RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 51, NUMBER 1 1 JANUARY 1995-I

Observation of neutral lines during flux creep in thin high-T_c superconductors

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(Received 30 September 1994)

The "neutral lines" which were recently predicted to occur during flux creep in thin superconductors in a transverse magnetic field, are observed by magneto-optics in $YBa_2Cu_3O_{7-\delta}$ strips and rectangular platelets. These stationary neutral lines or loops separate regions where the flux density increases or decreases during flux creep due to the large demagnetization field. The observations are in good agreement with theory, which is extended to rectangular specimen shape.

Recently a general analytic solution was given for the flux-creep problem in thin superconducting strips and disks in a transverse magnetic field.[1] These solutions for the space- and time-dependent electric and magnetic fields and for the decaying magnetic moment in this perpendicular geometry exhibit several interesting features:

(i) The results for infinitely long strips and circular disks are qualitatively very similar in this perpendicular geometry. This similarity was found also for the flux-penetration problem[2–4] and for the linear response to ac magnetic fields.[5]

(ii) The analytic solution for the electric field is universal,[6] being exact for an exponential current-voltage law of the pinned vortex lattice, and to a very good approximation applying also to any sufficiently nonlinear current-voltage dependence like power laws or the collective creep or vortex-glass pictures. The sheet current $\mathbf{J}(\mathbf{r},t)$ and magnetic moment $M(t)$ are obtained by inserting this universal electric field $\mathbf{E}(\mathbf{r},t) \sim 1/(t+\text{const})$ into the appropriate current-voltage law. The resulting moment $M(t)$ decays with a (roughly logarithmic) time law which is almost identical to the result obtained for parallel applied field.[6]

(iii) In contrast to the similarity of $M(t)$, the flux-density profiles during creep are qualitatively different in the transverse and longitudinal geometries. Whereas in longitudinal fields the induction $B(\mathbf{r},t)$ increases uniformly in the entire specimen after the increase of $H_a(t)$ is stopped, the flux creep in transverse geometry is nonuniform: In the central region of the strip or disk the transverse flux density $B_z(\mathbf{r},t)$ increases due to the penetration of flux as expected, but in the outer region $B_z(\mathbf{r},t)$ *decreases* with t. This anomalous decrease of the flux density is due to the field enhancement caused at the sample edges by the large demagnetizing field. During the relaxation away from the critical state, flux creep smoothes out the profile $B_z(\mathbf{r},t)$ such that $\partial B_z/\partial t > 0$ in regions where $B_z(\mathbf{r},t) < \mu_0 H_a$ and $\partial B_z/\partial t < 0$ in regions where $B_z(\mathbf{r},t) > \mu_0 H_a$. These regions are separated by "neutral lines" at fixed positions $x = \pm a/\sqrt{2}$ in strips of width $2a$ $(-a \leq x \leq a)$ and by a "neutral circle" at $r = 0.876a$ in disks with radius a (the value $0.652a$ in Ref. 1 is a misprint).

In specimens of different shape, e.g., squares or rectangles,[7] the "neutral loop" outside which $B_z(\mathbf{r},t)$ decreases is still at a fixed position, which in general is defined by the zero line of the current-caused field $B_z(\mathbf{r},t) - \mu_0 H_a$. For strips and disks an equivalent condition for the electric field E is $\partial E/\partial x = 0$ or $\partial(rE)/\partial r = 0$, respectively, which follows from $\partial \mathbf{B}/\partial t = -\text{curl}\mathbf{E} = \mathbf{0}$ at the neutral line; this condition for the neutral line, however, does not work with other specimen shapes.

In the present paper we report the observation of these neutral lines at the surface of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin strips and rectangular YBCO single crystals. We visualize the magnetic-field distribution by the magneto-optical Faraday effect, i.e., the rotation of the polarization plane of linearly polarized light which passes a magneto-optically active layer exposed to the magnetic field of the underlying superconductor. From flux-free regions the light is reflected without rotation and thus cannot pass the analyzer which is set in a crossed position with respect to the polarizer. In this way the flux-line lattice is imaged as bright areas, whereas the flux-free Meissner phase remains dark.

