Asymmetric Field Profile in Bose Glass Phase of Irradiated $YBa_2Cu_3O_{7-\delta}$: Loss of Interlayer Coherence around 1/3 of Matching Field

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(Received 9 May 2000)

Magneto-optical imaging in $YBa_2Cu_3O_{7-\delta}$ with tilted columnar defects (CD's) shows an asymmetric critical-state field profile. The observed hysteretic shift of the profile ridge (trough) from the center of the sample is explained by in-plane magnetization originating from vortex alignment along CD's. The extracted ratio of the in-plane to out-of-plane magnetization component has a maximum at 1/5 of matching field (B_Φ) and disappears above $B_\Phi/3$, suggesting a reduction of interlayer coherence well below B_Φ in the Bose glass phase. Implications are discussed in comparison with the vortex liquid recoupling observed in irradiated $Bi_2Sr_2CaCu_2O_{8+y}$.

DOI: 10.1103/PhysRevLett.86.5144 PACS numbers: 74.60.Ge, 74.25.Ha, 74.60.Ec, 74.72.Bk

An effective way to enhance the critical current density (J_c) in high temperature superconductors (HTSC's) is the introduction of the correlated disorder such as columnar defects (CD's) [1–3] and planar defects [4,5]. Heavy-ion irradiation is one of the most controllable techniques to introduce CD's in the sample whose diameter is of the order of coherence length in HTSC's. When the density of CD's, or dose-equivalent matching field B_Φ, is increased, the enhancement of J_c persists at higher fields [1]. However, the field dependence of J_c, which is proportional to the irreversible magnetization [6], has a maximum not at B_Φ, but at a field significantly smaller than B_Φ [1,2,7,8].

Recent studies on the vortex phase diagram of highly anisotropic $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) with CD's have suggested a nearly temperature independent boundary at $\sim B_\Phi/3$ [8,9]. In the vortex liquid (VL) regime above the irreversibility line, dramatic enhancement of the c-axis coherence at $(\sim 1/5-1/3)B_\Phi$ has been demonstrated by Josephson plasma resonance (JPR) studies [9]. In addition, the c-axis resistivity decreases at similar fields consistent with the enhancement of interlayer coherence [10]. Reduction of reversible magnetization [8,11,12] is also reported in the same field range. Theoretically, a Monte Carlo simulation by Sugano *et al.* [13] suggests a field-driven transition with enhancement of vortex trapping rate by CD's at $B_\Phi/3$. Their calculation shows that the interlayer coherence jumps at the transition consistent with JPR experiments in the VL phase of BSCCO. In less anisotropic $YBa_2Cu_3O_{7-\delta}$ (YBCO), no JPR experiments have been reported because the plasma frequency in YBCO is much higher than the accessible frequency range of JPR experiments [9].

An interesting conclusion in Ref. [13] is that in the solid phase below the irreversibility line, which is called the Bose glass (BG) phase [14], the sign of the interlayer phase coherence change becomes opposite: i.e., it *decreases* at $B_\Phi/3$. In the BG phase, the peak in $J_c(H)$ is actually located at $(\sim 1/5-1/3)B_\Phi$ in BSCCO [8], and similar behavior can be found in YBCO as well [1]. In the collective pinning theory [15], the reduction of the collective pinning length related to the interlayer coherence causes the enhancement of the critical current [16]. Thus, the origin of the $J_c(H)$ peak in HTSC's may be related to this $B_\Phi/3$ boundary. Note that in unirradiated BSCCO a steep magnetization increase [17] and an abrupt reduction of the phase coherence [18] occurs simultaneously at the second magnetization peak field. However, so far there is no direct evidence for anomalous behavior of the interlayer coherence in the BG phase.

In this Letter, we provide experimental evidence for the loss of interlayer coherence at $(\sim 1/5-1/3)B_\Phi$ in the BG phase of YBCO by using magneto-optical (MO) imaging of the critical state field profile. We found that the field profile in YBCO with slightly tilted CD's is asymmetric, which is explained by the alignment of vortices along CD's. The asymmetry, which can be utilized as a probe for the interlayer coherence, has a maximum at $B_\Phi/5$ and disappears above $B_\Phi/3$. This result strongly suggests that the field-driven boundary exists in YBCO in the same field range as BSCCO.

