

# Magneto-optical investigation of "super-cooled" disordered vortex states in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

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## Abstract

Magnetic induction profiles across the width of a  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  crystal were measured while the external magnetic field was ramped down from above the vortex solid-solid phase transition field down to zero. These profiles indicate dynamic coexistence of two vortex phases: a disordered phase in the sample interior and a quasi-ordered phase near the sample edges. The border between these two phases, marked by an abrupt change in the slope of the profiles, progresses towards the sample center and appears at the same induction,  $B_f$ , independent of the location. By increasing the sweep rate of the external field,  $B_f$  can be monotonically decreased to values well below the transition field. These results emphasize the role of the electric field in the vortex solid-solid phase transition, and question the interpretation of such "supercooling" experiments as signifying the first order nature of this transition.

*Key words:* Magneto-optics,  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ , Vortex states, Vortex phase transitions

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The nature of the vortex phase transition from a quasi-ordered solid to a disordered solid has been the subject of several recent investigations [1–7]. An indirect evidence for the first order nature of this transition was obtained in various experiments including vortex 'dithering' [4], history dependent magnetic measurements [5,8], and quenching of the disordered vortex by a rapid decrease of the field [7,9], demonstrating a "supercooling" effect. In this paper we show that in quenching experiments involving the generation of large electric fields, the apparent vortex solid-solid transition induction may be shifted down to arbitrary values well below the transition field  $B_{ss}$ . These results question the interpretation of such experiments as signifying supercooling effects related to the first order nature of the transition.

A  $1.55 \times 1.25 \times 0.05 \text{ mm}^3$   $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (BSCCO) single crystal ( $T_c=92 \text{ K}$ ) was cooled down in zero field to the measurement temperature (between 18 and 26 K). At this temperature, a large external magnetic field (approximately 850 G), well above the transition

induction  $B_{ss} \approx 450 \text{ G}$ , was applied for long enough time to ensure establishment of a disordered vortex state. The field was then ramped down to zero at a constant rate between 4 and 360 G/sec. During the field ramping, a high temporal resolution magneto-optical (MO) system [10] was employed to snapshot images of the induction distribution on the surface of the crystal at constant field interval of about 6 G.

Figure 1 shows the induction profiles across the sample's width, as deduced from MO images taken at  $T=22.5 \text{ K}$ , while the external field was ramped down at a rate of 6 G/sec. For external fields between 470 and 250 G the profiles exhibit breaks, progressing into the sample interior with time. Interestingly, the breaks occur at the *same* induction,  $B_f = 380 \text{ G}$ , *independent* of the location in the sample. These breaks are interpreted as revealing coexistence [10] of a quasi-ordered vortex phase (low persistent current,  $j_p$ ) near the sample's edge and a disordered vortex phase (high  $j_p$ ), in the sample interior. It is tempting to interpret  $B_f$  as the thermodynamic solid-solid transition induction  $B_{ss}$ . However, we find that the value of  $B_f$  depends strongly on the sweep rate; it can be suppressed, down

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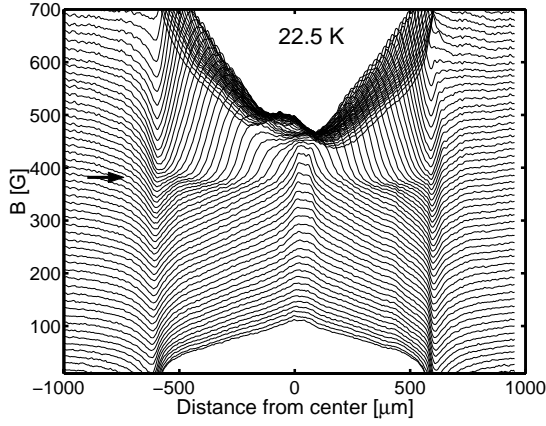


Fig. 1. Induction profiles in BSCCO at  $T=22.5$  K, measured during decrease of the external field from 850 to 0 G at a rate of 6 G/sec. The arrow marks the induction at the break appearing at 380 G.

to 320 G at a sweep rate of 47.6 G/sec, as demonstrated in Figure 2. The possibility that  $B_f$  represents the “supercooled” value of the transition induction is unlikely in light of the fact that  $B_f$  can be further suppressed. For example, for a rate of 360 G/sec,  $B_f$  is suppressed to a value of 200 G.

We argue that the observed results demonstrate the role of the electric field in the vortex solid-solid phase transition [11,12]. Large electric fields, induced by a rapid change of the external magnetic field, disturb the ordered vortex state and thus shift down the apparent solid-solid transition induction [11]. While ramping the field down, as  $B_{ss}$  is crossed, the generated electric field creates unstable disordered states with a spectrum of lifetimes  $\tau(B)$ . The lifetime of unstable disordered states created near  $B_{ss}$  is much longer than the lifetime

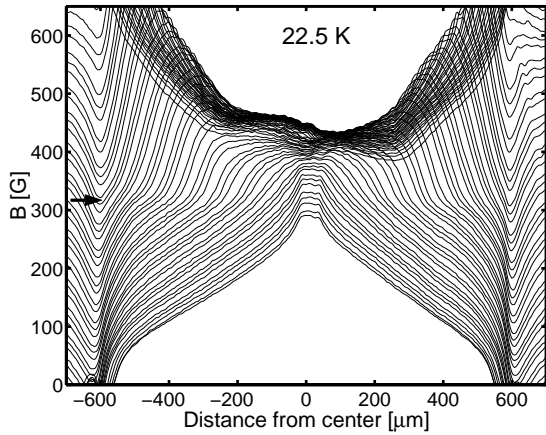


Fig. 2. Induction profiles in BSCCO at  $T=22.5$  K, measured during decrease of the external field from 850 to 0 G at a rate of 47.6 G/sec. The arrow marks the induction at the break appearing at 320 G.

of unstable disordered states created far below  $B_{ss}$  [10]. The onset of a disordered state is thus determined by the ability of the system to detect unstable states with short life times. For a given rate of change of field, the system records the onset  $B_f$  of a disordered state when its lifetime  $\tau(B_f)$  equals the time resolution of the experiment, i.e.  $\frac{\Delta B}{dB/dt}$ , where  $\Delta B$  is the field resolution of the measurement. Thus,  $B_f$ , determined from the equation  $\tau(B_f) = \frac{\Delta B}{dB/dt}$ , is independent of location as observed experimentally. Moreover, since  $\tau$  increases monotonically as  $B_{ss}$  is approached [10], this equation indicates that  $B_f$  is reduced as  $dB/dt$  increases, also consistent with the experiment. In fact, the dependence of  $\tau$  on  $B$  can be determined from our experiment, as the knowledge of  $\frac{\Delta B}{dB/dt}$  determines  $\tau$  at  $B_f$  [13].

In view of the role played by the electric field, it is not surprising that the apparent order-disorder transition induction can be suppressed to values well below  $B_{ss}$ . We therefore conclude that the results of such experiments do not necessarily signify supercooling effects related to the first order nature of the transition.

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