Suppression of matching field effects by splay and pinning energy dispersion in $YBa_2Cu_3O_7$ with columnar defects

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We report measurements of the irreversible magnetization M_i of a large number of $YBa_2Cu_3O_7$ single crystals with columnar defects (CD). Some of them exhibit a maximum in M_i when the density of vortices equals the density of tracks, at temperatures above 40 K. We show that the observation of these *matching field effects* is constrained to those crystals where the orientational and pinning energy dispersion of the CD system lies below a certain threshold. The amount of such dispersion is determined by the mass and energy of the irradiation ions, and by the crystal thickness. Time relaxation measurements show that the matching effects are associated with a reduction of the creep rate, and occur deep into the collective pinning regime.

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The rather complex vortex dynamics in high T_c superconductors (HTSC's) with columnar defects (CD's) results in the existence of a rich variety of pinning and creep regimes.[1,2] The simplest case to model[1,2] is that of **H** aligned with identical parallel CD. At low T and for $H \ll B_\Phi$ (where B_Φ is the *matching field*, at which the densities of vortices and CD are the same), vortex-vortex interactions are small and each vortex is individually pinned to an individual track, while for $H > B_\Phi$ pinning becomes collective. As T increases, thermal fluctuations reduce the effective pinning energy of the CD, thus the vortex-vortex interactions turn more significant and the accommodation field $B_a(T)$ (the boundary between individual and collective regimes) decreases.[3]

A peculiar situation occurs for $H \sim B_\Phi$. At low T a Mott insulator phase is predicted.[1,2] The infinite elastic compression modulus C_{11} of this phase results in a fixed density of vortices (constant B) over a finite range of H. The dynamics is also influenced by the matching condition. As all the CD's are occupied, a pinned vortex has no energetically convenient places to jump into. The result is a reduction of the flux creep rate, as indeed observed at very low T by Beauchamp *et al.*[4] in $YBa_2Cu_3O_7$ (YBCO) crystals and by Nowak *et al.*[5] in Tl:2201 crystals.

At high T the wandering of the vortices precludes localization into individual CD. Although this should inhibit the presence of the Mott phase,[1,2] some reduction in the vortex mobility is still expected due to the absence of empty tracks. However, many studies of pinning by CD in HTSC have failed to show any evidence of *matching effects* at high T. The exception is a recent study by Mazilu *et al.*[6] on YBCO thick films (thickness $\delta \sim 1$ μm) with CD $\|c$ axis. For **H**$\|$CD, they found that the transport critical current had a broad peak at $H \sim B_\Phi$, at T as high as 75 K.

In this work we report matching effects due to CD in YBCO crystals, deep into the collective pinning regime at high T. For tracks in various crystalline orientations and for **H**$\|$CD, the irreversible magnetization $M_i(H)$ exhibits a maximum at $H \sim B_\Phi$ and a minimum in its normalized time relaxation rate $S = -d(\ln M_i)/d(\ln t)$. We show that the appearance of these matching effects requires a narrow angular distribution (small splay) and a small pinning energy dispersion of the CD. These conditions impose a maximum track length (given by the sample thickness and the irradiation angle) that depends on the mass and energy of the irradiation ions.

We observed matching effects in four YBCO single crystals, and for comparison we show analogous measurements in several others that do not exhibit such effects. The information about the source, thickness, and irradiation conditions of all the crystals is given in Table I. A MPMS-5 superconducting quantum interference device (SQUID) magnetometer was used to determine M_i (proportional to the persistent current density J via the critical state model) from $M(H)$ loops, and its time relaxation over periods of 2 h. In all cases **H**$\|$CD, and in those crystals where $\Theta_D \neq 0$ (here Θ_D is the angle between the tracks and the c axis), both the longitudinal and transverse components of $\mathbf{M}_i(H)$ were recorded and the data were processed as previously described.[12]

Figure 1(a) shows M_i vs H for crystal A1 ($\Theta_D \approx 57°$) at several T between 40 and 75 K. These curves show a clear maximum at fields $H_m(T) \sim B_\Phi$, similar to that found[6] in transport measurements in YBCO thick films with **H**$\|$CD$\|c$ axis. Several features reinforce the similarity: (i) The maximum is only present above 40 K; (ii) at this temperature H_m is slightly higher than B_Φ, and (iii) H_m slowly decreases with increasing T.

