MAGNETIC FLUX EXPULSION STUDIES IN NIOBIUM SRF CAVITIES *

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Abstract

With the recent discovery of nitrogen doping treatment for SRF cavities, ultra-high quality factors at medium accelerating fields are regularly achieved in vertical RF tests. To preserve these quality factors into the cryomodule, it is important to consider background magnetic fields, which can become trapped in the surface of the cavity during cooldown and cause Q_0 degradation. Building on the recent discovery that spatial thermal gradients during cooldown can significantly improve expulsion of magnetic flux, a detailed study was performed of flux expulsion on two cavities with different furnace treatments that are cooled in magnetic fields amplitudes representative of what is expected in a realistic cryomodule. In this contribution, we summarize these cavity results, in order to improve understanding of the impact of flux expulsion on cavity performance.

INTRODUCTION

How strong is the impact of residual magnetic fields on the Q_0 of a superconducting RF cavity? Trapped flux degrades Q_0 and necessitates additional cryogenic capacity for cooling at a given accelerating gradient. With magnetic shielding and active compensation to reduce the residual axial field to ~5 mG, what will the impact on Q_0 be? Recent discoveries have shown that:

- Spatial thermal gradients during cooldown can significantly improve expulsion of magnetic flux [1]

- Flux expulsion behavior can be substantially enhanced through UHV furnace treatment [2]

In this contribution, we study two newly fabricated cavities produced using high RRR niobium from the same production group. Only one of these cavities is given high temperature furnace treatment at temperatures higher than 800 C. The impact on flux expulsion behavior is measured, as is the impact on Q_0 in a magnetic field that is of similar strength to what would be expected in an accelerator cryomodule.

MEASUREMENT TECHNIQUE

The setup for measuring flux expulsion, after the method in [3], is shown in Fig. 1. An axial magnetic field is applied to a cavity during cooldown, and fluxgate magnetometers at the middle of the cell measure the magnetic field before B_{NC} and after B_{SC} the superconducting transition. Thermometers measure the temperature at the top, bottom, and middle of the cavity cell. The temperature difference between the top and bottom of the cell is used to represent the thermal gradient. If the applied field is fully trapped in the cavity wall when the cavity passes through the superconducting transition temperature, the field should not change (B_{SC}/B_{NC}=1). If the field is fully expelled by the superconductor, simulations show that the field should be enhanced by a factor of approximately 70% (B_{SC}/B_{NC}=1.7). An uncertainty of 0.1 was assumed for B_{SC}/B_{NC} due to the exact distance of the fluxgate probe from the cavity surface, its alignment relative to the applied field and non-uniformities in the field. An uncertainty of 0.2 K was assumed for the temperature measurement in each probe, due to thermal impedance between cavity and thermometer and non-uniformity in temperature around the cavity.
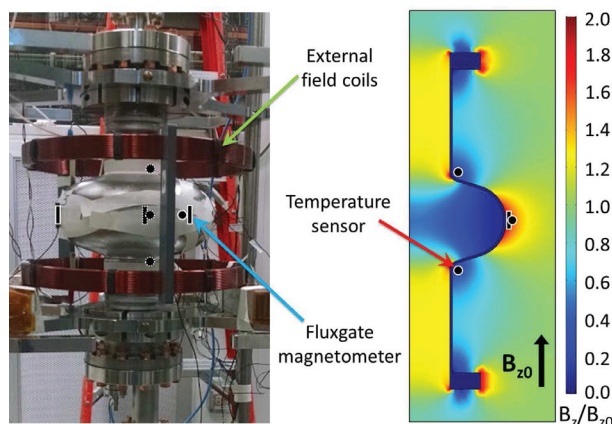

Figure 1: Apparatus used to measure flux expulsion (left) and simulation used to determine the magnetic field enhancement factor for full expulsion.

Two fine grain 1.3 GHz single cell cavities, AES024 and AES025, were fabricated by the same vendor using high RRR niobium from the same production run. Only AES025 was given 900 C furnace treatment for 3 hours. Then both received bulk EP, 800 C degas, and '2/6' nitrogen doping with 5 micron EP (which is the baseline recipe for the cavities for the LCLS-II project [4]). During cooldown in vertical test, spatial temperature gradient was measured from the bottom to the top iris when the bottom iris reached 9.2 K. For each cavity, many cooldown-warmup cycles were run. Unless RF data was taken, cooldown was stopped at 6 K.

