



Flux jumps driven by a pulsed magnetic field

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Abstract

The understanding of flux jumps in the high temperature superconductors is of importance since the occurrence of these jumps may limit the perspectives of the practical use of these materials. In this work, we present the experimental study of the role of heavy ion irradiation in stabilizing the HTSC against flux jumps by comparing un-irradiated and 7.5×10^{10} Kr ion/cm² irradiated $(Y_xTm_{1-x})Ba_2Cu_3O_7$ single crystals. Using pulsed field magnetization measurements, we have applied a broad range of field sweep rates from 0.1 to 1800 T/s to investigate the behavior of the flux jumps. The observed flux jumps, which may be attributed to thermal instabilities, are incomplete and have different amplitudes. The flux jumps strongly depend on the magnetic field, on the magneto-thermal history of the sample, on the magnetic field sweep rate, on the critical current density j_c , on the temperature and on the thermal contact with the bath in which the sample is immersed. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

In studying the influence of columnar defects, created by heavy-ion irradiation, on the magnetic properties of $(Y_xTm_{1-x})Ba_2Cu_3O_7$ superconducting single crystals by pulsed field magnetization measurements, we observed the presence of strong magnetic flux jumps. The use of the pulsed field experimental method is motivated by the large characteristic critical fields present in high temperature superconductors, certainly below a reduced temperature $t = T/T_c = 0.8$. In order to reach magnetic fields

up to 60 T, large sweep rates are inherent in this experimental method. These magnetic field sweep rates may reach values as high as 30 kT/s, and give rise to magneto-thermal instabilities, even in relatively small samples ($V \sim 0.1$ mm³). During a magnetic field sweep, a small perturbation may cause power dissipation ΔW_1 (due to thermally activated (giant) flux creep, flux flow, geometric current distribution inside the sample or due to the specific configuration of the pinning centers, etc.) that leads to an increase of the temperature ΔT_1 . This in turn influences the superconductor, and new dissipation ΔW_2 occurs thus resulting in a new increase of temperature ΔT_2 . If $\Delta T_2 < \Delta T_1$, then the next instability ΔT_3 will be smaller than ΔT_2 , and the superconductor will recover eventually its original state.

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If, on the other hand, the induced increase of temperature ΔT_2 is larger than the original fluctuation ΔT_1 , then an instability will be developed and the magnetic energy will be converted into heat. This gives rise to a flux movement in the form of an avalanche. In classical superconductors, flux jumps can easily result in the complete destruction of the superconducting state [3], but in the high T_c materials, very large temperature increases are needed ($\Delta T \sim 100$ K) before this effect takes place and, therefore, such observations have not been made so far. On the other hand, the thermal instabilities are much higher in high T_c compounds, which make the observation of partial flux jumps in these materials very common.

2. Experimental method

The K.U. Leuven pulsed field facility [1] allows us to perform magnetization measurements in fields up to 60 T, at temperatures down to 350 mK. The sensitivity of the home-made susceptometer is better than $\Delta m = 10^{-3}$ emu at fields below 20 T and 10^{-2} emu at higher fields [1]. In this work, we study an (i) un-irradiated ($\text{Y}_x\text{Tm}_{1-x}$) $\text{Ba}_2\text{Cu}_3\text{O}_7$ single crystal with $x = 0.14$, and an irradiated sample of the same stoichiometry with an irradiation dose of 7.5×10^{10} Kr-ion/cm². The single crystals are prepared using the standard flux growth method. Fig. 1 shows the

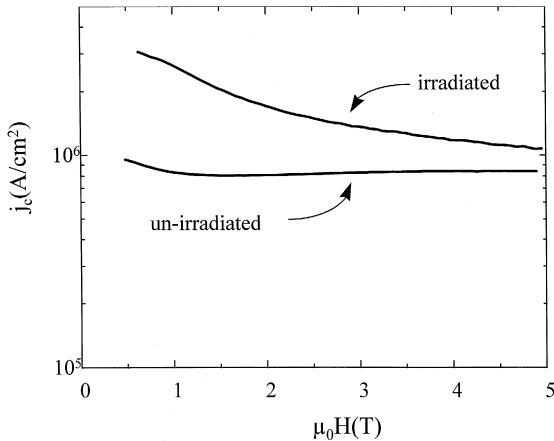


Fig. 1. Comparison of the magnetic critical current density at temperature $T = 50$ K of the un-irradiated and the 7.5×10^{10} Kr ion/cm² irradiated sample.

comparison of the magnetic critical current densities of both samples at temperature $T = 50$ K. At the lower fields ($B < 4$ T), the irradiated sample shows a larger critical current density than the reference un-irradiated sample. This observation is also valid for the lower temperatures.

