Accommodation of vortices to tilted line defects in high-T_c superconductors with various electronic anisotropies

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Columnar defects (CD's) inclined at 45° from the c axis have been introduced in single crystals of different compounds: $Bi_2Sr_2CaCu_2O_8$, $Tl_2Ba_2CaCu_2O_8$, $Tl_2Ba_2Ca_2Cu_3O_{10}$, $Tl_{2/3}Bi_{1/3}Sr_2CaCu_2O_7$, and $YBa_2Cu_3O_7$. In each case, hysteresis loops have been recorded with the magnetic field parallel to the columns ($\vec{H}_a \| \mathrm{CD}$) and perpendicular to them ($\vec{H}_a \perp \mathrm{CD}$). Two regimes are evidenced: an isotropic pinning enhancement [$J_c(\vec{H}_a \perp \mathrm{CD}) \equiv J_c(\vec{H}_a \| \mathrm{CD})$] at low temperatures and a directional effect [$J_c(\vec{H}_a \perp \mathrm{CD}) < J_c(\vec{H}_a \| \mathrm{CD})$] at higher temperatures. The isotropic regime is ascribed to the occurrence of a ''totally adjusted'' state where the vortices zigzag between the CD's and the ab planes, keeping their mean direction along the applied field. An analysis is proposed for the crossover between these two regimes, which accounts for the observed influences of the temperature and electronic anisotropy. The vanishing of the difference between the two configurations at zero field is discussed in terms of a complete reorientation of the vortices along the CD's in the case $H_a \perp \mathrm{CD}$. [S0163-1829(96)03625-9]

I. INTRODUCTION

The dimensionality of the vortex state in high-T_c superconductors (HTSC's) is a point of a crucial importance in the phenomenology of their transport properties and is still a subject of intense activity. Among the numerous ways of addressing this problem, columnar defects (CD's) induced by heavy-ion irradiations have already been used to probe the longitudinal correlations of vortices: After the introduction in single crystals or thin films of CD's at an angle θ_i with respect to the c axis, the critical current density J_c is recorded with the magnetic field applied along the columns, $\theta = +\theta_i$, and for the symmetrical configuration $\theta = -\theta_i$. Since these two configurations are strictly equivalent regarding the geometrical and intrinsic anisotropies, comparison of the pinning abilities gives direct insight into the accommodation of the vortices to the tracks. Up to now, one could consider that three major results have been obtained in this type of experiment. First, Civale *et al.*[1] have reported a larger pinning enhancement for $\theta = +\theta_i$ than for $\theta = -\theta_i$ in $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals. According to this result, the authors claimed the occurrence of an alignment effect of the vortices with the columns for $\theta = +\theta_i$ and not for $\theta = -\theta_i$. It is implicitly assumed that one deals with straight vortex lines whose direction inside the sample is essentially driven by the external magnetic field. A study in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) single crystals was carried out by Thompson *et al.*[2] They reported almost no differences between the configurations $\theta = +\theta_i$ and $\theta = -\theta_i$, and ascribed this result to the two-dimensional (2D) nature of the vortex state in Bi-2212 related to the high anisotropy of this compound. Indeed, if the vortex state consists in completely decoupled 2D pancakes, no directional pinning enhancement can be expected. More recently, this quite clear situation with a sharp contrast between a ''3D'' YBCO and a ''2D'' Bi-2212 has been reopened by a study on this latter compound. Klein *et al.*[3] have reported in Bi-2212 a larger pinning efficiency for $\theta = +\theta_i$ than for $\theta = -\theta_i$ at high temperatures, namely, above 40–50 K. This effect of unidirectional enhancement was considered as a proof of the ''line nature'' of the vortices in Bi-2212. Nevertheless, the peculiar temperature dependence of this line behavior remains still obscure.

Thus it appears that not only the electronic anisotropy, but also the temperature should play important roles in the occurrence of directional pinning enhancements. Consequently, we have investigated, in the present study, the question of such directional effects over a wide range of temperature in various compounds with different anisotropies: $Bi_2Sr_2CaCu_2O_8$ (Bi-2212), $Tl_2Ba_2CaCu_2O_8$ (Tl-2212), $Tl_2Ba_2Ca_2Cu_3O_{10}$ (Tl-2223), $Tl_{2/3}Bi_{1/3}Sr_2CaCu_2O_7$ [(Tl,Bi)-1212], and $YBa_2Cu_3O_7$ (YBCO).

Another interesting phenomenon is present in magnetic studies with such inclined defects: In all cases, even in the presence of a directional enhancement, the pinning abilities of the aligned and misaligned configurations tend to merge when the field is decreased towards zero and the remanent magnetizations reach the same value. This effect has been addressed by Klein *et al.*,[4] considering, for the configuration $\theta = -\theta_i$, a flux flop of the vortices towards CD's below a crossover field. Once again, important qualitative differences have been observed between YBCO and Bi-2212,[5] and thus we have also focused our attention on this flux-flop effect for the different compounds investigated in the present study.

II. EXPERIMENTAL DETAILS

Experimental data dealing with both the crystal growth procedure[6–10] and T_c's observed after irradiation are given in Table I for the five compounds. The irradiations were performed at room temperature at the national heavy-ion accelerator GANIL (Caen). The samples have been mounted in

TABLE I. References reporting the crystal growth process and the T_c value after irradiation for the five investigated compounds.

Name	Compound	Reference	T_c (K) after irradiation
Bi-2212	$Bi_2Sr_2CaCu_2O_8$	6	80
Tl-2212	$Tl_2Ba_2CaCu_2O_8$	7	97
Tl-2223	$Tl_2Ba_2Ca_2Cu_3O_{10}$	8	120
(Tl,Bi)-1212	$Tl_{2/3}Bi_{1/3}Sr_2CaCu_2O_7$	9	80
YBCO	$YBa_2Cu_3O_7$	10	90.5

order to be irradiated along a well-defined direction at 45° with respect to the c axis. All the compounds have been irradiated by 6-GeV Pb ions at a fluence of 10^{11} cm^{-2}. In addition, two of them have been also irradiated by 6-GeV U ions at a fluence of 3.5×10^{10} cm^{-2}.

Several high-resolution electron microscopy investigations have been previously performed on samples of almost all the present compounds [except (Tl,Bi)-1212] irradiated by these same ions.[6,11,12] It has been shown that columnar defects with diameters close to 100 Å are created in all cases, even when the incident direction of the ions is not along c.

