A QUANTITATIVE UNDERSTANDING OF THE ENHANCED
IRREVERSIBILITY LINE AND CRITICAL CURRENT DENSITY DUE TO
LINEAR DEFECTS IN $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ SINGLE CRYSTALS WITH THE
VORTEX DIMENSIONALITY-CROSSOVER MODEL

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A quantitative understanding of the enhanced irreversibility line and critical current density due to linear defects in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals with the vortex dimensionality-crossover model

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ABSTRACT

We show that the 3D-to-2D crossover model of Kim et al. (*Physica C* 177, 431, 1991) provides a quantitative understanding of recent results of Thompson et al. (*Appl. Phys. Lett.* 60, 2306, 1992) for *both* the enhanced irreversibility line and critical current density, J_c , in single-crystalline $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ after heavy-ion irradiation. Fits of the irreversibility lines indicate that these linear defects increase the pinning energy by a factor of ~ 4 , which is also consistent with the low-temperature J_c enhancement. The dependence of the pinning effectiveness on the nature of artificial or natural pinning sites is discussed.

High-temperature superconductors (HTS) exhibit anomalously large broadening of their resistive transitions in high magnetic fields, which generally limits the current carrying capability of the materials for moderate to high-field applications. Recently, enhancing the critical current density J_c and extending the magnetic irreversibility region in HTS has been studied by creating artificial defects in the materials by neutron, electron, proton and heavy ion irradiation [1]. Linear defects produced by heavy ion irradiation [2,3,4] have been shown to be very effective in pinning vortices, thus enhancing J_c and significantly extending the magnetic irreversibility region. Civale et al.[2] have reported quite enhanced pinning in Sn ion irradiated $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals particularly when applied fields are parallel to the linear damage tracks. Later, similarly enhanced flux pinning was observed in iodine ion irradiated single crystals of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ [3], and enhanced J_c and extended irreversibility region have been observed by Thompson et al. [4] in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals after Sn ion irradiation. In this report, we show that the enhanced irreversibility and J_c reported in Ref. 4 can be adequately understood with the model of Ref. 5 describing the irreversibility based on a dimensional crossover in highly-anisotropic HTS, and the increase in the pinning effectiveness can be quantitatively determined.

Kim et al.[5] showed that for a magnetic field (H) parallel to the c -axis ($H||c$), the magnetic-field-induced broadening of the resistive transitions of HTS is strongly affected by the Josephson coupling across the Cu-O layer spacing. For the highly-anisotropic HTS, experimental evidence was presented that thermally-activated *flux motion* is enhanced as the flux state crosses over from three dimensional (3D) vortex *lines* to 2D independent *pancake-like* vortices in the Cu-O layers [6]. This crossover occurs as thermal fluctuations overcome the Josephson coupling energy between these layers, and this severely reduces the effective pinning, since the 2D vortices must then rely on pinning only in their own individual Cu-O multilayer. Thus the 3D-to-2D crossover of vortex structures is the main mechanism for anomalous broadening of the resistive transitions and low current carrying capability in magnetic fields in highly anisotropic HTS, compared to, e.g., $\text{YBa}_2\text{Cu}_3\text{O}_7$. Nevertheless, this model [5] recognized that the pinning strength in the uncoupled 2D Cu-O layers can become effective, especially at low temperatures.

In this model, there are two relevant energies for the pancake-like vortices. The first is for vortex motion within isolated Cu-O bilayers, and is modeled by conventional depinning [7]. In a totally isolated Cu-O bilayer, as H and/or T increase, a characteristic temperature for vortex motion within its individual Cu-O bilayer was defined for core pinning by:

$$k_B T = E_p(H, T) = \alpha_p \pi \xi_{ab}^2 s \frac{B_c^2}{2\mu_0} (1-b)^2, \quad (1)$$

where $E_p(H, T)$ is the energy associated with 2D depinning, α_p ranges from zero to one and represents the effective strength of the pinning, ξ_{ab} is the in-plane coherence length, $b \equiv H/H_{c2}$, B_c is the thermodynamic critical field and s is the layer spacing (see footnote [8]). The second energy describes coupling between adjacent Cu-O bilayers and it is given [5] by the Josephson coupling energy, $E_{cj}(H, T)$, for the phase of the superconducting order parameter [9]. The model of Ref. 5 defined a characteristic crossover temperature from 3D to 2D vortices when $k_B T = 2E_{cj}(H, T)$, where the factor of 2 accounts for both Cu-O bilayers (above and below). Note that this crossover is meaningful only if the well-coupled 3D vortex lines are sufficiently pinned somewhere along their length. For weakly-coupled Cu-O bilayers, the pancake vortices must be excited out of the total potential well, either for relaxation of magnetization or the dissipation found in transport, and that condition is:

$$k_B T = 2E_{cj}(H^*, T) + E_p(H^*, T), \quad (2)$$

which can be solved for $H^*(T)$, the crossover field. At high temperatures, E_{cj} dominates while at low temperatures E_p is more important [5].

