Origin of the irreversibility line in thin $YBa_2Cu_3O_{7-\delta}$ films with and without columnar defects

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We report on measurements of the angular dependence of the irreversibility temperature $T_{irr}(\theta)$ in $YBa_2Cu_3O_{7-\delta}$ thin films, defined by the onset of a third-harmonic signal and measured by a miniature Hall probe. From the functional form of $T_{irr}(\theta)$ we conclude that the origin of the irreversibility line in unirradiated films is a dynamic crossover from an unpinned to a pinned vortex liquid. In irradiated films the irreversibility temperature is determined by the trapping angle. [S0163-1829(96)01245-3]

I. INTRODUCTION

The origin of the irreversibility line (IRL) in the field-temperature (H-T) phase diagram of high-temperature superconductors (HTS's) is intriguing and still a widely discussed topic.[1–9] Experimentally, this line is defined as the borderline at which the magnetic response of the sample changes from irreversible to reversible. In HTS's, large fluctuations and relatively weak pinning lead to a rich H-T phase diagram with a variety of dynamic and static transitions which can be responsible for the appearance of magnetic reversibility.[3–5,10–12] Thus, a thorough experimental investigation of the IRL is important for the understanding of the vortex-lattice behavior in superconductors in general and of the mechanisms responsible for the onset of irreversible magnetic response, in particular.

Several models, like thermally activated depinning,[2,3,6,13,14] vortex-lattice melting,[15–21] and a transition from vortex glass to vortex fluid,[22–24] were proposed to identify the origin of the IRL in HTS's. Also, attention was given to the possibility of pinning in the vortex-liquid phase[5,10,11,25] and to different dissipation mechanisms above the melting line.[5,13,26–28] Irreversibility due to geometrical[7,9] or surface barriers[29] has also been proposed, but this mechanism is less probable in thin $YBa_2Cu_3O_{7-\delta}$ films with strong pinning. The irreversibility line may be affected by sample-dependent properties such as the nature and density of pinning centers and by intrinsic or extrinsic anisotropy. For example, in superconductors with columnar defects, the irreversibility line may either be identified with the Bose-glass transition[5,28–37] or related to the concept of a trapping angle.[38] The configuration of the columnar defects is also very important, since it affects the possibility for different types of depinning mechanism. A splayed configuration, for example, inhibits creep from columnar defects.[39,40] Similarly ''crossed'' defects (i.e., defects at angles $\pm\theta$) were shown to act collectively; i.e., they introduce unidirectional anisotropy such that the current density reaches its maximum for magnetic field directed in a midangle between defects.[41,42]

Experimentally, the situation is even more complex, since different techniques (magnetization loops, field-cool vs zero-field-cool dc magnetization, peak in the imaginary part of the first harmonic, etc.) yield different IRL's.[24,43] To a great extent, the reliability of the determination of the IRL depends on the criterion for the onset of the irreversibility. We determine the irreversibility temperature at a given dc field by the onset of the third harmonic in the ac response, which, we believe, is one of the most reliable methods for contactless determination of the IRL.[44] In most experiments T_{irr} is measured as a function of the external field H. This information is insufficient to distinguish between different models for the origin of the irreversibility. Additional information, like the frequency dependence of the IRL (Refs. 24 and 45) or its angular variation,[18,20,21,32,34,36,46] is needed.

In this paper we report on a study of the angular dependence of the irreversibility temperature $T_{irr}(\theta)$ in thin $YBa_2Cu_3O_{7-\delta}$ (YBCO) films before and after irradiation with Pb ions.

II. EXPERIMENT

The 1500 Å YBCO films were ''sandwiched'' between $SrTiO_3$ layers.[47] First, a 500 Å layer of $SrTiO_3$ was deposited on a MgO substrate. Then, the YBCO film was laser ablated on top of the $SrTiO_3$ and finally, the YBCO was covered by a protective 300 Å layer of $SrTiO_3$. All three samples have the same lateral dimensions of 100×500 μm^2. One film, denoted as REF, was used as a reference sample. The other two, UIR and CIR, were irradiated at GANIL with 2×10^{11} ions/cm^2 5.8 GeV Pb ions along the c axis and along $\theta=\pm45°$, respectively. (UIR and CIR stand for ''uniform irradiation'' and ''crossed irradiation,'' respec-

