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Correlation of flux lines in single-crystal $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ with columnar defects

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A detailed study has been made of the irreversibility line in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$, both for unirradiated crystals and also for samples containing irradiation-induced columnar defects aligned at either 0° or 45° to the c axis. For the unirradiated reference sample the proposed scaling rules for the case of isotropic pinning provide an excellent description of the data. In contrast, for the case of the irradiated samples the breakdown of the scaling due to the presence of anisotropic pinning provides a powerful method with which to trace the development of anisotropic pinning due to correlated disorder. For fields below the matching field B_Φ the existence of strong anisotropic pinning is demonstrated, while for $B \gg B_\Phi$ pinning is shown to be isotropic. A characteristic temperature T_1 is identified, above which the effect of anisotropic pinning is strongly reduced due to increased thermally induced delocalization of the vortices away from the columnar defects.

I. INTRODUCTION

The static and dynamic properties of flux lines in type-II superconductors are substantially influenced by the presence of artificial disorder.¹⁻¹¹ Among the various types of random disorder, a distinction should be made between point disorder (e.g., electron or neutron irradiation-induced defects, impurities or oxygen vacancies) and correlated defect structures, such as twin-plane boundaries or columnar defects as obtained by heavy ion irradiation.^{2-6,9,12-14} The two classes of disorder give rise to a quite different pinning behavior of vortices. For a comprehensive review of this subject we refer to Refs. 13 and 14. In contrast to *isotropic* pinning of point defects, correlated disorder leads to strongly *anisotropic* pinning behavior, which is most effective for a configuration where the applied field is parallel to the extended defects.²⁻⁴ Thus the angular dependence of any quantity related to pinning allows a differentiation to be made between isotropic uncorrelated and anisotropic correlated disorder.^{9,13,14} Furthermore, the correlated pinning of vortex lines along the defects is expected to depend strongly on the temperature and applied field. For high fields where the density of flux lines exceeds by far the density of tracks, the interaction between vortices dominates, and the anisotropic pinning arising from the defects is essentially not effective due to strong intralayer vortex interactions. On the other hand, at low fields where the density of tracks exceeds the density of flux lines, the anisotropic pinning of the defects dominates, since flux lines tend to accommodate to the defects

(single-vortex pinning). Moreover, there is a characteristic temperature (depinning temperature) above which the thermal energy of vortices exceeds the pinning potential of the columnar defects and thermal delocalization of flux lines becomes important. This is in contrast to random disorder which produces isotropic uncorrelated weak pinning at all temperatures and fields.¹²⁻¹⁴

Nelson and Vinokur^{12,13} and Blatter *et al.*¹⁴ have recently reported a detailed study of the phase diagram of high- T_c superconductors with correlated disorder. On the basis of a vortex two-dimensional- (2D) boson analogy they^{12,13} proposed a second-order Bose-glass to flux-liquid transition, which is significantly shifted to higher fields as compared to the first-order melting line of the pristine material. In order to locate the Bose-glass transition line they have considered the relative importance of the pinning potential and the intervortex interaction. Recent resistivity and magnetization studies on twinned $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (YBCO) with the applied field parallel to the columnar defects are in good agreement with the theoretical expectations.^{9,10} As shown in Ref. 10, in YBCO the Bose-glass transition may be tracked at low fields by the generic melting line. They employed a perturbative approach which allows the position of the Bose-glass transition to be derived using only the melting line of the unirradiated sample and the density and radius of the columnar defects. However, Bose-glass-like behavior is not only expected in the presence of columnar defects but generally for any correlated disorder. For example, the sharp drop and hysteretic characteristics of the resistivity in twin-free YBCO crystals^{15,16} which suggests

