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Effects of crossed columnar defects on vortex pinning in $Bi_2Sr_2CaCu_2O_8$

V. Hardy[a], S. Hébert, J. Provost, and Ch. Simon

Laboratoire CRISMAT[b], ISMRA et Université de Caen, 6 boulevard du Maréchal Juin, 14050 Caen Cedex, France

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Abstract. To investigate the existence of a splay effect in $Bi_2Sr_2CaCu_2O_8$ (Bi-2212), vortex pinning has been studied in different configurations of strongly inclined columnar defects (75° from the *c* axis), installed by heavy-ion irradiation. It is shown that the symmetry of the track setting with respect to the field direction is a more influent parameter than the presence of a dispersion in the track directions. We claim that the enhanced pinning efficiency which is observed in some splayed configurations of columnar defects in Bi-2212 can be interpreted without invoking a splay effect.

PACS. 74.60.Ge Flux pinning, flux creep, and flux-line lattice dynamics – 74.60.Jg Critical currents – 74.72.Hs Bi-based cuprates

1 Introduction

In high-T_c superconducting oxides, it has been theoretically predicted that the vortex pinning associated with columnar defects can be improved by splaying them around the *c* axis [1,2]. This expectation is connected to both a slowing down of the creep at low currents and an overall entanglement of the vortex ground state. Pinning enhancements related to such splay effects have been experimentally observed in compounds of moderate anisotropy such as $YBa_2Cu_3O_7$ (YBCO) [3–6].

The occurrence of a similar effect in very anisotropic compounds like $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) is far from being so clear. First of all, it must be emphasized that the existence of a splay effect basically supposes a vortex line behavior which is not obvious in such compounds, even in the presence of columnar defects, owing to the weakness of the intrinsic pancake coupling along *c*. A great deal of work has been recently devoted to this question, in the particular case of the reversible regime when the field and the tracks are parallel to the *c* axis [7]. The irreversible regime when the field and the tracks are no longer parallel to each other is probably a still more complex situation, and it has received much less attention up to now.

From an experimental point of view, the existence of a splay effect in Bi-2212 is also very controversial. Indeed, splayed configurations in Bi-2212 yield pinning improvements relative to parallel configurations of tracks oriented along *c* only for very high irradiation angles, larger than 45° [5]. On the one hand, this feature is not inconsistent with theoretical expectations regarding the influence of the electronic anisotropy on the splay effect [2]. On the other hand, it must be emphasized that such very large tilting angles modify important parameters relevant to pinning, in addition to the angular dispersion itself. In particular, the increase of the track sections in the *ab* planes enhances the elementary pinning energy [8], which in turn can improve macroscopic pinning properties such as the persistent current densities [9]. Therefore, it becomes delicate to distinguish the role of the disorientation between the tracks from the one of their inclination with respect to *c*.

In a previous experiment [10], we have compared the pinning efficiencies in Bi-2212 crystals containing either only one direction of highly angled tracks ($n = 1$) or tracks inclined at the same angle and symmetrically distributed around *c* (2 or 3 directions, referred to as $n = 2$ and $n = 3$, respectively). In $n = 1$, all the tracks are parallel, so one cannot expect any splay effect. We have found evidence for a regime, at high temperatures and low fields, where the pinning efficiency of all these tilted configurations is higher than that of a parallel to *c* configuration. This result can be ascribed to the enlargement of the track sections in the *ab* planes. At higher temperatures, there is another regime where the pinning efficiency has been found to be smaller in $n = 1$ than in $n > 1$ [10]. This last feature, however, is not necessarily related to the presence of track crossings for $n > 1$. Indeed, these configurations are also characterized by an accommodation ability of linelike vortices to the defects which is better than that of $n = 1$, owing to the symmetry of the track distribution around the field direction.

The purpose of the present study is to try to separate the influence of the splay effect from the one of

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[a] e-mail: `vincent.hardy@ismra.fr`

[b] UMR 6508

accommodation phenomena. Preliminary results of this study have been reported in reference [11].

2 Experiment

Bi-2212 single crystals were grown by a self-flux method, leading to slightly overdoped samples. In the virgin state, the T_c values of the samples used in this study range between 82.5 and 84 K. They have been irradiated with 6 GeV-Pb ions at GANIL (Caen, France). We have considered a large irradiation angle $\theta_i = 75°$ from the c axis, for which clear pinning enhancements with respect to irradiations parallel to c have been observed [5,9]. Care was taken to use thin enough crystals in order to ensure the creation of amorphous latent tracks over their whole thickness (about 15 μm). According to high resolution electron microscopy investigations, the amorphous core of the tracks in these conditions has an average diameter equal to 9 nm [12]. All the samples have been irradiated at a fluence of 5×10^{10} cm^{-2}, corresponding to an equivalent field $B_\Phi = 1$ T. The magnetic studies, before and after irradiation, have been carried out with the field applied along the c axis. Owing to the irradiation angle, it must be specified that the "effective" equivalent field, for which the track and vortex densities in the ab planes are equal, is $B_{cd} = B_\Phi \cos\theta_i$, *i.e.* about 0.25 T in the present case.

