Vortex Dynamics in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ with In-plane Columnar Defects Introduced by Irradiation

Andra Petrean^{1,2}, Lisa Paulius³, Valentina Tobos⁴, Heather Cronk¹, and Wai-Kwong Kwok²

¹*Department of Physics, Austin College, Sherman, TX 75090, USA*

²*Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA*

³*Department of Physics, Western Michigan University, Kalamazoo, MI 49008, USA*

⁴*Department of Natural Sciences, Lawrence Technological University, Southfield, MI 48075, USA*

Abstract

We report on the effects of introducing columnar defects by irradiation in clean single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ in a direction *parallel* to the *ab*-plane. The defects were introduced by bombarding the samples with $^{208}\text{Pb}^{56+}$ ions at an energy of 1.4 GeV. We find that the defects suppress the first order melting transition for magnetic fields aligned parallel or at small angles relative to the defects. The columnar defects *inhibit* vortex motion of vortices parallel to the defects, while the vortices experience less pinning when they are perpendicular to the defects. Our results suggest that the pinning anisotropy is increased, at least for magnetic fields up to the matching field dose of 1 T.

Keywords

$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$
Columnar defects
Vortex dynamics
Pinning anisotropy

1. Introduction

The high temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ still holds a lot of interests for researchers, although it was discovered more than twenty-five years ago. Clean single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ display a first-order phase transition from a vortex solid state to a vortex liquid state [1-3]. In the presence of disorder, it was predicted [4-6] and shown [7-9] that the transition is second order, and the solid state is either a vortex glass [4] in the presence of random point defects generated by light particle irradiation [9] or chemical substitution [10], or a Bose-glass [5, 6] in the presence of columnar defects generated by heavy-ion irradiation [11, 12]. The order of the phase transition and the nature of the vortex solid are not the only ones changing upon the introduction of defects: the position of the irreversibility line, and hence the vortex pinning anisotropy of the material also changes. [The irreversibility line represents the position in the magnetic phase diagram at which a critical current first appears.] For example, it was shown that columnar defects raise the irreversibility line [7] and reverse the pinning anisotropy [13], while random point defects lower the irreversibility line even though they do not induce additional anisotropy [9, 14, 15]. In the quest to produce a more isotropic high temperature superconductor, researchers have shown [14] [16, 17] that a combination of both columnar defects oriented parallel to the c-axis and point defects reduces the anisotropy of the irreversibility line, $H_{\text{irr}} \parallel \text{ab} / H_{\text{irr}} \parallel \text{c}$, while increasing the overall pinning strength.

The role that the superconducting anisotropy plays in the nature of the vortex liquid (or even the existence of the vortex liquid) in the presence of columnar defects has also been of interest in recent years, and researchers have compared the pinning behavior of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ to that of the isotropic $(\text{K}, \text{Ba})\text{BiO}_3$ superconductor [18-20]. In one of these works [18] it was found that the irreversibility line moved up for magnetic field applied parallel to the defects introduced by heavy-ion irradiation in $(\text{K}, \text{Ba})\text{BiO}_3$, while for perpendicularly applied fields, the irreversibility line did not shift in regards to that of the pristine sample. In another work [19] the pinning energy near the Bose-glass transition was calculated for the two compounds and it was suggested that the nature of the transition is different in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ from that of $(\text{K}, \text{Ba})\text{BiO}_3$. Klein *et al.* [20] suggest that in this isotropic material, in the presence of columnar defects, there is no vortex liquid state, but the Bose glass directly sublimates into the normal state in which superconducting fluctuations still exist.

While the interplay between the columnar defects and the anisotropy of the material is of great interest [21], most studies involving columnar defects introduced by heavy-ion irradiation in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (or another $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$) have been performed with the defects oriented either *perpendicular* to, or at large angles relative to, the superconducting Cu-O planes. While some studies have focused on correlated defects parallel to the Cu-O planes [22-25], these studies have been performed on thin films and quasi-single crystals with Y_2BaCuO_5 precipitates. Given that these types of samples have a lot of intrinsic disorder, it is difficult to discern between the effects of the intrinsic disorder and those of the added columnar defects. Our study is

performed on a clean $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystal, with a well-defined anisotropy when pristine. Our main goal was to see if the pinning anisotropy of the material is increased upon irradiation.