a first-order melting of the flux-line lattice is suppressed in the presence of only a few twin plane boundaries.¹⁷ This also demonstrates the importance of the correlation of disorder in controlling the crossover from the reversible to the irreversible region of the phase diagram. Another system of interest is $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO), which differs in several respects from YBCO. For instance, because of its different crystal structure, BSCCO contains no twin boundaries, which if present would be a potential source of Bose-glass-like behavior, even in the pristine material.¹⁷ Small angle neutron diffraction measurements (SANS) revealed that in YBCO the presence of twin boundaries gives rise to severe distortions of the vortex arrangement.^{18,19} This is in contrast to BSCCO, where at low fields a clear diffraction pattern is observed arising from a well-ordered vortex lattice.²⁰ Another important difference concerns the size of the effective mass anisotropy γ , which is greatly enhanced in BSCCO ($\gamma > 150$) (Ref. 21) as compared to YBCO ($\gamma \simeq 5$) (Ref. 22). The ensuing extremely low tilt modulus leads to flux lines which are very flexible,^{20,23,24} and the thermal fluctuations of flux lines or pancake vortices play an essential role in the static and dynamic properties of the vortex system.²⁵ For instance, SANS (Ref. 20) and μSR (Ref. 23) measurements show that in the pristine material at a field of ≈ 50 mT, the highly flexible nature of the flux lines gives rise to a 3D-2D pinning crossover, whereby the presence of intrinsic point defects leads to local tilt deformations of the flux lines on the scale of the interplane separation.^{20,23} In irradiated samples this crossover is of greatly reduced significance, since the dominant interaction is that between the vortices and the anisotropic defects, rather than with the intrinsic point defects, as will be demonstrated. However, as a further consequence of the high anisotropy and corresponding low vortex stiffness in BSCCO, the irreversible behavior is strongly suppressed and the position of the measured irreversibility line (IL) in the pristine material is consistent with the expectations of a thermal melting of the flux-line lattice.^{20,23,24,26} For the above reasons, the manifestation of a Bose glass are expected to be much more pronounced in BSCCO than in less anisotropic materials such as YBCO. While in YBCO the influence of correlated disorder may be understood by means of a perturbative approach,^{10,14} in BSCCO the much more complex shape of the IL after irradiation requires an alternative treatment.²⁷ However, it is clear that a study of the crossover from the reversible to irreversible regime of the phase diagram is a useful method with which to investigate the influence of correlated disorder on the vortex system.

In this paper we present a detailed magnetization study of the IL in BSCCO single crystals with columnar defects either parallel or at 45° to the c axis and compare these results to the IL of the unirradiated reference sample. Particular attention is paid to the effect of columnar defects on the IL, especially to the modification of the IL for the different orientations of both the c axis and the columnar defects with respect to the applied field. This provides quantitative information on the temperature and/or field and angular dependence of the

correlation between flux lines and columnar defects. In the unirradiated reference sample we find excellent agreement with the scaling theory of Blatter *et al.*²⁸ This implies that in this unirradiated sample pinning is indeed dominated by isotropic disorder. The goal of this work is to utilize the scaling ansatz for *isotropic* disorder in order to demonstrate the presence of *anisotropic* disorder. The breakdown of the anisotropic scaling gives clear and unambiguous evidence for correlated disorder, arising from columnar defects. We report a deviation from the angular scaling properties of the IL for $B \lesssim B_\Phi$ (dose-equivalent field, see Sec. II), demonstrating that the flux lines are able to accommodate to the columnar defects. This is shown to be possible even for a broad range of angles between the defect direction and the applied field. However, even for $B < B_\Phi$ but above a characteristic temperature T_1 (depinning temperature) the effects of the anisotropic pinning are drastically reduced, suggesting a thermally induced delocalization of the vortices away from the defects.

II. EXPERIMENTAL DETAILS

High-quality single crystals of BSCCO were grown by a self-flux method described elsewhere.²⁹ The crystals were cut and cleaved into identical square plates of size approximately $1 \times 1 \times 0.05$ mm³ with the c axis along the shortest dimension. Heavy ion irradiation with 5.8 GeV Pb ions has been performed at GANIL (Caen, France) at 300 K, with a dose of 10^{10} /cm² parallel to the c axis (sample B00). A second sample was irradiated simultaneously at 45° relative to the c axis (sample B45). The irradiation process induced continuous amorphous tracks of diameter $d \simeq 5 - 7$ nm through the entire sample, either parallel to c axis (B00) or at 45° (B45) (Refs. 2, 3, and 5). It is convenient to describe the density of tracks by a dose-equivalent field B_Φ , which corresponds to the field for which the density of flux lines equals the density of tracks. The dose-equivalent field used in this study was $B_\Phi = 2$ kG. The critical temperature of both samples ($T_c \simeq 92$ K) as determined by the onset of the diamagnetic signal remained unchanged due to the irradiation process. The IL was determined either from the collapse of field-cooled (FC) and zero-field-cooled (ZFC) dc-magnetization measurements or by the additional complementary technique of measuring the collapse of the magnetic hysteresis as measured by high-precision torque magnetometry. The experimental evaluation of the IL and its physical meaning are still controversial. The main difficulty is a complicated relation between the *macroscopic criterion* for reversibility and the *microscopic mechanism* responsible for the occurrence of reversible behavior. Usually, the IL depends strongly on the experimental technique (e.g., time scale of the measurement) and on the criteria used to determine $B_{\text{irr}}(T)$ or $T_{\text{irr}}(B)$.^{27,30} The main difference between the two methods used in this study is the time scale of the measurements. In the limit of a vanishing field-sweep rate, the IL as measured by torque magnetometry is expected to fall on top of the IL as obtained

