

Observation of flux creep through columnar defects in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals

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Defects in the form of cylindrical amorphous tracks were introduced into $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals by irradiation with 5.3-GeV Pb ions. The columnar defects formed provide maximum possible pinning of flux lines parallel to the tracks and induce giant enhancement of magnetic irreversibility. However, even for this strong pinning, magnetic decay was measured at high temperatures. Relaxation is nonlogarithmic and exhibits an increase of the effective barrier for flux creep with decreasing persistent current. This behavior is interpreted in the framework of the nucleation creep model.

Columnar defects in the form of amorphous tracks can be produced in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals by heavy-ion irradiation. Flux pinning by this type of defect dramatically enhances critical current, shifts the irreversibility line, and depresses magnetic relaxation.¹⁻⁴ An increase of J_c and strong anisotropy of pinning are also observed after lighter-ion irradiation (580-MeV Sn) which creates elongated defects in the direction of the beam.⁴ All these effects testify to the high pinning energy of columnar defects, probably the most efficient of all possible pinning centers.

The investigation of magnetic irreversibility in crystals consisting of such amorphous tracks, embedded in a superconducting matrix, presents dual interest: i.e., probing the potentially highest critical current and exploring flux dynamics in a well-defined pinning context.

We report on magnetization measurements in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals irradiated by 5.3-GeV Pb ions. Irreversible magnetization of the samples arises mainly from pinning by columnar defects. Here we focus on magnetic relaxation observed in the temperature range explored close to T_c . The flux creep from columnar defects exhibits behavior similar to that controlled by collective pinning⁵ and can be interpreted in the framework of a nucleation-creep model recently proposed by Nelson and Vinokur.⁶

All magnetic measurements were made with the local Hall probe magnetometer (LHPM) technique.⁷ A miniature Hall probe placed on the surface of the sample, close to its center, served to record the magnetization field ΔH , defined as the difference between the field measured by the Hall probe and an externally applied field. For the platelet shaped samples which are of concern here, ΔH is

proportional to the persistent current.⁸

Three single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_7$ were irradiated by 5.3-GeV Pb ions at room temperature with the beam parallel to the c axis. Irradiation was made at the heavy-ion irradiation facility of GANIL (Caen, France). Though no TEM observations were done on these particular crystals, we can estimate from previous work¹ that continuous tracks of approximately 7 nm diameter were formed along the ion trajectory. These columnar defects penetrate 20- μm -thick samples from surface to surface. Samples 1, 2, and 3 were irradiated by a fluence of 10^{11} , 10^{10} , and 10^9 ions/cm², respectively. We estimate that the densities of the tracks correspond to those fluences.

Figure 1 presents the magnetic hysteresis loops recorded before and after irradiation on sample 2, irradiated by 10^{10} ions/cm². Regardless of the presence of twins in our samples, the magnetic hysteresis loops recorded before irradiation for temperatures above 75 K revealed very low bulk critical current and features characteristic of surface currents limited by a Bean-Livingston barrier.^{9,10}

Strong enhancement of magnetic hysteresis and the symmetric magnetization loop characteristic of bulk pinning are observed after irradiation. The magnetic hysteresis loops were recorded following two different procedures as described in Ref. 7: a monotonic loop when the applied field was increased and decreased step by step and a nonmonotonic one in which the external field was turned off after each step of the increasing or decreasing field. In the latter procedure, the recorded values of ΔH are independent of previous magnetic history when the applied field exceeds twice H^* (field of full penetration in the Bean model¹¹). This method provides precise measurement of H^* and an estimation of bulk critical

