 15 hours. The cavity again went to medium fields without strong Q-slope, as seen in Fig. 5. This seems to suggest that the process is not very sensitive to longer annealing times.
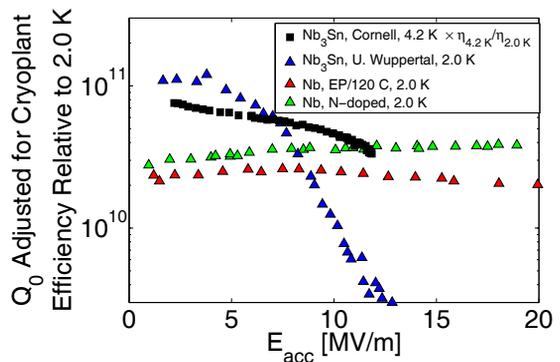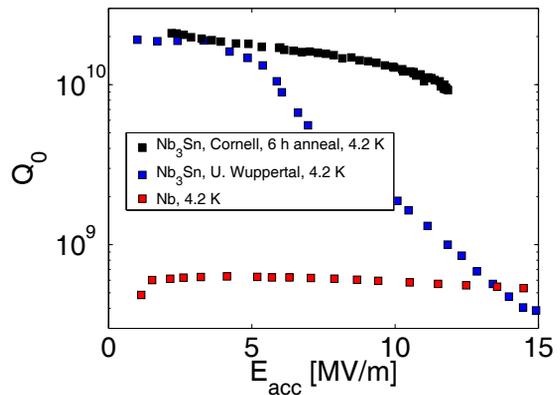
Figure 4: Comparison of new Cornell Nb_3Sn post-annealing results to Wuppertal's Nb_3Sn cavity and to niobium cavities at 4.2 K (top) and at 2 K (bottom). An effective Q_0 at 2 K is shown for the Cornell cavity by multiplying by the ratio of cryogenic efficiencies at these temperatures.

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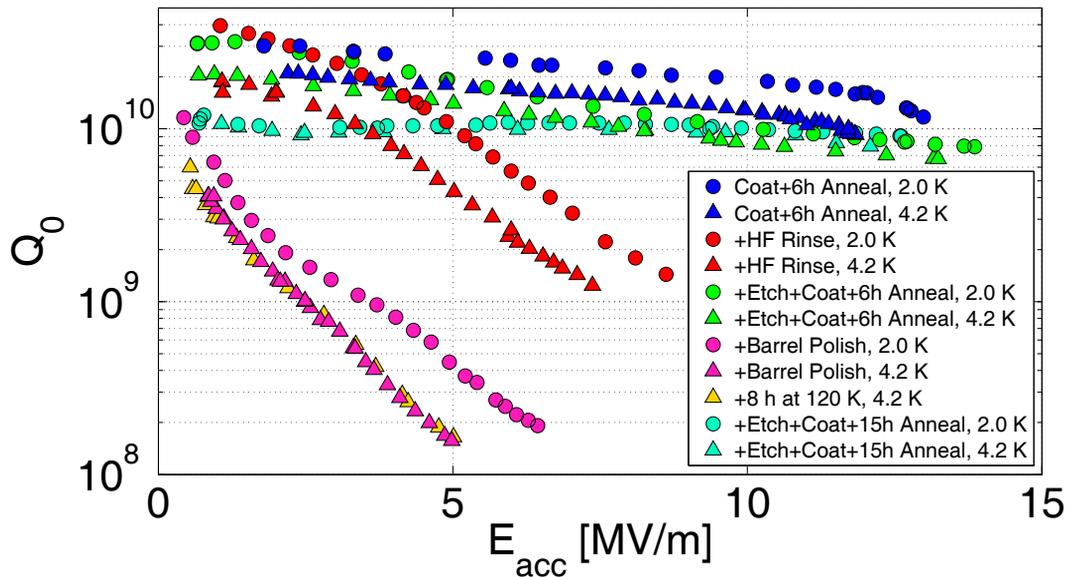
Figure 5: Various removal methods were attempted on one of the Cornell Nb_3Sn cavities. Q vs E curves are shown at 2 K and 4.2 K after each treatment. The cavity was given a high pressure water rinse to clean the surface before each test.

Figure 6: Centrifugal barrel polish machine loaded with Nb_3Sn cavity (left); and polishing media after 4.5 hours (right).

Since material removal after coating seemed to degrade performance, EP was used to give a smoother, more defect-free substrate surface before coating, in an attempt to improve the post-coating surface. The third Cornell cavity was given bulk EP, degas, and light EP, then the modified recipe with 6 hour anneal. Its performance can be seen in Fig. 2. The low field Q was improved, up to a maximum of 5×10^{10} at 2 K, with similar modest Q-slope, and the maximum field was approximately the same as with the BCP cavities, around 12 MV/m. It is interesting that the quench fields of these cavities are so close, but it is expected that this limitation can be overcome, since the cavities produced at Wuppertal reached higher fields without quench.