by dc magnetometry. A comparison of the *quasistatic* dc magnetization and the *dynamic* torque magnetization technique therefore allows one principle to differentiate between a continuous and/or time dependent transition versus a sharp first-order transition from the irreversible to the reversible regime.²⁷

III. RESULTS AND DISCUSSION

In Fig. 1 are shown the IL's of samples B00, B45, and the reference sample as determined by static dc magnetometry with the applied field B parallel to the c axis. In the irradiated samples there is a clear and pronounced shift of the IL to higher fields and temperatures due to the presence of columnar defects. The strong shift of the IL is also apparent for sample B45 with the tracks at 45° with respect to the applied field. The IL of both irradiated samples are similar and exhibit a more structured shape than that of the reference sample. For high fields $B \gg B_\Phi$ the IL of both irradiated samples show an almost exponential temperature dependence, similar to that measured in the reference sample. This demonstrates that the influence of the columnar defects is changing with temperature and/or field. In particular, in both irradiated samples two characteristic features are observed. The first feature occurs at a characteristic field which for sample B00 is the matching field $B_\Phi \simeq 2$ kG, or equivalently for sample B45 is the field equal to the projection of the defect density onto the plane perpendicular to the field direction, i.e., $B_\Phi/\sqrt{2} \approx 1.4$ kG. At their respective characteristic field (B_Φ , $B_\Phi/\sqrt{2}$) both samples B00 and B45 exhibit a crossover in their IL from an exponential to a linear behavior. The second feature observable in the IL is one related to a characteristic tem-

perature $T_1 \approx 80$ K, as we shall later show. Here there is a kink in the IL where a crossover from a linear to an initially very rapid temperature dependence occurs, as can be most clearly seen in the inset of Fig. 1. For sample B00 with the defects along the c axis and for fields $B \lesssim B_\Phi$, it is likely that flux lines are trapped by the columnar defects. The similar shape of the IL for sample B45 therefore suggests a similar correlation between the flux lines and the defect structure even for large angles between the defects and the flux lines. Indeed, a rough estimate of the trapping angle θ_t shows that in highly anisotropic material the flux lines are able to tilt for a large angle with respect to the applied field. Following the approach given in Ref. 14 we take $\theta_t \approx \sqrt{B_{cr}/B_\Phi}$, where B_{cr} denotes the crossover from the single-vortex to the many-vortex pinning regime. For temperatures $T \ll T_c$ we may take $B_{cr} \approx B_\Phi$ and the trapping angle becomes $\theta_t \sim 60^\circ$.

Here we propose a simple method based on a general scaling argument which makes possible a distinction between correlated disorder, causing an alignment of flux lines along extended defects, and that due to the presence of point defects. For uniaxial superconductors Blatter *et al.*²⁸ have developed an anisotropic scaling approach, which allows a physical quantity to be directly determined for an arbitrary direction of the applied field using only the known result for an isotropic superconductor. We note that in this scaling ansatz only isotropic disorder is considered, and that here no attempt is made to account for correlated disorder in this scaling theory. However, the influence of correlated anisotropic disorder will manifest itself as a deviation from the scaling behavior for isotropic disorder. Following the approach of Ref. 28 the IL may be written in the general form

$$B_{irr}(T, \vartheta) = B_{irr}(T, \vartheta = 90^\circ)/\epsilon(\vartheta), \quad (1)$$

where $\epsilon(\vartheta)$ denotes the temperature independent angular scaling function, defined as

$$\epsilon^2(\vartheta) = \frac{1}{\gamma^2} \cos^2 \vartheta + \sin^2 \vartheta. \quad (2)$$

