IMPACT OF TRAPPED FLUX AND SYSTEMATIC FLUX EXPULSION IN SUPERCONDUCTING NIOBIUM

J. Vogt, O. Kugeler, J. Knobloch, Helmholtz-Zentrum für Materialien und Energie (HZB)

Abstract

The intrinsic quality factor Q_0 of superconducting cavities is known to depend on various factors like niobium material properties, treatment history and magnetic shielding. To study trapped flux in Niobium we constructed a test stand at Horizontal Bi-Cavity Test Facility (HoBiCaT) at HZB using niobium rods equipped with thermal, electrical and magnetic diagnostics. The focus in this study was on the behaviour of the trapped flux when the sample is slowly warmed up towards the critical temperature T_c. Besides the (incomplete) Meissner effect we observed additional flux expulsion starting at ≈0.1K below T_c. The reduced level of trapped flux is maintained when the sample is cooled down again and can even be improved by repeating the procedure. Possible explanations for the effect are discussed.

INTRODUCTION

We already reported on the impact of temperature gradients during the cool-down on the obtained Q_0 [1]. In the quest for minimization of RF losses in SRF cavities the impact of trapped vortices is one main topic. The vortices have a normal conducting core with a surface resistance about 6 orders above that of superconducting Niobium. This surface fraction is proportional to the trapped magnetic flux. The surface resistance was determined to be 2.2nΩ per µT for a 1.5GHz cavity [2]. A crucial step in avoiding trapped flux is an improved understanding of flux trapping behaviour of Niobium.

The energetically most favourable state of bulk Niobium at 1.8K (4.2K) is the Meissner phase, in which all magnetic field present in the normal conducting state is expelled. However, expulsion of flux can be incomplete, yielding a remaining magnetization of the material even after removing the external field source. The dynamics of this trapped flux is still not well understood. One approach was the investigation of flux that is permitted to penetrate a marginal type II superconductor in the mixed state. Here, the flux tubes form a lattice and several studies [3, 4] 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 as indicated by the black dotted "melting line" in Figure 1.

The behavior of flux that is trapped in the Meissner state is uncertain. A continuation of the melting line in this phase is conceivable, so that flux lines in the check region (Figure 1) may be able to exit the Niobium below T_c. In our study, we examine the properties of the trapped magnetic flux in the Meissner phase when the rod is slowly warmed up.

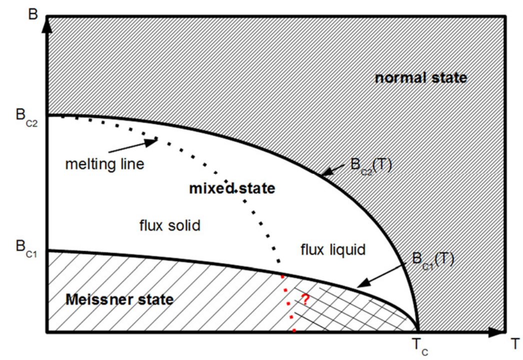

Figure 1: Magnetic phase diagram of marginal Type II superconductor [5]. The added red dotted line indicates a possible extension of the liquid/solid flux interface into the Meissner state. The size of the check region is exaggerated.

EXPERIMENTAL SETUP

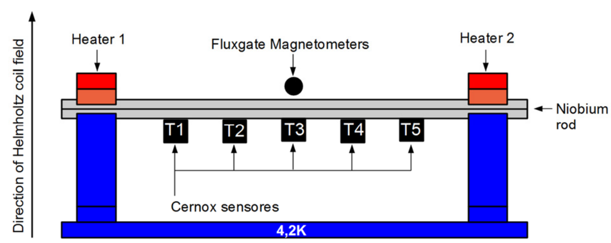

Figure 2: Experimental setup

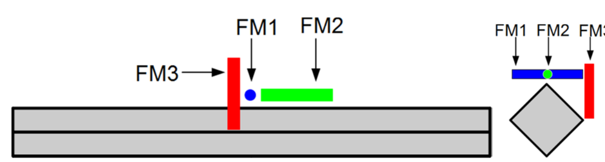

Figure 3: Positions of fluxgate magnetometers (FM): Longitudinal view (left) and cross section (right) of FM1 (black), FM2 (green) and FM3 (red)

For the experiments, a RRR=300 niobium rod (8.4x8.4x300mm) was positioned inside HoBiCaT [6]. It was conduction cooled through the posts to 4.2K. In order to reduce heat transfer into the Helium, heat conductivity was reduced by introducing a kapton foil between rod and support stands. Both ends of the rod were equipped with a resistive heater. They could be individually regulated to control the temperature of the rod with 10mK accuracy. Five Cernox temperature sensors with mK resolution and three fluxgate magnetometers with 1nT resolution (Bartington Mag-01H), one for each spatial direction,

ISBN 978-3-95450-122-9

were attached along the rod. A Helmholtz coil (HC) for the generation of a vertical magnetic field up to ±300μT enclosed the whole construction. The setup and the positions of the instruments are displayed in Figures 2 and 3.

