IMPACT OF TRAPPED FLUX AND THERMAL GRADIENTS ON THE SRF CAVITY QUALITY FACTOR

O. Kugeler, J. Vogt, J. Knobloch, Helmholtz-Zentrum für Materialien und Energie (HZB)
S. Aull, European Organization for Nuclear Research (CERN), Beams Department

Abstract

The obtained Q_0 value of a superconducting niobium cavity is known to depend on various factors like the RRR of the Niobium material, crystallinity, chemical treatment history, the high-pressure rinsing process, or effectiveness of the magnetic shielding. We have observed that spatial thermal gradients over the cavity length during cool-down appear to contribute to a degradation of Q_0. Measurements were performed in the Horizontal Bi-Cavity Test Facility (HoBiCaT) at HZB on TESLA type cavities as well as on disc- and rod-shaped niobium samples equipped with thermal, electrical and magnetic diagnostics. Possible explanations for the effect are discussed.

INTRODUCTION

Thermal losses in a superconducting cavity are determined by the surface resistance of the material according to $P_{diss}=\omega U/Q_0=\omega U(R_{BCS}+R_{res})/G$, where ω is the resonant frequency, U the stored energy, G a geometry factor, R_{BCS} the BCS-resistance and R_{res} the residual resistance. One of the loss mechanisms contributing to R_{res} originates from trapped vortices. These vortices have a normal conducting core which renders a small fraction of the cavity surface to 6 orders of magnitude higher resistivity. This surface fraction is proportional to the trapped magnetic flux, thus, $R_{res,B}\sim B_{trapped}$. The proportionality factor was determined to be 2.2nΩ/µT for a 1.5GHz cavity[1]. All experiments influencing Q_0 or the trapped flux were carried out well below 50K, thus hydrogen diffusion and Q-disease [2] can be excluded as cause in any of the described effects.

Q INCREASE BY THERMAL CYCLING

In horizontal tests of superconducting cavities at HoBiCaT[3] we have observed a dependency of the obtained Q_0 value on the cool-down conditions. Such conditions were experimentally realized by switching off the cryo-plant and warming up the cavity slightly above T_c and immediately cooling it down again. Variable quantity was the duration of the cryo-downtime which resulted in different temperature distributions due to the large inertia of the cryo-plant. The resulting obtained Q values of such thermal cycling procedures are presented in Figure 1. Here, "duration" means the *time difference* between the superconducting transition of both ends of the cavity. The smaller this value, the more uniform the temperature distribution in the cavity, the smaller the spatial gradient, and thus, the longer the cavity remained at temperatures close to T_c. This may seem counter-intuitive at first glance. This phenomenon has been attributed to the release of magnetic flux and investigated with a Niobium model system.

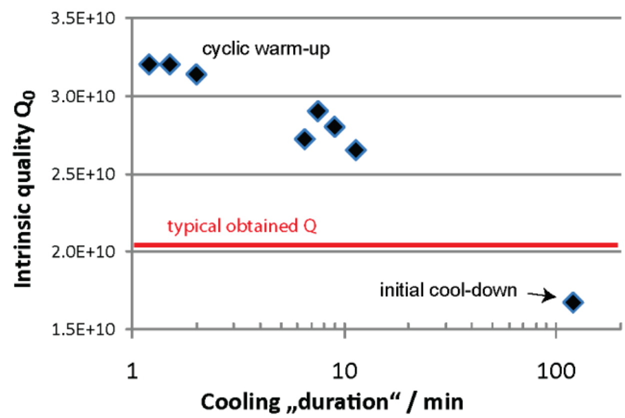

Figure 1: Dependence of obtained Q_0 on cool-down speed. Measurements were taken at 1.8K and E_{acc}=4MV/m.

FLUX TRAPPING

The energetically most favourable state of bulk Niobium at 1.8K (4.2K) is the Meissner phase, in which all magnetic field ambient at normal conducting conditions is expelled. However, expulsion of field lines can be incomplete when the material is cooled from T_c to 1.8K too rapidly, yielding a remaining magnetization of the material even after removing the external field source, as illustrated in Figure 2. This behaviour can be explained with a temperature dependence of the mobility of flux lines: their viscosity is lowest at T_c, (and zero above T_c) and it increases towards lower temperatures, as theoretically treated in [4].

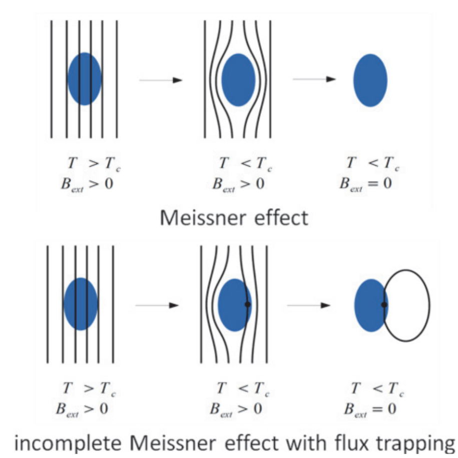

Figure 2: Meissner effect with flux trapping.

