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Relaxation of the remanent state in thin superconducting samples

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Abstract

We report the importance of the induction planar component B_x in the relaxation of the remanent state in thin superconducting samples. Analysis based on the one-dimensional rate equation for thermally activated flux motion, which considers only the normal component B_z, yields unphysical divergence of the average flux line velocity as the neutral line is approached. Two-dimensional analysis resolves this problem and yields a modified scenario for the flux creep process in which vortex bending and the neutral line play a major role. These results are demonstrated in analysis of the local relaxation data obtained from a thin $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ crystal in the remanent state. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: $Nd_{2-x}Sr_xCuO_4$; Magnetic relaxation; Neutral line

The description of flux creep in superconductors is commonly based on the assumption that the sample is infinite in the field direction (the z-axis) and that straight flux lines parallel to the field enter or exit the sample through its edges. Accordingly, analyses of magnetic relaxation data are based on the one-dimensional (1D) rate equation [1–4]:

$$\partial B_z/\partial t = -\partial/\partial x(B_z v_x), \quad (1)$$

where v_x is the average flux line velocity. For thin samples, especially in the remanent state, the assumption of straight flux lines is no longer valid and the above scenario must be modified. In this paper we analyze magnetic relaxation data for a thin $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ crystal in the remanent state using a two-dimensional (2D) rate equation [5,6] which takes into account both the normal and planar components of the induction $\boldsymbol{B}$. Based on this 2D analysis, a modified scenario for the relaxation process of the remanent state is described.

The $10\times340\times1200\ \mu m^3$ $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ crystal was in direct contact with an array of 11 miniature Hall-probes (active area of $10\times10\ \mu m^2$). After zero-field cooling the sample to 8 K, the magnetic field was ramped up to $H = 1300$ Oe and then turned off. The B_z profile of the remanent state was consequently measured by the Hall array every 50 s. Using the raw $B_z(t)$ data we calculate the local electric field $E_y = (1/c)Bv$ by integrating $\partial B_z/\partial t$ [4]. Results are shown in Fig. 1 (open circles). As expected, E_y increases with the distance x from the sample center up to the "neutral line"[1] [7] where it reaches a maximum. This calculation of E_y is valid in both the 1D and 2D analyses. The problem in the 1D approach becomes apparent when one considers the behavior of $v_x = cE_y/B_z$, as shown in Fig. 2 (solid circles); Since $B_z = 0$ at the neutral line, and has different signs on both its sides, the 1D analysis yields $v_x \to \pm\infty$ as this line is approached. This unphysical result is avoided by using a 2D version of the rate equation [5,6] as shown below.

For an infinite strip in the y direction, $\boldsymbol{B} = (B_x, 0, B_z)$ and $E_y = (1/c)(B_z v_x - B_x v_z)$, where v_x and v_z are the

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[1] The neutral line is defined as the contour of points in the sample for which B_z equals the external field H. Thus, for the remanent state, at the neutral line $B_z = \partial B_z/\partial t \equiv 0$.

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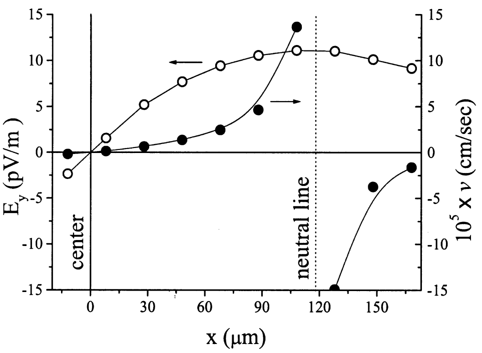

Fig. 1. Spatial distribution of E_y (open circles) and v_x (solid circles) at $t = 1$ s, computed by 1D analysis. Lines are guide to the eye.

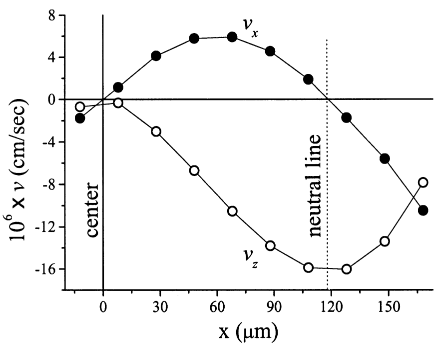

Fig. 2. Spatial distribution of v_x (solid circles) and v_z (open circles) at $t = 1$ s, computed by 2D analysis. Lines are guide to the eye.

x and z components of the flux line velocity $\boldsymbol{v}$. Since $\boldsymbol{v} \cdot \boldsymbol{B} = 0$,

$$v_x = cE_yB_z/B^2, \quad v_z = -cE_yB_x/B^2. \tag{2}$$

The spatial distributions of v_x and v_z are plotted in Fig. 2. Note that v_z is calculated at the sample surface where B_z is measured. In contrast to the divergence of v_x predicted by the 1D analysis, according to the 2D analysis $v_x(x)$ changes sign smoothly at the neutral line. Note that v_x always points towards the neutral line, and v_z is always directed towards the plane $z = 0$ going through half thickness of the sample ($v_z(z)$ changes sign at $z = 0$ because B_x changes sign at this plane).

The above analysis clearly indicates that the relaxation of the remanent state is not associated with flux exit through the sample edges. The 1D scenario of straight fluxons and anti-fluxons annihilation at the neutral line does not apply either. Instead, the remanent state relaxes by collapse of closed vortex loops [8] centered at the crossing line of the neutral line and the $z = 0$ plane.

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