Direct observation of the compression of a transport current by an alternating magnetic field

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A collapse of the transport current in an alternating magnetic field has been observed directly through measurement of the spatial distribution of the magnetic field. The transition of a superconductor to a resistive state under these conditions has been studied.

The critical-state model proposed by Bean about thirty years ago[1] is now widely used to describe the electromagnetic properties of high-T_c superconducting samples. The application of this model to conventional ("cold") superconductors has resulted in a successful explanation of the irreversibility of the magnetization curve of hard superconductors and has made it possible to calculate the loss in a low-frequency magnetic field. However, there has been no detailed analysis of the very simple situation in which the external magnetic field H is directed along the transport current $\vec{I}$, and there is a force-free configuration.

An analysis of the case $\vec{H} \| \vec{I}$ (($I < I_c$, where I_c is the critical current) carried out in Ref. 2 showed that a compression of a transport current (a collapse) by an alternating external magnetic field can be observed in this geometry. As a result, the region through which the transport current flows shifts toward the axis of the sample, and the current reaches the center of the sample at a certain field amplitude H^*. Under these conditions the transport current density rises to the critical value, and an electric field arises in the interior of the sample as a result of the dissipative flow of the current I. The current I^* at which the dissipation arises was measured as a function of the field amplitude H_0 in Ref. 2. It was shown that this dependence differs substantially from the corresponding dependence found under static conditions. This difference was indirect evidence for a collapse of the transport current.

In this letter we are reporting direct observation of the collapse effect in cylindrical samples of the high-T_c superconductor YBCO. For observation of the effect, a hole 0.8 mm in size was drilled along the direction perpendicular to the axis in a sample 10 mm in diameter. A miniature Hall pickup was inserted in the hole; the pickup could be moved within the hole with the help of a micrometer. The apparatus which was used made it possible to measure the spatial distribution of the azimuthal component H_φ (of the static magnetic field) produced by the transport current.

The experiments were carried out at a temperature of 77 K over the frequency range 30–1000 Hz. The critical current of the sample in the absence of an external magnetic field was 25 A. Figure 1 shows the measured spatial distribution of the magnetic field of the transport current, which was set at 10 A, at various values of the alternating external field H_0. In the absence of an external field (curve 1), or at a low

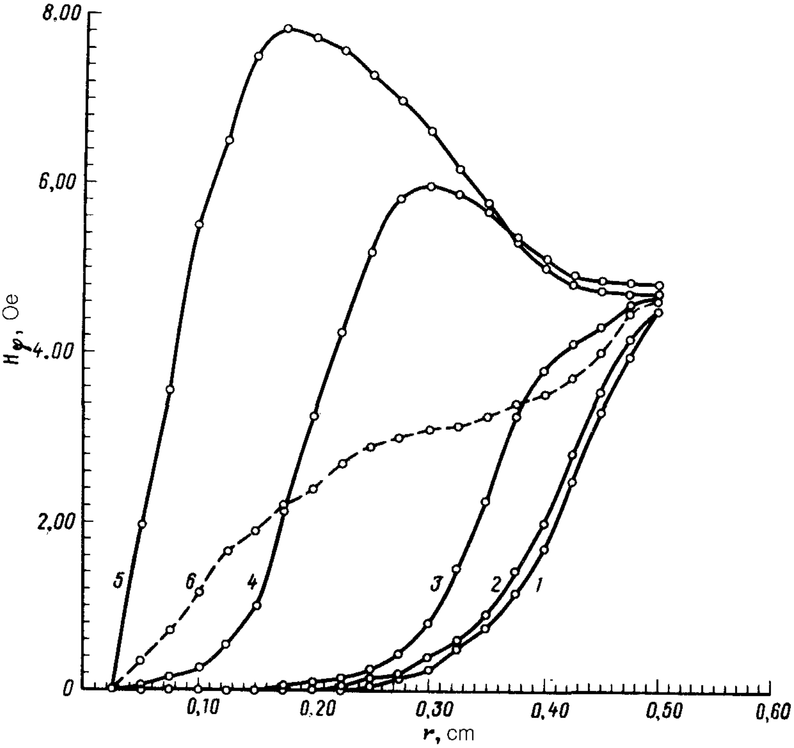

FIG. 1. Radial profiles of the azimuthal magnetic field of a transport current $I = 10$ A for various amplitudes of the alternating magnetic field, with a frequency of 73 Hz. 1—No alternating field; 2—$H_0 = 10.2$ Oe; 3—15 Oe; 4—20 Oe; 5—25 Oe; 6 (dashed line)—$H_0 = 35$ Oe.

amplitude H_0 (curve 2), the maximum azimuthal field H_φ is reached near the surface, $r = R = 0.5$ cm, while the field is approximately zero over a wide region near the axis. The meaning here is that the transport current is flowing in a surface layer. In a strong alternating field (curves 4 and 5), the $H_\varphi(r)$ profile changes qualitatively. A clearly defined maximum appears on the curves, and it shifts into the interior of the sample as the amplitude of the alternating field is increased. In a strong alternating external field, $H_0 = 25$ Oe (curve 5), the magnetic field H_φ reaches the axis of the sample. At this value of the current we observe the appearance of a static voltage across the sample, which is detected by means of potential contacts. This result means that at this value of H_0 the current density in the filament reaches a critical value, the sample goes into a resistive state, and the current flow is accompanied by a dissipation. Beginning at this value of H_0, the minimum on the $H_\varphi(r)$ profile begins to degenerate (curve 6), and as H_0 is increased further, the current distribution becomes progressively flatter.

These results thus provide direct proof of the collapse of the transport current in an alternating external field. The penetration of the alternating field H_z into the interior of the sample is accompanied by the appearance of an electric field in this region. This field causes the flow of an azimuthal screening current with a density equal to the critical value. Correspondingly, the transport current is displaced from this region. The formation of a peak on the $H_\varphi(r)$ curves essentially means that the transport-current tube, which starts with an outer radius close to the radius of the sample, contracts by a factor of about two in an alternating field of 20 Oe. That the alternating field in the surface region has a distribution which corresponds to the critical-state model is supported by direct measurements with the same Hall pickup, rotated 90° to detect the component of the alternating magnetic field along the axis of the sample. The boundary between the region of the current screening the alternating magnetic field and the region of the transport current lies near the maximum on the $H_\varphi(r)$ curves. When the flow of the transport current becomes dissipative (curve 5), the azimuthal and axial currents mix. A nonmonotonic distribution of the azimuthal field also occurs in the resistive state. The solution of the critical-state equations yields the current distribution in the sample under these conditions also. In particular, the distribution of the transport current is

$$j_z(r) \simeq E_z/(E_z^2 + E_\varphi^2)^{1/2},$$

where E_z and E_φ are the corresponding components of the electric field. In principle, by using the spatial distributions of the fields shown in Fig. 1 one can determine the local critical current at any point in the sample and obtain comprehensive information about the critical state. However, the hole in the sample distorts the calculated field distribution, so the entire discussion here is only qualitative.

We note in conclusion that this phenomenon is not a unique property of high-T_c superconducting samples. A similar effect can be observed in conventional hard superconductors. The only difference is that the collapse is more obvious in the high-T_c samples. Because of the low critical current density, the collapse can be observed in a low-frequency and weak alternating magnetic field.

[1] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962).
[2] I. V. Baltaga, N. M. Makarov, V. A. Yampol'skiĭ, L. M. Fisher, N. V. Il'in, and I. F. Voloshin, Phys. Lett. A **148**, 213 (1990).

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