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INVESTIGATION OF THERMOCURRENTS LIMITING THE PERFORMANCE OF SUPERCONDUCTING CAVITIES

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Abstract

As the surface resistance of superconducting cavities approach the theoretical limits parasitic effects limiting the performance came into focus of current research. One of these effects is that the quality factor of a cavity is impacted by the cool-down rate. We will present results from recent investigations on thermo-currents, driven by the temperature difference between the two material interfaces of the superconducting Niobium cavity and its Titanium helium-vessel. We will show that this leads to the presence of a magnetic field while the cavity transits into the superconducting state and impacts the quality factor of the cavity.

INTRODUCTION

During cavity testing inside the HTC [1] in the framework of our ERL R&D we confirmed a very interesting effect, initially reported by HZB [2]: The quality factor of a superconducting cavity can be increased after the initial cool-down by going through a second cool-down cycle which warms up the cavity to 15 -20 K and then slowly back to 4 K again. By this cycle, we were able to increase the Q at 1.8 K from $3.5*10^{10}$ to $6*10^{10}$. This has already been reported in [3]. As this is a very important factor on the seizing of the cryogenic environment we started investigating the effect in more details.

One of the theories behind that effect was that the magnetic shielding is weaker on the first cool-down as it is still too warm to be effective. To test this theory we equipped one of our horizontal tests (HTC-3) with a flux gate probe that measured the magnetic field close to the cavity inside the 2nd magnetic shielding. The result we saw was quite astonishing: as the module cooled down, the magnetic field started from an ambient value of 0.15 μT rising to 0.45 μT, going down and reversing direction to -0.25 μT to become -0.11 μT as the cavity transits through the critical temperature becoming superconducting [3]. This behaviour led us to the conclusion that a pure magnetic shielding efficiency explanation is not the appropriate explanation as no correlation to any magnetic shielding temperature has been observed.

BACKGROUND

As results from others indicated [4], thermo-currents seemed to be a candidate to explain not only the magnetic field excursions but also to explain the difference in the Q factors as this for high Q cavities it is strongly impacted by ambient magnetic field at the transition temperature.

Thermo-currents are the result of the Seebeck-Effect, which is well known in physics for more than a decade: If material junctions are hold at different temperatures, a potential difference between the material transitions can exist which is able to drive a current. As superconducting cavities are made out of Niobium while the helium vessel enclosing them is typically Titanium this effect is relevant for accelerator physics: During cool-down of a cavity welded into its helium vessel is it is easy to imagine that both ends of the cavity (where the Nb-Ti is located) have different temperatures.

The emf voltage following the Seebeck theory is given by

$$U_{TH} = \left(S_{Nb}(T) - S_{Ti}(T)\right) \cdot \Delta T$$

where S is the Seebeck coefficient which we write as being temperature dependant (see below). As can be seen, the induced voltage should be proportional to the temperature difference between the two transitions. However, it should be noted that reliable data below 77 K is not available which complicates predictions and triggered our research.

THERMO-CURRENT TEST SET-UP

To investigate the effect in detail we built a window-frame set-up, as shown in Fig. 1. It simulates a cavity/ he-vessel arrangement by having two transitions between Niobium and Titanium. Each transition was equipped with a cernox thermometer. While the lower end was immersed in liquid helium we were able to heat the upper end. The Seebeck voltage, which is expected in the order

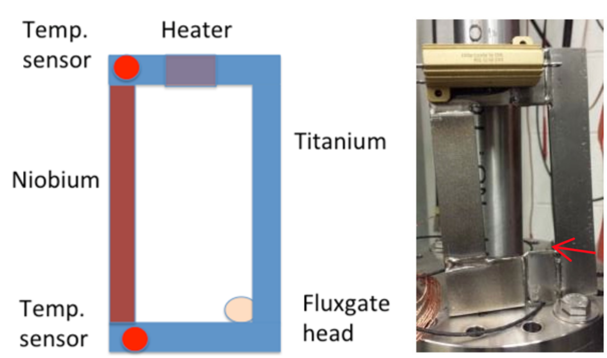

Figure 1: Set-up to measure the thermo-currents. On the left is a sketch of the arrangement with the principle components, on the right is a photograph of the set-up.

