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Effect of columnar defects on the elastic behavior of vortices in $YBa_2Cu_3O_{7-\delta}$ thin films

R. A. Doyle,* W. S. Seow, J. D. Johnson, and A. M. Campbell
Interdisciplinary Research Centre in Superconductivity, University of Cambridge, West Cambridge Site, Cambridge CB3 0HE, England

P. Berghuis, R. E. Somekh, and J. E. Evetts
Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street CB2 3QZ, Cambridge, England

G. Wirth and J. Wiesner
Gesellschaft fur Schwerionenforschung, Planckstrasse 1, D-64291, Darmstadt, Germany

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A sensitive ac transport technique is used to determine the force displacement response in the elastic regime of vortices pinned in $YBa_2Cu_3O_{7-\delta}$ thin films both before and after irradiation with 2.7 GeV U^{238} ions. The restoring force that pinning defects exert on the vortices, and the elastic limit of displacement of the vortices before they depin are extracted from these data. The columnar defects which lie parallel to the c axis are seen both to increase the restoring force on the vortices for $\mathbf{B}\|c$ and also to reduce the elastic limit in this orientation to a value very close to the damage track diameter. Estimates of the pinning energies and correlation volume for collective pinning before and after irradiation are made and discussed.

Dissipation in the mixed state of high-T_c oxide superconductors is intimately related to the large anisotropy, and the large thermal energy relative to the pinning energy.[1] For magnetic fields applied parallel to the c axis, vortices are unpinned at fields which are significantly lower than the upper critical field, B_{c2}. This irreversibility line, $B_{\mathrm{irr}}(T)$, has been described by various models in terms of flux-creep, vortex-glass (melting) transitions, or Josephson-type descriptions.[1,2] While much interest has focused on understanding this irreversibility line, rather less attention has been paid to the mechanisms by which static and thermal disorder determine J_c in the mixed state below the irreversibility line where the superconductor is practically useful.

For arbitrary orientation of applied magnetic field, pinning in high-T_c materials has mostly been thought of as resulting from a dense, random array of weak point pinning centers. The small coherence length means that defects on the scale of the unit cell can act to pin vortices. Planar modulations of the order parameter are very effective at pinning vortices when these are parallel to the defects and the driving force is normal to them. In particular, the superconducting CuO_2 bilayers cause "intrinsic pinning" for vortices parallel to them trying to move across the planes due to a normal force.[3] Twin planes also result in enhanced pinning when $J \times B$ is perpendicular to these planes.[4] For random orientations of an applied field, oxygen defects (vacancies) have often been suggested as the dominant point pinning center.[5] Griessen *et al.* have recently suggested that the pinning in $YBaCu_3O_{7-\delta}$ (YBCO) films is due to a $\Delta\kappa$ rather than a ΔT_c mechanism[6] and that pinning is attributed to oxygen vacancies. On the other hand, screw and edge dislocations have been shown to be strong line pinning centers at low to intermediate fields.[7]

Numbers of experiments have now also shown that introduction of random static disorder into high-T_c films and crystals by irradiation with protons,[8] neutrons,[9] light ions[10] or heavy ions[11] results (for sufficiently low doses that the superconducting volume fraction is not significantly reduced) in enhancement of the critical current. The former three projectiles introduce three-dimensional (3D) pointlike defects, while high-energy heavy ions result in introduction of amorphous columnar defects parallel to the projectile direction.[11] This correlated static disorder significantly enhances J_c and also shifts the irreversibility line to higher fields,[12] especially when the columns are splayed.[13] These columnar defects have been the subject of much interest since they are predicted[14] to produce a Bose-glass transition of the vortex lattice. Most studies of the effects of heavy ion irradiation have involved investigation of the transport or magnetization critical current.[15,16] Bitter pattern techniques,[17] magneto-optical studies[18] or microstructural analysis.[19] However, the explicit mechanism for the J_c enhancement is not yet fully understood. Clearly the introduction of disorder will introduce additional pinning sites, and in particular, planar or extended linear defects are expected to act as the most effective pins. In quasi-3D systems like YBCO it is important to determine whether vortices parallel to the c axis are depinned by shear (of the vortices into shorter segments), or activation along part or all of their lengths.

In addition to the vortex-defect interaction, dipole-dipole interaction between the flux lines results in "collective-pinning" effects. These were described for a weak dilute pinning systems by Larkin and Ovchinnikov[20] who introduced the concept of a correlation volume for bundles of vortices. In the presence of stronger and/or denser pinning, Yamafuji has shown that

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this theory has to be modified to take into account explicitly the elastic limit of the displacement d_0 of vortices before they depin.[21] In the layered high-T_c systems, the situation is complex because the effects of anisotropy, thermal fluctuations and thermal depinning on the nonlocal elastic behavior of the vortex lattice have to be taken into account.[7,22] Calculation of the correlation volume in order to identify regimes of single, small bundle and large bundle collective pinning are therefore, not straightforward, but reasonable estimates and have begun to be made from both Ginzburg-Landau (GL) and London theory.[1,7,22] Clearly there is a need for a consistent determination of these parameters in high-temperature superconductors (HTS), but very few estimates exist and these are mostly indirect. Longitudinal correlation lengths L_c have been inferred from varying YBCO/PBCO multilayer thicknesses,[23] collective-creep analyses of magnetic relaxation data,[24] vortex-glass scaling,[25,26] dc transformer measurements,[27] and some detailed theoretical calculations.[7] Transverse correlation lengths R_c have been evaluated from J_c data from vibrating reed experiments[28] and relaxation data using collective-creep analyses.[6,24]

It is well known that in the limit of small applied ac forces, vortices oscillate elastically in their pinning environments. Force-displacement measurements[29,30] allow the extraction of parameters in this elastic regime which are unavailable from dc transport or magnetic measurements. In particular, the restoring force which the vortices feel and the elastic limit of displacement before vortices depin may be extracted. These give valuable information which allows the mean effective gradient, and spatial extent of the pinning defects to be determined.[31] Transport force-displacement measurements have been made to investigate the effect of introduction of columnar defects and to calculate values for the transverse and longitudinal correlation lengths for collective pinning. These are presented and discussed and the results are compared with various recent studies[23–46] which have estimated single-vortex and collective-pinning parameters in HTS systems.