Since YBCO itself does not show a significant Faraday effect, the sample surfaces have to be covered by a magneto-optically active material. For the experiments presented in this paper, EuSe thin films and ferrimagnetic iron garnet films with an in-plane anisotropy were used as magneto-optical indicators. The EuSe thin films were deposited by electron-beam evaporation directly onto the sample surface, which before was coated with an aluminum layer of thickness about 200 nm in order to enhance its reflectivity.[8] This technique allows the flux distributions to be observed *directly* with a spatial resolution of about 1 μm in a temperature range of $5\,\text{K} \leq T \leq 20\,\text{K}$. The lower temperature limit is given by the cryostat and the upper limit is imposed by the temperature dependence of the Verdet constant of the europium chalcogenides, which results in very low rotation angles at higher temperatures.[9]

The iron garnet film was deposited by liquid phase epitaxy onto a gallium-gadolinium substrate with a thickness of about 3.5 μm (commercial firm Gamma Scientific Production, Russia).[10] This kind of indicator allows the flux penetration into high-T_c superconductor (HTSC) samples to be observed directly in the whole temperature regime of superconductivity with a higher magnetic sensitivity than with the EuSe thin films. However, its spatial resolution is limited by the thickness of the indicator to about 3 μm.

The external magnetic field is generated by a copper solenoid coil, which is cooled with liquid nitrogen and produces a maximum field of 0.6 T. The observations were per-

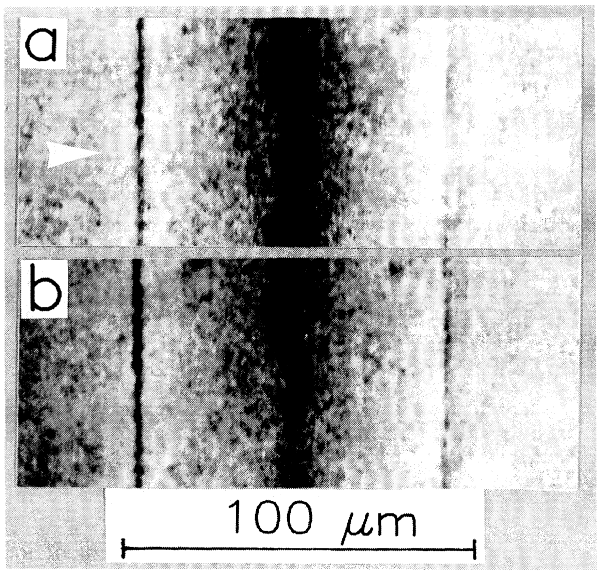

FIG. 1. Time evolution of the flux distribution in a strip at $T = 5$ K in a constant magnetic field of $\mu_0 H_a = 160$ mT. (a) $t = 7$ s; the white arrows indicate the line where the profiles shown in Fig. 2 were measured. (b) $t = 3420$ s.

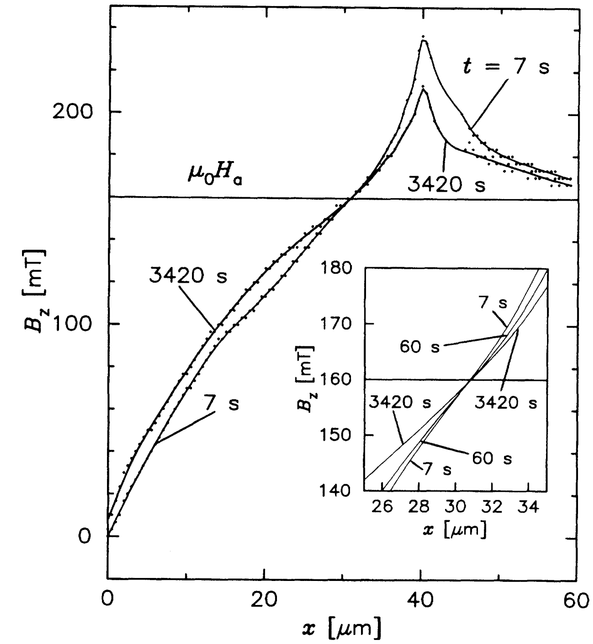

FIG. 2. Flux-density profiles corresponding to the flux distributions in Fig. 1. The inset shows the area around the neutral line in detail.

formed in the optical cryostat described in Refs. 8 and 11. All images can be observed directly via microscope or may be transferred to an image processing system for analyzing.[12] The image processing system measures the grey level pixel by pixel along a user-defined line.

To calibrate the measured intensity I in terms of the local flux density B_z, two fixed points are determined: In the Meissner phase we have $B_z = 0$ at the center of the sample. Far away from the sample edge on the substrate, the measured light intensity corresponds to the external field $\mu_0 H_a$ which is aligned with the z axis. With these fixed points, the measured intensity can be directly related to B_z.[13] In the field range of interest for our experiments, the field-intensity characteristics are approximately linear except near $B_z = 0$ (in crossed polarizer-analyzer setting).

