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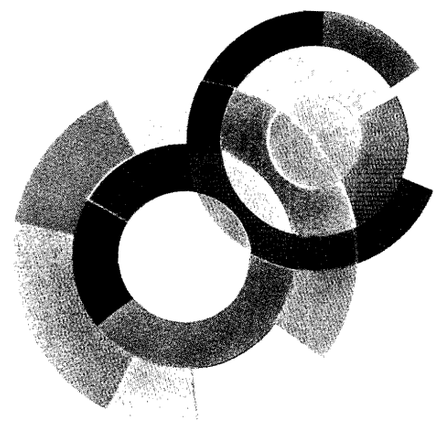

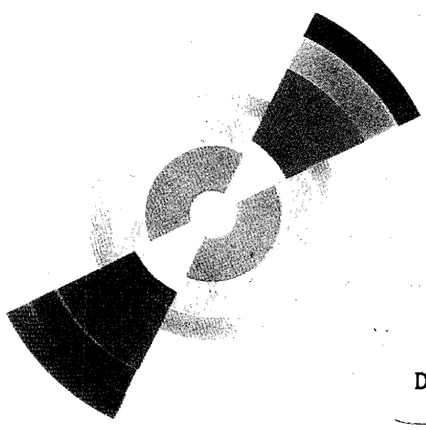

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FLUX TRAPPING IN SUPERCONDUCTORS AT LOW FIELD LEVELS

C. Vallet, M. Boloré, B. Bonin,
S. Jaidane, H. Safa

DAPNIA

Couverture : Sylvie Cabrit et Marc Sauvage

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Adresse : DAPNIA, Bâtiment 141
CEA Saclay
F - 91191 Gif-sur-Yvette Cedex

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Flux trapping in superconductors at low field levels

C. Vallet, M. Boloré, B. Bonin, S. Jaidane, H. Safa
Service d' Etude des Accélérateurs, DAPNIA,
CE Saclay, 91191 Gif sur Yvette cedex, France

Abstract

The flux trapped in various field cooled Nb, Pb and NbTiN samples (including thin films) has been measured. For small ambient fields 100% of the flux is trapped. This conclusion may be modified to some extent in the case of rapid, inhomogeneous cooling due to the influence of ferromagnetic objects close to the superconducting sample under investigation. The consequences of these results on the behavior of superconducting RF cavities are discussed.

Keywords: superconductivity, trapped flux, vortex pinning.

Introduction

In principle, a superconductor cooled in the presence of a static magnetic field smaller than H_c (H_{c1} for a type II superconductor) should be in the Meissner state, i.e. all flux pervading the sample in the normal state should be expelled below the critical temperature. In fact, at the critical temperature T_c, the magnetic flux coalesces into fluxons which may either be expelled out of the sample if the superconductor is ideal, or become trapped inside if pinning centers exist. The proportion of flux trapped in the superconductor may thus give information on the pinning force in the sample. Previous studies of the pinning of vortices in superconductors have relied mostly on magnetization experiments, done usually at constant temperature and variable external field. These experiments give insight on the pinning mechanisms, but they provide no direct information on the density of flux trapped in the material when it is cooled below its critical temperature in a constant external field. These reasons motivated us to measure the flux trapped in various field cooled superconducting samples by a dedicated experiment. A direct application of this study can be found in the domain of superconducting RF cavities. The high Q value of these resonators can be degraded if they trap ambient magnetic field during their cooldown. Information on the proportion of flux trapped by field cooled "practical" superconductors can thus help to understand the detailed mechanisms of residual dissipation in RF superconducting cavities, as well as to improve their performance.

Experiment and apparatus

The superconducting samples used for this experiment were planar sheets 2 mm thick of various shapes roughly 12–15 cm across, oriented perpendicular to the vertically applied magnetic field (Fig. 1). This geometry was chosen because the corresponding demagnetizing coefficient is easily calculable.

