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# Influence of pinning by columnar defects on the longitudinal and Hall resistivities of $YBa_2Cu_3O_7$ single crystals in the mixed state

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**Abstract**

We have measured the longitudinal and Hall resistivities of $YBa_2Cu_3O_7$ single crystals irradiated by energetic heavy ions. This type of irradiation results in creation of continuous cylinders of amorphous matter which act as very efficient pinning centers. As a consequence we observe a drastic narrowing of the transition curves in magnetic field ( parallel to the cylinders axis) and a strong increase of the pinning energies near $T_c$. In addition , the Hall voltage do present a sign change below $T_c$ even after irradiation, which confirms that the negative Hall voltage is related to an intrinsic property of the material.

## 1. Introduction

Irradiation of high-temperature superconduc -tors by different types of particles has been recently used to introduce additional pinning centers in these materials. Creation of point defects and/or small defect clusters by neutrons, electrons or keV ions irradiation results in a strong enhancement of magnetic hysteresis and critical current $J_c$ [1-3] . Nevertheless, these defects are efficient only at low temperatures and no change in the irreversibility line (IRL) has been observed [3].

On the contrary, columnar defects created by energetic heavy ions (such as GeV Pb ) irradiation, act as strong flux pinning centers ( when the magnetic field is parallel to them) in the whole temperature range, resulting not only in a dramatic increase of $J_c$ but also in an important shift of the IRL towards higher temperature [4,5]. Creation of such defects is strongly related to the value of the energy deposition by electronic excitation, $S_e$. Indeed, it is now well established [6] that when $S_e$ exceeds values of about 8 keV / nm defects are mainly created via inelastic collisions and when it reaches a threshold of about 20 keV / nm, continuous cylindrical amorphous latent tracks are produced.

In this paper, we present results of transport measurements in the *vortex liquid state* of low fluence ($10^{11}$ and 2 x $10^{11}$ ions / $cm^2$) $YBa_2Cu_3O_7$ single crystals irradiated with 5.8 GeV Pb ions. In this case, $S_e$ is about 33 keV / nm and therefore continuous cylindrical amorphous latent tracks with R=3.5 nm are produced in the ratio of one track per incident ion as shown in fig. (1).

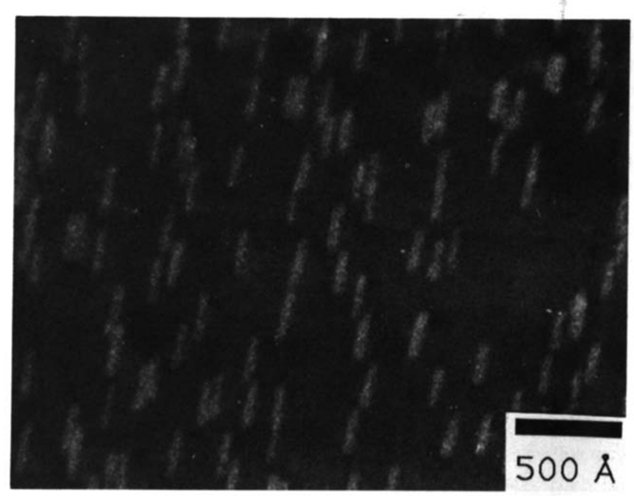


Figure 1. Dark field TEM image showing the amorphous tracks in a sample irradiated at 2 x $10^{11}$ ions / $cm^2$. The sample was tilted by 8° with respect to the incident beam direction.

As result of pinning enhancement, we observe an important narrowing of the resistivity transition curves in magnetic field

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parallel to the track axis, while the $\rho_{xy}$ dependence on magnetic field remains quite the same as in an unirradiated sample.

## 2. Experimental

### 2.1. Samples

Good quality single crystals ( $T_c \sim 92.8$ K ) were grown using the standard flux method. Samples were plates of about 2 x 2 x 0,02 $mm^3$. Good electrical contacts ( contact resistance of about 0.1 Ω ) were performed by sticking Pt wires with silver paste and then performing an annealing at 300 °C for one hour. Resistivity measurements performed on samples I and II irradiated at $10^{11}$ and $2x10^{11}$ ions/$cm^2$ respectively, were made using the standard Van der Pauw method. Hall resistivity measurements were made on sample III irradiated at $10^{11}$ ions / $cm^2$ by taking the odd voltage contribution when exchanging the voltage and current probes [7]. In all the cases, the current density was limited to 50 A / $cm^2$ and the magnetic field was parallel to the c axis.

