HIGH Q_0 AT MEDIUM FIELDS IN Nb_3Sn SRF CAVITIES AT 4.2 K*

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Abstract

Nb_3Sn has proven itself to be a very promising alternative SRF material. With twice the critical temperature of niobium cavities, 1.3 GHz Nb_3Sn cavities can achieve quality factors on the order of 10^{10} even at 4.2 K, significantly reducing cryogenic infrastructure and operational costs. In addition, its large predicted superheating field may allow for maximum accelerating gradients up to twice that of niobium for high energy applications. In this work, we report on new cavity results from the Cornell Nb_3Sn SRF program demonstrating a significant improvement in the maximum field achieved with high Q_0 in a Nb_3Sn cavity. At 4.2 K, accelerating gradients above 16 MV/m were obtained with Q_0 of 8×10^9, showing the potential of this material for future applications. In addition to this result, current limitations are discussed.

INTRODUCTION

For decades, niobium has been the material of choice for superconducting RF cavities in particle accelerators. It has excellent superconducting properties and is relatively easy to work with to fabricate cavities. However, because it has a critical temperature T_c of ~9.2 K, it is usually necessary to cool niobium cavities with subatmospheric helium at ~2 K in order to achieve high quality factor Q_0. Furthermore, while accelerating gradients E_{acc} in niobium cavities have been steadily increasing over years of development, cavities are now regularly being produced with fields close to the ultimate limit set by the superheating field B_{sh} of niobium.

Nb_3Sn is an alternative SRF material currently under development that already is showing great promise. It has a T_c of 18 K, approximately twice that of niobium, allowing for high Q_0 operation even at 4.2 K, opening up the possibility of operation with atmospheric helium, reducing the infrastructure costs for cryogenic plants, and increasing their efficiency. Nb_3Sn is also is predicted [1] to have a B_{sh} of 400 mT, approximately twice that of niobium, which could halve the number of cavities required to reach a given energy.

Many laboratories contributed to pioneering research in the 1970s-1990s into Nb_3Sn SRF cavities [2–8]. Building on their work based on the vapor diffusion process [9], a Nb_3Sn SRF program was started at Cornell University in 2009. After a successful program to demonstrate high quality coatings on small samples [10], the cavity program began.

RF TESTING

A coating chamber built for an ulta-high vacuum furnace (see details in [11]) was used to coat two single cell 1.3 GHz niobium cavities with Nb_3Sn. Cavity 1 received BCP chemical removal before coating, and Cavity 2 received EP. The performance of the cavities was evaluated in vertical RF test. After evaluation, the coating layer of Cavity 1 was removed with BCP, then it was coated and tested again. This was repeated a total of four times. Details of the coating are presented elsewhere [12]. The performance curves of these coatings are presented in Fig. 1.

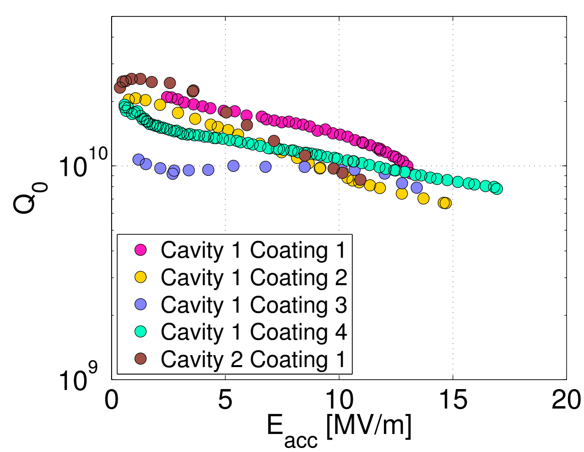

Figure 1: Q_0 vs E_{acc} at 4.2 K for single cell 1.3 GHz cavities over a series of five Nb_3Sn coatings.

In each test, Q_0 at 4.2 K on the order of 10^{10} is measured up to E_{acc} above 10 MV/m. Maximum fields are limited by quench without x-rays. An average quench field of 14 MV/m was measured, with an average Q_0 at quench of 8×10^9. The maximum field achieved was 17 MV/m. Moderate Q-slope was observed in each case, but it is far less strong than that observed by previous researchers studying Nb_3Sn accelerator cavities [13].

Material parameters were extracted during RF testing from fits to Q_0 versus temperature T data and resonant frequency f versus T data, as described in [14]. The results are shown in Table 1, along with the maximum fields in each test.