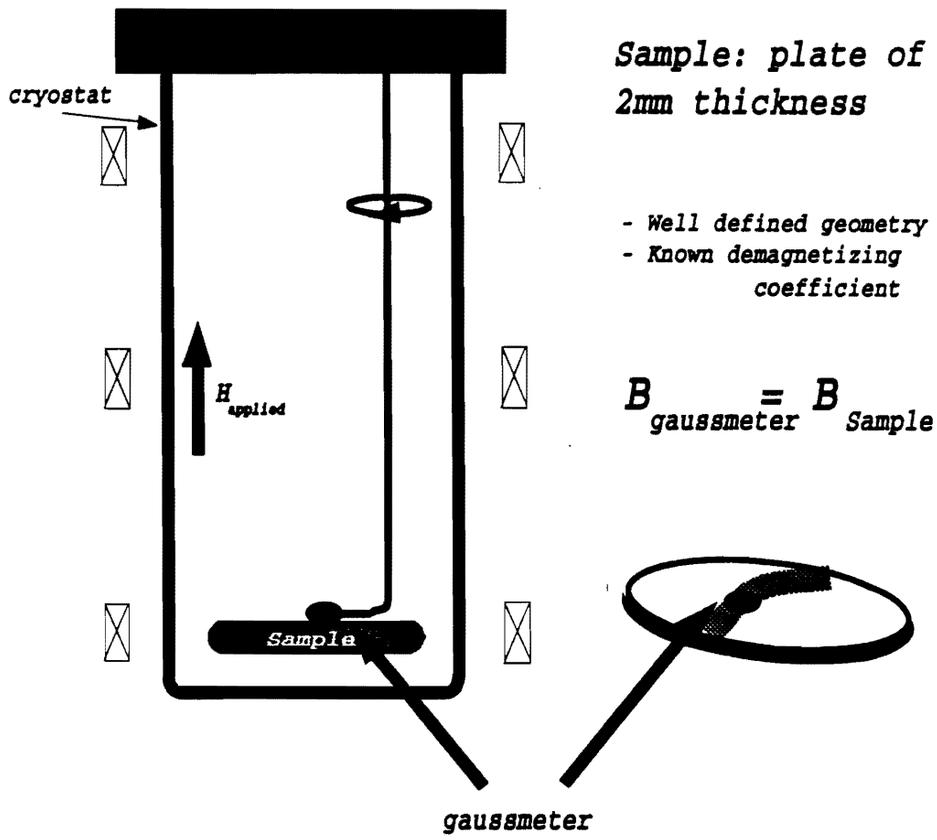

Figure 1 The apparatus

A Förster probe (ref 1) measuring the vertical component of the magnetic field could be moved parallel to the sample surface. The sensitive part of the probe had an active volume of 5 mm per 0.2 mm, and was at a distance of 5 mm from the sample surface. This distance was kept as small as possible in order to ensure that $B_{probe} \simeq B_{surface}$ with the best possible accuracy.

The samples were cooled in a Helium cryostat placed inside a set of three solenoids giving a roughly uniform vertical magnetic field adjustable in the range 0 – 3 Gauss. The earth's magnetic field was shielded by concentric sheets of CONETIC around the coils, leaving a remnant field smaller than 10 mGauss at the sample.

The Förster probe was found to work correctly at low temperatures. Its response turned out to be temperature dependent and was measured by a separate experiment in a static magnetic field. (Fig. 2). It can be seen that the variation of the probe response is about a factor of 2 between 300 K and 15 K, and almost constant between 15 K and 4 K. This variation was taken into account in all subsequent measurements.

