PHYSICAL REVIEW B VOLUME 45, NUMBER 5 1 FEBRUARY 1992-I

Spatially resolved magnetic hysteresis in a $YBa_2Cu_3O_{7-y}$ crystal measured by a Hall-probe array

T. Tamegai, L. Krusin-Elbaum, P. Santhanam, M. J. Brady, W. T. Masselink, C. Feild, and F. Holtzberg
IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598
(Received 23 September 1991)

We report local-magnetic-field measurements near a $YBa_2Cu_3O_{7-y}$ crystal by a linear array of Hall probes. Two distinct features are observed in the local-field hysteresis H_l vs H, which are not present in the integrated magnetization measured by a SQUID: (1) a peak in H_l right after the field reversal that we attribute to the field generated by the current flow in a platelike superconductor, and (2) a position-dependent suppression of H_l near zero external field which may be linked to H_{c1}. These local measurements suggest a relevant scale for the critical current variation of between 10 and 200 μm.

In this paper we examine the local features of the critical state in a single crystal of the high-temperature superconductor $YBa_2Cu_3O_{7-y}$. This is a study of the *steady-state* magnetic behavior of the superconductor on the length scale of only a few microns. Such an experiment is vital in establishing the validity of the critical-state model[1] and exploring the effect of the currently debated geometry effect[2-4] on the shape of the magnetic hysteresis.

The critical-state model proposed by Bean[1] is the principal means to evaluate the critical current density J_c from the measurement of magnetization versus external field (M vs H) in single crystals of high-temperature superconductors,[5] where making good electrical contacts is often difficult due to their small size and the condition of the surfaces. In this model, the hysteretic magnetization of a *homogeneous* type-II superconductor is related to J_c via Maxwell's equation $dB/dx=(4\pi/c)J_c$, where B is the locally averaged magnetic induction inside the superconductor. The assumption of homogeneity is crucial. If there is granularity on some scale, as has been implied for single crystals,[6] the critical-state description of an entire crystal becomes questionable.

In contrast to the local measurements, a more common measurement of the integrated magnetization, such as by a standard superconducting quantum interference device (SQUID) magnetometer,[7] will mask the suggested weak-link behavior in single crystals,[6] rendering the J_c estimates unreliable. Among the various techniques employed to probe the local fields,[8-13] the magneto-optical[8,9] and Hall-probe[11-13] measurements are most suitable for mapping out the overall magnetic-field distribution of a millimeter size crystal. The Hall-probe technique appears to be the least restricted in terms of field and temperature range, and it has also been demonstrated to be useful in studying the low-temperature magnetic relaxation.[13] For our steady-state study, we have designed an array of Hall probes with higher spatial resolution than reported previously[12,13] which allows us to cross correlate the local-field behavior at various locations on the crystal. We observe several local features as a result of the platelike geometry which enhance the role of the lower critical field H_{c1}; none of these effects can be seen in the integrated response.

The measurements near a $YBa_2Cu_3O_{7-y}$ single crystal[14] were performed by a photolithographically patterned linear array of Hall probes. The array used in this experiment was fabricated using silicon-doped GaAs epitaxial film (1500 Å, $n=10^{18}/cm^3$). Each Hall probe in the array is composed of a cross geometry of two 10-μm-wide wires, having a sensitivity of $\sim$63 V/AT. We surmise that each probe measures the local averaged field in the area of $\simeq 10\times 10\ \mu m^2$, as compared to the overall crystal area of $\simeq 1000\times 700\ \mu m^2$. The 6.5-$\mu$m-thick single crystal was glued directly to the Hall-probe array at a distance of $\simeq 5\ \mu$m. We used five probes for our experiment, one of which was 3 mm away from the others on the same chip for calibration. The other four probes, labeled P2 through P5, were spaced 200 μm apart as shown in the inset of Fig. 1. The magnetic field was applied along the c-axis and the component of the local field parallel to the external field near the sample surface was measured by passing a current of 40 μA through the probes.

