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Experimental evidence for vortex equilibration by an in-plane dc field in $Bi_2Sr_2CaCu_2O_8$

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ABSTRACT

Results demonstrating controlled suppression of magnetization hysteresis in $Bi_2Sr_2CaCu_2O_8$ are presented. We show this suppression at a temperature of 82 K and normal magnetic fields up to 20 Oe by applying a dc in-plane field up to 20 Oe. This work shows that in the mentioned region of phase diagram a dc in-plane field overcomes the geometrical barrier. In the presence of an in-plane field, we find vortex chains, formed by Josephson vortices, which extend all the way to the sample edges. We propose that these chains can act as equilibrating channels. This provides insight into the physics underlying the shaking method Avraham et al. (2001), Goldberg et al. (2009) [1,2], which is used extensively to equilibrate vortex matter.

1. Introduction

In type II superconducting platelet samples in perpendicular field H_z the vortices penetrate into the sample center under the influence of geometrical barriers (GB) [3]. The resulting dome-shaped vortex distribution profile is hysteretic upon increasing and decreasing field, which prevents investigation of equilibrium vortex properties. Using differential magneto-optics, we demonstrate that the hysteresis resulting from the GB is suppressed by an in-plane dc field. We believe that this suppression is a result of vortex chains, namely pancake vortices that decorate Josephson vortices [4–7], which act as channels connecting the vortex dome with the edges.

2. Experimental

In order to investigate the microscopic equilibration mechanism we carried out differential magneto-optical (MO) measurements in $Bi_2Sr_2CaCu_2O_8$ crystal $2000 \times 440 \times 10\ \mu m^3$ at $T = 82$ K for perpendicular (H_z) and in-plane fields (H_x) up to 20 Oe.

The image in Fig. 1 is obtained by modulating the current by $\delta I = 60$ mA. The dashed ($+\delta I/2$) and solid ($-\delta I/2$) curves above the image in Fig. 1 are two dome profiles that are shifted, with respect to each other, by the current. Their subtraction reproduces the experimental profile where the edges of the vortex dome are visible as bright and dark strips.

3. Results and discussion

We find vortex chains outside the dome that apparently extend with H_z all the way to the sample edges, see Fig. 1. The chains are formed by Josephson vortices (JVs) [4,5] and are present in the regions that are "vortex free" (outside the dome) in the absence of the in-plane field.

The density of chains grows with H_x. The inset of Fig. 2 shows the linear dependence of vortex chain separation on $H_x^{-1/2}$, which is in agreement with the theory [4]. The slope of the fit gives the anisotropy parameter $\gamma = 406$, which agrees with other published estimates [5].

Curve 1 in Fig. 2 presents cross-section of the dashed white strip in Fig. 1. 1D inverse Biot-Savart procedure retrieves the current density in curve 2. Curve 3 shows the B profile resulting from the calculated current distribution, which clearly matches the given B profile. As expected, there is no current flow inside the dome [3]. We determine the edges of the dome as the coordinate where the current starts growing from zero.

Fig. 3 shows the location of the dome edge on increasing and decreasing H_z in absence (●) and presence (○) of an in-plane dc field $H_x = 15$ Oe. It can be seen that the hysteresis due to the GB is significantly suppressed by the in-plane field. The main contribution to the hysteretic behavior is on the decreasing field H_z. This is due to the Lorentz force of Meissner currents which tends to focus vortices in the sample's center preventing their exit out from the sample [3].

To investigate the effect of H_x on the GB, we have plotted the dome width (the difference between the locations of dome edges) as a function of H_x. The inset of Fig. 3 is plotted for $H_z = 7$ Oe for

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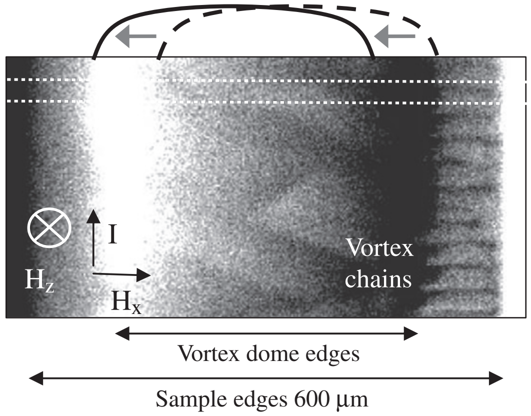

Fig. 1. Differential MO image of a $Bi_2Sr_2CaCu_2O_8$ crystal with modulation of applied current $\delta I = 60$ mA ($H_z = 11.5$ Oe, $H_x = 17$ Oe, $T = 82$ K). The edges of the vortex dome are visible as bright and dark strips resulting from the displacement of the vortex dome by the applied current in the differential image. In presence of an in-plane field H_x the vortex chains are visible to the right of the dome.