YBCO single crystals were grown by the flux method using gold crucibles [19]. Rectangular twinned single crystals were cut into typical dimensions of $1.0 \times 0.5 \times 0.015$ mm^3, so that the edges of the samples are along the a and b axes. The critical temperature of the pristine samples is about 91 K. Crystals were irradiated with 600 MeV iodine ions at doses corresponding to $B_\Phi =$ 10 kG (crystal A) and $B_\Phi = 3$ kG (crystal B) using the tandem Van de Graaff accelerator with superconducting booster at JAERI. The irradiated direction of both samples was tilted 10° from the c axis in the y-c plane (see inset of Fig. 1). Accordingly, we can distinguish the effect of CD's from that of twin boundaries (TB's). The longitudinal magnetization M parallel to the applied field H was measured by using a commercial SQUID magnetometer. We defined θ_{CD} as the angle of CD's from the c axis, θ_H

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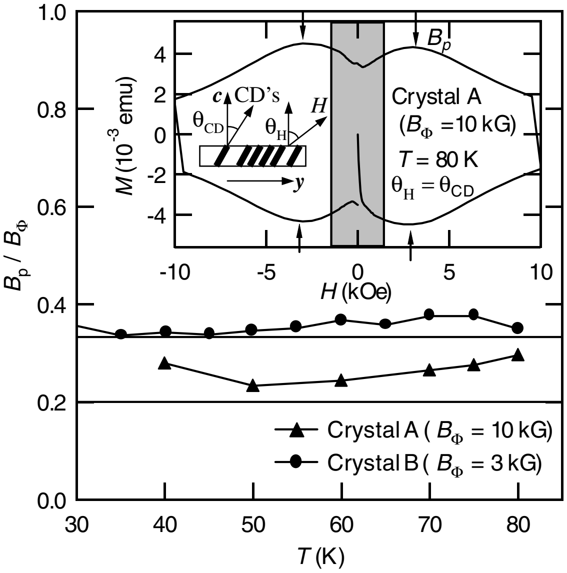

FIG. 1. Characteristic peak field B_p normalized by the matching field B_Φ as a function of temperature (see text). (Inset) Magnetization hysteresis loop at $T = 80$ K in crystal A ($B_\Phi = 10$ kG). The shaded area shows the field region where we performed MO imaging. Arrows indicate the peak field B_p. Schematic figure in the inset shows the configuration of the sample.

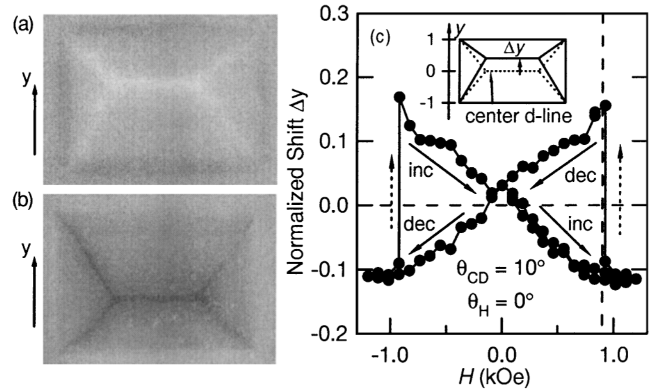

FIG. 2. Typical critical-state field profiles in the (a) decreasing and (b) increasing field branches at $H_{\parallel c} = 900$ Oe in crystal A. The bright region corresponds to higher fields. The direction of CD's is tilted 10° from the c axis towards the y direction. Note the asymmetry of the profile. (c) Hysteresis loop of the normalized d-line shift (Δy) at 80 K in crystal A. Inset shows the definition of Δy. The sign of Δy is positive when the shift direction is towards the y axis. Arrows with "inc" and "dec" indicate field sweep directions. When the field sweep direction is changed, the old d line disappears and a new d line is generated (dotted arrows) [23].

as the angle of applied field from the c axis. The critical state field profile was imaged by using an MO indicator garnet film with in-plane magnetization placed on the top surface of the sample in the field range $|H_{\parallel c}| \leq 1.5$ kOe, $|H_{\perp c}| \leq 1.0$ kOe [20].