2. Experimental Details

The single crystal of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ was grown using a self-flux method using powders of Y_2O_3 , BaCO_3 , and CuO with a purity of 99.99% or better as described elsewhere [26]. The crystal was subsequently annealed for 10 days under flowing oxygen at 420°C , yielding an optimally doped twinned single crystal with a transition temperature of 92.90 K. The presence of twin boundaries was detected under polarized light.

In order to create the irradiation defects uniformly throughout the thickness of the crystal, we need to thin the sample such that its thickness is less than the range of the ion in the material. SRIM calculations [27] show that for 1.4 GeV Pb ions to pass through a sample of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, the sample needs to be less than $38\text{ }\mu\text{m}$ in the direction of the irradiation. Typically, as-grown $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystals are platelet shaped and are much larger in the lateral ab-plane than in the c-axis direction. The single crystals also have a layered structure, with the layers parallel to the ab-plane. Both the dimensions of the samples and the layered structure make polishing them parallel to the ab-plane relatively straightforward. However, since we are irradiating the sample *parallel* to the ab-plane, we polished the crystal perpendicular to the ab-plane. The layered structure of the crystal makes this very difficult, as the

crystal is micaceous and breaks when thin. After numerous attempts, we successfully polished one of the lateral dimensions down to 27 μm . The crystal used in this study had final dimensions of 660(l) $\times$ 86(w) $\times$ 27(t) μm^3 .

The heavy ion irradiation was performed using the 36" diameter ATSCAT chamber at the Argonne Tandem Linear Accelerator System (ATLAS), at Argonne National Laboratory. We irradiated the sample with 1.4 GeV $^{208}\text{Pb}^{56+}$ ions at room temperature. The thickness of the sample (27 μm) was less than the 38 μm range of penetration of these ions in $\text{YBa}_2\text{Cu}_3\text{O}_7$, which ensures that the ions traverse the entire thickness of the sample. The ion radial range is 1.3 μm at the 38 μm range. The total irradiation dose was 5×10^{10} ions/ cm^2 , which can also be expressed as a “matching field B_Φ ” dose of 1T. At this dose, the number of ion tracks equals the number of vortices when a magnetic field of 1 T is applied. The defects are at an average distance of approximately 45 nm from each other.

As shown in the inset of Figure 1, the current is applied in the ab-plane and perpendicular to the columnar defects created by heavy ion irradiation. The resistivity was measured using a standard four-probe ac technique at a frequency of 23 Hz. The crystal was placed in the bore of two superconducting magnets: a 1.5 T split coil transverse magnet residing inside the bore of an 8 T solenoid magnet. By varying the strength of the two magnets, the net magnetic field H was rotated with respect to the crystal, as shown in the inset of Figure 1. The net field was always perpendicular to the current, for a maximum Lorentz force. The net magnetic field

could be rotated from parallel to the c-axis (*perpendicular* to the columnar defects) to parallel to the ab-plane (*parallel* to the defects).

3. Before the irradiation

Magneto-transport measurements were carried out along both the $H \parallel c$ and $H \parallel ab$ direction before the irradiation. The pre-irradiation normalized resistivity as a function of temperature is shown in Figure 1 for applied magnetic fields of 1, 2, 4, and 8 T for $H \parallel c$ and $H \parallel ab$, with an applied current of 0.5 mA. For both orientations of the field, the resistivity curves display the kink due to the first order vortex melting transition [28]. The vortex melting transition, as well as other features, can be seen clearly from the temperature derivative of the resistivity, shown in Figure 2 for an applied magnetic field of 4T. For both orientations, we see sharp peaks in the derivative, which correspond to the superconducting transition (SC) at higher temperatures, and to the first-order vortex melting transition (FOT) at lower temperatures. For $H \parallel ab$, the sample is slightly misaligned, as a perfect alignment of the magnetic field with the ab-plane would lead to the suppression of the first-order transition due to intrinsic pinning [29]. For $H \parallel c$ we see another peak due to twin boundary (TB) pinning, when the vortices are aligned with the twin boundaries. The first order transition is also accompanied by the onset of non-ohmic behavior (shown in the inset Figure 3 for $H = 4T$).

In order to determine the anisotropy of the crystal we plot the irreversibility lines for $H \parallel c$ and $H \parallel ab$ before the irradiation, determined from the peak in the

derivative of the resistivity vs. temperature at the first order transition, and shown by the open symbols in Figure 4.