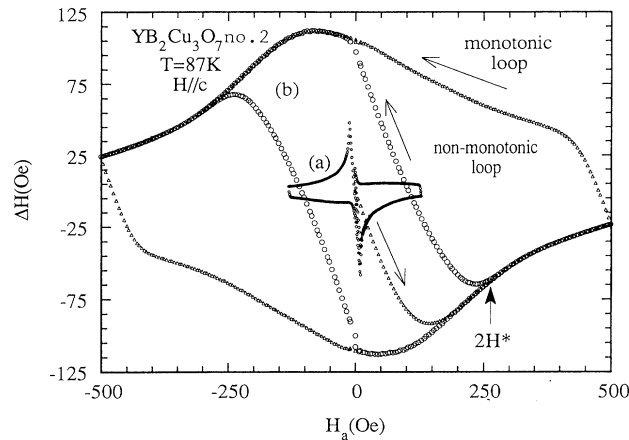


FIG. 1. Magnetization loops recorded on sample 2 at 87 K before and after irradiation by 10^{10} ions/cm 2 . (a) As grown (y coordinate multiplied by 5). (b) After irradiation with 5.3-GeV Pb ions 10^{10} /cm 2 .

current. In as-grown samples, H^* only exceeds the first magnetic penetration field H_p by a small amount. After irradiation H^* becomes much higher and the width of the loop is strongly enhanced. This means that *magnetic irreversibility in irradiated samples is almost entirely due to pinning by columnar defects*.

Two regimes of pinning can be distinguished in irradiated samples, depending on the relative density of columnar defects and flux lines. The first is a regime of incomplete filling of tracks by flux lines at low fields and the second is a regime in which flux line density exceeds the density of tracks. Complete filling occurs at magnetic fields of 20 kOe, 2 kOe, and 200 Oe for samples 1, 2, and 3, respectively. Here we discuss the regime of incomplete filling which was measured in all three samples. The problem of pinning in the complete filling regime will be addressed later.

We used the following procedure to trigger magnetic relaxation. First, the sample was cooled in a field $H_{\text{obs}} \geq 2H^*$. After stabilizing the temperature to less than 0.02 K at a selected value, the magnetic field was changed by a given field excursion, H_{exc} , for 100 s and then restored to its initial value. Positive and negative field excursions trigger the flux-leaving and the flux-penetrating relaxations respectively. For amplitudes of H_{exc} lower than $2H^*$, we observe nearly logarithmic magnetic decay which is dependent on the value of H_{exc} . This situation corresponds to an incomplete critical state in which the magnetic decay rate is limited by the propagation of the front of the inversion of the persistent current.¹² When H_{exc} exceeds $2H^*$, the magnetic relaxation become independent of the amplitude of the excursion field and nonlogarithmic. Because of the limitation of the field range in our setup to ≈ 600 Oe, we explore only the behavior at temperatures close to T_c where the complete critical state can be produced.

Typical time dependences of the magnetization field, recorded at an observation field of 500 Oe, are presented in Fig. 2. In the other series of decays recorded at 300 Oe, in both flux-penetrating and flux-leaving processes,

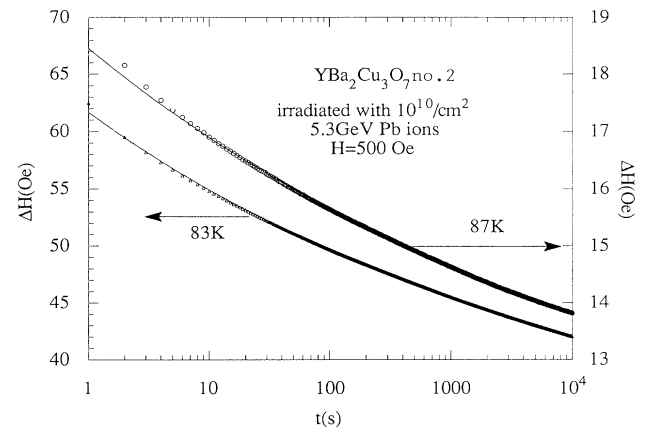


FIG. 2. Decay of the magnetization field recorded at an applied field of 500 Oe for flux penetration at 83 and 87 K on sample 2 irradiated with 10^{10} ions/cm 2 .

we observed the same nonlogarithmic decay.