FLUX EXPULSION RESULTS

Figure 2 shows example measurements of flux expulsion during cooldown from AES024 and AES025. Figure 3 shows a survey of many measurements, which together illustrate the significant difference in the expulsion characteristic of the two cavities. AES025, which received 900 C treatment for 3 hours, shows substantially stronger expulsion than AES024, which did not. Even for $\Delta T \sim 1$ K, nearly all flux is expelled from AES025, while $\Delta T \sim 5$ K gives only $B_{SC}/B_{NC} \sim 1.3$ for AES024. In fact, in later testing, AES025 was subjected to slow cooling in an attempt to trap as much flux as possible, but even with this procedure, approximately 70% of the flux was expelled due to its strong expulsion behavior.

RF MEASUREMENTS

In addition to the survey of flux expulsion data, RF data was measured for both cavities[1], after cooling them under carefully controlled thermal and magnetic conditions. In various tests, shown in Figs. 4 and 5, both cavities were cooled in a field <1 mG and in a field of 5 mG, which is the maximum tolerance for background field in LCLS-II cryomodules [4] [2]. For AES024, which showed weaker expulsion behavior, RF measurements showed substantial vulnerability to Q_0 degradation due to trapped flux. Even with a ΔT of 5 K across the cavity during cooldown, the Q_0 was degraded in the 5 mG field to below the specification of 2.7×10^{10}. However, for AES025, which showed strong expulsion, even with ΔT of of 2 K, no Q_0 degradation was observed relative to cooling in <1 mG field.

CONCLUSIONS

The results indicate that as-received high-RRR niobium material can be vulnerable to flux trapping that substantially degrades performance. For high Q_0 machines such as LCLS-II, achieving the highest Q_0 possible can allow for lower operating costs and the possibility of higher gradient operation. As a result, depending on the properties of the niobium material, it may be worthwhile to apply additional treatment steps to enhance flux expulsion. Placing a cavity in a UHV furnace at 900 C for 3 hours prior to bulk EP was shown to be effective for improving expulsion and preventing Q_0 degradation with a modest temperature gradient during cooldown.
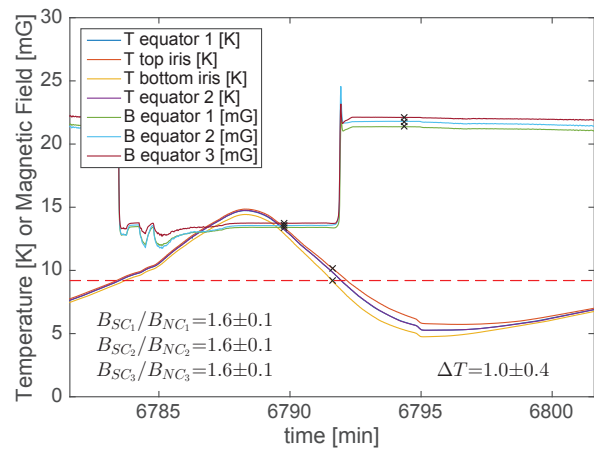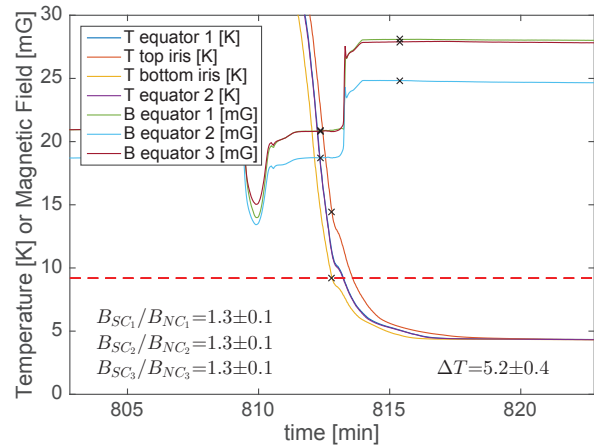

Figure 2: Example measurements of flux expulsion during cooldown from AES024 (top) and AES025 (bottom). The x's mark the values that are used to calculate ΔT and B_{SC}/B_{NC}.
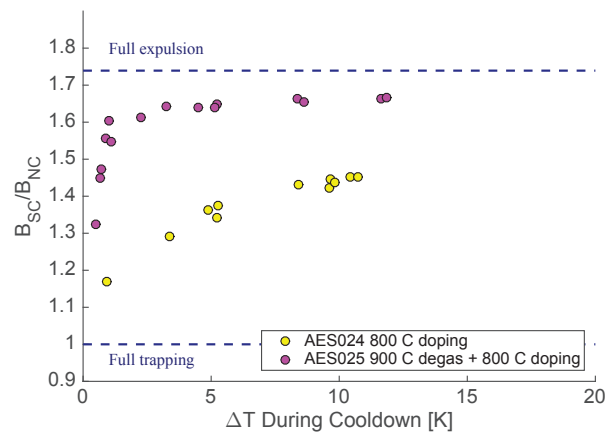

Figure 3: Survey of flux expulsion measurements for AES024 and AES025. AES025, which received 900 C furnace treatment, shows substantially stronger expulsion.

