

# Vortex liquid and solid correlation in untwinned $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$

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## Abstract

Longitudinal- and inter-vortex correlations in an untwinned  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  single crystal were studied in the liquid and driven solid state, using a modified, symmetric pseudo-flux transformer method. The response of the flowing vortex system below  $T_m$  was significantly different along the field ( $\mathbf{H} \parallel \mathbf{a}$ ) and perpendicular to it ( $\mathbf{H} \parallel \mathbf{c}$ ), with both cases probed by an in-plane current mainly parallel to  $\mathbf{b}$ .

*Key words:*  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ; vortex correlation;

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## 1. Introduction

The vortex system in high-temperature superconductors can form liquid, solid and glassy phases depending on temperature and vortex density. The dynamic response of the vortex phases is of interest since it controls the electrodynamic response of the superconductor. Closely related to this is the correlation along and between vortices. When going from the solid to the liquid phase, the global phase coherence is lost at the melting temperature  $T_m$  [1], but from measurements with the magnetic field parallel to the  $c$  axis it has been found that the correlation along vortex lines in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) is gradually lost within the liquid state [2,3]. Inter-vortex correlation in clean YBCO, however, seems to disappear at  $T_m$  [3,4].

In this paper we present symmetric, pseudo-flux transformer (PFT) measurements on untwinned YBCO in two different Lorentz force configurations ( $\mathbf{H} \perp \mathbf{j}$ ). Both longitudinal- and inter-vortex correlation are studied. The driven vortex solid is probed using high currents, and correlation in this state is compared to that of the vortex liquid.

## 2. Experimental

A standard self-flux method were used to grow YBCO single crystals, and an untwinned, plate-like crystal was selected. The sample was oxygenated to close to optimal doping and had a zero resistance  $T_c$  of 92 K. The dimensions were approximately  $330 \times 350 \times 10 \mu\text{m}^3$ . Using silver epoxy, eight contacts were attached, two on each side, see inset of Fig. 1. A magnetic field of 4 T was applied parallel to the  $c$  axis and parallel to the  $a$  axis, though tilted slightly out of the  $ab$ -plane, using a rotatable sample holder with an angular resolution of  $0.01^\circ$ . To study correlation in the vortex liquid, a dc current of  $50 \mu\text{A}$  was applied in the  $ab$  plane, while pulsed currents up to 100 mA were used to probe the vortex solid. The temperature of the high-current curves were corrected for some heating.

## 3. Results and discussion

Figure 1 presents measurements of the resistive transition at high and low currents in a magnetic field  $\mu_0 H = 4$  T along the  $a$  axis. A misalignment of  $1^\circ$  out of the  $ab$  plane was applied to avoid suppression of the Lorentz force induced melting step due to the effect of intrinsic pinning [5]. The total width of the

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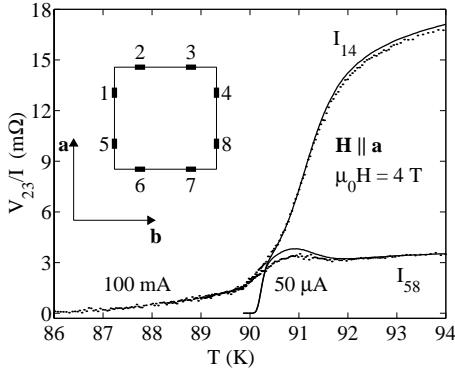


Fig. 1. Resistive transition at 4 T for  $\mathbf{H} \parallel \mathbf{a}$  but  $1^\circ$  from the  $ab$  plane. Current is sent between contacts 1-4, and 5-8; full curves  $50 \mu\text{A}$ , dotted curves  $100 \text{ mA}$ . The difference in  $V/I$  for the two current paths vanishes close to  $T_m$  for both currents. Inset: Schematic contact configuration.