The pinning properties of the irradiated single crystals have been studied by superconducting quantum interference device (SQUID) magnetometry. Hysteresis loops at different temperatures have been recorded for three orientations of the applied magnetic field $\vec{H}_a$: First, for $\vec{H}_a$ along the direction of the CD's; second, still for $(\vec{H}_a,c)=45°$, but along the symmetrical direction; and finally for $\vec{H}_a$ along the c axis (see Fig. 1). Note that with this particular value $\theta_i=45°$ the ''misaligned'' configuration leads to $\vec{H}_a$ being applied perpendicularly to the CD's. The three configurations will be labeled $\vec{H}_a\|$CD, $\vec{H}_a\perp$CD, and $\vec{H}_a\|c$, respectively. The adjustment of the angle $\theta=(\vec{H}_a,c)$ was achieved *ex situ* by means of a homemade rotating sample holder. It consists essentially of a small cylinder inserted in the usual sample rod, in such a way that its rotating axis is perpendicular to the magnetic field. The crystal is fixed inside the cylinder on a platform. Centering rings are attached at the two extremities of the sample rod to limit its bending inside the sample

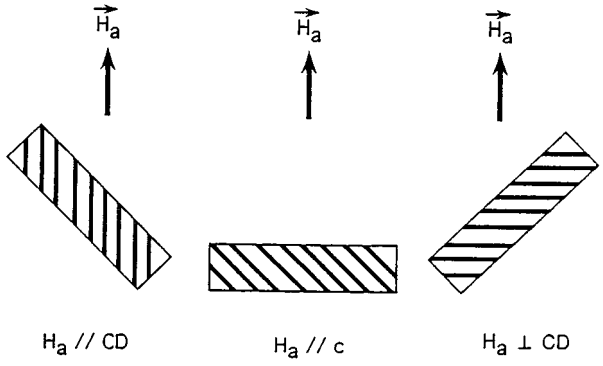

FIG. 1. Schematic representations of the three investigated configurations. The crystals have a platelike shape with the shortest dimension along the c axis. The columnar defects (CD's) are continuous cylinders inclined at 45° with respect to the c axis. The vector $\vec{H}_a$ is the applied magnetic field.

space. Finally, the required rotation of the cylinder is optically adjusted. Of course, this *ex situ* procedure cannot lead to a very high accuracy of the angular control. The $\vec{H}_a\|c$ measurements are not very sensitive to this uncertainty, but it can be more delicate for the measurements $\theta=\pm45°$. Thus we have systematically checked *a posteriori* these adjustments by using the fact that the initial slope of the virgin magnetization curve is a univocal function of θ.[13] The adjustments have been repeated until reaching, on the basis of such shielding measurements, a deviation smaller than 3° in the angle values. Since the angular dependence of J_c remains rather smooth (even around the CD's direction when a J_c peak exists[14]), one can reasonably consider that the obtained measurements are actually representative of the configurations $\vec{H}_a\|$CD and $\vec{H}_a\perp$CD.

The hysteresis loops have been analyzed by the Bean model to extract the values of the critical current density J_c. It has been assumed that, because of the geometrical and intrinsic anisotropies of the samples, the irreversible magnetization is always pointed along c whatever the $\vec{H}_a$ direction.[4] Thus the measured ΔM values in the cases $\vec{H}_a\|$CD and $\vec{H}_a\perp$CD have been multiplied by $\sqrt{2}$ to derive J_c. Moreover, the J_c curves are presented as a function of $H_a^{\|}$, the component of the applied field along the c axis. It will be shown that this choice is relevant to compare the results $\vec{H}_a\|c$ with the others. Anyway, it must be emphasized that the central part of this study, i.e., the comparison between $\vec{H}_a\|$CD and $\vec{H}_a\perp$CD, is absolutely not altered by these scalings.

III. RESULTS

The $J_c(H_a^{\|})$ curves at several temperatures in the configurations $\vec{H}_a\|$CD and $\vec{H}_a\perp$CD are shown in Fig. 2 for the different compounds. For the Tl- and Bi-based compounds, the curves are superimposed at low temperatures and diverge at higher temperatures, exhibiting a better pinning efficiency in the case $\vec{H}_a\|$CD. For YBCO, the curves are always shifted in the whole investigated T range. No data could be recorded at lower T because the two available crystals were broken during loops at 20 K, probably due to a large torque effect. It can be noted in Fig. 2 that, whatever the temperature and compound, the curves $\vec{H}_a\|$CD and $\vec{H}_a\perp$CD coincide at very low fields. This confirms the universality of the so-called flux-flop effect.[4,5] Furthermore, it must be emphasized that, when $J_c(\vec{H}_a\|\text{CD})$ is above $J_c(\vec{H}_a\perp\text{CD})$, there is a true shift of the location of the irreversibility line. Three other points deserve to be outlined.

(i) The results obtained with U ions at another fluence (3.5×10^{10} cm^{-2}) are similar to those presented here: In YBCO, $J_c(\vec{H}_a\|\text{CD})$ are systematically higher than $J_c(\vec{H}_a\perp\text{CD})$ for temperatures down to 30 K, while in Tl-2212 a difference appears only for $T\geqslant40$ K.

(ii) In the case of Bi-2212, measurements at $\theta=45°$ have been performed before irradiation. The direct comparison of these data (Fig. 3) with the measurements $\theta=\pm45°$ after irradiation shows that large pinning enhancements take place even in the case $\vec{H}_a\perp$CD at high temperatures, when