### 2. 2. Irradiation

All the samples were irradiated at room temperature at the National Laboratory GANIL*
The beam direction was parallel to the *c* axis and $S_e$ ranged from 35 keV/nm. at the entry of the samples and 31 keV / nm at the end of them. This ensures that continuous cylinders of amorphous matter with R = 3.5 nm run troughout the whole thickness (see fig.1) .

## 3. Results and Discussion

### 3.1 Longitudinal resistivity

For the low fluences we used, the $T_c$ reduction was of 0.3 and 0.9 K respectively for the samples irradiated at $10^{11}$ and 2 x $10^{11}$ ions / $cm^2$ while the corresponding resistivity increases were of 10 and 20%.

Irradiation induces large narrowing of the transition width in presence of magnetic field as displayed in fig. 2, where we have compared the resistivity transitions in different magnetic fields for sample II before and after irradiation.

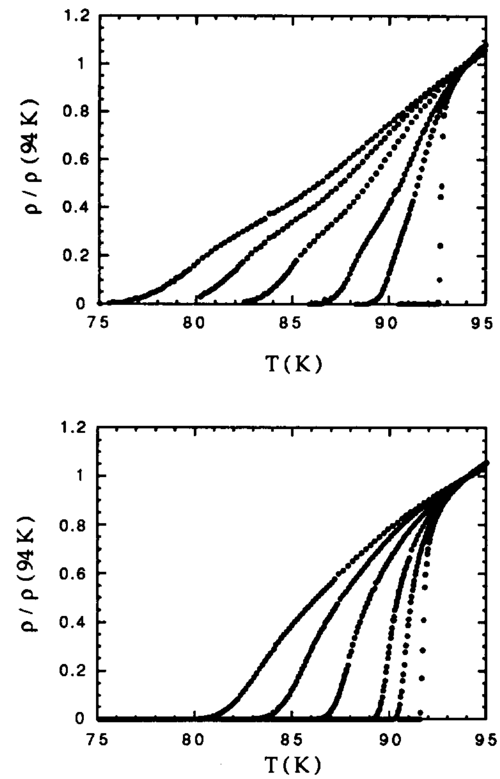


Figure 2. Resistivity transitions in different magnetic fields ( 0,1 ,2, 4, 6 and 8 T) for sample II before ( upper panel ) and after irradiation (lower panel).

We can see for instance that the transition narrowing is about 6 K at 8T, in contrast with results concerning proton and neutron irradiated $YBa_2Cu_3O_7$ single crystals where no significant changes in the transition curves have been observed.

Such a narrowing is strongly related to the shift of the irreversibility line towards higher temperatures. This clearly appears in fig.3 where we have plotted the irreversibility line as measured by the onset of the longitudinal resistivity for sample II before and after irradiation. This evolution is very similar to that observed by *Civale et al* [5] after Sn iradiation measured by ac-susceptibility techniques. It is worth mentioning that even if these two methods are not an absolute determination of the IRL, they give the same results as those obtained from the vortex glass transition determined from the V ( I ) curves in a single crystal irradiated at $10^{11}$ ions/$cm^2$ [7].

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In order to determine quantitatively the pinning enhancement due to the presence of columnar defects, we have carried out detailed analysis of the activated part of the resistivity transitions. For this purpose, we have taken a resistivity dependence on temperature and magnetic field as suggested by *Malozemoff et al* [8] :

$$\rho = \rho_0 \exp(-[A \times (1 - t^2)^{3/2} / (H \times t)] / k_B T_c) \quad (1)$$

where $t = T / T_c$. As in [8], we have neglected the $\rho_0$ dependence on temperature. By fitting the data using formula (1) we obtain different values of A summarized in table 1.

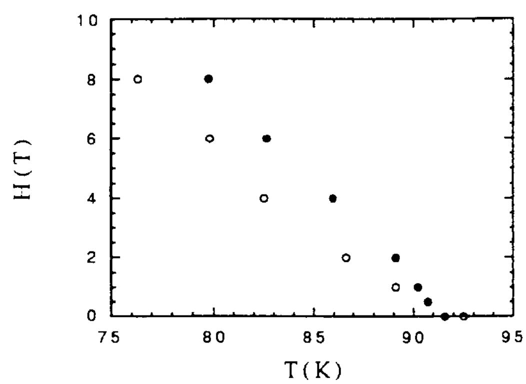


Figure 3. The $\rho_{xx} = 0$ line for sample II before (open circles) and after irradiation with 2 x $10^{11}$ ions / $cm^2$ (full circles).

