IMPACT OF COOLDOWN PROCEDURE AND AMBIENT MAGNETIC FIELD ON THE QUALITY FACTOR OF STATE-OF-THE-ART Nb_3Sn SINGLE-CELL ILC CAVITIES*

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Abstract

Single-cell Nb_3Sn cavities coated at Cornell University have demonstrated quality factors of $>1 \times 10^{10}$ at 16 MV/m and 4.2 K in vertical tests, achieving the performance requirements of contemporary modern accelerator designs. In this paper, we present results demonstrating the impact of the cooldown procedure and ambient magnetic fields on the cavity's ability to achieve these quality factors and accelerating gradients. The impact of the magnetic fields from thermoelectric currents, generated by thermal gradients across the cavity during cooldown, are shown to be equivalent to the impact of magnetic fields trapped from ambient sources. Furthermore, the increase in the residual surface resistance due to trapped magnetic flux, from both ambient sources and thermoelectric currents, is found to be a function of the applied RF magnetic field amplitude. A hypothesis for this observation is given, and conclusions are drawn regarding the demands on the cooldown procedure and ambient magnetic fields necessary to achieve quality factors of $>1 \times 10^{10}$ at 4.2 K and 16 MV/m or higher.

INTRODUCTION

Niobium cavities coated with Nb_3Sn at Cornell University have shown high quality factors of $Q > 1 \times 10^{10}$ at 4.2 K and 16 MV/m [1–5]. To achieve these record performances, a correctly executed cooldown through the transition temperature T_c is crucial. Due to the bimetallic interface of Nb_3Sn on niobium, thermal gradients along the boundary will result in thermoelectric currents, which in turn generate magnetic fields that will become trapped in the Nb_3Sn layer, resulting in increased losses and a lowered cavity efficiency.

In this paper we present the first results from a systematic study of the impact of the thermal gradients on the cavity performance, correlated with measurements of the increase in surface resistance from an increased amount of ambient trapped flux. The sensitivity to trapped flux is found to be dependent on amplitude of the RF field, regardless of the source of trapped flux being ambient magnetic fields or those generated by thermocurrents. From this measurement, the maximum amount of flux that can be trapped while still achieving a $Q > 10^{10}$ at 4.2 K and at a stated peak RF magnetic field is given.

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EXPERIMENTAL SETUP

A single-cell 1.3 GHz ILC-style cavity, designated LTE1-7, was used for the purpose of measuring the impact of thermal gradients and external magnetic fields on Nb_3Sn-coated cavities. The cavity preparation and performance has previously been presented in Ref. [3]. The cavity was tested in one of Cornell's vertical test cryostats; a simplified diagram of the experimental setup within the test insert is shown in Fig. 1. A Helmholtz coil was mounted on the cavity for the purpose of applying an external magnetic field, whose magnitude was monitored using flux gate magnetometers mounted on the cavity irises. The thermal gradient across the cavity during cooldown was controlled using a combination of a heater mounted at the base of the cryostat and another heater located in the helium delivery line. The temperature gradient across the cavity was monitored using temperature sensors mounted at the upper and lower irises and the equator.

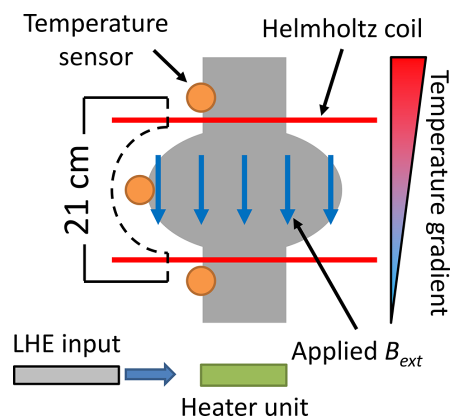

Figure 1: A simplified diagram of the experimental setup. A Helmholtz coil is used to apply a uniform external magnetic field during cooldowns that require ambient flux trapping. A heater located at the base of the cryostat is used to heat the helium entering the cryostat and establish a temperature gradient across the cavity, which is measured using the temperature sensors located at the irises and equator.

For the purposes of this experiment, two different cooldown styles were used: the first, focussed on thermal gradients, was done in no externally applied magnetic field while establishing a thermal gradient across the cavity during the transition through T_c. The second, focussed on ambient trapped flux, was done by cooling the cavity in as small a thermal gradient as possible while applying an external magnetic field using the Helmholtz coil. The field trapped in the cavity was then measured by turning off the Helmholtz coil once the cavity had reached 4.2 K.

A number of cooldowns were undertaken in both the thermal gradient and trapped flux styles. For each cooldown, the measurement consisted of the quality factor as a function of temperature (Q vs T) from 10 K to 1.6 K, and the quality factor as a function of accelerating field (Q vs E) at 2.0 K and 4.2 K. During each cooldown, care was taken to not cause the cavity to quench, as this would change the amount and distribution of flux trapped in the cavity. For illustrative purposes, the complete collection of Q vs Ts obtained during the experiment are shown in Fig. 2.