We have studied three track configurations depicted in Figure 1. All of them contain only tracks inclined at 75° from c. The characteristic size of the defects in the ab planes (R_{ab}), as well as their planar density (B_{cd}/Φ_0) are thus exactly the same in all cases. In the configuration $n = 1$, there is just one irradiation direction, yielding a track setting without crossings. In $n = 2$, both irradiation directions lie in a plane containing the c axis. This track distribution is symmetric with respect to the direction of the applied field. We have compared these configurations – already investigated in reference [10] – to a new configuration labelled $n = 2^*$. This configuration involves two track directions like $n = 2$. It has also been tailored in such a way that the density of track crossings is exactly the same as in $n = 2$ (see the Appendix). The irradiation angle θ_i, the number of track directions, and the density of track crossings are thus identical in $n = 2$ and $n = 2^*$. The only difference is about the symmetry of the track distribution with respect to the direction of the field. Actually, the configuration $n = 2^*$ is very close to $n = 1$ about this question of symmetry, since the plane containing the tracks of $n = 2^*$ is nearly at 75° from the c axis (see the Appendix). The accommodation abilities in $n = 1$ and $n = 2^*$ are thus nearly the same.

The comparison of $n = 2^*$ with both other configurations can provide us with qualitative informations about the relative influences of two important parameters relevant to vortex pinning. Firstly, the comparison of $n = 2^*$ with $n = 2$ can reveal the influence of the symmetry of the track distribution relative to the field direction. This feature is itself related to the question of vortex accommodation to columnar defects. Secondly, the comparison of $n = 2^*$ with $n = 1$ can reveal the specific role of the track crossings, an issue which is basically related to the splay effect.

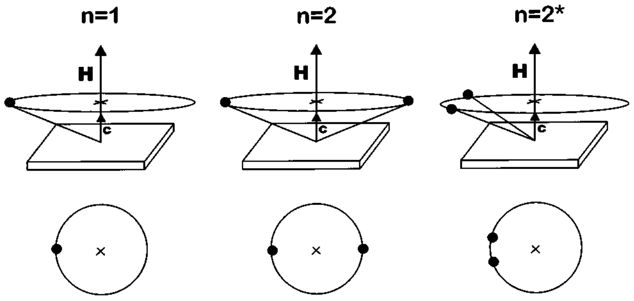

Fig. 1. Schematic description of the three configurations of inclined columnar defects investigated in this study. All the track directions are tilted by the same angle θ_i from the c axis. The lower panel displays the azimuthal angle(s) φ in the plane perpendicular to H and c.

The pinning properties of each sample have been investigated by SQUID (superconducting quantum interference device) magnetometry, before and after irradiation, with the magnetic field applied along the c axis. Hysteresis loops have been recorded with a waiting time of 3 min after each field change. Thermoremanent curves have also been recorded, starting from both branches of the loop at 5 K. The field and temperature dependences of the persistent current density, J, have been derived from these measurements by using the Bean model. The procedure used to ensure a reliable comparison between all the samples has been detailed in reference [5].

3 Results and discussions

The main features observed in the J-*vs.*-H curves are summarized in Figure 2. At low temperatures ($T \leq 40$ K), the $J(H)$ curves of the three configurations depicted in Figure 1 are well superimposed. A very contrasted behavior emerges at higher temperatures ($T \geq 50$ K). In this case, the J values in the configuration $n = 2$ are larger than those of configurations $n = 1$ and $n = 2^*$, while the latter remain very close to each other. We have used two samples for $n = 2$ as well as for $n = 2^*$, which exhibit the good reproducibility of these results. One can also note that the present data about $n = 1$ and $n = 2$ are very well consistent with those previously obtained in reference [10].

The new results deal with the configuration $n = 2^*$. Firstly, the close similarity between $n = 1$ and $n = 2^*$, in the high-T regime, shows that the existence of track crossings has not, in itself, a significant influence on the pinning efficiency. Secondly, the great difference observed between $n = 2$ and $n = 2^*$ demonstrates that the symmetry of the track distribution plays a determinant role. Qualitatively identical results have been obtained in another set of samples with $\theta_i = 60°$, a situation for which the disorientation angle between both directions of $n = 2^*$ is much larger, *i.e.* about 70° instead of 31° for $\theta_i = 75°$ (see the Appendix).