The inset of Fig. 1 shows magnetization hysteresis loop at $T = 80$ K in crystal A with $\theta_H = \theta_{CD}$. Irreversible magnetization shows a maximum at around $B_\Phi/3$, and we define B_p as this peak field. In crystal B, we determined B_p as a field where $[M(\theta_H = +\theta_{CD}) - M(\theta_H = -\theta_{CD})]/M(\theta_H = +\theta_{CD})$ shows a maximum, because the enhancement of the magnetization by CD's is smaller in this sample. Main panel of Fig. 1 demonstrates that in both crystals B_p/B_Φ is almost independent of temperature and its value is around $\sim 1/3$–$1/5$, which is similar to that reported in BSCCO [8].

Figures 2(a) and 2(b) show typical critical state field profiles at $H_{\parallel c} = 900$ Oe in decreasing and increasing field branches, respectively. The double-Y shaped current discontinuity lines (d lines) are clearly seen, where current direction abruptly changes [5,21,22]. The center d line is significantly shifted in the y direction. The shift of the d line is much larger than $t_s \tan\theta_{CD}$, where t_s is the thickness of the sample. The field dependence of the normalized d-line shift Δy in crystal A is plotted in Fig. 2(c). This curve shows hysteresis, which is symmetric with respect to $H = 0$. When the field is increased, the d line at the center of the sample shifts towards one of the edges [Fig. 2(b)], whereas it shifts to the opposite direction when the field is decreased [Fig. 2(a)]. The direction of the shift is always along the y axis, which is the same as that of the inclination of CD's. The hysteresis can be summarized as follows. When H and M have the same sign, the shift is positive, and if they are opposite, Δy is negative. When we reverse the field sweep direction, the critical current direction in the sample (or the sign of M) is reversed, and then the d line shifted to one direction disappears and a new d line shifted to the opposite direction appears, as shown by the dotted arrows in Fig. 2(c) [23]. A small positive shift Δy at $H = 0$ can be explained by the self-field trapped in the sample. It should be noted that TB's cannot explain the observed shift of the d line, since TB's run randomly along [110] and [1$\bar{1}$0] directions and the symmetry of TB's is different from that of the d-line motion.

To clarify the relationship between Δy and the alignment of vortices along CD's, we investigated the field profile under tilted fields. Figure 3 shows the normalized d-line shift Δy as a function of the misalignment angle ($\theta_H - \theta_{CD}$) in crystal A. A sign change of Δy occurs around $\theta_H - \theta_{CD} \approx 0$ in both increasing and decreasing field branches. When $|\theta_H - \theta_{CD}|$ is large, $|\Delta y|$ becomes smaller. This result shows that the misalignment of the field from CD's is an important parameter to determine the shift of the d line.

Previously, an asymmetric field profile was reported in YBCO with tilted CD's from the c axis by Schuster *et al.* [21]. They observed the in-plane anisotropy of J_c, and discussed it based on the difference in the nucleation energy of kinks in two cases, along and across the tilted CD's [24]. They considered that the asymmetric field profile originates from the different kink nucleation between the top and bottom surfaces because of the difference of the surface quality. However, we checked that Δy at the top and bottom surfaces have opposite polarities [see Fig. 4(d)], indicating that the asymmetry is a rather

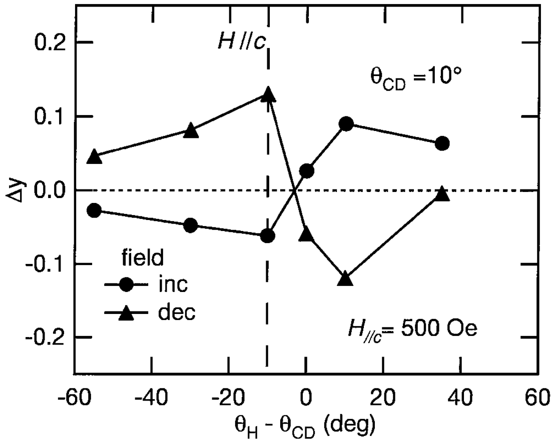

FIG. 3. Δy as a function of the misalignment angle ($\theta_H - \theta_{CD}$) for the increasing (circles) and decreasing (triangles) field branches at $H_{\|c} = 500$ Oe in crystal A. Dashed line shows the H direction parallel to the c axis.

intrinsic property of vortex systems. In addition, we performed MO imaging in the sample with nontilted CD's ($\theta_{CD} \sim 0°$) under tilted fields and confirmed that the asymmetric field profile depends only on the misalignment of CD's and H.