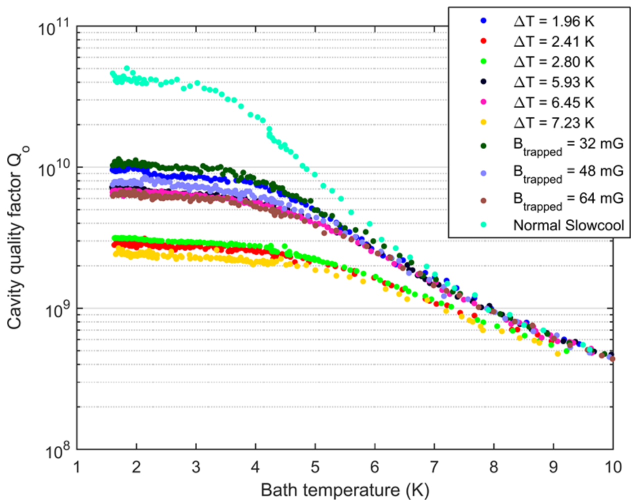

Figure 2: The collection of the Q vs T's collected during the experiment. An increasing thermal gradient, or a greater quantity of ambient flux trapped, results in a higher residual resistance and in turn a lower quality factor at the lowest measured temperature of 1.6 K.

RESULTS

The surface resistance, R_s, at 1 MV/m (equivalent to 4.28 mT peak RF magnetic field) and 2.0 K as a function of the temperature gradient across the cavity, dT/dx, and as a function of the amount of magnetic field trapped through use of the Helmholtz coil, B_{trapped}, is shown in Fig. 3. The relationship between the increase in the surface resistance and the amount of ambient magnetic field trapped has previously been seen to be linear [2,6], as the losses incurred from trapped flux are proportional to the number of extra vortices trapped. A similarly linear relationship is also suggested by the data of R_s vs. dT/dx. By taking a ratio of the two linear gradients, a measure of the amount of thermoelectrically generated flux trapped per unit of temperature gradient can be obtained:

$$\frac{dB_{\text{trapped}}}{dR}\left[\frac{dT/dx}{dR}\right]^{-1} = \frac{dB_{\text{trapped}}}{dT/dx}, \qquad (1)$$

which was found to be (6.2 ± 0.3) mG/(K/m) in Nb_3Sn.

Since previous measurements on Nb_3Sn [2] had suggested that the sensitivity to trapped flux might be a function of

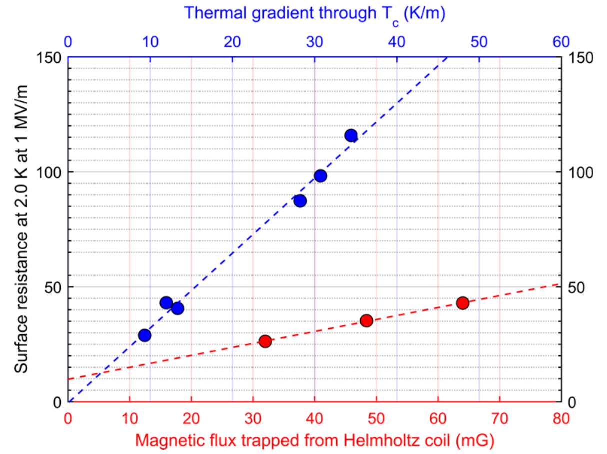

Figure 3: The surface resistance at 1 MV/m and 2.0 K as a function of the magnetic flux trapped by application of the Helmholtz coil (lower horizontal axis) and the thermal gradient per until length during the transition through T_c (upper horizontal axis). Both have been fitted with a linear relationship.

the applied RF field, the measurements of Q vs E at 2.0 K were converted to surface resistance against peak surface RF magnetic field, R_s vs B_{pk}, and fitted for B_{trapped} at different values of B_{pk}. This was done both for cooldowns done in an applied external magnetic field, and, through conversion from dT/dx to B_{trapped} using Equation (1), for the cooldowns undertaken in a thermal gradient. The result is two separate measurements of the sensitivity to trapped flux, dR/dB_{trapped}, as a function of the peak RF magnetic field, as shown in Fig. 4. Both measurements show a linear increase in the

