HIGH QUALITY FACTOR STUDIES IN SRF Nb_3Sn CAVITIES*

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Abstract

A significant advantage of Nb_3Sn coated on niobium over conventional bulk niobium is the substantial reduction in the BCS losses at equal temperatures of the former relative to the latter. The quality factor of a 1.3 GHz Nb_3Sn cavity is thus almost entirely dictated by the residual resistance at temperatures at and below 4.2 K, which, if minimised, offers the ability to operate the cavity in liquid helium at atmospheric pressure with quality factors exceeding 4×10^{10}. In this paper we look at the impact of the cooldown procedure – which is intrinsically linked to the effect of spatial and temporal gradients – and the impact of external ambient magnetic fields on the performance of a Nb_3Sn cavity.

INTRODUCTION

Recent work on Nb_3Sn cavities fabricated at Cornell University [1–3] has focused understanding sources of RF losses in these cavities. In particular, since Nb_3Sn cavities must be cooled slowly through T_c to avoid the creation of excessive flux-generating thermal currents between the Nb_3Sn layer and the niobium substrate, the sensitivity of the cavity to trapped flux must be determined. This is because previous studies in niobium [4] have shown that cooling a cavity slowly through T_c traps more external flux, which will cause an increase in the residual resistance. In this paper we present results on the impact on the cavity surface resistance of both the thermal gradient across the cavity during cooldown as well as the sensitivity of Nb_3Sn cavities to trapped magnetic flux. We also present the first results of a measurement of the change in the superconducting energy gap as a function of the RF magnetic field on the surface of the cavity. It has been theorised [5] that the spectral gap may close as the applied RF magnetic field is increased. The effect of this should be two-fold: firstly, the BCS resistance should increase with the accelerating gradient in the cavity, and secondly, the ultimate quench field can be reduced to lower than that expected by the superheating field H_{sh} of the material in the clean limit.

EXPERIMENTAL PROCEDURE

These studies were performed on the Nb_3Sn coated 1.3 GHz single-cell cavity designated ERL1-4, which has shown the best performance to date in a cavity coated at Cornell. The cavity was coated with tin for 3 hours, following which it was annealed for 30 minutes; a more in-depth description of the coating apparatus and procedure is given in Ref. [1]. The cavity was tested on a vertical test stand inserted in a cryostat that is magnetically shield with a mu-metal lining, resulting in an ambient magnetic field of 2-3 mG. To cool the cavity in a controlled manner, a specially designed heater is used to control the temperature of the helium that is introduced into the cryostat. The procedure is described more completely in Ref. [1]; recently, however, the procedure has been improved to allow a reduced temperature gradient across the cavity – by approx. a factor of 5 – while maintaining the same cooling rate.

The studies on the effects of trapped flux were performed using the method described in Ref. [4]. An external Helmholtz coil surrounding the cavity is used to apply an external magnetic field that is then trapped in the cavity as it transitions through T_c. The impact on the residual resistance is then measurement to gauge the cavity's susceptibility to trapped flux.

To measure the dependence of the superconducting energy gap on the surface RF magnetic field, a measurement of surface resistance against accelerating gradient was performed at different temperatures between 2.0 and 4.2 K when no external magnetic field was applied. The BCS fitting was then used to determine the value of the gap at different values of RF surface field based on the change in surface resistance between 2.0 and 4.2 K.

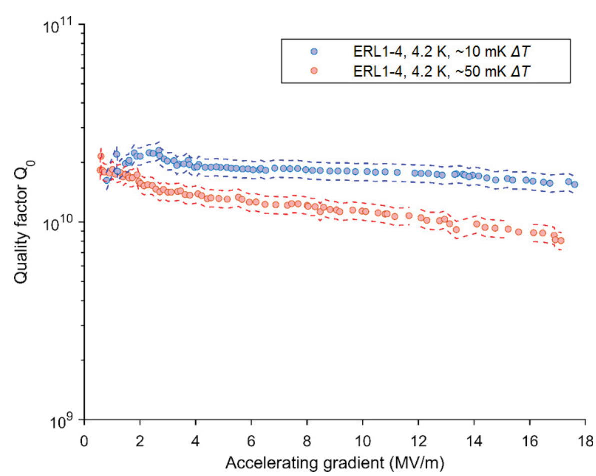

Figure 1: Two separate tests of the 1.3 GHz Nb_3Sn cavity designated ERL1-4, taken at a bath temperature of 4.2 K. The cooldown procedure was improved between the tests, with the thermal gradient across the cell, ΔT having been reduced by a factor of ≈ 5, which results in a significantly reduced Q-slope.