A high quality *c*-axis epitaxial YBCO film was prepared by dc sputtering. The film preparation and measurement details are described elsewhere.[33] The film, thickness $t \approx 200$ nm, was patterned into lines with length, $l = 1$ mm and width, $w = 20$ μm. The transport technique for extraction of the force-displacement curve involves the usual four-point geometry for measurement of resistance. However we use an ac current in the kilohertz range (3.3 kHz). The resistive component of the complex voltage measures dissipation in the sample and is analogous to a dc I-V curve, while the quadrature component is induced by reversible motion of the vortices in the elastic regime below J_c. The force-displacement curve can then be generated by plotting the (Lorentz) force $F_L = BJ\sin(\omega t)$ versus the displacement which is given by $V = El = \omega Bld\cos(\omega t)$ where d is the vortex displacement. The voltage is obtained directly using dual phase lock-in amplifiers and all values presented here are rms. All measurements are made in the maximum Lorentz force configuration with B normal to both the patterned line axis and the current. The sample could be rotated around this axis using stepper motors with a resolution of 0.1 degrees.

Care was taken to ensure the results were independent of frequency in this regime and that spurious background signals induced by inductive coupling in the leads and by common mode signals were removed to better than 0.1% using an ac bridge. The force-displacement characteristics of the film in the intermediate-field regime (0–1.5 T) were measured close to 77 K at $t = T/T_c = 0.86$. It is expected that effects of thermal activation are significant but not dominant at this temperature (at least at the lowest fields measured), since kT is about 7 meV and most estimates of the pinning or activation energies for YBCO in this regime are of the order of 10^2 meV. The different energies measured by various experiments (and their interrelations) are defined and discussed below. Further, since we compare the same sample before and after irradiation at very similar temperatures, we are able to separate the effect of the columnar defects. The dc magnetoresistance for $\mathbf{B} \| c = 0$–7 T was also measured to extract the resistive irreversibility line. The zero field dc J_c for the film at 77 K and zero applied field was 1.9×10^6 A/cm^2 before irradiation.

Irradiation with 2.7 GeV ^{238}U ions was performed at the UNILAC heavy ion accelerator in Darmstadt. The film was irradiated at room temperature with a flux of 4×10^7 ions cm^{-2} s^{-1} perpendicular to the film surface (parallel to the c axis). The dose, or number of impact sites per unit area, allows a matching field B_Φ to be defined where the defect spacing equals the vortex spacing, $a_0 = (2/\sqrt{3})^{1/2}(\Phi_0/B)^{1/2}$. This B_Φ is chosen to be close to 400 mT (with an estimated error of 10%). The range of the ions and the electronic energy loss are calculated to be 62 μm and 51 keV/nm, respectively, for YBCO. The range is considerably larger than the film thickness. Since the energy loss for U ions is close to the highest value attainable in such experiments and far above the threshold value for the creation of columnar defects (about 20 keV/nm), we are sure to have generated uniform straight columnar defects. Irradiation by U ions of this energy induces defects with an effective diameter of 5–10 nm.[41] The mechanism for pinning by such extrinsic defects is thought to be through disorder associated with this electronic energy loss.[42]

Figure 1 shows the zero-field resistive transitions for the film before and after irradiation. The insets show an expanded view of the resistive transition before and after irradiation and the corresponding irreversibility lines for $\mathbf{B} \| c$ determined using a criterion of 1% of the resistance at 100 K. The inset showing the resistance as a function of temperature reveals that the curves cross close to T_c. This indicates that the columnar defects markedly increase the average bulk disorder resulting in a larger ρ_N, while T_c itself is shifted from 89 K to a higher temperature of 90 K. The other inset shows that the irreversibility line is significantly shifted towards higher fields by the columnar damage. Whereas numerous reports have shown that the irreversibility line may be shifted, the sizeable shift in T_c is somewhat surprising. Since we measure at the same constant current before and after irradiation, this may be partly due to J_c being significantly

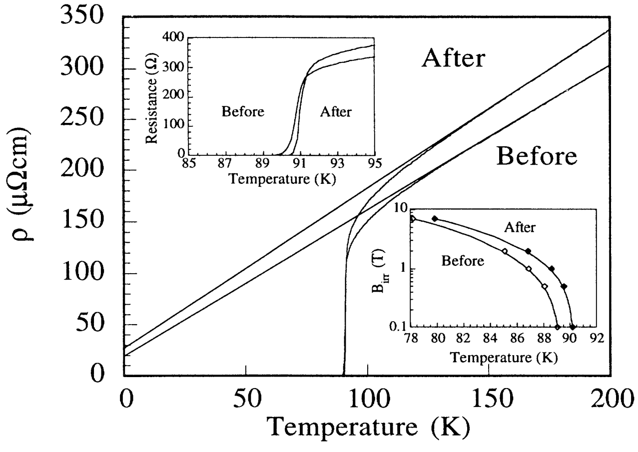

FIG. 1. Temperature dependence of the resistivity of the sample before and after irradiation with U ions. The normal-state resistivities are extrapolated to $T=0$ K. The top left inset shows an expanded view of the resistance transition indicating that T_c is moved to a higher temperature and R_N to a higher resistance (close to T_c) after irradiation. The lower bottom insert shows the effect of irradiation on the irreversibility line which is clearly moved to higher field values. The lines are guides for the eye in this latter inset.