The normalized logarithmic slope $S = -\partial \ln \Delta H / \partial \ln t$ was calculated numerically by moving a one-decade time window over the recorded $\Delta H(t)$ curve. The inverse of S was plotted vs time in Fig. 3. We observe an *increase of $1/S$ proportional to the logarithm of time* with a slope between 1 and 3 depending on field and temperature. This is a key observation of the paper, demonstrating that in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals in a *well-defined strong pinning limit, flux creep occurs and that an effective barrier for flux creep increases with decreasing persistent current*.

The quasilogarithmic relaxations with decreasing S persist up to 91 K. Relaxation recorded at 92 K exhibits power-law time dependence $\Delta H(t) \propto t^{-\alpha}$, corresponding to a constant slope $S = \alpha$.

The observed growth of the creep activation barriers with decreasing persistent current indicates that vortex motion must have occurred via the vortex loop nucleation process analogous to that in the collective creep description, when the activation barriers are due to point defects.^{5,13} It has been shown⁶ that if vortex creep is con-

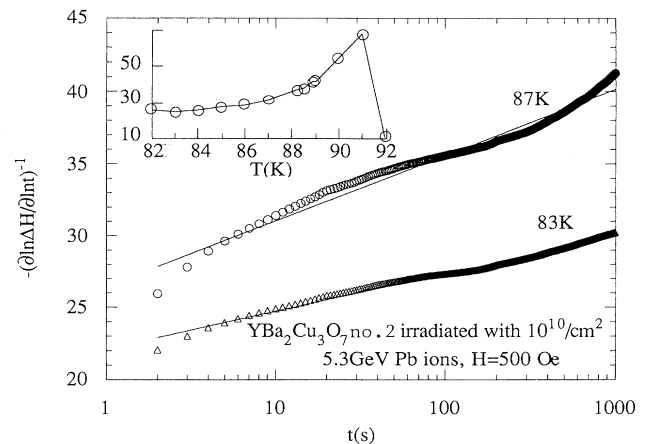


FIG. 3. Time variation of $1/S$ corresponding to magnetic decay recorded at 83 and 87 K. The inset represents temperature variation of $1/S$ taken at 10 s.

trolled by the strong pinning on linear defects, linear defects outnumbering vortex lines, the relevant creep barriers diverge as $U = U_c (J_c/J)^\mu$ giving rise to a current-voltage characteristic of the form

$$E \propto \exp[-(U_c/T)(J_c/J)^\mu]. \quad (1)$$

The origin of divergent creep barriers lays in the fact that the creep motion is controlled by the barrier corresponding to the formation of the critical nucleus or critical vortex loop. The latter, in turn, is determined by the competition between the Lorentz force driving the vortex away and the pinning force which binds the vortex to linear defects. The gain in energy for the critical loop formation due to the Lorentz force F_L is $\Delta E \approx F_L u L \approx F_L L^2$, where L and u are the longitudinal and transverse sizes of the critical loop. While the binding energy grows as $U_b \approx L$, the size of the critical loop grows as $L \propto 1/F_L$, and so does the nucleation energy. Therefore, at sufficiently large currents, when creep is determined by the thermal activation of the vortex from the single rod, one expects $\mu = 1$. At smaller current, when creep occurs via a thermally activated vortex hop from one rod to another, in a process analogous to variable range hopping conductivity in semiconductors, one expects $\mu = \frac{1}{3}$ provided that the concentration of vortex lines is low enough.⁶

Magnetization decay in this model is given by an interpolation formula:

$$M(t) = \frac{M_0}{[1 + (\mu T/U_c) \ln(t/t_0)]^{1/\mu}} \quad (2)$$

and the creep rate slope from (2) is

$$1/S = U_c T + \mu \ln(t/t_0). \quad (3)$$

Below some characteristic temperature T^* , the critical current does not depend on T . At $T_g > T > T^*$ the collective pinning of the vortex line by the ensemble of columnar defects takes place, giving rise to the critical-current decay as $J_c \propto (T^*/T)^4$, where T_g is the irreversibility temperature. In this temperature range exponent μ is expected to lie in the interval $\frac{1}{3} < \mu < 1$.

