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Vortex Dynamics in a Ring-Like Irradiated $Bi_2Sr_2CaCu_2O_8$ Crystal

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A $Bi_2Sr_2CaCu_2O_8$ crystal selectively irradiated near the edges is studied using a Hall-sensor array. Vortices penetrating into the central $J_c = 0$ region are "focused" in the center of the sample on increasing the applied field. In decreasing field, vortices leave the center and a large vortex accumulation is observed on the inner rim of the irradiated region. Spatially resolved magnetization measurements confirm the developed theoretical model.

In a thin, flat superconductor, shielding currents flow in the entire width of the sample, and they may exceed significantly the critical current J_c. We investigate vortex dynamics in a sample with very low pinning in the central region and enhanced J_c close to the edges. In the low-pinning region, vortex dynamics is governed by supercritical diamagnetic currents, which lead to novel dynamics.

Consider a long thin superconducting strip of width $2W$ ($-W < x < W$) and thickness $d \ll W$, which is exposed to an applied magnetic field $H_a \parallel z$. The edges of the crystal are irradiated by heavy ions. Therefore the critical current density J_c is large at $e_0 < |x| < W$ and zero at $|x| < e_0$. The field components $B_z(x)$ and $B_x(x) = (\frac{2\pi d}{c})J_y(x)$ at the sample surface must be respectively the real and the imaginary parts of an analytic function $G(s) = F(s)f(s)$, $s = x + iy$. $F(s)$ is the solution in the absence of bulk pinning. In steady state, $J_y(x)$ and $B_z(x)$ cannot coexist in the same region in the absence of pinning. $F(s)$ must, therefore, be purely real in the vortex-filled region and purely imaginary in the vortex-free region [1]. $f(s)$ introduces the necessary corrections in the finite J_c case, where $J_y(x)$ and $B_z(x)$ may coexist under following conditions: either $|J_y| = J_c$ or if $|J_y(x)| < J_c$. Then $B_z(x)$ must be invariant, since the vortices are immobile. This is achieved by defining $\mathrm{Im}\{f(x)\} \propto 1/|F(x)|$ and $\mathrm{Im}\{f(x)\} \propto B_z(x)/|F(x)|$ in the appropriate regions inside the sample. On initial field increase at low fields, $H_a < H_p = B_f \ln \frac{W+\sqrt{W^2-e_0^2}}{e_0}$, before vortex penetration into the central unirradiated region, the results of Ref. [2] are recovered ($B_f = 4dJ_c/c$). At $H_a > H_p$, we obtain:

$$J_y(x) = \begin{cases} 0, & 0 < x < b, \\ -\frac{2J_c}{\pi}\tan^{-1}\sqrt{\frac{(W^2-e_0^2)(x^2-b^2)}{(W^2-b^2)(e_0^2-x^2)}}, & b < x < e_0, \\ -J_c, & e_0 < x < W, \end{cases}$$

and $-J_y(|x|)$ for $x < 0$. At $H_a = H_{\max} > H_p$, the resulting field profile is:

$$B_z^m(x)/B_f = \begin{cases} \ln \frac{\sqrt{|e_0^2-x^2|(W^2-b_0^2)}+\sqrt{|b_0^2-x^2|(W^2-e_0^2)}}{\sqrt{(e_0^2-b_0^2)|W^2-x^2|}}, & |x| < b_0 \text{ or } |x| > e_0, \\ 0, & b_0 < |x| < e_0, \end{cases}$$

where $2b_0$ is the width of vortex-filled region in the center of the strip at $H_{\max}$. As the applied field is decreased from its maximum value, we obtain for $b > e_0$:

$$J_y(x) = \begin{cases} 0, & 0 < x < e_0, \\ J_c & e_0 < x < b, \\ -\frac{2J_c}{\pi}\mathrm{Re}\{G(x)\}, & b < x < e, \\ J_c, & e < x < W, \end{cases}$$

$$B_z(x) = \begin{cases} B_f\mathrm{Re}\{G(x)\}, & 0 < |x| < b, \\ B_z^m(x), & b < |x| < e, \\ -B_f\mathrm{Re}\{G(x)\}, & e < |x| < W, \end{cases}$$

