ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP011

HIGH FREQUENCY Nb_3Sn CAVITIES*

R. D. Porter†, M. Liepe, J. T. Maniscalco
Cornell Laboratory for Accelerator-Based Sciences and Education (CLASSE),
Ithaca, NY 14853, USA

Abstract

Niobium-3 Tin (Nb_3Sn) is currently the most promising alternative material for next-generation superconducting RF accelerator cavities. The material can achieve higher quality factors, higher temperature operation and potentially twice the accelerating gradients compared to conventional niobium. Cornell University has a leading program to coat 2-3 µm of Nb_3Sn on Nb cavities. These cavities achieve high Q of $2 \cdot 10^{10}$ at 1.3 GHz and 4.2 K with accelerating gradients in the typical CW operation range (17 MV/m). Most research into Nb_3Sn cavities has been done at 1.3 GHz. This material may have favorable frequency scaling, allowing for smaller cavities with the same efficiency. Here we present results from a 2.6 GHz Nb_3Sn cavity, including quality factor, magnetic flux trapping sensitivity and quench field measurements. Preliminary results from a 3.9 GHz cavity are also shown. We show 2.6 GHz Nb_3Sn cavities are viable and nearly as efficient as 1.3 GHz cavities.

INTRODUCTION

Niobium-3 Tin (Nb_3Sn) is a promising alternative superconductor to niobium for superconducting RF cavities. The material posses a critical temperature of 18 K [1] and a theoretical superheating field of 425 mT [2]. This allows the material to achieve high quality factors ($> 10^{10}$ at 4.2 K operation) and the potential to reach ≈ 96 MV/m in a TESLA elliptical style cavity (though the performance is currently limited to 17 MV/m, which is a topic of study [3]).

Cornell has a program to develop Nb_3Sn accelerator cavities [4–8]. Due to Nb_3Sn being a brittle material, a niobium substrate is formed into a cavity shape then Nb_3Sn is applied to the surface. This is accomplished using Sn vapor diffusion, wherein the Nb cavity is placed in a high temperature vacuum furnace where Sn is vaporized and allowed to settle on the Nb surface and form Nb_3Sn.

Most development of Nb_3Sn cavities has been done at 1.3 GHz. The frequency scaling of Nb_3Sn cavities residual resistance is unknown, so this may not be the ideal operating frequency (lowest loss/m of accelerator) for Nb_3Sn cavities. One main component of residual resistance in Nb_3Sn cavities is caused by magnetic flux trapped during cooldown [5], so the frequency scaling of this loss mechanism is of particular interest. This is referred to as the trapped flux loss sensitivity of the cavity and is expressed in terms of nΩ of residual surface resistance gained per mG of trapped magnetic flux. This paper examines the performance of a 2.6 GHz Nb_3Sn cavity, including cavity quality factor and trapped flux loss sensitivity. Preliminary results from a 3.9 GHz Nb_3Sn cavity are presented as well.

Similar research is simultaneously being conducted by Fermi National Accelerator Laboratory (FNAL) [9]. These studies both replicate and complement each other as both labs have not tested the same frequencies. In addition, the Nb_3Sn cavities produced at FNAL and Cornell differ in performance, where some of the initial FNAL Nb_3Sn cavities exhibit a Q slope before quench, while Cornell cavities do not. This creates a scenario where frequency studies by both labs help investigate the difference and similarities of the Nb_3Sn coatings and replication provides additional insight. However, as these studies are being completed and published near simultaneously, comparison of results between FNAL and Cornell will be minimal in this work, but may be addressed in future work.

2.6 GHz Nb_3Sn CAVITY PREPARATION

A new high-RRR Nb 2.6 GHz TESLA elliptical cavity recieved 100 µm of electropolishing. This was followed by the standard Nb_3Sn coating Cornell uses for 1.3 GHz Nb_3Sn cavities [10] that applies 2-3 µm of Nb_3Sn to the surface of the cavity. This process involves ≈ 2 days degas at 180 C, followed by nucleation using 0.220 g of Sn_2Cl at 500 C for 5 hours, a coating stage at 1120 C for 1.5 hours, and an annealing stage at 1120 C for 1 hour. During the coating stage a crucible of Sn is heated to 1400 C to increase Sn flux. A picture of the final coated cavity in Fig. 1 and a profile of the temperatures (excluding degas stage) are shown in Fig. 2. The cavity was prepared for test and tested in a vertical test cryostat with ≈ 2 mG of ambient magnetic field.