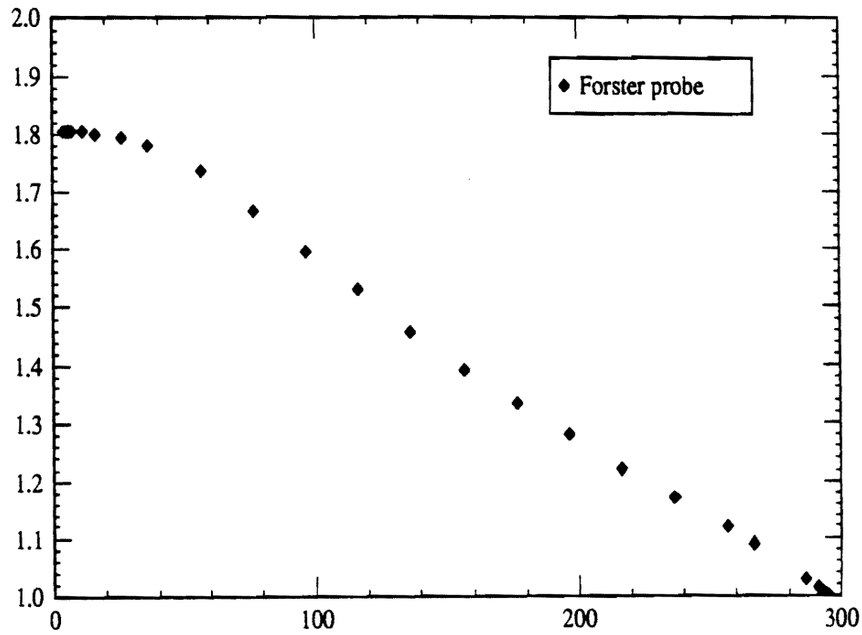

Figure 2 Temperature dependance of the Förster probe response B_{probe}/B_{real} versus T (K)

The samples chosen for this study had characteristics similar to the material in common use for manufacturing superconducting RF cavities. These characteristics are summarized in Table 1.

Sample	A	B	C	D	E	F
Material	Nb sheet 2 mm thick	Nb sheet 2 mm thick	Nb sheet 2 mm thick	Nb sheet 2 mm thick	Pb sheet 2 mm thick	NbTiN film on Cu substrate
RRR	180	300	500	300, unchanged after firing	1000	1
Grain size	50 μm	50 μm	50 μm	50 μm	-	0.01 μm
Origin	Heraeus	Heraeus	Giredmet	Heraeus	-	Sputtered film
Shape	disc Φ =12.6 cm	disc Φ =12.6 cm	square plate a=15 cm	disc Φ =12.6 cm	disc Φ =12.6 cm	disc Φ =12.6 cm
Treatment	BCP*	BCP*	BCP*	Fired T=2200C Reoxidized in air	Acid cleaning of the surface	None

Table 1 Characteristics of the superconducting samples used for this experiment. *Niobium samples A,B,C were cleaned in a "Buffered Chemical Polishing" bath (HF,HNO3,H3PO4 mixture of concentrated acids) and rinsed in deionized water.

The temperature of the sample was monitored by 100 Ω Allen Bradley Carbon resistors.

The thermal cycle used for this experiment consisted of three steps (Fig. 3):

Step 1. The temperature is above T_c (i.e. T=15 K for Nb, and T=25 K for NbTiN); There is an externally applied magnetic field H_a.

Step 2. The temperature is now below T_c (ie T=4.2 K in all cases); The magnetic field is still applied.

Step 3. The temperature is kept below T_c (4.2 K); The applied magnetic field is now cut off.

