HIGH Q_0 RESEARCH: THE DYNAMICS OF FLUX TRAPPING IN SUPERCONDUCTING NIOBIUM

J. Vogt, O. Kugeler, Helmholtz-Zentrum Berlin, Germany
J. Knobloch, Helmholtz-Zentrum Berlin and Universität Siegen, Germany

Abstract

The quality factor Q_0 that can be obtained in a superconducting cavity is known to depend on various factors like niobium material properties, treatment history and magnetic shielding. We believe that cooling conditions have an additional impact, as they appear to influence the amount of trapped flux and hence the residual resistance [1 – 3].

We constructed a test stand using a niobium rod shorted out by a titanium rod to mimic a cavity in its helium tank to study flux trapping. Here we can precisely control the temperature and measure the dynamics of flux trapping at the superconducting phase transition. We learned that magnetic flux can be generated when a temperature gradient exists along the rod and when the niobium transitions into the superconducting state it subsequently remains trapped. Furthermore, it was shown that the cooling rate during isothermal cooldown through the transition temperature can influence the amount of externally applied flux which remains trapped.

The acquired knowledge may be used to modify the cooldown procedure of SRF cavities leading to a reduced level of trapped flux and hence operation closer to the BCS limit.

INTRODUCTION

The energetically most favorable state of bulk niobium at 1.8 K (4.2 K) is the Meissner state in which all magnetic field present in the normal conducting state is expelled. However, the expulsion can be incomplete under certain conditions [4, 5] which are fulfilled when a cavity is cooled through T_c in an ambient magnetic field. In this case, flux tubes are pinned to imperfections of the crystal lattice such as impurities, dislocations and grain boundaries in the superconductor and are prevented from leaving the material during phase transition.

We already reported on the impact of temperature gradients during the cool-down on the obtained Q_0 in a TESLA cavity system due to, we believe, additional flux being generated by the thermoelectric effect [1 – 3]. Since the cavity is welded in a helium tank that is fabricated from titanium, the dissimilar metals at the junctions create a thermovoltage whenever a temperature difference between the two ends exists. A current thus flows, which produces additional flux under the magnetic shielding that then can be trapped when the cavity transitions to the superconducting state. The trapped vortices have a normal conducting core with a surface resistance about 6 orders above that of sc niobium. For a 1.3 GHz TESLA cavity, every µT of trapped flux increases the surface resistance by 3.5 nΩ [6]. In our measurements up to 10 nΩ of additional surface resistance depending on the temperature gradient during cooldown were observed. Hence, an important step towards avoiding Q_0 degradation by trapped flux is an improved understanding of the flux generation and trapping dynamics near the transition temperature. The experiments described here are designed to do so in a model system that allow for more rapid testing under controlled conditions than is possible with the rather cumbersome cavity units.

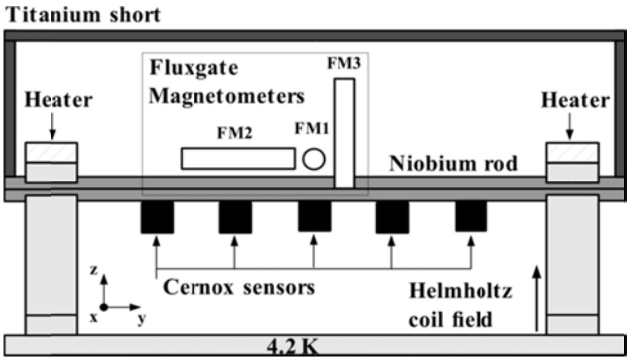

Figure 1: Experimental setup and positions of instruments.

EXPERIMENTAL SETUP

The setup for the experiments, shown in Figure 1, is based on a 30 cm long RRR 300 niobium rod (square cross section of 84×84 mm^2). It is anchored to a 4.2 K helium reservoir at both ends and equipped with two separately operable, resistive heaters (one on each end) to enable us to impose a well-defined spatial temperature gradient and to control the cooling rate through the superconducting transition. The temperature distribution is monitored with seven Cernox sensors. Five are attached along the rod axis and one close to each heater. Magnetic flux densities are observed by placing a 3D fluxgate magnetometer (FM1 – 3) near the center of the rod. To model a niobium cavity welded in a titanium helium tank we shorted out the niobium rod's ends with a grade 2 titanium rod forming a thermal and electrical circuit just as in the cavity-tank-system of a TESLA unit.

The whole construction is placed inside the Horizontal Bi-Cavity Test Facility (HoBiCaT [7]) with an ambient magnetic field of about 3 µT. A second, cold magnetic shield placed around the setup reduced the ambient field below 50 nT.