We define the local field, $H_l=B-H$ as the difference between the measured field and the external field. H_l is just the self-field generated by the current flowing in the sample. Temperature dependence of H_l at P3 and P5 for an external field, $H=50$ kOe is shown in Fig. 1. Before each

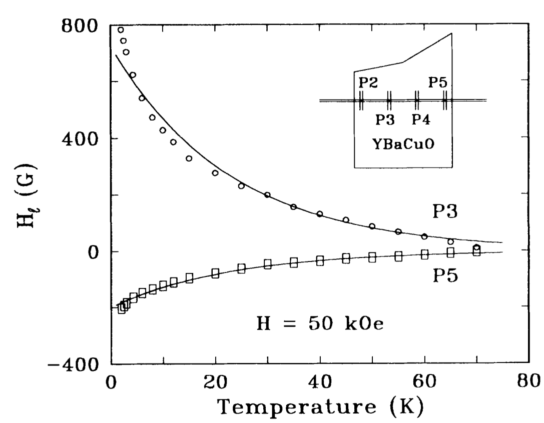

FIG. 1. Temperature dependence of the local field H_l in the decreasing branch of the hysteresis loop at 50 kOe at two positions near the sample. The solid lines are fits to $H_l(T)=H_l(0)\exp(-T/T_0)$ with $T_0\simeq 23$ K. Inset shows locations of four Hall probes.

measurement, the field is swept up to 70 kOe at a fixed temperature to be sure that the sample is in the critical state. This figure demonstrates that the magnitude as well as the sign of the local field can vary with the location of the probe on the crystal. The temperature dependence of the local field is well approximated by $H_l(T) = H_l(0)\exp(-T/T_0)$ with $T_0 \simeq 23$ K, where $H_l(0)$ is the local field at zero temperature and T_0 is a parameter. This formula was shown previously to be a good description of the temperature dependence of the critical current and hence magnetization.[15] Therefore, H_l is proportional to the magnetization at high fields, as expected. The positive field at P3 near the center of the sample shows that the flux is trapped there. At P5, however, which is near the edge of the sample, H_l is *negative.* This is clearly seen in Figs. 2(a) and 2(b) which show complete local low-temperature hysteresis loops at the above two locations up to a maximum field of 30 kOe with the direction of the field sweep indicated by the arrows. As implied by Fig. 1, P5 shows a hysteresis loop with an opposite direction to that of P3. There are two remarkable features in the local field loops, which are not observed in the integrated SQUID measurement on the same sample shown in Fig. 2(c) for comparison. The first feature is the peak in the local field at the field reversal (PFR), which is observed at all probe locations irrespective of the maximum field value of the local loop. The second feature is a suppression of the local field near zero external field shown on the expanded field scale in Fig. 3. Figure 3(a) corresponding to P2 demonstrates this effect most clearly. The positional dependence of this behavior in Figs. 3(a)–3(d) is surprising. Such a suppression is sometimes seen in the SQUID response, but with a much smaller magnitude.

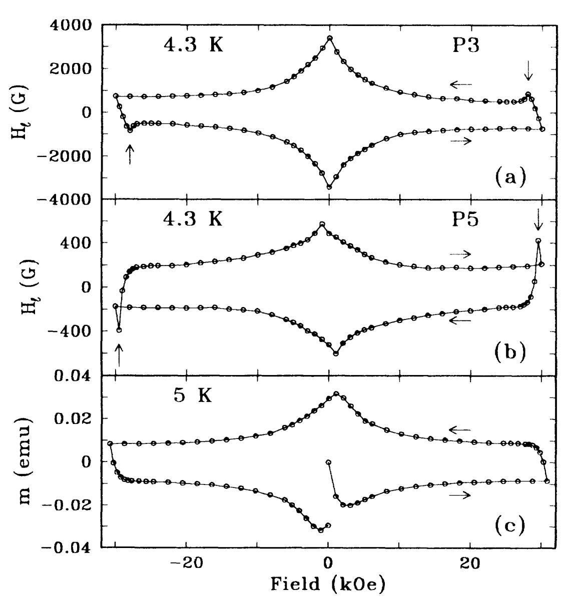

FIG. 2. Local-field hystereses at low temperatures (a) and (b) measured by two Hall probes of the array and (c) M-H loop measured by a SQUID on the same crystal. The horizontal arrows show the direction of the external field sweep. Vertical arrows indicate the peaks at the field reversal (PFR).