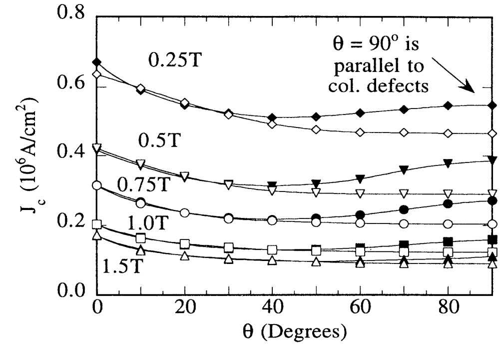

FIG. 2. The angular dependence of the critical current density for the sample at $t=0.86$ before and after irradiation. A criterion of 50 nV/mm is used to determine the critical current density, $\theta=0$ corresponds to $\mathbf{B}\|ab$. The closed symbols correspond to the behavior after irradiation. The lines are guides for the eye.

shifted relative to the measuring current ($J=2.5\times10^6$ A/m^2). However since the measuring current density is small we estimate a temperature shift of 5 mK from the slope of $J_c(T)$ approaching T_c due to this change in current density. Thus we suggest that this shift is more likely due to oxygen reordering or loss (these films are frequently slightly oxygen overdoped in the as-prepared state) or local recrystallization during the irradiation.

All measurements both before and after irradiation were made at the same reduced temperature taking the small enhancement of T_c into account. The angular dependence of J_c before and after irradiation at $t=0.86$ and several applied fields spanning the matching field are presented in Fig. 2. These are extracted from the resistive component of the complex voltage (using a criterion of 50 nV/mm) which are indicated in Fig. 3(a) for three angles at 0.5 T. While the results for $\mathbf{B}\|ab$ are unchanged, the critical current for $\mathbf{B}\|c$ is enhanced at all fields for angles about 40° either side of the c axis and the maximum enhancement occurs for $\mathbf{B}\|c$ and therefore parallel to the defect direction.

The force-displacement curves were extracted from the imaginary part of the voltage as explained above and are plotted in Fig. 3(b) for $B=0.5$ T for two angles. The slope α of the elastic (almost linear) regime in the force-displacement curve gives the restoring force from which the Labusch parameter, $\alpha_L=\alpha\Phi_0/B$, related to the mean initial curvature of the pinning well, may be calculated. In practice, we select a small number of points in the initial regime and use a least-squares fit to get the slope. This process is iterated, incrementing the number of points until a 5% error in the fit is induced. This fit is then taken to represent the initial slope. Extrapolation of the slope to the maximum pinning force (BJ_c) allows the elastic limit of displacement d_0 to be identified by the projection of this point onto the displacement axis. The restoring force is plotted in Fig. 4 at 0.5 and 1 T as a function of angle, before and after irradiation. The re-

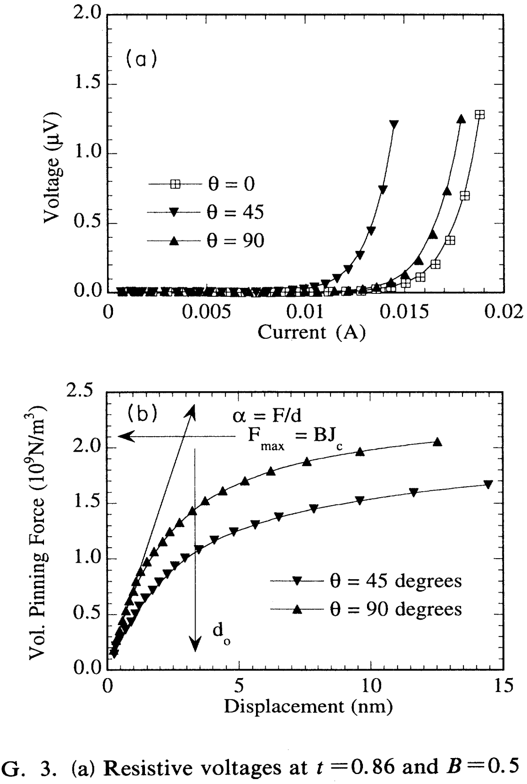

FIG. 3. (a) Resistive voltages at $t=0.86$ and $B=0.5$ T after irradiation for three angles of magnetic field with respect to the ab planes and (b) force displacement curve determined from the inductive voltage corresponding to angles 45° and 90° in 3(a). The lines indicate how the restoring force and elastic limit are determined from the initial slope, $\alpha=F/d$, and the maximum pinning force, BJ_c for the 90° curve.

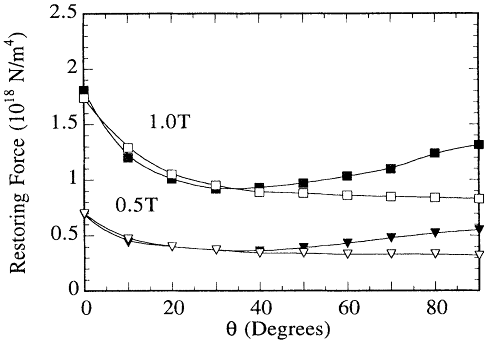

FIG. 4. The angular dependence of the restoring force (slope of the force-displacement curve) for two representative fields of 0.5 and 1 T at $t=0.86$ before and after irradiation. The closed symbols correspond to the case after irradiation. Lines are guides for the eye.

storing force for $\mathbf{B}\|ab$ is evidently unchanged, while for all fields there is a clear enhancement of the restoring force on the vortices when they are parallel to the c axis and the columnar defects. This is in agreement with the enhancement of J_c. The broad maximum in the enhancement is reasonably explained by the resolved component of the pinning force determined by the relative angle of the field and the columnar defects, much like the case for intrinsic pinning. The initial region of the force-displacement curves seems to suggest less curvature for $\mathbf{B}\|c$ and the irradiation tracks, indicating that the pinning wells are better approximated by a parabolic potential. This suggests an intriguing means of trying to determine the change in *shape* of the pinning potential well with respect to the crystal axes. However, the signals are small in this region, and we defer this to future work.