Here ϑ is the angle between the applied field and the ab plane, and $\gamma^2 = m_c^*/m_{ab}^*$ is the effective mass anisotropy. Equation (1) implies that the IL is the product of a term depending only on ϑ , and a second term which describes the temperature dependence $B_{irr}(T)$ for a fixed orientation with respect to the applied field. For highly anisotropic materials, such as BSCCO, the scaling function is reduced to $\epsilon(\vartheta) \approx \sin \vartheta$, as long as the applied field is not too close to the ab plane (i.e., $\vartheta > 1/\gamma$), and we obtain the simplified scaling rule:

$$B_{irr}(T, \vartheta) = B_{irr}(T, 90^\circ)/\sin \vartheta. \quad (3)$$

This implies that the IL in highly anisotropic superconductors is only determined by the c -axis projection of the applied field. The scaling rule Eq. (3) can easily be tested by measuring the IL as a function of the angle ϑ at a fixed temperature, and complementarily by measuring the temperature dependence of the IL for

FIG. 1. Irreversibility line (IL) for samples B00 (solid circles), B45 (open circles), and the unirradiated reference sample (solid triangles) for the field applied parallel to the c -axis direction. Due to the presence of columnar defects (sample B00, B45) the IL is shifted toward higher temperatures and/or fields. In the inset the sharp drop of the IL at $T_1 \simeq 78$ K is clearly seen for both irradiated samples (see text).

FIG. 2. (a) Irreversibility line (IL) of the unirradiated reference sample for the applied magnetic field at $\vartheta = 90^\circ$ (solid circles) and $\vartheta = 45^\circ$ (crosses) with respect to the ab plane. The IL for $\vartheta = 45^\circ$ is scaled by a factor $1/\sqrt{2}$ and falls on top of the IL for the field parallel to the c axis as expected from simple scaling arguments. (b) Angular dependence of the IL of the unirradiated reference sample for $T = 65$ K. The solid line is a single-parameter fit according to Eq. (3).

two fixed orientations of the sample with respect to the applied field. In the first case we expect the quantity $B_{\text{irr}}(\vartheta, T = \text{const.}) \times \sin \vartheta$ to be independent of ϑ for any given temperature. In the latter case it follows directly from Eq. (3) that the ratio of the IL's $b = B_{\text{irr}}(T, \vartheta_0)/B_{\text{irr}}(T, \vartheta_1)$ for two different orientations ϑ_0 and ϑ_1 of the sample is independent of temperature. We emphasize that the scaling ansatz applies only in the presence of uncorrelated isotropic disorder. Thus, any deviation of this scaling behavior is direct evidence for the effectiveness of anisotropic disorder. This provides us with a simple method to test the effectiveness of any correlated disorder, which is based only on a very general scaling ansatz. Furthermore, comparing the IL's for configurations in which the tracks are parallel or perpendicular to the applied field gives a qualitative measure of the pinning efficiency of flux lines along the defects.

In a first step, we test the validity of the scaling relation given in Eq. (3) for the *unirradiated* reference sample. In Fig. 2(a) the temperature dependence $B_{\text{irr}}(T)$ of the reference sample is shown, both for the field applied at $\vartheta = 90^\circ$ and $\vartheta = 45^\circ$ with respect to the ab plane. For $\vartheta = 45^\circ$ the irreversibility field has been scaled with a factor $\sin 45^\circ = 1/\sqrt{2}$. As seen in Fig. 2(a) the scaled IL for $\vartheta = 45^\circ$ falls on top of the IL as measured for $\vartheta = 90^\circ$, in excellent agreement with the simplified scaling rule given in Eq. (3). We also have measured the angular dependence $B_{\text{irr}}(\vartheta)$ at a fixed temperature $T = 65$ K, which is shown in Fig. 2(b). The solid line corresponds to a single-parameter fit to the function $B_{\text{irr}}(\vartheta) \propto 1/\sin \vartheta$ and is again in excellent agreement with the scaling ansatz (3) for highly anisotropic superconductors. Both experiments on the reference sample clearly confirm the concept of the scaling ansatz even for very highly anisotropic materials such as BSCCO. We note in particular that the data are in excellent agreement with the scaling ansatz for both the low and high temperature regime, where the nature of the vortex lattice in the reversible region may