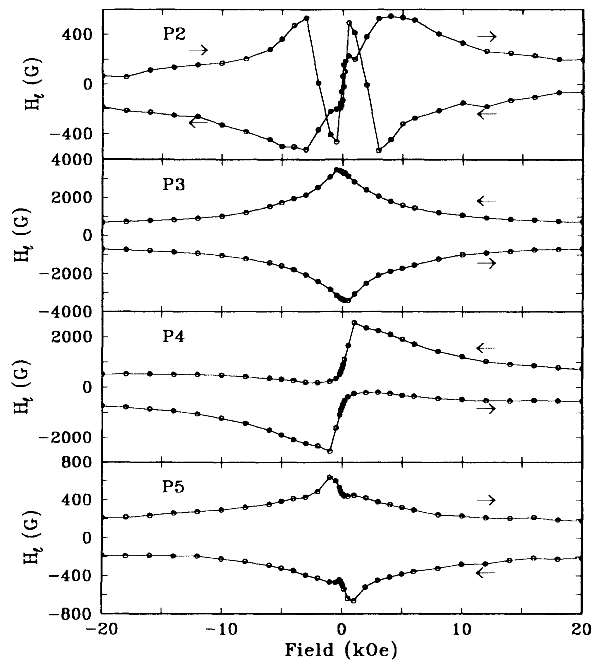

FIG. 3. Local-field hystereses near zero external field at 4.3 K. The suppression of the local field and its variation with the position of the Hall probe is apparent.

First we discuss the negative field at the edges and the PFR effect, both of which are not present for an infinite slab in a parallel magnetic field, originally considered by Bean.[1] We show them to be the consequence of the platelike geometry $YBa_2Cu_3O_{7-y}$ crystal[2–4] when the field is applied along the shortest dimension, c axis. Let us consider a thin strip of width w, thickness d, and an infinite length (see Fig. 4). The actual shape of the sample is better approximated by a disk, but the qualitative differences between the resulting field distributions are small.[3] For this geometry, in the critical-state uniform currents flow in opposite directions in either half of the strip [Fig. 4(d)]. This results in two kinds of divergences in the field component H_z perpendicular to the strip, namely, at the center and at the edges of the strip. The calculated H_z profile at a distance $d/2$ above the surface is shown in Fig. 4(d). *The strong decrease in* H_z *at the edge is the origin of the negative* H_l. Real divergence only occurs at the surface or inside of the superconductor and it is suppressed by the field dependence of J_c.

The PFR can be understood by considering the current distribution in a platelike superconductor during the field reversal. At the maximum external field in the critical state, the current induced by the external field will flow as shown in Fig. 4(a) (for simplicity, we assume a field independent J_c). When the field is slightly reduced, regions will be formed along the sample edges where the current is flowing in the opposite direction to the interior. New boundaries between the opposing currents near the edges will give rise to additional divergences of the local fields at these points [Fig. 4(b)]. Further reduction of the external field will move the boundaries between the opposing currents to the center of the sample [Fig. 4(c)]. Finally,

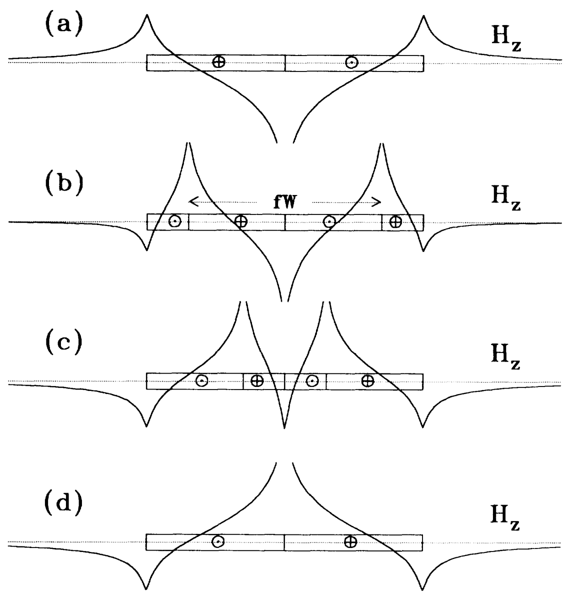

FIG. 4. Current distribution during the field reversal and calculated field distribution generated by the current in the infinite strip of width w and thickness d ($w/d=100$) measured $d/2$ above the strip. ⊕ and ⊙ indicate the current flow into and out of the paper, respectively. The field component, H_z (parallel to the external field), generated by the current, is calculated using Ampere's law. From one critical state (a) to another (d), the fractional region of interior currents f decreases from 1 to 0.

the current will completely flow in the other direction establishing an alternate critical state [Fig. 4(d)].

