Coexisting ordered and disordered vortex phases in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

A high temporal resolution magneto-optical system was employed to image the induction distribution on the surface of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal while the external magnetic field was ramped up at a constant rate. These data reveal coexistence of quasi-ordered and disordered vortex phases, near the order-disorder phase transition line. The coexistence region in the B-T phase diagram narrows down with increasing temperature or decreasing sweep-rate. These observations clarify previous interpretations of phenomena associated with the fishtail, e.g. the shift of the fishtail onset to higher inductions for slower sweep-rates and the absence of a fishtail at low temperatures.

Key words: Vortex states, Vortex phase transitions, $Bi_2Sr_2CaCu_2O_{8+\delta}$, Magneto-optics

Studies of the magnetic phase diagram of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) at low temperatures 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. Dynamic coexistence of these two phases, near the phase transition line, was observed in time-resolved magneto-optical measurements [1–4] and was inferred from global magnetic measurements at different sweep rates of the external field H_{ext} [5]. In the present work we exploit high temporal resolution magneto-optical system [1] to define the coexistence region in the B-T phase diagram at different sweep rates.

Measurements were preformed on a 1.55×1.25×0.05 mm^3 BSCCO single crystal with T_c=92 K, at different temperatures between 18 and 26 K. Field was swept up from zero to about 850 G (above the order-disorder transition field $B_{ss} \approx 450$ G), at a constant rate of either 6 or 47.6 G/sec. While the external magnetic field was swept up, the induction distribution on the surface of the crystal was imaged successively at a constant field interval of 6 G, using iron garnet indicators and a high speed CCD video camera with exposure time of 36 ms.

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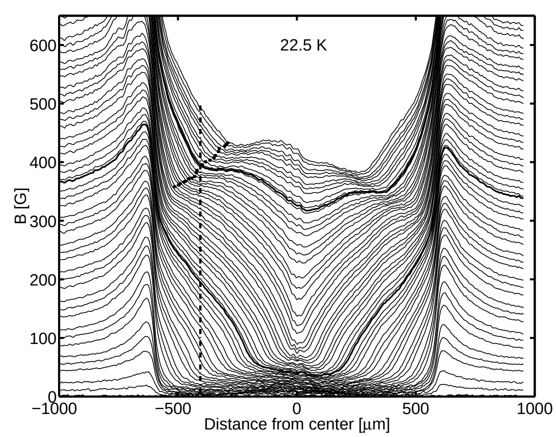

Fig. 1. Induction profiles in BSCCO at T=22.5 K, measured during increase of the external field from 0 to 850 G at a rate of 47.6 G/sec.

Figure 1 shows the induction profiles deduced from the magneto-optical images, taken at T=22.5 K, while the external field was swept at a rate of 47.6 G/sec. The initial bean profiles change gradually in the interior of the sample into dome-shape profiles, characteristic of a quasi-ordered state. As H_{ext} increases toward a value of about 400 G, a break appears in the profile, separating between a high persistent current region near the sample edges and a low persistent current region near the center. This break moves toward the sample center, and the induction at the break increases. In this experiment, coexistence of order and disorder phases appear for $H_{ext} = 400$ and disappears for $H_{ext} > 850$ G. Decreasing sweeping rate, or increasing temperature, narrows down the range of external magnetic fields for which the coexisting phases are observed.

The induction at the break, being time and location dependent, cannot signify the thermodynamic transition field B_{ss}. We therefore interpret the first appearance of the break as resulting from injection of transient disordered state through inhomogeneous surface barriers [6]. Following the approach of Paltiel *et al.* [7], this transient state anneals over a characteristic 'healing length' $L = v\tau$, where v, is the average velocity of the injected vortices and τ is the lifetime of this transient state. The velocity v increases with the sweep rate dH_{ext}/dt, whereas τ increases as B_{ss} is approached [1]. At low fields, far below B_{ss}, τ is too short to be detected in the time window of our experiment. Thus, the profiles appear smooth, without a break. As B_{ss} is approached, τ increases and the transient states penetrate deeper into the sample. These states generate a large induction slope near the edges, merging with the existing induction profile inside the sample. As the field increases the high induction slope region near the edges widens and, consequently, the disordered state penetrates deeper into the sample.

At larger sweep rates the healing length L increases because of the increasing v and τ. The vortex velocity v increases due to a larger $E = dH_{ext}/dt$. τ increases because at larger dH_{ext}/dt more fluxons enter the sample so B is larger and therefore closer to B_{ss}. The total effect is that L increases and as a result, the break in the profile appears at lower external fields. The same effect is observed as temperature is lowered; this is due to the increase in τ as the temperature decreases. Note the equivalent role played by temperature and time [8].

The dashed curve in Figure 2 exhibits local magnetization curve, $m_{local}=B_{local}-H_{ext}$, derived from the induction profiles of Figure 1 at -410 μm marked by the vertical dashed line in Figure 1. It is interesting to note that the appearance of a break in the profile is associated with an onset of a fishtail in m_{local}. Also, the front passing through -410 μm is associated with the kink in m_{local}. This is demonstrated by the lower bold profile in Fig. 1. This observation clarifies the absence of a fishtail at low temperatures [8] where τ is large and therefore L may exceed the sample dimension. As time elapses, the transient state anneals and the fishtail appears, as observed in Ref. [8].

The solid curve in Fig. 2 exhibits the local magnetization curve for smaller sweep rate (6 G/sec), at the same place on the sample. Because of the smaller v, the fishtail onset shifts to higher fields. This observation is in agreement with the results of global measurements reported by Küpfer *et al.* [5]. The shift of the fishtail onset to lower fields with increasing sweep rate observed in their global measurements was interpreted as resulting from injection of disorder into the vortex lattice from large electric fields at the sample surface. Our magneto-optical images provide visual confirmation to this interpretation.

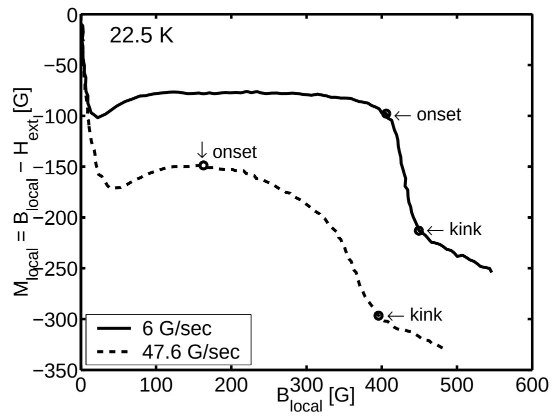

Fig. 2. Local magnetization vs. local induction at T=22.5 K, for sweep rates 47.6 G/sec (dashed curve) and 6 G/sec (solid curve). Curves were measured at x=-140 μm indicated by the vertical line in Figure 1.

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