

Geometrical Barriers in Type II Superconductors

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Vortex penetration in thin flat samples in perpendicular fields is governed by geometrical barrier effect. The main features of this novel barrier is vortex accumulation in the center of the sample and irreversible magnetization in the absence of bulk pinning. The developed theoretical model is confirmed by experimental results.

The magnetization behavior of thin superconducting samples is usually modeled by approximation to an elliptical cross-section [1]. This common procedure fails to resolve some important aspects of vortex dynamics which are specific to thin flat samples in perpendicular magnetic fields. In particular, in absence of pinning and surface barriers, a reversible magnetization is expected in elliptical samples. In contrast, flat samples exhibit unique *hysteretic* behavior which is the result of geometrical barriers as discussed below.

Consider a long thin superconducting strip of rectangular cross-section of width $2W$ ($-W < x < W$) and thickness d ($-d/2 < z < d/2$, and $d \ll W$) exposed to applied field $H_a \parallel z$. In absence of bulk pinning the resulting shielding current density averaged over the sample thickness is given by [2]

$$J_y(x) = \begin{cases} 0, & 0 < x < b, \\ -\frac{2J_E^0}{\pi} \arctan \sqrt{\frac{(W^2 - e^2)(x^2 - b^2)}{(W^2 - b^2)(e^2 - x^2)}}, & b < x < e, \\ -J_E^0, & e < x < W, \end{cases}$$

and $-J_y(x)$ for $x < 0$. The edge current J_E^0 is determined by the following consideration. In increasing applied field the vortices initially cut through the sharp rims of the sample without complete penetration and thus effectively round off the curvature of the edges on the order of $d/2$. As a result, the vortex energy increases gradually from zero to a maximum value of $\epsilon_0 d$ at $W - |x| \simeq d/2$. At steady state conditions the

resulting force due to this potential gradient has to be balanced by Lorentz force of the shielding currents, $J_E^0 \phi_0 d/c$, and hence $J_E^0 \simeq 2c\epsilon_0/\phi_0 d = cH_{c1}/2\pi d$. ϕ_0 is the flux quantum and ϵ_0 the vortex line energy. The corresponding transverse field profile inside and outside the sample is

$$B_z(x) = \begin{cases} \frac{2H_{c1}}{\pi} \ln \frac{\sqrt{|\epsilon^2 - x^2|(W^2 - b^2)} + \sqrt{|b^2 - x^2|(W^2 - \epsilon^2)}}{\sqrt{(\epsilon^2 - b^2)|W^2 - x^2|}}, & |x| < b \text{ or } |x| > e, \\ 0, & b < |x| < e, \end{cases}$$

with the resulting magnetization per unit volume

$$M = -\frac{H_{c1}}{4\pi W d} \sqrt{(W^2 - b^2)(W^2 - e^2)}.$$

The parameters b and e are determined by the applied field

$$H_a = \frac{2H_{c1}}{\pi} \ln \frac{\sqrt{W^2 - b^2} + \sqrt{W^2 - e^2}}{\sqrt{e^2 - b^2}}$$

and by the history of the magnetic cycle as follows. As the field is initially increased, $b = 0$ and the vortices penetrate partially only into the edge regions $e < |x| < W$. The resulting current and field profiles are similar to the case in which vortex penetration is limited by bulk pinning [3] with J_E^0 replacing J_c . This situation holds as long as $e > W - d/2$ and hence $H_a < H_p \simeq (2H_{c1}/\pi)\sqrt{d/W}$. Above the penetration field $e = W - d/2$ and the penetrating vortices are dragged by the extended shielding currents towards the center, where a vortex-filled region of width $2b$ is formed as shown in Fig. 1. The

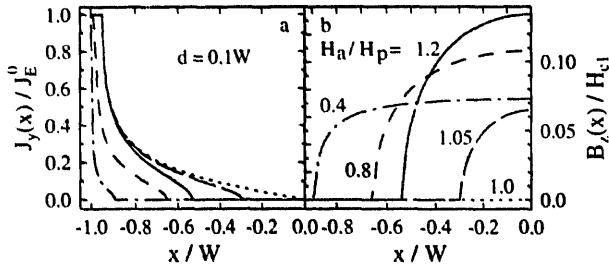


Figure 1. Calculated current (a) and field (b) profiles in half of a strip in ascending ($H_a/H_p=1, 1.05, 1.2$) and descending (0.8, 0.4) fields. Maximum applied field is $H_{max} = 1.2H_p$.

resulting apparent flux growth from the center of the sample is a unique consequence of the flat geometry. This situation, however, is not reversible since on decreasing field the central vortices are effectively trapped by the shielding currents. In this case both b and e increase with the declining field and their values are determined by H_a and the condition of constant trapped flux inside the sample. Fig. 1 shows the resulting current and field profiles, and the irreversible magnetization loops are shown in Fig. 2. Note that in contrast to bulk J_c the edge current J_E^0 does not change polarity as field decreases and hence $M < 0$ also on the descending branch. The trapped vortices exit the sample when $b \simeq W - d/2$. At high fields a reversible magnetization is obtained when $e = W - d/2 \simeq b$ at $H_a > H_{IL} \sim 1.5H_{c1}$.

We have measured the $B_z(x)$ profiles in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ crystals using sensitive microscopic GaAs/AlGaAs Hall-sensor arrays. Fig. 3 shows the experimental field profiles at $T = 50\text{K}$ in ascending applied field. For $H_a < 45\text{Oe}$ no vortices penetrate into the sample. As field increases, the flux build-up in the center of the sample and the expansion of vortex-filled region are clearly visible. The observed increase of the background field inside the crystal close to the edge is the result of small finite gap between crystal surface and the sensors.

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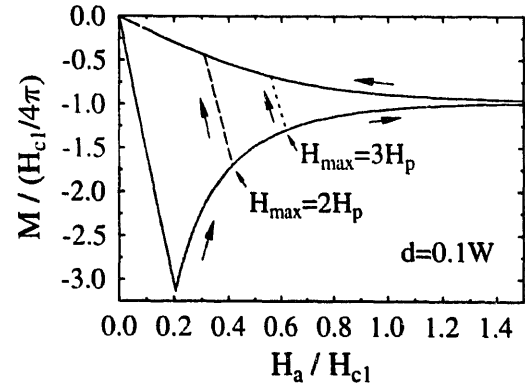


Figure 2. Calculated magnetization loops of a strip showing irreversible behavior due to geometrical barrier.

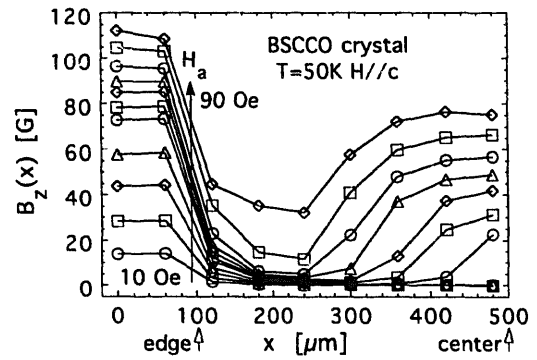


Figure 3. Experimental local field profiles in ascending H_a . Hall-sensor array consisted of nine $30 \times 30 \mu\text{m}^2$ elements $30 \mu\text{m}$ apart. The connecting lines are guide to the eye.

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