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Local magnetic characterization of superconductors based on magneto-optics and Hall-probe array techniques

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Abstract

Local magnetic measurements using magneto-optics and Hall-probe arrays have emerged as a powerful technique in the study of the vortex matter in high temperature superconductors (HTS). Unlike conventional global techniques in which the averaged magnetic response of the entire sample is measured, local techniques provide the detailed spatial distribution and time evolution of the magnetic field and current across the sample. This local information has led to several important findings regarding the static and dynamic phase diagrams of the vortex matter in HTS. We briefly review these results and then focus on a new type of experiment in which the formation of vortex phases is monitored by means of high-temporal resolution magneto-optics system. In particular, this technique has been used to study the vortex solid-solid transition in HTS. This unique technique allows, for the first time, the observation of the entire flux creep process, from the very beginning of flux entry till equilibrium is reached. In addition, the time evolution of the boundary between the two phases, initially coexisting in the sample, can be monitored.

Key words: High temperature superconductors; Vortex phases; Local magnetic measurements; Hall-probe array; Magneto-optics.

The magnetic properties of superconductors are usually studied by global techniques in which the information is averaged over the entire sample, (for reviews see [1-3]). In contrast, local techniques provide the detailed profile of the magnetic field across the sample from which valuable information can be extracted. For example, the shape of the profile determines the relative importance of bulk and surface pinning [4]. In addition, because of the nonuniform field distribution, sharp vortex phase transitions may be detected by local techniques [5], whereas their global signature is significantly blurred and may become unrecognizable. Thus the local techniques have fundamental advantages in resolving the detailed mechanisms of vortex statics, dynamics, and pinning.

The two leading experimental methods for local magnetic measurements involve Hall-Probe Array (HPA) [4-9] and Magneto-Optics (MOP) [10] techniques. The MOP technique provides two-dimensional images, and in addition, the data acquisition is relatively fast. The HPA technique offers typically two to three orders of magnitude better sensitivity (10 mG as compared to typically 1-10 G in MOP) in a wide range of magnetic fields (up to few Tesla as compared to saturation fields of about 0.2 T for typical MOP indicators). However, HPA s are presently limited by a small number of sensors (typically ten) in a one-dimensional array.

The power of the HPA technique has been demonstrated in discovery and study of a wide range of static and dynamic properties of HTS, including the first-order vortex lattice phase transition [5], geometrical barrier [7], disorder driven solid-solid transition [8], elastic to plastic creep transition [9], surface barriers [11,12], and properties of transport current distributions [13]. MOP is routinely used for quality control of superconductors. The visualization of flux distribution offered by the MOP technique has been utilized for the study of the effect of extended defects (twin and grain boundaries, cracks, sample edges) in single crystals, films, sintered materials and tapes [14]. The role of geometry and finite size sample dimensions has also been extensively explored [14].

Recently, MOP has proven useful in study and visualization of vortex phase transitions in superconductors [15,16]. The traditional view of a type-II superconductor was that an ordered solid vortex lattice exists over the entire mixed state. For the highly anisotropic HTS, however, the enhanced role of thermal fluctuations and the presence of quenched disorder result in a much more complex mixed-state phase diagram [17]. Three distinctly resolved phases of the vortex matter have been identified [5,8,18-21]: a quasi-ordered solid, a highly disordered solid, and a liquid phase. The fascinating phenomenon of the first-order vortex lattice melting have recently been examined by Soibel *et al.* [15] utilizing high sensitivity MOP system. Direct two-dimensional imaging of the vortex lattice melting process revealed complex behavior of nucleation, phase separation, and solid-liquid interface propagation as the field is increased. In this article we focus on a different type of experiment which demonstrate the power of the MOP technique as a new research tool in monitoring the *time* evolution of vortex phases. We utilize a high temporal resolution MOP system to study the disorder induced vortex solid-solid transition in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystal.

The study was carried out on a 0.66x0.24x0.03 mm^3 BSCCO single crystal. Magnetic induction was detected on the sample s surface employing magneto-optically active Iron-Garnet films with in-plane anisotropy. Polarized light passing through the indicator changed its polarization as a function of the *local* magnetic induction. The image was captured by analog video camera and digitized at a rate of 25 frames per second, yielding time resolution of approximately 40 ms. Measurements were performed immediately after sudden application of the external field H_a (rise-time less than 50 ms), at time intervals of 40 ms.

Figure 1 shows typical magnetic induction profiles of BSCCO at 23 K for applied field H_a between 350 to 580 Oe. Each of these profiles presents the induction measured approximately 6 s after the application of the field. At low fields, the profiles exhibit a dome shape typical of geometrical barrier and negligible bulk currents. If the applied field is furhter increased, the induction gradient starts to increase from the edge toward the sample center. These results are in accordance with previous observations by Berry *et al.* [22], Majer *et al.* [4], and Giller *et al.* [8] who performed similar measurements using a Hall-probe array technique. On the basis of these results one can estimate B_{ss} to be approximately 400 G.