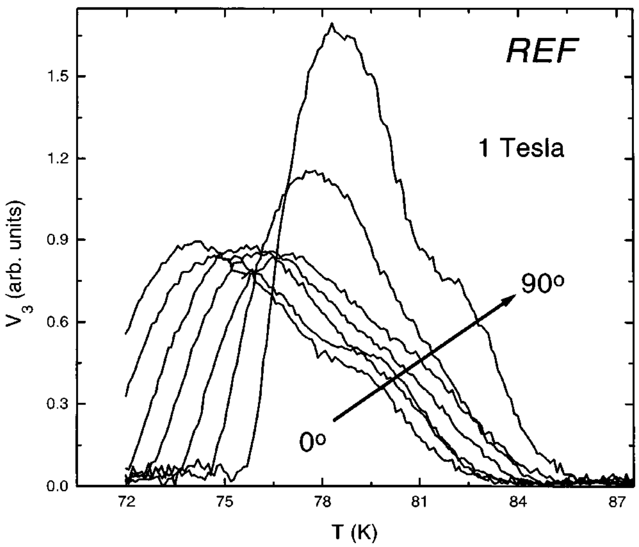

FIG. 1. Third-harmonic signal V_3 vs temperature during field cooling at 1 T for sample REF at θ=0°, 10°, 30°, 40°, 60°, 80°, and 90°.

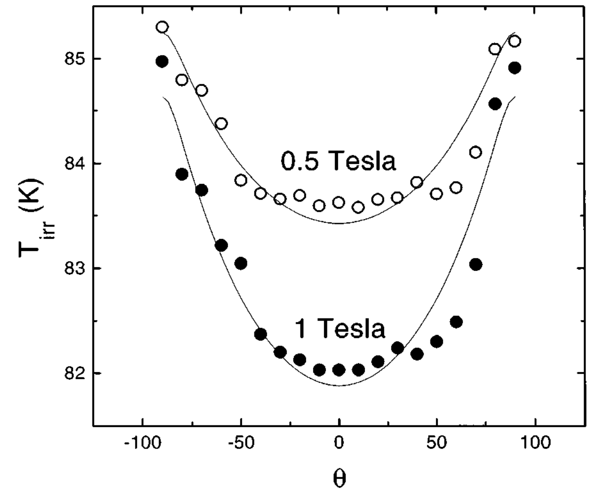

FIG. 2. Irreversibility temperature in the unirradiated sample REF at two values of the external field: $H=0.5$ and 1 T. The solid lines are fits to Eq. (8).

tively.) The superconducting transition temperatures, measured by a Quantum Design superconducting quantum interference device (SQUID) susceptometer and defined as the onset of the Meissner expulsion in a dc field of 5 G, are $T_c \approx 89$ K for the samples REF and UIR and 88 K for CIR.

For the ac measurements reported below we used a miniature $80\times 80\ \mu m^2$ InSb Hall probe, which was positioned in the center of the sample. The 1 G ac magnetic field, always parallel to the c axis, was induced by a small coil surrounding the sample. An external dc magnetic field, up to $H_a=1.5$ T, could be applied at any direction θ with respect to the c axis. In our experiments dc magnetic field was always turned on at a fixed angle at $T>T_c$ and then the ac response was recorded during sample cooling. The irreversibility temperature $T_{irr}(\theta)$ is defined as the onset of the third-harmonic signal in the ac response measured by the Hall probe.[44] This procedure was repeated for various dc fields and at various angles θ of the field with respect to the c axis.

III. RESULTS

Figure 1 presents measurements of V_3, the third harmonic in the ac response, versus temperature T, during field cooling at 1 T for the sample REF at various angles between 0 and 90°. Apparently, as the angle θ increases the whole V_3 curve shifts to higher temperatures and becomes narrower. The onset of irreversibility $T_{irr}(\theta)$ is defined by the criterion $V_3^{onset}=0.05$ in the units of Fig. 1.

Figure 2 exhibits typical $T_{irr}(\theta)$ data for the unirradiated sample REF, measured at two values of the external field: 0.5 T and 1 T. Both curves exhibit a shallow minimum around $\theta=0$ and they reach their maximum values for H along the ab plane, at angles $\theta=\pm 90°$. We also measured the frequency dependence of T_{irr} for the same values of magnetic field. As shown in Fig. 3, the slope $\partial T_{irr}/\partial \ln(f)$ is larger for larger field.

