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Anomalous flux propagation through interface separating regions of different critical currents in $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals

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Abstract. Magneto-optical imaging was employed to study magnetic flux propagation through an interface separating between heavy-ion irradiated and non-irradiated parts of the same $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal. As the flux front hits the interface the local induction increases abruptly at a rate considerably larger than that of the external field. This induction jump is accompanied by the appearance of a finger-like flux pattern at the interface. At low temperatures or high field ramp-rates, the induction at the interface increases gradually, finger patterns do not form and the flux front crosses the interface smoothly. We explain the flux behavior at the interface on the basis of the magnetic diffusion equation, and propose that the induction jump triggers the formation of finger patterns.

Irregular magnetic flux propagation in type II superconductors, forming finger and dendritic patterns, has attracted much attention in recent years [1-19]. Although theoretical models have been developed for both, thin films [14-17] and bulk samples [18-19], experimental observations of such phenomena have been mainly reported for thin films [1-13, 20]. We have recently observed magnetic flux finger patterns in bulk $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals formed at a border between heavy-ion irradiated and non-irradiated parts of the same sample [21]. In this paper we further study this phenomenon and correlate it with other events occurring at this interface, in an attempt to gain more insight into the mechanism of flux pattern formation in our bulk samples.

$Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals (T_c = 92 K) grown by the floating zone method [22] were partially irradiated by 5 GeV Pb ions at the Grand Accelerateur National d'Ions Lourds (GANIL), Caen, with different doses corresponding to matching fields between 5 and 40 G. In this paper we present typical data, for a sample (2x1x0.03 mm^3) irradiated to a matching field of 40 G, producing columnar defects with an average distance of approximately 0.7 μm. The irradiated and non-irradiated parts of this sample created two symmetrical 1x1 mm^2 regions separated by a well defined border across the sample centre. Magneto-optical images of the induction distribution were taken using an iron-garnet indicator with in-plane anisotropy, and a high speed, 12 bit, Hamamatsu CCD camera with a maximum frame rate of 25 Hz [23, 24]. In a typical magneto-optical measurement, the sample was zero-field-cooled to a target temperature between 20 and 70 K, and was then subjected to an external

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magnetic field applied parallel to the crystallographic c axis of the crystal, and ramped up from 0 to 200 Oe at different rates between 0.1 Oe/s and 1000 Oe/s.

Figure 1 shows magneto optical images of the sample subjected to an external field, H_{ext}, ramped at a rate of 0.75 Oe/sec at different temperatures. The flux initially penetrates into the non-irradiated region, and propagates inside it maintaining either Bean or dome-like distribution depending mainly on temperature. Figures 1a and 1b show the flux distribution at 25 K, 9 seconds before hitting the border of the irradiated region, and 25 seconds after crossing this border, respectively. Notice that after crossing over to the irradiated region the flux front looks rather smooth. Repeating this procedure at higher temperatures reveals a dramatic change in the form taken by the flux front after crossing the irradiation border. Specifically, with increasing temperature the front is transformed gradually from smooth to rough and eventually forms pronounced finger patterns as portrayed in figure 1c, taken at 40 K 15 seconds after crossing the border.

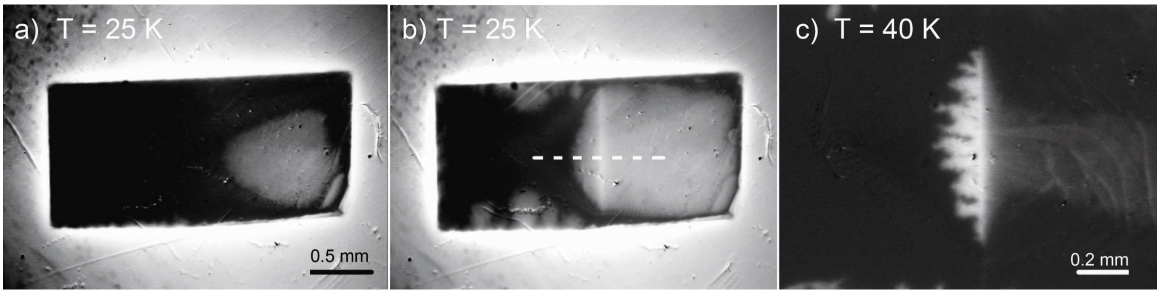

Figure 1. Magneto optical images of the partially irradiated sample at 25 K subjected to external field ramped at 0.75 Oe/sec, 9 seconds before (a) and 25 seconds after (b) the flux front hits the interface (brighter tones indicate higher induction). At 40 K (c) the flux front develops a pronounced flux finger pattern along its entire length.