3. Experimental results and discussion

3.1. Un-irradiated sample

Figs. 2a and b show the magnetization versus field for the un-irradiated reference sample at $T = 4.2$ K (contact gas). The thin line curve in Fig. 2a corresponds to the field sweep rate versus field at which the experiment was performed. The arrows indicate the sweep direction. During this experiment, the field sweep rate varies from ~ 1800 to ~ 0.1 T/s. Initially, the magnetization loop opens normally, and we can estimate the full flux penetration field $\mu_0 H^* \sim 1$ T. When the magnitude of the field is decreased, sharp jumps appear around H^* .

Details of these experiments are given in Fig. 2b which illustrates the time dependence of such a flux jump. Only a few, seemingly periodical jumps are observed, for both the positive as well as the negative field polarities. These sharp flux jumps occur at the end of the field sweep (in lowering the magnitude of the magnetic field) for all temperatures below $T = 30$ K. This effect does not demonstrate any obvious field sweep history dependence. In these experiments, a fixed field interval between the flux jumps of $\mu_0 H = 0.3$ T is observed. Although such a periodicity is not universal, it has been described by Swartz and Bean [2] using the following expression [which was derived from the Bean critical state model, i.e., $j(T, H) = j_c(T)$]. By taking into account the empirical relation $j_c(T) \sim j_{c0} \exp(T/T_0)$, we further simplified Eq. (1):

$$\Delta B = \dot{B} \Delta t \leq \sqrt{\frac{\mu_0 C_v j_c}{|\partial j_c / \partial T|}} = B_j \approx \sqrt{\mu_0 C_v T_0}, \quad (1)$$

where ΔB is the field difference between the applied field and the field at the center of the sample, j_c is the critical current density and C_v the specific heat.