Many studies of M_i in YBCO crystals with CD in the same H and T ranges of Fig. 1(a) have been reported, but usually the maximum is not observed. The question is why these matching effects are visible only in some cases. A dis-

TABLE I. Irradiation ion and energy, matching field, irradiation angle, and thickness of all the crystals studied. Group A was grown at the Centro Atómico Bariloche (Ref. 7) and irradiated at the Tandar facility in Buenos Aires, Argentina (Ref. 8). Groups B and C were grown at the T.J. Watson Research Center of IBM (Ref. 9), and irradiated at the TASCC facility in Chalk River Laboratories, Canada (group B) (Ref. 10), or at the Holifield accelerator, Oak Ridge, USA (group C) (Ref. 11). The crystals labeled with an asterisk present matching effects.

Crystal	ion	$B_\Phi(T)$	Θ_D	$\delta(\mu m)$	$\delta/\cos\Theta_D(\mu m)$
A1*	300 MeV Au^{24+}	2.2	57°	4.1	7.5
A2	300 MeV Au^{24+}	3.7	15°	8.2	8.5
A3	300 MeV Au^{24+}	3.0	32°	8.5	10.0
B1*	1080 MeV Au^{23+}	4.7	0°	11.5	11.5
B2*	1080 MeV Au^{23+}	5.7	30°	11.5	13.3
B3*	1080 MeV Au^{23+}	2.4	0°	24.7	24.7
B4	1080 MeV Au^{23+}	0.6	0°	26.8	26.8
B5	1080 MeV Au^{23+}	1.0	65°	11.4	27.0
B6	1080 MeV Au^{23+}	1.1	2°	31.0	31.0
C1	580 MeV Sn^{30+}	1.0	2°	20.5	20.5
C2	580 MeV Sn^{30+}	3.0	2°	22.0	22.0
C3	580 MeV Sn^{30+}	3.0	30°	20.9	24.1
C4	580 MeV Sn^{30+}	3.0	2°	25.7	25.7
C5	580 MeV Sn^{30+}	5.0	2°	27.0	27.0

tinctive characteristic of crystal A1 is that it is unusually thin, $\delta\approx 4.1\ \mu$m. The films of Mazilu *et al.*[6] are of course even thinner, $\delta\sim 1\ \mu$m. In contrast, most crystals with CD reported in previous studies have typically $10\ \mu\text{m}\leqslant\delta\leqslant 30\ \mu$m. This suggests that these matching effects may be restricted to thin samples.

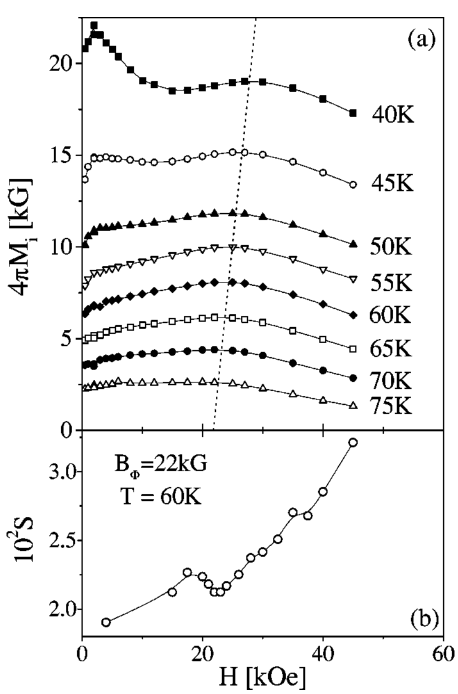

FIG. 1. (a) Irreversible magnetization M_i vs H for crystal A1 at several T. The dotted line is a guide to the eye indicating the maximum at $H_m(T)$. (b) Normalized relaxation rate vs H at $T=60$ K.

