# Vortex liquid-to-solid transition in underdoped $YBa_2Cu_3O_{7-\delta}$ single crystals with $B \parallel ab$

Magnus Andersson [a,1], Björn Lundqvist [a], Östen Rapp [a]

[a] *Solid State Physics, IMIT, KTH, Electrum 229, SE-164 40 Kista. Sweden*

**Abstract**

A nearly magnetic field independent vortex liquid-to-solid transition has been observed in both the *ab*-plane and in the *c*-axis resistivity of underdoped $YBa_2Cu_3O_{7-\delta}$ single crystals for magnetic fields $B \parallel ab$-plane. These observations suggest that intrinsic pinning caused by the superconducting layers do neither lead to a system of completely decoupled superconducting layers nor to a smectic vortex phase at high fields. A possible explanation may include a transition driven by changes in elastic properties (e.g. the shear modulus) of the vortex system.

*Key words:* vortex liquid-to-solid transition ; $YBa_2Cu_3O_{7-\delta}$ ; single crystals

## 1. Introduction

In high temperature superconductors (HTS), the superconducting order parameter is modulated along the crystallographic *c*-axis due to the layering of the materials leading to anisotropic material properties. For electrical transport, this is usually modelled through the anisotropy factor, $\gamma = (m_c/m_{ab})^{1/2}$, where $m_{ab}$ and $m_c$ are the effective masses for electron transport in the *ab*-plane and along the *c*-axis respectively. The vortex behaviour in the superconducting state depends sensitively on $\gamma$. By oxygen doping in $YBa_2Cu_3O_{7-\delta}$ (YBCO), $\gamma$ can be controlled from $\gamma \approx 7$ in optimally doped single crystals with a superconducting transition temperature $T_c = 92$ K to at least $\gamma \approx 35$ in underdoped crystals with $T_c = 52$ K [1]. This experimental flexibility makes YBCO single crystals a useful test system for studying vortex dynamics in HTS.

For magnetic fields, $B$, parallel to the *ab*-plane, vortices are intrinsically pinned between the superconducting $CuO_2$ planes due to the *c*-axis modulation of the order parameter. Vortex fluctuations perpendicular to the planes are strongly reduced and in-plane vortex fluctuations dominate the vortex liquid at high temperatures. At high fields, this has been suggested to result in a smectic vortex liquid-to-solid (freezing) transition driven by in-plane vortex fluctuations [2,3] or in a decoupling of the superconducting layers. In both cases, one would expect a significant difference between in-plane and out-of-plane transport properties.

For $B \parallel ab$ and with the current $I \parallel ab$ and $I \perp B$, an almost magnetic field-independent freezing transition has been observed at high magnetic fields in oxygen deficient YBCO single crystals [3–5]. Surprisingly, we later observed a similar behaviour in the *c*-axis transport properties [6]. Here, we will further discuss the implications of this observation for the freezing transition in underdoped YBCO single crystals.

## 2. Experimental

Single crystals of YBCO were grown by a self-flux method and chosen crystals were then annealed at different temperatures for 5 days to obtain the desired oxygen content. Electrical contacts were prepared by using silver paint, giving contact resistances below 1.5 Ω. Resistive measurements were performed with a

[1] E-mail: magnus@ftf.kth.se

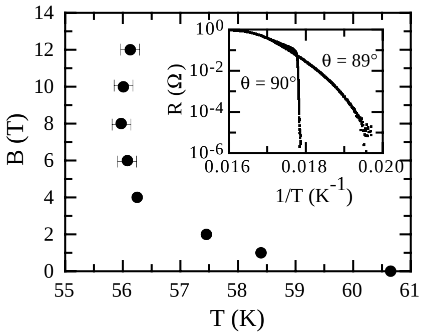


Fig. 1. The vortex liquid-to-solid transition for $B \parallel ab$ in our underdoped YBCO single crystal. Inset: the change in $R(T)$ at $B = 12$ T when the sample is tilted $1^{\mathrm{O}}$ away from the $ab$-plane.

four-probe dc method and the samples were mounted in a rotatable sample holder with an angular resolution of $0.01^{\mathrm{O}}$ for accurate sample alignment with respect to the magnetic field. A dc picovoltmeter was used as a voltage preamplifier resulting in a resolution of better than 300 pV. The results presented here are from a sample with $T_c = 60.6$ K and $\gamma \approx 29$.

