

## Local Magnetic Measurement of Strong Pinning by Columnar Defects

M. Konczykowski<sup>a</sup>, E. Zeldov<sup>b</sup>, D. Majer<sup>b</sup>, S. Bouffard<sup>c</sup>

<sup>a</sup>Laboratoire des Solides Irradiés, CNRS URA-1380, Ecole Polytechnique, 91128 Palaiseau, France

<sup>b</sup>The Weizmann Institute of Sciences, Rehovot 76100, Israel

<sup>c</sup>Centre Interdisciplinaire de Recherche sur Ions Lourds, GANIL, Caen, France

Local magnetic measurements by Hall-sensor arrays are used to study flux penetration and trapping in heavy ion irradiated YBCO:123 crystals. From the Bean-like flux profiles we obtain loops of the field gradient  $dB_z/dx$  vs local induction  $B_z$ , which show an asymmetry between the flux penetration and exit processes. The asymmetry is related to a sudden acceleration of the relaxation at some characteristic value of the local induction during flux penetration only.

### 1. INTRODUCTION

Strong pinning by columnar defects leads to difficulties in the interpretation of magnetic hysteresis. A fully penetrated critical state cannot be obtained without exceeding the matching field  $B_\Phi$  (induction at which the number of flux lines is nominally equal to the number of tracks)<sup>1</sup>. The global magnetisation resulting from integration of the persistent current  $J_s(B,x)$  over the sample volume with an *a priori* unknown field dependence of  $J_s$  cannot be interpreted straightforwardly. The use of local magnetic measurements like Hall-array<sup>2</sup> or magneto-optics<sup>3</sup> allows measurement of the gradients of magnetic induction. The value of  $dB_z/dx$  measured on the sample surface (away from edge and centre) is proportional to the persistent current  $J_s$  with some corrections for the flat geometry of the samples<sup>4</sup>. Except in a low field region where  $dB_x/dz$  contributes, a plot of the local gradient  $dB_z/dx$  vs. local induction  $B_z$  represents the variation of  $J_s$  vs.  $B$ . We have carried out such local magnetic measurements on YBCO:123 crystals containing columnar defects.

### 2. EXPERIMENT

We used 2D electron gas Hall-arrays composed of 11 sensors of area  $10 \times 10 \mu\text{m}^2$ , each spaced by  $10 \mu\text{m}$ . Samples were cut to  $200 \mu\text{m}$  wide strips from a  $20 \mu\text{m}$ -thick single crystal of lightly twinned YBCO:123, and irradiated at GANIL (Caen) with 5.8 GeV Pb ions (known

to produce amorphous tracks). The samples were placed on the Hall detector with the short axis parallel to the line of sensors. The isothermal magnetisation loops were recorded after Zero-Field-Cooling (ZFC). The field was increased and decreased step by step, and sets of values of the local induction were measured. Moreover, the magnetic relaxation was recorded during the 100 s following each step.

We have investigated several samples with various concentrations of columnar defects. Here we present measurements on the sample with  $B_\Phi = 1.12\text{T}$ , representative for all samples with  $B_\Phi$  exceeding  $0.1\text{T}$ .

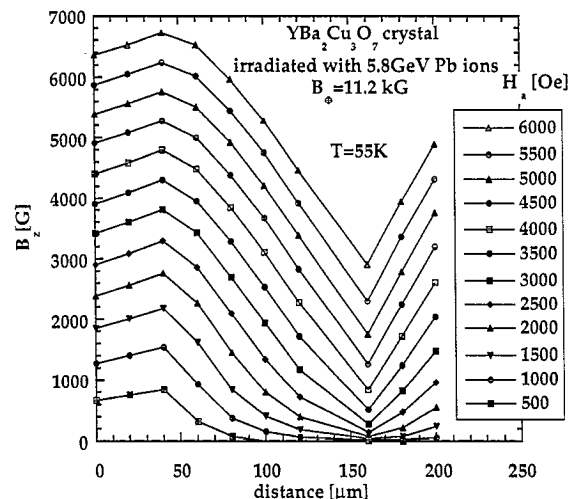


Figure 1. Magnetic flux profiles recorded on the surface of irradiated YBCO:123 crystal at 55 K on increasing field after Zero-Field-Cooling.