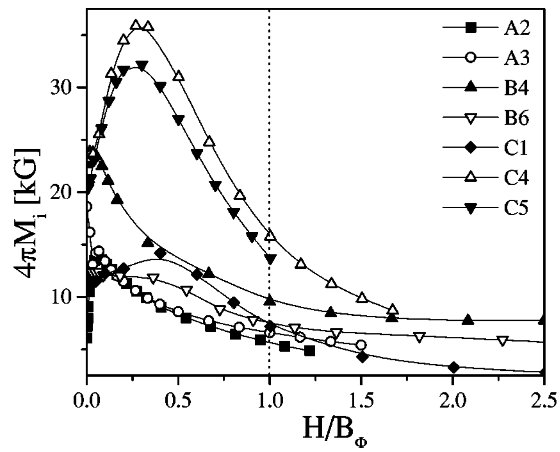

FIG. 2. Irreversible magnetization M_i vs H/B_Φ for several crystals. None of these samples show any hint of matching effects at $H\sim B_\Phi$.

To test this hypothesis, we collected $M_i(H)$ data for $\mathbf{H}\|$CD for a representative group of 13 additional crystals irradiated with ions of different mass and energy, at various B_Φ and Θ_D (see Table I). Figure 2 shows $M_i(H)$ for 7 crystals at $T=60$ K. None of them show evidence of matching effects. In all cases the maximum is also absent at other T in the range 40 K$\leqslant T\leqslant$80 K. In contrast, the $M_i(H)$ curves of crystals B1 and B2, shown in Figs. 3(a) and 3(b), respectively, do exhibit a clear maximum near B_Φ. Again in these two crystals H_m decreases slowly with T. Finally, Fig. 3(c) shows crystal B3, where a small structure in $M_i(H)$ just suggests the existence of matching effects. In the three cases (B1, B2, and B3) the matching effects disappear below 40 K.

Figures 1 and 3 show that (at $T\sim 40$ K), $H_m/B_\Phi\sim 1.1$ for A1, but is only ~ 0.85 for B2 and ~ 0.75 for B1. This may be due to clustering of the tracks.[3] As B_Φ increases, so does the probability that two or more CD are so close together that they act as a single pin. The result is an "effective" matching field lower than the nominal B_Φ. For B1, the effective tracks' density was found[3] to be $\sim 0.7B_\Phi$, while for a crystal with a dose similar to A1 the result was $\sim 0.9B_\Phi$. Thus, there is a reasonable agreement indicating that H_m is in all cases slightly higher than the *effective* matching field.

To some extent Figs. 2 and 3 reinforce the idea that matching effects appear in thin samples, as crystals B1 and B2 are among the thinnest in the group. However, the correlation is far from perfect: A2, A3, and B5, that are as thin as B1 and B2 or thinner, show no maximum, while B3, that is rather thick, shows at least a hint of it.

A simple reason for the absence of matching effects in thick crystals could be that the spatial variation of the internal field in the critical state[13] $\Delta B\sim(4\pi/c)J\delta/2$ is large enough to wash away those effects. However, even in our thickest crystals $\Delta B\leqslant 0.6$ kG, much smaller than the width of the peaks around H_m, which is well above 10 kG in all cases. Thus, the variation in B cannot be the reason for the absence of matching effects.