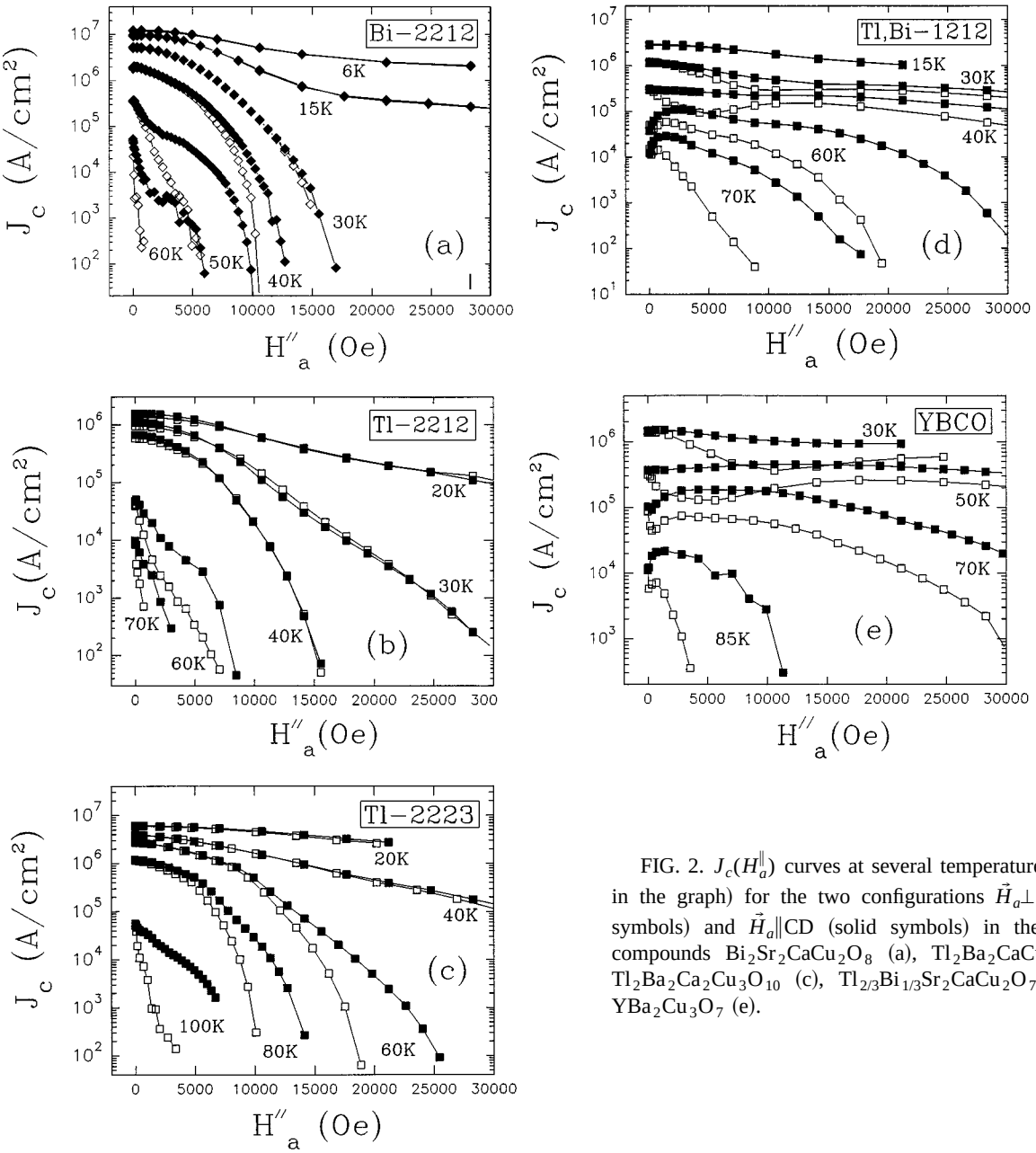

FIG. 2. $J_c(H_a^{\parallel})$ curves at several temperatures (labeled in the graph) for the two configurations $\vec{H}_a \perp$ CD (open symbols) and $\vec{H}_a \parallel$CD (solid symbols) in the different compounds $Bi_2Sr_2CaCu_2O_8$ (a), $Tl_2Ba_2CaCu_2O_8$ (b), $Tl_2Ba_2Ca_2Cu_3O_{10}$ (c), $Tl_{2/3}Bi_{1/3}Sr_2CaCu_2O_7$ (d), and $YBa_2Cu_3O_7$ (e).

$J_c(\vec{H}_a \perp \text{CD})$ is lower than $J_c(\vec{H}_a \parallel \text{CD})$.

(iii) The measurements $\vec{H}_a \parallel c$ provide additional information on the angular dependence of J_c (Fig. 3). First, it is observed that $J_c(\vec{H}_a \parallel c)$ comes to merge the curves $J_c(\vec{H}_a \parallel \text{CD})$ and $J_c(\vec{H}_a \perp \text{CD})$ when they are superimposed. Such a result supports the relevancy of the 2D scaling for this regime. Second, when the pinning efficiencies of the two inclined configurations are different, the curves $J_c(\vec{H}_a \parallel c)$ lie between $J_c(\vec{H}_a \parallel \text{CD})$ and $J_c(\vec{H}_a \perp \text{CD})$. One can observe as a general rule that $J_c(\vec{H}_a \parallel c)$ is a bit closer to $J_c(\vec{H}_a \perp \text{CD})$ than to $J_c(\vec{H}_a \parallel \text{CD})$.

IV. DISCUSSION

Two main observations emerge from the set of data presented above: (1) the existence or the absence of a difference between the curves $J_c(\vec{H}_a \parallel \text{CD})$ and $J_c(\vec{H}_a \perp \text{CD})$ depending on both the compound and temperature, and (2) the systematic occurrence of a flux-flop-like effect.

These two points will be discussed separately. The range of very low fields where the flux flop takes place will be considered only in the second part.

A. Directionality of the track-induced pinning enhancement

At first glance, it is tempting to relate the observed difference between YBCO and the other compounds to the value of the electronic anisotropy γ ($\gamma = \xi_{ab}/\xi_c = \lambda_c/\lambda_{ab}$), which is known to be much lower for YBCO. Nevertheless, a crude separation between two classes of materials with high and low γ could be not relevant. We have reported in Fig. 4, for the different compounds, the variation of the angular behavior as a function of the reduced temperature $t = T/T_c$. The