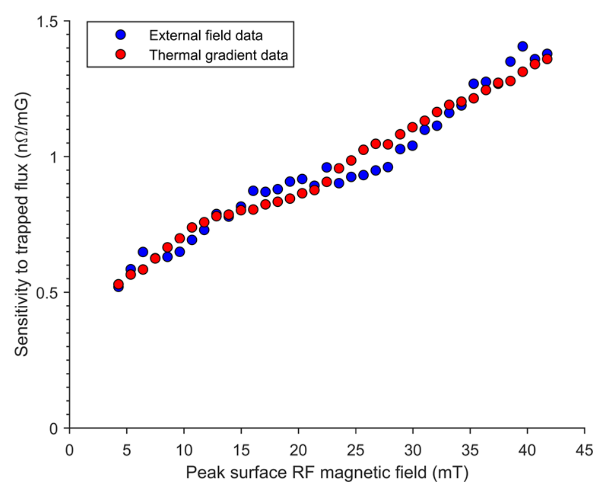

Figure 4: A measurement of the sensitivity to trapped magnetic flux as a function of peak RF magnetic field, for data taken in an applied external magnetic field, and, via conversion using Equation (1), an applied thermal gradient during cooldown.

sensitivity to trapped magnetic flux with increasing applied RF field, up to fields of 40 mT. By linear fitting to an average of this data, a field-dependent sensitivity can be obtained,

$$\frac{dR_s}{dB_{\text{trapped}}}(B_{RF}) = (21 \pm 1)\ \text{p}\Omega/\text{mG/mT} \times B_{RF} + (0.47 \pm 0.02)\ \text{n}\Omega/\text{mG}\,. \quad (2)$$

DISCUSSION

The reason for a field-dependent sensitivity is not yet clear; however, we propose that the increased losses are due to the gradual depinning of oscillating flux lines in the material. As described by the theory given in Ref. [7], flux vortex lines pinned at pinning sites in the material can oscillate when subjected to the force of an RF field. The drag of the vortices through the superconductor as they oscillate about the pinning sites results in dissipated heat. Under this theory, for a given average distance between pinning sites, the sensitivity to trapped flux – and with it, the additional effective surface resistance from vortex oscillation – are given, and independent of RF field. What we propose is that the pinning sites in the Nb_3Sn coating are especially weak, and that as the RF amplitude increases, a greater fraction of pinning sites become unable to act as such, as the flux lines break free from these weaker pinning locations. This increases the mean distance between pinning sites at higher RF amplitudes, resulting in a greater amplitude of vortex oscillation and with it, a greater sensitivity to trapped flux and its associated losses. Work at Cornell continues with the purpose of testing this hypothesis.

A contour plot showing the increase in surface resistance for a given amount of trapped flux – regardless of source – at a chosen operating peak RF magnetic field is shown in Fig. 5. Overlaid on this contour plot are lines indicating the maximum amount of flux that can be trapped and still achieve the given Q at 4.2 K, accounting for BCS resistance.

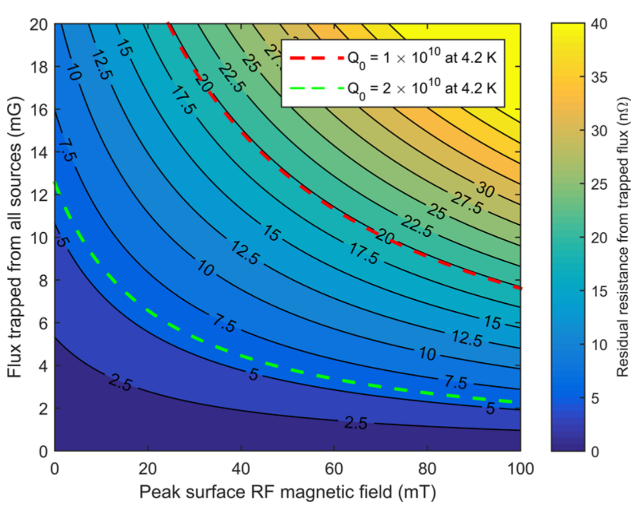

Figure 5: Contour plot of the increase in surface resistance given a set amount of trapped flux – from any source – at a chosen operating RF magnetic field.

For example, for a cooldown gradient of 50 mK across the cell, 1.5 mG would be trapped from thermal gradients. In an ambient field of 5 mG, in which all 5 mG are trapped, the increase in surface resistance would be approx. 3 nΩ at very low RF fields, increasing with the applied RF field. Given the increase in sensitivity as a function of RF field given in Equation (2), we can expect to maintain a $Q > 10^{10}$ up to surface fields of 100 mT, approximately 23 MV/m. However, at twice the ambient magnetic field and double the cooldown gradient, the total flux trapped would be 13 mG, and the cavity would only exceed $Q > 10^{10}$ at fields up to 11 MV/m.

CONCLUSION

A systematic study of the impact of ambient magnetic flux and thermal gradient during cooldown has revealed that the sensitivity to trapped flux of Nb_3Sn-on-Nb cavities is a function of the applied RF magnetic field. This field-dependent sensitivity has been measured at RF fields up to 40 mT, although cavity performance at 2 K up to the current quench fields of 17-18 MV/m indicate that this measurement holds true up to fields of 75 mT. To achieve high quality factors at high accelerating gradients, it is therefore necessary to ensure that the cavity is both cooled slowly, to minimise thermal gradients along the cavity structure, and also in as small an ambient magnetic field as can be achieved.

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