Figure 5 shows the field dependence of d_0 for $\mathbf{B}\|ab$ and $\mathbf{B}\|c$ before and after irradiation. The inset shows the angular dependence of d_0 at 0.5 T to indicate how it decreases for $\mathbf{B}\|c$ after irradiation. Again, the behavior for $\mathbf{B}\|ab$ is unchanged within experimental uncertainty while for $\mathbf{B}\|c$, the columnar defects result in a *decrease* of the elastic limit—an important result. The decrease in d_0 is clear for all fields, but most pronounced below the matching field, $B_\Phi=400$ mT. Figure 6 shows d_0 versus $1/(B^{1/2})$, the field dependence of the vortex spacing. The linear fits indicate that the d_0 values for $\mathbf{B}\|c$ before irradiation, and after irradiation above the matching field, have the same dependence on field as the vortex spacing.

The reduced dependence of d_0 on field below B_Φ after irradiation is expected for strong pinning where the defect density exceeds the vortex density and the hexagonal symmetry of the Abrikosov lattice is thus significantly perturbed as observed elsewhere.[17] Above B_Φ (where each column pins one vortex), additional vortices entering the sample lie in the undamaged regions and the behavior returns to a strong-field dependence. However the columnar defects still act to damp lattice perturbations, decreasing d_0 and increasing the longitudinal correlation length (see below).

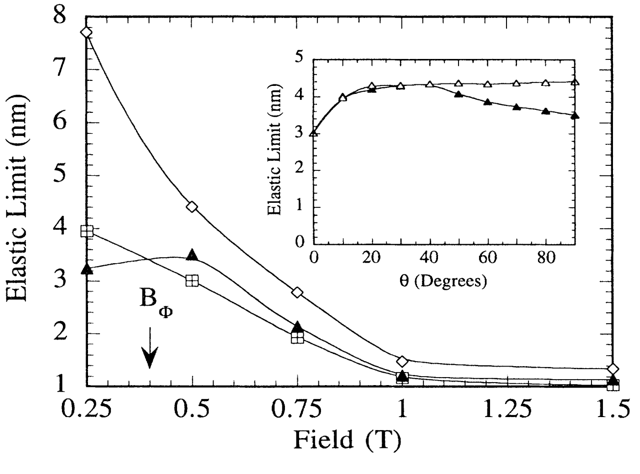

FIG. 5. The field dependence of the elastic limit at $t=0.86$. The crossed squares are for $\mathbf{B}\|ab$ both before and after irradiation. The open diamonds and closed triangles are for $\mathbf{B}\|c$ before and after irradiation respectively. The matching field, B_Φ, is indicated by the arrow. The inset shows the angular dependence of the elastic limit at 0.5 T (which is representative of the data for $B>0.5$ T) before (open triangles) and after (closed triangles) irradiation.

First, we discuss the values for d_0 before irradiation. The elastic limit for $\mathbf{B}\|ab$ has previously been shown to be closely related to the interlayer spacing and determined by intrinsic pinning.[33] The out-of-phase data from the same report suggests that d_0 is always larger for $\mathbf{B}\|c$. The absolute value here ranges from 8 nm at 0.25 T to 1 nm at 1.5 T and is more strongly dependent on magnetic field than for $\mathbf{B}\|ab$, expected from weaker pinning. It is widely accepted that pinning of vortices for $\mathbf{B}\|c$ in YBCO is determined by a dense array of small pinning defects of the same size as the coherence length (oxygen defects, dislocations, etc.). However, the large value of several nm we measure here (at 0.25 T) for the elastic limit cannot easily be reconciled with the size of oxygen vacancies which are typically of order of 0.2–0.3 nm (and the coherence length must represent a lower limit for the elastic limit in the single-vortex or amorphous regime). The value of 8 nm for d_0 at 0.25 T is about twice the coherence length ξ_{ab}, which we estimate as 3.5 nm at this temperature. Other measurements of d_0 on YBCO powders,[43] polycrystals,[44] crystals,[45] and melt-processed

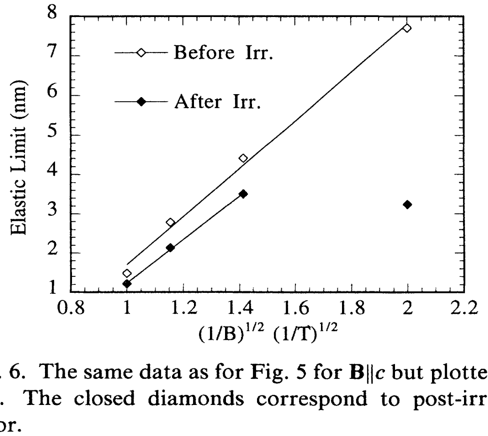

FIG. 6. The same data as for Fig. 5 for $\mathbf{B}\|c$ but plotted versus $1/B^{1/2}$. The closed diamonds correspond to post-irradiation behavior.

monoliths[35] find even larger values of between 20 and 100 nm. The large value for d_0 could be caused by the vortices bending between pinning sites within the film thickness. This is rather difficult to reconcile with the dense array of point pinning sites but in agreement with several studies[23,25,27] indicating that the longitudinal correlation length L_c is a few tens of nm but smaller than the film thickness (200 nm). Alternatively, the strain fields associated with screw dislocations[7] may be involved, being larger than oxygen defects. However there are probably too few of these dislocations to account for the large values of critical current at significant fields and these are therefore probably not the dominant pinning centers in our experiment. It is also apparent from Figs. 5 and 6 that the field dependence of d_0 is the same as that of the vortex spacing as noted above and discussed elsewhere.[46] This suggests that collective effects are playing an important role in determining the bulk pinning force in this regime.