The pre-irradiation irreversibility lines can be fit to an equation of the form $H = H_0(1 - T/T_{C0})^\alpha$ where T_{C0} is the zero-field transition temperature and H_0 and α are fitting parameters. These fits can be seen as solid lines through the open symbols in Figure 4. The form given in the above equation allows us to extract information about the anisotropy of the crystal. Our fits yielded values of $H_{0c} = 114 \pm 3$, $\alpha_c = 1.41 \pm 0.02$ for $H \parallel c$ and $H_{0ab} = 781 \pm 141$, $\alpha_{ab} = 1.38 \pm 0.05$. The ratio of H_{0ab}/H_{0c} yields the anisotropy ratio γ . Our results for the power exponents α and for $\gamma = 6.8 \pm 1.5$ are in agreement with values obtained in other works [1] [13].

4. After the irradiation

4.1 Increase in the anisotropy

As a result of the irradiation, the zero-field transition temperature has shifted from 92.90 K to 92.51 K. For $H \parallel$ defects (and hence $H \parallel ab$), the kink in the resistivity curve is absent after the irradiation and replaced with a smooth curve at all the magnetic fields investigated, indicating a complete suppression of the first order vortex melting transition. Previous experiments also reported a complete suppression of the first order melting transition for magnetic fields applied parallel to the columnar defects introduced by heavy ion irradiation [13], although in that study the defects (and the applied fields) were parallel to the c-axis. In our study we still observed non-ohmic behavior: the resistivity curves taken at different currents

separate as the temperature is decreased. Figure 3 shows the post-irradiation normalized resistivity as a function of temperature for applied magnetic fields of 1, 2, 4, and 8 T and for currents of 0.5 mA and 0.1 mA. The data is plotted on a semi-log scale, to better observe the non-ohmic behavior. In the inset we show both the unirradiated and the irradiated resistivity data at 4 T. It clearly shows that the onset of non-ohmic behavior occurs at higher temperatures for the post-irradiated than the pre-irradiated sample. We use the onset of non-ohmic behavior in order to determine the irreversibility line. Figure 4 shows the magnetic field versus temperature phase diagram. For $H \parallel ab$, the irreversibility line shifts to higher temperatures as a result of the irradiation. Therefore the columnar defects *inhibit* vortex motion when the vortices are aligned with the defects, in this case, for $H \parallel ab$. The irradiation dose was equivalent to a “matching field B_Φ ” of 1 T, and we see that even at a field of 8 T, where vortices outnumber defects by a factor eight, the post-irradiation irreversibility line lies above the pre-irradiation curve.

Previous experiments in which the irradiation was done parallel to the c-axis found that the irreversibility line also shifts to higher temperatures when the vortices are aligned with the defects, and hence the columnar defects also *inhibit* vortex motion. Paulius *et al.* [13] conducted studies in which single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ were irradiated parallel to the c-axis with 1-GeV uranium ions at a matching field dose of 2 T. They found that for $H \parallel ab$ (vortices perpendicular to the defects) the irreversibility line shifts *down* following the irradiation. This behavior was attributed to the suppression of intrinsic pinning by the defects, which create new channels for

vortex creep motion between the layers, hence lowering the irreversibility line for $H \parallel ab$. In their work, for applied fields larger than 0.2 T, the irreversibility line for $H \parallel c$ shifted above the line for $H \parallel ab$, showing a reversal in the anisotropy line. Taken together, our work with that of Paulius *et al.*, indicate that defects parallel to the c axis decrease the anisotropy of the irreversibility line, while defects parallel to the ab -plane increase that anisotropy. In clean samples of YBCO, the irreversibility line for $H \parallel c$ is lower than $H \parallel ab$ due to the inherent anisotropy of the system. Irradiating along $H \parallel c$ increases the pinning in this direction and hence lowers the anisotropy. In contrast, irradiation along $H \parallel ab$ increases the pinning along ab and hence enhancing the pinning anisotropy.

The irreversibility line's shift to higher temperatures for $H \parallel ab$ suggests that the pinning anisotropy of the material is increased by the columnar tracks. The behavior of the irreversibility line for $H \parallel c$ would completely clarify this issue: if the irreversibility line for this orientation moves down, or is not affected by the irradiation, that would indicate an increase in the anisotropy. Although we were unable to take a complete set of the resistivity data for $H \parallel c$ after the irradiation due to the irreparable degradation of the electrical contacts, we did obtain data at 1T and 0.5T. The irreversibility at 1T and 0.5 T for $H \parallel c$ after the irradiation does lie *below* the irreversibility line at the same fields before the irradiation, as shown in Figure 4, indicating an increase in the anisotropy at these fields. The downward shift in the irreversibility line for $H \parallel c$ can be attributed to the creation of easy channels for the vortices to creep along the length of the columnar defects.