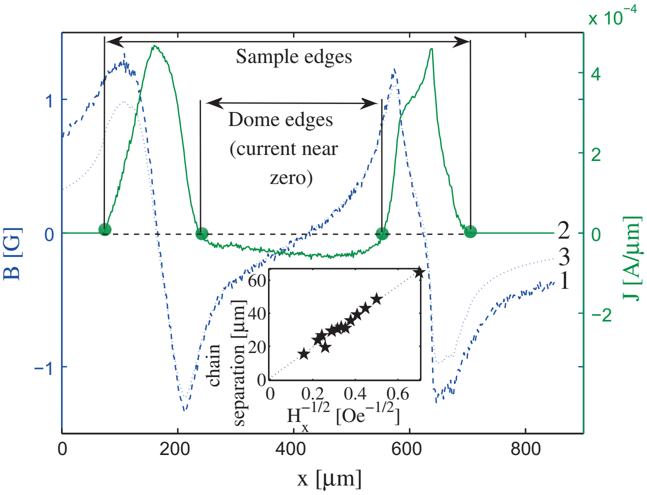

Fig. 2. Curve 1 – cross-section integrated between the dotted lines in Fig. 1. Curve 2 – inverse Bio-Savart 1D current inversion of curve 1. Curve 3 – Bio-Savart inversion of curve 2, which reproduces curve 1. Inset: linear dependence of vortex chain separation on $H_x^{-1/2}$.

decreasing field. The width of the vortex dome is reduced by 35% from $W_{\rm dome} = 440$ μm to $W_{\rm dome} = 290$ μm as $|H_x|$ is increased from 0 Oe to the equilibration field of $|H_x| = 15$ Oe.

We propose that suppression of the GB and equilibration of the vortex system are carried out by vortex chains, which act as channels connecting the vortex dome with the edges of the sample. A full explanation requires a detailed comparison between the energy per pancake vortex required to equilibrate the dome edges, and the energy of a pancake vortex in the vortex chain outside the dome. That is beyond the scope of this paper. Preliminary calculations indicate that vortex chain energy is high enough to move the vortex dome edges, resulting in the whole system equilibration [8].

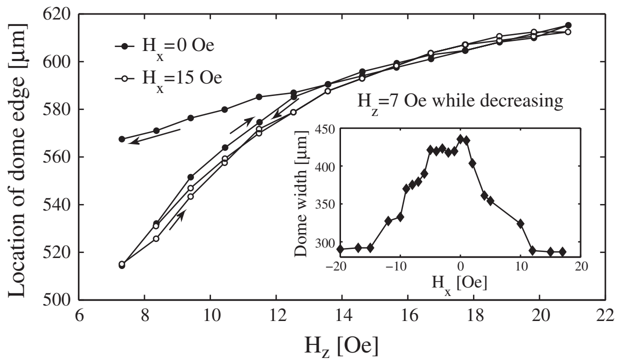

Fig. 3. Location of the dome edge on increasing and decreasing H_z in absence (●) and presence (○) of in-plane dc field $H_x = 15$ Oe. For the nonzero H_x, the vortex dome edge position becomes reversible as the separation between the curves on increasing and decreasing H_z diminishes. Inset: dome width reduction due to applying in-plane field.

4. Conclusions

We observed vortex chains outside the vortex dome that extend to the sample edges. The hysteresis in the dome edges is suppressed as H_x is increased and the chain separation decreases. We propose that the chains can act as channels for vortex system equilibration.

In order to equilibrate the vortex matter, shaking by in-plane ac field is often employed to overcome bulk pinning as well as surface and geometrical barriers [1,2]. This work advances the understanding of GB suppression by the shaking method.

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