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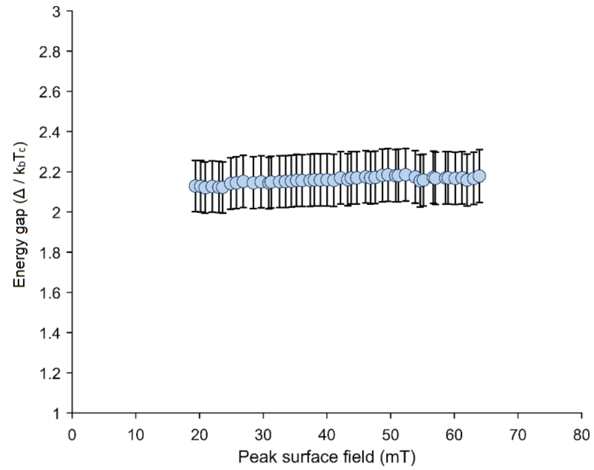

Figure 2: A measurement of the energy gap as a function of RF field on the surface for a Nb_3Sn cavity.

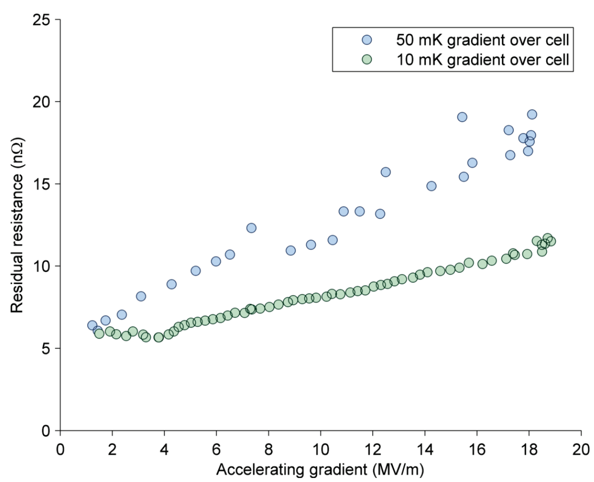

Figure 3: Residual resistance vs. accelerating field for the two different cooldowns of ERL1-4.

RESULTS

RF Performance

The results of two separate vertical tests of ERL1-4 are shown in Fig. 1. In the first test, the cavity was cooled at a rate of (19.4 ± 1.4) min/K with a thermal gradient across the cavity of (48.6 ± 6.4) mK when going through T_c. In contrast, the second test was performed with a cooldown rate of (13.05 ± 0.72) min/K with the thermal gradient across the cavity being (8.1 ± 2.2) mK when going through T_c. The results both showed a similar quench field of (17.2 ± 1.3) MV/m at 4.2 K, but the second test showed a reduction in the Q-slope, resulting in a Q_0 that was almost a factor of 2 higher at 16 MV/m than that seen in the first test.

