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Vortex order–disorder transition in relaxation and field-sweep measurements

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Abstract

Time evolution of the induction profile across a $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal was magneto-optically recorded in two experiments: during ramping the external magnetic field or after a sudden application of the field. The results of these experiments reveal a front-like propagation or retreat of a transient disordered vortex state, respectively. Analysis of the front velocity shows that while the retreat is continuously decelerated, the propagation is accelerated, approaching a constant velocity when the front induction reaches the vortex order–disorder phase transition field B_{od}. The latter observation suggests a method for determining the value of B_{od}, eliminating transient state effects.

Keywords: Vortex phase transitions; Transient vortex state; Annealing time

Recent studies of the vortex order–disorder phase transition in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) showed that proper characterization of this transition must take into account effects of transient disordered vortex states [1–4]. In this paper we show how these transient states manifest themselves in two commonly used magnetic measurement techniques—field sweep at a certain rate and relaxation over a certain time period after abrupt application of a field (rise time < 50 ms).

Measurements were carried out on a $1.55\times1.25\times0.05$ mm^3 BSCCO single crystal ($T_c = 92$ K), using a magneto-optical (MO) imaging system coupled to a 40-ms/frame CCD camera. The MO images were generated using an iron-garnet indicator with in-plane anisotropy. Magneto-optical snapshots of the local induction distribution across the sample were taken at $T = 21$ K, under fields 140–840 G, applied parallel to the crystal c axis.

In relaxation measurements, after a sudden application of the field (rise time < 50 ms), images were collected over a time period of ~4 s every 40 ms and over an additional time period of ~26 s every 300 ms. In the field sweep experiment, MO images of the induction distribution were collected while the external field was ramped at a constant rate of 4–1600 G/s.

Fig. 1 illustrates a typical result obtained in a relaxation experiment with a field step of 480 G. Following the abrupt increase in the external field, a transient disordered vortex state exists throughout the entire sample [1]. Subsequently, the thermodynamically favored quasi-ordered phase nucleates at the center of the sample where the field is minimal, and thus the lifetime of the transient state is shortest. Coexistence of quasi-ordered and transient disordered vortex states is indicated by a "break" in the local induction profile, separating between the low j ordered phase near the center and the high j disordered phase near the edge [5]. Growth of the quasi-ordered state, and concurrent retreat of the transient disordered state, is demonstrated by a movement of the break towards the sample edge, as shown in Fig. 1. The inset to this figure illustrates that as the induction B_f at the break approaches the transition field B_{od}, the velocity, v_f, of the front drops down. Only

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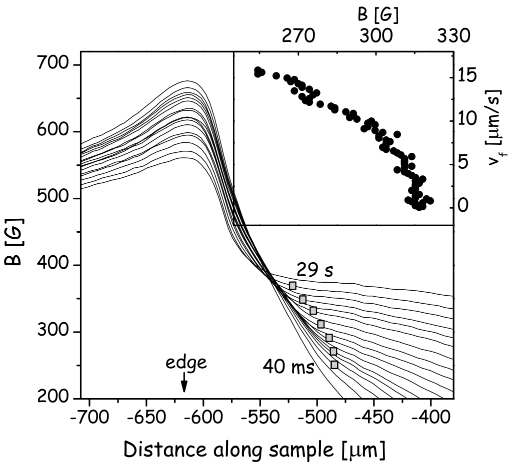

Fig. 1. Time evolution of induction profiles in relaxation experiment after a field step of 480 G at $T = 21$ K (sample center is at $x = 0$). Profiles correspond to times: 0.04, 0.5, 1, 1.2, 1.4, 1.6, 2, 2.4, 3, 3.6, 4.5, 6, 7.5, 9, 12, 16.5, and 29 s. Squares indicate the position of the expanding ordered phase front. Inset: Front velocity vs. induction.

in the absence of flux creep one would expect that $v_f \to 0$ for $B_f \to B_{od}$. Indeed, the data show that v_f approaches zero well below B_{od}, indicating continuous injection of disordered states due to flux creep.

The situation is different in field sweep experiments. Typical results are illustrated in Fig. 2 for $dH_{ext}/dt = 11$ G/s. Here, two competing processes take place simultaneously: continuous injection of transient disordered states from the sample edges towards its center, and concurrent annealing of these states proceeding in the opposite direction. The position of the break is determined by the competition between these two processes. For low fields, far below B_{od}, the annealing process is faster than the injection rate and, hence, one does not observe any "break" in the induction profile. With the rise in field, the lifetime of the transient state continuously increases, slowing down the annealing process to a degree allowing the first appearance of a break near the sample edge. Subsequently, as the external field continues to increase, the annealing process is further attenuated, and the injection of the transient disordered state becomes more dominant. As a result, the break progresses towards the sample center, indicating the growth of the disorder transient state throughout the sample. The slowing down of the annealing process with increasing field gives rise to an accelerated motion of the break towards the center. Eventually, as B_{od} is closely approached, the lifetime of the transient disordered states diverges [3] bringing the annealing process to a halt. At this point, the front of the disordered state continues to move at a constant velocity determined by the rate of change of the external field. This behavior of

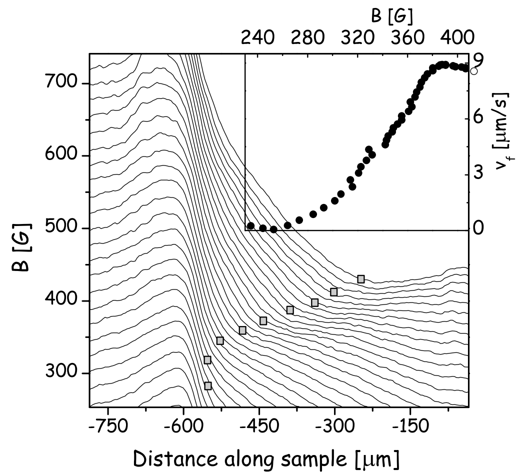

Fig. 2. Time evolution of induction profiles in sweep-field experiment for $dH_{ext}/dt = 11$ G/s at 21 K. Squares indicate the position of the penetrating disordered state front. Inset: Front velocity vs. induction.

the front velocity v_f is illustrated in the inset to Fig. 2. Evidently, while in relaxation experiments v_f decreases with time, in sweep experiments v_f increases with time approaching a constant value determined by the rate of change of the external field. The transition field B_{od}, can be determined as the field, B_f, for which the velocity v_f reaches a constant value. For the measured sample of BSCCO, this approach yields $B_{od} = 390$ G.

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