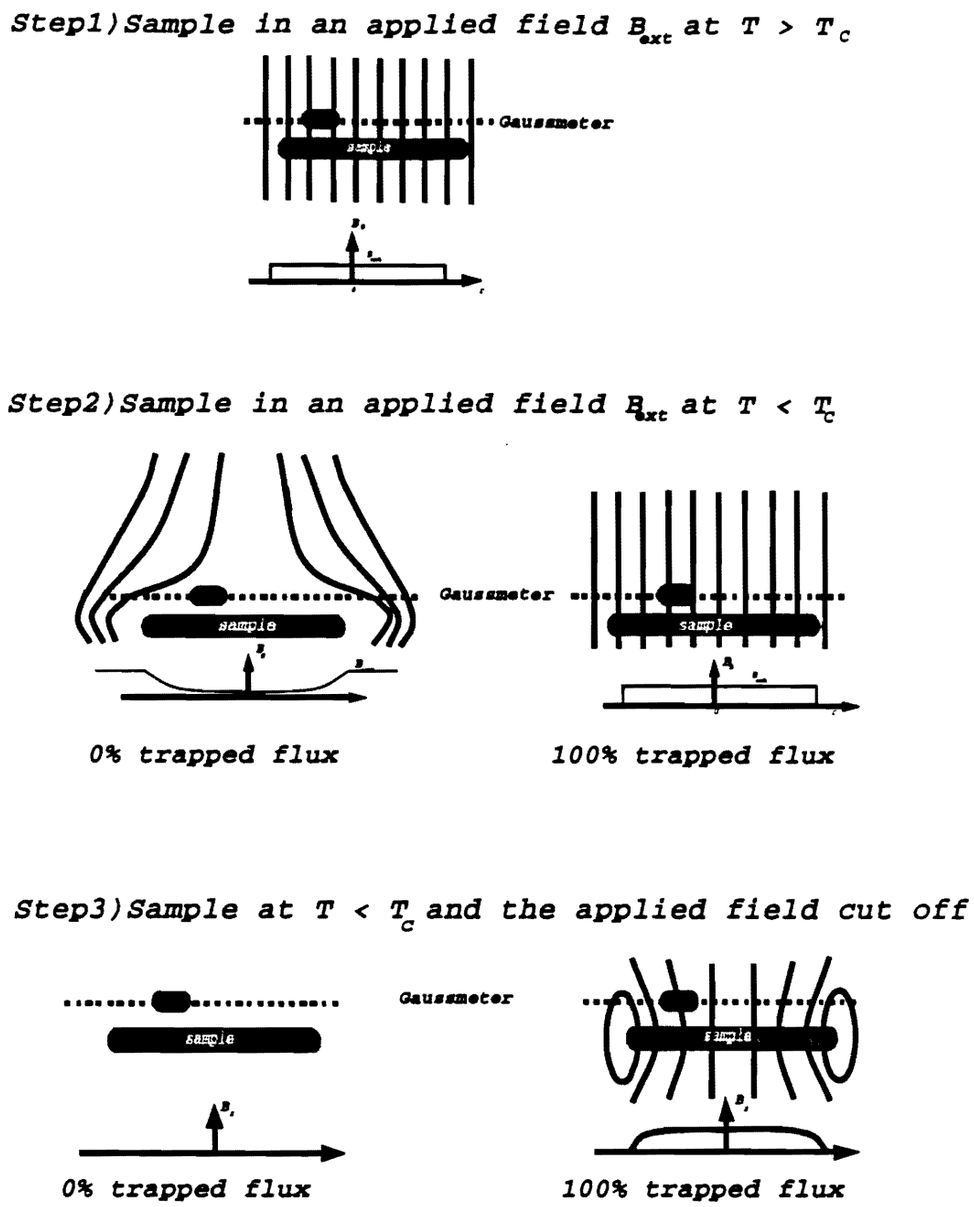

Figure 3 Flux trapping in a superconducting plate. Left and right columns correspond to the cases 0% and 100% trapped flux respectively.

In the following, the quantities B_i will refer to the field measured by the Förster probe during step i.

Results for Nb and Pb sheets

The demagnetizing coefficient (1–N) of all our Nb samples is about 1/60 and the applied magnetic field H_a was always kept smaller than 3 Gauss. The magnetic field seen at the edge

of the disk is thus $H_a/(1-N)$, much smaller than the critical field H_{c1} of the Nb samples used in this experiment (1300 G, measured with a Foner magnetometer, ref 2). We should thus observe a complete Meissner effect, except if pinning effects occur. It can be seen on Fig. 4 that the ratio of magnetic fields B_2/B_1 equals 1 for all the samples studied. This shows that the flux lines in the neighborhood of the sample are not disturbed by the superconducting transition, thus indicating that 100% of the flux is trapped.

The ratio of magnetic fields B_3/B_1 is shown in Fig. 4. It should equal 1, assuming 100% trapped flux, and a pointlike probe on the surface sample. In fact, it is only 80% at the center of the sample, and falls down to even lower values near the edges. The radial dependence of this ratio can be explained, if one remembers that the probe is not pointlike, and is located at a distance 5 mm from the sample surface. The probe is thus sensitive to the distortion of the flux lines caused in step 3 by cutting off the externally applied magnetic field. This distortion has been calculated, assuming 100% trapped flux, and approximating the disk by a flat ellipsoid with identical radius and thickness. The theoretical B_3/B_1 thus obtained is in excellent agreement with the measured value, confirming that there is 100% trapped flux in all the samples studied.

For sample C, the result B_3/B_1 is slightly different because of the square geometry of the sample, but it can be safely concluded from the measured value: $(B_2/B_1) = 1$ that also in this case, we have 100% trapped flux again.