The applicability of the 3D-to-2D crossover model has been convincingly demonstrated for a number of highly anisotropic HTS [5], including oxygen-deficient $YBa_2Cu_3O_{7-y}$ [10]. The crossover fields $H^*(T)$ were fit to Eq. 2 with the parameters $\alpha_p B_c^2(0)/2\mu_0$, $H_{c2}(0)$ and the c -axis resistivity, ρ_c , which are in good agreement with available experimental results or reasonable expectations. Furthermore, the fitted values of ρ_c showed approximately exponential dependence on the insulator spacing with a reasonable barrier height, supporting a Josephson tunneling model for the coupling.

A stringent, further test of the above model is whether it can explain the enhanced irreversibility lines of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals after Sn ion irradiation by reasonable changes in the pinning strength, E_p , alone. The irreversibility line and J_c for two crystals, #2 and #7, have been measured [4] before and after irradiation with an ion-flux density equivalent to the magnetic flux density of $B = 5$ and 10 T, respectively. Linear damage tracks were created parallel to the beam directions at angles of 2° and 30° from the crystalline c -axis and large enhancement of J_c and irreversibility regions were observed. The crossover fields before and after irradiation are shown in Fig. 1 as a log-log plot of $H^*/H_{c2}(0)$ vs. $1-t$, where $t = T/T_c$ and the symbols are the same as Ref. 4. We show $H^*(T)$ from the onset of ac response, since these data extended to the low-field, high-temperature region and were available both before and after irradiation. Each T_c was approximated by the lowest-field data points ($\sim 0.5\text{G}$) from Fig. 2 of Ref. 4.

The solid (dotted) lines are a fit of the model [5] to the data of crystals #2 (#7) using the clean-limit temperature dependence ($1-t^2$) for B_c and H_{c2} . At high temperatures, the fit determines the Josephson-coupling parameter, which is essentially ρ_c , while the rise in H^* at low temperatures determines the 2D depinning parameter, E_p . Matching $H^*/H_{c2}(0)$ with the reduced field, b , in the fitting equation determines $H_{c2}(0)$. As shown in Fig.1, the 3D-to-2D crossover model fits all data sets of $H^*(T)$ very well, suggesting that the basic mechanisms responsible for the irreversibility crossover remain unchanged. However, the magnitudes of the parameters are changed due to the heavy-ion tracks, which introduce defects in each and every Cu-O layer. The fitting parameters for both before and after irradiation are listed in Table 1 as well as those from other unirradiated $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals [5,11] for comparison. Although there is a tendency in the fit for the Josephson coupling energy to increase after irradiation, the number of the high-temperature, low-field H^* data available are insufficient to clarify this issue without further systematic work. Even so, this has an insignificant effect on E_p , which is the essential focus of this paper.

Differences of parameters among unirradiated samples are also observed (see Fig. 1); crystals #2 and #7 have narrower irreversible regions than Bi-2212A. Note that crystals #2 and #7 have higher T_c , but lower $H_{c2}(0)$ than those of Bi-2212A and B. We suggest these variations

originated more from composition than from the different methods used to obtain $H^*(T)$. Note that a resistive criterion of $\rho/\rho_n=10^{-5}$ was used to determine $H^*(T)$ in Ref. 5, where ρ_n is the normal-state, a-b plane resistivity at T_c , and this method is equivalent to a voltage criterion of $\sim 10^{-6}$ V/cm. The higher voltage criterion in the ac response of Ref. 4 ($\sim 10^{-5}$ V/cm) would lead to a larger irreversible region, so it cannot explain the above variations.

