QUENCH STUDIES IN SINGLE-CELL Nb_3Sn CAVITIES COATED USING VAPOUR DIFFUSION*

D.L. Hall†, P. Cueva, D.B. Liarte, M. Liepe, J.T. Maniscalco, D.A. Muller, R.D. Porter, J.P. Sethna
Cornell University,
Ithaca, NY 14853, USA

Abstract

The superconductor Nb_3Sn is known to have a superheating field, H_{sh}, of approximately 400 mT. This critical field represents the ultimate achievable gradient in a superconducting cavity, and is equivalent to an accelerating gradient of 90 MV/m in an ILC single-cell cavity for this value of H_{sh}. However, the currently best performing Nb_3Sn single-cell cavities remain limited to accelerating gradients of 17-18 MV/m, translating to a peak surface magnetic field of approx. 70 mT. In this paper, we consider theoretical models of candidate quench mechanisms, and compare them to experimental data from surface analysis and cavity tests.

INTRODUCTION

Niobium cavities coated with Nb_3Sn at Cornell University are currently limited by quench at fields from 14 up to 17-18 MV/m, largely independent of substrate preparation, coating recipe, and post-processing techniques [1–4]. This quench field, corresponding to a peak magnetic field of 60-70 mT, is considerably lower than the expected superheating field of approximately 400 mT [5].

In an effort to understand the dynamics of these quenches, and from it their cause, we utilised high-speed temperature mapping to observe the behaviour of the cavity, particularly the surface near the quench location, as the cavity was brought close to the quench field. Here we present the first results from this study.

EXPERIMENTAL METHOD

The temperature mapping system in use at Cornell University [6] is an array of cryogenic temperature sensors that are mounted onto a single-cell 1.3 GHz cavity, as seen in Fig. 1. Composed of 768 sensors, each one a 100Ω (at room temperature) carbon resistor, the array is mounted on 38 boards equipped with 17 sensors each that surround the cavity. Through the use of set screws, the resistors are pressed against the cavity surface, with good thermal contact being ensured through the application of thermal paste to each sensor head. Each sensor is capable of a resolution of 1 mK or less at a bath temperature of 2.0 K.

The temperature map can be operated in one of three modes. In the most basic mode, the cavity is kept at a constant RF power while the voltage across each sensor (equivalent to its temperature via a known calibration) is measured. Such a measurement takes approximately 15 minutes per acquisition. In the second mode, the cavity is allowed to quench multiple times while the system scans board-per-board, searching for sudden spikes in temperature associated with a cavity quench. In this mode, the resolution of the system is sorely impacted, but due to the large temperature spikes associated with a quench, this is not a problem for the purposes of the measurement. This particular mode results in a *quench map*, indicating the location(s) of the cavity quench.

A third mode was designed specifically for this experiment, dubbed *single-scan* mode, in which a single sensor is scanned at high speed – 20 kHz – while maintaining the high resolution of the temperature mapping basic mode. The sacrifice to be made is that only a single sensor can be operational at any one time. However, for the purposes of monitoring a specific location, such as the region known to be the centre of the cavity quench, this mode is ideal.

RESULTS

A quench map of the cavity, shown in Fig. 2, located the cavity quench to a region on the lower half-cell of the cavity, centre at board 28, resistor 4. This sensor was chosen to be

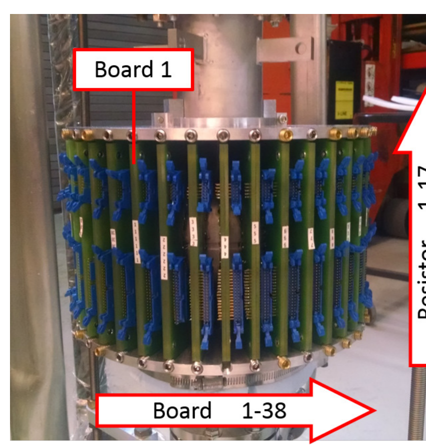

Figure 1: The single-cell temperature mapping system in use at Cornell University, mounted onto a 1.3 GHz single-cell ILC-style cavity coated with Nb_3Sn. The cables connecting the boards to the data acquisition system have been removed for better visibility.