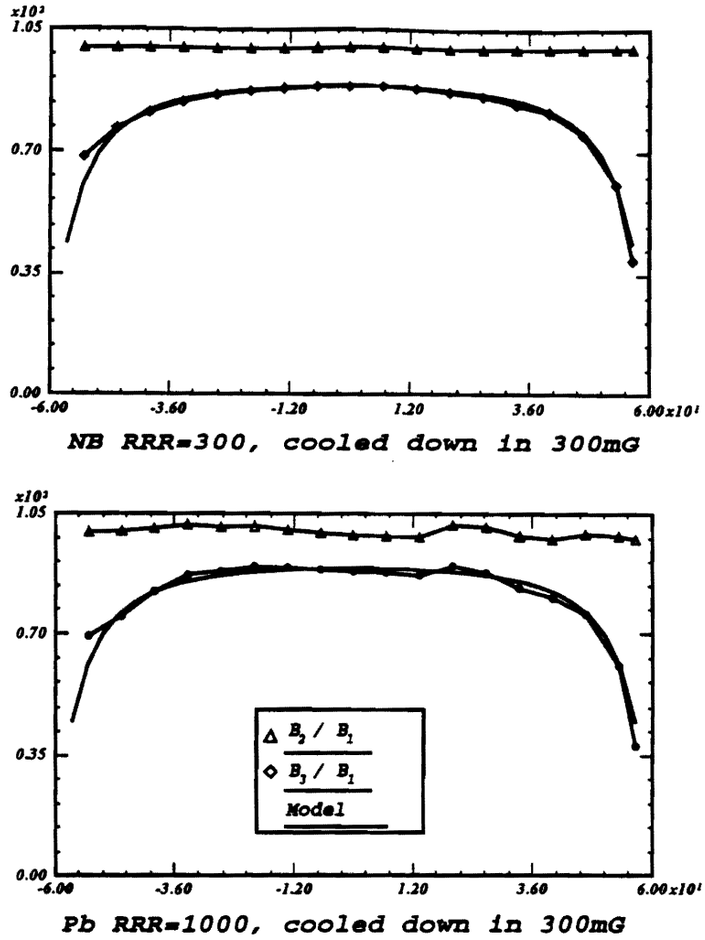

Figure 4 The ratios B_2/B_1 and B_3/B_1 versus the position(mm) on the plate for Nb and Pb samples.

Very little information is available on the pinning mechanisms in pure niobium. Grover et al. (ref. 3) measured the magnetic behavior of Nb samples of moderate purity, both in rod and powder form. From their measurements, it is not possible to discriminate the origin of the pinning: impurities, lattice or surface defects. The complete trapping observed in our measurements shows that even a very pure material exhibits efficient pinning for low applied fields. In the particular case of niobium, this result may also be due to the attractive interaction between vortices, well known in this material (ref.4), which might favor the coalescence of vortices, and prevent their expulsion from the superconductor volume.

F. Palmer (ref. 5) measured the sensitivity of variously treated niobium RF cavities to trapped flux. He observed that the increase of surface resistance due to cooling of the cavity in a given uniform magnetic field was markedly (about five times) smaller for fired cavities as for usually treated ones. A natural explanation might be that the firing cures the defects of the material and kills the pinning centers, thus enabling the cavity to expel magnetic flux during cooldown. We measured sample D in order to check this hypothesis. Disappointingly, though, we measured 100% trapped flux again for this fired sample. One significant difference

might lie in the fact that, contrary to sample D, Palmer's cavity was not allowed to reoxidize in air after firing.

The magnetic properties of type I and type II superconductors are known to be markedly different. We measured a lead sample, hoping to observe a deviation in its flux trapping behavior as compared to Niobium. But here again, the results are compatible with 100% trapped flux for fields smaller than 3 Gauss. A coalescence of the flux lines into macroscopic regions of the sample could have been expected in the case of a type I superconductor like Pb. As shown in Fig. 4, the resolution of the Förster probe did not permit to detect any spatial fluctuation in the repartition of the magnetic flux. Therefore, the size of these "flux bundles" does not exceed a few millimeters, if they exist at all.

A copper sample of identical geometry was also measured using the same experimental procedure. The measured ratios B_2/B_1 and B_3/B_1 gave the expected values of 1 and 0 respectively, thus proving that no parasitic effect was due to the sample surrounding.

