RECENT STUDIES ON THE CURRENT LIMITATIONS OF STATE-OF-THE-ART Nb_3Sn CAVITIES[*]

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Abstract

Recent advances in the study of Nb_3Sn at Cornell University have yielded single-cell cavities that show excellent performance without the limiting Q-slope seen in previous work. This performance has been shown to be repeatable across multiple cavities. However, they are still limited by a quench field of approximately 16 MV/m, as well as residual resistance. In this work we present results quantifying the impact of ambient magnetic fields on Nb_3Sn cavities, as well as discuss the impact of cavity cooldown procedures on cavity performance. Finally, we will briefly discuss XRD results that shed light on the composition of the Nb_3Sn layer and how this relates to the current limits of these cavities.

INTRODUCTION

Studies on the fabrication and use of Nb_3Sn in superconducting radio-frequency (SRF) cavities at Cornell University have recently made considerable progress in developing Nb_3Sn as an alternative to niobium [1–4]. In this work we present results from the most recent work on Nb_3Sn at Cornell, with particular emphasis on measurements to determine the impact of ambient magnetic fields on the residual resistance of Nb_3Sn cavities. We also present data from two different cavity tests that demonstrate the impact that the procedure used to cool the cavity below its superconducting transition temperature has upon the cavity's performance. These measurements are critical in predicting how a Nb_3Sn cavity will behave when placed inside a cryomodule assembly, and what, if any, modifications will need to be made to accommodate it. Finally, we will briefly describe other recent measurements that have been made to determine both the fundamental properties and material parameters of Nb_3Sn fabricated at Cornell University using the vapour deposition method.

EXPERIMENTAL PROCEDURE

Cooldown Procedure

It is critical that niobium cavities coated with Nb_3Sn be cooled slowly through the transition temperature T_c of 18 K down to below 6 K to minimise the effects of magnetic fields generated by electric currents induced from thermal gradients. The method used to cool the cavities below their transition temperature is more completely described in Ref. [1], although a condensed version will be surmised here: the cavity is mounted upon an insert that is placed into a magnetically shielded cryostat, whereupon liquid helium is passed at a low flow rate through an injection port that is lined with heating elements, warming the incoming helium and thus allowing fine control of the temperature inside the cryostat. As the power of the heating elements is slowly reduced, the rate of the temperature decrease inside the cryostat is carefully controlled to ensure a minimal impact from thermal currents. This control system allows a rate control of between 2-30 min/K, with spatial gradients across the cavity of < 50-1000 mK (the latter being dependent upon the rate with time).

Flux Trapping Measurements

The method used to quantify the impact of external DC magnetic fields has been used in previous studies to investigate both standard niobium cavities as well as niobium cavities that have been doped with nitrogen [5]. Two solenoid coils are placed above and below the cavity in a Helmholtz configuration, to generate a magnetic field parallel to the cavity axis. Two flux gate magnetometers are placed on the cavity, one placed on the upper iris in parallel with the cavity z-axis (considering a cylindrical coordinate system in which the z-axis is placed along the path of the beam through the cavity), and one placed next to the previous pointing in the $\hat{\phi}$ direction. These are used to measure the field that is applied by use of the solenoids. As the cavity passes into the superconducting state and a fraction of the magnetic flux is expelled from the bulk of the cavity, these measurements are used to determine the amount of magnetic flux that has been trapped. A subsequent measurement of the cavity quality factor Q as a function of both temperature T and accelerating gradient E_{acc} is then used to quantify the impact of the externally applied magnetic field on residual surface resistance and its field dependence.

XRD and Phase Determination

XRD measurements were carried out at the APS at Argonne National Lab on Nb_3Sn samples fabricated at Cornell. The XRD provides a diffraction pattern from a region of spatial extent of approximately 1 mm wide and deep. The diffraction spectrum is used to determine the lattice parameter of the Nb_3Sn crystals, which is in turn used to infer

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the superconducting temperature of the material. The XRD results are used in conjunction with other measurements, including SEM and TEM, to determine the grain structure, composition, and stoichiometry of the Nb_3Sn layer.

RESULTS

Cavity Cooldown

Cornell University's best-performing Nb_3Sn cavity, designation *ERL1-4*, is a single-cell 1.3 GHz Cornell ERL-style cavity that has achieved fields up to 17 MV/m and Q's of 10^{10} at 4.2 K. It has recently been tested twice, once in September 2014 and again in February 2015. The results of a Q vs. E_{acc} measurement for these two tests are shown in Fig. 1. Between the two tests, the cooldown procedure was modified in an attempt to minimise the temperature gradient across the cavity at the expense of cooling rate, resulting in a faster cooldown of 10 min/K with a gradient of < 50 mK across the cavity in February 2015 as compared to September 2014, in which the cooldown rate was 20 min/K with a gradient of ≈ 100 mK over the cavity. Between these tests, the Q_0 increased by a factor of 2 at 14 MV/m, although the quench field was lower by ≈ 3 MV/m. Furthermore, the Q-slope of the cavity was reduced by $\approx 40\%$, resulting in less decrease of cryogenic efficiency with accelerating field. It is therefore crucial that Nb_3Sn cavities be cooled in a fashion that minimises spatial thermal gradients.