The sample irradiated along the c axis exhibits an additional feature, a *peak* around $\theta=0$. This is clearly shown in Fig. 4 where we compare $T_{irr}(\theta)$ at $H=1$ T for the samples REF and UIR. As discussed below, this peak is a signature of the unidirectional magnetic anisotropy induced by the columnar defects. Intuitively, one would therefore expect two peaks, along $\theta=\pm 45°$, for the third sample, CIR, crossed irradiated at $\theta=\pm 45°$. Instead, we find one strong peak around $\theta=0$, similar to that found in Bi-Sr-Ca-Cu-O crystals.[42] This is demonstrated in Fig. 5 where we compare $T_{irr}(\theta)$ at $H=0.5$ T for this sample (CIR) and for the unirradiated sample (REF). We argue below that the peak around $\theta=0°$ is a result of a collective action of the crossed columnar defects, and its origin is the same as that for unidirectional enhancement of critical current density observed in Bi-Sr-Ca-Cu-O crystals.[41,42]

IV. ANALYSIS

The ''true'' irreversibility temperature T_0 is defined as a temperature below which the irreversibility sets in. Such

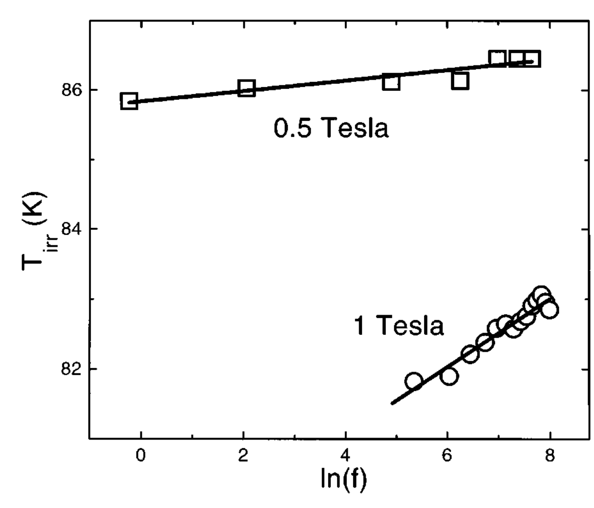

FIG. 3. Frequency dependence of T_{irr} in the unirradiated sample REF at two values of the external field: $H=0.5$ and 1 T. The solid lines are fits to Eq. (9).

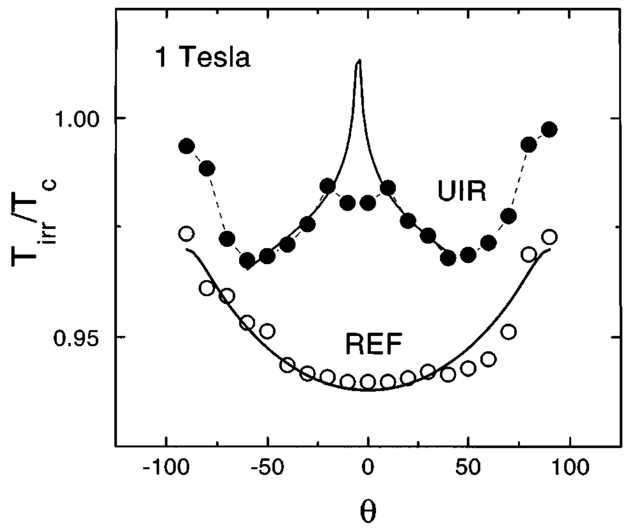

FIG. 4. Irreversibility temperature for two samples: REF (unirradiated, open circles) and UIR (irradiated along the c-axis sample, solid circles) at $H=1$ T. Solid lines are fits to Eq. (8) and Eq. (12), respectively.

appearance of pinning can be of static (true phase transition), as well as of dynamic origin (gradual freezing, pinning in liquid). In practice, one determines the irreversibility temperature $T_{\rm irr}(\Delta)$ as the temperature above which the critical current density is less than some threshold value Δ. Therefore, by definition, $T_0=\lim_{\Delta\to 0}[T_{\rm irr}(\Delta)]$. The apparent current depends on temperature T, magnetic field B, and the frequency f of the exciting field which defines a characteristic time scale $1/f$ for the experiment. By solving the equation $j(T,B,f)=\Delta$ with respect to T one finds the experimental irreversibility temperature $T_{\rm irr}$ for constant B and f. In the following we argue that in our experiments the measured $T_{\rm irr}$ is a good approximation of T_0. In order to estimate $T_{\rm irr}$ we employ a general form for the apparent current density *in the vicinity of the irreversibility line* (IRL):[4–6,48]

$$j(T,B,f)\propto j_c(0)\frac{(1-T/T_0)^{\alpha}}{(B/B_0)^{\beta}}\left(\frac{f}{f_0}\right)^{\gamma}, \tag{1}$$

where the parameters B_0 and f_0 are temperature independent [Eq. (1) is thus valid only in a narrow temperature interval near the IRL and for fields larger than H_{c1}]. From Eq. (1) we get

$$T_{\rm irr}=T_0(B)\left\{1-\left[\frac{\Delta}{j_c(0)}\left(\frac{B}{B_0}\right)^{\beta}\left(\frac{f_0}{f}\right)^{\gamma}\right]^{1/\alpha}\right\}. \tag{2}$$

