# STUDIES OF SYSTEMATIC FLUX REDUCTION IN SUPERCONDUCTING NIOBIUM

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*Abstract*

The intrinsic quality factor $Q_0$ of superconducting cavities is known to depend on factors like niobium material properties and treatment history. It is also degraded by trapping of magnetic flux. We study the dynamics of trapped flux in the superconducting state in a model system resembling a cavity: a niobium rod equipped with thermal, electrical and magnetic diagnostics. The focus of this study lays on the behavior of the flux tubes when the sample is slowly warmed up towards the critical temperature $T_c$. Besides the (incomplete) Meissner effect at phase transition we observe additional flux expulsion starting as one approaches $T_c$ from below within 0.1K. The reduced level of trapped flux is maintained when the sample is cooled down again and even additional reduction is achieved by repeating the procedure. Possible explanations for the effect are discussed.

## INTRODUCTION

The energetically most favorable state of bulk niobium at 1.8K (4.2K) 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 [1, 2] which are fulfilled when a cavity is cooled down in a magnetic field. Here, flux tubes are pinned in the superconductor and prevented from leaving the material.

We already reported on the impact of temperature gradients during the cool-down on the obtained $Q_0$ which is one potential consequence of trapped flux [3, 4]. The vortices have a normal conducting core with a surface resistance about 6 orders above that of sc niobium. For a 1.5 GHz cavity, every μT of trapped flux hence increases the surface resistance by 2.2 nΩ [5]. A crucial step towards avoiding flux trapping and the associated $Q_0$ degradation is an improved understanding of trapped flux dynamics.

For this approach, one needs to consider that niobium is a marginal type II superconductor with a mixed state in which the flux tubes form a lattice and several studies [6, 7] indicate a phase transition from localized (solid, fixed regular lattice) flux tubes towards moveable (liquid) flux tubes when the superconductor exceeds certain temperature / magnetic field combinations. One can conceive a similar thermal activation of pinned flux tubes in the (incomplete) Meissner state, which may enable them to move and therefore to exit the niobium even below $T_c$.

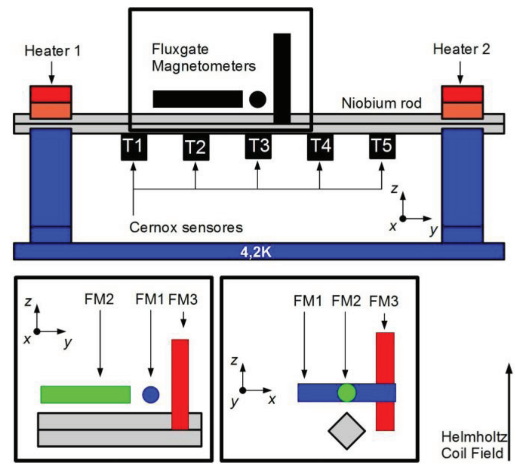


Figure 1: Experimental setup and position of instruments: Longitudinal view (left) and cross section (right) of FM1 (black), FM2 (green) and FM3 (red).

## EXPERIMENTAL SETUP

In our study, we examine the properties of the trapped magnetic flux in the superconducting state when the rod is slowly warmed towards $T_c$. An RRR = 300 niobium rod (8.4x8.4x300mm) is positioned inside the Horizontal Bi-Cavity Test Facility (HoBiCaT [8]). It is conduction cooled through its support posts to 4.2 K. Both ends of the rod are equipped with a resistive heater which can be controlled individually. The resulting temperature distribution along the rod is measured with 10 mK accuracy by five Cernox sensors. Rods and support stand are electrically insulated with a kapton foil which also reduces heat conduction into the helium. Thereby the required heater power for the generation of thermal gradients on the rod is reduced. Three fluxgate magnetometers (FM) with 1nT resolution (Bartington Mag-01H), one for each spatial direction, are attached along the rod. A Helmholtz coil (HC) for the generation of a vertical magnetic field up to ±300 μT encloses the whole construction. The setup and the positions of the instruments are displayed in Figure 1.

## MANIPULATION OF TRAPPED FLUX

In every performed experiment a magnetic field is applied by the HC while the niobium rod is cooled through $T_c$. Afterwards, the rod is smoothly warmed by manually adjusting the two heaters and the change in the magnetic field is observed by three fluxgate magnetometers. Precise temperature control was exercised to ensure that temperatures never exceeded $T_c$.



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*Manipulation without Applied Field*

In the first set of experiments the HC is turned off after the rod reached the minimum temperature. Hence, the signal registered subsequently by the FMs roughly corresponds to the frozen flux inside the rod. Figure 2 displays the measured magnetic field time. Only the signals obtained by FM1 and FM3 are presented because the signal of FM2 is more than one order of magnitude smaller due to the orientation of HC, rod and FM2.