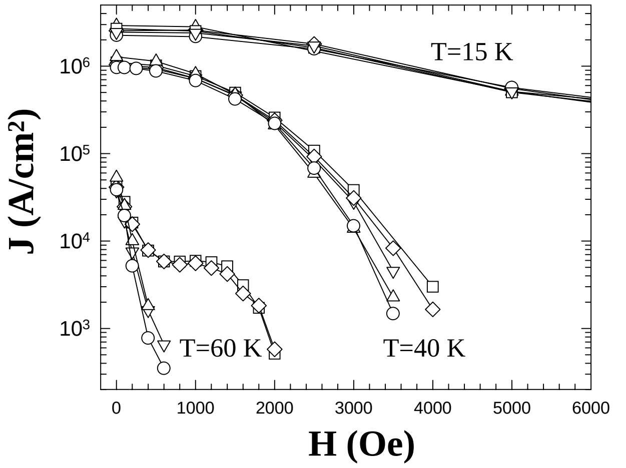

Fig. 2. Field dependence of the persistent current density, at various temperatures, in the configurations of columnar defects depicted in Figure 1, for $\theta_i = 75°$ and $B_\Phi = 1$ T: $n = 1$ (◯); $n = 2$ (□ and ◊); $n = 2^*$ (△ and ▽).

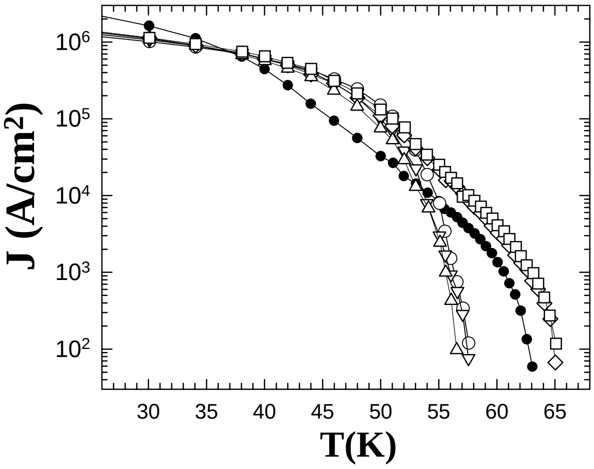

Fig. 3. Temperature dependence of the persistent current density, under 0.1 T, in various configurations of columnar defects, corresponding to the same ion fluence, $B_\Phi = 1$ T. We have compared a configuration of tracks parallel to c (●) with the three configurations of tracks tilted at $\theta_i = 75°$ which are depicted in Figure 1: $n = 1$ (◯); $n = 2$ (□ and ◊); $n = 2^*$ (△ and ▽).

The existence of a crossover temperature separating two very different pinning regimes has been already observed in angular studies on Bi-2212 crystals containing one direction of inclined columnar defects (configuration $n = 1$) [13,14]. At low-T, the pinning efficiency is essentially the same when the field is applied along the tracks or in the symmetric orientation outside the tracks. Above about 50 K, the pinning efficiency becomes much larger in the aligned configuration. We have proposed an interpretation involving the accommodation ability of linelike vortices to the columnar defects [14]. At low-T, the vortices in the misaligned configuration could zigzag between the tracks and the *ab* planes, yielding an overall pinning efficiency similar to that of the aligned configuration. Such an accommodation cannot hold at too high temperatures, *i.e.* when the linear pinning energy becomes too small to counterbalance the elastic energy related to vortex distortions. This results in a pinning efficiency which becomes smaller than in the aligned orientation, for which a linear trapping of the vortices is still possible. In this approach, the merging of all J-*vs.*-H curves approaching zero field can be well accounted for by a flux-flop phenomenon [13,14]. Another explanation has been proposed in terms of activation energy [15,16]. According to Brandt [17], a crossover can occur between the 3D form of the activation energy, which decreases as J increases, and the current-independent 2D form. At low-T, *i.e.* when J is large enough, it is supposed that the relevant activation process just involves one pancake, which leads to similar relaxation effects for all orientations of field with respect to the tracks.

In the present study, the low-T regime where the pinning efficiency is independent of the track configuration can be equally well accounted for in the frame of both above-mentioned models. At high temperatures, the existence of different pinning behaviors demonstrate that the vortices do not behave as decoupled pancakes in all configurations. One can even state that the vortices act as linelike objects in the configuration $n = 2$. It is admitted in the literature that there is a vortex line behavior at high-T in Bi-2212 when the field is applied along the tracks [13,14,16,18]. The present study demonstrates that such a line behavior also holds with two track directions strongly misaligned with the field, provided that they are symmetrically distributed around it. Each vortex can either be linearly trapped along one of the tracks or zigzag between crossed tracks, both arrangements keeping the internal field parallel to c. The nature of the vortex state at high-T in the configurations $n = 1$ and $n = 2^*$ cannot be unambiguously determined. The first possibility consists of linelike vortices only partly accommodated to the tracks, resulting in a reduced pinning effect. In this case, the negligible role of the track crossings attested to by the similarity between $n = 1$ and $n = 2^*$ can be ascribed to easy vortex cutting owing to the large electronic anisotropy [19]. Alternatively, the vortex state at high-T in these misaligned configurations could be characterized by individual pinning of pancake vortices, yielding in a small activation energy. The absence of crossing effect is obvious in this case.