Inserting reasonable numerical estimates $j_c(0)\simeq 10^7$ A/cm^2, $\Delta\simeq 100$ A/cm^2 for our experimental resolution, $B_0\simeq 10^3$ G, $B\simeq 10^4$ G, $\beta\simeq 1$,[48] $\gamma\simeq 1$,[6] $f\simeq 10^2$ Hz, and $f_0\simeq 10^7$ Hz,[6] we get, from Eq. (2), $T_{\rm irr}=T_0(B)(1-0.005^{1/\alpha})$. Thus, with 0.5% accuracy we may say that $T_{\rm irr}$, the measured onset of the third-harmonic component in the ac response, marks some ''true'' irreversibility crossover line $T_0(B)$. The nature of this line $T_0(B)$ is our main interest, since, as discussed in the Introduction, it is directly related to the pinning properties of vortex lattice in type-II superconductors at elevated temperatures.

A. Unirradiated YBCO film

We turn now to consider the effect of the intrinsic anisotropy on $T_{\rm irr}(\theta)$. Following the anisotropic scaling approach proposed by Blatter *et al.*,[49,50] we replace T by εT and B by $B_{\rm eff}=\varepsilon_\theta B$, where $\varepsilon_\theta=\sqrt{\cos^2(\theta)+\varepsilon^2\sin^2(\theta)}$ and $\varepsilon\approx 1/7$ is the anisotropy parameter for YBCO. It should be emphasized that we can use this scheme only in the case of *intrinsic* anisotropy $\varepsilon=\sqrt{m_{ab}/m_c}$, where m_c and m_{ab} denote the effective masses of the electron along the c axis and in the ab plane, respectively. In the case of some *extrinsic* magnetic anisotropy (columnar defects or twin planes), the critical current depends on the angle not only via the effective magnetic field $B_{\rm eff}$, but also because of this extrinsic anisotropy.

As we have already indicated in the Introduction, there are several possible origins for a crossover from irreversible to reversible magnetic behavior in unirradiated samples. We exclude the vortex-glass to vortex-fluid transition as a possible origin for the IRL, because this transition was shown to occur at temperatures lower than the onset of dissipation.[23,25,51] The thermal depinning temperature *increases* with increase of field,[5] $T_{\rm dp}\propto\sqrt{B}$, and therefore is excluded as well. Vortex-lattice melting transition is believed to be responsible for the appearance of reversibility.[15,16,18,19] The explicit angular dependence of T_m was derived by Blatter *et al.*[5,49] using their scaling approach:

$$T_m(\theta)\simeq 2\sqrt{\pi}\varepsilon\varepsilon_0 c_L^2(\Phi_0/B\varepsilon_\theta)^{1/2}$$

$$\approx\frac{c_L^2 T_c}{\sqrt{\beta_m Gi}}\left(1-\frac{T_m}{T_c}\right)\left(\frac{H_{c2}(0)}{\varepsilon_\theta B}\right)^{1/2}, \tag{3}$$

where Φ_0 is the flux quantum, ξ is the coherence length, $\beta_m\approx 5.6$ is a numerical factor, estimated in Ref. 5, $c_L\simeq 0.1$ is

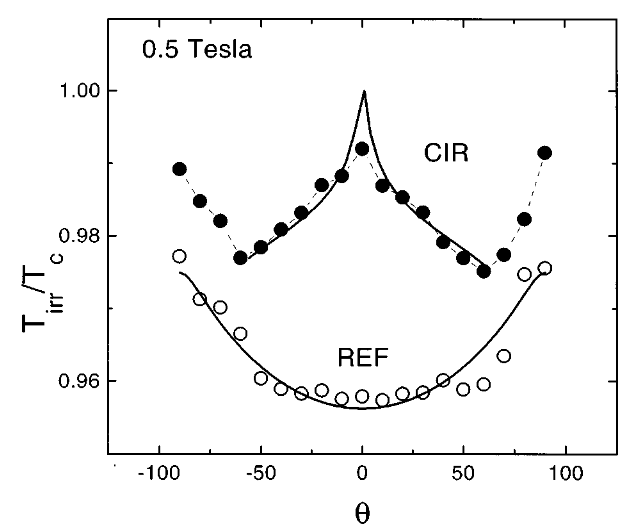

FIG. 5. Irreversibility temperature for two samples: REF (unirradiated, open circles) and CIR (irradiated along $\theta=\pm 45°$, solid circles) at $H=0.5$ T. Solid lines are fits to Eq. (8) and Eq. (12), respectively.

