Vortex Line Pinning and Bose-Glass Dynamics in Heavy-Ion Irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ Single Crystals

C. J. van der Beek,[1] M. Konczykowski,[2] V. M. Vinokur,[1] T. W. Li,[3] P. H. Kes,[3] and G. W. Crabtree[1]
[1]*Materials Science Division and Science and Technology Center for Superconductivity, Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Laboratoire des Solides Irradiés, Ecole Polytechnique, 91128 Palaiseau, France*
[3]*Kamerlingh Onnes Laboratorium, Leiden University, P.O. Box 9506, 2300RA Leiden, The Netherlands*
(Received 3 June 1994)

The angular dependence of the ac screening of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals irradiated with 5.8 GeV Pb ions is used to demonstrate the importance of interactions between vortex segments in different CuO_2 layers. The field tilt angle below which pinning by the columnar defects is effective is very large: $\Theta_a \approx 70°$. The magnitude and frequency dependence of the shielding current as well as the frequency dependence of the irreversibility line are self-consistently described by the Bose-glass theory. The irreversibility line is shown to be determined by the flux creep rate.

PACS numbers: 74.60.Ge, 74.60.Jg

One of the most promising high-temperature superconductor compounds from the point of view of applications is $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). Unfortunately, the layered structure and ensuing huge effective mass anisotropy $\Gamma \equiv m_z/m_\perp \approx 2 \times 10^4$ [1] mean that vortex lines in the mixed state in BSCCO are extremely sensitive to thermal fluctuations. Vortices may even decouple into independent two-dimensional (2D) segments, or "pancake vortices," with a response to external disturbances that is independent from that of their neighbors in adjacent layers [2,3]. The small energies associated with the pinning of 2D vortex segments are responsible for giant flux creep and small critical current densities at high temperatures, which are detrimental to the material's usefulness. The critical current density j_c of high-temperature superconductor samples can be considerably enhanced by heavy-ion irradiation [4–6]. The enhancement of j_c is the result of the coincidence between the linear geometry of the vortex lines and that of the randomly situated irradiation-induced columnar defects, whereby the vortex lines can be pinned along their entire length. However, when vortices are decoupled, the advantages of the columnar defect geometry may be lost. Since quantities related to pinning and motion of 2D vortex "pancakes" should depend only on the field component $B_\perp$ perpendicular to the crystalline layers, the lack of angular dependence of the irreversible magnetization of heavy-ion irradiated BSCCO single crystals was taken as evidence that, indeed, vortices in this material are decoupled [7].

In this Letter, we show that the introduction of columnar defects in BSCCO in fact overcomes the effects of material anisotropy: Vortices in heavy-ion irradiated BSCCO single crystals behave as well-coupled lines at fields up to the matching field B_Φ (see below). Moreover, vortex dynamics is consistently described by the Bose-glass theory for vortex *line* pinning by columnar defects [8]. Following the analogy with the quantum mechanics of 2D bosons on a disordered substrate, this theory predicts the localization of vortex lines on or between the columnar defects below a temperature T_{BG} [8]. It describes, for the first time, a system in which exact results for vortex pinning and thermal line wandering can be derived, and directly compared to experiment. In particular, the theory predicts a sharp cusplike angular dependence of physical quantities related to vortex pinning when the field is aligned with the columnar defects, and the rapid decrease of the effectiveness of pinning above the depinning temperature $T_1 < T_{BG}$. We will show below that the magnitude of the ac shielding current exhibits a sharp cusp around the angle where the field is aligned with the columnar defects. The field tilt angle Θ_a at which the nonlinear ac response resulting from vortex pinning by the columnar defects disappears drops rapidly above a temperature which we identify with T_1, and that coincides with the temperature where a sharp drop of the irreversibility field parallel to the columns is observed. The frequency and temperature dependence of the shielding current near depinning are shown to be in complete agreement with the Bose-glass predictions, and can be used to extract the theory's basic parameters, such as the characteristic energy scale $T^*(T)$, creep exponent μ, and vortex binding energy U_0. In turn, these parameters self-consistently describe the experimentally found T_1 and Θ_a, and the frequency dependence of the irreversibility line.

$Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals were grown using the traveling-solvent floating-zone technique [9]. Two crystals of size $0.67(l) \times 0.40(w) \times 0.064(t)$ mm^3 (crystal 1) and $0.66(l) \times 0.34(w) \times 0.030(t)$ mm^3 (crystal 2) were cut from a larger piece, and irradiated at doses of 1×10^{13} and 2.5×10^{14} m^{-2} 5.8 GeV Pb ions, respectively, at the Grand Accélérateur National d'Ions Lourds at Caen, France. The ion beam was aligned parallel to the sample c axis. This type of irradiation has previously

 0031-9007/95/74(7)/1214(4)$06.00

been shown to produce continuous amorphous tracks of diameter ≈ 7 nm, traversing the entire crystal [5]. The density of columns corresponds to the irradiation dose, and to the matching fields $B_\Phi \approx 200$ G (sample 1) and $B_\Phi \approx 5$ kG (sample 2). The matching field is the induction at which there are equally many vortices and columnar defects in the sample. After irradiation, samples 1 and 2 had $T_c = 93.1$ and 90.7 K, respectively. All measurements were carried out using the local Hall probe magnetometer [10]. A small InSb Hall probe was placed on top of the sample. Both were surrounded by a small coil that could produce an ac field of rms magnitude $h_{\mathrm{ac}} = 2.1$ Oe. The whole assembly was placed in an external magnetic field $H < 15$ kG, which could be rotated in a plane perpendicular to that of the sample. The ac field orientation did not change with respect to the sample. In the dc mode, the setup was used to measure the field difference due to the presence of the sample, $\Delta H_s = B - H$, which is proportional to the magnetic moment. The application of an ac field allowed for the measurement of the ac screening properties of the samples in a frequency range $0.5 \text{ Hz} < f < 5$ kHz. The results are expressed in terms of the broadband fundamental transmittivity $T_H \equiv [B(f,T) - B(f,T \ll T_c)]/[B(f,T \gg T_c) - B(f,T \ll T_c)]$ and the third harmonic transmittivity $T_{H3} \equiv B(3f,T)/[B(f,T \gg T_c) - B(f,T \ll T_c)]$ [11]. The advantages of the transmittivity experiment are the flat frequency characteristic of the Hall probe and the fact that the in-phase component of the fundamental, T_H', can be straightforwardly related to the magnitude of the shielding current in the sample. The presence of a nonzero T_{H3} implies the presence of a nonlinear $I(V)$ response, which is the result of flux pinning.

Typical results of transmittivity versus temperature are shown in Fig. 1 for sample 1, at different dc fields, $0 < H < 300$ G, applied parallel to the c axis and the columnar defects. We define an "irreversibility line" $T_{\mathrm{irr}}(B)$, or, alternatively, $B_{\mathrm{irr}}(T)$, by the locus of $|T_{H3}|$ onset temperatures. It is shown on a logarithmic scale for both samples in Fig. 2. Also included is the line $B_{\mathrm{dc}}(T)$ defined by the vanishing of ΔH_s. At low temperatures, $B_{\mathrm{irr}}(T)$ is greater than the matching field B_Φ and decreases approximately linearly with T. At $T \sim 75$ K, B_{irr} and B_{dc} are approximately equal to B_Φ. The irreversibility line of both samples shows a break, whereupon $B_{\mathrm{irr}}(T)$ drops exponentially with T. This correlation between B_{irr} and B_Φ is suggestive of the role of the columnar defects. The frequency dependence of $B_{\mathrm{irr}}(T)$, which is quite strong at fields $B > B_\Phi$, becomes much weaker at lower fields. We will show below that the frequency dependence of B_{irr} is essential to the understanding of the onset of magnetic reversibility.