Q_0 on the order of 10^{10} at 4.2 K is a significant development in the effort to reduce power consumption in cryogenic

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Table 1: Comparison of extracted parameters and critical fields from five cavity coatings. Parameters presented are critical temperature T_c, reduced energy gap $\Delta/k_B T_c$, mean free path l, residual resistance R_{res}, penetration depth λ, coherence length ξ, and Ginzburg-Landau parameter κ. All parameters are given at $T = 0$ and $E_{acc} \sim 1$ MV/m. London penetration depth λ_L and intrinsic coherence length ξ_0 are from Ref [15]. Combined fits refer to a simultaneous fit of Q vs T and f vs T data.

Property	Cavity 1 Coating 1	Cavity 1 Coating 2	Cavity 1 Coating 3	Cavity 1 Coating 4	Cavity 2 Coating 1	Derivation
T_c [K]	18.0 ± 0.1	18.0 ± 0.1	18.0 ± 0.1	18.0 ± 0.1	18.0 ± 0.1	measured from f vs T
$\Delta/k_b T_c$	2.5 ± 0.2	2.5 ± 0.2	2.6 ± 0.2	2.25 ± 0.12	2.5 ± 0.2	combined fit
l [nm]	3.0 ± 1.0	1.7 ± 1.0	2.4 ± 1.0	4.8 ± 2.0	1.7 ± 1.0	combined fit
R_{res} [nΩ]	9.5 ± 1.5	10.3 ± 1.2	21 ± 2	8.5 ± 1.2	7.2 ± 1.0	combined fit
λ [nm]	161 ± 25	198 ± 50	174 ± 32	139 ± 23	198 ± 50	$\lambda_L \sqrt{1 + \frac{\xi_0}{l}}$ [16]
ξ [nm]	3.0 ± 0.4	2.4 ± 0.6	2.8 ± 0.4	3.4 ± 0.5	2.4 ± 0.6	$0.739 \left[\xi_0^{-2} + \frac{0.882}{\xi_0 l}\right]^{-1/2}$ [17]
κ	54 ± 11	82 ± 28	63 ± 16	41 ± 9	82 ± 28	λ/ξ [16]
$E_{acc,max}\|_{T=4.2K}$ [MV/m]	13 ± 1	15 ± 1	13 ± 1	17 ± 2	11 ± 1	Directly from RF measurements

plants for high duty factor accelerators. The impact can be shown by calculating the AC power required to cool a cavity:

$$P_{AC} = \frac{\text{COP}^{-1} E_{acc}^2 L^2}{\frac{R_a}{Q_0} Q_0} \qquad (1)$$

where R_a is the shunt impedance, L is the active length of the cavity, and COP^{-1} is the inverse coefficient of performance of the cryogenic plant, which determines its efficiency. For thermodynamic reasons, cryoplant efficiency is significantly worse at low temperatures—for example, for a bath temperature of 2 K, approximately 830 W of input power are needed to remove 1 W of heat, compared to approximately 240 W/W at 4.2 K.

In this paper, we present cavity performance in terms of P_{AC}/E_{acc}^2 instead of Q_0, as this allows us to directly compare cryogenic power requirements for different operating temperatures. It is additionally helpful to normalize performance to per cell values of P_{AC}/E_{acc}^2, so that cavities with different numbers of cells can be compared. Figure 2 shows P_{AC}/E_{acc}^2 per cell vs E_{acc} for the fourth coating of Cavity 1 (cryoplant efficiency relative to Carnot is taken from [18]). Even with moderate Q-slope, P_{AC}/E_{acc}^2 per cell of the Nb_3Sn cavity at 16 MV/m is still below the target values for the planned accelerators LCLS-II and Cornell ERL. It also exceeds the gradient specifications.

Figure 4 presents normalized AC power required versus temperature for 1.3 GHz Nb_3Sn and Nb cavities. For niobium, the curve was calculated from BCS theory based on the LCLS II performance goals. It used material parameters from a test of a nitrogen-doped cavity [19] at the LCLS II operating gradient of 16 MV/m, with its R_{res} specification of 5 nΩ. Calculations for the Nb_3Sn cavity used BCS material parameters from the fourth coating of Cavity 1. For this material, the figure shows three different values of R_{res}: 9 nΩ, corresponding to E_{acc} values at ~1 MV/m of the fourth coating of Cavity 1; 29 nΩ, corresponding to E_{acc} values at ~16 MV/m of the same cavity; and 3 nΩ, corresponding