* This work was primarily supported by U.S. DOE award DE-SC0008431. This work was supported in part by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams. This work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1120296). Travel to IPAC'17 supported by the Division of Physics of the United States National Science Foundation (Accelerator Science Program) and the Division of Beam Physics of the American Physical Society.

† dlh269@cornell.edu

ISBN 978-3-95450-182-3

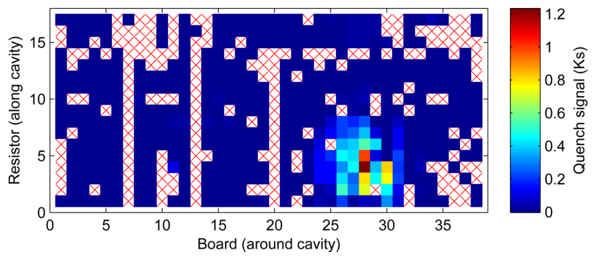

Figure 2: A quench map of the cavity, indicating the location of the quench. The quench map integrates with respect to time the temperature of the sensor after the quench is detected on the RF signal. Regions that remain hotter for longer indicate a sensor closer to the quench origin. A red cross indicates a non-responsive sensor.

the primary sensor of interest for measurements done using the new single-scan mode of the temperature map.

An example of a single-scan trace is shown in Fig. 3. A trigger signal initiates the acquisition of the chosen sensor on the temperature map, as well as the power meter monitoring the transmitted power from the cavity. From a previously obtained calibration factor, this transmitted power measurement provides a measurement of the peak RF field in the cavity. Shortly after the trigger signal is sent, the RF power is turned on, and the power in the cavity is allowed to raise to a maximum level determined by the Q_0 of the cavity and the power setting on the amplifier. Provided the cavity does not quench, the RF power will be turned off approximately 20 seconds afterwards, whereupon the cavity is allowed to ring down. After 50 seconds, the acquisition is complete.

The quench field of an Nb_3Sn cavity, once known, is precisely defined and highly repeatable. This allows operation at only 2-4 mT beneath the quench field of the cavity. By carefully increasing the power setting on the amplifier, the

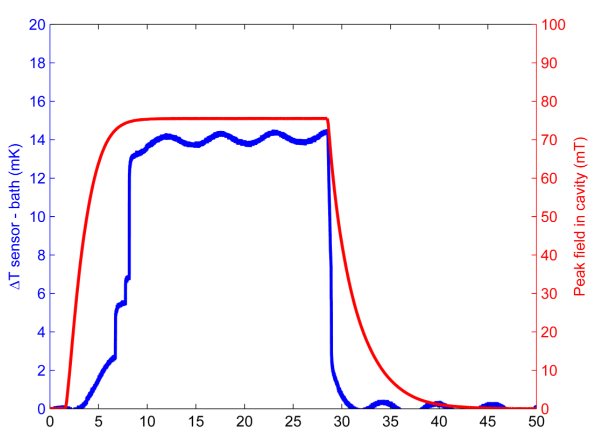

Figure 3: A single-scan trace, showing the RF field in the cavity (in red) and the temperature of the sensor at located at the quench origin (in blue). The oscillations seen on the temperature signal are due to the valve oscillations from the pumping system that keeps the bath temperature at 2.0 K.

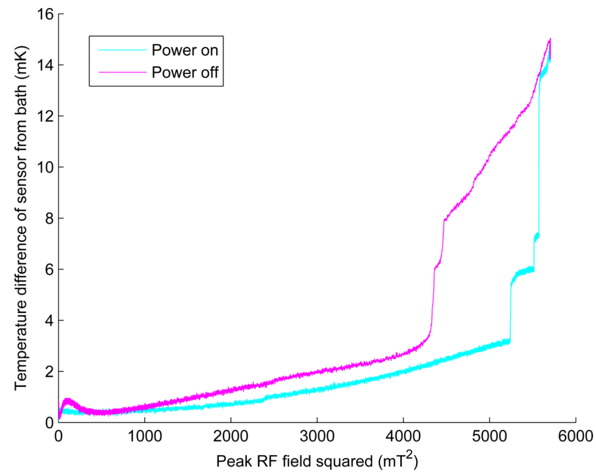

Figure 4: A plot of the ΔT of the sensor at the quench origin with respect to the bath versus the square of the RF magnetic field in the cavity. In this plot, Ohmic losses appear as a linear dependence. The cyan line is data obtained as the cavity powered up, while the magenta line was obtained as the cavity was allowed to ring down.

field at which the cavity equilibrates can be set to be just beneath the quench field.