FIG. 3. Irreversibility line (IL) of (a) sample B00 and (b) sample B45 for field orientations as shown in the figure. The IL for sample B00 and $\vartheta = 45^\circ$ is scaled by a factor $1/\sqrt{2}$ (see text). Only for $B \gg B_\Phi$ or $T_1 < T \rightarrow T_c$ are the expectations of the scaling behavior Eq. (3) recovered. The presence of columnar defects otherwise gives rise to correlated disorder, which is clearly demonstrated by the fact that the IL's do not coincide.

differ. We turn now to the samples containing columnar defects. In Fig. 3 the IL of both samples B00 and B45 are shown for the orientation angles $\vartheta = 90^\circ$, $\vartheta = 45^\circ$ and $\vartheta = -45^\circ$, $\vartheta = 45^\circ$, respectively. First we consider sample B00, with the tracks parallel to the c axis. In Fig. 3(a) the IL is shown for the field orientation angles $\vartheta = 90^\circ$ and $\vartheta = 45^\circ$. For $\vartheta = 45^\circ$ the IL has been scaled by a factor $1/\sqrt{2}$ as described above. For both orientations of the sample the IL exhibits similar characteristics, i.e., a sharp upturn close to T_c , a linear temperature dependence of $B_{\text{irr}}(T)$ for $B > B_\Phi/2$, and a kink at $B = B_\Phi$ and $T \simeq 78$ K. A detailed discussion of this particular temperature dependence of the IL will be presented elsewhere.²⁷ More significantly, in contrast to the pristine material, the scaled IL's for the two orientations

FIG. 4. Ratio of the irreversibility lines (IL) of the reference sample and samples B00, B45 for the same orientations of the samples as in Figs. 2 and 3. These are $b_1 = B_{\text{irr}}(45^\circ)/B_{\text{irr}}(90^\circ)$, $b_2 = B_{\text{irr}}(45^\circ)/B_{\text{irr}}(90^\circ)$, and $b_3 = B_{\text{irr}}(+45^\circ)/B_{\text{irr}}(-45^\circ)$, respectively. For ease of comparison of data b_1 and b_2 have been scaled by $1/\sqrt{2}$. Note the distinct maximum at $T \simeq T_1$, which coincides with the sharp drop of the IL's as seen in Fig. 1.