## 3. Results

Fig. 1 shows some main features of the $c$-axis transport properties in our sample. For $B \geq 4$ T, the freezing transition is almost field independent (within our experimental uncertainties). However, the small *increase* in transition temperature at the highest $B$ is most probably a real effect as suggested from other studies [3]. The dramatic effect on the transport properties is shown in the inset of Fig. 1, where the sharp transition curve with $B \parallel ab$ ($\theta = 90^{\mathrm{O}}$) is compared with the one for an angle of $1^{\mathrm{O}}$ away from the $ab$-plane. This shows that lock-in of vortices is important in this geometry.

In Fig. 2, the angular dependence of the $c$-axis resistance is shown at temperatures close to the freezing transition at $B = 12$ T. At high temperatures, there is a bump in the curves for $B \parallel ab$-plane as one would expect due to the Lorentz force acting within the $ab$-plane (this bump is not observed when $I \parallel ab$ and the Lorentz force is acting in the $c$-direction). At lower temperatures, a sharp dip develops for $B \parallel ab$ in a narrow temperature region just above the transition temperature. This observation is seemingly not consistent with a decoupling or a smectic vortex liquid-to-solid transition, where one would expect easy movements of vortices in between the $ab$-planes to also dominate the dynamics close to the transition. Instead, experiments show that the vortex liquid-to-solid transition appears to occur at the same temperature independent of current $I \parallel ab$ or $I \parallel c$ [6].

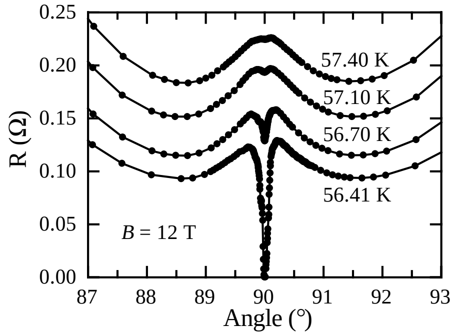


Fig. 2. The angular dependence of the resistance at a few temperatures close to the vortex liquid-to-solid transition.

A qualitative way to understand these observations can be based on a vortex liquid state where e.g. the shear modulus of the vortex system is growing from (almost) zero at high temperatures to a finite value below the freezing transition. This results in a transition similar to the usual melting transition observed in clean systems. Similarly, the resistance drops sharply to zero at the transition as shown in the inset of Fig. 1. When vortex-vortex interactions become increasingly important while approaching the freezing point, weak pinning centres are sufficient to prevent the vortex system from moving at small driving forces. Since the transition is driven by a rapid change in the elastic properties of the vortex system, the freezing transition will at low driving currents occur at almost the same temperature irrespectively of the current direction as is also observed experimentally.

## Acknowledgements


Part of this work has been supported by the Swedish Natural Science Research Council and the Göran Gustafsson Foundation.


## References


[1] B. Lundqvist, A. Rydh, Yu. Eltsev, Ö. Rapp, M. Andersson, Phys. Rev. B **57** (1998) R14 064.

[2] S. A. Grigera, E. Morré, E. Osquiguil, G. Nieva, F. de la Cruz, Phys. Rev. B **59** (1999) 11 201.

[3] S. N. Gordeev, A. A. Zhukov, P. A. J. de Groot, A. G. M. Jansen, R. Gagnon, L. Taillefer, Phys. Rev. Lett. **85** (2000) 4594.

[4] B. Lundqvist, Ö. Rapp, M. Andersson, Physica B **284-288** (2000) 705.

[5] B. Lundqvist, Ö. Rapp, M. Andersson, Phys. Rev. B **62** (2000) 3542.

[6] B. Lundqvist, Ö. Rapp, M. Andersson, Yu. Eltsev Phys. Rev. B **64** (2001) 060503(R).