Brandt[47] has calculated the range and strength of pins collectively interacting with a flux-line lattice and predicts this dependence ($d_0 \propto a_0$) for both point and extended defects. In the former case, the behavior is expected to saturate for very low inductions where d_0 should become equal to the radius of the flux-line core. We see no such crossover in our data but note both that the theory does not take into account the effects of thermal fluctuations (which will begin to artificially reduce d_0 as the irreversibility line is approached) and also that at the lowest fields our experiment looses sensitivity and we may overestimate the low-field data slightly, thereby missing the expected saturation.

Next we consider the results for displacements after irradiation. The decrease in d_0 after introduction of columnar defects implies that after irradiation, vortices parallel to the c axis are pinned in narrower pinning wells than before. The elastic limit after irradiation below and in the vicinity of the matching field approaches a value of 3.4 nm which is very close to the radius of the columnar tracks, $R_p = 2.5-5$ nm, and the coherence length, $\xi_{ab} = 3.6$ nm. The columnar defects introduced after irradiation act to increase the number of strong pins, and a significant change in the residual resistance ratio (in an already highly disordered and strongly pinned system) suggests a large change in the imperfection and pinning ability of the film. More importantly, the columns ensure that the active defects are aligned. Thus bending of the vortices between pins is suppressed, resulting in an effective enhancement of the stiffness of the vortices, and the elastic limit drops accordingly.

Finally we consider in more detail possible collective effects and the correlation lengths perpendicular and parallel to the field. The transverse correlation length is given[38] by $R_c = l_{66} = (c_{66}\Phi_0/\alpha_L B)^{1/2}$. Here c_{66}, the shear modulus, which is weakly and anisotropically dispersive, is given[48–50] using the London theory, by $c_{66} = (B_c^2/4\mu_0)b(1-b)^2(1-0.29b)$, where $b = B/B_{c2}$. Assuming $B_c(0) = 1.1$ T and $B_{c2}(0) = 130$ T and a BCS dependence for B_c, we calculate values for R_c at 0.25 T of 27 and 16 nm before and after irradiation, respectively, and correspondingly 25 and 21 nm at an applied field of 1.5 T. The intervortex spacing, $a_0 \approx (\phi_0/B)^{1/2}$, at 0.25 and 1.5 T are 90 and 37 nm, respectively. There are two conclusions to be drawn from this. The correlation radius decreases after irradiation as expected from the increased pinning. The relative decrease is much larger below the equivalent field of 400 mT. Further, the calculated values suggest that the single-vortex regime ($R_c < a_0$) applies for the entire field regime explored here putting the measurement in the amorphous limit of collective pinning. We estimate a crossover into the small bundle regime ($R_c > a_0$) at a field of about 3 T at this temperature. Figure 6 suggests that $d_0 \propto a_0$ for the entire range of fields before irradiation and above B_Φ after irradiation despite the suggestion above that we are always in the amorphous limit. This would suggest that the field dependence of d_0 below the small bundle regime is determined by the pinning energy rapidly approaching kT as the field is increased. Further, the data does not extrapolate to the zero of the x axis, thereby supporting a crossover to a small bundle regime with an associated change in slope at a field beyond the range measured here (see Ref. 24 for a discussion of onset of large bundle effects). This is in rather good agreement with Ziese and Esquinazi[28] who calculate (from the temperature dependence of J_c) a crossover field from the single vortex to small bundle regime of 1.9 T at 77 K. Griessen *et al.*[6] also suggest single-vortex pinning in the intermediate-field regime below about 2 T at this temperature. Civale *et al.*[24] found that a crossover from the single-vortex to the small bundle regime occurs at 2 T in single crystal YBCO at 40 K which is just below the temperature above which the single-vortex regime is suppressed by thermal fluctuations of the vortices. However $J_c(T)$ is much lower in YBCO crystals than films, and their values at 40 K for $B = 0$ are rather close to those here, so direct comparison between the two systems at different temperatures in the two experiments may not be inappropriate.

In all of the above discussion, we have ignored the possible effect of the factors leading to the irreversibility line on the elastic moduli. It is still by no means clear whether the measured values for the moduli should vanish discontinuously at B_{irr} (which is what one might expect for a true thermodynamic transition) or whether they will vanish continuously as the length scales for thermal fluctuations of the vortices approach the vortex spacing. In this latter scenario, one might be tempted to replace B_{c2} in the reduced induction by B_{irr}. This shifts all of the behavior to smaller fields and increases the correlation lengths by a factor very close to 2. This result agrees better with the strong-field dependence we observe for the elastic limits of displacement at low fields and we estimate a crossover from the amorphous limit to the small bundle regime at a field close to 0.5 T in this case. A really clever experiment is required to determine exactly how these moduli behave at B_{irr}.

The isotropic prediction for the longitudinal correlation length is mathematically identical to the Campbell pinning penetration depth. This defines the distance over which perturbations in the vortex lattice decay and is given[31,51,52] by ${}^{i}L_c=\lambda_{\text{pin}}=(Bd_0/\mu_0 J_c)^{1/2}$. This number is always greater than the film thickness for all fields with $\mathbf{B}\|c$ both before and after irradiation. It would suggest that the vortices move as straight lines in the film.[32,51] Clearly the film thickness must impose an upper limit on the longitudinal length, L_c. The value for the thickness here is close to 200 nm, about four times greater than the lower limit for L_c of 45 nm inferred by Brunner *et al.*[23] Collective theory predicts ${}^{c}L_c$ is given by $(c_{44}\Phi_0/\alpha_L B)^{1/2}$. In the isotropic limit, c_{44} is simply given by B^2/μ_0 and ${}^{c}L_c={}^{i}L_c$ as expected. However if we use the anisotropic nonlocal predictions from Ginzburg-Landau theory[49] then c_{44} is given by $c_{44}=B^2(1-b)/(\mu_0\Gamma 2b\kappa^2)$ where Γ is the anisotropy ratio, m_c/m_{ab} ($=30$), and κ is the GL parameter ($=70$). If we use the London prediction,[22] this only changes the results for ${}^{c}L_c$ by a factor of about 2 or 3 and does not change the conclusions. The isotropic prediction gives values for ${}^{i}L_c$ of 575 nm and 1.33 μm at 0.25 T before and after irradiation, respectively, and 344 nm and 1.10 μm for a field of 1.5 T in those two cases. However the anisotropic prediction suggests that ${}^{c}L_c$ is only 12 nm before and after irradiation at 0.25 T and 7.2 and 9.3 nm, respectively, at 1.5 T before and after irradiation.