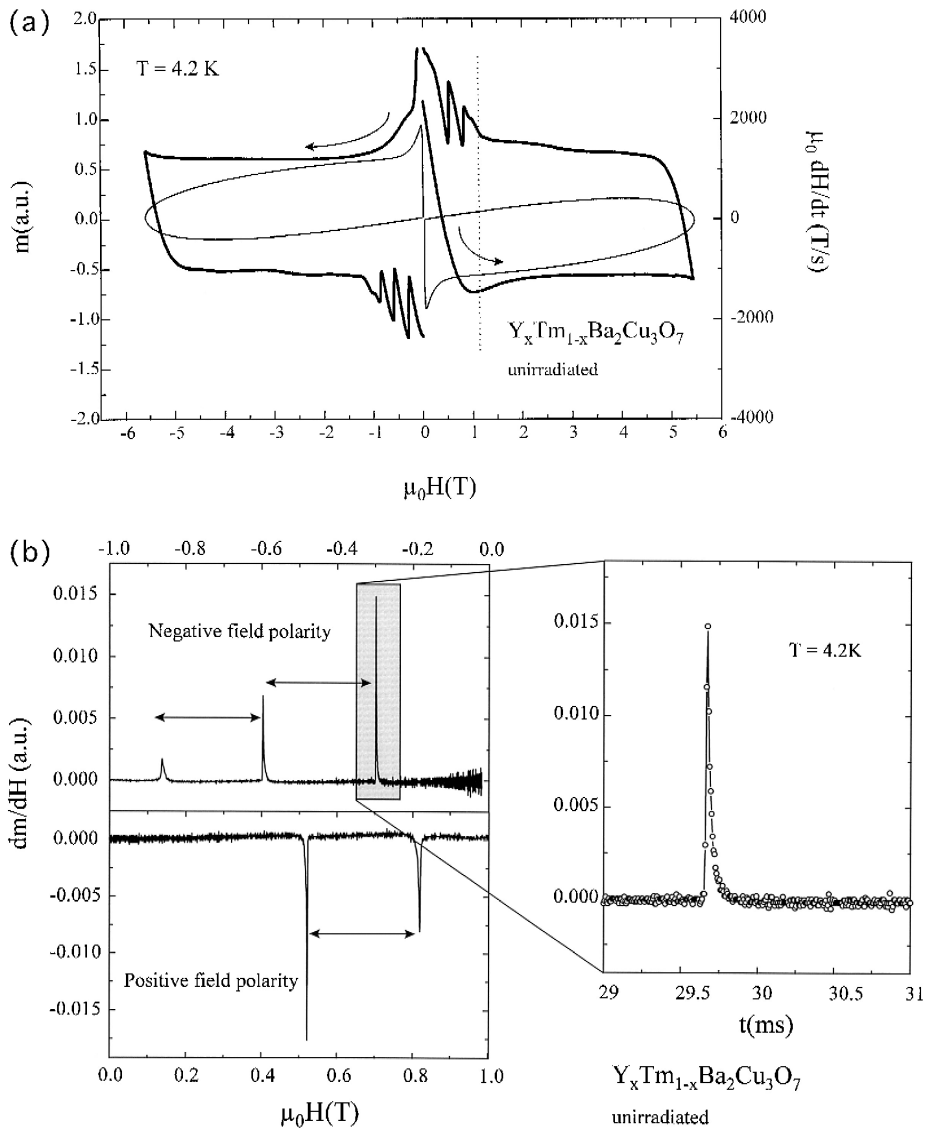


Fig. 2. (a) The bold line shows the magnetization versus magnetic field for $(Y_x Tm_{1-x})Ba_2 Cu_3 O_7$ un-irradiated single crystals at temperature $T = 4.2$ K, whereas the thin line shows the magnetic field sweep rate versus the magnetic field. (b) The dynamic susceptibility at the end of the field sweep for both the negative and positive field sweeps (the graphs at the left). The right graph shows the time dependence of the dynamic susceptibility.

Eq. (1) is only valid if the flux front penetrates the sample sufficiently fast, i.e., when the vortex front speed v_f obeys:

$$v_f \geq \left(\frac{\Delta B}{\mu_0 j_c} \right) \frac{1}{\Delta t} \approx \frac{\dot{B}}{\mu_0 j_c}. \quad (2)$$

Using pulsed field conditions $\dot{B} = 1$ kT/s and $j_c = 10^8$ A/m², we find $v_f \sim 1$ km/s, a velocity which is realistic and which indicates that Eq. (2) can be satisfied. As follows from Eq. (1), a flux jump occurs each time a field difference $\Delta B > B_j$ is applied. In this way, the jumps are expected to be equidistant $\sim B_j$. By taking experimental values T_0

~ 30 K and $C_v \sim 3000$ W s K⁻¹ m⁻³, we find $B_j \sim 0.3$ T as observed on the un-irradiated sample (see Fig. 2b).

The graph at the right of Fig. 2b shows the dynamic susceptibility $\chi = dm/dH$ versus time. The $\chi(H)$ amplitude diverges when the instability occurs. The rise time of the instability is $t_{\text{rise}} \sim 10$ μ s, whereas the lowering time $t_{\text{lower}} \sim 100$ μ s. A typical time constant $\tau_B \sim 50$ μ s for such a jump can be defined in this way. The observation of flux movement within such a small time interval is novel and it has become possible due to the use of fast data acquisition systems (~ 1 MHz sampling).

3.2. Irradiated sample

The magnetization versus magnetic field for the irradiated ($Y_x\text{Tm}_{1-x}$)Ba₂Cu₃O₇ single crystal at $T = 4.2$ K is given in Fig. 3. In this graph, curves (1) and (2) correspond to almost identical experiments, the difference being that curve (1) was measured after switching the polarity of the magnetic field, whereas curve (2) is a second measurement performed at the same field polarity. As such, the flux jump effect is clearly dependent upon the field sweep

sequence. The occurrence of the jumps is completely reproducible, although the details of the flux jumps (i.e., the fields at which they appear, the magnitude of the jump) are different. Note that the flux jumps are seen at the beginning of the field sweep, and if they appear, the width of the magnetization loop becomes smaller, which is a clear indication that the jumps have raised the overall temperature of the sample (estimated from the $j_c(T)$ dependence to be $\Delta T \sim 5$ K). The insert of this figure shows the dynamic susceptibility $\chi = dm/dH$, which diverges when the flux jumps occur. The rising and lowering time constants of these flux jumps are both around 20 μ s, and the jumps are more symmetric than in the case of the un-irradiated sample. Equidistant flux jumps are not observed (see the insert in Fig. 3).