Results for a NbTiN film

The flux trapped in a field-cooled NbTiN thin film sample (ref. 6) was also measured following the same procedure. The film thickness was 1 μm, and the demagnetizing coefficient in a perpendicular field was roughly (1–N) = 1.e-4. For an applied field H_a = 3 Gauss, the field at the edge of the sample is $H_a/(1-N) = 3.10^4$ Gauss, well above H_{c1}. The sample is thus in the mixed state, and the critical state theory (ref. 7) applies if the repulsion between fluxons exceeds the pinning force. It can be seen from Fig. 5 that the ratios B_2/B_1 and B_3/B_1 have exactly the same behavior for the NbTiN film and for the Nb sheet samples. All the fluxons pervading the material when the film is cooled in a field of 3 Gauss thus remain trapped when the applied field is cut off. This result (100% trapped flux) is identical to the one for niobium sheet, with the important difference that the field-cooled thin film of NbTiN was in the case H>Hc1/(1–N), whereas the Nb sheet samples were not. Here again, the pinning force is thus larger than all other forces acting on the fluxons.

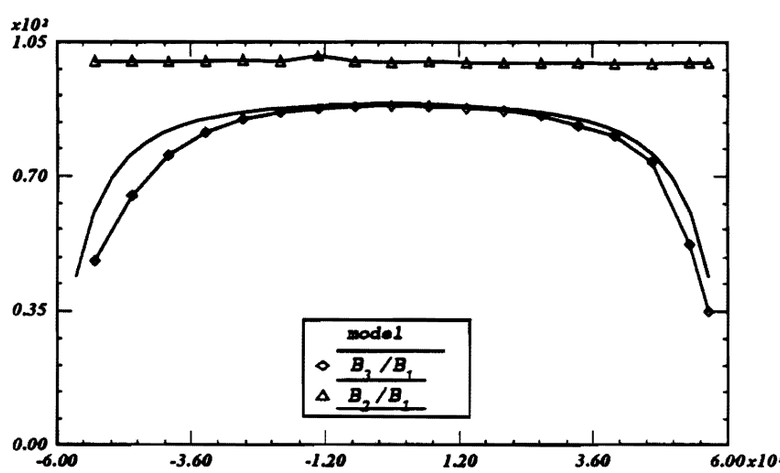

Figure 5 The ratios B_2/B_1 and B_3/B_1 for the NbTiN samples.

Critical state experiments

Another thermal cycle was used for experiments of critical state, and for verification:

Step 4. The sample is cooled below T_c with no applied magnetic field

Step 5. The temperature is kept below T_c (4.2 K); The magnetic field is now applied.

Step 6. The magnetic field is again cut off.

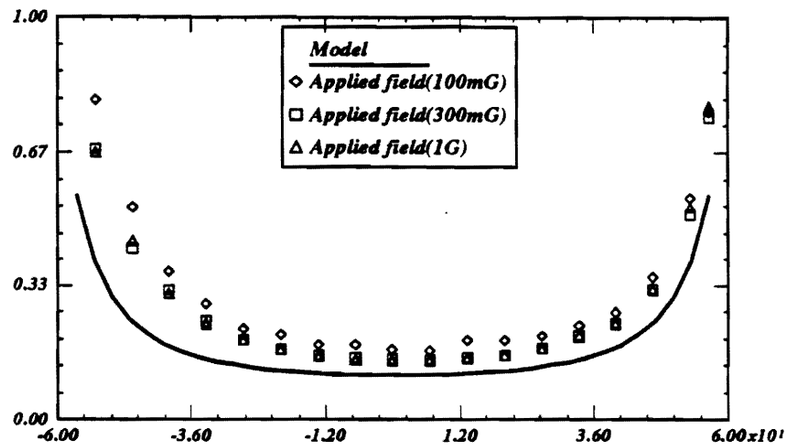

Figure 6 The ratios B_4/B_5 for the NbTiN sample.

The same sample was also zero field—cooled, and its magnetization was measured in a subsequently applied magnetic field (steps 4 and 5). The experimental result (Fig. 8) shows that no measurable flux penetration occurs, even for applied fields much larger than $H_{c1}/(1-N)$. The field repartition B_4/B_5 measured at a distance z from the film is almost exactly the one expected for a perfectly diamagnetic flat ellipsoid. Also, the field B_6 measured in step 6 after cutting off the applied magnetic field is zero, as if no fluxons had entered the sample. This can be understood from the Bean critical state model (ref. 7): if the pinning force is very large, the fluxons penetrate the sample only in a very thin outside ring with a very strong fluxon density gradient. The total number of fluxons is then small and their effect on the sample magnetization is negligible.