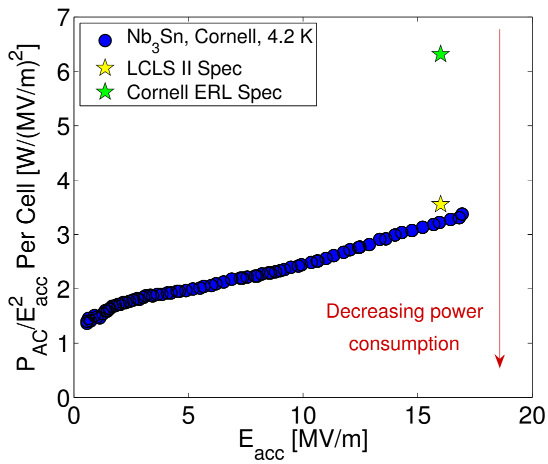

Figure 2: P_{AC}/E_{acc}^2 per cell versus gradient calculated from the Q_0 vs E_{acc} curve of a 1.3 GHz cavity coated with Nb_3Sn (coating 4 of Cavity 1). The calculated cryogenic efficiency is higher than the targets for both LCLS-II and the Cornell ERL.

to R_{res} measured at low fields in a 1.5 GHz Nb_3Sn cavity from [20].

In the Nb_3Sn cavity tests presented here, quench occurred between 11 and 17 MV/m. To investigate the cause of quench, microscopic studies were performed at ANL on a witness sample coated together with Cavity 1 [21]. Figure 5 shows the results of X-ray diffraction (XRD) studies at the Advanced Photon Source. The doubled peaks suggest that the volume is dominated by Nb_3Sn with composition of approximately 25 atomic percent tin, and by Nb_3Sn with approximately 18 atomic percent tin (based on data of lattice parameter as a function of tin content from [22–24]). This may be consistent with the observation of material with T_c of about 6 K in some RF tests after material removal [12]. Low tin content material may also have lower critical fields.

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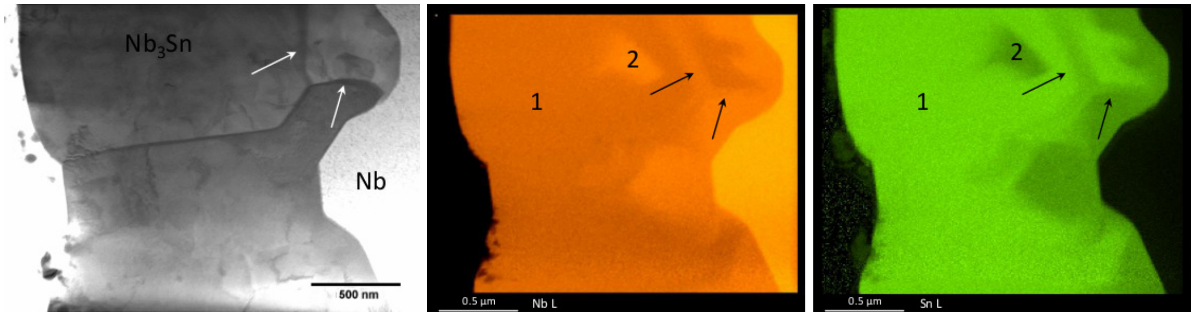

Figure 3: Left: TEM image of the Nb_3Sn layer and the Nb substrate below it (RF surface is on the left of the image). Arrows indicate what appear to be grain boundaries. Right: XEDS scans for the TEM sample, with niobium (middle) and tin (right) concentrations by brightness of the color. Most areas near the surface (region 1) have tin content of approximately 25 atomic percent, but the grain boundaries, the areas near the Nb bulk, and one region near the RF surface show a smaller tin content (region 2 shows a content of approximately 17 atomic percent).

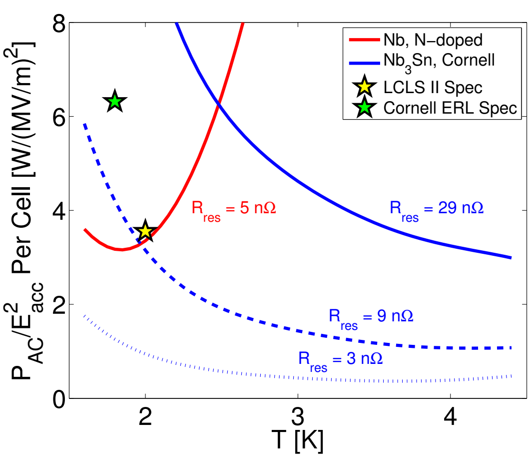

Figure 4: P_{AC}/E^2_{acc} per cell versus T for a 1.3 GHz cavity based on BCS calculations. Due to their small BCS resistance, if R_{res} is fairly small, Nb_3Sn cavities can have significantly improved cryogenic efficiency compared to nitrogen-doped Nb cavities at their respective optimal temperatures.

