Macroscopic Persistent Currents in $\text{YBa}_2\text{Cu}_3\text{O}_7$

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Received December 1, 1987

Persistent currents in polycrystalline $\text{YBa}_2\text{Cu}_3\text{O}_7$ rings have been investigated by measuring the spatial distribution of the magnetic flux trapped in field-cooled samples. The results unambiguously show that macroscopic persistent ring currents exist. The critical current density depends very sensitively on the sample quality, reaching $j_c \approx 250 \text{ A/cm}^2$ at 77 K for our best samples.

I. Introduction

One of the crucial experiments in superconductivity is to demonstrate the existence of persistent currents in a superconducting ring. Different attempts have been performed to observe this phenomenon in the new high- T_c materials. The first experiment reported by Gough et al. [1] exhibited persistent currents in a ring made out of the Y–Ba–Cu–O ceramic up to magnetic flux densities of $B_{\text{max}} \sim 5 \cdot 10^{-8} \text{ T}$. Above this value the critical currents between the superconducting grains and/or the critical currents across domain boundaries [2] were exceeded, and flux could penetrate the bulk material. The critical current density in this experiment was of the order of several $\mu\text{A/cm}^2$. Yeh et al. [3] measured the remanent magnetization of rings of the high- T_c ceramic cooled in a magnetic field, and inferred from it the existence of macroscopic supercurrents around the ring. Similar conclusions were drawn by Kedves et al. [4] who measured the time dependence of the trapped flux in a bulk superconductor. As we conclude from our results, all these experiments only demonstrate that some flux is trapped when a ring of this material is cooled below T_c in a magnetic field. It is not clear, however, whether the flux is really trapped in the central free area of the ring (as is necessary for a macroscopic persistent current around the ring), or whether the flux lines are pinned in the ring material between the grains.

II. Experimental Procedures

An obvious way to distinguish between these two possibilities is to determine the spatial distribution of the magnetic field $B(x)$ across the ring. Figure 1 schematically shows the two cases under consideration. Whereas a persistent current leads to a single maximum in B at the centre of the ring (Fig. 1a), trapped flux in the ring material gives rise to two maxima

Fig. 1a and b. Schematic magnetic field distribution of ring samples cooled in an external field B_{ext} (pointing upwards). a An ideal superconducting ring carrying a persistent current, which encloses the trapped magnetic flux. b A ring which has only trapped magnetic flux inside the bulk material. The bottom figures show the pick-up signal – proportional to $B(x)$ – expected when the magnetic field probe is moved along the dashed lines

near the ring perimeter, and correspondingly to a minimum at the centre (Fig. 1b).

In order to measure the field distribution we have used a small magnetic field probe, which was scanned across the ring along a path indicated in Fig. 1 by the dashed line. The probe consisted of a vibrating rectangular pick-up coil (length 15 mm, width 3 mm) oriented perpendicular to the plane of the ring. It allowed to resolve variations of the magnetic field on a mm scale. The samples which we have investigated were prepared in various laboratories in the usual pellet form, typical dimensions being 10–12 mm in diameter at a thickness of 1–2 mm. Holes with a diameter of about 5–6 mm were produced in the centres of these discs by careful grinding or ultrasonic drilling. The measurements were performed in liquid N_2 at 77 K. The samples were cooled from above T_c in a magnetic field B_{ext} applied along the ring axis. Then the external field was reduced to zero, and the pick-up coil was scanned across the ring. Since our probe also works in liquid nitrogen, the sample surface could be approached to a few tenths of a mm.

III. Results and Discussion

A typical result, obtained for most of our samples in magnetic fields B_{ext} from $1 \cdot 10^{-2}$ T down to $2 \cdot 10^{-5}$ T, is shown in Fig. 2. Evidently the field distribution resembles that of Fig. 1b. In particular, the signal in the ring centre is slightly negative. Hence the macroscopic current around the ring must be small compared to the local currents in the grains, which give rise to the trapped flux in the ring material. We want to point out that these samples were prepared according to standard recipes, see e.g. [5], and that they displayed the "usual" behavior when they were characterized by resistivity ($R=0$ at 92 K), magnetization measurements, Raman spectroscopy and X-ray diffraction. The upper limit for magnetic fields, at which persistent currents can exist in the samples presented above, is distinctly less than the magnetic field of the earth.

We observe that measurements of the overall magnetization M of discs from such a material often reveal inhomogeneities, which give rise to irregularities and nonreproducible results in the magnetization curves. Superficially, the observed deviations from linear M vs. B relations could be interpreted as an indication for the existence of macroscopic persistent currents. Our spatially resolved measurements of the trapped magnetic flux clearly show, however, that this conclusion cannot be drawn. Rather, inhomogeneities in the trapping of the flux between the grains can lead to similar observations. Integral magnetization measure-

Fig. 2. Field distribution of an Y–Ba–Cu–O ring (sample I: outer and inner diameter 12.5 and 6.5 mm, respectively, thickness 1.5 mm), which was cooled in a magnetic field of $5.7 \cdot 10^{-4}$ T. It displays the flux trapped in the bulk material, but shows no indication of a magnetic field caused by persistent currents. The slight asymmetry of the curve is due to sample inhomogeneities. Similar curves were obtained for external fields down to $2 \cdot 10^{-5}$ T, and also for several other rings with comparable dimensions

ments alone are thus not a reliable signature for macroscopic supercurrents.

