Flux trapping in superconducting cavities

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Abstract

The flux trapped in various field cooled Nb and Pb samples has been measured. For ambient fields smaller than 3 Gauss, 100% of the flux is trapped. The consequences of this result on the behavior of superconducting RF cavities are discussed.

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, ie all flux pervading the sample in the normal state should be expelled below the critical temperature. In fact, very close to T_c, the magnetic flux coalesces into fluxons, which may either be expelled out of the sample if the superconductor is very perfect, 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 studied sample. It is also an important practical parameter because trapped flux is a significant cause of surface resistance in superconducting RF cavities. These two reasons motivated us to measure by a dedicated experiment the flux trapped in various field-cooled (FC) superconducting samples.

Experiment and apparatus

The superconducting samples used for this experiment were discs of thickness 2 mm and diameter 12.6 cm, with characteristics similar to the material in common use for manufacturing superconducting RF cavities. The discs were oriented perpendicular to the vertically applied magnetic field (Fig. 1). This geometry was chosen because the corresponding demagnetizing coefficient is easily calculable. The Nb sample purity varied between RRR = 180 and RRR = 500. Prior to the measurements, all samples underwent a chemical polishing similar to the one used for treating RF cavities. One of the Nb samples was fired at 2200° C under vacuum in order to simulate a heat treated cavity.

A Förster probe measuring the vertical component of the magnetic field could be moved across the sample surface. The distance between the probe and the sample surface was kept as small as possible (5 mm) in order to ensure that $B_{probe} \simeq B_{surface}$ with the best possible accuracy.

The cryostat was placed inside a triplet of Helmholtz coils giving a roughly uniform vertical magnetic field adjustable in the range 0 — 3 Gauss. The shielding of the earth magnetic field was made by concentric sheets of CO-NETIC around the coils, leaving a remanent field smaller than 10 mGauss.

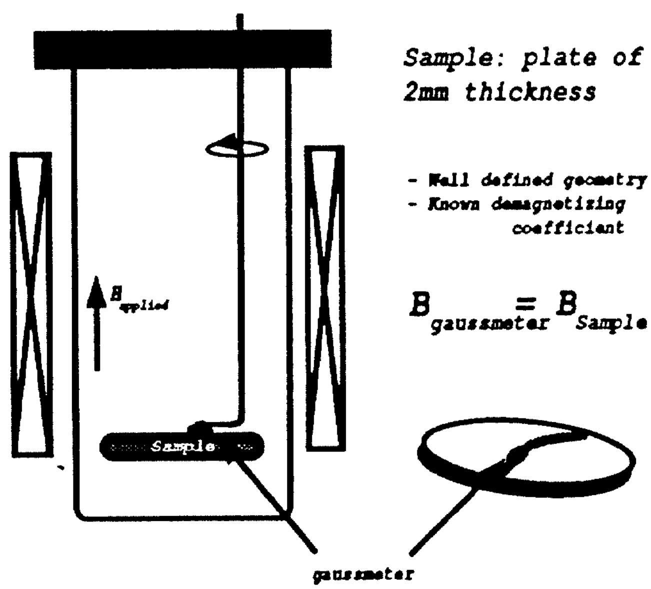


fig.1: The apparatus

The thermal cycle used for this experiment had mainly three steps:

Step 1. The temperature is above T_c (ie T=15 K for Nb); 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.

Results

The demagnetizing coefficient 1–N of all 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 disc is thus $H_a/(1-N)$, much smaller than the critical field H_c or H_{c1} of the Pb and Nb samples used in this experiment (for Nb: 1300 G, measured with a Foner magnetometer [1]). The superconductor should thus be in the Meissner state, except if pinning effects occur. It can be seen on Fig. 2 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. 2. It should equal 1, assuming 100% trapped flux, and a point like 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 is due to the fact that the probe is not point like, and is located at a finite distance from the sample surface. The probe is thus sensitive to the distortion of the flux lines caused in step 3 by cutting off the magnetic field. This distortion could be 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.

Little information is available on the pinning mechanisms in pure Niobium. A.K. Grover et al. [2] measured the magnetic behavior of Nb samples of moderate purity, either in rod or powder form. From their measurements, it is not possible to discriminate the origin of the pinning: impurities, lattice or surface defects. Our measurements show 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 [3], which might favor the coalescence of vortices, and prevent their expulsion from the superconductor volume.