As the equilibrated field in the cavity was brought closer to the quench field (although never actually allowing the cavity to quench, as this would cause the Q_0 to degrade significantly and require a thermal cycling), sudden jumps in temperature were seen on the sensor immediately on top of the quench location. These jumps were found to be highly repeatable, always happening at the same level of RF field in the cavity, and always showing the same jump in temperature across multiple scans.

By plotting the square of the peak RF field in the cavity as a function of the temperature difference of the sensor from the helium bath, as shown in Fig. 4, the phenomenon is evident. When plotted again B^2, ohmic losses appear as a linear dependence in ΔT. The jumps in temperature are evident at higher fields, as is the significant hysteresis seen between when the cavity powers up vs. when it rings down.

SURFACE DEFECT CANDIDATES AND POSSIBLE EXPLANATIONS

The presence of sudden, repeatable jumps in temperature as the quench field is approached, as well as the hysteresis seen between powering up and ringing down, strongly suggest the presence of flux entry at a defect. Furthermore, the height of the jumps are, to within measurable accuracy, integer multiples of the smallest jump observed, which lends further credence to the suspicion that we are seeing flux entry, since vortices are quantised. However, the exact nature of the feature that would cause this flux entry has yet to be ascertained.

One candidate for flux entry is the presence of tin-depleted phases of Nb_3Sn at the surface of the layer. Tin depletion of Nb_3Sn, which can range from its stoichiometric form at 25

ISBN 978-3-95450-182-3

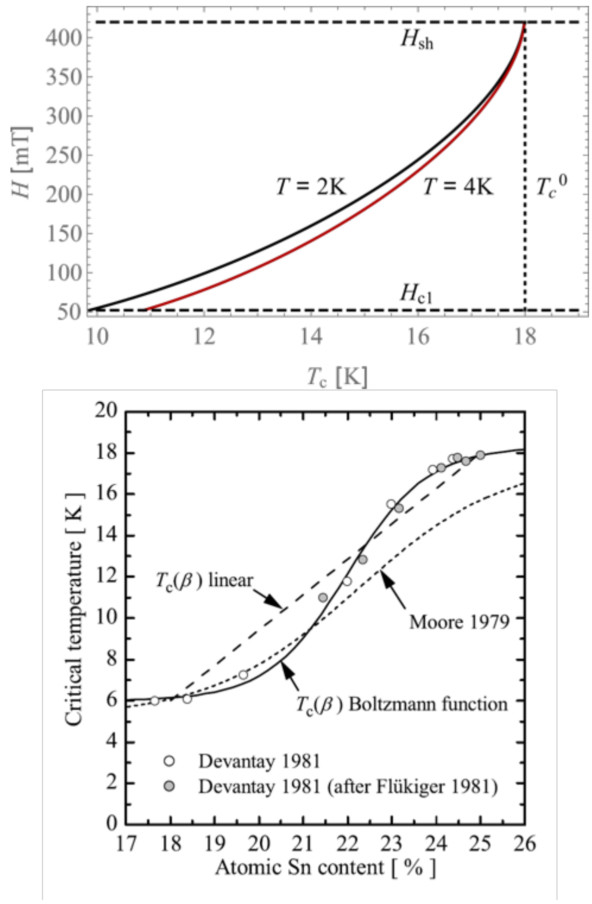

Figure 5: (Top) Calculations of the flux entry field as a function of the T_c suppression in the first 100 nm of the RF surface and (Bottom) the dependence of the T_c on the atomic-% Sn [7].

atomic-% Sn down to 16-17 atomic-% Sn, suppresses the superconducting transition temperature of the material [7]. Calculations using the Bean-Livingston model in a model of disorder-mediated nucleation of vortices demonstrate that the flux entry field is swiftly reduced by even minor suppressions of T_c [8]. This result is shown in Fig. 5.