In view of these results one might wonder whether persistent currents in sintered samples are principally restricted to magnetic fields well below $1 \cdot 10^{-4}$ T. This could result from imperfect coupling of the superconducting grains, associated with dissipation already at very low current levels. It is shown below, however, that persistent currents are observed indeed up to fields of several gauss, but their existence obviously depends in a very sensitive way on the sample preparation.

As an example we present in Fig. 3 results for a ring of sintered material from a commercial laboratory [6], obtained with the same set-up and the same procedures as before:

- When the sample is cooled in a small magnetic field ($5.7 \cdot 10^{-5}$ T, Fig. 3c) we observe a distribution of the trapped flux density which has its maximum at the centre of the ring. By comparison with Fig. 1 this clearly demonstrates that the dominating contribution to the trapped flux in this case is due to persistent currents around the ring. Within our accuracy of 1% we find no decay of the persistent currents on the time scale of the measurement, 10^3 s.
- For cooling in a somewhat larger field ($5.7 \cdot 10^{-4}$ T, Fig. 3b) the trapped flux in the ring centre increases, but its distribution remains essentially unchanged.
- For even larger B_{ext} ($5.7 \cdot 10^{-3}$ T, Fig. 3a) two maxima appear in the pick-up signal near the positions of the ring perimeter indicating the growing contribution of flux frozen in the ring material.

The relationship between the cooling field B_{ext} and the persistent magnetic field at the ring centre is

Fig. 3a–c. Distribution of the flux density for a ring of better quality (sample II: o.d. 10.8 mm, i.d. 6.2 mm, thickness 2 mm), which clearly shows the magnetic field of the persistent currents in the ring. Applied fields during cooling: a $5.7 \cdot 10^{-3}$ T, b $5.7 \cdot 10^{-4}$ T, c $5.7 \cdot 10^{-5}$ T

shown in more detail in Fig. 4 (solid circles). The deviation from the linear dependence (see inset in Fig. 4) at $B_{\text{ext}} > 4 \cdot 10^{-4}$ T and the drop for $B_{\text{ext}} > 1 \cdot 10^{-3}$ T are signatures that the critical currents through the weak links is reached and that the persistent currents are partially destroyed. A calculation of the critical current density from the dimensions of the ring and the applied magnetic field yields a value of 50 A/cm^2 .

The crucial experimental test to demonstrate that the flux in the centre of the ring is in fact due to supercurrents is to reduce the cross-section of the ring or even break the material. Therefore, in a first step a radial notch was ground into the ring, so that the cross section was locally reduced from 5.3 to 2.7 mm^2 . As a result, the maximum persistent field in the ring centre dropped by a factor of two, in accordance with the expected reduction of the critical current at the notch. Next the sample was broken, which definitely eliminated currents around the ring, and the measurement was repeated. As seen in Fig. 5, the contribution from a macroscopic ring current has disappeared, and

Fig. 4. Circles: Persistent magnetic field at the centre of sample II plotted versus the magnetic field B_{ext} applied during cooling of the ring above T_c . The departure from the linear increase at small fields (inset) displays the upper limit for persistent currents in the ring. Squares: Persistent magnetic field near the ring circumference, after suppressing the supercurrent around the ring by breaking the sample (see Fig. 5)

Fig. 5a and b. Field distribution of sample II after breaking the ring, under otherwise identical conditions. The persistent currents are suppressed, which leads to a field distribution similar to the imperfect sample shown in Fig. 2. Applied fields during cooling: a $5.7 \cdot 10^{-5}$ T, b $5.7 \cdot 10^{-4}$ T

the flux distribution is now as expected from Fig. 1b for flux trapped inside the ring material alone. There is also a striking similarity with the curves in Fig. 2, which corroborates the interpretation that in this earlier sample noticeable persistent ring currents did not

exist. The flux trapped in the bulk of the broken ring also displays saturation (solid squares in Fig. 4), reached at applied cooling fields $B_{\text{ext}} \approx 5 \cdot 10^{-3}$ T, which is significantly larger than the external field where the critical current is exceeded.

IV. Conclusions

To our knowledge in all measurements on persistent currents in the new high- T_c superconductors only the integral magnetization of the samples was investigated. As shown above, these experiments are not conclusive because of possible inhomogeneities within the sample and the bulk trapping of magnetic flux. In contrast, the measurements with spatial resolution presented here allow to distinguish directly between magnetization due to macroscopic persistent ring currents and magnetization caused by flux trapping in the bulk material. We find that in the best samples available to us persistent currents exist on a macroscopic scale with critical densities of about 50 A/cm^2 and in fields of the order of some 10^{-4} T.

This work was supported in part by the Deutsche Forschungsgemeinschaft, Sonderforschungsbereich 252.

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Note added in proof

In samples supplied by Prof. K. Andres (Walther-Meißner-Institut, Garching) and by the Forschungsinstitut für Anorganische Werkstoffe -Glas/Keramik- GmbH (Höhr-Grenzhausen) persistent currents have been observed with critical current densities $j_c \approx 250 \text{ A/cm}^2$