Fig. 4 shows the magnetization data at $T = 1.7$ K. We clearly see a large difference in overall behavior at temperatures $T = 4.2$ and 1.7 K. In the latter experiment, the sample was immersed in superfluid He. At $T = 1.7$ K, the sample shows flux jumps both in the field increasing and decreasing branches. The details of the jumps are illustrated by the graph at the right side, which shows dm/dH versus the magnetic field, for the increasing (upper graph) and

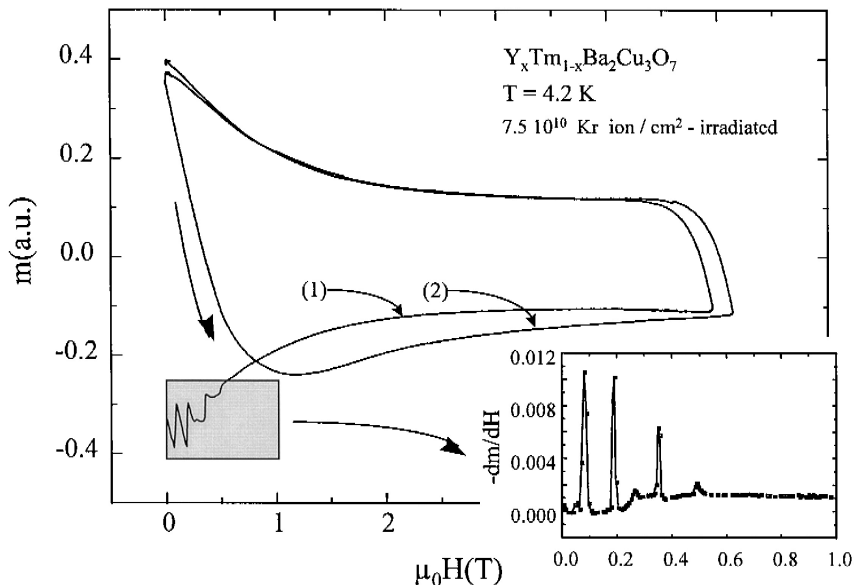


Fig. 3. Magnetization versus magnetic field for a 7.5×10^{10} ion/cm² Kr-irradiated ($Y_x\text{Tm}_{1-x}$)Ba₂Cu₃O₇ single crystal at temperature $T = 4.2$ K. Curve (1) was measured after switching the polarity of the magnetic field, whereas curve (2) is a second measurement performed at the same field polarity.