Inhomogeneous cooling of superconductors in a magnetic field

Technical superconductors (for instance RF cavities) are usually cooled rapidly, and it is not uncommon to have temperature differences of the order of 10 K at different places of the superconductor during cooldown. This thermal gradient may a priori influence its flux trapping behavior. In order to simulate this situation, we field-cooled superconducting samples in a thermal gradient, using the same apparatus described above, producing the thermal gradient by putting the liquid helium supply pipe close to one sample edge. The temperature across the sample was monitored by two Allen Bradley carbon resistors located at two opposite ends of the discs. Using this method, a gradient as large as 1 K/cm at an average temperature of 10 K could be produced across the sample diameter. The main result

of this series of experiments can be summarized very simply : we measured 100% trapped flux in all samples, as for the homogeneous cooling. Two interesting additional effects were noted in the inhomogeneous case, however:

1) **Thermoelectric effects**

In addition to the field- cooling experiments, the samples were also zero field-cooled in order to make sure that no parasitic effects —eg thermoelectric currents — came into play. The output signal of the Förster probe did show small fluctuations during cooldown (Fig. 7). These fluctuations seem to be largest when the temperature gradient was large. The fluctuations stopped completely when the sample temperature became smaller than the critical temperature. A plausible explanation is as follows : thermoelectric currents generated by the temperature gradient across the sample create variable magnetic flux around the sample. This flux is then frozen in at the superconducting transition temperature, and therefore stays constant at later times. The interpretation of this effect in terms of thermoelectric currents is supported by the observation that the amplitude of the fluctuations are largest for larger temperature gradients. The effect, however, is not large since the magnitude of the measured fluctuations is of the order of a few mG. This corresponds to currents of about 30 mA. Given the electrical resistance of the sample (1 $\mu\Omega$), one can deduce a value of the emf of 0.03 μV for a temperature gradient of 15K across the sample diameter. The interpretation of these fluctuations in terms of thermoelectric currents is not unambiguous, because the output signal of the Förster probe itself fluctuates slightly during a very rapid cooldown, with an amplitude of a few mG. We thus give only a cautious statement: if thermoelectric effects exist, they do not generate emf larger than a few nanoVolts /K in Niobium at 10 K.

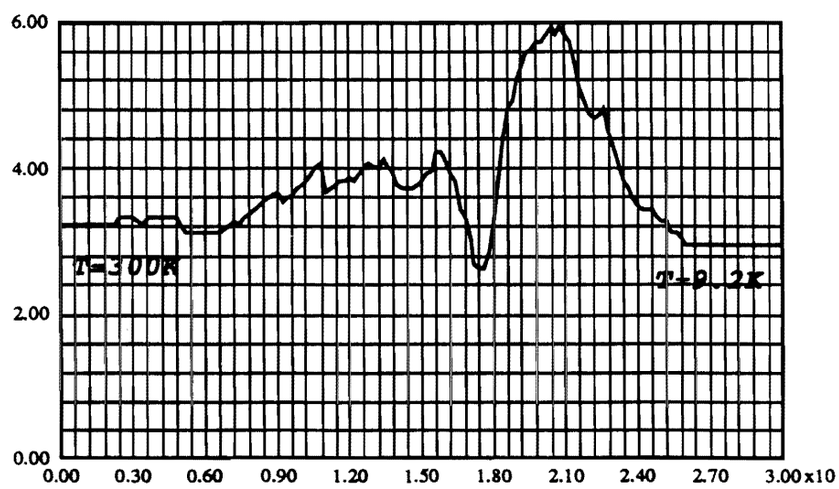

Figure 7 Time dependence (mn) of the magnetic field (mG) measured during a rapid zero field-cooling of a superconducting cavity. The fluctuations are attributed to thermoelectric currents. Note the plateau for t > 25 min. At this time, the cavity has become superconducting.