A measurement of the energy gap as a function of the applied RF field is shown in Fig. 2. A simulation [1] of the theoretical framework described in Ref. [5] postulates that for a Nb_3Sn cavity the spectral gap should decrease by approximately 5% from 0 to 60 mT of RF surface field. It should be noted that the error bars in Fig. 2 are largely

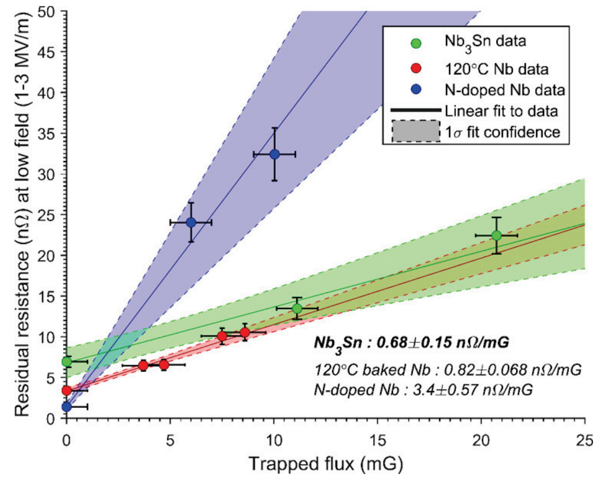

Figure 4: A comparison of the residual resistance at 1-3 MV/m with trapped flux for a 120°C niobium cavity, a N-doped niobium cavity [4], and a Nb_3Sn cavity. The latter shows a similar sensitivity to more conventional niobium cavities.

systematic, affecting each point equally, and that the statistical variation is on the order of 1%, suggesting that such a closing of the energy gap should be visible at these fields. However, it is entirely possible that other effects are conspiring to extend the closing of the gap, which might still be seen at higher RF fields, once these are reached. This result does show that the Q-slope seen in this cavity is a function of the residual resistance, and not a change in the BCS resistance of the material. The change in the residual resistance that brings about this change in Q-slope is seen in Fig. 3.

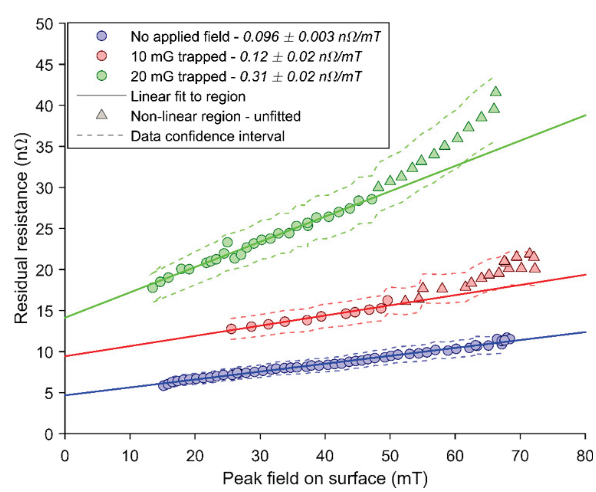

Figure 5: Residual resistance vs. peak magnetic RF field on the cavity for different values of trapped flux. The Q-slope increases the more flux is trapped. The departure from the linear fit at higher field values for the two measurements in which an external field was applied is believed to indicate the onset of thermal instabilities from defects on the surface.

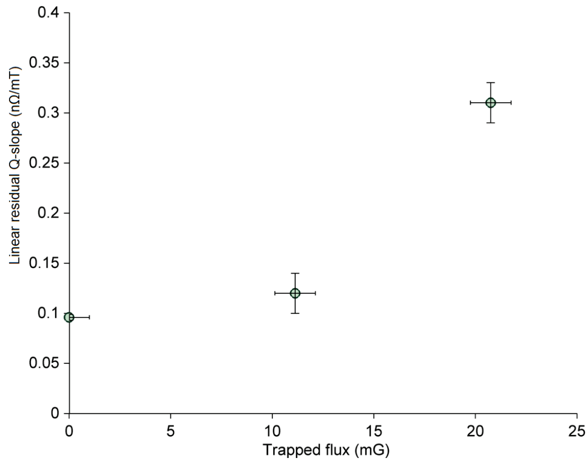

Figure 6: Linear Q-slope in the residual resistance as a function of the amount of trapped flux, measured from 2-12 MV/m. As the trapped flux increases, the Q-slope increases.