In order to view the dynamics of the flux front we plot a series of consecutive induction profiles along the long side of the sample (dashed line in figure 1b) crossing the border at its centre. These profiles, taken at time intervals of 2 sec, are shown in figure 2 for T = 25 K (a) and T = 40 K (b). The external field, H_{ext}, was ramped from zero at time $t=0$ at a rate of 0.75 Oe/sec. The points on the profiles where the induction approaches zero indicate the location of the flux front. The profiles measured, both at 25 K and 40 K show that upon crossing the border into the irradiated region, the front movement slows down [21] and the induction slope increases, demonstrating a crossover of vortices from higher into lower magnetic diffusivity region. Note, however that the front velocity inside the non-irradiated region is much higher at 40 K. It is also evident that flux accumulation at the interface is much faster at 40 K than that at 25 K. This is better demonstrated in figure 3 which shows the time evolution of the induction at the interface for several temperatures. The figure shows that at 25 K, after the flux front reaches the interface, the induction at this location increases linearly at the same rate as the external field, as expected from the Bean model. In contrast, at 40 K, one clearly observes an abrupt build-up of the induction, at a rate considerably larger than that of the external field which subsequently reverts to increase at the same rate as the external field. This rapid increase in induction develops gradually with increasing temperature, between 30 K and 45 K.

Our experimental results reveal strong correlation between the appearance of flux finger patterns and the induction jump at the interface. At temperatures below 30 K where the jump is absent, the finger pattern does not appear. Likewise, at high field ramping rates, above 200 Oe/sec, both the induction jump and the finger pattern disappear. On the basis of these observations, we conclude that the finger pattern formation is a direct consequence of the abrupt flux build-up at the interface. This rapid build-up is expected on the basis of the magnetic diffusion equation, $\partial B/\partial t=-\partial E/\partial x$ [25]; A transition from a higher magnetic diffusivity region (high vortex velocity, v) into a lower one (low v),

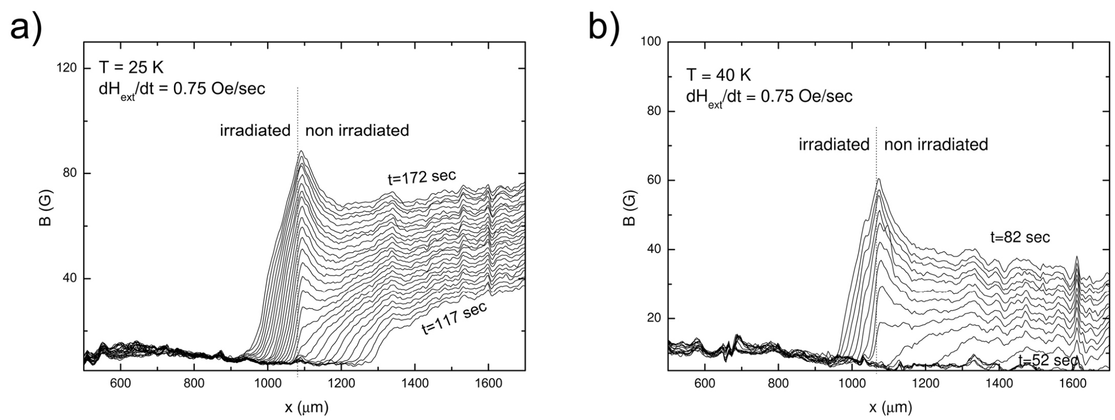

Figure 2. Induction profiles taken parallel to the long side of the sample (dashed line shown in figure 1b) for T = 25 K (a) and T = 40 K (b). Points where induction approaches zero indicate the location of the flux front. Time interval between each curve is 2 sec.

is accompanied by a sharp drop in the electric field, $E=Bv$, thus giving rise to a rapid increase of the induction. The negative gradient of the electric field upon crossing the border into the irradiated part is suppressed at lower temperatures, or at high field-ramp rates, as the magnetic diffusivity mismatch between the two parts of the sample is reduced.

In conclusion, we found strong correlation between the appearance of flux finger patterns and the induction jump, taking place at the interface between the irradiated and the non-irradiated parts of the sample. On the basis of this observation we propose the following scenario: as a consequence of the rapid flux build-up along the interface, accompanied by generation of a large electric field gradient, flux breaks into the irradiated part through easy-flow gates, where pinning is weaker. Easy flow channels are subsequently developed via thermomagnetic effect [6]. Namely, local temperature increase due to flux motion through the penetrated gates, decreases flux pinning and hence facilitates flux motion in channels perpendicular to the current flowing along the interface.

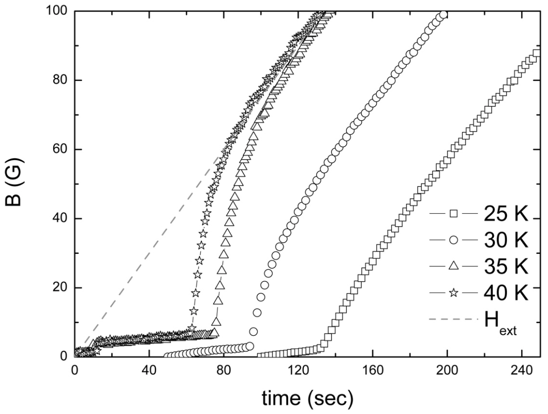

Figure 3. Time dependence of the local induction at the irradiation interface plotted for several temperatures. At 25 K the induction increases at the rate of the external field, at 40 K a rapid increase in induction takes place after which the increase rate reverts to that of the external field.

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