It is important to note that this is the first time that centrifugal barrel polishing has ever been used on a Nb_3Sn cavity, and the first time that Nb_3Sn coating has been applied to a cavity with an EP surface. Very little has been tried with Nb_3Sn cavities—it is still at the beginning of development.

More fundamental studies were also performed, including measurements of pulsed quench field and DC flux penetration. In pulsed mode, fields as high as 25 MV/m were reached, supporting the idea that the CW quench limit may

be caused by small defects. These results are presented elsewhere.

After the advances at Cornell, there has been increased interest around the world in Nb_3Sn SRF cavities. Researchers at Jefferson Lab recently began a program, and have coated and tested their first single cell cavity. It showed an excellent T_c of 18 K, but as shown in Fig. 7, strong Q-slope reduced the Q_0 to 1×10^9 at 8 MV/m at 2 K. An upgrade is planned to install an auxiliary heating source for the tin source, as indicated in the Wuppertal recipe, in order to improve performance.
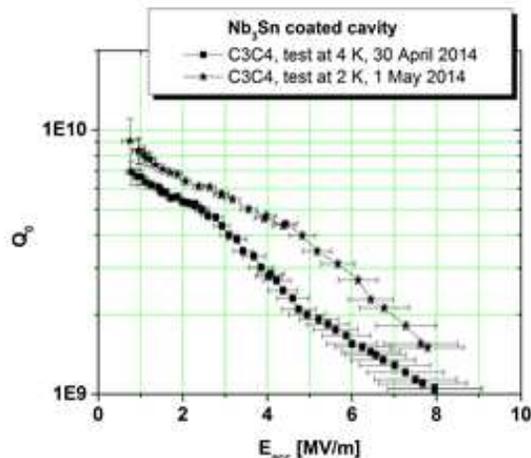
Figure 7: Q vs E of a single-cell 1.5 GHz CEBAF cavity coated with Nb_3Sn and tested at JLab (courtesy G. Eremeev).

Table 2: Measured and Calculated Properties of the Nb_3Sn Film

Property	Value	Derivation
$\lambda_L(0)$ [nm]	89 ± 9	[22], 10% uncertainty assumed
$\xi_0(0)$ [nm]	7.0 ± 0.7	[22], 10% uncertainty assumed
T_c [K]	18.0 ± 0.1	observed from f vs T
$\Delta/k_b T_c$	2.47 ± 0.15	combined fit to Q vs T and f vs T
l [nm]	3.25 ± 0.37	combined fit to Q vs T and f vs T
R_{res} [nΩ]	9.3 ± 1.3	combined fit to Q vs T and f vs T
$\lambda_{\text{eff}}(0)$ [nm]	160 ± 20	$\lambda_L \sqrt{1 + \frac{\xi_0}{l}}$ [23]
$\xi_{GL}(0)$ [nm]	3.0 ± 0.2	$0.739 \left[\xi_0^{-2} + \frac{0.882}{\xi_0 l} \right]^{-1/2}$ [24]
κ	52 ± 7	$\lambda_{\text{eff}}/\xi_{GL}$ [23]
$B_c(0)$ [T]	0.49 ± 0.06	$\frac{\phi_0}{2\sqrt{2}\pi \lambda_{\text{eff}} \xi_{GL}}$ [23]
$B_{c1}(0)$ [T]	0.026 ± 0.005	$B_c \frac{\ln \kappa}{\sqrt{2}\kappa}$ [23]
$B_{c2}(0)$ [T]	36 ± 7	$\sqrt{2}\kappa B_c$ [23]
$B_{sh}(0)$ [T]	0.40 ± 0.05	$B_c \left(\frac{\sqrt{20}}{6} + \frac{0.5448}{\sqrt{\kappa}} \right)$ [4]

MATERIAL PARAMETERS

A combined polymorphic fit was performed on Q_0 vs T and frequency vs T data to extract the material parameters of the Nb_3Sn from its RF performance. The measurements were performed during the first test of Cornell's annealed BCP cavity. The detailed analysis is presented in [25], but the results are summarized in Table 2. Based on these parameters, the critical fields of the superconductor were also calculated and included in the table.

When $B_{pk}=B_{c1}$, $E_{acc}=6\pm1$ MV/m. Figure 6 shows that before removal, the cavity reaches fields far above this, indicating that B_{c1} does not represent a fundamental limit for Nb_3Sn. Figure 8 shows that the calculated B_{c2} agrees with correlations in [26].

CONCLUSIONS

While still far below the ultimate potential of the material, Nb_3Sn cavities are now outperforming Nb cavities at useful gradients at 4.2 K. A significant improvement in performance is observed after the addition of an annealing step to the coating process to increase grain size. Results are also presented for the first time for Nb_3Sn cavities treated with EP prior to coating with Nb_3Sn, and for cavities that were treated with centrifugal barrel polishing after coating with Nb_3Sn, but these changes did not provide additional significant benefit. Nevertheless we are just beginning to understand this material and its limitation mechanisms, and these tests provide valuable information in this respect. Future work will focus on studying the cause of the post-removal Q-slope and finding preparation methods to push the quench field without inducing Q-slope.