Figure 1: Left to right: A 1.3 GHz, 2.6 GHz, and 3.9 GHz Nb_3Sn cavities. The 3.9 GHz cavity has a top plate and clamps attached for testing.

* This work was supported by the U.S. National Science Foundation under Award PHY-1734189
† rdp98@cornell.edu

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP011

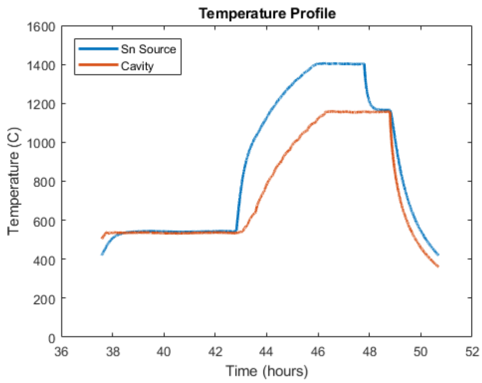


Figure 2: Temperature profile from the coating of the 2.6 GHz cavity. Both the temperature of the cavity and the Sn source are shown.

2.6 GHz CAVITY PERFORMANCE

Figure 3 shows the cavity performance at 4.2 K and 1.7 K. The cavity achieved a low field quality factor of $8 \cdot 10^9$ at 4.2 K and $3.5 \cdot 10^{10}$ at 1.7 K with only 5 nΩ of residual resistance.

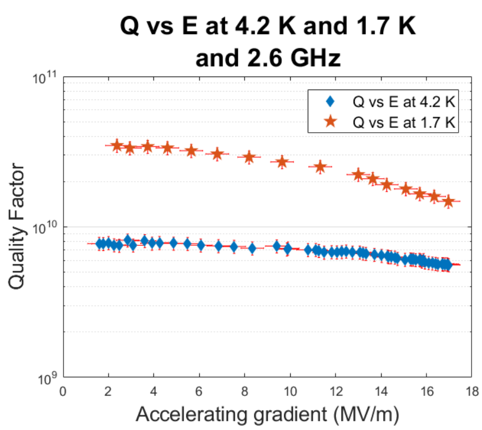
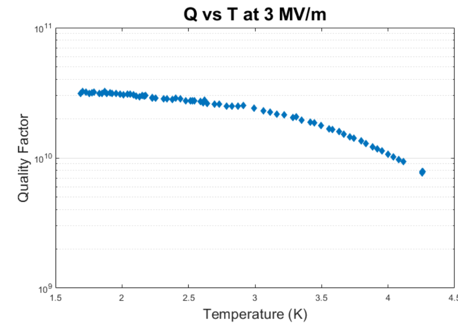


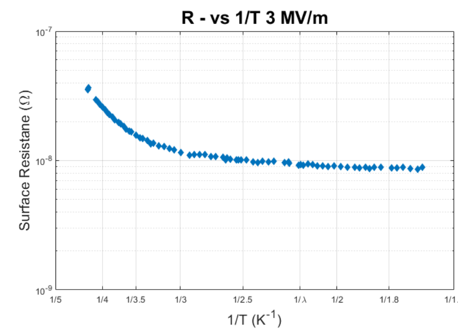
Figure 3: Q vs E curve at 4.2 K and 1.7 K of the 2.6 GHz Nb_3Sn cavity.

The quality factor at 4.2 K is 50 times larger than that of Nb at 4.2 K and 2.6 GHz, and comparable to Nb at 2 K and 2.6 GHz. Note that quality factors of different frequency resonators cannot be directly compared and a 2.6 GHz cavity with a Q of $8 \cdot 10^9$ is roughly equivalent to a 1.3 GHz cavity with a Q of $1.6 \cdot 10^{10}$.