Figure 2 shows the time evolution of the magnetic induction profiles after a step increase of the external magnetic field from zero to 350 Oe. The time elapse between subsequent profiles is 40 ms. As indicated by the profiles, the induction at the sample edge B_a ¯ 280 G is smaller than B_{ss}. Initially, Bean-type profiles are observed, gradually evolving into a dome-shaped profile, characteristic of a geometrical barrier. This is indicative of weak flux pinning characterizing the quasi-ordered phase. The solid lines in the figure are theoretical fits to the induction profiles, based on the Biot-Savart law, with two parameters: surface current j_s and homogeneous, time-dependent, bulk current j_b. The derived time dependence of the bulk current is described in the inset to the figure. The bulk current j_b decays exponentially with time at final stages of the relaxation; after relatively short period of time (less than 6 sec) the (dome shape) profile is determined by surface currents with no measurable contribution from bulk currents.

A much more complicated picture is observed for $B_a > B_{ss}$. Figure 3 shows the time evolution of the magnetic induction profiles after a step increase of the external magnetic field from zero to 510 Oe, corresponding to an induction B_a ¯ 430 Oe at the sample s edge. As before, initially Bean type profiles are observed. After a short time these profiles exhibit a sharp change in the slope at a depth x_p, after which the slope becomes smaller. As the field inside the sample increases with time, due to magnetic relaxation, the location x_p changes slowly (logarithmically with time) in a non-monotonic fashion, while the field B_p at x_p steadily increases.

We propose the following interpretation of these data: As the flux initially flushes the sample, a transient disordered state is created throughout the whole sample. This unstable state relaxes to the quasi-ordered state in the region near the sample center where the field is smaller than B_{ss}. In the regions near the sample edges, where the field is larger than B_{ss}, the disordered state is favorable, thus a break in the induction profile is created at x_p, defining a boundary between the two distinct vortex solid phases, initially coexisting in the sample. Indeed, one can fit the induction profiles assuming two time-dependent bulk currents: A relatively low current j_l around the center, and high bulk current j_h from x_p up to the edge. These fits are shown in figure 3 by the solid lines. The inset to this figure shows the fitting parameters j_l and j_h as a function of time.

It is important to emphasize that initially the field at x_p is smaller than the transition field B_{ss}, as the quasi-ordered state starts to nucleate at the sample center, where the field is minimal, and expands outward. The contour defined by x_p is determined by two competing processes during relaxation: growth of the quasi-ordered state towards the sample edges and expansion of the disordered state towards the sample center as the field inside the sample increases with time. The contour defined by x_p starts to move towards the sample center when the field B_p at x_p reaches the value corresponding to the thermodynamic field of transition B_{ss}.

In conclusion, local magnetic measurement techniques are developing as unique research tools for characterization of superconducting materials. Especially, the magneto-optical technique allows a direct two-dimensional visualization of the flux distribution as a function of time, temperature and field. Utilizing this technique in the study of the vortex phase diagram in high temperature superconductors has proven extremely useful. In particular, MOP study of the disorder induced vortex solid-solid transition described in this article provides insight into the formation process of the two distinct vortex solid phases. Both the quasi-ordered and the highly disordered states are preceded by a transient disordered state throughout the whole sample. For applied fields smaller than the transition field B_{ss}, this transient state relaxes to an equilibrium quasi-ordered state characterized by a dome-shaped induction profile. For applied fields larger than B_{ss}, initially both vortex solid phases coexist in the sample: the disordered phase near the sample edges and the quasi-ordered state near the sample center, expanding toward the sample edges until the local induction at the boundary x_p reaches the B_{ss} value, marking the beginning of penetration of the highly disordered state deeper into the sample.