The c-axis-oriented YBCO thin films were produced at the Max-Planck-Institut für Festkörperforschung in Stuttgart, Germany, by a laser-ablation technique.[14] All thin films were patterned chemically to be used for four terminal resistivity measurements. The YBCO single crystals were grown by a self-flux method as described in Ref. 15 (Universität Karlsruhe, Germany).

In order to study flux creep effects in HTSC's, we performed time-resolved magneto-optical observations of flux motion in constant applied magnetic field.[16,17] In Fig. 1 the flux distribution of an YBCO strip (width $2a = 80\,\mu$m, thickness $d = 300$ nm) in the critical state is shown at $T = 5$K at two times of (a) $t = 7$ s and (b) $t = 3420$ s after the increase of the applied magnetic field was stopped at $\mu_0 H_a = 160$ mT. For these observations EuSe thin films were used as magneto-optical indicators. The external magnetic field is oriented perpendicular to the sample surface and hence parallel to the c axis. The bright areas of the sample correspond to the Shubnikov phase, where flux lines have penetrated while the flux-free Meissner phase remains dark. The dark lines at the sample edges are due to damage of the surface during the patterning process, which causes diffuse scattering of light at these places.

Comparison of both photographs shows that (i) the central dark zone $[B_z(\mathbf{r},t) < \mu_0 H_a]$ of the strip is much smaller and brighter in (b) than in (a). Here the flux line density increases with increasing t; (ii) in the edge zone $[B_z(\mathbf{r},t) > \mu_0 H_a]$ the intensity, i.e., the flux line density, decreases with increasing t; (iii) far away from the sample, the intensity does not change with time, reflecting the constant applied field.

The profiles presented in Fig. 2 were averaged over ten lines parallel to the one indicated by the white arrows in Fig. 1(a). From these profiles the thermally activated flux motion and the location of the neutral line at $x = 0.74a$ are clearly visible, see the inset in Fig. 2. This value agrees well with the predicted universal value of $x = a/\sqrt{2}$; the slightly larger value is due to the finite thickness (400 nm) of our magneto-optical indicator.[18] Note also the sharp overshoot of $B_z > \mu_0 H_a$ at the sample edges caused by the transverse geometry, see also Fig. 3.

Figure 3 shows the flux distribution of a rectangular YBCO single crystal (width $2a = 1.05$ mm, length $2b = 1.65$ mm, thickness $d = 0.2$ mm) at $T = 60$ K measured at two times of (a) $t = 5$ s and (b) $t = 3600$ s after the increase of the applied magnetic field was stopped at $\mu_0 H_a = 171$ mT. Here, to visualize the flux distributions we used ferrimagnetic iron-garnet films with in-plane anisotropy. Since in the critical state with current saturation the uniform current has to flow parallel to the sample edges it has to bend sharply at the so-called discontinuity lines (d lines),[19] which for an isotropic rectangle are inclined by 45°. In both photographs the typical double Y structure of the d lines of our rectangular sample is clearly visible since the transverse field

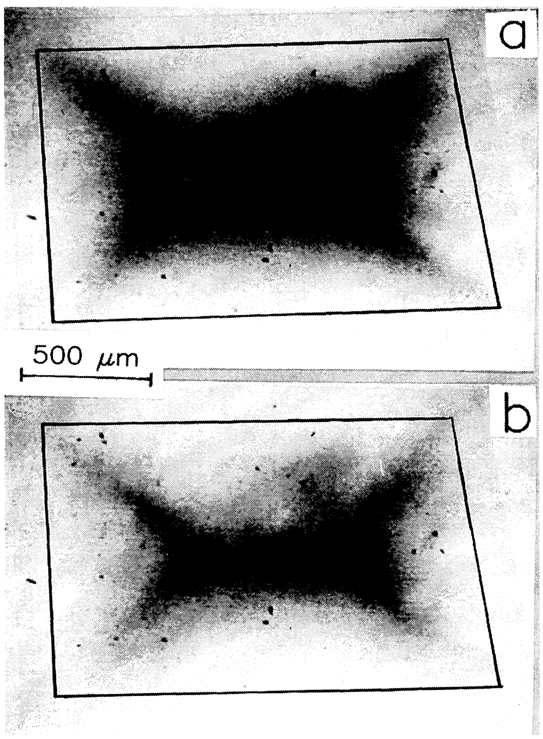

FIG. 3. Time evolution of the flux distribution of a rectangular YBCO single crystal at T = 60 K and $\mu_0 H_a$ = 171 mT. The black frames indicate the sample edge. (a) t = 5 s; (b) t = 3600 s. The time was measured after the increase of the external magnetic field was stopped.