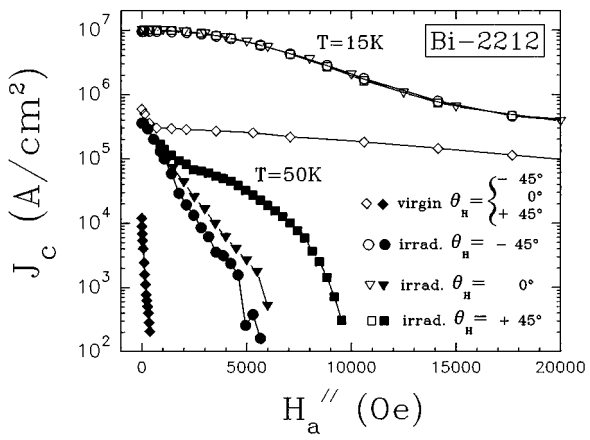

FIG. 3. $J_c(H_a^{\parallel})$ in Bi-2212 for two temperatures (15 K, open symbols; 50 K, solid symbols) and different configurations (indicated in the legend). The angle θ_H is between $\vec{H}_a$ and c. The angle between the CD's and c axis is $\theta_i = +45°$. The configurations $\vec{H}_a \| \mathrm{CD}$ and $\vec{H}_a \perp \mathrm{CD}$ correspond to $\theta_H = +45°$ and $-45°$, respectively.

labels I and D refer to situations where $J_c(\vec{H}_a \perp \mathrm{CD})$ and $J_c(\vec{H}_a \| \mathrm{CD})$ are identical (isotropic effect) or different (directional effect), respectively. The shaded areas denote the temperature ranges where the crossovers are located between these two regimes. In the case of YBCO, no isotropic behavior has been observed and it just can be concluded that the crossover temperature, if it exists, is lower than $t \approx 0.33$. Owing to the overlapping of the crossover ranges, no clear distinction can be made among the Tl and Bi bilayers (Tl-2223, Tl-2212, and Bi-2212). Fortunately, the intermediate location of the crossover range for (Tl,Bi)-1212 gives new insight into the influence of the intrinsic anisotropy. Indeed, according to previous results,[9,15,16] one can remark that the location of the crossover range for the three Tl-based compounds seems to be shifted to lower temperature as the anisotropy

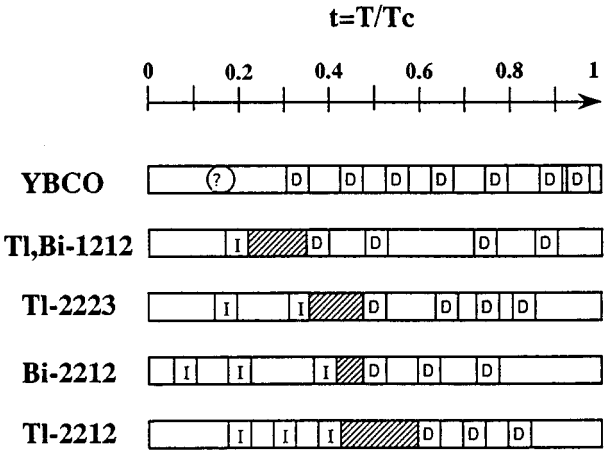

FIG. 4. Isotropic (I) or directional (D) character of the pinning enhancement as a function of the reduced temperature, for the different compounds (see text). The crossovers between (I) and (D) are within the shaded temperature ranges. For YBCO, such a crossover was not evidenced.

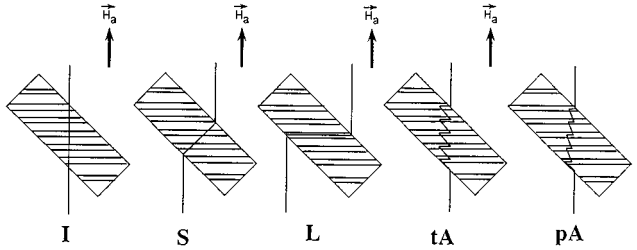

FIG. 5. Schematic representation of the five considered vortex states for the configuration $\vec{H}_a \perp \mathrm{CD}$ (see text). In the pA state, note that the vortex pieces out of the CD's are not in the (ab) planes.

decreases. This observation suggests a continuous evolution of T_{cross} with γ rather than only two classes of materials with 3D or 2D behaviors.

The J_c values reflect the pinning efficiency and therefore, in our case, essentially the accommodation of the vortices to the tracks. The different vortices-track arrangements which appear as the most relevant are the (i) inclined state (I state), characterized by straight vortex lines aligned along the $\vec{H}_a$ direction, (ii) shortened state (S state), characterized by straight vortex lines aligned along the shortest dimension of the crystal, i.e., the c axis, (iii) locked state (L state) for which the vortices are linearly pinned in the CD's, (iv) totally adjusted state (tA state) for which the vortices make kinks between the CD's and ab planes, keeping their mean direction along $\vec{H}_a$, and (v) partially adjusted state (pA state), very close to the above one except that the energy minimization yields vortex pieces out of the (ab) planes to connect the pieces located in the CD's. These different vortex states are schematically depicted in Fig. 5 for the case $\vec{H}_a \perp \mathrm{CD}$. In the case $\vec{H}_a \| \mathrm{CD}$, only the L and S states are actually relevant.

The relation between these vortex arrangements and the J_c values is not straightforward. Nevertheless, one can reasonably consider that the pinning efficiency is closely related to the fraction of vortex length strongly pinned, i.e., in our case located in CD's or in (ab) planes. Within such an assumption, the states L and tA should have the same high pinning efficiency, while the states I and S have the same weaker efficiency. Finally, an intermediate pinning efficiency is expected for the state pA. Now, the problem is to determine what is the actual vortex state for a given $\vec{H}_a$ orientation. Since one investigates the irreversible regime, the use of a thermodynamic function can be questionable. Nevertheless, this is the only available simple approach and it can be noted that it has been already applied to similar problems.[17] In our case, the relevant thermodynamic function is the Gibbs energy[18]

$$G = F - (\vec{B} \cdot \vec{H}_i)/8\pi - \vec{H}_a \cdot (\vec{B} - \vec{H}_i)/8\pi, \qquad (1)$$

where F is the free energy, $\vec{B}$ is the magnetic induction, $\vec{H}_a$ is the external magnetic field, and $\vec{H}_i$ is the internal magnetic field (Maxwell magnetic field). Nevertheless, when comparing two vortex arrangements with the same $\vec{B}$ (vector pointing along the mean direction of the vortices), one can just consider the free energy F or even the energy of a single vortex line E.