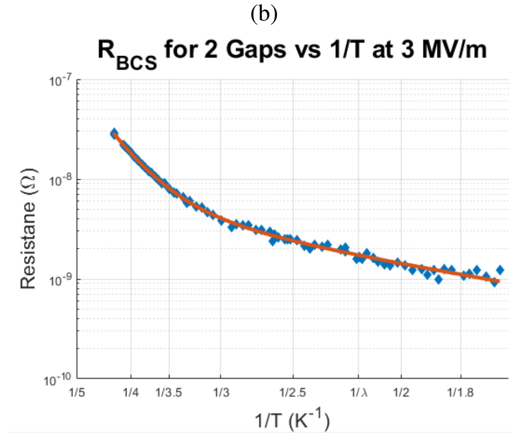
Figure 4 shows the quality factor vs temperature, resistance vs temperature, and R_{BCS} vs temperature of the cavity. The R vs 1/T plot exhibits an unexpected behavior: the low temperature resistance should be residual dominated ($R_{BCS}(T = 2\,K) \approx 10\,p\Omega$) and be flat, but instead has a mild slope. This appears to be caused by a multi-gap behavior recently observed in Cornell Nb_3Sn cavities (1.3 GHz and 2.6 GHz) and discussed further in R. D. Porter *et al.* [11]. This multi-gap behavior may be caused by non-stoichiometric regions of Nb_3Sn with different T_c's creating a spread of T_c's on the cavity surface. The residual resis-



(a)



(b)



(c)

Figure 4: (a) Q vs T curve of the 2.6 GHz cavity. (b) R vs 1/T curve of the 2.6 GHz cavity. (c) R_{BCS} vs 1/T curve of the 2.6 GHz cavity with fit 2-gap curve.

tance has been found by fitting two BCS curves to the data, one that is typical Nb_3Sn and one that is a low T_c material that covers a small fraction of the cavity surface (the fit finds $\approx 10^{-5}$ of cavity surface). The fit parameters of the second material may not be physically relevant, but the fit is good and allows for the separation of temperature and non-temperature dependent (residual) components of the surface resistance. This finds a residual resistance of 5 nΩ with the second gap contributing an additional ≈ 5 nΩ of surface resistance at 4.2 K.

TRAPPED FLUX LOSS SENSITIVITY

The magnetic trapped flux loss sensitivity of the 2.6 GHz cavity was measured by trapping 60 mG and 100 mG ap-

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP011

plied by a Helmholtz coil during separate cool-downs. The trapped flux was measured using fluxgate magnetometers on the top iris, equator, and bottom iris. The trapped flux was determined in 3 ways: 1. by measuring the change in magnetic field through the superconducting transition (no change for 100% trapping). 2. By measuring the magnetic field after transition with the Helmholtz coil off and comparing to magnetic simulations of expelling and trapping flux. 3. By measuring the magnetic field after transition with the Helmholtz coil off and comparing to a cooldown with (near) zero field trapped, after transition, and measuring the magnetic field with the Helmholtz coil turned on to the same current as the trapping scenario (measures full expulsion magnetic field). These three methods replicate the Cornell, FNAL, and JLab (Thomas Jefferson National Accelerator Facility) methods of measuring trapped magnetic flux. All find 100% flux trapping, which is expected for the slow cooldown rates used for Cornell Nb_3Sn cavities (0.1 K/min).

The trapped flux loss sensitivity results are shown in Fig. 5 along with 1.3 GHz Nb_3Sn cavity results[1] [12, 13]. The trapped flux loss sensitivity curve is different in shape: while the trapped flux loss sensitivity for a 1.3 GHz is linear with the accelerating gradient/surface magnetic field, for the 2.6 GHz cavity the sensitivity is flat at low fields. This has also been observed in 3.9 GHz Nb_3Sn cavities at FNAL [9].

In the 'high' fields region (above 25 mT), the slope is 17.5 pΩ/mG/mT, which is roughly $\sqrt{2}$ times higher than the 1.3 GHz cavity result of 12.2 pΩ/mG/mT. This suggests a $\sqrt{f}$ scaling of flux trapping sensitivity in Nb_3Sn cavities in this frequency region. It was not theoretically obvious that this would be the case. Theoretical models developed by D. Liarte *et al.* predicts various frequency scaling depending on the material parameters and frequency [14].