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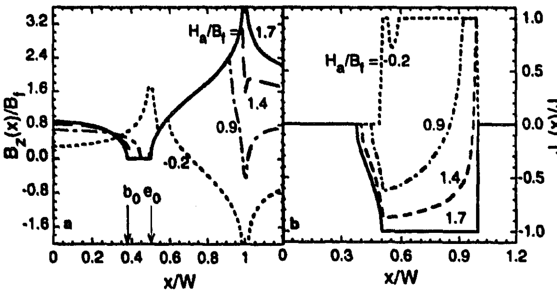

Figure 1. Calculated field (a) and current (b) profiles for decreasing field ($H_{\max} = 1.7B_f$).

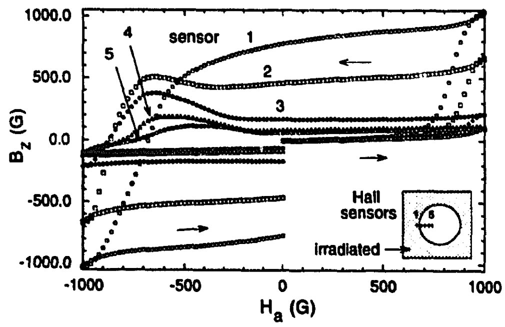

Figure 2. Experimental magnetization loops at T=40K. The Hall sensors are of $10 \times 10\mu m^2$ size with separation of $10\mu m$.

where $\mathrm{Re}\{G(x)\} = \sqrt{|(x^2-b^2)(e^2-x^2)|} \times$

$$\left[\mathrm{P}\int_{e_0}^{b} g(t)\,dt + \mathrm{P}\int_{b}^{e} \frac{B_z^m(t)}{\pi} g(t)\,dt - \mathrm{P}\int_{e}^{W} g(t)\,dt\right]$$

and $g(t) = \frac{t}{(t^2-x^2)\sqrt{|(t^2-b^2)(t^2-e^2)|}}$. The parameters b and e are determined by the applied field and by the condition of trapped flux conservation.

For increasing field, at $H_a > H_p$, the vortices that enter the irradiated region are forced by the shielding currents towards the center of the sample and "focused" there [1]. As a result, the central vortex-filled region is surrounded by an annular vortex-free region in which $J_y(x) > J_c \cong 0$. As field is decreased the trapped vortices start to "defocus" and move outwards as shown in Fig. 1. For $b < e_0$ the first integral term of $\mathrm{Re}\{G(x)\}$ is absent. As the expanding vortex-filled region reaches the inner rim of the irradiated region ($x = b_0$), vortices accumulate at the rim and partially penetrate into the irradiated region. In this state $|J_y(x)| = J_c$ at $|x| > e_o$ (Fig. 1). The local induction in the rim region *increases* with *decreasing* external field. This unusual effect has been observed experimentally.

Magnetization measurements were performed on a $Bi_2Sr_2CaCu_2O_8$ crystal ($700\times800\times20\ \mu m^3$) with edges irradiated by 0.9 GeV Pb ions with fluency 10^{10}ions/cm^2 along the c-axis of the crystal. After such irradiation the critical current increases up to approximately 10^6A/cm^2 in contrast to 10^3A/cm^2 in defect-free region. This region in our sample was a circle of 400 μm diameter located approximately in the center of the crystal. The measurements were performed using a sensitive GaAs/AlGaAs 2DEG Hall-sensor array. The array of 7 sensors was brought into direct contact with the crystal surface, so that the z-component of the local induction was measured at different points on the crystal (Fig. 2). Magnetization loops measured inside the defect-free region show a large "hump" at negative decreasing magnetic field. This vortex accumulation grows and shifts towards the edges of the irradiated region, in agreement with the theoretical results. Hence the vortices are "defocused" and forced into the irradiated region as the field decreases. As the applied field approaches $-H_{\max}$ negative vortices move through the irradiated region and annihilate the trapped positive vortices.

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