The $H_{c2}(0)$ reductions, by 2 and 4 T respectively after heavy ion irradiation, are proportional to the decrease of T_c , implying that the slope of the upper-critical field near T_c remains nearly unchanged. The corresponding increase of ~ 2 Å in $\xi_{ab}(0)$ indicates that electron transport in the remaining superconducting regions has not been greatly affected by the introduction of localized defects in every Cu-O layer. The most noticeable change due to the induced linear defects is an increase by a factor of 3-4 in the zero-field, zero-temperature pinning energy, $E_p(0,0) = \alpha_p \pi \xi_{ab}(0)^2 B_c^2(0) / 2\mu_0$. Because $\xi_{ab}(0)$ is determined by $H_{c2}(0)$, the fit value of the pinning parameter $E_p(0,0)$ is a measure of $\alpha_p B_c^2(0)$. Since $B_c(0)$ would decrease slightly following the decrease of T_c after irradiation, the increase of the pinning energy is mainly due to the increase of α_p . However, the meaning of α_p is not obvious. The model presumes that all flux lines are pinned with effective strength α_p . Experimentally, α_p could represent the strength of many such equivalent pinning sites, or some suitable average, or a measure of the weakest occupied sites. We have no independent method to measure α_p , but we can obtain a value from the fit, if $B_c(0)$ is known. We estimate $B_c(0)$ by scaling the thermodynamic critical field of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals to the measured value of $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals [12] by their T_c ratio, thus presuming that the nature of the Cu-O bilayers in these materials are the same (see Ref. 10). The scaled $B_c(0)$ for the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ samples are given in Table 1, together with the resulting effective pinning strength, α_p from $B_c(0)$ and fitted values of $E_p(0,0)$ and $\xi_{ab}(0)$. Indeed α_p increases by a factor of ~ 4 after irradiation, implying that the highly disordered or amorphous material produced by heavy ions are significantly more effective at pinning vortices than the direct pinning by residual defects arising from the crystal growing process or indirect pinning via interactions with neighboring pinned vortices. The α_p of Bi-2212A and B are higher than those of unirradiated crystals #2 and

#7, indicating better effective pinning in Bi-2212A and B, but not as good as damage induced by heavy ion irradiation. Note however that $E_p(0,0)$ for individual 2D vortices is roughly equal for all unirradiated samples, because differences in ξ_{ab} compensate for differences in α_p .

We now show a quantitative agreement with the J_c enhancement. The authors of Ref. 4 measured a J_c enhancement of factors of 2.5 and 3.5, respectively, for samples #2 and #7 at 5 K and 1 T. The factor of 3 to 4 increase of $E_p(0,0)$ found from the irreversibility line is in a good agreement with these measurements. Since the vortices are of 2D characteristics at 5 K and 1 T according to the 3D-to-2D crossover model, the increase of 2D pinning energy can be directly related to the enhancement of J_c . This view is consistent with the observation of little enhancement of the magnetic hysteresis loops when the magnetic field is oriented parallel to the damage tracks for $T = 5 - 50\text{K}$ [4] and the explanation that 2D vortices can adjust their positions easily to find pinning sites due to the relatively weak interlayer (Josephson) coupling. At zero temperature there are no fluctuation effects and J_c for 2D vortices can be estimated by equating the pinning force per unit length, i.e., $E_p/s\xi_{ab}$, to the Lorentz-force per unit length [7]:

$$\alpha_p \pi \xi_{ab}(0) \frac{B_c(0)^2}{2\mu_0} (1-b)^2 = J_c(0)\Phi_0. \quad (3)$$

From Table 1, we obtain $J_c(0)$ using Eq. 3 to be 1.0×10^7 and $9.2 \times 10^6 \text{ A/cm}^2$, for crystals #2 and #7 respectively, at a 1 T field where the $(1-b)^2$ factor is close to one. Since the parameters used to calculate $J_c(0)$ in Eq. 3 are derived from the irreversibility line data with the voltage criterion of $\sim 10^{-5} \text{ V/cm}$, the actual comparison with J_c data should consider the different voltage criterion employed in the J_c measurement [13]. In Ref. 4, J_c of 5.4 and $3.8 \times 10^6 \text{ A/cm}^2$, for crystals #2 and #7 respectively, at 5 K and 1 T were obtained with the voltage criterion of $\sim 10^{-9} \text{ V/cm}$. For example, the J_c obtained from two different voltage criteria can be matched by a power law V-I characteristic with exponent ~ 13 . This exponent is reasonable [13] for low temperatures ($\sim 5 \text{ K}$) and modest magnetic fields ($\sim 1 \text{ T}$).

It is interesting to compare to conventional superconductors the presently obtained effective pinning strength, α_p , namely the ratio of the pinning energy to the core energy. Previous systematic studies of the J_c dependence on pinning center density for Nb46.5%Ti alloy [14], NbN films [7], and NbN/AlN multilayers [7] have shown that α_p depends on the ratio of core diameter, 2ξ , to the width of the superconductors between pinning centers, d , both measured in the direction of flux motion, and reaches a maximum near $2\xi/d=1$. For $2\xi/d \ll 1$, the small density of pinning centers reduces α_p . For $2\xi/d > 1$, the narrow superconducting regions are a less-effective barrier against flux motion, and in addition, for the case of like defects of constant size, the current carrying capability is reduced because of less superconducting material. For irradiated $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ crystals, the corresponding values of $2\xi/d$ are ~ 0.6 and ~ 1.2 for #2 and #7, respectively, indicating that the ion flux was in an optimal range. However, α_p was only 0.08. Low as it is, this value is not inconsistent with low-temperature superconductors. The peak value of α_p , obtained from the very highest measured J_c in Nb46.5%Ti by Cooley et al. [14], is only ~ 0.065 . For NbN films, a higher value of 0.18 was obtained when applied magnetic fields are parallel to the grain boundaries [7]. In NbN/AlN multilayers, much higher value of ~ 0.5 was obtained for magnetic fields parallel to the very regular, planar AlN pinning layers [7].