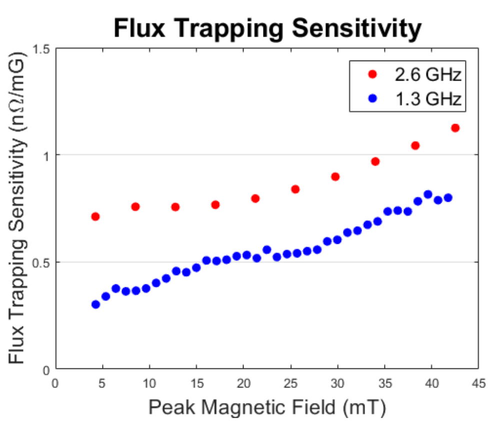


Figure 5: Trapped flux loss sensitivity of 2.6 GHz and 1.3 GHz [13] Nb_3Sn cavities.

[1] The flux trapping data from the cited paper is off by a factor 0.58 and has been corrected for this paper. The correction was discussed at a Tesla Technology Collaboration (TTC) meeting and has not been published in a paper at the time of writing [12].

FREQUENCY DEPENDENCE OF QUENCH FIELD

Nb_3Sn can potentially reach 96 MV/m for a TESLA elliptical cavity, but current Cornell cavities are limited to ≈ 17 MV/m in CW by a local surface defect [15]. Identifying and removing this defect is the subject of important research. The 2.6 GHz cavity quenched at (17 ± 1) MV/m, consistent with 1.3 GHz cavities. This suggests the quench defect has little or no frequency dependence.

PRELIMINARY 3.9 GHz CAVITY RESULTS

A 3.9 GHz Nb_3Sn cavity has also been made and a preliminary Q vs E curve at 4.2 K is shown in Fig. 6. This initial test was plagued by fundamental power coupler problems that prevented complete measurement of the cavity and may have compromised the data that is shown. For this reason the displayed 3.9 GHz cavity data that is shown should be considered preliminary and may change after additional testing. The preliminary data finds a low field Q of $\approx 2 \cdot 10^9$ and quench field consistent with lower frequency Nb_3Sn cavities.

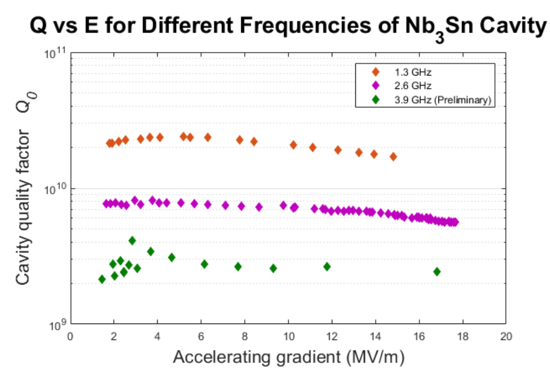


Figure 6: Q vs E curve at 4.2 K of 1.3 GHz, 2.6 GHz, and 3.9 GHz Nb_3Sn cavities.

CONCLUSION

Niobium-3 Tin cavities have comparable efficiency at 2.6 GHz to 1.3 GHz Nb_3Sn cavities and trapped flux losses appear to scale $\sqrt{f}$, a favorable result for high frequency Nb_3Sn cavities. This allows for the use of smaller accelerator cavities without loss of performance. In addition, these higher frequency cavities provide insight into current performance limitations because the lack of (or small) dependence of the quench field on frequency limits the types of defects that could be responsible for quench. Finally, trapped flux loss sensitivity measurements are not only important to characterize for construction of accelerators; it provides feedback for theoretical models that multiple researchers have been trying to create.

Figure 7 shows the cooling wall power per meter of active accelerator for Nb at 1.3 GHz and 2 K, Nb_3Sn at 1.3 GHz and 4.2 K, and Nb_3Sn at 2.6 GHz and 4.2 K. The 2.6 GHz

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP011

Nb_3Sn cavity is almost as efficient as the 1.3 GHz Nb_3Sn cavity. This shows the favorable scaling of Nb_3Sn with frequency. The 2.6 GHz and 3.9 GHz cavities can operate at 4.2 K while achieving higher efficiencies than standard Nb cavities at 3.9 GHz.