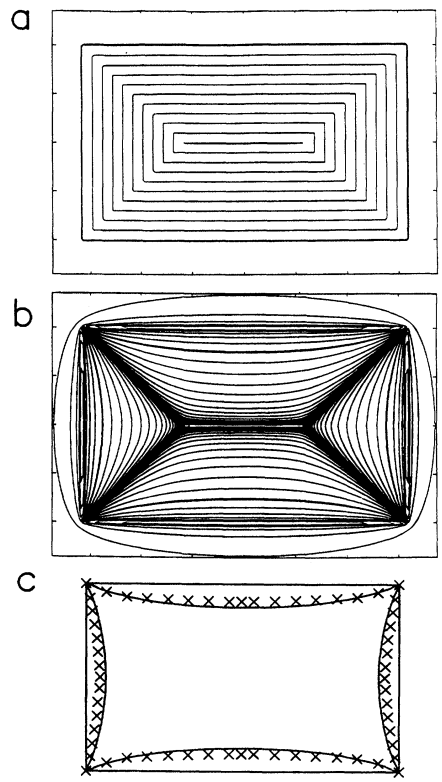

FIG. 4. (a) The current distribution of a (thick or thin) type-II superconductor in the critical state. The equidistant streamlines indicate the constant $|\mathbf{j}| = j_c$ within the whole sample. (b) Contour plot of the flux distribution for a thin superconductor in the critical state. The increment of B_z is $0.1\mu_0 H_a$. The bold line is the neutral line $B_z = \mu_0 H_a$. (c) Comparison of the calculated neutral line (solid line) with the experimentally determined line (×).

component B_z has a logarithmic infinity along these lines, cf. Eq. (1) below.

The comparison of Figs. 3(a) and 3(b) shows that with increasing time the flux density increases near the center and decreases near the edges of the sample, as with the strip in Fig. 1. According to Ref. 1 the neutral line in specimens of arbitrary shape is determined by the flux distribution in the critical state where the sample is completely filled with flux and the modulus of the current **j** has reached its critical value everywhere in the sample. In Fig. 4 the current and field distributions in this critical state are shown for a rectangular sample with side ratio $b/a = 1.58$. For a thin rectangular plate with $|x| \leq a$, $|y| \leq b$, $|z| \leq d/2 \ll a \leq b$, in the critical state $|\mathbf{j}(x,y)| = j_c$ the Biot-Savart law yields the flux density $B_x = \mp \mu_0 j_y d/2$ and $B_y = \pm \mu_0 j_x d/2$ at $z = \pm d/2$, and

$$B_z(x,y) = \mu_0 H_a + \frac{\mu_0 j_c d}{4\pi} \sum_{p=\pm 1} \sum_{q=\pm 1} f(px,qy),$$

$$f(x,y) = \sqrt{2} \ln \frac{\sqrt{2}P + a + b - x - y}{\sqrt{2}Q - a + b - x - y} + \ln \left| \frac{(P+y-b)(y-b+a)(P+x-a)x}{(y-b)(Q+y-b+a)(x-a)(Q+x)} \right| \quad (1)$$

with $P = [(a-x)^2 + (b-y)^2]^{1/2}$, $Q = [x^2 + (b-a-y)^2]^{1/2}$. This B_z is shown as a contour plot in Fig. 4(b) with the neutral line $B_z(x,y) = \mu_0 H_a$ emphasized as a bold line. The flux concentration in the middle of the sample edges and the steep slope (logarithmic infinity) near the d lines and near the edges are clearly seen.

During flux creep away from the critical state, the current density decreases nearly uniformly with qualitatively unchanged current pattern, $|\mathbf{j}(x,y,t)| \approx j(t) \approx j_c - j_1 \ln(t/t_0)$ where j_1 and t_0 are constants.[1] Therefore, the flux distribution, too, stays qualitatively the same, given by Eq. (1) with j_c replaced by $j(t)$. The neutral line defined by $\partial B_z / \partial t = 0$ or by $B_z(x,y) - \mu_0 H_a = 0$ remains thus at the same position.

