Magneto-Optical Imaging of Transient Vortex States in $Bi_2Sr_2CaCu_2O_{8+\delta}$ Crystals

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Transient vortex states, created after a sudden exposure of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal to a steady magnetic field, are observed using a high-temporal resolution magneto-optical imaging system. The images reveal dynamic coexistence of a disordered phase near the sample edges and a quasi-ordered phase in the sample interior, prior to the establishment of a quasi-ordered state throughout the entire sample as dictated by the thermodynamic conditions. Different points on the borderline between these two phases move toward the sample edges at different rates, depending on the local induction.

Studies of the magnetic phase diagram of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) [1-4], have revealed the existence of two distinct vortex solid phases: A quasi-ordered lattice at low fields, and a highly disordered solid at high fields. In this paper we utilize a high temporal resolution magneto-optical method to follow the time evolution of the vortex structure in a $Bi_2Sr_2CaCu_2O_8$ (BSCCO) crystal after a sudden application (rise time ≅ 50 ms) of an external magnetic field. The field is in a range causing the induction field B_a at the sample edge to be *smaller* than the transition field B_{ss} separating the two solid vortex phases. Our experiments reveal that the quasi-ordered vortex phase, dictated by the thermodynamic conditions, is preceded by a transient disordered state. The purpose of this paper is to characterize the decay process of this transient state, and the concurrent growth of the quasi-ordered state.

The study was carried out on a 1.5x0.68x0.03 mm^3 BSCCO crystal ($T_c \approx 88$ K) [5]. The transition field, B_{ss}, between the two vortex solid phases, as measured from the onset of the second magnetization peak, is ≈ 460 G. In each experiment, more than 100 two-dimensional images were captured by a CCD video camera at time intervals of 40 ms.

Figure 1 shows the time evolution of the magnetic induction profiles at 20 K, after a sudden increase in the external magnetic field from zero to 470 Oe. Surface currents result in the sharp induction step observed at the edges [6], reducing the edge induction to $B_a \approx 450$ G. A remarkable feature in the induction profiles of Fig. 1 is the sharp

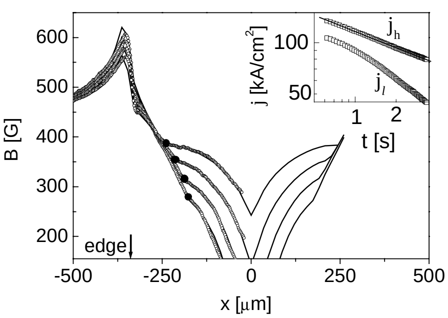

Figure 1 Time evolution of the magnetic induction profiles for applied field 470 Oe (B_a = 450 G < B_{ss}). Profiles shown are measured at t = 0.62, 1.02, 1.75, and 3.47 s. Bold circles denote the location x_f of the breaks in the profiles. Solid lines are theoretical fits. Inset: Log-log plot of $j_h(t)$ and $j_l(t)$.

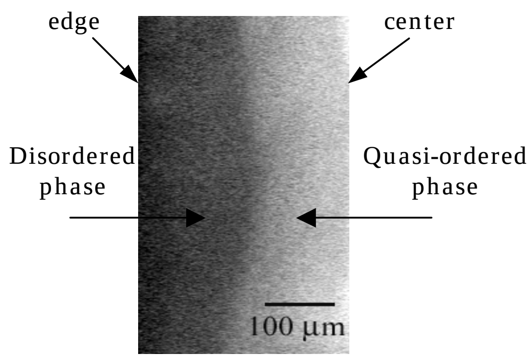

Figure 2. Illustration of the border between the two vortex phases by taking the difference of two consecutive images.

change in their slope at $x = x_f$, (marked by bold circles), indicating a change in the bulk current density. As evident from the figure, the point x_f moves progressively with time toward the sample edges and, simultaneously, the induction B_f at x_f increases. The point x_f also signifies a remarkable change in magnetic relaxation characteristics. To illustrate this point we employ the Biot-Savart law to fit the data of Fig. 1, using surface current j_s, and two bulk currents j_h and j_l as fitting parameters. As shown in the log-log plot in the inset to Fig. 1, the bulk current j_h, corresponding to the part of the profile near the edges, exhibits a power-law decay with time ($j_h \propto 1/t^{0.31}$), whereas deviations from a power-law are evident for j_l.

The break in the induction profile at x_f, which marks a change in the bulk current density and in the relaxation characteristics, indicates a dynamic coexistence of two distinct vortex states on both sides of x_f. The nature of these phases is explained as follows. The *sudden* injection of vortices into the sample through its edges creates a transient disordered state of the vortex matter. A quasi-ordered thermodynamic vortex state starts to nucleate near the sample center where the field is minimum, and expands toward the sample edges. x_f is a point on the border between the expanding quasi-ordered phase and the decaying transient disordered phase.

In order to construct the *borderline* between the two phases, we utilize their different relaxation characteristics. We subtract consecutive 2D induction images and plot the difference. In the quasi-ordered state the decay is relatively fast and the differnces are relatively large (bright in our gray scale). The slow decay of the disordered state results in a relatively small difference (dark color). Figure 2 illustrates a result of such a procedure, showing a clear border between the two phases. This border can be viewed as the front of the growing quasi-ordered phase. The curved shape of this front results from the dependence of the growth rate on the local induction [7]. The 2D distribution of the induction field for a thin rectangular sample [8] leads to the curved front shown in Fig. 2.

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