the Lindemann number, $Gi=[T_c/\varepsilon H_{c2}(0)\xi^3(0)]^2/2$ is the Ginzburg number, and $H_{c2}(0)$ is the *linear* extrapolation of the upper critical field from T_c to zero. Solving Eq. (3) with respect to T_m we get

$$T_m(\theta)\simeq\frac{T_c}{1+[\beta_m Gi/c_L^4 H_{c2}(0)]^{1/2}(\varepsilon_\theta B)^{1/2}}\equiv\frac{T_c}{1+C\sqrt{\varepsilon_\theta B}}. \tag{4}$$

Equation 4 predicts that the melting temperature decreases as B_{eff} increases. This is due to the fact that the intervortex distance $a_0^2\propto 1/B_{\mathrm{eff}}$ decreases faster than the characteristic amplitude of fluctuations $\langle u^2(B_{\mathrm{eff}},T_m)\rangle_{\mathrm{th}}\propto 1/\sqrt{B_{\mathrm{eff}}}$. Therefore, the condition for the vortex-lattice melting $\langle u^2(B_{\mathrm{eff}},T_m)\rangle_{\mathrm{th}}\simeq c_L^2 a_0^2$ implies larger melting temperatures for smaller effective fields, i.e., for larger angles. In agreement with this prediction, the experimental data of Fig. 2 show that T_{irr} increases with the angle, i.e., decreases with B_{eff}. The solid lines in Fig. 2 are fits to Eq. (4). From this fit we get $C\simeq 0.0005$. However, a reasonable estimate of $C\simeq\sqrt{[\beta_m Gi/c_L^4 H_{c2}(0)]}$ yields $C\simeq 0.01$, where we take $H_{c2}(0)=5\times 10^6$ G, $c_L=0.1$, $Gi=0.01$, and $\beta_m=5.6$.[5] Also, Yeh *et al.* showed that the onset of irreversibility occurs above the melting temperature (Ref. 28, Fig. 4). In addition, the important effect of the frequency (see Fig. 3) is not included in Eq. (4).

We discuss now another possibility for the onset of the irreversibility, namely, pinning in the vortex liquid (for a discussion see Chap. VI in Blatter *et al.*[5] and references therein). Any fluctuation in the vortex structure in the liquid state has to be averaged over the characteristic time scale for pinning t_{pin}. In the absence of viscosity the only fluctuations in the liquid state are thermal fluctuations, which have a characteristic time $t_{\mathrm{th}}\ll t_{\mathrm{pin}}$. (As shown in Ref. 5, $t_{\mathrm{pin}}/t_{\mathrm{th}}\propto j_0/j_c$, where j_0 is the depairing current.) Thus, such a liquid is always unpinned. The situation is different for a liquid with finite viscosity. In this case there exists another type of excitations in the vortex structure, i.e., *plastic* deformations with a characteristic time scale t_{pl}. The energy barrier, corresponding to plastic deformation is shown to be[5,12]

$$U_{\mathrm{pl}}\simeq\gamma\varepsilon\varepsilon_0 a_0\simeq\gamma\left(\frac{H_{c2}}{4Gi}\right)^{1/2}(T_c-T)B^{-1/2}, \tag{5}$$

where γ is a coefficient of the order of unity. The corresponding characteristic time scale is

$$t_{\mathrm{pl}}\sim t_{\mathrm{th}}\exp(U_{\mathrm{pl}}/T). \tag{6}$$

Thus, depending on the viscosity, t_{pl} can be smaller or larger than t_{pin}. In the latter case, after averaging over a time t_{pin}, the vortex structure remains distorted and such a liquid shows irreversible magnetic behavior. Thus, on the time scale of t_{pin} the distorted vortex structure is pinned. The crossover between pinned and unpinned liquid occurs at temperature T_k where the characteristic relaxation time for pinning $t_{\mathrm{pin}}(T)$ becomes comparable to that for plastic motion $t_{\mathrm{pl}}(T)$. Thus, using Eqs. (5) and (6) we obtain

$$T_k=\frac{T_c}{1+(1/\gamma)[4Gi/H_{c2}(0)]^{1/2}\ln(t_{\mathrm{pin}}/t_{\mathrm{th}})\sqrt{B}}. \tag{7}$$