Another way we can obtain information regarding the pinning anisotropy is by measuring the angular dependence of the resistivity. We have obtained data by applying a magnetic field of 1 T at selected angles with respect to the defects (and hence to the ab-plane) and then measuring the resistivity as a function of temperature at each angle. We have defined an irreversibility line from the zero resistivity temperature using a criterion of $\rho^* = 1.0 \mu\Omega\text{-cm}$. We can therefore extract T^* for each angle at a field of 1 T. Palstra *et al.*[30] claim that a resistivity criterion that is independent of the current is more meaningful in determining the onset of a critical current, and hence the position of the irreversibility line. In our case, we are not in the ohmic regime, so in effect, the criterion is current dependent. However, using a different criterion (such as $\rho^* = 0.2 \mu\Omega\text{-cm}$) does not affect the relative position of the irreversibility lines in the phase diagram. The inset in Figure 4 shows T^*/T_C versus the angle θ with the ab-plane of the 1 T applied magnetic field. In the pre-irradiation data we see that T^*/T_C decreases as we move away from the ab-plane: this is due to the anisotropy of the material. As the applied magnetic field becomes more closely aligned with the c-axis, (at about 20 degrees and less) we see an increase in T^*/T_C : this is due to the presence of the twin boundaries. The post irradiation data shows a steeper angular dependence of T^*/T_C than the pre-irradiation curve. This indicates an increase in the anisotropy: the larger the departure from a flat line, the higher the anisotropy. We conclude that the pinning anisotropy for our sample was increased at $H = 1\text{T}$, where the number of vortices matches that of the defects. Due to the

deterioration of the electrical contacts, we do not have reliable data at other fields, so we do not know if this trend continues when the vortices outnumber the defects.

From the same inset of Figure 4, we notice that the value of T^*/T at $\theta = 90^\circ$ ($H \parallel c$), is higher after the irradiation, which suggests that the irreversibility line moves down for this orientation. This result implies that when the vortices are perpendicular to the defects they experience less pinning. In this orientation the Lorentz force is parallel to the defects, and it is possible that the defects create ‘channels’ through which the vortices can ‘slide.’

4.2 Recovery of melting

As previously mentioned, the irradiation produces a complete suppression of the first order melting transition for $H \parallel$ defects (and hence the ab-plane). We measured the resistivity for magnetic fields tilted away from the defects. We applied a magnetic field at selected angles with respect to the defects and then measured the resistivity as a function of temperature at each angle. For fields applied parallel to the defects ($H \parallel ab$), after the irradiation the kink in the resistivity curve is absent and replaced with a smooth curve. However, as we tilt away from the defects we recover first order melting transition, as shown in the bottom inset of Figure 5 for an applied magnetic field of 4 T. As shown in the inset, the temperature derivative of the resistivity shows only one peak, corresponding to the superconducting (SC) transition for $H \parallel$ defects. As the field is tilted away, a second peak, corresponding to the first order (melting) transition - FOT, appears. Figure 5 plots the angle at which this transition reappears as a function of applied field. We see that the angle decreases as the magnetic field increases.

In other works [31] [32], where similar samples were irradiated with Uranium ions in a direction *perpendicular* to the ab-planes, no recovery of melting for any orientation of the magnetic field with respect to the defects was observed. In the study by Paulius *et al.* [32], samples were irradiated parallel to the c-axis with 1-GeV $^{238}\text{U}^{40+}$ ions at a matching field dose of 2T. This irradiation produced much more drastic effects than ours: the transition temperature dropped by $\sim 5\text{K}$ (compared to only $\sim 0.4\text{K}$ in our study). They observed a dip in the angular resistivity when the vortices are aligned with the defects; beyond a certain angle, called the depinning angle, the resistivity recovers the pre-irradiation shape, due to the intrinsic anisotropy of the material. They related the depinning angle to the microscopic pinning characteristics: when the field is applied at angle with respect to the columnar defects, a vortex line trapped in the columnar defect consists of a trapped piece and two healing regions on each side of the trapped piece. At low temperatures, where thermal energies can be neglected, the depinning angle coincides with the accommodation angle, at which the trapped length goes to zero

