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Magnetic Flux Distribution in $YBa_2Cu_3O_{7-x}$

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Abstract:

The spatial distribution of magnetic flux in $YBa_2Cu_3O_{7-x}$ has been measured for various sintered pellets and thin films. In ring-shaped samples macroscopic persistent currents have been observed. In discs, the penetration of the magnetic field has been investigated, and in general qualitative agreement with the Bean model has been found. In some cases, however, pronounced deviations from the prediction of the Bean model occur.

Introduction

The magnetic behavior of high-T_c superconductors is of central importance both for the application and for the basic understanding of these materials. Studies of the Meißner effect, shielding and remanent magnetization are therefore among the standard methods for characterizing the properties of HTSC. In most cases, however, these measurements determine only the magnetization of the sample as a whole. We present here measurements of the spatial distribution of the magnetic flux, which in some cases show pronounced deviations from the theoretically expected behavior, a result hard to derive from integral measurements.

The samples that have been investigated were $YBa_2Cu_3O_{7-x}$ sintered pellets and thin films (polycrystalline as well as epitaxial). Both full, disc shaped samples and rings were studied, with an outer diameter of typically 12 mm and, in the case of rings, a diameter of the central hole of about 7 mm.

I. Ring samples

Our original objective to study the magnetic behavior of rings was to demonstrate that HTSC can indeed carry macroscopic persistent currents. Shortly after the discovery of the ceramic superconductors it was not obvious that macroscopic currents exist in these materials over an extended period, because most experiments at that time could not distinguish between the contribution of intergrain and intragrain currents. Using a ring, however, it was

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possible to separate the two contributions, since the spatial distribution of magnetic flux is quite different for a macroscopic steady state current flowing around the ring and microscopic (intragrain) currents shielding only the interior of the grains /1/.

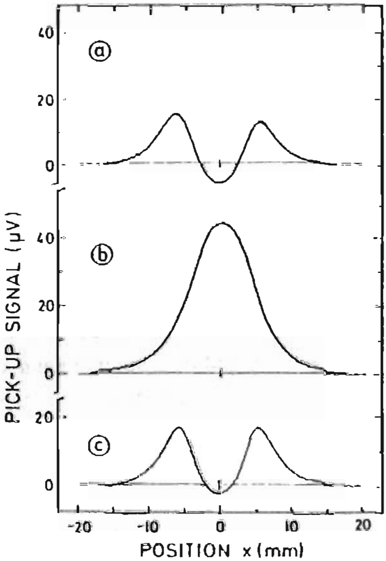

Fig.1: Remanent field distribution of YBCO rings after cooling in a magnetic field of B_{ext} = 5.7G (the pick-up signal of the vibrating coil sensor is proportional to the local magnetic field).

a) sample 1: no macroscopic ring current; the field results from flux trapped between the superconducting grains. Insert: Size of the ring
b) sample 2: the ring carries a current of 11A
c) sample 2, broken: the ring current is suppressed

Fig.1 shows three results for magnetic field distributions of rings of sintered YBCO. In all cases the rings were field-cooled to 77 K in an external field B_{ext} = 5.7 G; then the field was slowly removed, and the remanent flux distribution was measured by scanning a small vibrating coil probe across the sample. Our first results, represented by Fig.1a, showed maxima of the magnetic field directly above the ring material; at the ring centre,the magnetic field was small and moreover in its sign opposite to the applied field during cool-down. Such a pattern implies that the main contribution to the magnetization of the sample was due to flux trapped between the grains, and that a macroscopic ring current did not exist in this case (or was at least very small, as a result of the poor quality of the early samples).

As the preparation techniques improved, the critical (intergrain) current densities increased, and macroscopic steady state currents could indeed be observed. Fig.1b shows an example of a field distribution which clearly demonstrates the existence of a current flowing around the ring perimeter. A simple proof that in this sample one was really dealing with a macroscopic current is given by Fig.1c, where the ring had been broken and reassembled again. In this way the superconducting path around the ring was interrupted, leading to a pattern which closely resembles Fig.1a.