Typical flux penetration profiles are presented in Fig. 1. Textbook-like critical state flux penetration starting from the sample edges is observed. The full penetration field  $H^*$  can be determined precisely by the appearance of flux in the centre of the sample. At 55K, the value of  $H^*$  is  $\approx 3$  kG, at temperatures below 25 K it exceeds 1 T and hence,  $B_\Phi$ , in contradiction with the results of Ref. 5.

Loops of  $dB_Z/dx$  vs.  $B_Z$  were obtained by numerical differentiation and averaging of  $B_Z$  from every two adjacent sensors. This procedure yields results that are nearly independent on the sensor location, apart from those near the edges and the centre of sample. Typical loops of  $dB_Z/dx$  are presented in upper panel of Fig. 2. On the increasing field branch (flux penetration),  $dB_Z/dx$  exhibits a kink followed by a rapid drop, in contrast to the decreasing field branch (flux exit) where a smooth variation is observed.

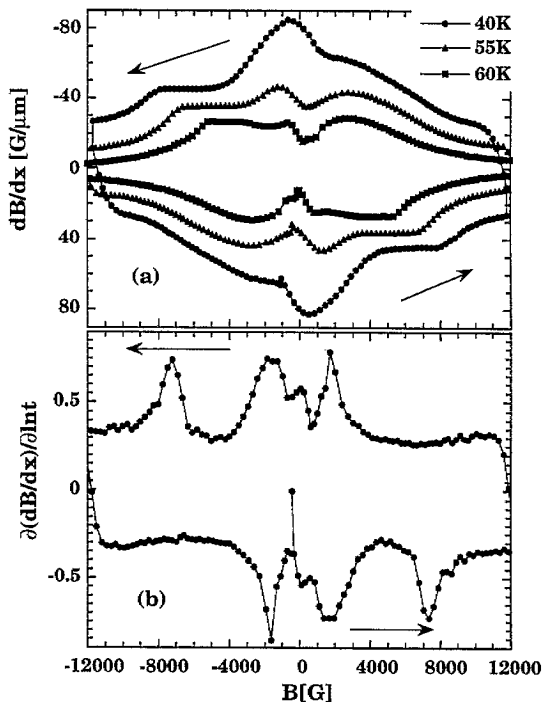


Figure 2. (a) Plots of the local gradient loop  $dB_Z/dx$  vs.  $B_Z$  measured at 40  $\mu\text{m}$  from the sample edge at various temperatures on irradiated YBCO:123 with  $B_\Phi=1.12$  T

(b) The slope of logarithmic decay of the local gradient measured at 55 K plotted vs.  $B_Z$ .

The same features are reproduced when the direction of the field is inverted, and field with opposite direction penetrates. The kink is not related to  $H^*$  and shifts to higher fields with decreasing temperature. Qualitatively, the same behaviour is observed in samples with different defect concentration, with a more pronounced effect for higher  $B_\Phi$ .

Short-time magnetic relaxation of  $dB_Z/dx$ , recorded after each step in field, is close to logarithmic. This allows the relaxation rate  $d(dB_Z/dx)/d\ln t$  vs.  $B$  to be plotted in the lower panel of Fig. 2. A marked peak in the relaxation rate is observed on the penetrating flux-branch, exactly at the same field as the kink in  $dB_Z/dx$ . This means that the kink results from a sudden acceleration of flux creep. It should be noted that even in the peak region, the temporal decay is smooth and flux jumps are not observed.

### 3. DISCUSSION

To our knowledge the difference between the flux penetration and flux exit process in the bulk pinning regime, with an enhancement of creep during flux entry is not predicted by any model. The association of enhancement of creep with the accommodation field<sup>5</sup> is inconsistent, because the same effect should then appear during both flux entry and exit. An interesting aspect of vortex loop nucleation mediated creep, which may present a clue for the explanation of the enhancement of creep, was pointed out in ref. 3. Bending of vortex lines by surface currents may provide a easier way to create superkinks between columns and thereby enhance creep.

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