These would both expected to contribute to a lower quench field.

Transmission electron microscopy studies support these observations. They revealed the presence of low tin content volumes in close proximity to the RF surface, as shown in Fig. 3.

CONCLUSIONS

Very promising results were obtained on Nb_3Sn 1.3 GHz single cell SRF cavities coated and tested at Cornell. In five coatings, RF testing at 4.2 K showed an average quench field of 14 MV/m, with an average Q_0 at quench of 8×10^9. The highest quench field obtained was 17 MV/m. Taking into account the efficiency of the cryogenic plant, this single-cell cavity exceeds the gradient and cryogenic power requirements of the LCLS-II cavities. Future research and development to reduce residual resistance is expected to increase Q_0 values even further. Microscopic investigations at Argonne into the cause of quench using XRD and TEM suggest the presence of tin deficient volumes near the RF layer may be the culprit. For additional details, please see [25, 26]. Several other labs are now starting programs to continue the development of Nb_3Sn cavities, including Fermilab, where a large coating chamber is being designed to fabricate Nb_3Sn coated 9-cell 1.3 GHz cavities and 5-cell 650 MHz cavities. A collaboration between Cornell and Fermilab is underway to investigate an early cavity coating whose poor performance appeared to be connected to problems with the niobium substrate.

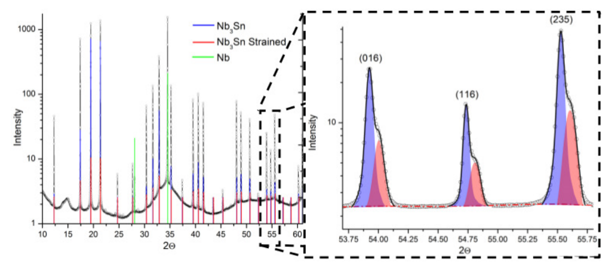

Figure 5: XRD scan of a witness sample consistently shows two strong peaks (blue and red) suggesting the presence of Nb_3Sn with the expected 25 atomic percent tin composition and Nb_3Sn with lower tin content, closer to 18 percent.

REFERENCES

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

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

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

[4] G. Arnolds and D. Proch, *IEEE Trans. Magn.* 13, 500 (1977).

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

ISBN 978-3-95450-168-7

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

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

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

[9] E. Saur and J. Wurm, *Naturwissenschaften* 49, 127 (1962).

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

[11] S. Posen and M. Liepe. Phys. Rev. ST-AB 17 112001 (2014).

[12] S. Posen, *Understanding and Overcoming Limitation Mechanisms in Nb3Sn Superconducting RF Cavities*, Ph.D. thesis, Cornell University (2015).

[13] M. Peiniger, M. Hein, N. Klein, G. Müller, H. Piel, and P. Thuns, in Proc. Third Work. RF Supercond. (Argonne National Laboratory, 1988).

[14] S. Meyers, S. Posen, and M. Liepe, Proc. of the 27th LINAC Conference, TUPP018 (2014).

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

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

[17] T. Orlando, et al., Phys. Rev. B 19, 4545 (1979).

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

[19] D. Gonnella and M. Liepe, Proc. Fifth Int. Part. Accel. Conf. (2014).

[20] G. Müller, H. Piel, J. Pouryamout, P. Boccard, and P. Kneisel, in Proc. Work. Thin Film Coat. Methods Supercond. Accel. Cavities, edited by D. Proch (TESLA Report 2000-15, Hamburg, 2000).

[21] C. Becker et al. *App. Phys. Lett.* 106, 082602 (2015).

[22] H. Devantay, J. L. Jorda, M. Decroux, and J. Muller, *J. Mater. Sci.* 16, 2145 (1981).

[23] L. J. Vieland RCA Rev. 25 (1964).

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

[25] S, Posen, M. Liepe, and D. L. Hall. *App. Phys. Lett.* 106 082601 (2015).

[26] D. L. Hall et al. "Recent Studies on the Current Limitations of State-of-the-Art Nb3Sn Cavities," WEPTY074, this conference (2015).