2) Role of ferromagnetic material

In a second part of the experiment, the sample was cooled down in a magnetic field produced by a ferromagnet, either a slightly magnetic stainless steel screw, or a magnetized iron disc of the same size as the superconducting sample and parallel to it. In all cases, the magnetic field produced by the magnets on the sample was smaller than 3 Gauss. A significant deviation of the flux line geometry was observed at the transition temperature of the studied sample (Nb plate "B") (Fig. 8). Keeping the same experimental configuration, no deviation was observed in the case of a slow cooling of the sample (100% trapped flux again in this case). No flux line motion was observed in the presence of a magnetic field produced by coils, as opposed to a field produced by a ferromagnet. A possible explanation might involve the large value of μ of the ferromagnet : any slight motion of the initial flux line geometry in the superconductor may be amplified by the neighboring ferromagnet due to its large μ value. This amplified modification would then be frozen in the part of the superconductor undergoing transition at that moment. This would then result in a larger modification of the flux line geometry in that part of the material still in the normalconducting state, and this modification would be again amplified by the same mechanism. This sort of regenerative, autoamplified mechanism can describe the experimental results : both a thermal gradient and a ferromagnet close to the superconductor are required to cause a modification of the flux line geometry.

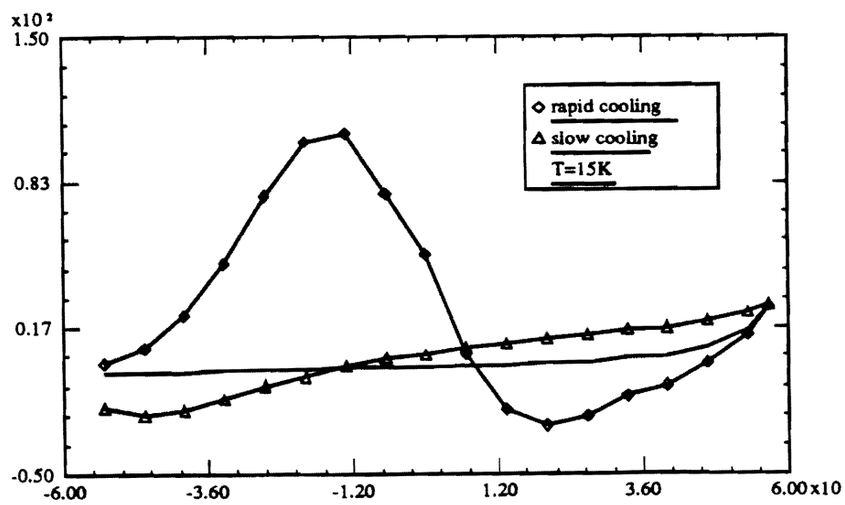

Figure 8 Fig. 10 Trapped flux (mG) across a superconducting disc (position in mm) cooled close to a ferromagnet : 1) rapid cooling, $T < T_c$; 2) slow cooling, $T < T_c$; 3) $T > T_c$.

The above mentioned effect may seem to be rather anecdotic, but it bears some relevance for the case of superconducting cavities. The cavities are usually cooled in a thermal gradient, and in the presence of ferromagnets which can be either imperfectly demagnetized parts of the cryostat stand (eg screws) or even the magnetic shield itself. No flux will be trapped in the ideal case of perfect magnetic shielding, leaving null magnetic flux in the neighborhood of the superconductor. On the other hand, even a small remnant magnetic flux might result in a

substantial flux trapping, depending strongly on the details of the superconductor surroundings and cooling procedure.

Conclusion

The flux trapped in various field-cooled Nb and Pb and NbTiN superconducting samples has been measured in ambient fields smaller than 3 Gauss. 100% of the flux is trapped in all samples, in complete violation of the Meissner effect. It was not possible to disentangle the contributions to trapping due to impurities, lattice imperfections, or surface serration following oxidation. The complete trapping observed here was expected, since the small fields used in the experiments corresponds to very small fluxon densities in the superconductor. The repulsion between vortices is then negligible compared with the pinning force, even for very pure superconductors. In this experiment, the magnitude of the ambient field, the sample nature, geometry and treatment was purposely very close to the case of superconducting cavities. We can therefore conclude that 100% of the flux is trapped also in Niobium superconducting cavities, even for RRR values as high as 500.

If temperature gradients appear during cooling of the superconductor, the picture is more complicated. We observed time dependent fluctuations of the magnetic field close to the superconducting sample. A plausible explanation of this effect can be given in terms of (weak) thermoelectric currents. In any case, before experiment, the neighborhood of the cavity has to be studied with a great care to remove magnetic (even weak) materials.

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