of the field no longer coincide, indicating a clear breakdown of the scaling rule. Equivalent results are obtained for sample B45. This is seen in Fig. 3(b), where the IL is shown for a configuration where the tracks are parallel and perpendicular to the applied field. Here, for both experiments the sample was mounted with an identical orientation of the ab plane with respect to the applied field ($\vartheta = \pm 45^\circ$). Thus, any difference in the IL can only arise due to the different orientation of the tracks with respect to the applied field. This also proves that the breakdown of the scaling ansatz in sample B00 is not influenced by shape effects, which would arise from the different orientation of the sample with respect to the applied field. For $B \gg B_\Phi = 2$ kG the IL's for both orientations fall on top of each other, whereas at low fields the IL for the tracks perpendicular to the field is significantly lower than for the configuration with the field parallel to the tracks. However, in contrast to the reference sample (Fig. 2), in the presence of columnar defects and for $B \lesssim B_\Phi$ the IL is not consistent with the proposed scaling rule given in Eq. (3), since in both irradiated samples the scaled curves do not coincide. This is most clearly seen in Fig. 4, where for each sample the ratio of the irreversibility field as measured for two orientations is plotted as a function of temperature. As expected from the scaling rule given in Eq. (3) for the reference sample the ratio $b_1(T) = B_{\text{irr}}(T, 45^\circ)/B_{\text{irr}}(T, 90^\circ) = \sqrt{2}$ is independent of temperature. In contrast to expectations of the scaling given in Eq. (3), for the irradiated samples B00 and B45 the ratio $b_2(T) = B_{\text{irr}}(T, 45^\circ)/B_{\text{irr}}(T, 90^\circ)$ and $b_3(T) = B_{\text{irr}}(T, +45^\circ)/B_{\text{irr}}(T, -45^\circ)$, respectively, shows a characteristic temperature dependence. For $T = T_1 \simeq 78$ K, a distinct maximum is resolved, which coincides with that temperature where a clear kink in the IL is observed (see Figs. 1 and 3). First, we consider the region $T < T_1$, where the quantity $b_2(T)/\sqrt{2}$ (b_3 for sample B45) is decreasing and reaches 1 for $T \lesssim 40$ K, which is the value expected from the scaling ansatz given in Eq. (3). This shows that disorder in the vortex arrangement is becoming less correlated in this region, which could arise for one of two reasons. One possibility is that at low temperatures, where the influence of thermal fluctuations diminishes, the effectiveness of the intrinsic isotropic pinning sites increases. In this case one would expect the IL's of the irradiated and pristine samples to rapidly converge as the temperature is lowered. An alternative explanation is that the effect of the columnar defects become more isotropic as the field is increased above the matching field, leading to increasingly uncorrelated disorder. In order to distinguish between these two effects we consider the IL's in the irradiated samples for different orientations of the field relative to the track direction. By referring to Fig. 3 we note that for $B \gg B_\Phi$ the IL's of the irradiated samples approach one another, independent of the field orientation with respect to the columnar defects. Since for the case of the tracks orientated perpendicular to the field these defects act only as pointlike pinning centers, this demonstrates that for all orientations the disorder is uncorrelated. By further noting that all of these IL's lie above that of the unirradiated sample, this demonstrates that this additional uncorrelated disorder is largely due to the presence of the tracks. We thus conclude that for $B > B_\Phi$ the effect of the columnar defects becomes increasingly isotropic. We further note that even for $B \approx B_\Phi$ the failure of the scaling rule indicates a significant influence of anisotropic pinning, and it is only for $B \gg B_\Phi$ that the isotropic scaling is fully recovered. Now we consider the region $T > T_1$, where $b_2(T)/\sqrt{2}$ (b_3 for sample B45) also falls from its peak value at T_1 and approaches a value of 1 as $T \rightarrow T_c$. Here we may roughly identify the experimentally determined T_1 as the depinning temperature where the thermal energy becomes comparable to the pinning energy, so that the flux lines start to delocalize from the columnar defects.^{13,14} Thus the effect of the correlated disorder, i.e., anisotropic pinning, is decreasing as the temperature is increased toward T_c . However, although the effect of the anisotropic pinning decreases rapidly for $T > T_1$, there is still evidence for some influence of the artificial defects even close to T_c (see also inset of Fig. 1).

FIG. 5. Angular dependence of the irreversibility line (IL) $B_{\text{irr}}(\vartheta) \sin \vartheta$ of sample B45 and the unirradiated reference sample at $T = 70.5$ K and 65 K, respectively. For the reference sample excellent agreement of the IL with the expectations of the scaling behavior Eq. (3) is observed, while for sample B45 a distinct maximum at $+45^\circ$ is observed, while the tracks are parallel to the applied field. The large angular width of this peak demonstrates that the flux lines can accommodate to the tracks even when the field is applied at a large angle. This reflects the extreme softness of the flux lines in this highly anisotropic material. The minimum which occurs around $\vartheta = 0^\circ$ is due to the reduced effect of the tracks as the penetrating flux threads preferentially along the ab plane of the layered crystal structure.

radiated sample, this demonstrates that this additional uncorrelated disorder is largely due to the presence of the tracks. We thus conclude that for $B > B_\Phi$ the effect of the columnar defects becomes increasingly isotropic. We further note that even for $B \approx B_\Phi$ the failure of the scaling rule indicates a significant influence of anisotropic pinning, and it is only for $B \gg B_\Phi$ that the isotropic scaling is fully recovered. Now we consider the region $T > T_1$, where $b_2(T)/\sqrt{2}$ (b_3 for sample B45) also falls from its peak value at T_1 and approaches a value of 1 as $T \rightarrow T_c$. Here we may roughly identify the experimentally determined T_1 as the depinning temperature where the thermal energy becomes comparable to the pinning energy, so that the flux lines start to delocalize from the columnar defects.^{13,14} Thus the effect of the correlated disorder, i.e., anisotropic pinning, is decreasing as the temperature is increased toward T_c . However, although the effect of the anisotropic pinning decreases rapidly for $T > T_1$, there is still evidence for some influence of the artificial defects even close to T_c (see also inset of Fig. 1).