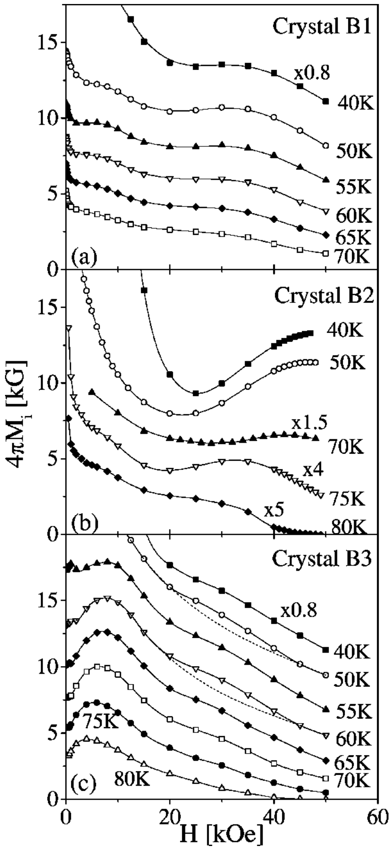

FIG. 3. Irreversible magnetization M_i vs H at several T for three crystals that exhibit matching effects. For clarity, some curves are multiplied by a factor, as indicated.

Sample thickness influences pinning by CD in a more indirect way, as it affects the morphology and disorder of the tracks. The irradiation ions arrive to the sample surface with a very narrow distribution of energy and orientations, thus at $x=0$ (where x is the distance traversed by the ions inside the sample) all the CD are identical and parallel. But as their energy decreases rapidly with x due to the very large electronic stopping power, the diameter of the tracks first decreases, then becomes oscillatory and eventually the tracks turn discontinuous,[14] thus producing a dispersion in the pinning energy. In addition, the scattering with the atomic cores of the material (associated with the small but nonzero nuclear stopping power) deviates the ions generating[10,15] an angular dispersion (splay) of the tracks that grows with x, first slowly and then dramatically near the ion penetration range. The distributions of pinning energies and orientations are then wider for thicker samples.

We will argue below that the larger dispersion in the CD precludes the observation of matching effects in thick crystals, and to that end we need a quantitative measure of the disorder. Splay and energy dispersion depend on x in a complex way.[14,15] Splay can be quantified by the median radial angle of the angular distribution of tracks $\alpha_{SP}(x)$, as we have previously done[10,15] for CD produced by 1.08 GeV Au^{23+} and 580 MeV Sn^{30+} in YBCO crystals. That determination was based on TRIM simulations that coincided very

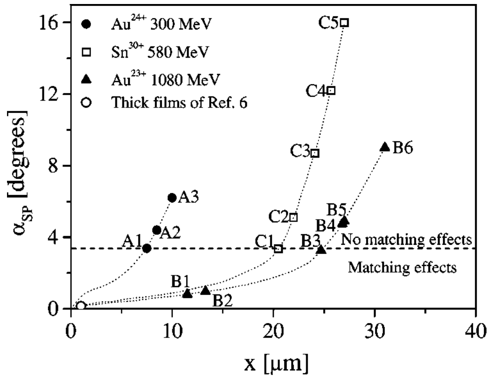

FIG. 4. Median radial angle α_{SP} of the CD as a function of the distance traversed by the ions inside the material x for the three irradiation conditions (dotted lines). The symbols indicate the values of $\alpha_{SP}(x=l_D)$ at the back end of the tracks for all the samples investigated. Samples with $\alpha_{SP}(l_D)<3.4°$ exhibit matching effects, as opposed to the crystals with $\alpha_{SP}(l_D)>3.4°$.

well with direct measures of α_{SP} at selected x from TEM images. We have now extended those calculations to 300 MeV Au^{24+}, and in Fig. 4 we plotted the $\alpha_{SP}(x)$ curves for the three cases.

As we look for a simplified description, we quantify the disorder in each crystal by a single parameter, namely, the maximum value of α_{SP} which occurs at the back end of the tracks ($x=l_D=\delta/\cos\Theta_D$). Thus, in Fig. 4 we collected the values of $\alpha_{SP}(x=l_D)$ for all our crystals and for the thick films of Ref. 6. It is unmistakably clear that there is a threshold value of $\alpha_{SP}(l_D)\approx 3.4°$ above which the matching effects disappear. All samples with $\alpha_{SP}(l_D)$ well below the threshold (B1, B2, and the films) exhibit clear matching effects. None of the nine crystals well above the threshold show any hint of it. Finally we have three crystals, irradiated in different conditions, with almost exactly the same $\alpha_{SP}(l_D)\approx 3.4°$. One of them shows a clear matching effect (A1, see Fig. 1); another one shows just a minor hint [B3, Fig. 3(c)]; and the third one shows no effect (C1, Fig. 2).