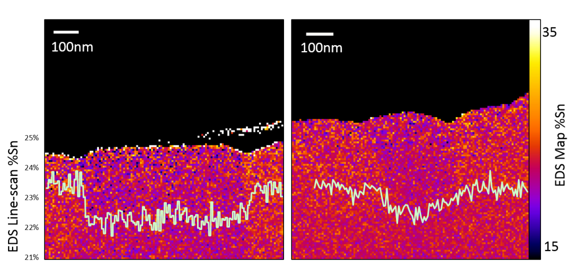

Figure 6: An EDS map of two grains on the surface of the Nb_3Sn layer, seen in a cross-section view by TEM. Superimposed on the grains are linescans giving a more detailed observation of the atomic-% Sn content in the grain relative to its neighbours.

Such candidates for T_c suppression have already been found in cut-outs from sample coupons coated in the sample furnace utilised for coating cavities, with the exact same recipe. In Fig. 6, EDS maps of grains at the surface of the Nb_3Sn layer are seen, with EDS line scans revealing a reduction in the tin content of some grains relative to their neighbours. Although the tin depletion is only minor, as can be seen in Fig. 5, a decrease of approximately 2-3 atomic-% Sn is all that is necessary for the flux entry field to fall from 400 mT to below 200 mT.

CONCLUSION

Detailed temperature mapping studies of a niobium cavity coated with Nb_3Sn at Cornell University demonstrate that the quench, which occurs at approximately 17 MV/m (equivalent to 72 mT peak RF magnetic field) in this instance, is localised to a well defined region on the lower half-cell of the cavity. A new temperature mapping method for high-speed, high-resolution scanning of the quench origin as RF power is fed into the cavity reveals sudden jumps in temperature at the quench origin as the field in the cavity approaches the quench field.

The nature of these jumps strongly suggests quantised flux entry preceding the quench. The cavity in question will soon be dissected for the purposes of careful surface analysis of the quench origin. Until more can be ascertained, potential candidates for the nature of a defect that could cause the behaviour seen here are tin-depleted regions at the RF surface resulting in a T_c suppression with associated lowered flux entry field, and quantised flux entry at grain boundaries acting as strongly coupled Josephson junctions [9].

REFERENCES

[1] Daniel Leslie Hall, John Julian Kaufman, Matthias Liepe, Ryan Douglas Porter, and James Sears. First Results from New Single-Cell Nb3Sn Cavities Coated at Cornell University. In *Proceedings of IPAC 2017*, Copenhagen, May 2017.

[2] Sam Posen and Daniel Leslie Hall. Nb 3 Sn superconducting radiofrequency cavities: fabrication, results, properties, and prospects. *Superconductor Science and Technology*, 30(3):33004, 2017.

[3] Daniel Leslie Hall, Matthias Liepe, and James Maniscalco. RF Measurements on High Performance Nb3Sn Cavities. In *Proceedings of IPAC 2016*, Busan, May 2016.

[4] Daniel Leslie Hall. Next generation Nb3Sn cavities: Current performance, limitations, and considerations for practical use. In *Presented at the Tesla Technology Collaboration meeting at CEA Saclay*, Paris, 2016.

[5] Mark K. Transtrum, Gianluigi Catelani, and James P. Sethna. Superheating field of superconductors within Ginzburg-Landau theory. *Physical Review B*, 83(9):094505, March 2011.

[6] Jens Knobloch. *Advanced Thermometry Studies of Superconducting Radio-Frequency Cavities*. Phd, Cornell University, 1997.

ISBN 978-3-95450-182-3

[7] A Godeke. A review of the properties of Nb3Sn and their variation with A15 composition, morphology and strain state. *Superconductor Science and Technology*, 19(8):R68—-R80, August 2006.

[8] Danilo B Liarte, Sam Posen, Mark K Transtrum, Gianluigi Catelani, Matthias Liepe, and James P Sethna. Theoretical estimates of maximum fields in superconducting resonant radio frequency cavities: stability theory, disorder, and laminates. *Superconductor Science and Technology*, 30(3):033002, 2017.

[9] A. Sheikhzada and A. Gurevich. Dynamic transition of vortices into phase slips and generation of vortex-antivortex pairs in thin film Josephson junctions under dc and ac currents. *ArXiv e-prints*, March 2017.