Residual Resistance and Trapped Flux

The sensitivity of Nb_3Sn to external magnetic fields, in the form of the increase in residual resistance at low field per milligauss trapped, is shown in Fig. 4, and is compared to the same measurement performed in both a conventional niobium cavity that received a 120°C bake as well as a nitrogen doped cavity [4]. This result is in good agreement with that seen in Ref. [6], which was measured for a 3 GHz cavity. Nb_3Sn shows a similar sensitivity to trapped flux as conventional niobium, indicating that no extra magnetic shielding is required for the same amount of residual resistance incurred from trapped flux. This is a fortunate result, as Nb_3Sn is unable to benefit from the fast cooldown techniques that are used to offset comparatively higher sensitivity to trapped flux seen in nitrogen doped cavities.

A measurement of the residual resistance as a function of field for different values of trapped flux in the cavity indicates that the Q-slope changes with the amount of flux trapped in the cavity, as shown in Fig. 5. The Q-slope as a function of trapped flux is shown in Fig. 6. This dependence explains the change in the Q-slope for the improved cooldown: since the thermal gradient across the cavity is less, the flux generated by thermal currents is reduced and hence less flux is trapped in the cavity. This in turn results in less Q-slope. The functional form of the dependence of the Q-slope on the trapped flux is not yet known, however the initial data indicates that it is non-linear. The change in the slope in the residual resistance for the two different cooldowns is illustrated in Fig. 3.

CONCLUSION

The results presented in this paper demonstrate that the requirement to cool Nb_3Sn cavities in a slow fashion does not impact the performance any more than has already been seen in equivalent tests of conventional niobium cavities. Since current cryomodule intended for conventional niobium cavities are already designed with a slow cooldown in mind,

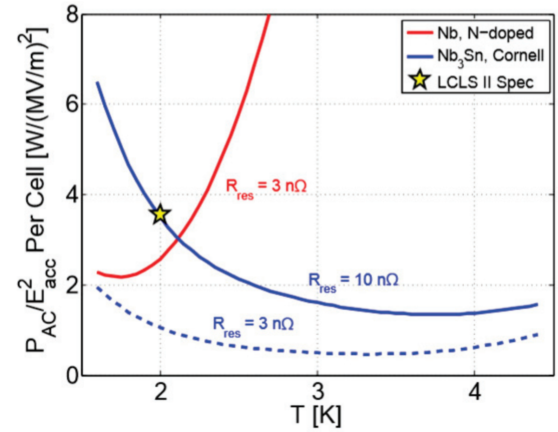

Figure 7: A 2-D plot of power draw from an SRF cavity (per $(MV/m)^2$) with temperature. A line drawn indicates the power draw for a cavity at that operating temperature. Any specification above the line is achieved or exceeded. The plot shows three cases: in red is a typical N-doped cavity with a residual resistance of 3 nΩ; in solid blue is the current state-of-the-art Nb_3Sn cavity; in dashed blue is the same cavity if it were to have a residual resistance at 16 MV/m of 3 nΩ. We can see that at 4.2 K, the current state-of-the-art exceeds the specification for LCLS-II by over a factor of 2.

this suggests that no changes are required for adapting them for use with Nb_3Sn cavities. A controlled cooldown with as small a thermal gradient across the cavity as possible has been shown to produce good performance at 4.2 K in current Nb_3Sn cavities coated at Cornell. Furthermore, measurements of the spectral energy gap up to 65 mT of applied RF surface field do not show a change in the gap, indicating that the Q-slope seen in these cavities is a function of the residual resistance. Future studies will focus on the impact of the coating parameters on both the residual resistance and the BCS properties of the material, with the aim of optimising the coating for high efficiency cavities.

Even at this early stage, the state-of-the-art in Nb_3Sn has already achieved a gradient and energy efficiency that meet and exceed the specification of a contemporary state-of-the-art accelerator. Shown in Fig. 7 is a plot of the power draw of a cavity (per $(MV/m)^2$) with temperature. As can be seen, the Nb_3Sn cavity result shown in Fig. 1, with a residual resistance of 10 nΩ at 16 MV/m, exceeds the specification for LCLS-II when operating at 4.2 K by quite a considerable margin.

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