Yeh[26] has also found a marked decrease, after introduction of columnar defects, in the measured value of L_c from vortex-glass scaling analyses of single-crystal YBCO data. These rather small values are in disagreement with the requirement of a value for L_c which is of the order of μm to explain the thickness dependencies found in YBCO crystals using multiterminal measurements.[53] However this may be related to the differences in disorder between crystals and films and will be the subject of further investigation. If the anisotropic predictions are to be believed then the vortices do not move as straight lines in the film. These small values for L_c can next be compared with the collective-pinning predictions[1] for the single-vortex limit, $L_c<a_0/(\Gamma^{1/2})$. This gives a value at 1 T and 0 K of 4 nm. We avoid the rather complicated calculation of the explicit temperature dependence expected for L_c but note (i) that this parameter should diverge at the irreversibility line and (ii) that we are quite far below this line so we expect a value larger (but not much larger) than the zero-temperature value. This is just what we find, and is in agreement with the discussion of the transverse correlation lengths above.

If one assumes that vortices do not bend significantly between pinning centers, then the pinning energies may be evaluated directly from $U_p=p(\mu_0 H_c^2/2)V_c=F_p d_0 V_c$ where p is the reduced fraction of the condensation energy, F_p is the maximum pinning force, BJ_c, and V_c is the correlation volume, $R_c^2 L_c$. For straight flux lines in the single-vortex regime $V_c=a_0^2 t$. We present this assumption with the following justification at this stage; the calculated values for L_c above indicate values of about a tenth of the film thickness. Other reports[23] suggest lower bounds of a quarter of the film thickness. The validity of this provisional assumption will be self-consistently checked below where the measured values for U_p are compared with those reported in the literature. When evaluating U_p we insist that when the calculated R_c is less than the vortex spacing the latter must be used (since a smaller correlation length than vortex spacing is unphysical). Further, the film thickness must represent an upper limit for L_c so t also replaces L_c where appropriate.

Clearly, the measured forces and displacements are determined by the difference between the pinning energy and the background thermal energy, kT. Thus the real pinning energy is given by the sum of the measured energies and kT at 77 K. We therefore add 6.6 meV to all of the values for comparison with other measurements. Thus we obtain values for U_p in the local c_{44} case at 0.25 T of 98.6 meV before irradiation and 54.6 meV after irradiation. If we use the anisotropic prediction from Ref. 49, then at 0.25 T we find 12.1 meV before irradiation and 6.7 meV after irradiation. At the highest field of 1.5 T the corresponding values are 9.7 meV before and after irradiation in the isotropic case and 6.7 meV before and after irradiation in the anisotropic case. In summary, the anisotropic theory results in values for U_p which are generally about ten times smaller than for the isotropic case. The reason for the small U_p values, especially at 1.5 T is the fast decrease of $J_c(B)$ which is "thermally activated" and results in the irreversibility line at this temperature lying at a few (7 T) Tesla. This field is slightly larger than the field at which the pinning energy appears to vanish, but the discrepancy results from the more sensitive criterion we are able to place on determination of the irreversibility line. It should further be noted that the calculated values of U_p *decrease* after irradiation.

The decrease of U_p after irradiation, despite the enhanced J_c and irreversibility line, is apparently contradictory. It is however allowed by collective-pinning theory[54] in which $U_p=(V_c W)^{1/2}d_0$ and $J_c B=(W/V_c)^{1/2}$ where W is the pinning strength. U_p should not be confused with the energy, $U(J)$, for flux creep. $U(J)$ is the energy for activation or creep of a vortex or vortex bundle and is what is probed by relaxation measurements.[55] In the collective-creep or vortex-glass models, the effective current dependent activation energy (which determines the irreversibility line) is given by $U(J)=(U_c/\mu)(c_{11}/c_{66})^{1/2}[(J_c/J)^{\mu}-1]$. Here, J_c is the critical current density which would be measured in the absence of creep and μ is the characteristic exponent (which is of order unity). In general the prefactor $U_c[\approx(c_{11}/c_{66})^{1/2}U_p]$ is not equal to U_p, but in the amorphous limit $c_{11}\approx c_{66}$ and $U_p\approx U_c$. If we assume that we induce the same error in J_c by the characteristic time scale of our experiment (a few minutes) before and after irradiation, then it is apparent that U can increase even if U_p decreases, so long as J_c increases. Other studies have shown that there is a weak correlation between the enhancement in U (determined from Arrhenius plots or magnetic relaxation) and the enhancement of J_c after irradiation.[56] Indeed the activation energies which we calculate from Arrhenius plots, linearly fitting the data below 0.1% R_N are 2.5 and 4.7 eV before and after irradiation at 0.1 T and 1.1 and 2.5 eV, respectively, at 1 T, showing a marked increase both below and above the matching field. Due to the well known dependence of the activation energy on field and temperature in high-temperature superconductors, care must be taken with comparison of these absolute values with the pinning energies or activation energies extracted from other methods.[57,58] The above values indicate the activation energy at 0 K which is considerably larger than at 77 K.[34]