The initially trapped magnetic field at minimum temperature is labeled (A). When the rod is warmed up again, the magnetization observed by the FMs stays constant until a temperature of $T \approx 9.1$ K ($< T_c$) is reached. At this point the amount of trapped flux suddenly starts to drop (B) until a minimum level is reached (C). When the warming is stopped during the decrease and the rod is cooled once more, the level of trapped flux in the instance of stopping remains. It does not return to the initial value (A) which would have been the case had the rod been normal conducting.

The change in the trapped flux indicates that heating leads to a thermal activation of the trapped flux lines as described in the introduction. The thermal energy exceeds the pinning potential and the pinning potential barrier does not hinder the movement of flux lines anymore. Driving force for the movement could be the striving for approaching the energetically most favorable state – the complete Meissner state – given by a minimum of sc / nc interface area. Not all flux is expelled because different pinning centers have different pinning potentials [9] and not all of them can be overcome by the thermal activation. Also the driving force decreases as the flux remaining in the sample is reduced. In the experiments we observe:

(1) A redistribution of flux lines (here even change in sign due to geometry as indicated by the sign change in Fig. 2) and
(2) A reduction of the absolute amount of frozen flux.

Table 1 displays the absolute values of the initially trapped field and reduced field in the end of the procedure measured by the three FMs for different HC fields. We achieved a reduction of trapped field of up to 75%.

Table 1: Magnetic field before and after reduction

| $B_{HC}$ [μT] | $\|B_{trapped}\|$ [μT] | $\|B_{minimised}\|$ [μT] | Reduction [%] |
|---|---|---|---|
| 33 | 1.98 | 0.50 | 75 |
| -32 | 1.87 | 0.88 | 53 |
| 65 | 3.91 | 1.19 | 70 |
| -66 | 3.80 | 1.57 | 59 |
| 97 | 5.84 | 1.88 | 68 |
| -98 | 5.73 | 2.26 | 61 |

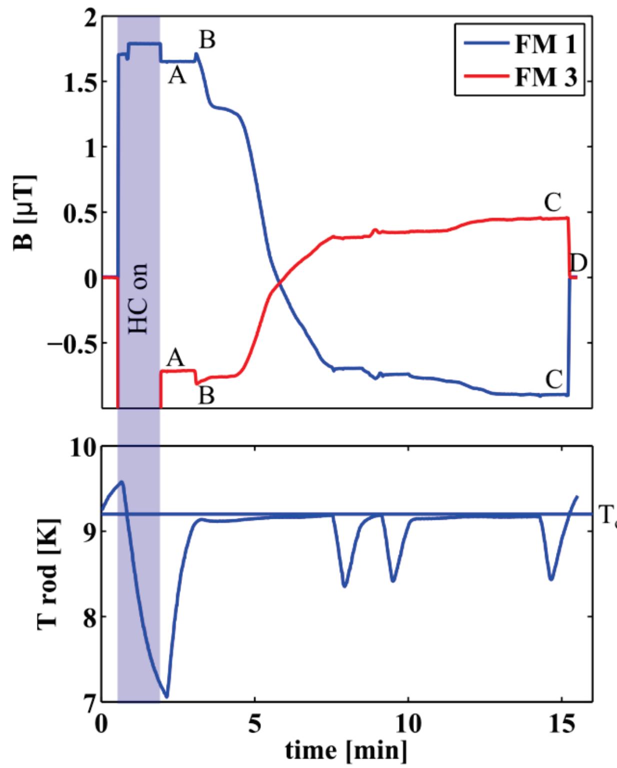


Figure 2: Behavior of trapped flux and temperature when a HC field of 33μT is applied and trapped: Initially trapped flux (A), reduced trapped flux (C) and level of flux ambient in HoBiCaT ≈ 3μT (D). This value has been subtracted from all data points.

The change in sign in the magnetic signal occurs due to the geometry of the setup). The FMs are fabricated for use in homogenous magnetic field. However, the field around the rod is inhomogeneous. Figure 3 displays RADIA simulations of the magnetic field distribution assuming a constant magnetization of the rod along z-axis and tilted by 45° towards the x-axis. Comparison of simulation and experiment indicate that the FMs measure rather the integrated field strength along their position than the absolute value. The orientation of the initially trapped field was calculated yielding an angle of 45°. The corresponding field distribution is given in Figure 3b. During the experiment, flux is redistributed by thermal activation and the orientation of the rod's magnetization changes. Figure 2 shows a zero-crossing of the FM values after approx. 6 min. It is indicating that at this point the field is in an orientation that results in zero measured magnetic field due to FM position and averaged measurement. Note that FM3 is positioned off center which strongly influences the calculation. For the point of no measured field, simulations yield an orientation of magnetization close to the one presented in Figure 3a. In the end of each experiment the field contribution is stable again (constant measured value, Figure 2(C)). The achieved reduced field may now be compared to the initially trapped field. Both values and the respective reduction are displayed in Table 1.




