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Large fishtail effect in $DyBa_2Cu_3O_{7-\delta}$ single crystals containing columnar defects

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Using capacitance torque magnetometry, hysteresis loops were measured on a Pb-ion irradiated $DyBa_2Cu_3O_{7-\delta}$ single crystal as a function of magnetic field, temperature and angle Θ between the field direction and the c axis of the sample. The superconducting current densities, $j_c(T, B, \Theta)$, determined using the extended Bean model, show a clear fishtail effect at temperatures above 30 K despite the large enhancement of j_c due to the columnar tracks. The enhancement of j_c due to irradiation was magneto-optically determined to $j_c(\phi t)/j_c(0) = 10$ at T = 30 K. The pinning energy U_0 is, however, only slightly increased by the irradiation. Our measurements indicate clearly that the fishtail effect is a general feature of the high-T_c superconductors and not related to a special arrangement of pinning centres.

The fishtail or peak effect in the dependence of the superconducting current density j_c on the external magnetic field H_{ext} is observed in many bulk high-T_c superconducting samples [1], both single-crystalline and melt-textured. Explanation of this effect is not yet clear. Different hypotheses include granularity appearing in the samples at large external magnetic fields [2], oxygen vacancies as pinning centres changing their efficiency with field, oxygen-deficient zones in the sample [3], creep effects of the vortex lattice [4] or a crossover in the pinning regimes, e. g. from single vortex pinning to a pinning of vortex bundles [5] etc. An artificial introduction of strong pinning centres into a sample exhibiting the fishtail effect should clarify the situation. The boundary between different pinning regimes should shift and hence significantly influence the appearence of the minimum in the $j_c(H_{\text{ext}})$ curve. In this paper we show a pronounced fishtail effect in $DyBa_2Cu_3O_{7-\delta}$ (DyBCO) single crystals which have been irradiated by Pb ions.

The DyBCO single crystal (dimensions ($a \times b \times c$) $800 \times 800 \times 15\ \mu m^3$) showed a fishtail effect already before irradiation [4]. The irradiation was performed at GANIL, Caen using Pb ions with $E = 0.9$ GeV, $\phi t = 1.15 \times 10^{11}$ ions/cm^2. The direction of the beam was parallel to the c axis and lead to formation of columnar tracks which are very strong pinning centres [6]. The dose-equivalence field B_ϕ, where the number of vortices equals the number of columnar tracks, is in our case $B_\phi = 2.4$ T. To characterize the samples, magneto-optic observations of flux distributions in low external fields (up to 500 mT) were carried out [7] before and after the irradiation using the Faraday effect in thin EuSe layers [8]. At $T = 30$ K, the enhancement of j_c before $[j_c(0)]$ and after irradiation $[j_c(\phi t)]$ is determined to be $j_c(\phi t)/j_c(0) = 10$. So, the irradiation produced a large enhancement of j_c and therefore the boundary between the different pinning regimes must

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have moved up. The pinning energy U_0 is only slightly increased by means of the irradiation [6].

Torque ($\vec{\tau} = \vec{M} \times \vec{H}$) hysteresis loops were measured using a capacitance torque magnetometer in external magnetic fields up to ±7 T, oriented at an angle Θ with respect to the c axis of the crystal. The current densities $j_c(T, \mu_0 H_{\rm ext}, \Theta)$ were calculated using the extended Bean formalism $j_c = \tau/(\Omega B \sin\Theta)$ where τ is the amplitude in torque and $\Omega = a^2(b - a/3)c/4$.

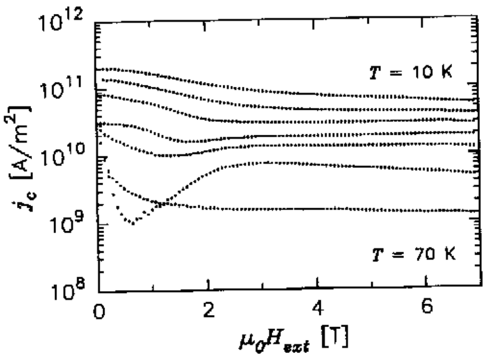

Figure 1. *j_c plotted logarithmically as a function of $\mu_0 H_{ext}$ for various temperatures (from top to bottom) T = 10, 20, 30, 40, 50, 60 and 70 K at a fixed angle Θ = 5°.*

In fig. 1, j_c is shown as a function of $H_{\rm ext}$ for various temperatures at a fixed angle Θ = 5°. At 5°, we may safely assume that the vortices are aligned parallel to the columnar tracks. At temperatures larger than 20 K, a dip appears in the $j_c(\mu_0 H_{\rm ext})$-curves like in the case of an unirradiated crystal and shifts to smaller values of $H_{\rm ext}$ with increasing T. The position of this dip is nearly equal to the full penetration field H^*. The second peak appears here only at elevated temperatures and it is not related to the dose-equivalence field B_ϕ. At 70 K, the fishtail shape disappears. Fig. 2 presents similar measurements at Θ = 60°. Now, the vortices are no longer aligned parallel to the columnar tracks. The fishtail effect is now more pronounced at low temperatures and the positions of the dip are shifted to higher values of $H_{\rm ext}$. From our measurements, we may conclude that the fishtail effect cannot be related to a specific arrangement of pinning centres. The explanation of this behaviour must be a more general one. Relaxation measurements in the dip of the fishtail [4,9] have shown that the shape of the $j_c(H_{\rm ext})$ curves is strongly influenced by varying the sweep rate of $H_{\rm ext}$. Moreover, the angular dependence of the dip depths indicates that the orientation of vortices with respect to the pinning centres plays an important role. We believe that the fishtail shape is due to a reorientation of the vortex lattice after reaching the full penetration field, H^*.

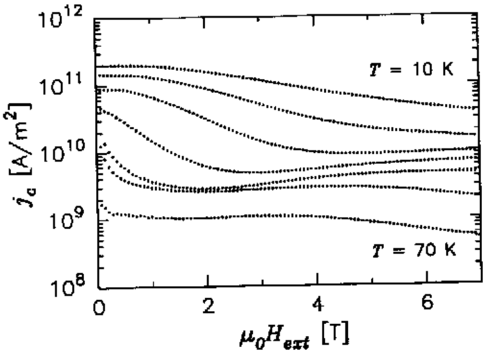

Figure 2. *j_c plotted logarithmically as a function of H_{ext} for various temperatures T = 10, 20, 30, 40, 50, 60 and 70 K at a fixed angle Θ = 60°.*

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