MANIPULATION OF TRAPPED FLUX

In each of the performed experiments a magnetic field is applied using the HC while the Nb 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 (FM). Precise temperature control was exercised to ensure that at no time T exceeded T_c.

Manipulation without applied field

In the first set of experiments the HC is turned off after the rod has reached the minimum temperature. Hence, the signal registered subsequently by the FMs roughly corresponds to the frozen flux inside the rod. Referring to Figure 4, this is position (A).

When the rod is warmed up again, the magnetisation observed by the FMs stays constant until a temperature of T≈9.1K (<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, the level of trapped flux at the instance of stopping remains - even upon subsequent cooling.

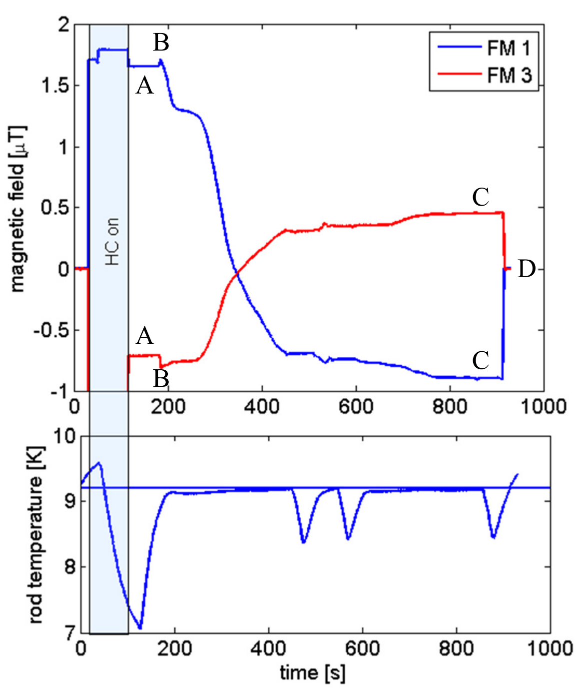

Figure 4: Behaviour of trapped flux and temperature when a HC field of 33μT is applied and trapped: Initially trapped flux (A), minimal trapped flux (C) and level of flux ambient in HoBiCaT ≈3μT (D). This value has been subtracted from all data points.

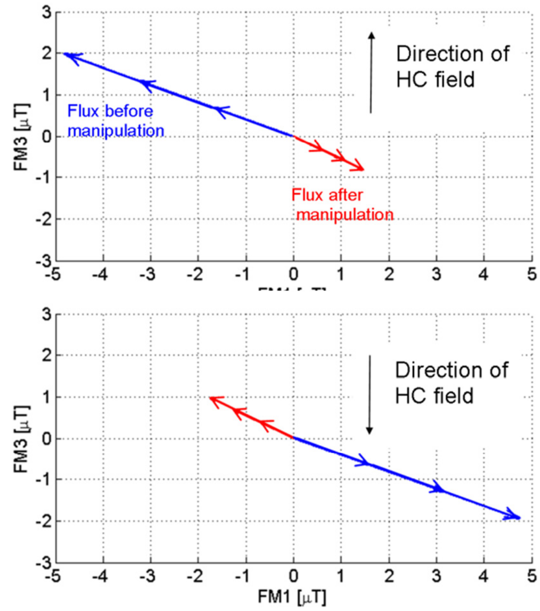

Figure 5: Trapping for HC fields: 33μT, 65μT, 97μT (above) and -32μT, -66μT, -98μT (below). The initially trapped field is blue and the field after additional expulsion is red.

The signals obtained by FM1 and FM3 are displayed in Figure 4. For better visualization their values can be combined to a vector indicating the spatial orientation of the trapped flux, see Figure 5. The signal of FM2 is more than one order of magnitude smaller than the signals of FM1 and FM3 due to the orientation of HC and rod and therefore is not displayed here.