We propose a model to explain our observations. In our model, the shift of the d line is caused by the alignment of vortices along CD's, which is schematically shown in Fig. 4(a). Even when the field is applied away from the direction of CD's, vortices can be aligned by CD's if the misalignment is not so large. To compensate the difference in the directions of H and B, in-plane magnetization (M_y) is induced as shown in Fig. 4(a), which is realized by the current (J_y) flowing both in and across the CuO_2 planes [Fig. 4(b)]. At the same time, out-of-plane magnetization (M_z) is generated by the in-plane current as shown in Fig. 4(c). Actual current density in the sample is the sum of both currents, and it is limited by $J_{c\perp}$ or $J_{c\|}$, where $J_{c\|}$ and $J_{c\perp}$ are the in-plane critical current densities parallel and perpendicular to the y axis, respectively [24]. The existence of J_y breaks the balance between J_{c1} and J_{c2}, because J_{c1} is always antiparallel to J_{c2}. This imbalance makes the shift of the d line, since the MO indicator can detect only the out-of-plane induction B_z close to the top surface.

To check this idea, we calculate $B_z(y)$ assuming a current density distribution $J_{c\perp}(y, z) = \pm|J_{c\perp}|$ as shown in Fig. 4(d), where the contribution of J_y is introduced. The calculated $B_z(y)$ in Fig. 4(e) shows a d line whose position is shifted from the center of the superconductor, just as we observed. One may notice that the in-plane magnetization produces small stray fields near the edges ($y \sim \pm 1$), but in the total $B_z(y)$ this effect is negligibly small. Our images in Fig. 2 are qualitatively consistent with this calculation.

Our model naturally explains (1) the hysteresis observed in Fig. 2 by the change of the direction of $J_{c\perp}$, (2) the opposite polarity between top and bottom surfaces, and (3) the Δy sign change at $\theta_H \approx \theta_{CD}$ by the change of the direction of J_y. In the full critical state of a rectangular sample, we can estimate the relative critical current densities in the four regions separated by the double Y-shaped d lines [22]. In Fig. 4, the ratio $(1 + \Delta y)/(1 - \Delta y)$ gives J_{c1}/J_{c2}, and Δy is therefore equal to the ratio of the current densities $J_y/J_{c\perp}$. An important point is that the measurements of the shift Δy is much easier than the global transverse magnetization (M_y) measurements [25] in thin samples, since $J_y/J_{c\perp}$ can be large due to the small thickness even if the integrated M_y is small.

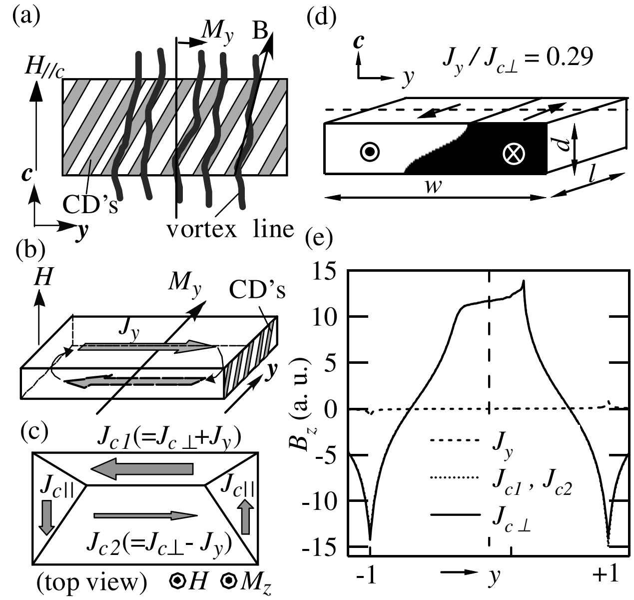

FIG. 4. (a) In-plane magnetization M_y is generated by the misalignment of B and H, when the vortex is partially trapped. In-plane (b) and out-of-plane (c) components of magnetization and their accompanying currents in the field decreasing branch at a positive field. Arrows on the sample show the direction and magnitude of current density. J_{c1} and J_{c2} are determined by the constraint that the sum of current densities in (b) and (c) cannot exceed the in-plane critical current density $J_{c\perp}$. With an assumed current distribution ($J_y/J_{c\perp} = 0.29, J \perp z, y$) in a finite strip sample (w:l:d = 675:350:15), field profile $B_z(y)$ along the broken line in (d) is calculated (e). Induction profiles from J_y, $J_{c1} + J_{c2}$, and $J_{c\perp}$ are shown in broken, dotted, and solid lines, respectively. The divergence at the d line is clearer in the MO image, because the intensity is proportional to B_z^2.