This simple calculation qualitatively reproduces our experimental results. We measure the local field at a fixed position near the surface; the local field shows a maximum as the boundary between two opposing currents passes right under this point, irrespective of the position of the probe. Namely, the local field will always *increase* in the *decreasing* branch of the hysteresis loop, giving rise to a *crossing* of the local-field hysteresis which we observe at P5. The absence of PFR in the integrated magnetization [Fig. 2(c)] is not surprising; divergences at the edges and the center cancel each other. Indeed, the magnetization calculated from our current distribution is given by $M(f)=M_0(2f^2-1)$, where M_0 is the magnetization in the critical state and f is the ratio of the distance between the current boundaries to the total width of the strip [see Fig. 4(b)]. The magnetization increases monotonically from $-M_0$ to $+M_0$ for any field. According to the above model, the peak in H_z occurs in the earlier stage of the field reversal near the edge. Experimentally, the peak at the P3 occurs at $\simeq 28.0$ kOe, whereas it is observed at $\simeq 29.5$ kOe at P5, consistent with this model.

Now we turn to the behavior at low fields. As is clearly seen in Fig. 3(a), below about 3 kOe at low temperatures, there is a suppression of H_l near zero external field and the field distribution at the sample shows much variation from point to point. We discuss possible mechanisms to explain this observation. One possibility is that the crystal is *not homogeneous*, i.e., there is a granularity on some length scale as has been discussed by Daeumling *et al.*[6] As each of our Hall probes has an effective area of $\simeq 10\times 10$ μm^2, we cannot detect any granularity much smaller than this size. Alternatively, it is conceivable that there are changes in the current paths on a size scale comparable to our probe dimensions or larger. For example, for a thin superconducting disk, the current flows in a concentric manner and there is an anomalous point at the center where the current will be reduced to zero. However, for a sample with an irregular shape, it may be possible to have a line consisting of points where $J_c=0$. The location and the pattern of the line might vary depending on the field value and will give rise to abrupt changes in the local field, as seen experimentally. This explanation is unlikely, however, since there is no reason why the phenomenon should occur only at low magnetic fields.

We propose that the local-field suppression is related to the lower critical field H_{c1}. In general, experiments on high-T_c superconductors reveal an enhancement of the average magnetization close to zero field in their M-H loops [see Fig. 2(c), for example]. This has been interpreted as the field dependence[16] of J_c or due to the anisotropy of J_c in a thin-disk geometry.[17] But occasionally, M-H loops show a measurable decrease in magnetization just as we observe in the local-field measurements. Chaddah *et al.*[18] have suggested that this suppression in the M-H loop at low fields is due to H_{c1}. In the region where the local field is below H_{c1}, the critical-state model is no longer a good description. This is because the vortices are far apart and a macroscopic current cannot be supported in the superconductor. In the case of an infinite slab in a parallel field, the suppression of the macroscopic current

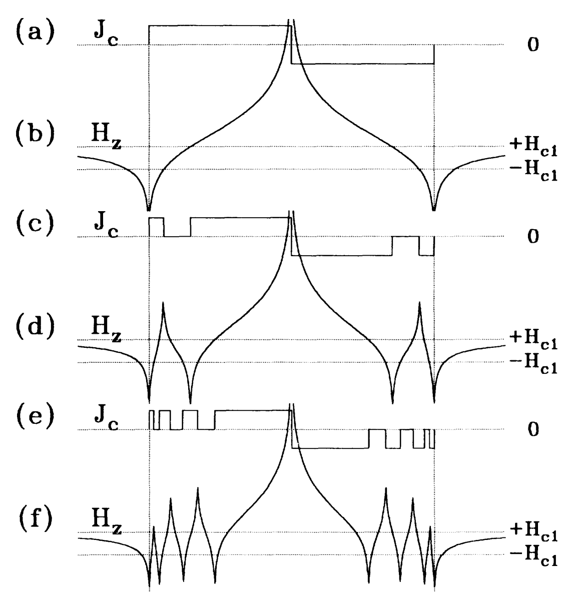

FIG. 5. A possible mechanism of the suppression of the local field at low fields inside a strip discussed in Fig. 4. A starting current distribution (a) produces the field profile (b). Due to the divergence of the field at the edge, the current in the region, where the local field is between $\pm H_{c1}$, will be suppressed to zero (c). The current distribution (c) tries to produce the field distribution shown in (d). This process continues (e), (f) leaving many small regions of $J_c=0$.