Figure 4 shows that, using a single parameter, we have been able to ascertain under what conditions matching effects are observable in YBCO with CD. Although we do not claim that $\alpha_{SP}(l_D)$ is the only or even the best quantifier of the tracks disorder, we emphasize that our simple scenario successfully describes the behavior of our 14 crystals and all the films of Ref. 6, with no exceptions.

The observation of the maximum at H_m at temperatures as high as 80 K is somewhat surprising, since the Mott phase is only expected at low T.[1,2] It is true that the broad peak in $M_i(H)$ seen in our crystals is a feature far less dramatic than the Meissner-like response of the Mott insulator, but the physical origin is clearly the same: The maximum in the pinning efficiency at $B\sim B_\Phi$ occurs because, being all the vortices pinned and all the tracks occupied, there are no energetically convenient places for a vortex to move on from its initial position.

If our picture is correct, the maximum in $M_i(H)$ should be accompanied by a decrease in the creep rate, which is precisely the feature used previously[4,5] to identify the Mott insulator phase at very low T. Figure 1(b) shows the normalized relaxation rate S as a function of $\mathbf{H}\|$CD at $T=60$ K for crystal A1. A minimum appears for $H\sim B_\Phi$, thus confirming that matching fields effects at high T are due to a reduction of creep.

It is important to note that in the temperature range of our study vortex pinning is collective.[3] Crystals B1, B3, and B6 were investigated in Ref. 3, where it was shown that in the three cases $B_a(T)$ drops abruptly at the B_Φ-independent *depinning temperature* $T_{dp}\approx 40$ K, above which pinning is collective except at extremely low $H\ll B_\Phi$. We have recently shown[16] that T_{dp} for irradiations with 580 MeV Sn^{30+} and 300 MeV Au^{24+} (in particular for crystal C4) is also very similar.

Previous determinations of $B_a(T)$ were done for CD parallel to the c axis. To check whether the large Θ_D makes any difference in this respect, we obtained $B_a(T)$ for crystal A1 through creep measurements at several T and $\mathbf{H}\|$CD, as was previously done.[3] The results again show that $T_{dp}\approx 35$ K, demonstrating that also in this case the vestiges of the Mott insulator phase [the $H_m(T)$ field] lie well inside the collective pinning regime. Within this regime and at fixed T, a monotonically increasing $S(H)$ is expected.[1,2] This is consistent with the results in Fig. 1(b), where the creep minimum at B_Φ is mounted on the increasing curve.

The two main results of our study are that matching effects occur deep into the collective pinning regime, and that these effects are destroyed by sufficiently large splay and dispersion of pinning energy in the system of CD. We will now discuss the second result, and later we will address the first one.

The main features of the pinning diagram by CD are expected[1,2] to be robust with respect to the energy dispersion and splay: Pinning should still be individual and strong at low T and H, and should become collective and weaker above $B_a(T)$. Experiments confirm that expectation,[3,8,11,16] as the basic pinning behavior is similar in all crystals in spite of the different amounts of disorder in their CD. In contrast, the dynamics at $J\ll J_c$ is strongly influenced by the dispersion in the CD,[10,16] thus the link between matching effects and dispersion must be related to differences in the creep processes.