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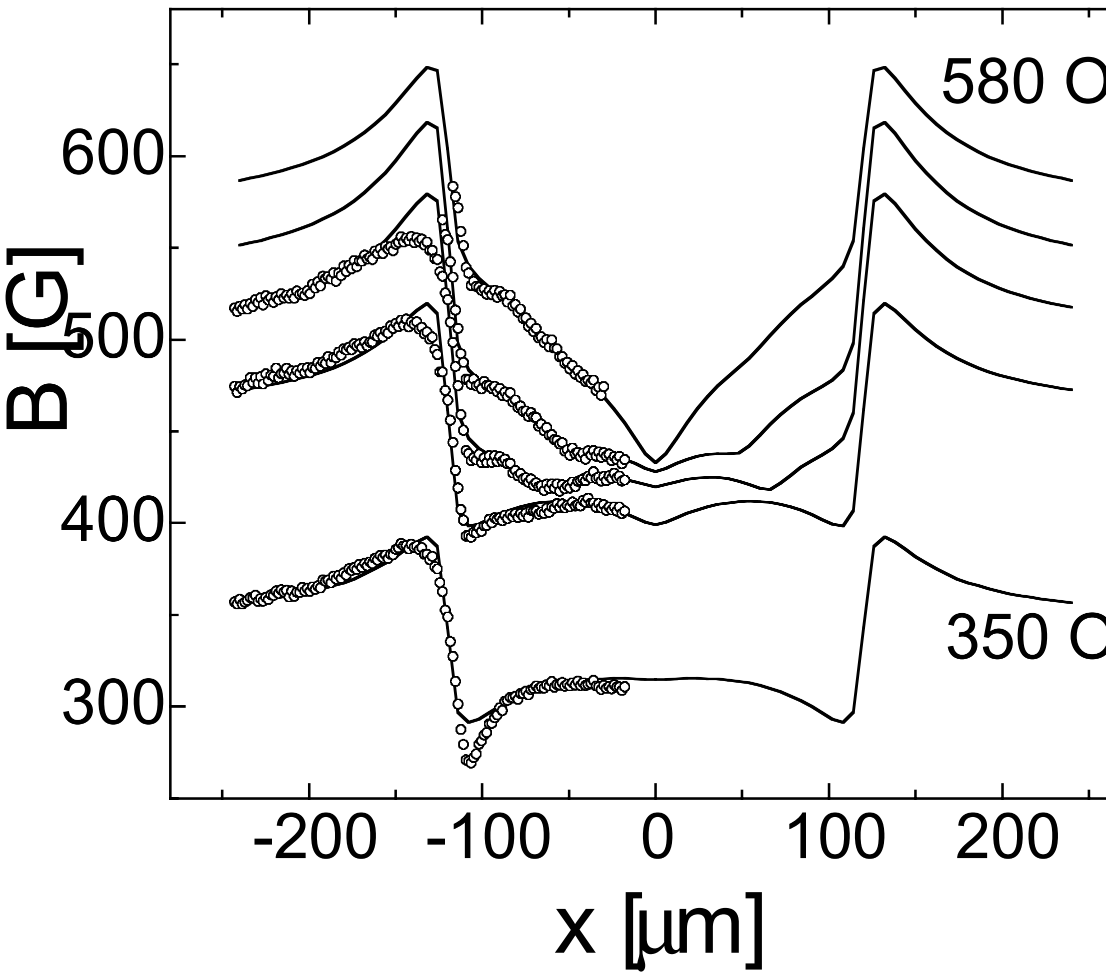
Figure Captions

Figure 1. Induction profiles in BSCCO crystal at T = 23 K, for different applied external fields.

Figure 2. Time evolution of the magnetic induction profiles in BSCCO crystal at T = 23 K, after sudden application of external field H_a = 350 Oe. Solid lines are theoretical fits. Inset: Time dependence of the fitting parameter, the bulk current j_b. The solid line is guide to the eye for the exponential tail.