The change in the trapped flux indicates that the warming enables the trapped flux lines to move. A possible explanation could be that the thermal energy exceeds the pinning potential and the pinning potential barrier does not hinder the movement of flux lines anymore ("liquid flux state"). Driving force for the movement could be the strive for approaching the energetically most favourable state – the complete Meissner state – given by a minimum of sc/nc interface area. Not all flux is expelled because different pinning centres have different pinning potentials [7] and not all of them can be exceeded by the thermal activation. Also the driving force reduces, the less flux remains in the sample. We observe:

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

The latter is evident from the shortening of the vectors in Figure 5. Table 1 displays the values of the initially trapped field and the minimal trapped field in the end of the procedure for different HC fields. We achieved an expulsion of up to 75%.

Table 1: Magnetic field before and after expulsion

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

Manipulation with applied field

These investigations 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 6 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. 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 (C) which coincides with the onset of Paramagnetic Meissner Effect (PME) reported by Thompson [8]. The onset temperature does not depend on the applied field strength in the range of ±300µT 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 behaviour in the Meissner state and the normal conducting state. Note the difference to classical frozen flux which is a topological coexistence of normal conducting and Meissner-like areas.

When the rod is warmed up further, a second effect occurs. When T_c is approached an additional expulsion of flux is evident (D) 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 (E) and each time we observe the PME. Further repetition leads only to the jumps in magnetisation due to PME but no further change in the level of trapped flux.

A possible explanation for this systematic flux expulsion could be an increased mobility of flux lines in a temperature regime close to T_c consistent with the data obtained in the first set of experiments.

In this set of experiments, HC fields of up to ±300µT were applied leading to expulsion pattern that were all similar to Figure 6. Hence, systematic flux expulsion works under these conditions.

CONCLUSION

The amount of trapped magnetic flux can be manipulated and systematically minimized while the material remains superconducting. The complete Meissner state is thus being approached.

If one could apply such a procedure to SRF cavities, this effect could lead to higher Q_0 values and operation close to the BCS-limit. In addition, the major impact of the cooling dynamics in the temperature range between 9.08K and T_c on the flux trapping behaviour could explain the impact of temperature gradients during the cool-down on the obtained Q_0 values as described in [1].

ACKNOWLEDGMENT

We would like to thank A. Frahm for the design of the testing apparatus and S. Klauke and M. Schuster for help with setting up the experiment.

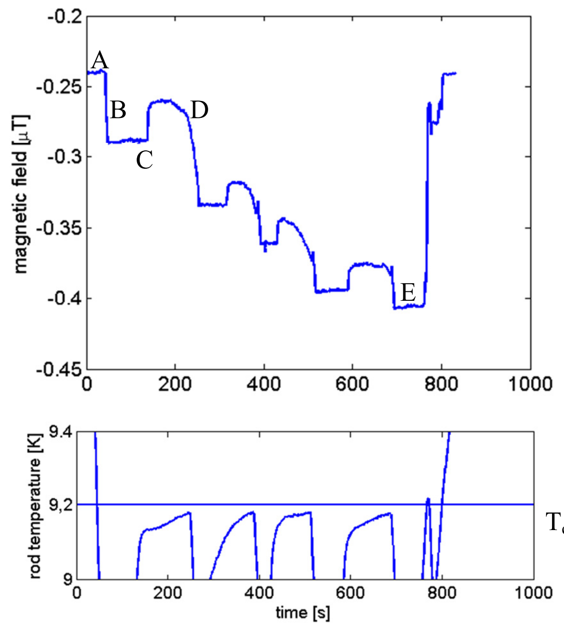

Figure 6: Behaviour of trapped flux (FM1) and temperature upon heating in ambient field (background field trapped and partially expelled)

REFERENCES

[1] O. Kugeler, J. Vogt, J. Knobloch, S. Aull, "Impact of Trapped Magnetic Flux and Thermal Gradients on the SRF Cavity Quality Factor", *Proc. 5th IPAC2012*, New Orleans (2012), p. 2203.

[2] P. Kneisel and B. Lewis, Tech. Rep. Tech. Note 94–028, Continuous Electron Beam Accelerator Facility, 1994

[3] J.W. Lynn, N. Rosov, T.E. Grigereit, H. Zhang, T.W. Clinton, Phys. Rev. Lett. 72, 1994

[4] J. Kierfeld, Phys. Rev. B 69, 2004

[5] C. Poole,"Handbook of Superconductivity", 2000

[6] O. Kugeler, A. Neumann, W. Anders, and J. Knobloch, Review of scientific instruments, vol. 81, Jul. 2010, p. 074701.

[7] W. Buckel, R. Kleiner, "Superconductivity", 2004

[8] D.J. Thompson, M.S.M. Minhaj, L.E.Wenger and J.T. Chen, Phys. Rev. Lett. 75, 1995

ISBN 978-3-95450-122-9