Paulius *et al.* [13] found that for magnetic fields of 1 T and 4T, the depinning angle increases roughly linearly with decreasing temperature and then saturates to a maximum value at lower temperatures. In a 1T applied field, this saturation angle is 75° and in 4T the value is $\sim 24^\circ$. In our case, as shown in the upper inset of Figure 5, we observe that the angle at which the first order transition appears has a similar behavior: it increases roughly linearly with decreasing temperature. The angular dependence in both studies implies that when the magnetic field is tilted far enough from the defects, the vortices become un-trapped from the defects. One key

difference between these studies is that the first order transition is observed in our work but not in that of Paulius *et al.* This may be due to the type of ions used in the irradiations (Lead vs. Uranium), the different matching dose (1T vs. 2T), or the different irradiation configuration (parallel to the *ab-plane* vs. parallel to the *c-axis*).

5. Conclusions

We irradiated clean single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ in a direction *parallel* to the *ab-plane*. Before the irradiation the samples display the first-order melting transition. After the irradiation this transition is suppressed for magnetic fields aligned parallel or at small angles relative to the defects. We found an increase in pinning for $H \parallel ab$. Therefore the columnar defects *inhibit* vortex motion for vortices parallel to the defects ($H \parallel ab$). The downwards shift of the irreversibility line for $H \parallel c$, the upward shift of the irreversibility line for $H \parallel ab$, and the angular dependence of the onset of irreversibility $H = 1\text{T}$ all suggest that the pinning anisotropy is increased over the magnetic field range measured.

This work was supported by the US Department of Energy, under contract DE-AC02-06CH11357 and by National Science Foundation under grant No. DMR-0072880.

References

- [1] W.K. Kwok, S. Fleshler, U. Welp, V.M. Vinokur, J. Downey, G.W. Crabtree, M.M. Miller, Vortex lattice melting in untwinned and twinned single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, *Physical Review Letters*, 69 (1992) 3370-3373.
- [2] H. Safar, P.L. Gammel, D.A. Huse, D.J. Bishop, J.P. Rice, D.M. Ginsberg, Experimental evidence for a first-order vortex-lattice-melting transition in untwinned, single crystal $\text{YBa}_2\text{Cu}_3\text{O}_7$, *Physical Review Letters*, 69 (1992) 824-827.
- [3] M. Charalambous, J. Chaussy, P. Lejay, V. Vinokur, Superheating of the Abrikosov flux lattice, *Physical Review Letters*, 71 (1993) 436-439.
- [4] M.P.A. Fisher, Vortex-glass superconductivity: A possible new phase in bulk high- T_c oxides, *Physical Review Letters*, 62 (1989) 1415-1418.
- [5] D.R. Nelson, V.M. Vinokur, Boson localization and pinning by correlated disorder in high-temperature superconductors, *Physical Review Letters*, 68 (1992) 2398-2401.
- [6] D.R. Nelson, V.M. Vinokur, Boson localization and correlated pinning of superconducting vortex arrays, *Physical Review B*, 48 (1993) 13060-13097.
- [7] L. Civale, A.D. Marwick, T.K. Worthington, M.A. Kirk, J.R. Thompson, L. Krusin-Elbaum, Y. Sun, J.R. Clem, F. Holtzberg, Vortex confinement by columnar defects in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals: Enhanced pinning at high fields and temperatures, *Physical Review Letters*, 67 (1991) 648-651.
- [8] M. Konczykowski, F. Rullier-Albenque, E.R. Yacoby, A. Shaulov, Y. Yeshurun, P. Lejay, Effect of 5.3-GeV Pb-ion irradiation on irreversible magnetization in Y-Ba-Cu-O crystals, *Physical Review B*, 44 (1991) 7167-7170.
- [9] A.M. Petrean, L.M. Paulius, W.K. Kwok, J.A. Fendrich, G.W. Crabtree, Experimental Evidence for the Vortex Glass Phase in Untwinned, Proton Irradiated $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, *Physical Review Letters*, 84 (2000) 5852-5855.
- [10] M. Angst, S.M. Kazakov, J. Karpinski, A. Wisniewski, R. Puzniak, M. Baran, Critical currents and order-disorder phase transition in the vortex states of $\text{YBa}_2\text{Cu}_3\text{O}_8$ with chemically introduced disorder, *Physical Review B*, 65 (2002) 094518.
- [11] W. Jiang, N.C. Yeh, D.S. Reed, U. Kriplani, D.A. Beam, M. Konczykowski, T.A. Tombrello, F. Holtzberg, Evidence of a Bose-glass transition in superconducting $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals with columnar defects, *Physical Review Letters*, 72 (1994) 550-553.
- [12] D.S. Reed, N.C. Yeh, M. Konczykowski, A.V. Samoilov, F. Holtzberg, Critical scaling of third-harmonic transmissivity near the Bose-glass transition in $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals with columnar defects, *Physical Review B*, 51 (1995) 16448-16451.
- [13] L.M. Paulius, J.A. Fendrich, W.K. Kwok, A.E. Koshelev, V.M. Vinokur, G.W. Crabtree, B.G. Glagola, Effects of 1-GeV uranium ion irradiation on vortex pinning in single crystals of the high-temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, *Physical Review B*, 56 (1997) 913-924.
- [14] J. Hua, U. Welp, J. Schlueter, A. Kayani, Z.L. Xiao, G.W. Crabtree, W.K. Kwok, Vortex pinning by compound defects in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, *Physical Review B*, 82 (2010) 024505.
- [15] J.A. Fendrich, W.K. Kwok, J. Giapintzakis, C.J. van der Beek, V.M. Vinokur, S. Fleshler, U. Welp, H.K. Viswanathan, G.W. Crabtree, Vortex Liquid State in an Electron Irradiated Untwinned $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Crystal, *Physical Review Letters*, 74 (1995) 1210-1213.
- [16] B. Maiorov, S.A. Baily, H. Zhou, O. Ugurlu, J.A. Kennison, P.C. Dowden, T.G. Holesinger, S.R. Foltyn, L. Civale, Synergetic combination of different types of defect to optimize pinning landscape using BaZrO₃-doped $\text{YBa}_2\text{Cu}_3\text{O}_7$, *Nat Mater*, 8 (2009) 398-404.