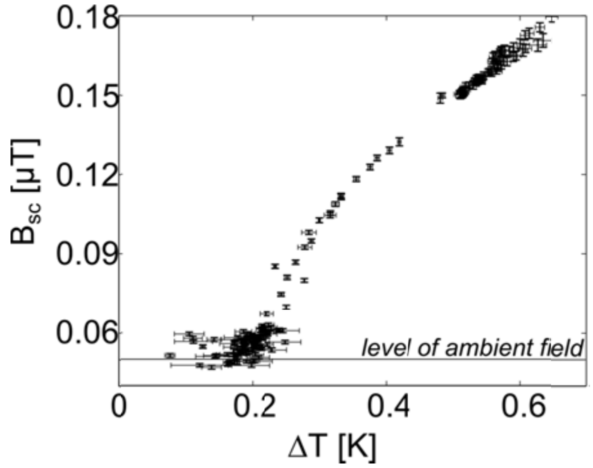

Figure 2: Trapped magnetic flux in the superconducting sample measured by FM1 (at equilibrium) as a function of the temperature difference between the two ends of the niobium rod at the instance of phase transition.

THERMAL CURRENTS

First, we investigated the thermoelectric effect in the niobium-titanium system to test whether indeed flux is generated which then is trapped by the niobium. The heaters were employed to bring the two contact points of niobium and titanium to different temperatures. Afterwards, the rod cooled down to ≈ 7 K while a temperature gradient existed as the rod cooled through T_c. The superconducting phase transition was defined as the instance when the Cernox sensor at the center of the rod fell below the transition temperature of 9.2 K. The temperature difference along the rod was measured at this instance. Finally, the flux density in superconducting state B_{sc} measured by FM1 was acquired after equilibrium (ΔT = 0) was reached and the rod was fully superconducting.

As shown in Figure 2, we obtained a distinct correlation between ΔT at the phase transition and the subsequent trapped flux in the superconducting state. As measured by FM1. Since the ambient field was shielded down below 50 nT, the measured field values of up to 180 nT reveal that additional magnetic flux must have been generated and trapped inside the system. The results is a strong indication for a thermoelectric contribution to trapped flux and hence we expect this to have an impact on residual resistance in SRF cavities, as observed in [1 – 3].

Note that the experiment was limited to temperature gradients < 1 K whereas in cavities during the cooldown the gradient was shown to be up to 100 times greater. Furthermore, the dependency of generated flux on the temperature difference is assumed to depend on the geometry of the setup and can thus the results here cannot be directly applied to the cavity-tank system.

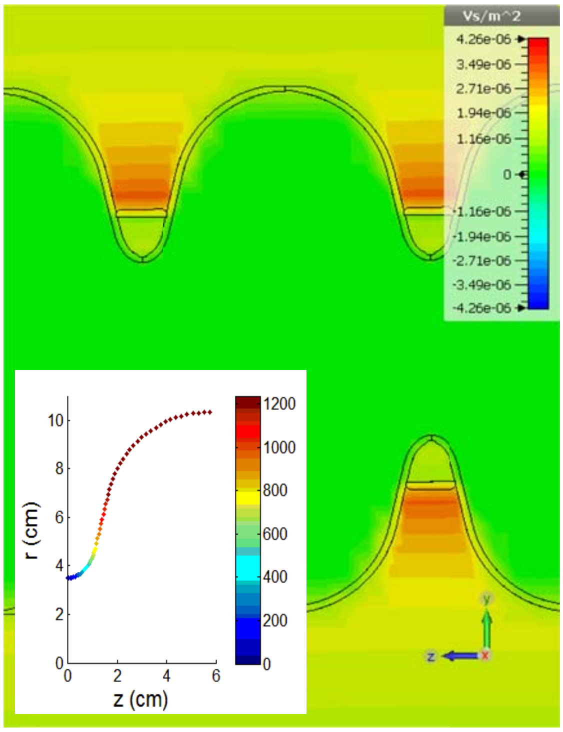

Figure 3: Simulation of the magnetic field distribution around a TESLA cavity that carries a current of 1A. Insert: Simulation of the surface H-field distribution of the accelerating π-mode (courtesy Axel Neumann).

Nevertheless, it should be sufficient to estimate the order of magnitude: In the model system a temperature difference of 0.6 K is sufficient to create 0.12 µT additional trapped flux. The same amount of trapped flux would increase the surface resistance of a TESLA-type cavity by 0.4 nΩ. Given that the gradients in the cavity-tank system during cooldown are up to 100 times larger, a variation in the surface resistance in the 10 nΩ range, as presented in References 1, 2 and 3, can reasonably be expected.