Figure 4(d) shows the calculated neutral line (solid line) together with points (×) extracted from the experiment. These points were determined, as with the strip in Fig. 2, by scanning profiles at different times. The resulting neutral line of the lower left quadrant of the sample was then continued symmetrically. Note the nice agreement between theory and experiment. The small difference between the measured and calculated positions is due to the finite thickness (3.5 μm) of the magneto-optical indicator. The calculated neutral line in the middle of the longer side is at $|y| = 0.7071a$ for $b/a \to \infty$ (strip), $|y| = 0.75a$ for $b/a = 1.58$, $|y| = 0.77a$ for $b/a = 1.35$, $|y| = 0.810a$ for $b/a = 1$ (square), and for a disk of radius a the neutral circle is at $r = 0.876a$.

In conclusion, we have demonstrated the existence of neutral lines where $\partial B_z(x,y,t)/\partial t=0$ at fixed positions during flux creep away from the critical state in thin superconducting strips and rectangles. A compact exact analytic expression is given for the magnetic field generated by the currents in the critical state of a thin rectangle with arbitrary side ratio $b/a \geqslant 1$. For general specimen shape the neutral line is obtained from the condition $B_z(x,y,t)=\mu_0 H_a$ with the flux density B_z of the critical state inserted.

We wish to thank Professor H. Kronmüller and our colleagues for their constant interest in this work, H.-U. Habermeier (MPI für Festkörperforschung, Stuttgart) for preparation of the YBCO thin films, and M. Kläser and G. Müller-Vogt (Universität Karlsruhe) for providing us with large excellent YBCO single crystals.

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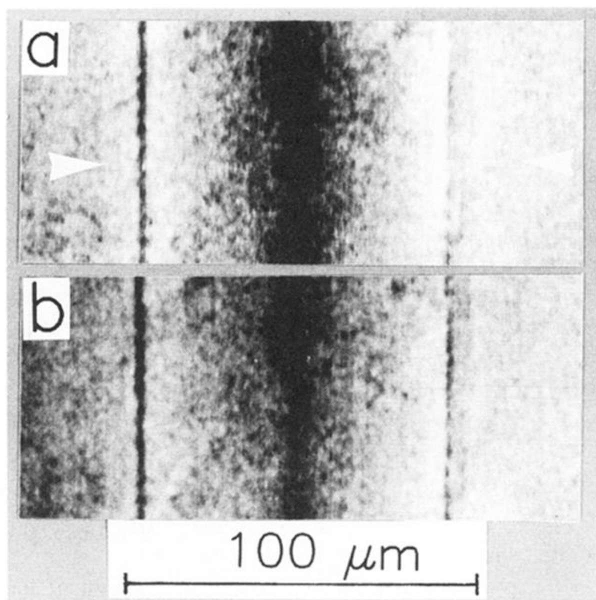

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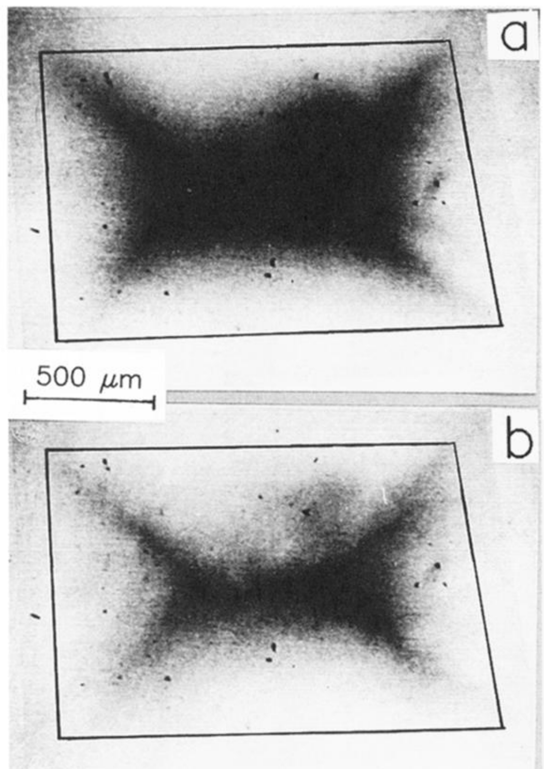

FIG. 3. Time evolution of the flux distribution of a rectangular YBCO single crystal at $T = 60$ K and $\mu_0 H_a = 171$ mT. The black frames indicate the sample edge. (a) $t = 5$ s; (b) $t = 3600$ s. The time was measured after the increase of the external magnetic field was stopped.