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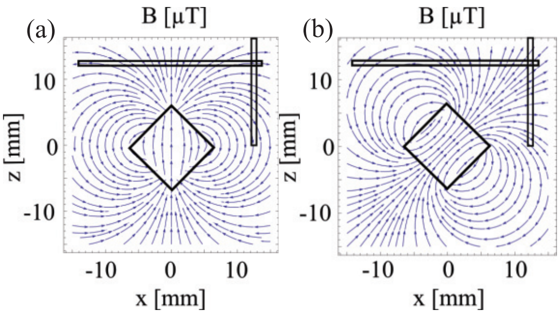


Figure 3: Magnetic field distribution for a constant magnetization of the niobium rod in z-direction (a) and tilted by 45° (b). The black rectangle indicates the positions of FM1 and FM3.

### *Manipulation with Applied Field*

The investigations presented so far raise the question how the flux tubes behave when an external field is not turned off during warm up as opposed to the above experiment, where an external field was trapped but only the ambient field remained during warm up.

Figure 4 displays a typically obtained signal of FM1. In the beginning the rod is normal conducting (A). It is cooled below $T_c$ where flux is expelled by Meissner effect (B). The magnetic field probe measures an *increase* in the field density outside the rod (C). Afterwards the rod is slowly warmed using the heaters. Starting at a temperature of (9.08±0.01) K we observe a sudden decrease in expelled flux (D) which coincides with the onset of Paramagnetic Meissner Effect (PME) reported by Thompson [10]. The onset temperature does not depend on the applied field strength in the range of 0 to ±300 μT tested here. The PME is a phenomenon observed in some high temperature superconductors and in niobium. These materials exhibit a paramagnetic phase between the perfect diamagnetic behavior in the Meissner state and the normal conducting state.

When the rod is warmed up further, a second effect occurs. When $T_c$ is approached an additional expulsion of flux is evident (E) resulting in a lower level of residual frozen flux (i.e. a higher level of expelled flux). Subsequent repetition of cooling and heating leads to a minimized level of trapped flux (F) and each time we observe the PME. Further repetition leads only to the jumps in magnetization due to PME but no further change in the level of trapped flux. This systematic flux reduction can be explained by a thermal activation of flux as described above.

## CONCLUSION

The amount of trapped magnetic flux can be manipulated and systematically reduced while the niobium remains superconducting. Thus, the complete Meissner state is approached.

If one could apply a similar procedure to SRF cavities, this effect could lead to higher $Q_0$ values and operation close to the BCS-limit. Furthermore, an adapted cavity cooldown procedure may lead to significantly reduced level on initially trapped flux considering the major impact of the cooling dynamics in the temperature range between 9.08K and $T_c$ on the flux trapping behavior.

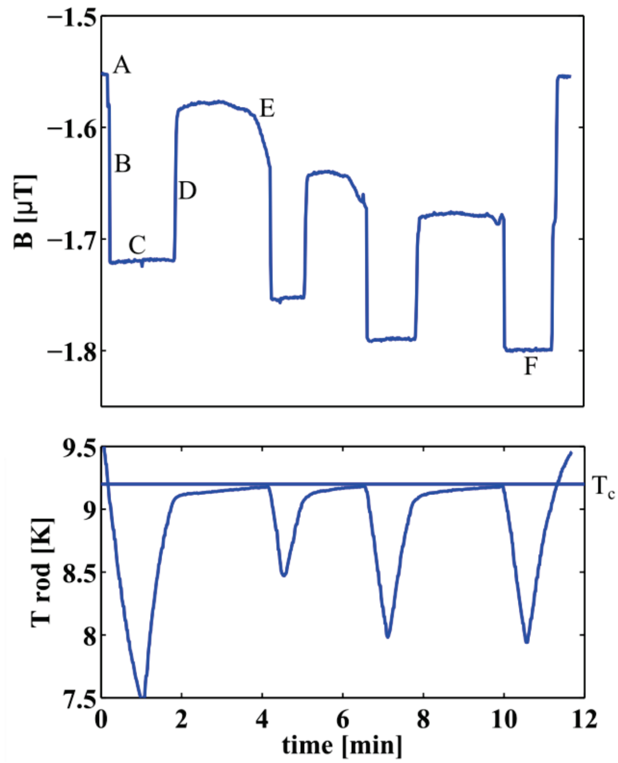


Figure 4: Behavior of trapped flux (FM1) and temperature upon heating in $B_{HC}$ = 33μT.

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