Note that these quoted values of α_p depend strongly on $B_c(0)$, which was determined in NbN by extrapolating the bulk specific heat jump [15] to individual T_c values, and from the lower and upper critical fields [7,12] for Nb46.5%Ti. However, we suggest that the variation of the maximum values of α_p among the materials is more likely at least partly related to the randomness of pinning centers. For example, NbN/AlN multilayers have the largest α_p for regularly-spaced, planar insulating AlN layers as pinning centers, while for the smaller α_p found in Nb46.5%Ti and irradiated $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ crystals, the regularity of defect locations are least controllable. This implies that in order to maximize the effectiveness of artificial defects, regularly-spaced pinning centers seem necessary. The large intrinsic pinning in HTS for magnetic fields parallel to the highly regular Cu-O bilayers is also consistent with this viewpoint. For example, the highest J_c

measured [16] in $\text{YBa}_2\text{Cu}_3\text{O}_7$, with the magnetic field carefully aligned to the a-b planes of epitaxial films, corresponds to $\alpha_p \sim 0.6$, using [12] $B_c(0) = 0.82 \text{ T}$.

We have shown that the 3D-to-2D crossover model can explain the enhancement of J_c and the irreversibility line recently found in single-crystalline $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ after heavy-ion irradiation. The parameters resulting from the fit of the crossover field H^* show a factor of ~ 4 increase in the pinning effectiveness which accounts for the J_c enhancement as well. In the fits of Ref. 5, the experimental data could not distinguish between 2D depinning and 2D melting. Here we have addressed only depinning because the very large shift in the irreversibility lines seems to us to be inconsistent with any simple concept of 2D melting. A recent theory of 3D vortices by Nelson and Vinokur [16] suggests that columnar defects can increase the melting transition temperature, also resulting in a shift of the irreversibility line to higher temperatures. However, this theory may be more appropriate to the strictly 3D vortex structure found in fully-oxygenated $\text{YBa}_2\text{Cu}_3\text{O}_7$ [2,5].

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dynamic measurements. This leads to a smaller value of α_p by a factor of $s/d_s \sim 5$ for the data presented in Fig. 3 of Ref. 10: thus $\alpha_p \sim 0.05$, instead of the quoted value of 0.25.

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Figure Caption

Fig. 1. The crossover fields before and after irradiation for single crystals #2 and #7 of Ref. 4 and an unirradiated single crystal Bi-2212A are normalized by the fit value of $H_{c2}(0)$ and plotted vs. $1-t$. The solid (dotted) lines are fits to the 3D-to-2D crossover model for the data of crystal #2 (#7).

Table Caption

Table 1. The parameters obtained from the fits shown in Fig. 1 are listed, with $H_{c2}(0)$, ρ_c and $E_p(0,0)$ obtained directly and the others derived. The pinning energy per unit area is expressed as a fraction α_p of the condensation energy per unit area, e_c , that is, $\alpha_p e_c(0) \equiv \alpha_p s B_c^2(0)/2\mu_0$. We determined $B_c(0)$ by scaling to the measured value for YBa₂Cu₃O₇ single crystals by the T_c ratio thus allowing the determination of α_p from Eq. 1.

Table 1

Sample	Ref.	T_c (K)	$\mu_0 H_{c2}(0)$ (T)	$\xi_{ab}(0)$ (Å)	ρ_c (Ω cm)	$\alpha_p \epsilon_c(0)$ (10^{-9} J/cm ²)	$E_p(0,0)$ (10^{-22} J)	$B_c(0)$ (T)	α_p (-)
#2, $B\phi=0$	4	89	25	36	140	0.98	3.9	0.79	0.025
#7, $B\phi=0$	4	89	25	36	250	0.86	3.4	0.79	0.022
#2, $B\phi=5$ T	4	85.7	23	37	87	2.94	13	0.76	0.082
#7, $B\phi=10$ T	4	81	21	39	170	2.58	12	0.72	0.081
Bi-2212A	5	80	40	28	34	1.55	3.9	0.71	0.049
Bi-2212B	11	79	40	28	84	1.48	3.7	0.70	0.049

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