The values for U_p which we obtain at low fields are in reasonable agreement with magnetic relaxation data U_c for YBCO films. Magnetic relaxation experiments probe a similar regime to the elastic technique here. The rather small number of published values of energies from these studies in YBCO thin films show values of between 35 and 45 meV at $T=70$ K in the low field ($B=0.1-0.3$ T) regime,[59] about 14 meV at 0.2 T at 77 K (Ref. 60) or about 60–70 meV at 1 T at 77 K.[61,62] Values of U_c from relaxation studies of single crystals after proton irradiation[63] reveal $U_c=40-80$ meV at $T=70$ K, $B=2$ T, a slight increase on the 30 meV recorded[64] for unirradiated crystals. All the above values are intermediate between the values we calculate in the isotropic and anisotropic cases. Essentially this means that our assumption that the vortices move as straight lines is not quite accurate. However, it also implies that the longitudinal correlation lengths are almost certainly greater than the anisotropic estimates. A simple linear interpolation between the upper bound in the isotropic case, the film thickness (200 nm), and the lower bound provided by the anisotropic prediction gives a value of about 100 nm at 0.25 T and 77 K, in very good agreement with Brunner,[23] Yeh,[25] and Eltsev.[27]

The pinning properties of precharacterized YBCO thin films have been changed by heavy ion irradiation. The effects of this change on the elastic properties of the vortex lattice were investigated using transport force-displacement measurements. The elastic limits after irradiation indicate explicitly that the columnar tracks control the pinning. We have extracted, for the first time, collective-pinning correlation lengths directly from parameters of the vortices in the elastic regime. The values which we obtain agree very well with other estimates of these values. We present evidence that the YBCO films are in the single-vortex limit at all fields measured and suggest that a crossover to small bundle pinning occurs close to 3 T at 77 K. Irradiation increases pinning and the critical current density and shifts the crossover field to larger fields. The longitudinal correlation length appears to be close to 100 nm. The discrepancy between this number and the larger ones (thickness effects) required to explain the dc transformer measurements remains to be resolved. The usefulness of force-displacement studies are clearly demonstrated by this treatment of collective effects using the elastic parameters. A detailed description, and comparison with dc transport measurements and analyses are deferred to a later paper, since the primary objective of this work was the investigation of effects of irradiation on the elastic parameters.

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[*] Electronic address: rad1005@hermes.cam.ac.uk

[1] G. Blatter, M. V. Feigelman, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[2] K. Kadowaki, Y. Songliu, and K. Kitazawa, Supercond. Sci. Technol. **7**, 519 (1994).

[3] M. Tachiki and S. Takahashi, Solid State Commun. **70**, 291 (1989).

[4] W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu, Phys. Rev. Lett. **64**, 966 (1990).

[5] M. Tinkham, Helv. Phys. Acta **61**, 443 (1988).

[6] R. Griessen, Hai-hu Wen, A. J. J. van Dalen, B. Dam, J. Rector, H. G. Schnack, S. Libbrecht, E. Osquiguil, and Y. Bruynseraede, Phys. Rev. Lett. **72**, 1910 (1994).

[7] H. Douwes and P. H. Kes, Physica B **194-196**, 1923 (1994).

[8] M. E. Reeves, B. D. Weaver, D. A. Kriegler, D. B. Chrisey, J. S. Horowitz, S. A. Wolf, and G. P. Summers, Phys. Rev. B **45**, 2585 (1992).

[9] W. Gerhäuser, H. W. Neumüller, W. Schmidt, G. Ries, G. Saemann-Ischenko, H. Gerstenberg, and F. M. Sauerzopf, in *Proceedings of the International Conference on Materials and Mechanisms of Superconductivity High Temperature Superconductors III,* Kanazawa, Japan, edited by M. Tachiki, Y. Muto, and Y. Syono (Elsevier Science, Amsterdam, 1991), p. 2273.

[10] H. G. Neumüller, G. Ries, W. Schmidt, W. Gerhäuser, and S. Klaumünzer, J. Less-Common Met. **164 & 165**, 1351 (1990).

[11] B. Roas, B. Hensel, S. Henke, S. Klaumünzer, B. Kabius, W. Watanabe, G. Saemann-Ischenko, L. Schultz, and K. Urban, Europhys. Lett. **11**, 669 (1990).

[12] L. Civale, A. D. Marwick, T. K. Worthington, M. A. Kirk, J. R. Thompson, L. Krusin-Elbaum, Y. Sun, J. R. Clem, and F. Holtzberg, Phys. Rev. Lett. **67**, 648 (1991).

[13] L. Civale, L. Krusin-Elbaum, J. R. Thompson, R. Wheeler, A. D. Marwick, M. A. Kirk, Y. R. Sun, F. Holtzberg, and C. Feild, Phys. Rev. B **50**, 4102 (1994).

[14] D. R. Nelson and V. M. Vinokur, Phys. Rev. B **48**, 13 060 (1993).

[15] B. Holzapfel, G. Kreiselmeyer, M. Kraus, G. Saemann-Ischenko, S. Bouffard, S. Klaumünzer, and L. Schultz, Phys. Rev. B **48**, 600 (1993).

[16] W. Gerhäuser, G. Ries, H. W. Neumüller, W. Schmidt, O. Eibl, G. Saemann-Ischenko, and S. Klaumünzer, Phys. Rev. Lett. **68**, 879 (1992).

[17] M. Leghissa, L. A. Gurevich, M. Kraus, G. Saemann-Ischenko, and L. Ya Vinnikov, Phys. Rev. B **48**, 1341 (1993).

[18] Th. Schuster, H. Kuhn, M. R. Koblischka, H. Theuss, H. Kronmüller, M. Leghissa, M. Kraus, and G. Saemann-Ischenko, Phys. Rev. B **47**, 373 (1993).

[19] Y. Zhu, H. Zhang, M. Suenaga, and D. O. Welch, Philos. Mag. A **68**, 1079 (1993).

[20] A. I. Larkin and Y. M. Ovchinnikov, J. Low. Temp. Phys. **34**, 409 (1979).