The angular dependence of T_H and T_{H3} in a field of 5 kG is shown in Fig. 3 for crystal 2. Both harmonics of the transmittivity show a clear cusplike behavior at the angle where the external field is aligned with the columnar defects. This is the first important result of this paper: It implies that vortex segments in adjacent CuO_2 layers are sufficiently coupled in our samples for the vortices to show linelike response. A similar conclusion was arrived at by Klein *et al.* from measurements of the angular dependence of magnetic hysteresis of BSCCO single crystals [12] and by Budhani, Holstein, and Suenaga from resistivity measurements on $Tl_2Ba_2CaCu_2O_8$ epitaxial

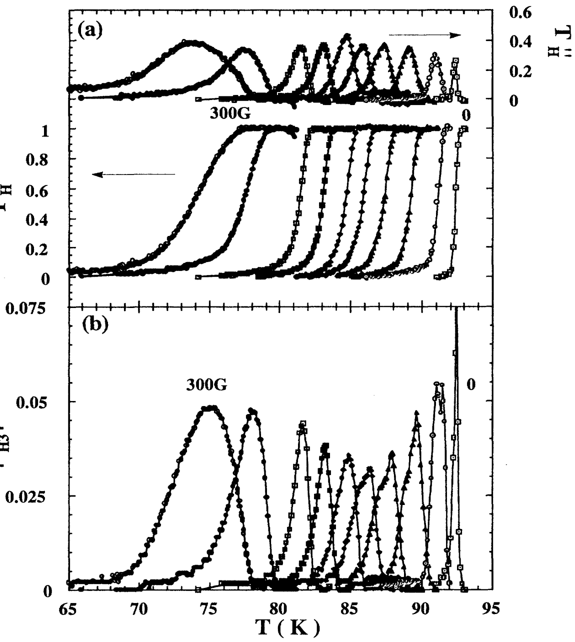

FIG. 1. The temperature dependence of the fundamental broadband transmittivity (a) and modulus of third harmonic transmittivity (b) of sample 1 ($B_\Phi = 200$ G) in applied fields between 0 (far right) to 300 G (far left), measured using an ac field of 2.1 Oe and $f = 7.75$ Hz.

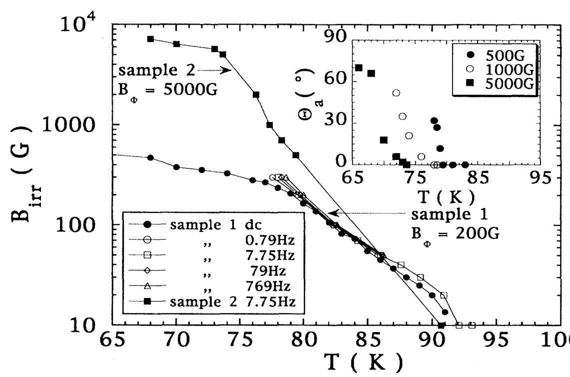

FIG. 2. The irreversibility lines B_{irr} (at several frequencies) and B_{dc} as determined by the onset of the third harmonic transmittivity and closing of the ΔH_s loop, respectively, for both samples 1 and 2. The inset shows the accommodation angle Θ_a, also determined by the onset of T_{H3} (sample 2, $B_\Phi = 5$ kG).

