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Distributed injection of transient vortex states in a prism-shaped $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal

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Abstract

Magneto-optical measurements in $Bi_2Sr_2CaCu_2O_{8+\delta}$ demonstrate enhanced effects of transient disordered vortex states (TDVS) in a prism-shaped sample. The existence of such transient states is indicated by the appearance of a sharp change ('break') in the slope of the induction profiles. As the external magnetic field is swept up or down, the break, which signifies the front of the TDVS, moves towards the sample center at a constant velocity determined by the rate of change of the external field. We discuss the results in terms of a competition between injection and annealing processes, the latter being ineffective in the prism due to direct injection of disorder into the bulk through surface barriers distributed along the tilted facets of the prism.

Keywords: $Bi_2Sr_2CaCu_2O_{8+\delta}$; Metastable vortex states; Surface barriers

It has been recently shown that transient disordered vortex states (TDVS) are generated by injection of vortices through inhomogeneous surface barriers [1] during field increase, or by supercooling the high-field disordered vortex phase during field decrease [2,3]. The important role of the surface in generating TDVS was demonstrated in transport measurements in $NbSe_2$ showing that TDVS are absent when vortices are injected directly into the bulk of the sample, bypassing the surface, in a Corbino disk configuration [4]. In the present work we elucidate the role of surface barriers in magnetic measurements, by studying the generation and annealing of TDVS in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystal with prism geometry [5]. While for a platelet geometry surface barriers influence only the flux entry process at the edge of the sample ($x = \pm d$, see inset to Fig. 2), in the prism geometry vortex motion involves activation over surface barriers for any location, x, across the sample [6]. This is because an inward displacement of a vortex, due to a small increase of the applied field, results in a change of the vortex length, and hence requires addition of extra vortex pancakes at the top of the stack; each addition of a pancake involves a single local penetration event over a surface barrier. In this work we examine how these distributed surface barriers affect the dynamics of TDVS.

A prism-shaped sample ($2.5 \times 1.4 \times 0.1$ mm^3, with angle of $\sim 10°$ between the tilted facets and the base – the *ab* plane) was cut from an optimally doped BSCCO single crystal ($T_c = 92$ K). A magneto-optical system was employed to image the induction distribution across the *ab* plane while the external field was swept up and down at a constant rate (4–1600 G/s) between zero and 850 G (well above the order–disorder vortex transition $B_{od} \sim 400$ G). Snapshots of the induction distribution were taken successively, using iron-garnet indicators with in-plane anisotropy and a CCD video camera.

Fig. 1a presents induction profiles measured while the field was swept up at a rate of 4 G/s at 29 K. At low and high fields, the profiles are Bean-like with relatively low and high slopes, characterizing the quasi-ordered and

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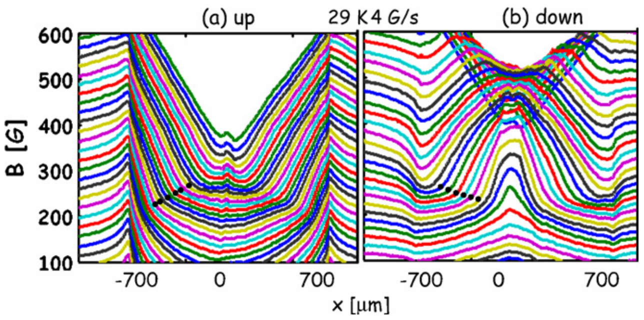

Fig. 1. Induction profiles obtained during sweeping of the field up (a) and down (b) at a rate of 4 G/s at 29 K.

disordered vortex states, respectively. The profiles in the intermediate field range are of particular interest; they are characterized by a sharp change in the slope ('break'), signifying a border between coexisting low-current quasi-ordered phase and a high-current transient disordered state [3,7]. This border, indicated by a circle in the figure, moves towards the sample interior as the field is increased, creating a disordered state throughout the entire sample.

Fig. 1b describes the profiles obtained in field sweep down at a rate 4 G/s. Similar breaks are observed, indicating dynamic coexistence of TDVS in the sample interior and a quasi-ordered state near the sample edges. The front between these two states moves towards the sample interior, indicating propagation of the quasi-ordered state towards the sample center.

Fig. 2 shows the location of the front x_f *vs.* time at 29 K, for fields sweep up (squares) and down (circles) at a rate of 4 G/s. The figure shows quite surprising results: In both cases the front propagates at a constant velocity from the moment of its inception at the edge. Since the front dynamics are generally determined by a competition between injection and annealing processes of TDVS [7], one would expect accelerated motion of the front for field ascending, starting from zero velocity at the edge approaching a finite value determined by the rate of change of the external field. At low fields, the annealing rate is high, preventing propagation of the TDVS into the bulk of the sample. As the external field increases, the annealing rate decreases, approaching zero as the order–disorder vortex transition induction is approached. At a certain induction field, where the injection rate equals the annealing rate, the TDVS appears at the sample edge with zero velocity. As the field continues to increase the annealing rate further decreases, and consequently, the front velocity increases until it reaches a final value for which the annealing is ineffective.

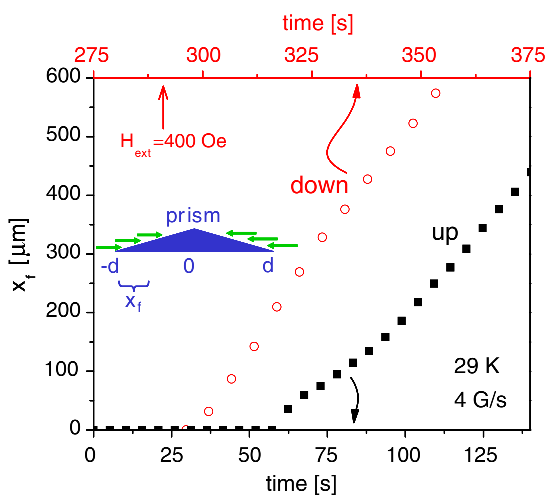

Fig. 2. x_f *vs.* time for sweep up (squares) and down (circles) at a rate of 4 G/s at 29 K.

The observed constant front velocity in the prism for field sweep up (Fig. 2) is therefore unique, indicating that annealing processes are ineffective in this geometry. This surprising result is explained as follows. In the prism geometry, surface barriers are distributed along the tilted facets of the prism, from $x = \pm d$ to $x = 0$, see inset to Fig. 2. As the external field increases, the induction corresponding to the appearance of TDVS is first obtained at the prism edges ($x = \pm d$) and subsequently across the entire prism surface (at points corresponding to smaller and smaller x, see arrows near the prism sketch in Fig. 2). This sequential injection of TDVS directly into the bulk ($|x| < d$), creates a front at x that progresses into the sample center at the same rate as the injection progresses across the tilted surface, i.e. at a rate proportional to dH/dt, bypassing the annealing process. As a result, the front velocity in the prism is faster than in a platelet where the annealing process impedes the front propagation. The faster front velocity in the prism gives rise to lower inductions at the front, since it propagates deeper into the sample bulk where the induction is lower. Thus, enhanced effects of TDVS are observed in the prism geometry, causing a further shift down of the apparent order–disorder transition induction, as compared to a platelet sample.

In sweeping the field down, the disordered state is 'supercooled' to inductions below B_{od}. The front of the ordered state nucleates at $x = \pm d$ where the induction is minimal, propagating towards the sample center. The constant velocity during field descent is understood as follows [7]: When the break appears at inductions not too far below B_{od}, the induction of the break is approximately constant as the annealing rate of the TDVS is slow. As a result, x_f progresses at a rate determined by the rate of change of the external field.

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