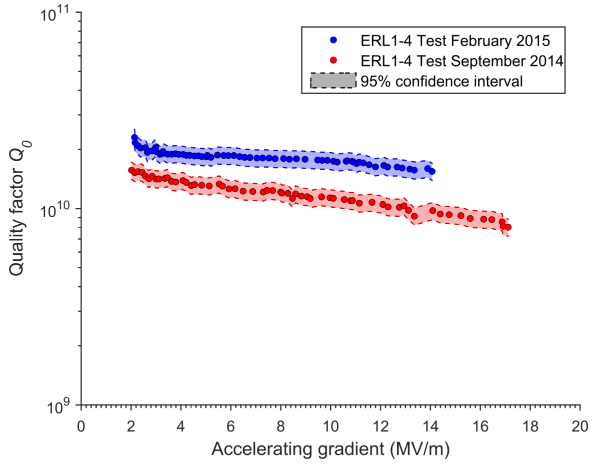

Figure 1: Two separate tests of the 1.3 GHz Nb_3Sn cavity designated ERL1-4, taken at a bath temperature of 4.2 K. The cooldown procedure was improved between the tests, which results in a higher quality factor and reduced Q-slope.

Flux Trapping Results

A plot of the residual resistance of the Nb_3Sn cavity at low accelerating field (1-3 MV/m) as a function of the amount of flux trapped in the walls of the cavity is shown in Fig. 2, compared to results from both a standard niobium cavity treated with a 120°C bake and a nitrogen-doped niobium cavity that has subsequently received 6 μm of vertical electropolishing [5]. Nb_3Sn shows a very similar trend to standard niobium, indicating that no extra magnetic shielding is required in a cryomodule when compared to the latter. Furthermore, Nb_3Sn shows a similar susceptibility to trapping magnetic flux as a function of the cooldown rate as for standard niobium.

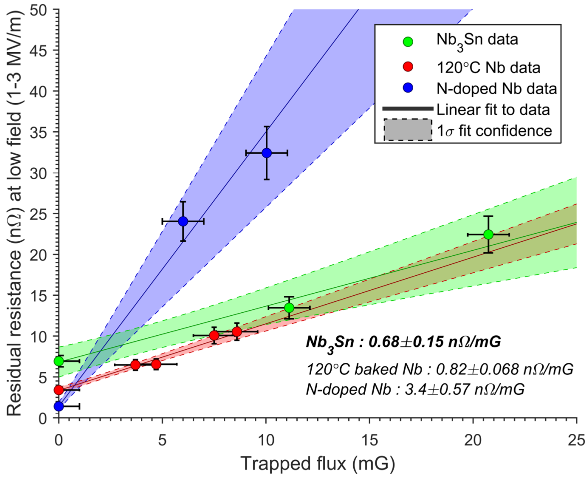

Figure 2: The residual resistance at low accelerating gradient (1-3 MV/m) as a function of trapped magnetic flux for a Nb_3Sn cavity, compared to a standard niobium cavity that has received a 120°C bake and a nitrogen-doped niobium cavity [5].

Results of a measurement of the residual resistance as a function of accelerating field, plotted in Fig. 3, show that the Q-slope is aggravated by the presence of external magnetic fields. Furthermore, the development of non-linearities in the Q-slope indicate the presence of thermal feedback, which quickly increases RF losses.

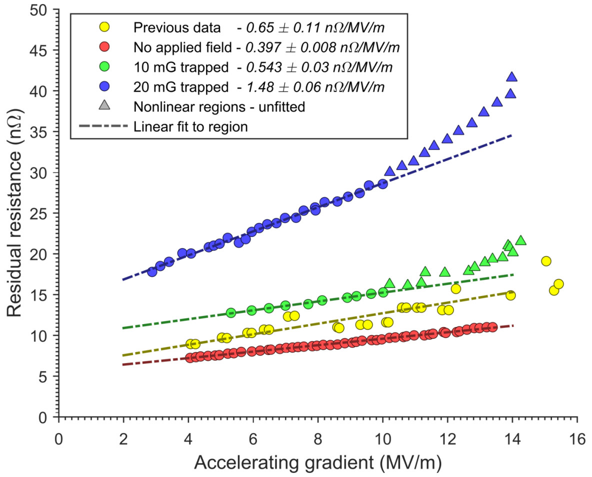

Figure 3: Residual resistance as a function of accelerating field for ERL1-4 with varying amounts of flux trapped. The Q-slope is increased as more flux is trapped, with the onset of non-linear regions indicating the presence of thermal feedback mechanisms at higher fields. These are compared to a previous test without applied field but different cool down procedure taken in September 2014.