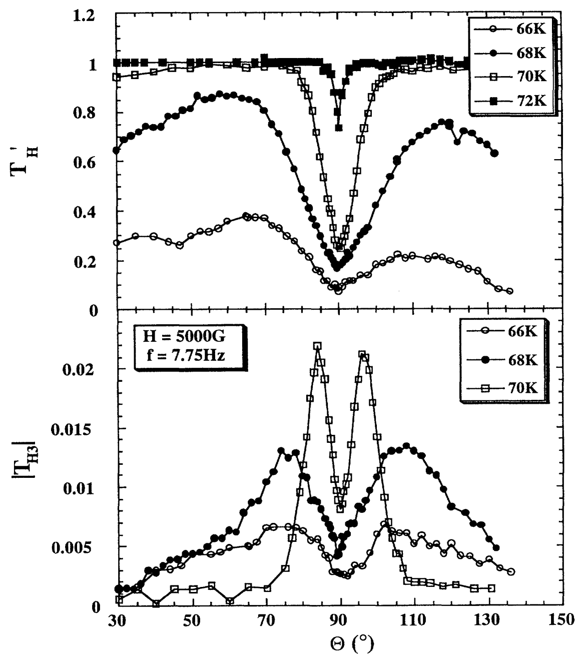

FIG. 3. Angular dependence of the fundamental (a) and third harmonic (b) transmittivity of sample 2, measured at $f = 7.75$ Hz in a field of 5000 G. The angle $\Theta = 0$ corresponds to the $H \| ab, \Theta = 90^\circ$ means that the field is parallel to the sample c axis and to the columnar defects.

films [13]. It is surprising that the cusplike behavior persists up to 5 kG. This field is not only much higher than the maximum field where angular dependence of the magnetization was observed in Ref. [12] but also much higher than the induction, $B \approx 60$ mT, above which the flux lattice neutron diffraction pattern disappears in an unirradiated BSCCO crystal [14]. This field was interpreted as the crossover field above which vortex pancake interactions are always essentially 2D [2].

We determine the "accommodation angle," or maximum field tilt angle Θ_a at which columnar defect pinning is effective, as that where $T_{H3}(\Theta)$ disappears. In the measurements at $H = 500$ G, the T_{H3} signal caused by pinning by the ion tracks overlapped, below $T = 78$ K, with the signal due to point defect pinning for fields close to the ab direction, and Θ_a could not be determined. A plot of T versus Θ_a depicts the angular dependence of the irreversibility line (inset to Fig. 2). At low temperature, $\Theta_a \approx 70^\circ$ is very large, a consequence of the extreme bending softness of the vortex lattice in BSCCO. This large value of Θ_a can explain the apparent lack of angular dependence in the experiments of Ref. [7]. Namely, the vortex lines may be locked to the columnar defects at all angles $\Theta < \Theta_a$. The depinning rate, which determines the width of the magnetic hysteresis loop, will then remain constant over this large angular range. Above the temperature T_1 where the irreversibility line starts its exponential decrease, the accommodation angle also drops rapidly with increasing temperature.

We have elucidated the mechanism that determines the transmittivity curves and the onset of magnetic (ir)reversibility by measuring the frequency dependence of the transmittivity at different fields below and above B_Φ. From the T_H' data, we obtain the normalized shielding current density $J \equiv ja/h_{\mathrm{ac}}$ using $J \approx \pi^{-1} \arccos(2T_H' - 1)$. This expression is a close approximation to the result of Ref. [11] for the ac screening by a single inductive loop obeying the critical state model. The parameter a is a characteristic sample dimension which we estimate as $a \approx \sqrt{lw}$. The frequency dependence $J(f)$ for sample 1 at a field of 200 G is shown in Fig. 4(a). The functional form of $J(f)$ is determined by evaluating the inverse instantaneous creep rate, $S^{-1} \equiv (\partial \ln J / \partial \ln f)^{-1}$. At low frequency, a plot of S^{-1} vs $\ln f$ tends toward a straight line with negative slope -1.3 ± 0.2. This means that the frequency dependence of the current density can be described as

$$J(f) \approx J_x \left[\frac{k_B T}{U} \ln\!\left(\frac{1}{2\pi f \tau} \right) \right]^{-1/\mu}, \tag{1}$$

with the exponent $\mu \approx 1$. The parameter J_x is a characteristic current density for creep, U is an activation energy, and τ is the normalization time for flux motion through the sample. This $J(f)$ dependence corresponds to the exact result of the Bose-glass theory [8] for thermal depinning at high current density, when vortex lines liberate themselves from the columnar defects by the nucleation of critical vortex half loops. In fact, accurate fits of $J(f)$ can be made over a frequency range of two decades