In the following, we analyze the temperature dependence of the relaxation processes recorded at 500 Oe between 82 and 91 K in 1-K steps. The time dependence of $1/S$ presented in Fig. 3 follows that predicted by the interpolation formula. We can deduce directly the exponent μ from the slope of $1/S$ vs $\ln(t)$. From Fig. 3, we conclude that the exponent μ is temperature dependent. The absolute precision of this determined value of μ is poor, especially at the high-temperature limit. The intercept of $1/S$ vs $\ln(t)$, Eq. (3), contains both U_c/T and $\mu \ln(t_0)$ and only the lower limit for t_0 can be found,¹⁴ putting $U_c = 0$. It should be noted that t_0 here is a macroscopic parameter,¹⁵ estimated to be in the range $10^{-5} - 10^{-8}$ s.

The J - E curves were extracted from magnetic relaxation data by numeric differentiation of $\Delta H(t)$ with respect to time.¹⁶ Because $\partial \Delta H / \partial t$ is proportional to the electrical field and ΔH to the current, plots of $\partial \Delta H / \partial t$ vs ΔH represents E - J dependence.

Typical E - J dependences obtained by this procedure from magnetic decay curves measured on sample 2 at 500 Oe are presented in Fig. 4. The representation of $\ln \partial \Delta H / \partial t$ vs $[\Delta H(1s) / \Delta H(t)]^\mu$ allows easy fit to Eq. (1) and extraction of $J_c d (U_c/T)^{1/\mu} = \Delta H_0$ (d is sample thickness). The value of μ was adjusted for each temperature form slopes of corresponding $1/S$ vs $\ln(t)$ variation.

The power-law characteristic, $E \propto J^\alpha$, can also provide apparently good fit of $\partial \Delta H / \partial t$ vs ΔH curves. But this E - J characteristic implies no time variation of the corresponding normalized logarithmic slope S of the magnetic decay. Moreover, values of α obtained in this fit are in the range of several tens.

The values of $J_c (U_c/T)^{1/\mu}$ obtained from fitting of E - J curves to formula (1) are presented in Fig. 5. Comparison of these values to persistent current recorded at 1s shows that U_c/T should not exceed 10. In this case the interpolating formula, Eq. (2), can be simplified by neglecting 1 with respect to $(T/U_c) \ln(t/t_0)$ in the denominator. Moreover, from the temperature dependence of $1/S$ represented in the inset of Fig. 3, we can conclude that the constant values of $t_0 \approx 10^{-6}$ and $U_c/T \approx 10$ fit our data. This means that variation of $1/S$ with temperature reflects the evolution of the exponent μ .

An alternative treatment of the relaxation data adjusts $\Delta H(t)$ to a function of the form $\Delta H_0 \ln(t/t_0)^{-1/\mu}$ with $t_0 = 10^{-6}$ s, yielding a very precise determination of μ and $\Delta H_0 = J_c d (U_c/T)^{1/\mu}$. The results of these adjustments are presented in Fig. 5 as full symbols.

The J_c deduced from the data shown in Fig. 5 decreases rapidly with increasing temperature between 82 and 91 K. This suggests that the characteristic temperature T^* below which J_c becomes temperature independent is below 82 K. We note that preliminary relaxation data at 40 K (Ref. 2) is consistent with $T^* > 40$ K. Exact determination of T^* is still a challenge.