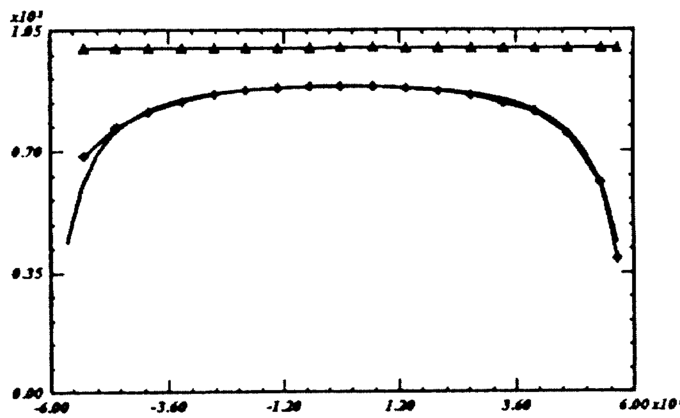
F. Palmer [4] measured the sensitivity of variously treated Niobium RF cavities to trapped flux. He observed that the increase of surface resistance due to cooling of the cavity in a given uniform magnetic field was markedly (about five times) smaller for fired cavities as for usually treated ones. A 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. Disappointingly enough, we measured 100% trapped flux again for a fired Nb sample. One significant difference might lie in the fact that, contrary to our sample, 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. The resolution of the Förster probe did not permit to detect any spatial fluctuation in the repartition of the magnetic flux.

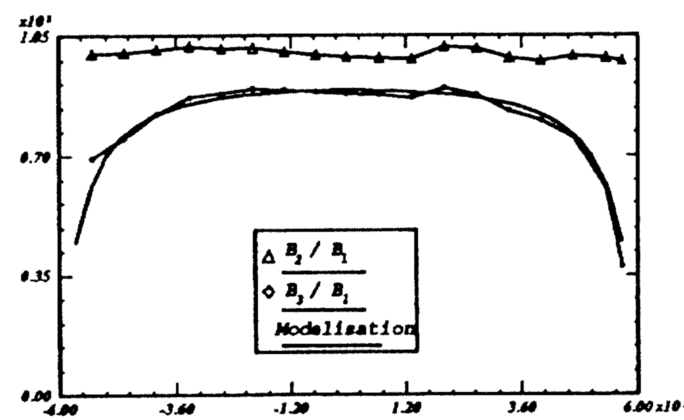
Residual RF surface resistance due to trapped flux

Trapped flux is a well known cause of residual surface resistance in superconductors [5–10]. It is usually studied experimentally by cooling a superconducting resonator in a known static magnetic field, and by measuring its Q value.

We used a monocell accelerating cavity on the TM010 mode at 1.5 GHz, made out of 2 mm thick high purity Niobium sheet. The cavity was immersed in a cryostat equipped with a solenoid able to produce a uniform static magnetic field B < 3 Gauss at the cavity location. The cavity was equipped with a thermometer arm [11, 12] and with a Förster probe able to rotate along parallels around the cavity axis.



NB RRR=300, cooled down in 300mG



Pb RRR=1000, cooled down in 300mG

Fig.2: the ratios B_2/B_1 and B_3/B_1 versus the position (mm) on the plate

The cavity was successively measured in field-cooled and zero field-cooled conditions. As for the disc samples, the Förster probe yielded a ratio: $B_2/B_1 = 1$ compatible with 100% trapped flux. The temperature map measured in subcooled Helium showed that the dissipation was uniformly distributed, and proportional to the trapped fluxon density.

The surface resistance of the cavity in the superconducting state was measured by the decrement method. The sensitivity of Rs to trapped flux is 0.35 nΩ/mG (this value is an average over the cavity area). A re-analysis of the experiments done in various laboratories to measure the surface resistance brought about by flux trapping shows that all results (with the exception of Palmer's fired cavities [4], and, possibly Nb/Cu cavities from CERN [10] are compatible with the formula [5–9]:

$$R_s = R_n \frac{H_a}{H_{c2}(T)} \qquad (1)$$

where R_n is the surface resistance of the sample in the normal state. Unfortunately, the large uncertainty on the value of H_{c2} hinders a very precise comparison between eq. 1 and experimental results.

The apparent insensitivity of Nb/Cu cavities to trapped flux (noticed in CERN [10] might be due in part to a high value of H_{c2}. (In our laboratory, thin films of Niobium exhibited H_{c2} values larger than 2 Tesla)

Conclusion

The flux trapped in various FC Nb and Pb samples has been measured. For ambient fields smaller than 3 Gauss, 100% of the flux is trapped in all samples. The trapping may be due to impurities, lattice imperfections, or surface serration due to oxidation. In this experiment, the sample nature, geometry and treatment was purposefully very close to the case of superconducting cavities. We can therefore conclude safely that 100% of the flux is trapped also in Niobium superconducting cavities, even for RRR values as high as 500. This result is in line with the measured surface resistance due to trapped flux in superconducting RF cavities: $R_s = R_n \cdot \frac{H}{H_{c2}(T)}$. This formula, theoretically justified if one assumes 100% trapped flux, finds thus here an independent confirmation.

Acknowledgements

We thank F. Guémas. P. Bosland, M. Juillard, B. Mahut, J. P. Poupeau, and H. Piel for preparing or lending the studied samples, and C. Aguillon for measuring the H_{c1} of Niobium samples.

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