Finally, using the anisotropic scaling[49] we may rewrite Eq. (7) for $f_{\mathrm{pin}}<f<f_{\mathrm{th}}$ as

$$T_{\mathrm{irr}}(\theta)=T_k(\theta)=\frac{T_c}{1+(1/\gamma)[4Gi/H_{c2}(0)]^{1/2}\ln(f_{\mathrm{th}}/f)\sqrt{B\varepsilon_\theta}}\equiv\frac{T_c}{1+A\sqrt{\varepsilon_\theta B}}, \tag{8}$$

with $f_{\mathrm{th}}\equiv 1/t_{\mathrm{th}}$ and $f_{\mathrm{pin}}\equiv 1/t_{\mathrm{pin}}$. Note the apparent similarity with the expression for the melting temperature, Eq. (4). The numerical estimate for

$$A=\frac{1}{\gamma}\left(\frac{4Gi}{H_{c2}(0)}\right)^{1/2}\ln(f_{\mathrm{th}}/f)$$

gives $A\simeq 10^{-4}\ln(f_{\mathrm{th}}/f)/\gamma$. This is in agreement with the value found from the fit (solid line in Fig. 2) for $H_{c2}(0)=5\times 10^6$ G, $Gi=0.01$, $f_{\mathrm{th}}\sim 10^{10}$ Hz, and $\gamma\simeq 4$.

To further confirm that in our YBCO films the most probable physical mechanism for the onset of irreversibility is a dynamic crossover from unpinned to pinned vortex liquid we discuss now the frequency dependence of T_{irr}. Equation (8) has a clear prediction for the frequency dependence of T_{irr}. To see it directly we may simplify it by using the experimentally determined value of the fit parameter $A\simeq 0.0005$. This small value allows us to expand Eq. (8) (for not too large fields) as

$$T_k\approx T_c\left[1-\frac{1}{\gamma}\left(\frac{4Gi}{H_{c2}(0)}\right)^{1/2}\ln(f_{\mathrm{th}}/f)\sqrt{\varepsilon_\theta B}\right], \tag{9}$$

which results in a linear dependence of T_{irr} upon ln(f) with a slope

$$S\equiv\partial T_{\mathrm{irr}}/\partial\ln(f)\approx\frac{T_c}{\gamma}\left(\frac{4Gi}{H_{c2}(0)}\right)^{1/2}\sqrt{\varepsilon_\theta B}=T_c A\sqrt{\varepsilon_\theta B}\ln(f/f_{\mathrm{th}}).$$

Note that the slope is proportional to $\sqrt{B}$. This is indeed confirmed by the experimental data, as is demonstrated by the solid lines in Fig. 3. From this fit we get $S/\sqrt{B}=0.004$ and we can independently verify the parameter A appearing in Eq. (8), $A=S/[T_c\sqrt{\varepsilon_\theta B}\ln(f/f_{\mathrm{th}})]=0.0008$, which is in an agreement with the value obtained above.

We note that the approximated expression for the frequency dependence of T_{irr}, Eq. (9), is valid in the whole experimentally accessible range of magnetic field since Eq. (8) predicts a maximum in the slope S at $B_{\max}=(A\sqrt{\varepsilon_\theta})^{-2}\approx 400$ T for the experimental parameters. This value is, of course, beyond the experimental limits and, probably, even exceeds H_{c2}.

Another support for the onset of the irreversibility in a vortex liquid is the ac field amplitude dependence of the IRL. In both thermal-activated (TAFF) and pure flux-flow (FF) regimes the *I-V* curves are linear and the onset of the third harmonic is due to a change in the slope (from ρ_{FF} to ρ_{TAFF}). In this case we expect the amplitude dependence for this onset. Contrary, at the melting transition the onset of irreversibility is sharp and is not expected to depend upon the amplitute of the ac field. In our experiments we find a pronounced amplitude dependence of the IRL, thus confirming the above scenario.

B. Irradiated YBCO films

For the irradiated films the situation is quite different. The models for $T_{\text{irr}}(\theta)$ in unirradiated films cannot explain the experimental features exhibited in Figs. 4 and 5, in particular the increase in T_{irr} in the vicinity of $\theta=0$. Such a discrepancy can only be due to the angular anisotropy introduced by columnar defects, i.e., the angle-dependent pinning strength. It was shown, both theoretically[5,30] and experimentally,[37] that for a magnetic field oriented along the defects the irreversibility line is shifted upward with respect to the unirradiated system. Thus, our results in Fig. 4 suggest that the measured $T_{\text{irr}}(\theta)$ is a superposition of the angular variation of T_{irr} in unirradiated film (denoted in this section as $T_{\text{irr}}^{\text{REF}}$) and the anisotropic enhancement of the pinning strength due to irradiation.

