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Gigantic surface pinning created by columnar defects

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Columnar tracks created by high energy heavy ions are considered to be the most efficient defects since they pin the vortices over their whole length. However, our magneto-optical observations and local Hall-probe measurements of the magnetization of $YBa_2Cu_3O_{7-\delta}$ single crystals with columnar defects reveal that at moderate fields the shielding current due to pinning by the columns is not proportional to the sample thickness, as it should be in the case of bulk pinning. We conclude that, in contradiction to what is commonly believed, the vortices are depinned from the columnar defects only at the surface. Experiments supporting this idea are reported and the peculiarities of this gigantic surface pinning are discussed.

The major problem in high current applications of high-T_c superconductors is the creation of strong pins preventing vortex motion. One of the most effective methods for strong enhancement of the critical current is irradiation by heavy ions [1]. Heavy ions create amorphous tracks (columnar defects) through the superconductor, thus providing what naturally seems the best way to trap the straight vortex lines along their whole length. Theoretical studies of this pinning considered infinite vortices parallel to the columnar defects [2,3]. However, these are not applicable to the realistic situation, where the superconductor is finite and the vortices should be curved in the presence of a large bulk critical current, and thus would be inclined with respect to the columns. It seems evident that vortex kinks connecting those parts of the inclined vortex that are trapped by the columns can slide easily along them. Thus, parallel columns should not produce efficient pinning in the bulk. The only obstacle which will prevent the continuous motion of the vortices in a real (finite) sample is kink nucleation at the surface. So, only the surface critical current is necessary.

Recently we have realized a number of experiments in order to demonstrate whether parallel columnar defects provide a surface or a bulk critical current. The idea is to check the difference of flux penetration into samples of variable thickness. In the case of surface depinning, the total shielding current and, therefore, the penetration field, the self-field and the saturation magnetization should be thickness independent, contrary to the usual proportionality to the thickness expected from the Bean model for bulk pinning. In order to exclude a possible scatter of the crystal properties we study thin and thick parts of the *same* crystal and find the striking insensitivity of the field penetration depth on thickness [4]. Here we present additional experiments in support of our idea.

$YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals were irradiated at GANIL in Caen, France and the flux penetration was studied by means of the high sensitivity magneto-optical imaging technique and local Hall-probe measurements (see details in [4]).

For the demonstration of all observed effects on the same sample we have chosen a 18 μm thick irradiated crystal, which we have cut with a wire saw to a depth of 10 μm, parallel to its edges; one side part was cleaved away in order to have an edge with thickness of 8 μm (see Fig. 1a). The initial penetration was equal at both long edges and no preferential penetration along the cuts across the crystal (vertical in the figure) was observed (Fig.1b). The subsequent penetration of the flux across the "horizontal" long step did not produce any flux concentra-

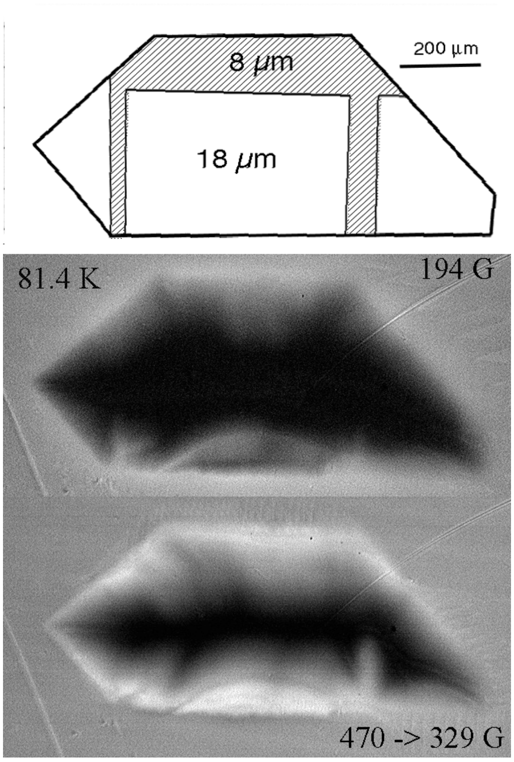

Figure 1. Homogeneous flux penetration into a very irregular YBCO crystal irradiated with 6 GeV Pb ions. (a) Sketch of the cuts, with the corresponding crystal thickness; (b) flux penetration at $H_a = 194$ G, T = 81.4 K; (c) after subsequent H_a increase to the maximum field of 470 G and reduction to 329 G. The higher image intensity corresponds to the higher local perpendicular field.

tion at it, while the thickness of the superconductor increases abruptly by more than a factor 2 (Fig.1c). These observations clearly demonstrate the supposed thickness independence of the shielding current.

Nevertheless, the dominating role of the surface shielding current does not hold towards fields approaching the matching field field B_ϕ at which the density of the columns is equal to the vortex density. In order to access this region, where the magneto-optical technique does not work, we use Hall probe measurements [4]. While at low fields the magnetization loops for the thick and thin parts practically coincide in agreement with the magneto-optical observations, at fields comparable to B_ϕ the magnetization on the thick and thin parts of the crystal start to decrease and, at the same time, to deviate from each other. At $B > B_\phi$, where, evidently, many vortices are not trapped by the columns, the proportionality of the magnetization to the thickness is restored.

The obtained data allow us to conclude that in the low field regime, when all vortices find a column and are pinned individually, parallel columns do not provide bulk pinning. On the contrary, they create a *gigantic surface pinning* with the surface critical current approaching the depairing limit according to the initial theoretical predictions [2,3]. Unlike the ordinary surface pinning at surface irregularities, in this case the vortices are trapped along their whole length, thus providing the observed surface shielding current, comparable to the bulk shielding current created by the highest known bulk pinning. At $B \lesssim B_\phi$ free vortices start to appear and the individual surface pinning becomes less and less effective. In order to answer the questions: what is the mechanism of the high-field bulk collective pinning, and why the field at which the gigantic surface pinning starts to decrease depends on the thickness, additional experimental and theoretical studies are necessary. We believe that the background preexisting weaker pinning on point defects and twins should be taken into account.

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