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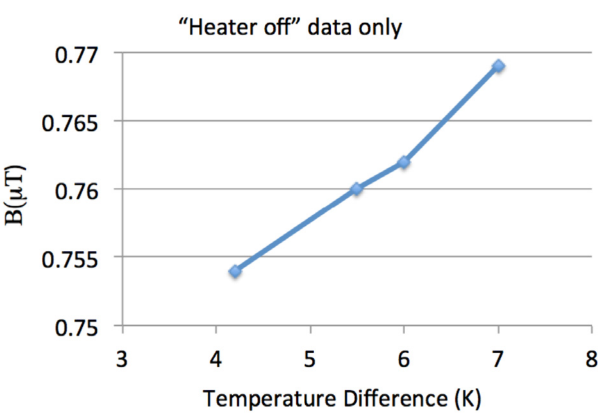

Figure 2: Measured thermo-current induced magnetic field. For details see text.

of µV drives a current, which due to the low resistance of the circuit, given by

$$R = \frac{\rho L}{A}$$

is potentially in the order of 10-100 Ampere.

Even with these rather high currents there was no direct way to measure them as this would have required additional material transitions. We decided to measure the current indirectly by its generated magnetic flux. Therefore, a fluxgate sensor was place in the corner of the window-frame and the analysis was guided by Biot-Savart's law

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l} \times \vec{r}}{r^2}.$$

The result of the measurement is given in Fig. 2: As the heater in the set-up influenced the magnetic reading due to its (small but visible) stray field we only considered data taken without heater current to be relevant. By that, we found a very clear linear dependency from the temperature difference- as theory predicted. In principle, detailed investigations could be conducted with this set-up. However, within the ERL cavity production and testing we were able to get better insight as we report below.

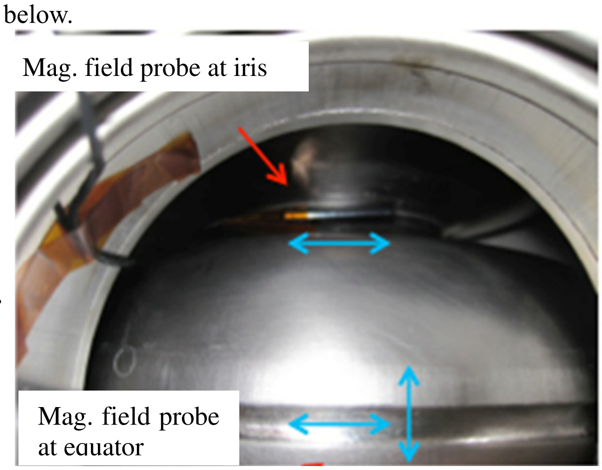

Figure 3: Positions of the flux-gate probes inside the He-vessel/ magnetic shielding.

VERTICAL CAVITY TEST DATA

In the framework of the ERL program we built 6 cavities for the MLC prototype. All of them were tested vertically before the helium vessel was welded to the cavity. As two of the cavities were accidentally exposed to laboratory air after the helium vessel welding we deceided to retest them after an HPR treatment, allowing us to compare the results (bare cavity versus a cavity with Ti-vessel), evaluating also the effect of thermo-currents.

In Fig. 3 we show how the fluxgate probes have been positioned on the cavity surface: two sensors were placed perpendicular to the cavity axis, one close to the iris and the other at the equator. One probe is placed parallel to the cavity axis at the equator. The idea was to understand and distinguish between generated fields driven by thermo-currents and expelled or frozen flux during transition to superconductivity.

We conducted several test going through slow and fast cool-down cycles, the results of which are shown in Fig. 4 and 5. Beside the stronger fields observed on the fast cool-down there is an important difference in the data: the field remaining in the iris area was 0.1 µT for the slow cool-down but as high as 0.53 µT after a fast cool-down. Concluding that this is the frozen flux seems to be too bold, as the kink in the data close to transition temperature reveiles a rather complicated dynamics, However, it can be stated that higher fields are present on cool-down for a fast cycle.

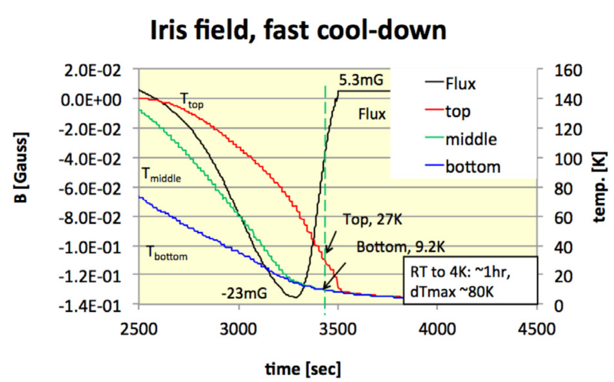

Figure 4: Fast cool-down cycle: shown are temperatures of the cavity and the magnetic flux measured at the iris location.