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The viscosity is determined by the occurrence of non- or weakly superconducting areas in the material via crystallinity (grain boundaries) or the chemical and heat treatment history (dislocations, impurities). An overview of these topics is given in [5].

Flux trapping has been investigated at HoBiCaT with disc and rod-shaped Niobium samples [6]. Samples were connected to the 4K liquid Helium reservoir. They could be heated by resistors attached at two sides of the samples enabling the creation of temperature gradients. Temperatures were monitored with CERNOX sensors at various positions, magnetic fields were measured with a fluxgate magnetometer that could be moved in two directions along the sample plane (discs) or axis (rod). External magnetic fields could be generated with a Helmholtz coil encompassing the setup.

Influence of Cooling Rate on Flux Trapping

The fraction of trapped magnetic field was measured as a function of the cooling rate. Cooling rates in the range of 0.5-60mK/s could be produced with the experimental setup. A logarithmic dependence on the cooling rate was found for all single crystal samples within the measurement range. Polycrystalline samples showed no dependence, i.e. they trap 100 % respectively 83.1 % regardless of the cooling rate. Figure 3 shows the fraction of trapped field as a function the cooling rate for the single crystal sample tempered at 800°C. It seems likely that this effect is suppressed in the polycrystalline samples since grain boundaries seem to have the strongest pinning force so that all flux flow is prevented.

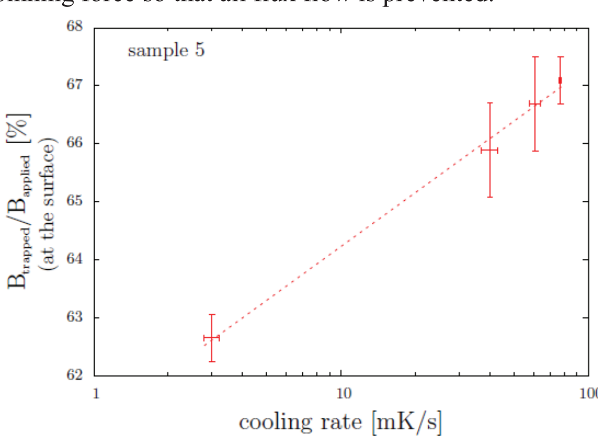

Figure 3: Dependence of the trapped field on the cooling rate for a single crystal sample with 800°C tempering.

Flux Release

Flux expulsion measurements are presented in Figure 4. Here, a sample with a certain amount of frozen flux was prepared by cooling it in an external magnetic field. The trapped field was monitored with a fluxgate magnetometer while the sample was slowly heated up. We observed a significant dependence of the flux release on the material properties. In polycrystalline material that was post annealed at 800°C the density of pinning centers is highest and the flux release starts 20mK below T_c. The

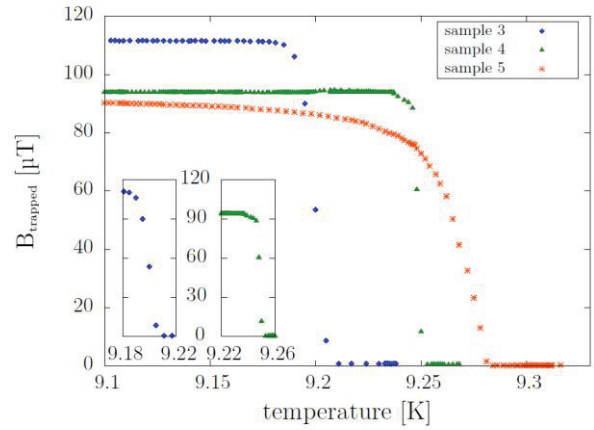

Figure 4: Flux release as a function of sample preparation history. Polycrystalline, BCP treated and post annealed at 800°C (blue squares); single crystal, BCP treated (green triangles); single crystal, BCP treated and post annealed at 800°C (red crosses). The time step between two neighbouring points is 1 sec. Note that slightly different field levels were applied and the thermo sensors had slightly different offsets.

same applies to a BCP treated single-crystal sample that wasn't subject to post annealing. In a sample that was both BCP-treated and 800°C post-annealed, the situation changes drastically. Flux release starts more than 250mK below T_c. It is duly noted that the sample stayed entirely superconducting during the process of flux release. This was verified with a simple test: The flux-release process was interrupted by switching off the heaters and simultaneously applying a large magnetic field.

If this magnetic field could be trapped in the material during cool-down, the sample (or at least a small area) must have been normal conducting – if the level of trapped magnetic flux stayed the same, the entire sample must have remained superconducting and additional field lines could not enter due to the Meissner effect. The result of the test was the latter.