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FIELD LIMITATION WORK

Other recent studies on Nb_3Sn have focused on fundamental material parameters as well as the nature of the material produced using the vapour deposition method used at Cornell. Studies at Argonne National Lab [6] have shown that regions exist in the Nb_3Sn layer, at a depth comparable to the penetration depth, that are tin-deficient and so have a lower critical temperature. These regions may well be responsible for causing quench at low fields, well below the theoretical limit. The existence of multiple atm. % Sn variants of Nb_3Sn are confirmed by new, high angular resolution XRD measurements, an example of which is shown in Fig. 4. Peaks in the diffraction pattern imply the presence of phases of Nb_3Sn that range from atm. % Sn of 27%, with a T_c of 18 K, down to 19%, with a T_c of 8-12 K. In the interests of increasing the cavity quench field, work is currently underway to modify the deposition process in an attempt to improve the stoichiometry of the Nb_3Sn layer and either commit these tin-deficient regions deep enough into the bulk as to render them irrelevant, or remove them entirely.

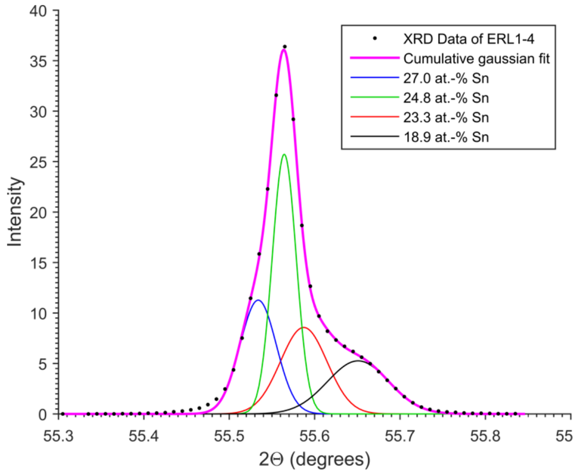

Figure 4: A single peak from an XRD spectrum showing the (116) peak of Nb_3Sn. The shape of the peak indicates the presence of Nb_3Sn phases that have a lower T_c, which may be the cause of the cavity quench at 13-17 MV/m.

Another study, carried out at Cornell University, has focussed on the measurement of the value of the upper critical field, H_{c2}, using a Physical Property Measurement System (PPMS) device to determine material properties. More details of this analysis can be found in Ref. [7].

CONCLUSION

Recent studies of the cooldown procedure on Nb_3Sn have shown that a slow cooldown with minimal gradient both across the length of the cavity and across the depth of the metal are most favourable for achieving a low residual resistance and Q-slope. Fortunately, current-generation cryomodules designed for niobium cavities such as Cornell's Horizontal Test Cryomodule and Main Linac Cryomodule are already capable of performing such cooldowns without any modification to the helium delivery system. Furthermore, measurements on the impact of external magnetic fields on the performance of Nb_3Sn indicate that no extra magnetic shielding is required compared to standard niobium cavities. These promising results suggest that a Nb_3Sn cavity could be accommodated into a current-generation cryomodule with only minimal modifications necessary.

Studies on the material properties of the Nb_3Sn with XRD have shown that multiple phases of Nb_3Sn exist within the Nb_3Sn layer, some of which are detrimental to the RF performance of the cavity. It is suspected that regions of these tin-deficient phases are responsible for the quench at fields of around 13-17 MV/m. Changes to the fabrication procedure are currently being experimented with in an effort to improve the stoichiometry of the Nb_3Sn layer. However, even the current state-of-the-art 1.3 GHz Nb_3Sn cavity, with a residual resistance of 10 nΩ at 14 MV/m, is a factor of 2 more power efficient when compared to a nitrogen-doped niobium cavity with a residual resistance of 3 nΩ, as seen in Fig. 5.

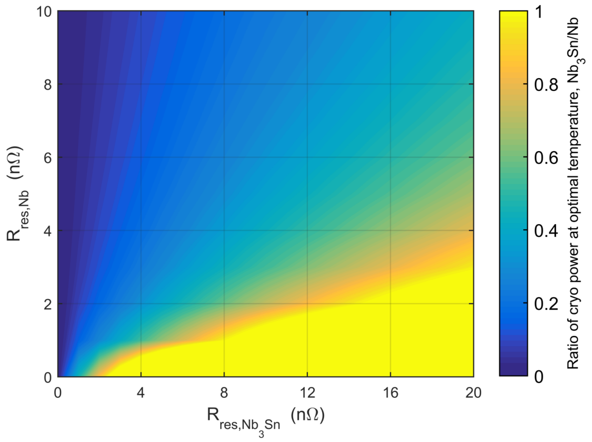

Figure 5: A contour plot of the ratio of the power draw of a 1.3 GHz Nb_3Sn against that of an identical N-doped Nb cavity, both operating at their respective optimal temperatures (in the range of 1.8 and 4.6 K) as a function of their residual resistance. A ratio of 0.5 indicates that the Nb_3Sn cavity is drawing half as much wall power than the Nb cavity for the same accelerating gradient.

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