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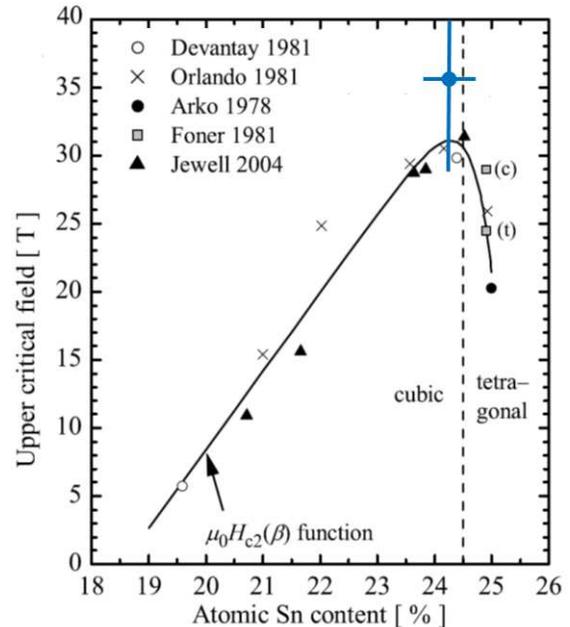
Figure 8: Comparison of upper critical field calculated from measured material parameters to correlations presented in [26]. Tin content measured via EDX on witness samples.

REFERENCES

[1] T. Behnke et al., International Linear Collider Technical Design Report, www.linearcollider.org (2013).

[2] M. Liepe, in Proc. Third Work. Energy Recover. Linacs (Ithaca, 2009).

[3] T. Powers, in Proc. Sixt. Conf. RF Supercond. (Paris, 2013).

[4] M. Transtrum, G. Catelani, and J. Sethna, Phys. Rev. B 83, 094505 (2011).

[5] W.J. Schneider, P. Kneisel, and C.H. Rode, Proc. PAC 2003, 2863-2868 (2003).

[6] A Grassellino et al., Supercond. Sci. Technol., 26 102001 (2013).

[7] B. Hillenbrand, H. Martens, H. Pfister, K. Schnitzke, and Y. Uzel, IEEE Trans. Magn. 13, 491 (1977).

[8] P. Kneisel, O. Stoltz, and J. Halbritter, *IEEE Trans. Magn.* 15, 21 (1979).

[9] M. Peiniger, G. Müller, H. Piel, and P. Thüns, in Proc. First Eur. Part. Accel. Conf. (Rome, 1988) pp. 1295-1297.

[10] J. Stimmell, PhD Thesis, Cornell Univ., Ph.D. thesis, Cornell University (1978).

[11] G. Müller, P. Kneisel, and D. Mansen, in Proc. Fifth Eur. Part. Accel. Conf. (Sitges, 1996).

[12] G. Arnolds-Mayer and E. Chiaveri, in Proc. Third Work. RF Supercond. (Chicago, 1986).

[13] I. E. Campisi and Z. D. Farkas, in Proc. Second Work. RF Supercond. (Geneva, 1984).

[14] G. Müller, H. Piel, J. Pouryamout, P. Boccard, and P. Kneisel, in Proceedings of the Workshop on Thin Film Coating Methods for Superconducting Accelerating Cavities, edited by D. Proch (TESLA Report 2000-15, Hamburg, 2000).

[15] M. Perpeet, A. Cassinese, M. Hein, T. Kaiser, G. Muller, H. Piel, and J. Pouryamout, IEEE Trans. App. Superc. 9, 2496 (1999).

[16] S. Posen and M. Liepe, in Proc. Fifteenth Conf. RF Supercond. (Chicago, 2011).

[17] S. Posen and M. Liepe, in Proc. Sixteenth Conf. RF Supercond. (Paris, 2013).

[18] S. Posen, M. Liepe, and T. Proslier, this conference, MOPP019 (2014).

[19] B. Hillenbrand, in Proc. First Work. RF Supercond. (Karlsruhe, 1980).

[20] C. A. Cooper, A.C. Crawford, C. Ginsburg, A. Grassellino, R. Kephart, O.S. Melnychuk, A.S. Romanenko, A. Rowe, and D.A. Sergatskov, in Proc. Sixteenth Conf. RF Supercond. (Paris, 2013).

[21] A. D. Palczewski, C. A. Cooper, B. Bullock, S. Joshi, A. A. Rossi, and A. Navitski, in Proc. Sixteenth Conf. RF Supercond. (Paris, 2013).

[22] M. Hein, *High-Temperature Superconductor Thin Films at Microwave Frequencies* (Berlin: Springer, 1999).

[23] M. Tinkham, *Introduction to Superconductivity* (New York: Dover, 1996).

[24] T. Orlando, et al., Phys. Rev. B 19, 4545 (1979).
M. Transtrum, G. Catelani, and J. Sethna, Phys. Rev. B 83, 094505 (2011).

[25] S. Meyers, S. Posen, and M. Liepe, this conference, TUPP018 (2014).

[26] A. Godeke, Supercond. Sci. Technol. 19, R68 (2006).