A further test for the anisotropic pinning properties of columnar defects comes from the angular dependence of the IL. Since the irreversibility field is sharply increasing for the applied field turning towards the ab plane, we

focus here on the sample B45, where the tracks are at 45° with respect to the ab plane. In Fig. 5 the quantity $q(\vartheta) = B_{\text{irr}}(\vartheta) \times \sin \vartheta$ measured at a fixed temperature $T = 70.5$ K is shown as a function of the sample orientation ϑ . For comparison, the same quantity is also plotted for the reference sample at $T = 65$ K, and is found to be independent of ϑ over all angles $5^\circ < \vartheta < 90^\circ$ investigated, as expected from Eq. (3). In contrast to the reference sample, for sample B45 $q(\vartheta)$ depends strongly on ϑ , in contradiction to the expectations of scaling rule given in Eq. (3). In particular, we note, that the angular dependence of $q(\vartheta)$ is asymmetric with respect to the ab plane, showing a pronounced maximum at $\vartheta = +45^\circ$, where the applied field is parallel to the defects. This suggests that for this particular configuration the flux lines are locked completely along the defects. Indeed, for $B_{\text{irr}} < B_\Phi$ an upper limit of the crossover field B_{cr} between the single-vortex pinning and the many-vortex pinning regime is given by $B_{\text{irr}}(T)$, with which an estimation of the trapping angle $\theta_t \approx \sqrt{B_{\text{cr}}/B_\Phi}$ can be made.¹⁴ For $T = 70.5$ K we obtain $\theta_t \approx 25^\circ$, a value which corresponds approximately to the half-width of the peak in the angular dependence of q (see Fig. 5). Following these arguments, we further note that for temperatures $T > T_1$, where the IL drops abruptly, the trapping angle is substantially reduced. This is also clear from the temperature dependence of the scaling behavior of the IL given above. For $T > T_1$ the flux lines start to delocalize from the tracks and the anisotropic scaling is recovered. An additional minimum in the angular dependence of the scaled IL is also seen around $\vartheta = 0^\circ$. This arises because for fields applied close to the ab plane the flux lines accommodate to the layered crystal structure of BSCCO, thus rendering the columnar defects ineffective.

The deviation from the scaling behavior Eq. (3) is obviously a direct consequence of the anisotropic pinning due to the presence of columnar defects. In contrast to the reference sample with weak isotropic pinning, in the irradiated samples the IL is not only determined by the projection of the applied field to the c direction, as predicted by the simplified scaling ansatz, but also by the orientation of the columnar defects with respect to the applied field. This implies that the columnar defects give rise to a correlation of flux lines vortices along the defect. The gradual decrease of $b(T)$ with decreasing temperature shown in Fig. 4 suggests a gradual crossover from anisotropic to isotropic pinning for fields $B > B_\Phi$ or $T_1 < T \rightarrow T_c$. We note especially that the angular asymmetry is not only visible in a narrow angular regime when the tracks are parallel to the applied field, but it is extended up to field orientations far away from the tracks. This is a direct consequence of the large effective-mass

anisotropy of BSCCO, which causes an extreme reduction of the line tension. This allows flux lines to accommodate partially to the defects, even for a large angle between the applied field and the tracks.

IV. SUMMARY

In this work we have presented a detailed study of the IL in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals with columnar defects either in the c direction or at 45° with respect to the ab plane. In the unirradiated crystal with isotropic pinning the predicted scaling rule for isotropic disorder was found to be well obeyed, whereas for the irradiated samples strong deviations from this scaling behavior were observed. This gives clear evidence for the presence of anisotropic pinning, which is most pronounced at a temperature T_1 , where also a kink in the IL is observed. In particular, we have shown that in contrast to weak isotropic pinning, the anisotropic pinning arising from columnar defects strongly depends on temperature and field. For the region $T < T_1$ and $B \gg B_\Phi$, the influence of columnar defects has been shown to become isotropic, whereas for $B < B_\Phi$ the defects give rise to correlated disorder along the track directions. For $T > T_1$, the effectiveness of anisotropic pinning has been shown to decrease toward T_c , as thermally induced fluctuations cause increasing delocalization of the vortices. We have also shown that the columnar defects affect significantly the vortex structure, even for large angles between the track direction and the applied field. This is not unexpected given the extreme softness of the flux lines in this highly anisotropic material. In summary, important information has been obtained on the competition between isotropic and anisotropic disorder in a high- T_c material in the presence of columnar defects. This has been obtained by considering only simple scaling arguments, which provide a powerful method with which to probe the presence of correlated disorder independent of any specific theory for the disordered phase.

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