The present problem is the existence or not of a difference between $J_c(\vec{H}_a\perp \mathrm{CD})$ and $J_c(\vec{H}_a\|\mathrm{CD})$ for nonzero H_a values. For $\vec{H}_a\|\mathrm{CD}$, it can be assumed that a locked state takes place whatever the compound and temperature. Indeed, the J_c enhancements are very large and the term of magnetic alignment $(G-F)$ allows one to rule out the occurrence of a shortened state for not too small H_a values. Consequently, the question deals solely with the configuration $\vec{H}_a\perp \mathrm{CD}$. To account for the regime of directional enhancement, one can consider the I or S states. Nevertheless, the term of magnetic alignment strongly promotes the I state against the S state. Moreover, as will be shown further, the reduction of vortex length in S is counterbalanced by the increase of vortex line energy. To account for the regime where $J_c(\vec{H}_a\perp \mathrm{CD})\equiv J_c(\vec{H}_a\|\mathrm{CD})$, one can consider the L or tA states. Since the energy cost of the vortex pieces located in the (ab) planes is very small, the tA state which preserves the magnetic alignment between $\vec{B}$ and $\vec{H}_a$ is energetically more favorable than the L state.

Thus, as a first approach, let us just consider the difference of individual vortex energy between the states I [for which $J_c(\vec{H}_a\perp \mathrm{CD})<J_c(\vec{H}_a\|\mathrm{CD})$] and tA [for which $J_c(\vec{H}_a\perp \mathrm{CD})=J_c(\vec{H}_a\|\mathrm{CD})$]. As shown in Fig. 5, a vortex in the I state is just a straight line making an angle $\pi/4$ with respect to c, while in the tA state, it consists of a zigzag line with segments lying successively in (ab) planes and in CD's. As a crude simplification, we will neglect in the I state the interaction energy between a vortex and the CD's. Thus we will consider for this state the intrinsic form of the vortex line energy[19,20]

$$\varepsilon_1(\theta)=\varepsilon_0\varepsilon(\theta)\{\ln[\kappa/\sqrt{\varepsilon(\theta)}]+\alpha_c\}, \tag{2}$$

where θ is the angle between the local vortex direction and the c axis,

$$\varepsilon_0(T)=[\phi_0/4\pi\lambda_{ab}(T)]^2,$$

λ_{ab} is the in-plane penetration depth, ξ_{ab} is the in-plane coherence length, κ is the Ginzburg-Landau parameter $(=\lambda_{ab}/\xi_{ab})$, $\alpha_c\approx 0.5$, and

$$\varepsilon(\theta)=\sqrt{\cos^2\theta+\gamma^{-2}\sin^2\theta}, \tag{3}$$

where γ is the electronic anisotropy $(\xi_{ab}/\xi_c=\lambda_c/\lambda_{ab})$.

For a vortex piece running along a CD, the line energy is modified in two ways: First, the α_c contribution related to the core energy disappears; second, the magnetic energy is changed since the inner edge of the vortex currents is no longer ξ_{ab}, but R, the radius of the CD. Finally, the line energy for a vortex segment located in a CD can be written[20]

$$\varepsilon_p(\theta)=\varepsilon_0\varepsilon(\theta)\{\ln[\kappa/\sqrt{\varepsilon(\theta)}]+\alpha_p\}, \tag{4}$$

with

$$\alpha_p(T)=\ln[\xi_{ab}(T)/R].$$

It can be noted that a pinning effect is expected only when $\alpha_p(T)<\alpha_c$.

Let us consider the energy difference between the two vortex arrangements over one period which corresponds to the mean spacing between the tracks a_Φ:

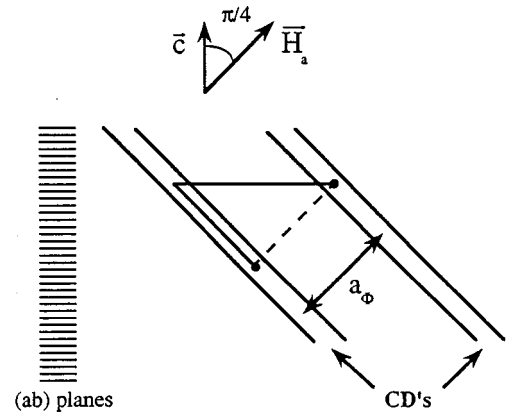

FIG. 6. Schematic representation of the difference, over one CD spacing (a_Φ), between the I and tA states in the case $\vec{H}_a\perp \mathrm{CD}$ (dashed and solid lines, respectively).

$$\Delta E=E(tA\ \text{state})-E(I\ \text{state}).$$

On the basis of Fig. 6, one finds

$$\Delta E=a_\Phi\sqrt{2}\varepsilon_1(\pi/2)+a_\Phi\varepsilon_p(\pi/4)-a_\Phi\varepsilon_1(\pi/4).$$

According to Eq. (3),

$$\varepsilon(\pi/2)=\gamma^{-1},\quad \varepsilon(\pi/4)=\sqrt{2(1+\gamma^{-2})}/2\cong\sqrt{2}/2$$

(this approximation is valid for the relevant range of γ values, i.e., $\gamma\geqslant 5$). Taking into account these values,

$$\Delta E=a_p\varepsilon_0(\sqrt{2}/2)\{\alpha_p(T)-\alpha_c+[2/\gamma][\ln(\kappa\sqrt{\gamma})+\alpha_c]\}.$$

It derives that a total adjustment (tA state) is more favorable than the inclined state (I state) as soon as

$$\alpha_c-[2/\gamma][\ln(\kappa\sqrt{\gamma})+\alpha_c]>\alpha_p(T). \tag{5}$$

The right-hand side of Eq. (5) is temperature dependent, but is also very sensitive to the input parameters $\xi_{ab}(0)$ and R. The κ values of all the considered compounds are quite close $(\cong 100)$, and this parameter enters only in a logarithmic term. Consequently, it can be considered that the left-hand side of Eq. (5) is completely driven by the γ value. In Fig. 7, the left- and right-hand sides of Eq. (5) are represented as a function of γ and $t=T/T_c$, respectively. Different plausible sets of values have been used for the parameters $(\xi_{ab}(0),R)$. The assumed temperature dependence of ξ_{ab} is $\xi_{ab}(t)=\xi_{ab}(0)/(1-t)^{1/2}$. The two graphs of Fig. 7 allow one to describe the observed directional crossover. From Fig. 7(a), the considered γ value yields a threshold value of the left-hand side of Eq. (5). This same value in Fig. 7(b) determines, for a given set of parameters $(\xi_{ab}(0),R)$, the crossover temperature below which Eq. (5) is satisfied $[J_c(\vec{H}_a\perp \mathrm{CD})\equiv J_c(\vec{H}_a\|\mathrm{CD})]$ and above which it is not $[J_c(\vec{H}_a\perp \mathrm{CD})<J_c(\vec{H}_a\|\mathrm{CD})]$. First, it can be observed that the γ dependence of the crossover temperature is the expected one: T_{cross} decreases as γ is decreased. Second, it is important to emphasize that this description accounts for the peculiar temperature dependence of this phenomenon, i.e., a directional enhancement appearing only at high temperatures. Finally, it must be pointed out that the model is also