The crossover of the type of decay process from quasi-logarithmic [$\Delta H(t) \propto \ln(t/t_0)^{-1/\mu}$] to a power law

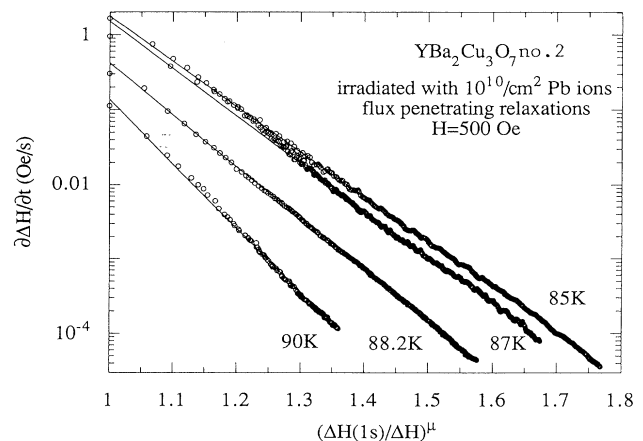


FIG. 4. Typical E - J curves derived from the magnetic relaxation processes following the procedure described in the text. Presentation in reduced scale in $1/J$ coordinate $[\Delta H(1s) / \Delta H(t)]^\mu$ was chosen in order to represent data from the whole temperature range and to illustrate the adjustment to the expected exponential E - J curve (1).

$[\Delta H(t) \propto t^{-\alpha}]$ occurs above 91 K at applied fields of 500 Oe. This crossover sets lower limits to the irreversibility line.

We can suppose that collective pinning by an ensemble of columnar defects is an appropriate model for the temperature range (82–91 K). The drop of J_c is much sharper than the expected $J_c \propto (T^*/T)^4$. Instead, $J_c(T)$ drops as $(1 - T/T_c)T^{-4}$. The term $(1 - T/T_c)$ may arise from the temperature dependence of λ and ξ , close to T_c .

In conclusion we present here magnetic relaxation measurements in a regime of flux pinning by columnar defects. These defects represent potentially the highest possible pinning force and provide strong enhancement of J_c . Nevertheless, in a broad temperature range from 82 to $T_c - 1$ K, flux creep is still pronounced and the observed persistent current represents only a fraction of the critical current. Observed magnetic decays are well described by a nucleation creep model⁶ with an effective energy barrier increasing with time or with decreasing persistent current. The quasilogarithmic magnetic decay, corresponding to exponential E - J curves persists up to temperatures ≈ 1 K below T_c at moderate magnetic fields.

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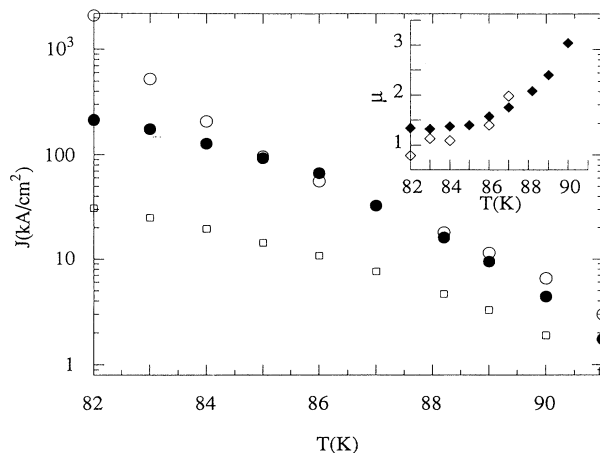


FIG. 5. Temperature variation of $J_c(U_c/T)^{1/\mu}$ extracted from E - J curves (open circles) and from the power-law fit: $\Delta H(t) = \Delta H_0 \ln(t/t_0)^{-1/\mu}$ with $t_0 = 10^{-6}$ s (full circles). Squares represent persistent current recorded at 1 s. The inset represents temperature variation of the exponent μ deduced from the slope of $1/S$ vs $\ln(t)$ (open diamonds) and from a power-law fit (full diamonds).

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