We can estimate the latter contribution by employing the concept of a ''trapping angle'' θ_t, the angle between the external field and the defects at which vortices start to be partially trapped by columnar tracks. (For a schematic description, see Fig. 43 in Blatter *et al.*[5]) as we show in the Appendix,

$$\tan(\theta_t)\approx\sqrt{2\varepsilon_r/\varepsilon_l}, \qquad (10)$$

where $\varepsilon_r(T)$ is the trapping potential of a columnar defect and ε_l is the line tension. In the experiment we cool down at a fixed θ, and the onset of irreversibility must occur when $\theta=\theta_t(T)$, provided that the temperature is still larger than $T_{\text{irr}}^{\text{REF}}(\theta)$. Otherwise, the onset occurs at $T_{\text{irr}}^{\text{REF}}$. This defines the condition for the irreversibility temperature T_{irr} for angles $\theta\leqslant\theta_c\equiv\theta_t(T_{\text{irr}}^{\text{REF}}(\theta_t))\simeq 50°$ in our case:

$$\tan(\theta)=\tan[\theta_t(T_{\text{irr}})]\approx\sqrt{2\varepsilon_r/\varepsilon_l}. \qquad (11)$$

At high temperatures $\varepsilon_r(T)\propto\exp(-T/\widetilde{T}_{\text{dp}}^r)$, where $\widetilde{T}_{\text{dp}}^r$ is the depinning energy.[5] Thus, we can write for T_{irr}

$$T_{\text{irr}}(\theta)=\begin{cases} T_{\text{irr}}^{\text{REF}}(\theta)-D\ln[C|\tan(\theta t)|], & \theta\leqslant\theta_c, \\ T_{\text{irr}}^{\text{REF}}(\theta), & \theta>\theta_c, \end{cases} \qquad (12)$$

where D and C are constants. This expression is in an agreement with our results shown in Fig. 4 (solid line). We note, however, some discrepancy in the vicinity of $\theta=0$, where we find quite weak dependence of T_{irr} on angle. We explain this deviation by considering the influence of relaxation, which, in the case of parallel defects, depends on angle. The relaxation rate is maximal, when vortices are aligned along the defects, and retains its normal ''background'' value for perpendicular direction.[52] A vortex, captured by a defect, can nucleate a double kink which slides out resulting in a displacement of a vortex on a neighboring column. In our irradiated samples the defect lattice is very dense (the matching field $B_\phi=4$ T, i.e., distance between columns $d\approx 220$ Å) and such a double-kink nucleation is an easy process. Thus, the irreversibility temperature should be shifted down around $\theta=0$ as compared to the ''ideal,'' nonrelaxed value, Eq. (12). This explains the reduction in T_{irr} in Fig. 4.

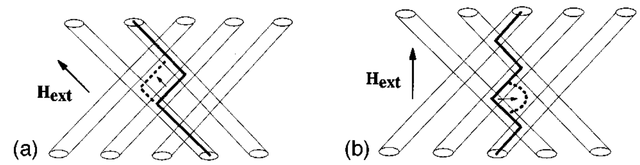

FIG. 6. Schematic description of a possible depinning modes of a vortex line in the case of crossed columnar defects: (a) magnetic field is directed along $\theta=45°$; (b) magnetic field is along $\theta=0$.

We may now conclude that in irradiated films, for angles less than the critical angle θ_c, the irreversibility line is determined by the *trapping angle* θ_t. The Bose-glass transition can probably only be found for small angles within the lock-in angle $\theta_L\leqslant 10°$. This conclusion is also indirectly confirmed in Ref. 53.