[21] K. Yamafuji, T. Matsushita, T. Fujiyoshi, and K. Toko, Adv. Cryog. Eng. Mater. **34**, 707 (1988).

[22] E. H. Brandt, Phys. Rev. B **34**, 6514 (1986); Physica C **195**, 1 (1992).

[23] O. Brunner, L. Antognazza, J.-M. Triscone, and Ø. Fischer, Phys. Rev. Lett. **67**, 1354 (1991).

[24] L. Civale, L. Krusin-Elbaum, J. R. Thompson, and F. Holtzberg, Phys. Rev. B **50**, 7188 (1994).

[25] N.-C. Yeh, W. Jiang, D. S. Reed, U. Kriplani, and F. Holtzberg, Phys. Rev. B **47**, 6146 (1993).

[26] N.-C. Yeh (private communication).

[27] Yu. Eltsev, W. Holm, and Ö. Rapp, Phys. Rev. B **49**, 12 333 (1994).

[28] M. Ziese and P. Esquinazi, Z. Phys. B Condens. Matter **94**, 265 (1994).

[29] A. M. Campbell, J. Phys. C **2**, 547 (1972).

[30] J. Lowell, J. Phys. F **2**, 547 (1972).

[31] A. M. Campbell and J. E. Evetts, Adv. Phys. **21**, 199 (1972).

[32] E. J. Tomlinson, P. Przyslupski, and J. E. Evetts, Cryogenics **33**, 28 (1993).

[33] R. A. Doyle, A. M. Campbell, and R. E. Somekh, Phys. Rev. Lett. **71**, 4241 (1993).

[34] W. S. Seow, R. A. Doyle, J. D. Johnson, D. Kumar, R. Somekh, D. J. C. Walker, and A. M. Campbell, Physica C **241**, 71 (1995).

[35] B. Ni, H. Kitagawa, T. Wakuda, T. Shigemitsu, K. Funaki, K. Yamafuji, and T. Matsushita, Jpn. J. Appl. Phys. **32**, L1215 (1993).

[36] C. J. van der Beek, Ph.D. Thesis, University of Leiden, Holland, 1992.

[37] K. Yamafuji, T. Fujiyoshi, K. Toko, T. Matsuno, K. Kishio, and T. Matsushita, Physica C **212**, 424 (1993).

[38] K. Yamafuji, T. Fujiyoshi, K. Toko, T. Matsuno, T. Kobayashi, and K. Kishio, Physica C **226**, 133 (1994).

[39] T. Matsushita, Physica C **217**, 461 (1993).

[40] T. Matsushita, T. Nakatani, E. S. Otabe, K. Yamafuji, K. Tanamaku, and N. Koshizuka, Jpn. J. Appl. Phys. **32**, L720 (1993).

[41] See, for example, M. Konczykowski *et al.*, Phys. Rev. B **44**, 7167 (1991), where a track diameter of 7 nm is reported for YBCO at an electronic energy loss of 35 keV/nm.

[42] V. Hardy, D. Groult, M. Herrieu, J. Provost, B. Raveau, and S. Bouffard, Nucl. Instrum. Methods, Phys. Res. Sect. B **54**, 472 (1991).

[43] A. M. Campbell, Cryogenics **30**, 809 (1990).

[44] A. M. Campbell and F. J. Blunt, Physica C **172**, 253 (1990).

[45] J. D. Johnson, A. M. Campbell, R. A. Doyle, N. Athanassopolou, and J. R. Cooper, in *Proceedings of the 7th International Workshop on Critical Currents, Alpbach, Austria,* edited by Harald. H. Weber (World Scientific, Singapore, 1994), p. 185.

[46] A. M. Campbell, Philos. Mag. **37**, 149 (1978).

[47] E. H. Brandt, Phys. Rev. Lett. **57**, 1347 (1986).

[48] Hendrik Douwes, Ph.D. thesis, University of Leiden, 1994.

[49] A. Houghton, R. A. Pelcovits, and A. Sudbo, Phys. Rev. B **40**, 6763 (1989).

[50] E. H. Brandt, Phys. Status Solidi **77**, 551 (1976).

[51] J. E. Evetts, IEEE Trans. Magn. **MAG-19**, 1109 (1983).

[52] A. M. Campbell, in *Concise Encylcopedia of Magnetic and Superconducting Materials,* edited by J. Evetts (Pergamon, London, 1992), p. 305.

[53] D. Lopez, E. Rodriguez, G. Nieva, F. de la Cruz, and S. W. Cheong, Physica B **197**, 1977 (1994).

[54] E. H. Brandt, Physica B **197**, 1803 (1994).

[55] M. P. Maley, J. O. Willis, H. Lessure, and M. E. Mc Henry, Phys. Rev. B **42**, 2639 (1990).

[56] V. Hardy, D. Groult, J. Provost, and B. Raveau, Physica C **190**, 289 (1992).

[57] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).

[58] T. T. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B **41**, 6621 (1990).

[59] E. Sandvold and C. Rossel, Physica C **190**, 309 (1992).

[60] W. H. Lee, S. W. Hsu, Y. C. Chen, C. M. Chang, J. J. Chu, and P. T. Wu, Physica C **185-189**, 1881 (1991).

[61] L. W. Song, M. Yang, E. Chen, and Y. H. Kao, Phys. Rev. B **45**, 3083 (1992).

[62] N. Kobayashi, Y. Minagawa, K. Watanabe, S. Awaji, H. Yamane, H. Kurosawa, and T. Harai, Physica C **185-189**, 2353 (1991).

[63] Y. R. Sun, J. R. Thompson, D. K. Christen, F. Holtzberg, A. D. Marwick, and J. G. Ossandon, Physica C **194**, 403 (1992).

[64] O. Dobbert, K. P. Kinse, W. Goldacker, and T. Wolf, Physica C **177**, 17 (1991).