- [17] D.M. Feldmann, T.G. Holesinger, B. Maierov, H. Zhou, S.R. Foltyn, J.Y. Coulter, I. Apodoca, 1000 A cm⁻¹ in a 2 μ m thick YBa₂ Cu₃O_{7-x} film with BaZrO₃ and Y₂ O₃ additions, *Superconductor Science and Technology*, 23 (2010) 115016.
- [18] C. Marcenat, S. Blanchard, J. Marcus, L.M. Paulius, C.J. van der Beek, M. Konczykowski, T. Klein, Anisotropic Enhancement of Superconductivity in Heavy-Ion Irradiated (K,Ba)BiO₃, *Physical Review Letters*, 90 (2003) 037004.
- [19] C.J. van der Beek, M. Konczykowski, L. Fruchter, R. Brusetti, T. Klein, J. Marcus, C. Marcenat, Thermodynamics of the vortex liquid in heavy-ion-irradiated superconductors, *Physical Review B*, 72 (2005) 214504.
- [20] T. Klein, C. Marcenat, S. Blanchard, J. Marcus, C. Bourbonnais, R. Brusetti, C.J. van der Beek, M. Konczykowski, Direct Transition from Bose Glass to Normal State in the (K,Ba)BiO₃ Superconductor, *Physical Review Letters*, 92 (2004) 037005.
- [21] L. Fang, Y. Jia, V. Mishra, C. Chaparro, V.K. Vlasko-Vlasov, A.E. Koshelev, U. Welp, G.W. Crabtree, S. Zhu, N.D. Zhigadlo, S. Katrych, J. Karpinski, W.K. Kwok, Huge critical current density and tailored superconducting anisotropy in SmFeAsO_{0.8}F_{0.15} by low-density columnar-defect incorporation, *Nature Communications*, 4 (2013).
- [22] T. Steinborn, H. Adrian, E. Brecht, H. Fuess, M. Maul, G. Mieke, K. Petersen, M. Rodewald, M. Rao, W.W. Schmahl, C. Traeholt, J. Wiesner, G. Wirth, H. Zandbergen, J. Zegenhagen, Orientational Changes in the ab plane of YBa₂Cu₃O_{7- δ} Films on Different Substrates, *Journal of Applied Crystallography*, 29 (1996) 125-133.
- [23] J.I. Martin, E.M. Gonzalez, W.-K. Kwok, J.L. Vincent, Flux pinning forces in irradiated a-axis oriented EuBa₂Cu₃O₇ films, 1999.
- [24] L.M. Civalé, B. MacManus-Driscoll, J.L. Wang, H. Holesinger, T.G. Foltyn, S.R. Serquis, A. Arendt, P.N., Identification of intrinsic ab-plane pinning in YBa₂Cu₃O₇ thin films and coated conductors *Applied Superconductivity*, *IEEE Transactions on* 15 (2005) 2808-2811.
- [25] T.P. J Figueras, X Obradors, R J Olsson, W K Kwok and G W Crabtree, Multidirectional in-plane linear correlated disorder pinning of vortices in YBa₂Cu₃O₇, *Superconductor Science and Technology*, (2008) 025002.
- [26] D.L. Kaiser, F. Holtzberg, M.F. Chisholm, T.K. Worthington, Growth and microstructure of superconducting YBa₂Cu₃O_x single crystals, *Journal of Crystal Growth*, 85 (1987) 593-598.
- [27] J.P.B.a.J.F. Ziegler, Transport of Ions in MATTER (TRIM) - Monte Carlo Simulation Program Ver. 91.14.
- [28] J.A. Fendrich, U. Welp, W.K. Kwok, A.E. Koshelev, G.W. Crabtree, B.W. Veal, Static and Dynamic Vortex Phases in YBa₂Cu₃O_{7- δ} , *Physical Review Letters*, 77 (1996) 2073-2076.
- [29] W.K. Kwok, U. Welp, V.M. Vinokur, S. Fleshler, J. Downey, G.W. Crabtree, Direct observation of intrinsic pinning by layered structure in single-crystal YBa₂Cu₃O_{7- δ} , *Physical Review Letters*, 67 (1991) 390-393.
- [30] T.T.M. Palstra, B. Batlogg, R.B. van Dover, L.F. Schneemeyer, J.V. Waszczak, Dissipative flux motion in high-temperature superconductors, *Physical Review B*, 41 (1990) 6621-6632.
- [31] W.K. Kwok, L. Paulius, D. Lopez, H. Safar, R.J. Olsson, A.M. Petrean, G.W. Crabtree, Induced Point and Correlated Disorder Pinning in Untwinned YBa₂Cu₃O_{7- δ} Crystals, *Materials Science Forum* 315 - 317 (1999) 314-321.
- [32] L.M. Paulius, W.K. Kwok, J.A. Fendrich, R.E. Shamu, A.M. Petrean, S.M. Ferguson, G.W. Crabtree, Using radiation damage to increase critical currents in high temperature superconductors, *AIP Conference Proceedings*, 392 (1997) 919-922.