intrinsic-pinning dip, i.e., the dip in  $\rho(\vartheta)$  around  $\vartheta = 0^\circ$ , was  $0.7^\circ$  in this sample. The  $1^\circ$  tilt of the magnetic field thus prevents the vortices from being pinned by the periodic potential of the  $ab$  planes, but is small enough not to significantly change the magnitude of the Lorentz force (directed out of plane). The voltage between contacts 2 and 3 is measured for currents applied between contacts 1 and 4, and contacts 5 and 8 (see inset), i.e., with  $\mathbf{H} \perp \mathbf{j}$  and  $\mathbf{j}$  mainly parallel to  $\mathbf{b}$ . This gives information about longitudinal vortex correlation in the liquid state. By using high currents, the properties of the driven solid state can be probed. The  $V/I$  curves of the two current paths [ $V_{23}/I_{14}$  (*top*) and  $V_{23}/I_{58}$  (*bot*)] agree close to the melting temperature for the low-current measurements, indicating a significant longitudinal vortex-correlation length. As can be seen, the two pulsed-current curves also coincide close to  $T_m$ , resulting in a *bot/top* ratio approaching unity. This would be a sign of rigid vortices, where current can flow without dissipation along the straight vortex lines, giving a homogeneous current distribution and thus the same voltage on both sides of the sample. It is interesting that the longitudinal correlation is maintained even in the solid state for a flowing system, i.e., that the vortices remain uncut.

In Fig. 2 the field is rotated to  $\mathbf{H} \parallel \mathbf{c}$ , keeping the same current direction as above. This setup probes the inter-vortex correlations. The appearance of the transition from a solid to liquid vortex system is similar to that of almost in-plane vortices. The difference in the solid state behavior is, however, striking. Even though 4 T is below the upper critical point of the solid-to-liquid transition, marking the change from a strongly disordered solid at high fields to a fairly well-ordered lattice at lower fields, the two current paths clearly do not coincide until well below  $T_m$ . The correlation length is thus small even in the solid state. Using the ideas

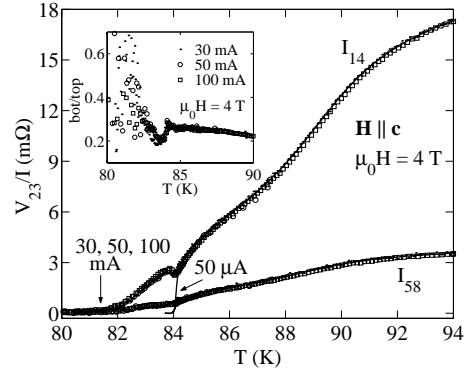


Fig. 2. Resistive transition at 4 T for  $\mathbf{H} \parallel \mathbf{c}$  and  $\mathbf{j}$  mainly parallel to  $\mathbf{b}$ . For current densities above  $j_c$  a kink in the transition curves coincides with  $T_m$ . The  $V/I$  curves do not agree until well below  $T_m$ . Inset: Resistive ratio *bot/top* (as defined in text) for high currents. Below the dip at  $T_m$  the ratio increases towards 1 with decreasing  $T$ .

of Ref. [4], we can perhaps consider the driven system to consist of clusters of rigid vortex lines, moving with velocities depending on current density. As temperature decreases below the melting temperature, the size of the clusters increases, until one rigid lattice extending through the whole sample is formed. With increasing cluster size, the difference between the two current paths diminishes and a ratio of unity is reached.

To summarize, symmetric PFT measurements were made on untwinned YBCO, to probe correlation along and between vortices in the liquid and solid state. The longitudinal vortex-correlation length may exceed the sample size at  $T_m$  for  $\mathbf{H} \parallel \mathbf{a}$ , indicating rigid vortex lines in the solid. A striking difference is seen for the field  $\mathbf{H} \parallel \mathbf{c}$ . This geometry probes the inter-vortex correlation, which is small even well below  $T_m$ .

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## References

- [1] D. López *et al.*, Phys. Rev. Lett. **76** (1996) 4034; A. K. Nguyen and A. Sudbø, Phys. Rev. B **58** (1998) 2802.
- [2] H. Safar *et al.*, Phys. Rev. Lett. **72** (1994) 1272; E. F. Righi *et al.*, Phys. Rev. B **55** (1997) 14156.
- [3] A. Rydh and Ö. Rapp, Phys. Rev. Lett. **86** (2001) 1873.
- [4] D. López *et al.*, Phys. Rev. Lett. **82** (1999) 1277.
- [5] T. Björnängen *et al.*, Phys. Rev. B **64** (2001) 224510.