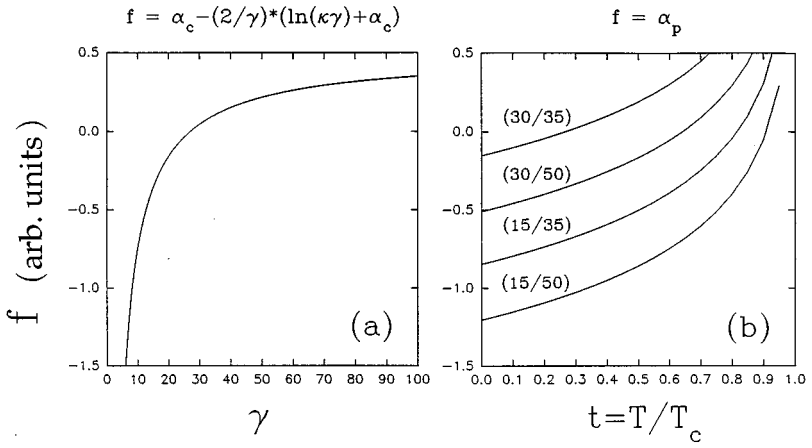

FIG. 7. (a) Plot of the function $f(\gamma)=\alpha_c-[2/\gamma][\ln(\kappa\sqrt{\gamma})+\alpha_c]$. The variable γ is the electronic anisotropy ($\xi_{ab}/\xi_c=\lambda_c/\lambda_{ab}$). (b) Plot of the function $f(t=T/T_c)=\alpha_p=\ln[\xi_{ab}(0)/R\sqrt{1-t}]$. The parameters $\xi_{ab}(0)$ and R are the in-plane coherence length at $T=0$ and the CD's radius, respectively. The different curves correspond to different ratios $[\xi_{ab}(0)/R]$.

satisfying from a quantitative viewpoint since the values of all the parameters $\xi_{ab}(0)$, R, γ, and T_{cross} are consistent. For instance, it can be observed that for Bi-2212 with suitable parameters[6] [$\xi_{ab}(0)=30$ Å , $R=35$ Å] the observed crossover around $t\cong 0.5$ yields a value $\gamma\cong 50$. Nevertheless, it must be recognized that the parameters $\xi_{ab}(0)$ and R can vary noticeably for the different compounds and are generally not known with a sufficient precision to extract very reliable γ values. The relevancy of our approach based on a competition between the I and tA states is the central result of this paper.

This problem of the vortex accommodation to tilted CD's has been already addressed by Blatter *et al.*[21] Using the analogy with the vortex accommodation to twin boundaries,[17] two characteristic angles are obtained: the trapping angle θ_t, below which an accommodation process starts to develop, and the lock-in angle θ_L, below which the vortices become completely trapped by the CD's. After Ref. 21, using our notation

$$\theta_t\cong\gamma\sqrt{\ln[1+(R^2/2\xi^2)]/\ln\kappa}, \tag{6}$$

$$\theta_L\cong(H_{c1}/H)\,\theta_t. \tag{7}$$

In the present study, this model predicts no directional effect as long as $\theta_L\geqslant\pi/2$. This analysis [Eqs. (6) and (7)] presents some similarities with the one developed here [Eq. (5)]. For instance, in both cases, it appears clearly that an isotropic pinning enhancement needs high γ and large R/ξ ratios. Nevertheless, it must be emphasized that the underlying analysis, from which Eqs. (6) and (7) are derived, deals with an accommodation in an isotropic plane (ab) plane and for small angles only. The use of an anisotropic scaling approach in this case can be questionable since this ansatz applies only in the presence of uncorrelated isotropic disorder.[21,22] Moreover, according to Eq. (7), the crossover between the directional and isotropic regimes should be strongly influenced by the magnetic field value. In Fig. 2, it appears that the crossover is rather driven by the temperature even if the amplitude of the difference between $J_c(\vec{H}_a\perp\text{CD})$ and $J_c(\vec{H}_a\|\text{CD})$ is field dependent.

Let us now address another important observation described in Sec. III, i.e., the existence of a large pinning enhancement for $\vec{H}_a\perp$CD even at high T when $J_c(\vec{H}_a\perp\text{CD})<J_c(\vec{H}_a\|\text{CD})$. One possibility is to invoke the occurrence of a partially adjusted state (pA state). This state can be characterized by the angle Ψ between $\vec{H}_a$ and the direction of the vortex pieces out of the CD's. The inclined and totally adjusted states correspond to $\Psi=0$ and $\Psi=\pi/4$, respectively. The energy difference over one period a_Φ between the I and pA states is

$$\Delta E=(a_\Phi\tan\psi)\varepsilon_p(\pi/4)+(a_\Phi/\cos\psi)\varepsilon_1(\psi+\pi/4)-a_\Phi\varepsilon_1(\pi/4). \tag{8}$$