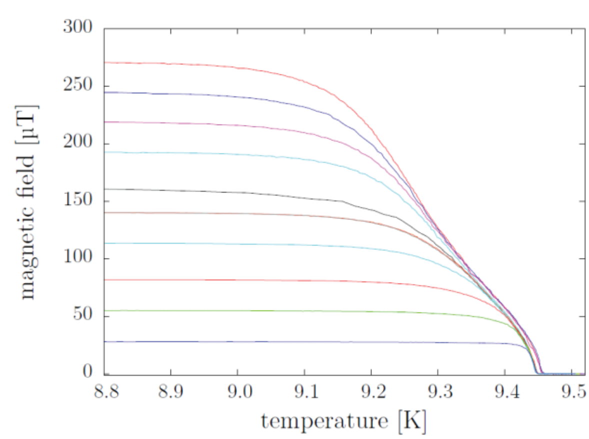

Figure 5: Flux release of different levels of trapped magnetic field in a single crystal Niobium sample (BCP + 1200°C) upon heating in zero external field.

The driving force of the fluxoid movement is the minimization of the energy. In order to quantify this, a progression of warm up procedures of samples with different initial levels of frozen flux was measured, see Figure 5. The onset temperature of the flux release decreases with the amount of frozen flux. The progressions merge, once same levels of frozen flux are reached. Flux release is accelerating towards higher temperatures which means that the decrease in viscosity dominates over the decrease in flux-line repulsion due to reduced amount of trapped flux.

Another verification that the sample was still superconducting is the following estimation: The cylindrical sample shape with D=37.7mm diameter and d=2.8mm height yields a demagnetization factor of $\delta=1-\pi\, d/D=0.766$ in the axial direction. This implies a maximum field enhancement factor at the edges of the sample of $1/(1-\delta)=4.3$. The reduced H_{c1} at the highest measured frozen flux, see Figure 5, is $H_{c1}(T)=H_{c1}(0)(1-(T/T_c)^2)=12.6\text{mT}/\mu_0$ which is an order of magnitude higher than the maximum utilized field of 270µT x 4.3=1.16mT. Also, the equation for the reduced flux does not explain the dependence of the flux release on the treatment history as in Figure 4.

In an alternative setup, Niobium rods have been investigated rather than discs. The original purpose of the rod geometry was to investigate the influence of thermal currents on the frozen flux. However, results of these measurements are still inconclusive. Additionally, the setup with the rod geometry was used to investigate the question, if one could manually drive frozen flux out the superconductor through appropriate cycles and approach the complete Meissner phase.

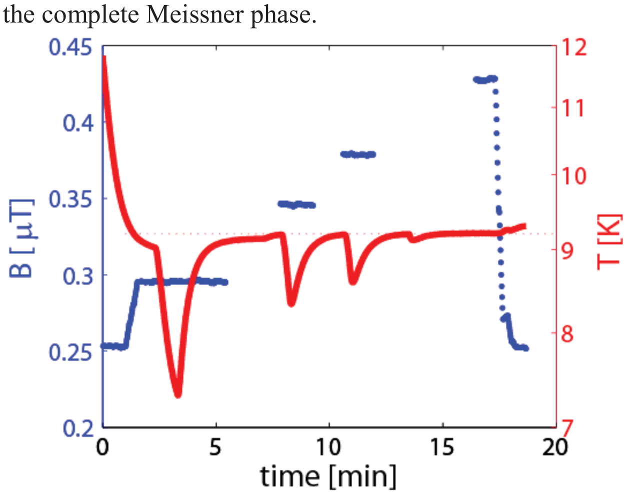

Figure 6: Manual expulsion of frozen flux from a superconducting rod by heating below T_c. The absolute value of B increases because flux is driven out of the rod increasing the measured flux density at the sensor position. Once, T_c is exceeded flux re-enters the sample reducing the measured value at the sensor position.

This is illustrated in Figure 6. In the experiment, a $8x8x300mm^3$ Niobium rod could be heated and cooled at both ends. Temperatures were monitored with Cernox sensors arranged along the rod axis allowing for precise temperature measurement and also control. It was possible to increase the flux density measured by the sensor that is positioned above the rod, purely by approaching T_c from lower temperatures. This is equivalent to expulsion of flux lines from the rod or approaching the complete Meissner state. The relationship between expelled and measured flux is determined by the demagnetization factor of the respective geometries. Once, Tc is exceeded and the sample becomes normal conducting (minute 24), flux is re-entering the rod and the measured field returns to its original value.

CONCLUSION

In order to obtain the highest possible Q_0 values in a superconducting cavity, it is desirable to reduce the amount of trapped magnetic flux. For this, the cool-down procedure of a superconducting cavity should be adjusted such, that it remains close to the transition temperature for a long time. Near T_c the driving force for flux expulsion can exceed the viscosity-inhibited movement of the flux-lines and the complete Meissner state is being approached which is equivalent to a high Q_0.

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