Figure 1. Normalized electrical resistivity before irradiation for $H \parallel c$ (open symbols) and $H \parallel ab$ (solid lines), at 8, 4, 2, and 1 T, going from left to right. The inset shows the sample configuration. The sample was thinned perpendicularly to the ab -plane. The ions bombarded the sample *parallel* to the ab -plane. The current flowed in the ab -plane while *perpendicular* to the defects. The applied magnetic field was oriented perpendicular to the current.

Figure 2. The normalized resistivity (symbols) and its temperature derivative (continuous and dashed curve) at 4T. The peaks in the derivative are due to the superconducting transition (SC), the first order transition (FOT) and for the $H \parallel C$ data, the twin boundary pinning (TB).

Figure 3. Normalized electrical resistivity after the irradiation for $H \parallel ab$ for two currents, 0.5 mA (symbols) and 0.1 mA (continuous line). The inset shows both the unirradiated and the irradiated resistivity data at 4 T for 0.5 mA (symbols) and 0.1 mA (continuous line).

Figure 4. Phase diagram for the crystal before and after irradiation. The irreversibility line is determined from the onset of non-ohmic behavior. The inset shows the irreversibility line as a function of the angle θ between the applied field and the defects at an applied field of 1T.

Figure 5. The angle at which first order melting reappears as the magnetic field is tilted away from the defects. The lower inset shows the normalized resistivity and its derivative as a function of temperature for a magnetic field of 4T applied parallel to the defects ($\theta = 0^\circ$) and for $\theta = 20^\circ$ away from the defects. The upper inset shows the dependence of the angle on the first order melting transition temperature.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5