Additional measurements performed with the experimental setup presented here yielded a thermopower of the niobium-titanium system of the order of ΔS = 10 µV/K [8]. Assuming typical cooldown conditions when the phase transition of a TESLA cavity starts ($\Delta T \approx$ 100 K, ohmic resistance of the titanium tank of order R = 100 µΩ [9]), we expect a thermocurrent of order 1 A to flow along the cavity wall and back through the helium tank:

$$I = \Delta V / R = \Delta S \cdot \Delta T / R = 10\ \mu\mathrm{V/K} \cdot 100\ \mathrm{K} / 100\ \mu\Omega = 1\mathrm{A}$$

Figure 3 shows a simulation of the magnetic field distribution around a TESLA cavity that carries 1 A induced current. The maximum surface field is 2 µT. The insert in Figure 3 gives the surface H-field of the accelerating π-mode. Assuming that the thermally induced flux is trapped where it is generated, a significant portion will be in the high surface-magnetic field region and hence will significantly increase the cavity's power dissipation (and thus the effective average surface resistance as determined by the Q measurements). Given the empirical correlation of trapped flux and surface resistance [6], 2 µT trapped flux correspond to an additional surface resistance of 7 nΩ which is in good agreement with the cavity thermal cycling results that reported a variation of up to 10 nΩ in the residual resistance depending on the temperature gradients [1 – 3].

MEISSNER EFFECT

Beside the thermoelectric influence on the amount of trapped flux, we studied the impact of temporal gradients (i.e., the rate at which the material transitions through the superconducting phase change). Past measurements [5] had shown that the expulsion of flux is impacted by the cooldown rate. The cold magnetic shielding was removed, increasing the total value of ambient field at the rod to 3µT (0.3µT in FM1 direction). We then cooled the rod isothermally (i.e., zero temperature gradient) to the superconducting state by adjusting the power of both heaters and measured the amount of expelled flux. We defined "expelled flux" to be the difference in the flux density measured in the superconducting state (after the rod reached equilibrium) and in the normal-conducting state ($B_{sc} - B_{nc}$). The maximum temperature difference along the rod was always below 0.1K. Given the data in Figure 2, any potential thermoelectric contribution to the measured magnetic field is of the order of the noise and hence does not influence this measurement.

We calculated the cooling rate from the slope of the rod's temperature in time during the phase transition and measured the expelled flux after the rod reached the equilibrium state. The result is presented in Figure 4. We observed that the expulsion of the ambient magnetic field due to the Meissner effect was suppressed for high cooling rates (above 40 mK/s) where the rod passed quickly through the transition temperature. For smaller cooling rates (down to 3.6 mK/s) the flux expulsion became improved. The slower the rod cooled down, the more flux was expelled and the less flux remained trapped in the rod. This finding is in agreement with earlier published results for a disc-shaped geometry of the sample [5] as well as RF measurements made with samples [10]. Again, the application to a real cavity can only be made qualitatively, since the demagnetization factor influences the driving force of flux expulsion and differs from for cavity and rod.

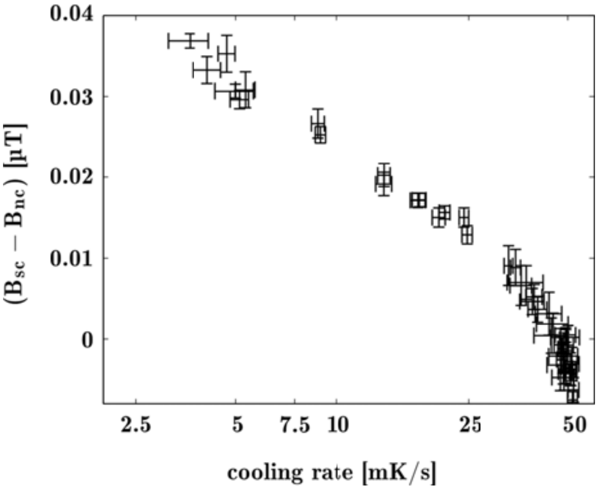

Figure 4: Expelled flux measured by FM1 versus cooling rate in the model system. B_{nc} during the measurement was 0.3 µT in FM1 direction and 3 µT in total.

The measurements on the model system revealed that flux expulsion via Meissner effect, with the Meissner state being energetically more favorable than a state with frozen flux, seems to be more effective when the system remains near T_c for longer periods of time. For further investigation we dedicated the following experiments to the dynamics of flux trapping close to the transition temperature. They were performed on the same niobium rod model system [11].