Distributions like the one shown in Fig.1b were found to be stable on a time scale of months for samples kept at 77 K. At a ring current of 10 A, corresponding to a current density of 200 A/cm^2, the decay over a period of 60 days was less than our accuracy of 1%. Taking into account the ring geometry this yields an upper limit $\rho \lesssim 2x10^{-19}$ Ωcm for the specific resistance. At higher current densities flux creep in the polycrystalline material led to a fast decay. In rings of epitaxial YBCO film on $SrTiO_3$, however, persistent current densities of 10^5 A/cm^2 at 77 K have been measured /2/.

II. Disc samples

The penetration of magnetic flux into conventional superconductors is well described by the Bean model /3/. Although originally developed for long slabs in a field parallel to the slab surface, qualitatively the same behavior is found also for discs with diameters larger than their thickness /4/: As the field is increased above a critical value it penetrates from the sample perimeter in a roughly linear way (i.e. with the field gradient being nearly constant), giving rise to a minimum of the field at the centre of the disk.

We have investigated the flux distribution in various YBCO discs using the same scanning technique as in section I, again with a vibrating coil and in addition with a small Hall probe as sensor /5/. For the majority of the samples results were found as shown in Fig.2. Here the pellet was first cooled to 77 K at zero field and then exposed to B_{ext}, which leads to the shielding curves in Fig.2a; removing the external field gives the remanent magnetization in Fig.2b. Both curves are in qualitative agreement with the Bean model.

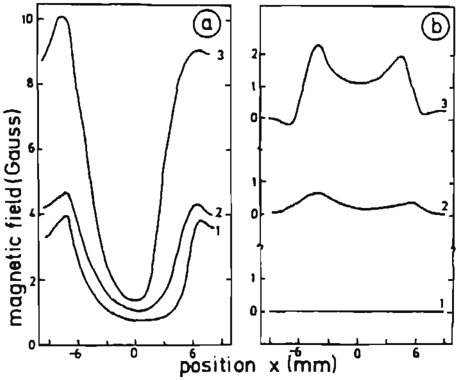

Fig.2: Magnetic field at a distance of 0.3 mm above the surface of a sinter pellet (12 mm diam., 1.8 mm thickness).

a) Shielding signal, with externally applied fields for trace 1: 3G; 2: 4G; 3: 8G.

b) Remanent signal. Traces 1-3 were each taken immediately after the corresponding trace in Fig.1a.

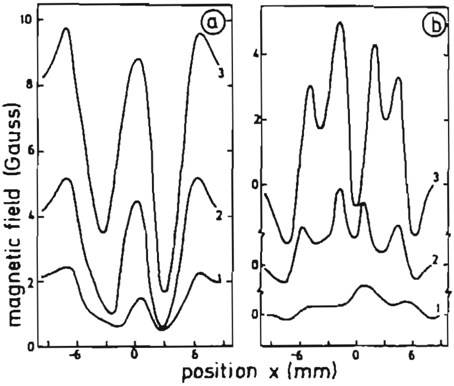

Fig.3: Shielding (a) and remanent field (b) for the same sample as in Fig.2, but with the thickness reduced to 0.45 mm. Trace 1: 2G; 2: 4G; 3: 8G.

For a number of samples, however, striking deviations from the distribution predicted by the Bean model were observed (see Fig.3). Instead of a minimum the shielding curve now displays a maximum at the disk centre, and the remanent magnetization even has two additional maxima. Since ceramic samples might suffer from inhomogeneities caused by the preparation process, we have carefully investigated the influence of the following parameters in order to be sure that one is not dealing with an artifact:

- <u>Sample thickness:</u> Anomalous field distributions were observed for various pellet thicknesses between 0.3 and 2 mm. In particular, thinning a pellet with "Bean-like" behavior by a grinding process often resulted in a "non-Bean" distribution (cf. Figs.2 and 3). This procedure is reversible in that putting two samples, which show the anomaly, on top of each other can eliminate the anomalous behavior (Fig.4). Obviously the demagnetization factor of the sample is of influence here.