The crossover in temperature suggested in Figure 2 can be suitably studied in J-*vs.*-T curves. Such curves under 0.1 T ($< B_{cd}$) are shown in Figure 3, in the three configurations of Figure 1. At low temperatures, the J values are the same within experimental uncertainties in $n = 1$, $n = 2$ and $n = 2^*$. The curve of $n = 2$ separates from those of $n = 1$ and $n = 2^*$ around 50 K. Although it always remains close to this value, this crossover temperature tends to increase as the field is decreased. One can see in Figure 3 that the temperature for which J drops to zero is significantly larger for $n = 2$ than for $n = 1$ or $n = 2^*$. This shift in the depinning temperature clearly demonstrates the higher pinning efficiency of the configuration $n = 2$.

Let us now compare these highly angled configurations to the case of an irradiation along c, at the same fluence. In such a parallel configuration, the characteristic size of the track projections on the ab planes (R_{ab}) is smaller than in the previous cases, which leads to a lower individual pinning energy [8,9]. On the other hand, the planar track density in the ab planes is larger, which is beneficial to the pinning capability. This last difference could explain that the J values at low temperatures (below about 35 K) are higher in the parallel configuration than in the configurations $n = 1$, $n = 2$ and $n = 2^*$ [9]. Between about 40 and 50 K, the J values of the parallel configuration become smaller than those of the tilted configurations, these latter being still superimposed. This feature can be ascribed to the larger pinning energy of the inclined configurations related to the larger R_{ab} value [8,9]. Above 55 K, the curve of the parallel configuration crosses those of $n = 1$ and $n = 2^*$. This new feature can be attributed to the fact that the accommodation of vortex lines to the tracks is no longer possible in these latter cases. On the other hand, the J-*vs.*-T curve of $n = 2$ remains above the one of the parallel configuration, since vortex accommodation in this symmetric configuration can persist up to high temperatures, which allows to take advantage of the higher individual pinning energy.

4 Conclusion

In Bi-2212 single crystals, the pinning efficiencies of various configurations of columnar defects inclined at large angle $\theta_i = 75°$ from the c axis have been compared. Our goal was to determine whether the pinning improvement which can be observed with *splayed configurations* in Bi-2212 is actually related to a genuine *splay effect*, as described in theoretical works and experimentally observed in weakly anisotropic compounds.

To get evidence for a true splay effect, we consider that, at least, two conditions must be fulfilled: (i) a larger pinning efficiency than in a parallel to c configuration at the same fluence, *i.e.* the same volumic fraction of amorphized material; (ii) a larger pinning efficiency in the presence of track crossings than in a reference configuration containing parallel tracks inclined at the same angle from c.

According to these requirements, it was shown that a splay effect in Bi-2212 can only be invoked in a very restricted domain of high temperatures, *e.g.* T higher than about 55 K for $\theta_i = 75°$. However, even in this case, the relevancy of a splay effect is still questionable. Indeed, we have observed that the presence of track crossings does not play a significant role in itself. Actually, the enhanced pinning efficiency observed in symmetric distributions of splayed defects at very large angles can be accounted for by the combined effects of a larger individual pinning energy (related to the track inclination), and a high accommodation ability (related to the symmetry of the distribution around the field direction).

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Appendix

Let us calculate the azimuthal angle φ between the track directions in a configuration $n = 2^*$, yielding the same density of track crossings as in the configuration $n = 2$. According to reference [10], this density just depends on $\sin \varDelta$, where $\varDelta$ is the crossing angle between the two track directions which is given by

$$\cos \varDelta = \sin^2 \theta_i \cos \varphi + \cos^2 \theta_i . \tag{A.1}$$

Since $\varDelta = 2\theta_i$ for $n = 2$, the required value for φ is defined by the condition $\varDelta(\theta_i, \varphi) = \pi - 2\theta_i$, leading to

$$\varphi = \arccos \left[3 - (2/\sin^2 \theta_i) \right] . \tag{A.2}$$

Solutions only exist for $45° < \theta_i < 90°$.

In a configuration $n = 2^*$, the misalignment angle ψ between the c axis and the plane containing both track directions is equal to

$$\psi = \arcsin \left[\frac{\sin^2 \theta_i \sin \varphi(\theta_i)}{\sin 2\theta_i} \right] , \tag{A.3}$$

with $\theta_i = 75°$, $\varphi \simeq 31.1°$ and $\psi \simeq 74.5°$.

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