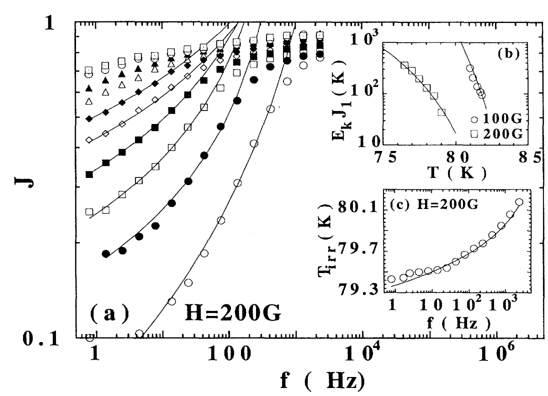

FIG. 4. (a) Frequency dependence of the normalized shielding current in crystal 1 at a field of 200 G, and temperatures $T = 80.0$ K (o), 79.5 K (●), 79.0 K (□), 78.5 K (■), 78.0 K (◇), 77.5 K (◇), 77.0 K (△), 76.5 K (△), 76.0 K (⨀), and 75.5 K (⊡). Lines denote fits by Eq. (1) with $\mu = 1$. The product UJ_x as extracted from the fits is shown in the inset (b), for fields $H = 100$ G (o) and 200 G (□). Lines denote fits by Eq. (2). The inset (c) shows the irreversibility temperature T_{irr} as a function of frequency for crystal 1 ($B_\Phi = 200$ G), in a field $H = 200$ G. The solid line corresponds to the evaluation of the condition $J(\omega, T) = J_{\min} \equiv 10^{-3}$ with *no* adjustable parameters.

using Eq. (1) and the Bose-glass prediction $\mu = 1$ (see Fig. 4). The parameters extracted from such a fit are the product $UJ_x(T)$, shown in Fig. 4(b), and the normalization time $\tau \approx 10^{-3}$ s. Note that Eq. (1) is no longer valid at frequencies $2\pi f \tau > \exp(-U/k_B T)$, where the probability of thermal activation of vortices becomes exponentially small. The parameter $UJ_x(T)$ exhibits an extremely rapid (faster than exponential) decrease with temperature, meaningful fits of which can be obtained using the Bose-glass result for the pinning energy at high temperatures:

$$E_k J_1 = \frac{a}{h_{\rm ac}} \frac{T{*}U_0}{\Phi_0 b_0} \left(\frac{T}{T{*}}\right)^3 \exp\left[-3\left(\frac{T}{T{*}}\right)^2\right]. \qquad (2)$$

We identify U with the energy E_k of a kink extending the average distance d between neighboring columnar defects, and J_x with the current density $J_1 \equiv U_0/\Phi_0 d$ associated with this distance ($\Phi_0 = 2.07 \times 10^{-15}$ Wb is the flux quantum). The quantity U_0 is the vortex binding energy per unit length at low temperature, $T*(T) = T*(0)(1 - T/T_c)$ is the characteristic energy scale describing vortex positional fluctuations, and b_0 is the effective radius of the pinning well. Note that the two energies $T*$ and U_0 completely characterize the system of vortices and columnar pins. From the fits of UJ_x by Eq. (2), we obtain $T*(0) = 360$ K, independent of the applied field. The effective vortex binding energy $U_0 \approx 2 \times 10^{-14}$ J m^{-1} at 200 G, increasing to 4×10^{-13} J m^{-1} at 100 G. These numbers amount to 2.7 and 47 K per pancake vortex, respectively.

Having found the two characteristic energy scales for vortex (de)pinning, one can infer all other physical quantities related to the experiment. For instance, from the condition $T*(T_1) = T_1$ the depinning temperature $T_1 \approx 74$ K is found. This corresponds to the temperature where both the irreversibility line and the accommodation angle start their steep descent. Thus we conclude that the sharp drop of $B_{\rm irr}(T)$, $B_{\rm dc}(T)$, and $\Theta_a(T)$ is caused by thermal wandering of vortices near their equilibrium positions. The value of the accommodation angle at low temperature can itself be found by comparing U_0 and the vortex line tension, $\tilde{\epsilon}_1 \approx 2 \times 10^{-15}$ J m^{-1}: $\Theta_a \approx \arctan(U_0/\tilde{\epsilon}_1)^{1/2} \approx 75^\circ$ [8]. This value, too, is in remarkably good agreement with experiment. The complete and consistent agreement of temperature, frequency, and angular dependence of the ac screening with the boson localization theory of Nelson and Vinokur is the second important result of this paper.