Figure 5 displays the behavior of the trapped flux when the rod was warmed <u>in the superconducting state</u> towards transition temperature without exceeding T_c at any time.

At the beginning of the experiment, the superconducting phase transition is evident. The magnetic field density outside the rod increased due to the Meissner effect (ΔB = 50nT). Afterwards the rod was slowly warmed towards the transition temperature. We observed that the trapped flux decays starting at ≈ 0.1 K below T_c leading to an increased amount of expelled flux (ΔB = 200nT). Figure 5 shows how the reduction was achieved in a gradual process of warming and cooling, but never exceeding T_c. In further experiments, a Helmholtz coil was used to increase the initially trapped flux. A reduction of up to 75% of the initially trapped flux in the niobium rod by a similar procedure of warming and cooling was demonstrated [11].

We conclude that the trapped flux in the niobium enters a state of increased mobility close to the transition temperature. Hence, the energetically more favorable state, the Meissner state, is approached leading to a reduction of trapped flux. Furthermore, this observation may explain why the cooling rate influences the amount of trapped flux. When the rod is cooled with a low cooling rate, it remains in the temperature region of increased flux mobility (between T_c and ≈ 0.1K below T_c) for a longer period of time. Thus more flux is able to leave the material.

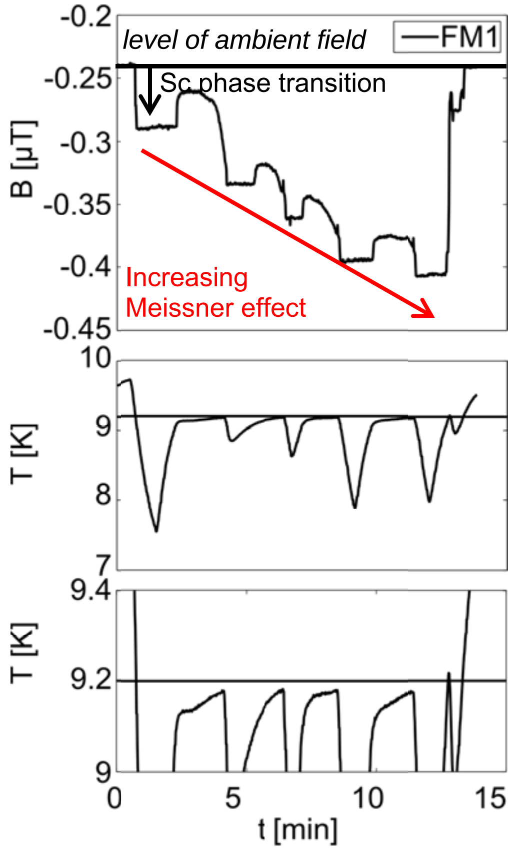

Figure 5: Behavior of trapped flux (FM1) and temperature upon heating in ambient field (0.3 µT in FM1 direction, 3 µT in total).

SUMMARY AND CONCLUSION

Earlier measurements [1, 2] have shown that a temperature gradient along a TESLA cavity during the superconducting transition adversely affects the quality factor. We suspect that the niobium-titanium junction drives a thermocurrent whose magnetic field remains trapped in the niobium when it goes superconducting. To test this hypothesis we measured the effect in a model system consisting of niobium and titanium rods that are designed to mimic the material properties of a cavity in its helium tank. Indeed we were able to demonstrate that a temperature gradient along the rods generates a thermocurrent near 10 K. The current generates a magnetic field which is subsequently trapped in the superconducting material during the phase transition. Simulations show that the field expected in a TESLA system is commensurate with the observed variations in surface resistance observed after different cooldown cycles.

In addition, the cooling rate during the superconducting phase transition was found to impact the amount of trapped flux even when the niobium is cooled isothermally. A high cooling rate inhibited the expulsion of flux from our sample. When the rate is reduced, more flux can be expelled. Both, thermal and spatial gradients, work in the same direction: The larger they are the greater is the amount of trapped flux. In contrast, a homogenous transition trough T_c leads to a reduction of trapped flux.

Based on these results we propose to add a step to the standard cavity cooling procedure The fast cool down to avoid Q-disease should be terminated before the cavity undergoes the superconducting transition, somewhere between 10K and 30K. The system should then be given ample time to thermally settle. After achieving a sufficiently uniform temperature distribution, cooling can proceed, ideally in a slow isothermal manner. Alternatively, a short thermal cycle to ≈ 20K should be introduced following the initial rapid cooldown below T_c. The next set of experiments at HoBiCaT will attempt such a modified cooldown cycle.

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