As was pointed out in the Introduction, crossed defects should hinder the relaxation due to forced entanglement of vortices. Thus, the irreversibility temperature is expected to be closer to that predicted by Eq. (12). Figure 5 shows a good agreement of the experimental data with Eq. (12) (solid line). To explain why defects crossed at large angle act collectively and force unidirectional magnetic anisotropy, we follow here the approach outlined in Ref. 41, and extend that description to account for arbitrary orientation of the external field with respect to the crossed columnar defects and to the c axis. In Ref. 41 the authors consider the possible motion of vortices in a ''forest'' of crossed defects for field oriented along the c axis. In our case of a dense lattice we may exclude from consideration free kink sliding and consider only depinning from the intersections. We sketch in Fig. 6 the two limiting situations: (a) the external field is parallel to one subsystem of the columnar defects ($\theta=45°$) and (b) the external field is oriented along the c axis, between crossed columns ($\theta=0$). In case (a), Fig. 6(a), vortices can depin just by nucleation the single kinks which are sliding from intersection to intersection or by nucleation of superkinks, resulting in a kind of motion, similar to a variable-range hopping. This type of thermally assisted vortex depinning does not cost any additional energy on vortex bending. Another situation arises for field along the c axis, Fig. 6(b). Now vortices can depin *only* via nucleation of multiple half-loops, which characteristic size depends upon current density. This results in an additional barrier for vortex depinning, which even diverges at zero current.[5] As a result, the relaxation rate is anisotropic; i.e., it is suppressed when the external field is oriented along the mid-direction between the two subsystems of the crossed columnar defects. This is just opposite to a situation in uniformly irradiated samples.

V. CONCLUSIONS

We presented angle-resolved measurements of the irreversibility temperature in unirradiated $YBa_2Cu_3O_{7-\delta}$ film and in two films with columnar defects, induced by 5.8-GeV Pb-ion irradiation, either parallel to the c axis or ''crossed'' in $\theta=\pm 45°$. We find that in the unirradiated film the transition from irreversible to reversible state occurs *above the melting line* and marks the *crossover from a pinned to an unpinned vortex liquid*. In irradiated films, within the critical angle $\theta_c \simeq 50°$, the irreversibility line is determined by the temperature-dependent *trapping angle*. For larger angles T_{irr} is determined by the intrinsic anisotropy via the effective field. The formulas for $T_{irr}(\theta)$ for both unirradiated and irradiated films are given. We also discuss the possible influence of anisotropic enhancement in relaxation rate which leads to a smearing of the expected cusp at $\theta = 0$ in the $T_{irr}(\theta)$ curve in the uniformly irradiated film. Finally, we demonstrate the collective action of crossed columnar defects, which can lead to suppression of relaxation and enhancement of pinning strength along the mid direction.

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APPENDIX

We describe here the derivation of our Eq. (10), which differs slightly from the analogous Eq. (9.173) of Blatter *et al.*[5] We derive it using exactly the same approach (and notions) as in Ref. 5, but in view of the experimental situation avoid the assumption of small angles, which allows Blatter *et al.* to approximate $\tan(\theta) \approx \sin(\theta) \approx \theta$. In order to estimate the trapping angle one has to optimize the energy change due to the vortex trapping by columnar defects. This energy is written as[5]

$$\varepsilon(r,\theta) = \varepsilon_l \left\{ r + \left[d^2 + \left(\frac{d}{\tan(\theta)} - r \right)^2 \right] - \frac{d}{\sin(\theta)} \right\} - r\varepsilon_r , \tag{A1}$$

where $r(\theta)$ is the length of the vortex segment trapped by a defect, d is the distance between the columns, ε_l is the line tension, and ε_r is the trapping potential of the defects. The variation of Eq. (A1) with respect to r at fixed angle θ defines the angular dependence of $r(\theta)$. The trapping angle θ_t can be found by solving the equation $r(\theta_t) = 0$. This results in

$$\tan(\theta_t) = \frac{\sqrt{\varepsilon_r(2\varepsilon_l - \varepsilon_r)}}{(\varepsilon_l - \varepsilon_r)}, \tag{A2}$$

which, at sufficiently small ε_r, can be approximated as

$$\tan(\theta_t) = \sqrt{\frac{2\varepsilon_r}{\varepsilon_l}} + O(\varepsilon_r^{3/2}). \tag{A3}$$

Apparently, at very small angles we recover the original result of Ref. 5. In the paper, for the sake of simplicity, we use Eq. (A3) instead of the full Eq. (A2). However, as noted above we cannot limit ourselves to small angles and, generally speaking, the trapping angle may be quite large ($\theta_t \approx 40°$ in our case). The error due to use of Eq. (A3) can be estimated as follows: At $\theta \approx 40°$ Eq. (A2) gives $\varepsilon_r/\varepsilon_l \simeq 0.24$, whereas Eq. (A3) gives $\varepsilon_r/\varepsilon_l \simeq 0.35$, which is suitable for our implication of Eq. (A3), since we consider exponential decrease of ε_r. Also, as shown in Ref. 5 in a system with anisotropy ε, the trapping angle is enlarged by a factor of $1/\varepsilon$.

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