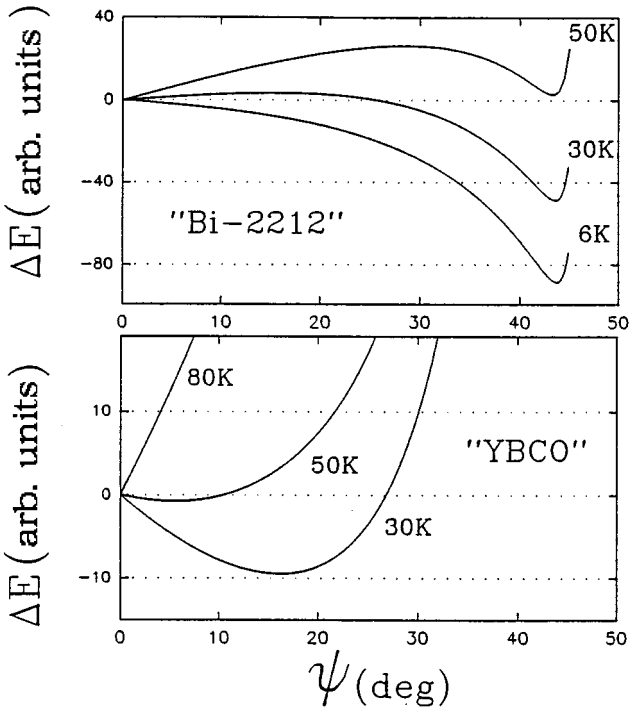

FIG. 8. Energy difference between the inclined and partially adjusted states [Eq. (8)] as a function of the characteristic angle Ψ of this latter state, i.e., the angle between $\vec{H}_a$ and the direction of the vortex pieces out of the CD's. The upper graph corresponds to input parameters representative of Bi-2212 ($\gamma=50$) and the lower one to YBCO ($\gamma=5$). The labels close to the curves are the temperature values in kelvin.

Curves $\Delta E(\Psi)$ are shown in Fig. 8 for two sets of input parameters illustrating the case of Bi-2212 (high $\gamma=50$) and YBCO (low $\gamma=5$). Assuming that the actual state corresponds to the minimization of ΔE, it is shown that a *pA* state can occur for low γ values, but not for high γ values. In the latter case, there is a direct crossover between a *tA* state ($\Psi\cong 45°$ for $T\leqslant 50$ K) and a *I* state ($\Psi\cong 0°$ for $T\geqslant 50$ K). However, it must be recalled that the above results are derived with the strong assumption that the mean orientation of the vortices points along the external magnetic field. In a more precise analysis, this orientation should be considered as a free parameter in the minimization of G. Thereby, a new kind of ''partial adjustment'' can take place and can be involved in the large increase of the critical current $J_c(\vec{H}_a\perp \mathrm{CD})$ observed even for high γ at high T.

B. Flux-flop phenomenon

It can be observed in Fig. 2 that in all cases the $J_c(H_a^{\parallel})$ curves for $\vec{H}_a\|\mathrm{CD}$ and $\vec{H}_a\perp \mathrm{CD}$ merge at $H_a=0$. This type of observation has been ascribed by Klein *et al.*[4] to a flux-flop phenomenon: Below a crossover field, the vortices of the configuration $\vec{H}_a\perp \mathrm{CD}$ flop towards the CD's, yielding thereby a vortex state identical to the one of the configuration $\vec{H}_a\|\mathrm{CD}$. This analysis is based on the minimization of G in the configuration $\vec{H}_a\perp \mathrm{CD}$ considering straight vortices, no pinning, and an adjustable angle θ_B between $\vec{B}$ and the c axis. It was found that θ_B tends towards zero as H is decreased and, at a crossover field H_{fl}, the Gibbs energy of this state becomes higher than the one of the locked state. The value of H_{fl} is found to be around one-tenth of H_{c1}. One can consider that this analysis has pointed out the key of the problem, but it must be emphasized that the demagnetizing factors and the anisotropy have not been taken into account. This last point is of importance since it turns out that the reduction of length gained by straight vortices when they rotate toward c is counterbalanced by the increase of the line energy $\varepsilon_1(\theta)$. This is especially the case for $\pi/4$ since $\varepsilon(\pi/4)\cong\cos(\pi/4)$. In the following, we will take into account the electronic anisotropy as well as the demagnetizing factors, but on the other hand, the only vortex states presented in Fig. 5 will be considered.

Searching for the occurrence of a same vortex state for $\vec{H}_a\|\mathrm{CD}$ and $\vec{H}_a\perp \mathrm{CD}$, one can advance two possibilities: the locked state or the shortened state. As shown in Appendix A, this last possibility (*S* state) can be ruled out and the question finally focus on the occurrence of a transition inclined state $\rightarrow$ locked state for $\vec{H}_a\perp \mathrm{CD}$ as the field is decreased. This problem is developed in Appendix B considering the difference of the Gibbs energy between the two states. It is found that

$$G_I-G_L=B\{[\varepsilon_0(\alpha_c-\alpha_p)/\phi_0\sqrt{2}]-[H_a/2\pi(1+n)]\}, \tag{9}$$

where n is the demagnetizing factor for $\vec{H}_a\|c$.

At high fields, the second term on the right-hand side of Eq. (9) is large and promotes the *I* state, but it is clear that when $H\rightarrow 0$ the locked state becomes more favorable. The crossover takes place at a field

$$H_{\mathrm{cross}}=\pi\sqrt{2}(1+n)\varepsilon_0(T)[\alpha_c-\alpha_p(T)]/\phi_0. \tag{10}$$

It can be pointed out that γ is not involved in Eq. (10) and the demagnetizing factor n plays only a minor role. This result supports the validity of the approach developed by Klein *et al.*[4] For reasonable values [$\lambda_{ab}(T)=2500$ Å, $n=0.8$, $\alpha_p(T)=-0.5$], one obtains $H_{\mathrm{cross}}\cong 10$ G. It must be emphasized that the curves $J_c(\vec{H}_a\|\mathrm{CD})$ and $J_c(\vec{H}_a\perp \mathrm{CD})$ merge completely only for such very low fields.

From an experimental viewpoint, a distinction can be made among the different compounds. For YBCO and (Tl,Bi)-1212, there is a marked kink on the reverse leg of the hysteresis curve $M_-(H_a)$ for $\vec{H}_a\perp \mathrm{CD}$, with a steep increase of the magnetization approaching the zero field. On the contrary, for the more anisotropic compounds there is no knee on $M_-(\vec{H}_a\perp \mathrm{CD})$: As the field is decreased, one can just observe for this configuration a steeper raising of M, which progressively tends to join the curve $\vec{H}_a\|\mathrm{CD}$. The more pronounced behavior for YBCO and (Tl,Bi)-1212 could be simply due to the arrowhead shape of their hysteresis loops.[9] Anyway, in all cases, the crossover appears as a continuous process. A more precise analysis, which could account for the smooth variation of the pinning efficiency, would require one to minimize G with a lot of adjustable parameters such as θ_B, but it is not an easy task.