In the single vortex pinning regime, initial relaxation takes place[1,2] via nucleation and expansion of *half loops*. As J decreases the size of the critical nucleus grows and reaches the nearest CD. Further relaxation proceeds by spreading of *double kink* excitations. Ideally, in the absence of energy dispersion and splay there is no barrier for the expansion of a double kink critical nucleus, and J should decrease very rapidly.[1,2] Creep mechanisms in the collective pinning regime are different and less explored theoretically, but vortex bundles are still expected to relax via collective double kinks,[2] whose expansion is again unimpeded in the absence of splay and energy dispersion.

Both splay and energy dispersion of the CD arrest the expansion of double kinks by reducing the number of sites with equivalent energy available for hopping and spreading. Topological constrains to vortex hopping were first discussed by Hwa *et al.*[17] It is indeed established experimentally that a certain amount of splay, either naturally occurring[10] or artificially introduced[18] enhances M_i and reduces the creep rate in YBCO. Energy dispersion makes the expansion of double kinks energetically unfavorable in the limit $J\rightarrow 0$.[1,2] Double kinks are then substituted by *superkinks*, whose time relaxation is much slower (the so-called *variable range hopping* regime). We have recently shown[16] that fast relaxation by double kinks does occur in YBCO crystals, and that the slow-down of creep due to the crossover to the superkinks regime takes place at a current density J_{VRH} proportional to the energy dispersion.

The above discussion leads us to propose the following scenario. If splay and energy dispersion are small, creep is fast and the overall measured M_i is low, except near matching condition where creep slows down due to the absence of available sites. As a result, the M_i measured at a given time is higher around B_Φ than in the rest of the field range, thus producing the observed maximum. In contrast, the large amount of splay and energy dispersion in thick samples arrests the expansion of double kinks, thus the relaxation is slow in the whole field range and the reduction of the creep rate near B_Φ becomes negligible or absent. In these conditions, the overall M_i is high and the maximum at the matching condition disappears.

With regards to the presence of matching effects in the collective pinning regime, numerical simulations[19] have indeed predicted some effects of the Mott phase at high T, but only for $\lambda/d\leqslant 1$, where $d=\sqrt{\Phi_0/B_\Phi}$ is the average distance between CD. This results from the condition that the vortex-vortex interactions have to be of short range as compared with d. However, in our case $\lambda\approx 1400$ Å and d ranges from 190 Å for crystal B2 to 300 Å for crystal A1, thus $\lambda/d\geqslant 4.7$ in all cases. Krauth *et al.*[20] have studied the problem of 2D bosons in a disordered environment, which is analogous to the problem of flux lines in the presence of CD.[1] Through Monte Carlo simulations they found that the Mott phase could be present up to the transition to the Bose-glass phase, but they only considered on-site repulsion, which is again equivalent to the condition $\lambda/d<1$.

Recently, Sugano *et al.*[21] performed Monte Carlo simulations of pancake vortices in the much more anisotropic $Bi_2Sr_2CaCu_2O_8$, with CD$\|c$ axis. Neither splay nor pinning energy dispersion were included. One of their results, particularly relevant to our present work, was the observation[21] of a high-temperature anomaly at $\sim B_\Phi$, thought to be a *remnant* of the low-temperature Mott insulator phase. This anomaly is accompanied by a sudden increase in the vortex trapping rate (a slow down of creep), which according to those simulations is dominated by expansion of double kinks. All those results are consistent with our scenario, according to which the maximum in $M_i(H)$ at $H\sim B_\Phi$ is due to the reduction of the rate of creep by double kinks.

In summary, we have observed matching field effects in the irreversible magnetization and its time relaxation in $YBa_2Cu_3O_7$ single crystals with columnar defects. A necessary condition for the appearance of these effects is a low level of angular and energy dispersion in the CD system. To achieve this situation, an adequate combination of thin samples and high irradiation energy is required. Large dispersion precludes the appearance of matching effects by slowing down creep over the whole field range. We propose the value of the splay at the back face of the sample $\alpha_{SP}(l_D)$, as a convenient parameter to quantify the dispersion. Surprisingly, these matching effects are observed at high T, deep into the collective pinning regime, where the Mott phase is not expected.

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