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[1] It should be noted that a cable used in these tests showed inconsistent Q_{ext2} values in other measurements. This may have introduced some systematic error. In addition, since relatively low fields ~5 mG were applied in the RF measurements, small background fields in perpendicular directions may have a significant impact relative to the applied field.

[2] Note that even if 5 mG were trapped, nitrogen doping would still have a significant advantage compared to non-doped niobium [5].
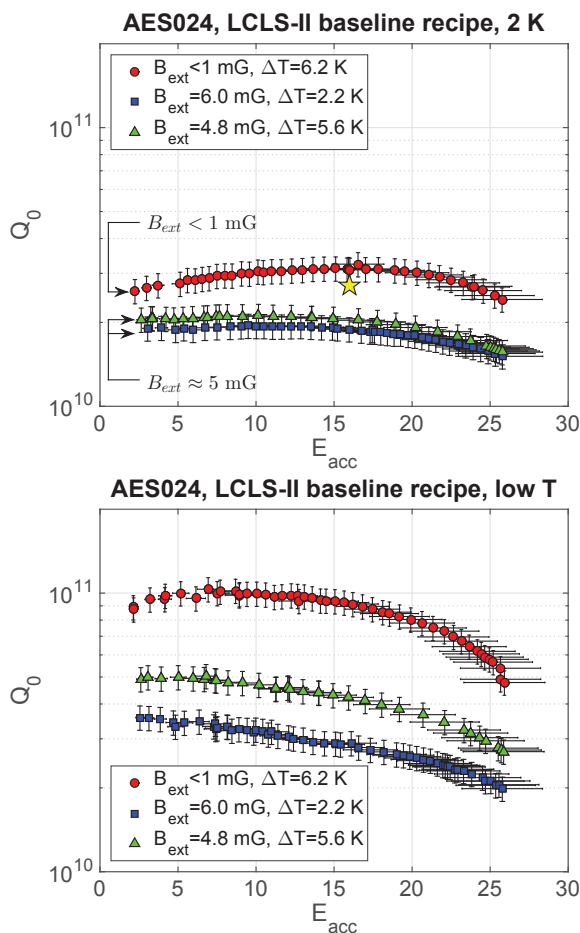
Figure 4: AES024 exhibits a substantial impact of a small background field on the Q_0. When the cavity is cooled in 5 mG, even with a ΔT of 5 K across the cavity, it shows substantial degradation compared to cooling in a <1 mG field. Measurements are shown for a bath temperature of 2.0 K (top) and ~1.5 K (bottom).
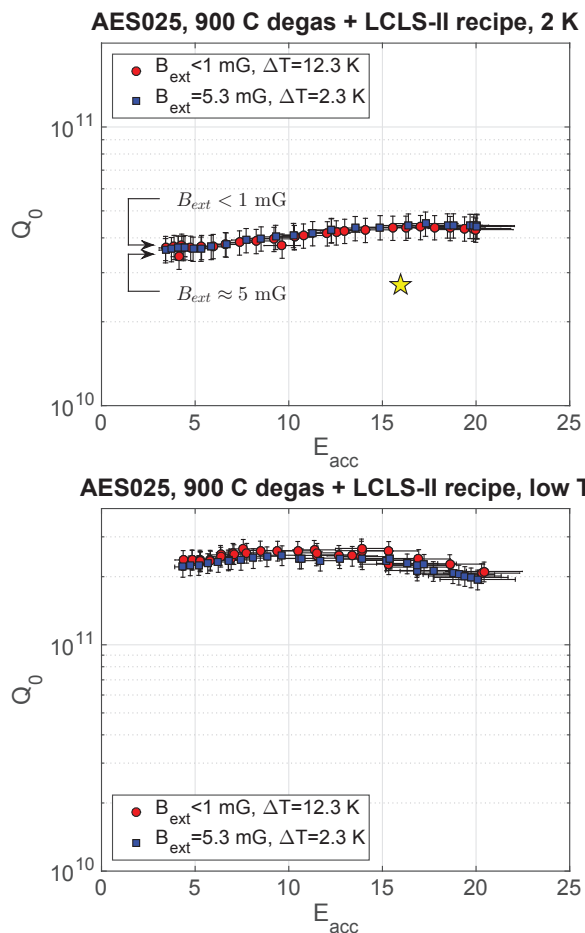
Figure 5: AES025 exhibits minimal impact of a small background magnetic field on the Q_0. When the cavity is cooled in 5 mG with ΔT of only 2 K, the Q_0 appears unchanged relative to cooling in a field <1 mG. Measurements are shown for a bath temperature of 2.0 K (top) and ~1.5 K (bottom).

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