V. CONCLUSION

This paper reports on the directionality of the pinning enhancement by columnar defects inclined at 45° relative to the c axis in HTSC's. The crossover between the isotropic and unidirectional regimes has been described as a transition between inclined and totally adjusted states, which both preserve the alignment between the mean vortex direction and the applied field. The occurrence of such a transition was shown to explain easily the observed influences of the temperature and of the electronic anisotropy. It must be pointed out that the effect of T deals with its direct influence on the pinning efficiency of CD's via the ratio (R/ξ). Moreover, it can be noted that the proposed model assumes the existence of a line behavior of the vortices whatever the temperature. Several previous studies have provided evidence of such an incomplete decoupling of the vortices, even in highly anisotropic superconductors.[3,23] For instance, a nonzero line tension of the vortices is also assumed in the analysis of Blatter *et al.*,[21] but the absence of a directional effect is ascribed to a locked state and not to a totally adjusted state. In the present study, such a lock-in transition (the flux-flop effect[4]) is only invoked to account for the isotropy of the pinning at very low fields whatever the temperature.

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APPENDIX A

To search for the occurrence of a transition between two vortex states, we compare their Gibbs energies. The subscripts I, S, and L refer to the inclined, shortened, and locked states, respectively (see Fig. 5). It must be noted that the free energy F depends only on the accommodation of the vortices to the CD's, while the alignment term $(G-F)$ is only driven by the relative orientation between $\vec{B}$ and $\vec{H}_a$. Consequently,

$$(G_I-F_I)_{\perp \mathrm{CD}}=(G_L-F_L)_{\parallel \mathrm{CD}},$$

$$(G_S-F_S)_{\perp \mathrm{CD}}=(G_S-F_S)_{\parallel \mathrm{CD}}=(G_S-F_S).$$

According to Ref. 20,

$$F_I=\frac{B^2}{8\pi}+\frac{\Phi_0 B\varepsilon(\pi/4)}{(4\pi\lambda_{ab})^2}\left[\ln\left(\frac{\eta B_{c2\perp}}{B\varepsilon(\pi/4)}\right)^{1/2}+\alpha_c\right], \quad \text{(A1)}$$

where η is a constant close to 1 and $B_{c2\perp}=B_{c2}(\theta=\pi/2)$.

The free energy in the locked state can be directly derived substituting α_c by α_p,[20]

$$F_L=\frac{B^2}{8\pi}+\frac{\Phi_0 B\varepsilon(\pi/4)}{(4\pi\lambda_{ab})^2}\left[\ln\left(\frac{\eta B_{c2\perp}}{B\varepsilon(\pi/4)}\right)^{1/2}+\alpha_p\right]. \quad \text{(A2)}$$

$F_L<F_I$ as long as there is a pinning effect of the CD's, i.e., $\alpha_c>\alpha_p$.

For F_S, one has $\varepsilon(0)=1$, but a factor $1/\sqrt{2}$ must be included to take into account the reduction of vortex length. Finally, to logarithmic accuracy, $F_S=F_I$.

Considering an uniaxial ellipsoid and using projections along the principal axis of the crystal, one obtains

$$8\pi(G-F)=\frac{1}{1-n}(H_a^c-nB^c)(H_a^c-B^c)+\frac{2}{1+n}\left(H_a^{ab}-\frac{1-n}{2}B^{ab}\right)(H_a^{ab}-B^{ab})-B^cH_a^c-B^{ab}H_a^{ab}, \quad \text{(A3)}$$

where n is the demagnetizing factor along c (value close to 1). For $\vec{H}_a\perp$CD, $H_a^{ab}=H_a^c=H_a/\sqrt{2}$. In the I state for $\vec{H}_a\perp$CD, $B^{ab}=B^c=B/\sqrt{2}$. In the S state, $B^{ab}=0$ and $B^c=B$. In the L state for $\vec{H}_a\perp$CD, $B^c=-B^{ab}=B/\sqrt{2}$.

Let us now investigate the relevancy of the shortened state to explain the isotropy of the remanent magnetization. We have to address the possible transitions

$$L\rightarrow S \quad \text{for } \vec{H}_a\parallel \mathrm{CD},$$

$$I\rightarrow S \quad \text{for } \vec{H}_a\perp \mathrm{CD}.$$

The difference of alignment energy is the same in both transitions:

$$8\pi\{(G_I-F_I)_{\perp \mathrm{CD}}-(G_S-F_S)\}=8\pi\{(G_L-F_L)_{\parallel \mathrm{CD}}-(G_S-F_S)\}=A.$$

According to Eq. (A3), it is found that

$$A(1-n^2)/B^2=(1-3n)/2+[(\sqrt{2}-3)+(\sqrt{2}+1)n][H_a/B].$$

In the present conditions ($n\approx 1$ and $H<B$), A is negative. Thus, since $F_L<F_S$ and $F_I=F_S$, none of the investigated transitions is expected. The isotropy of the remanent magnetization cannot be related to the occurrence of the shortened state at low fields in both configurations $\vec{H}_a\perp$CD and $\vec{H}_a\parallel$CD.

APPENDIX B

Let us address the question of a crossover between the I and L states as H_a is decreased for $\vec{H}_a\perp$CD. According to Eq. (A3), the difference of alignment energy between the two states is

$$8\pi\{(G_I-F_I)_{\perp \mathrm{CD}}-(G_L-F_L)_{\perp \mathrm{CD}}\}=-[4/(1+n)]BH_a$$

and thus

$$(G_I-G_L)_{\perp \mathrm{CD}}=(F_I-F_L)-[4/(1+n)][BH_a/8\pi].$$

According to Eqs. (A1) and (A2),

$$(G_I-G_L)_{\perp \mathrm{CD}}=(\Phi_0 B\sqrt{2}/2)(\alpha_c-\alpha_p)/(4\pi\lambda_{ab})^2-[4/(1+n)][BH_a/8\pi],$$

$$(G_I-G_L)_{\perp \mathrm{CD}}=B\{[\varepsilon_0(\alpha_c-\alpha_p)/\Phi_0\sqrt{2}]-[H_a/2\pi(1+n)]\}.$$

At high fields, the second term of the right-hand side is large and promotes the I state, but it is clear that when $H\rightarrow 0$ the locked state becomes more favorable.

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