We can see that before irradiation A is around 3 eV x T and is field independent. Such values are in agreement with previously published results (see ref. [8] for instance). After irradiation we observe an increase of the pinning energies as well as a step dependence on magnetic field. For high fields, the enhancement factor is about 3, while it is close to 6 when we approach fields lower than 2 T. Such a field dependence evidences the drastic changes in the pinning mechanisms induced by the presence of columnar defects. If we define the field $B^*$ as the value of the magnetic field at which the tracks density equalises the flux lines density, then $B^* = \Phi_0 \times \phi t$ where $\Phi_0$ is the flux quantum and $\phi t$ is the irradiation fluence. Within this description, the fluences we used correspond to 2 and 4 T respectively for samples I and II. Such values seem to separate two different pinning regimes : for $H_{ext} < B^*$ ,there are more tracks than flux lines and then pinning is more efficient than for $H_{ext} > B^*$ where the flux lines overtake the number of tracks. Within each regime, the pinning mechanism does not seem to depend on magnetic field, even if irradiations at different fluences should be useful in order to confirm this observation.

### *3. 2 Hall resistivity measurements*

The anomalous behaviour of the Hall effect in the liquid state has attracted an important attention. Two main points have been intensively discussed : the scaling behaviour of the Hall versus longitudinal resistivities ($\rho_{xy} \propto \rho_{xx}^{\alpha}$ with $\alpha$ close to 2) [9-11] and the sign change just below $T_c$. Concerning this last point, it has been recently suggested [12] that the negative part of the Hall voltage could be due to the existance of pinning centers in the bulk. If this should be the case, then significant changes in the Hall behaviour are expected after introduction of very efficient pinning centers like columnar defects. Preliminary results concerning sample III and displayed in fig.4, show that this not seems to be the case.

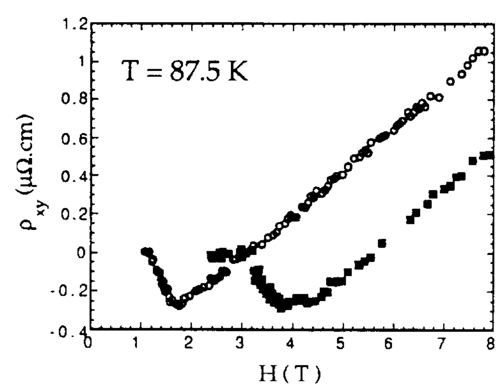


Figure 4. $\rho_{xy}$ vs magnetic field at T = 87.5 K for sample III before (open circles) and after irradiation at $10^{11}$ ions /$cm^2$ (full squares).

Table 1.Summary of the A values for samples I and II at different magnetic fields before and after irradiation

| $H_{ext}$ (T) | A (eV.T ) sample I before irradiation | A (eV.T ) sample I after irradiation | A (eV.T ) sample II before irradiation | A (eV.T ) sample II after irradiation |
|---|---|---|---|---|
| 0,5 | | 20.1 | | 18.1 |
| 1 | | 24.9 | 2.9 | 20.1 |
| 2 | 3.6 | 24.2 | 2.6 | 19.3 |
| 4 | 3.3 | 16 | 2.9 | 12.9 |
| 6 | | 10.2 | 2.4 | 10.8 |
| 8 | | 9.3 | 2.5 | 10.9 |

Indeed we can see that within our experimental accuracy there is no significant modifications in the $\rho_{xy}$ dependence on magnetic field - for a fixed temperature close to $T_c$ - excepted a shift towards higher fields. Nevertheless, more accurate measurements are needed to study the $\rho_{xy}$ vs $\rho_{xx}$ curves in the activated regime in order to examine if the scaling form $\rho_{xy} \propto \rho_{xx}{}^{\alpha}$ holds after irradiation .

## 4. Conclusion

In this paper, we have studied by means of transport measurements, the influence of irradiation induced columnar defects on the transport properties in the liquid state of $YB_2Cu_3O_7$ single crystals. Our results confirm that a new pinning mechanism, different from the one induced by point defects or randomly distributed clusters of defects, have to be considered in order to explain not only the shift of the irreversibily line but also the existence of two different pinning regimes in the activated region, separated by $B^*$. Moreover, it seems clear that the negative part of the Hall voltage below $T_c$ is not a pinning consequence.

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