will give rise to an exclusion of the magnetic flux. The situation is completely different for a thin-plate geometry in a perpendicular field. We demonstrate below that such a geometry introduces an intrinsic instability. Here we consider the same strip of Fig. 4 and calculate H_z in the $z=0$ plane inside the superconductor. We assume $H=H_{c1}=530$ Oe,[19] and a field independent critical current of $J_c d=4000$ G, where d is the thickness of the sample. In the decreasing branch of the hysteresis loop for an external field close to H_{c1}, the current distribution shown in Fig. 5(a) tries to establish the field distribution shown in Fig. 5(b). If the field in some region of the sample becomes lower than H_{c1}, the current in this region is reduced to zero as shown in Fig. 5(c). The new current distribution tries to establish a new field profile shown in Fig. 5(d). These processes continue [Figs. 5(e) and 5(f)] because of the divergences of the local field at the edges of the region where the current is suppressed. If we take into account the field dependence of the critical current, the process will occur only close to the external field window of $\pm H_{c1}$ and stop at a certain stage, leaving several regions where the current is suppressed to zero and the corresponding large modulations in the field profile.[20] In the real system, the process will not evolve as we have described; instead, the current distribution will organize itself to accommodate the local pinning distribution and suppress the local-field divergence. Although the resulting effect depends on the location in the sample, the general trend is to suppress the local field because of the severe reduction of the current in many small regions. This mechanism qualitatively explains our observation of the position-dependent suppression of the local field at low fields.

Finally, we want to comment on the length scale of the field variation in this regime. The observed differences in the local field near H_{c1} at different probe positions, which are 200 μm apart, indicate the presence of a large field modulation on a length scale between 10 and 200 μm. This is also supported by our preliminary measurement with much higher spatial resolution.[21]

In conclusion, we have shown that in the usual platelike geometry of high-T_c single crystals, the divergence of the local field coupled with the finite lower critical field H_{c1} explains the local-field variations. This effect is *not* a result of the weak-link behavior and is fully consistent with the critical-state picture used in the estimates of J_c.

The authors thank A. P. Malozemoff and M. Konczykowski for introducing them to Hall probe magnetometry and L. Civale for stimulating comments.

[1] C. P. Bean, Rev. Mod. Phys. **36**, 31 (1964).
[2] D. J. Frankel, J. Appl. Phys. **50**, 5402 (1979).
[3] M. Daeumling and D. C. Larbalestier, Phys. Rev. B **40**, 9350 (1989).
[4] L. W. Conner and A. P. Malozemoff, Phys. Rev. B **43**, 402 (1991).
[5] A. P. Malozemoff, in *Physical Properties of High Temperature Superconductors I*, edited by D. M. Ginsberg (World Scientific, Singapore, 1989), p. 71.
[6] M. Daeumling, J. M. Seuntjens, and D. C. Labalestier, Nature (London) **346**, 332 (1990).
[7] L. Civale, A. D. Marwick, M. W. McElfresh, T. K. Worthington, A. P. Malozemoff, F. Holtzberg, J. R. Thompson, and M. A. Kirk, Phys. Rev. Lett. **65**, 1164 (1990).
[8] A. I. Belyaeva, S. V. Vojtsenya, and V. P. Yuriyev, Cryogenics **31**, 373 (1991).
[9] S. Gotoh and N. Koshizuka, Physica C **176**, 300 (1991).
[10] J. Moreland and P. Rice, IEEE Trans. Magn. **27**, 1198 (1991).
[11] V. N. Kopylov, A. E. Koshelev, and I. F. Schegolev, Physica C **170**, 291 (1990).
[12] M. Konczykowski, F. Holtzberg, and P. Lejay, Supercond. Sci. Technol. **4**, 8337 (1991).
[13] L. Fruchter, A. P. Malozemoff, I. A. Campbell, J. Sanchez, M. Konczykowski, R. Griessen, and F. Holtzberg, Phys. Rev. B **43**, 8709 (1991).
[14] F. Holtzberg and C. Feild, Eur. J. Solid State Inorg. Chem. **27**, 107 (1990).
[15] P. H. Kes, Physica C **153–155**, 1121 (1988).
[16] S. Senoussi, C. Aguillon, and P. Manuel, Physica C **175**, 202 (1991).
[17] L. W. Conner, A. P. Malozemoff, and I. A. Campbell, Phys. Rev. B **44**, 403 (1991).
[18] P. Chaddah, G. Ravi Kumar, A. K. Grover, C. Radhakrishnamurty, and G. V. Subba Rao, Cryogenics **29**, 907 (1989).
[19] L. Krusin-Elbaum, A. P. Malozemoff, Y. Yeshurun, D. C. Cronemeyer, and F. Holtzberg, Phys. Rev. B **39**, 2936 (1989).
[20] This process can occur at any field if there is a real divergence.
[21] T. Tamegai *et al.* (unpublished).