A useful implication of our model is that when vortices lose the interlayer coherence with zigzaglike structure along the z direction, the in-plane magnetization M_y and hence Δy will disappear. Therefore, the asymmetry of the field profile in the critical state can be a powerful probe for the interlayer coherence.

Next let us discuss what happens on the asymmetry when we cross B_p in sample B. Figure 5 shows $J_y/J_{c\perp}$ as a function of applied field H at $T = 55$ K and $\theta_H = 0°$. The low field part of Fig. 5 ($|H| < 0.4$ kOe) is consistent with the hysteresis in sample A [Fig. 2(c)]. Surprisingly, the absolute value of $J_y/J_{c\perp}$ has a maximum at $\sim B_\Phi/5$ and becomes almost zero (with no hysteresis) above $B_\Phi/3$. This behavior indicates that vortices are aligned along

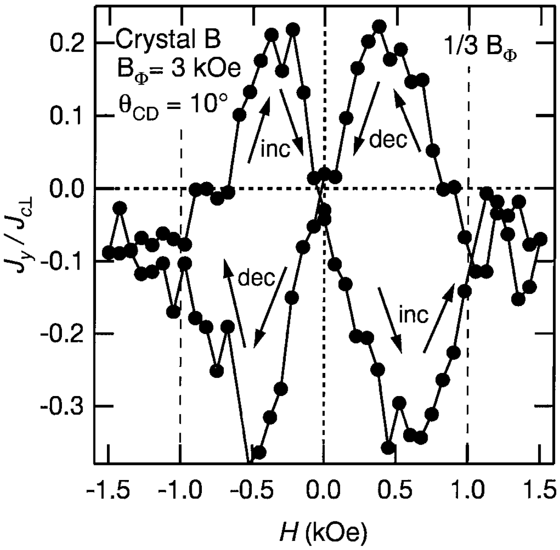

FIG. 5. $J_y/J_{c\perp}$ as a function of the applied field H at $T = 55$ K in crystal B ($B_\Phi = 3$ kG). Arrows with "inc" and "dec" indicate the field sweep directions.

CD's below $B_\Phi/3$, and the interlayer coherence is suppressed above $B_\Phi/3$ [26]. This field range of the interlayer coherence anomaly is quite similar to that of field-induced recoupling in the VL phase of irradiated BSCCO observed by JPR experiments [9]. Furthermore, at the same field range, the enhancement of J_c is observed in the BG phase (Fig. 1), also consistent with BSCCO [8]. This similarity between YBCO and BSCCO implies that the field-driven $B_\Phi/3$ anomaly does not depend on the anisotropy of the system. Actually, recent JPR studies in irradiated BSCCO with different oxygen contents have shown no dependence of anomaly field on the anisotropy [27]. Moreover, our results that the interlayer coherence shows a dramatic decrease at $\sim B_\Phi/3$, in contrast to the increase in the VL state, are consistent with the prediction of the simulation result [13] in the BG phase.

Finally, the reason why this anomaly field is around $(\sim 1/5-1/3)B_\Phi$ is still an open question. It is well known that the matching effect is observed at $H = B_\Phi$ [28] when the distribution of the pinning center is periodic [29]. In the irradiated crystals, however, CD's are randomly distributed, which suggests that the statistical averaging may be important to understand the underlying mechanism of this number.

In summary, we observed an asymmetric critical-state field profile in YBCO with CD's when the field is tilted away from CD's. The asymmetry depends on the field sweep direction and the misalignment of the field from CD's. We interpret this asymmetry in terms of the in-plane magnetization, which is originated from the alignment of vortices along CD's. We proposed that the asymmetry of the critical state field profile can be used as a powerful probe of the interlayer coherence. The coherence of vortices along CD's has a maximum at $\sim B_\Phi/5$ and becomes small above $B_\Phi/3$. This result in YBCO is analogous to the results of JPR in BSCCO.

We thank R. Sugano for fruitful discussions. This work is supported by Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan.

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