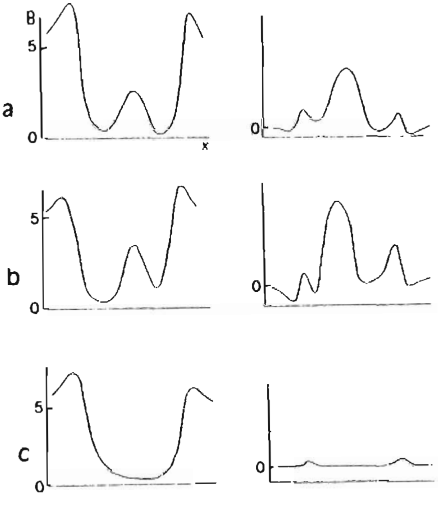

Fig.4: Shielding (left) and remanent field (right) of two samples with "non-Bean" behavior (a) and b)). In c) the two samples are put on top each other. The resulting distribution is "Bean-like".

- Sample density: Among several samples prepared with the same dimensions but at different densities (from 4.4 to 5.4 g/cm^3) /6/ only the pellet with the lowest density showed a "non-Bean" field distribution. Since the strength of the weak links of the intergranular network in general increases with sample density /7/, this indicates that the anomaly is characteristic for samples with weak coupling between the grains. This suggestion is supported by the fact that the critical current density, which is a measure of the coupling strength, was always found to be relatively low in "non-Bean" samples.
- Temperature: The variation of the remanent magnetization curves with temperature, as shown in Fig.5, reveals that the anomalous structures are restricted to a certain temperature range (in this case T < 60 K). The range depends on the particular sample and also on the applied fields. Increasing the field lowers the temperature where the anomaly starts to disappear. We relate this observation to the degree of flux pinning, which is strongly temperature dependent. At high temperatures where pinning becomes weak the structures are washed out.

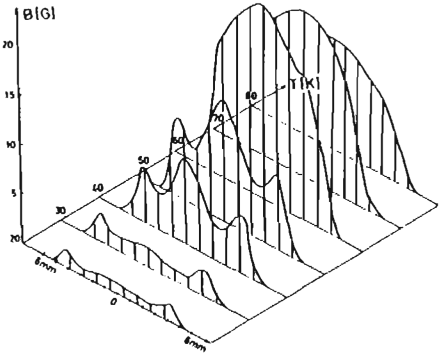

Fig.5: Temperature dependence of the remanent field distribution for a sintered sample after zero field cooling and application of B_{ext} = 25 G.

The observed "non-Bean" like behavior might be interpreted in the following way: As the applied field is increased beyond the value where the critical current along the disc perimeter is reached, Josephson flux bundles start to enter the sample. The Lorentz force acting on the flux bundles due to the macroscopic ring current is directed towards the centre of the pellet. On the other hand, the motion of the flux bundles is hampered by pinning forces. Thus the detailed structure of the flux distribution in the polycrystalline material will depend on the relative magnitude of pinning and driving forces. If pinning dominates, Bean-like behavior will be observed. If pinning is weak, then the flux bundles will move under the influence of the Lorentz force to the centre of the disc. The resulting central maximum in the shielding curve (cf. Fig.3a) will split in the remanent magnetization (Fig.3b), if the repulsion of the flux is strong enough to overcome the pinning forces near the centre, but not further out. For extremely weak pinning, e.g. near T_c, flux is expected to enter and leave the sample quite readily, and therefore pronounced structures cannot occur in this region (cf. Fig.5, T > 60 K).

For thin films we have similary found marked differences depending on the sample structure: Polycristalline films on random ZrO_2 substrates, where the coupling between the grains is weak, usually display "non-Bean" behavior; by contrast, the flux distribution in epitaxial films on $SrTiO_3$ with very few weak links is "Bean-like".

Conclusions

In summary, spatially resolved measurements of the flux distribution in YBCO rings have demonstrated that macroscopic currents can persist in this material on a time scale of months without noticeable decay. The experiments on discs have revealed flux distributions which under certain conditions deviate strongly from the predictions of the Bean model. The observations are ascribed to a delicate balance of pinning and Lorentz forces, which varies across the sample. It should be mentioned that in the case of such anomalous flux distributions integral magnetization measurements may lead to erroneous results if their analysis is based on the Bean model.

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