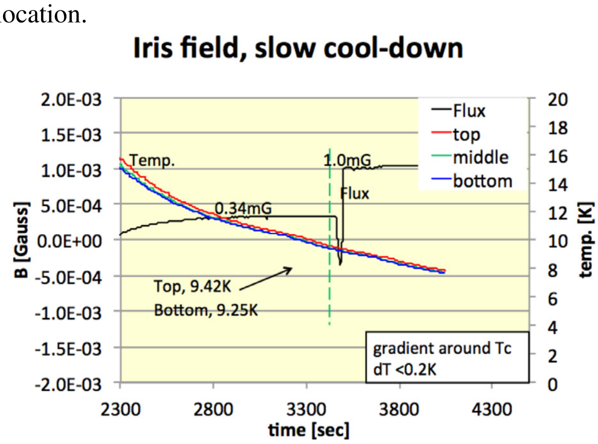

Figure 5: Slow cool-down cycle.

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IMPACT ON CAVITY Q

After each cool-down cycle we measured the quality factor of the cavities. As an example, Fig. 5 summarizes the results of the ERL7-3 cavity. It should be noted that the cavity was not removed from the dewar between the tests. Depending on the cool-down cycle we found different Q factors with Qs higher for a slow cool-down. As the effect increases with decreasing temperature we conclude that a slow cool-down impacts the residual resistance, only.

Even though theoretical models based on symmetry arguments suggest that the cavity inner surface is not affected by the magnetic field of a thermocurrent [5] and thus the quality factor/ residual resistance is unaffected, too, we confirmed by several measurements a decrease of 1 nΩ in the residual after a slow cool-down. It should be noted that these results confirms results from [2] and contradict [6].

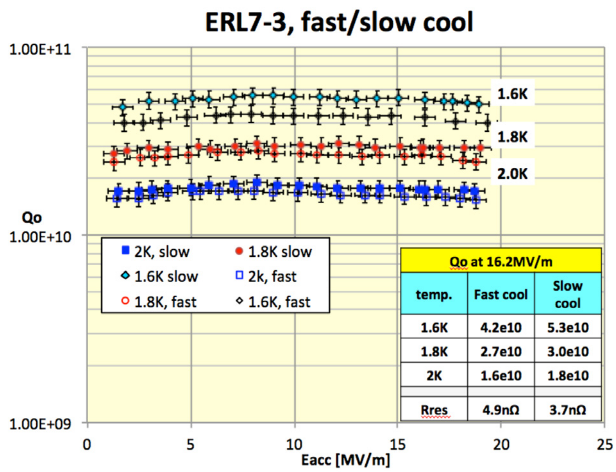

Figure 5: Cavity Qs of the ERL7-3 cavity (welded into a Ti helium-vessel) for different temperatures and different cool-down cycles. Consistently, a reduction of 1 nΩ in the residual surface resistance has been found for a slow cool-down.

OUTLOOK

As can be seen from the data shown in Fig. 6 the magnetic situation during cool-down is complex. The magnetic fields in the iris region are much stronger influenced than at the equator requiring a numerical field simulations to understand the field configuration and the enhancement. These calculations will also help to understand the effect of the partial Meisner effect leading to an incomplete flux expulsion at transition (Fig. 4 at t=3550s) and allows understanding how the measured data relates to the frozen flux which we don't think relates one to one to the measured flux in the superconducting state.

In addition, the horizontal field at the iris shows an unexpected behaviour: up to t=1500s, the temperature difference between the material transitions increases, generating only small magnetic fields. After t=1500s, the difference decreases while the magnetic field strongly increases. This can be explained by the decreasing resistance in the circuit, however, it cannot explain why the magnetic field decreases around t=2200s but increasing thereafter. A more detailed analysis is needed to determine if this is related to a temperature dependency of the Seebeck coefficients.

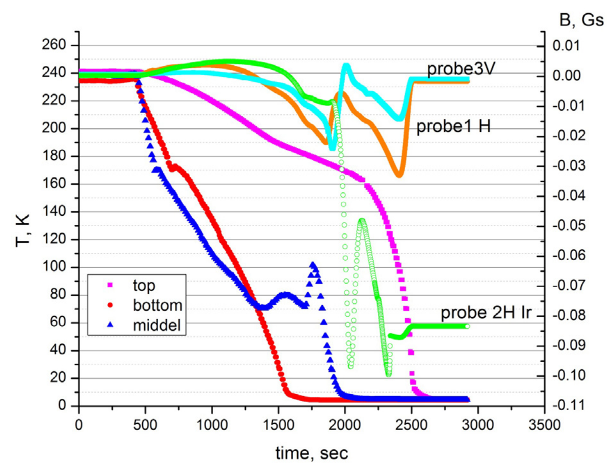

Figure 6: Full magnetic field measurement during cool-down with probes places as shown in Fig. 3, displaying a rather unexpected, complicated dynamics. The measurements were conducted twice to guarantee validity.

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