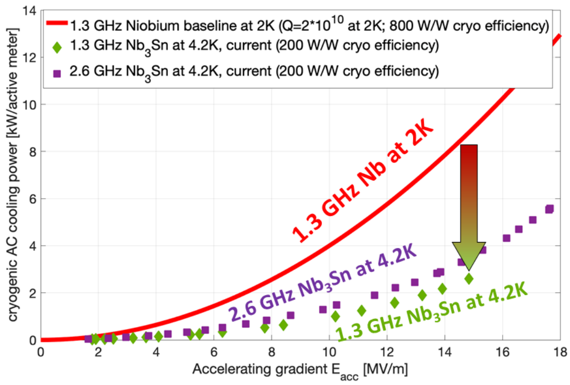


Figure 7: Cryogenic AC cooling power requred per meter of accelerator made using Nb_3Sn and standard Nb cavities.

REFERENCES

[1] A. Godeke, "A review of the properties of Nb_3Sn and their variation with A15 composition, morphology and strain state," *Superconductor Science and Technology*, vol. 19, no. 8, p. R68, Aug. 2006. doi:10.1088/0953-2048/19/8/r02

[2] G. Cetelani and J. P. Sethna, "Temperature Dependence of the Superheating Field for Superconductors in the high-kappa London Limit," *Phys. Rev. B*, vol. 78, no. 22, p. 224509, Dec. 2008. doi:10.1103/PhysRevB.78.224509

[3] R. D. Porter *et al.*, "Field Limitation in Nb_3Sn Cavities," presented at SRF'19, Dresden, Germany, July 2019, paper THFUA5, this conference

[4] S. Posen, "Understanding and Overcoming Limitation Mechanisms in Nb_3Sn Superconducting RF Cavities," Ph.D. dissertation, Phys. Dept., Cornell University, Ithaca, NY, USA, 2014.

[5] D. L. Hall, "New Insights into the Limitations on the Efficiency and Achievable Gradients in Nb_3Sn SRF Cavities," Ph.D. dissertation, Phys. Dept., Cornell University, Ithaca, NY, USA, 2017.

[6] D. L. Hall, J. J. Kaufman, M. Liepe, R. D. Porter, and J. Sears, "First Results From New Single-Cell Nb3Sn Cavities Coated at Cornell University," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 40–43. doi:10.18429/JACoW-IPAC2017-MOOCA2

[7] S. Posen and M. Liepe, "Advances in development of Nb_3Sn superconducting radio-frequency cavities," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 112001, Nov. 2014. doi:10.1103/PhysRevSTAB.17.112001

[8] S. Posen and D. L. Hall, "Nb3Sn Superconcdution Radiofrequency Cavities: Fabrication, Results, Properties, and Prospects," *Superconductor Science and Technology*, vol. 30, no. 3, p. 33004, Jan. 2017. doi:10.1088/1361-6668/30/3/033004

[9] S. Posen, "Frequency dependence studies of Nb_3Sn cavities," presented at TESLA Technology Collaboration Meeting, Vancouver, Canada, Feb 2019

[10] D. L. Hall, M. Liepe, and J. T. Maniscalco, "RF Measurements on High Performance Nb_3Sn Cavities," in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2320–2322. doi:10.18429/JACoW-IPAC2016-WEPMR024

[11] R. D. Porter *et al.*, "Optimization of Nb_3Sn Coatings for SRF Cavities," presented at SRF'19, Dresden, Germany, July 2019, paper MOP012, this conference

[12] R. D. Porter, "T-mapping, B-measurements and vertical diagnostics at Cornell," presented at TESLA Technology Collaboration Meeting, Vancouver, Canada, Feb 2019

[13] D. L. Hall *et al.*, "Impact of Trapped Magnetic Flux and Thermal Gradients on the Performance of Nb_3Sn Cavities," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1127–1129. doi:10.18429/JACoW-IPAC2017-MOPVA118

[14] D. Liarte *et al.*, "Vortex dynamics and losses due to pinning: Dissipation from trapped magnetic flux in resonant superconducting radio-frequency cavities," *Phy. Rev. App.*, vol. 10, no. 5, p. 054057, Nov. 2018. doi:10.1103/PhysRevApplied.10.054057

[15] D. L. Hall *et al.*, "Cavity Quench Studies in Nb3Sn Using Temperature Mapping and Surface Analysis of Cavity Cutouts," in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 840–843. doi:10.18429/JACoW-SRF2017-THPB041