Figure 3. Time evolution of the magnetic induction profiles in BSCCO crystal at T = 23 K, after sudden application of external field H_a = 510 Oe. Solid lines are theoretical fits. Inset: Time dependence of the fitting parameters, the low and high bulk currents j_l and j_h, respectively.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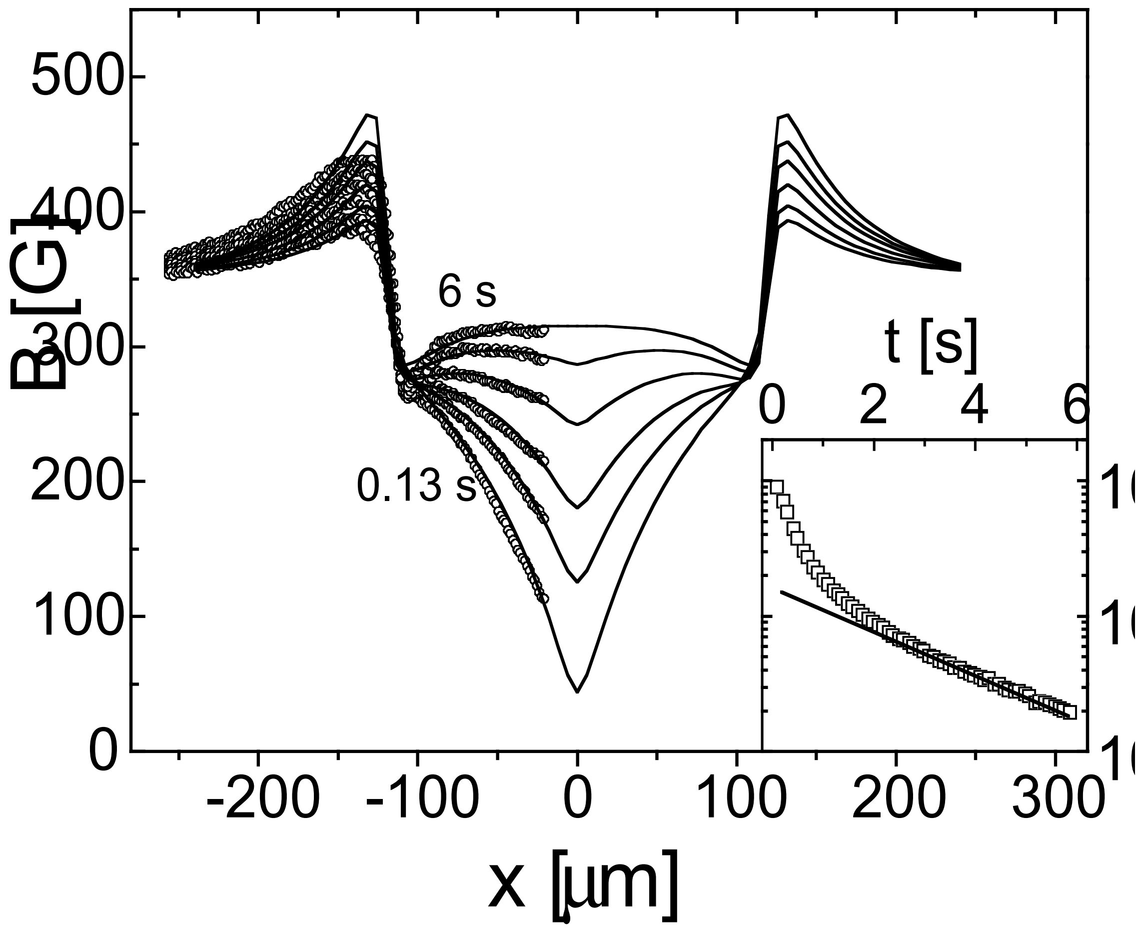
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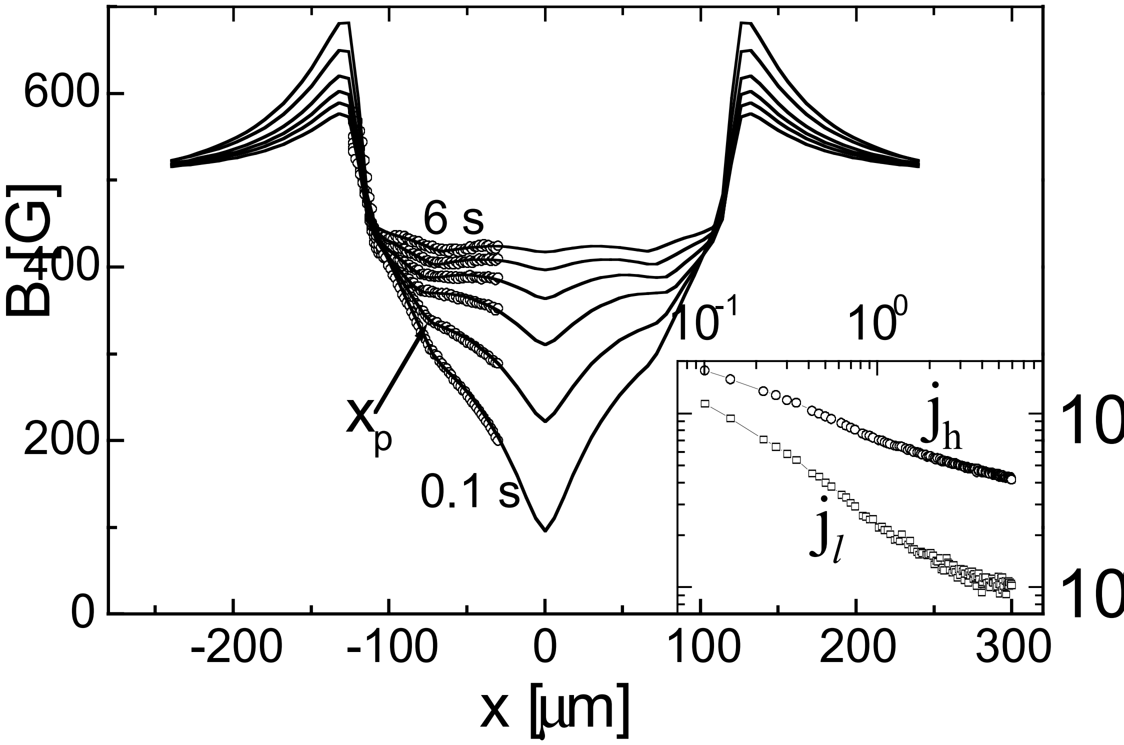

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