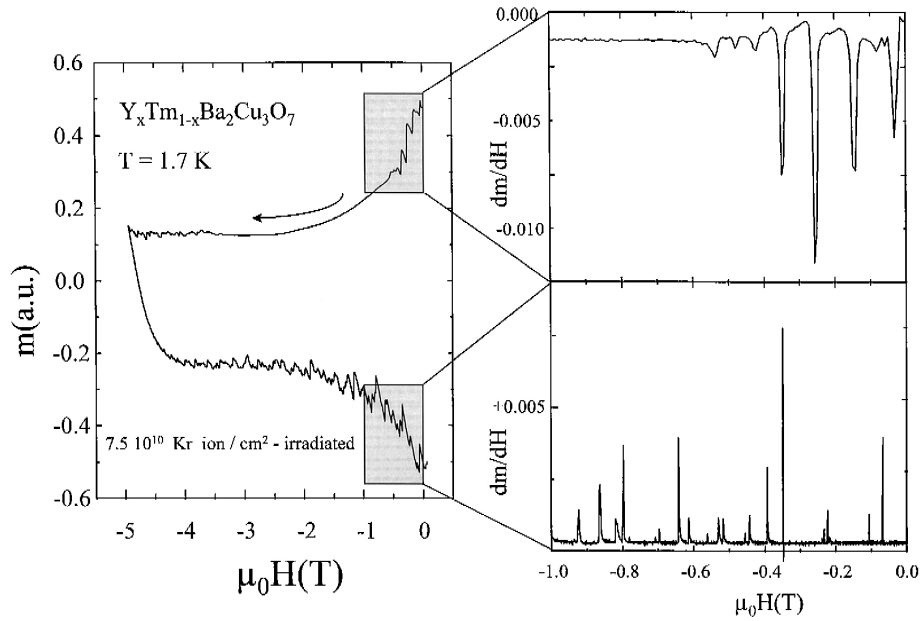


Fig. 4. The magnetization versus magnetic field for a 7.5×10^{10} ion/cm² Kr-irradiated $(Y_xTm_{1-x})Ba_2Cu_3O_7$ single crystal at temperature $T = 1.7$ K (the graph at the left).

decreasing (lower graph) branch. The coupling of the sample to the superfluid He bath is apparently the

cause of this difference between the $m(H)$ behavior at $T = 4.2$ and 1.7 K. If the heating power released

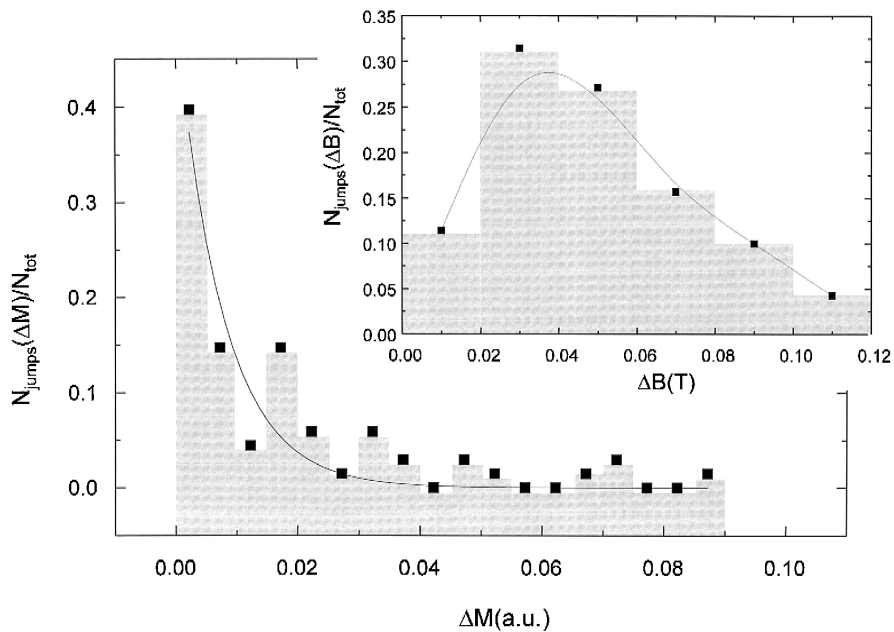


Fig. 5. Statistical analysis of the flux jumps observed in the lowering field branch in Fig. 4.

per unit volume can be removed by the heat conductivity, then Eq. (1) must be changed [2–4] to:

$$\Delta B \leq \mu_0 \sqrt{\frac{\kappa \sigma j_c}{|\partial j_c / \partial T|}} = B_j \quad (3)$$

where σ is the electrical conductivity and κ/C_v is the thermal diffusion coefficient. In this case, the typical field interval value B_j is to be different and the distance in field between the successive flux jumps is not constant either.

We observe also that the $\chi(H)$ peaks in the rising and lowering field branch are different. In the rising field branch (large dB/dt), the peaks are wider, indicating larger amounts of jumping flux.

To shed some light on the irregular behavior of flux jumps, we performed a statistical analysis of the jumps in the lowering field branch of Fig. 4 (lowest experimental sweep rate, $T = 1.7$ K). Fig. 5 shows this analysis. The main graph shows the jump distribution as a function of the change in magnetization. From the latter, we observe that most of the jumps are rather small (incomplete) and giant flux jumps

are rather sporadic. The line is a fit by an exponential decay. The insert shows the distribution of a function of the field distance between two successive jumps. Jumps with intervals of $\Delta B \sim 0.03$ T are most common for this particular experiment.

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