The above analysis can be cross-checked by evaluating the frequency dependence of $T_{\rm irr}$. Since $|T_{H3}|$ is a smooth and continuous function of the normalized shielding current J, the onset of the $|T_{H3}|$ corresponds to the smallest observable current, which we estimate from the noise level in the experiment to be $j_{\rm min} \approx 3 \times 10^2$ A m^{-2}, or $J_{\rm min} = j_{\rm min} a/h_{\rm ac} \approx 1 \times 10^{-3}$. The line $T_{\rm irr}(\Theta, B, f)$ then corresponds to the locus of $J(\Theta, T, B, f) = J_{\rm min}$. In particular, we can estimate the frequency dependence of $T_{\rm irr}$ by combining Eqs. (1) and (2) for J with the experimentally obtained values of $T*(0)$ and U_0, and inverting the condition $J = J_{\rm min}$. The result is shown in Fig. 4(c): the frequency dependence of the $|T_{H3}|$ onset is accurately described over nearly four decades. This means that the irreversibility line is determined by the rate of the flux creep process and does *not* correspond to the phase boundary T_{BG}.

In conclusion, we have found that heavy-ion irradiation significantly reduces the effects of material anisotropy of BSCCO and renders interlayer interactions crucial to the vortex dynamics. The temperature, angular, and current density dependence of the thermal depinning rate has been determined and was found to be in excellent agreement with the Bose-glass predictions for vortex line pinning by columnar defects. The depinning rate is determined by the vortex half-loop nucleation process. The rapid drop of both the irreversibility line and the accommodation angle above the depinning temperature $T_1 \approx 75$ K is due to vortex line wandering near the equilibrium positions. This triggers the exponential decrease of the vortex binding energy with temperature and giant flux creep.

We would like to acknowledge Dr. L. Klein for useful discussions and The Netherlands Foundation FOM (ALMOS) where the crystals were grown. This work was supported by the Centre National pour la Recherche Scientifique (CNRS), the U.S. Department of Energy, BES-Material Sciences, under Contract No. W-31-109-ENG-38 (V. M. V., G. W. C.), the NSF, through the Science and Technology Center for Superconductivity (Cooperative Agreement No. DMR91-20000) (C. J. v. d. B.), and NATO Grants for International Collaboration in Research.

[1] J. C. Martinez *et al.*, Phys. Rev. Lett. **69**, 2276 (1992).
[2] L. I. Glazman and A. E. Koshelev, Phys. Rev. B **43**, 2835 (1991).
[3] L. L. Daemen *et al.*, Phys. Rev. Lett. **70**, 1167 (1993); Phys. Rev. B **47**, 11 291 (1993).
[4] L. Civale *et al.*, Phys. Rev. Lett. **67**, 648 (1991).
[5] M. Konczykowski *et al.*, Phys. Rev. B **44**, 7167 (1991).
[6] W. Gerhaüser *et al.*, Phys. Rev. Lett. **68**, 879 (1992).
[7] J. R. Thompson *et al.*, Appl. Phys. Lett. **60**, 2306 (1992).
[8] D. R. Nelson and V. M. Vinokur, Phys. Rev. Lett. **68**, 2398 (1992); Phys. Rev. B **48**, 13 060 (1993).
[9] T. W. Li *et al.* (to be published).
[10] M. Konczykowski, F. Holtzberg, and P. Lejay, Supercond. Sci. Technol. **4**, S331 (1991).
[11] J. Gilchrist and M. Konczykowski, Physica (Amsterdam) **212C**, 43 (1993).
[12] L. Klein *et al.*, Phys. Rev. B **48**, 3523 (1993).
[13] R. C. Budhani, W. L. Holstein, and M. Suenaga, Phys. Rev. Lett. **72**, 566 (1994).
[14] R. Cubitt *et al.*, Nature (London) **365**, 410 (1993).