Magneto-optical imaging of flux turbulence in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ crystals

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Abstract. We report remagnetization studies on thin single crystals of optimally doped Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ using magneto-optical imaging. We observe enhanced irregular penetration of the remagnetization front above 15 K associated with flux turbulence. The steps in the local magnetic induction profiles across the flux front are explained via the “Meissner hole” scenario. We compare our results with the macroscopic flux turbulence observed earlier in cuprate superconductors.

1. Introduction
Magneto-optical (MO) imaging has been widely used for the study of various features in the vortex state of different type-II superconductors spanning the range from conventional to high-temperature cuprate superconductors [1]. MO imaging has distinct advantages due to its ability to capture vortex dynamics with mesoscopic spatial resolution. In the family of 123-type cuprate superconductors a major focus of investigation had been the observation of macroscopic flux turbulence in samples that have been remagnetized by a field of opposite polarity. This turbulence is manifested as a swirling of the remagnetized flux front at the boundary between vortices and antivortices. The origin of the instability at the flux front is due to the formation of flux-free loops called “Meissner holes” and the local increase of the current along the loops [2-7]. These features contribute to substantial modification of the critical-state model in the superconductors. However, it is still debated whether this turbulent instability is a generic feature of type-II superconductors or a feature confined only to the 123-type cuprates [8]. Recently, superconductivity in the newly discovered iron-based compounds has attracted increased attention among researchers. The iron-based superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ is particularly well studied due to the ease of growing high-quality single crystals [9]. The vortex state in this material has been characterized via magnetization and relaxation measurements as well as by MO imaging of the flux distribution [9-11]. Here we investigate, via MO imaging, the effect of remagnetization on single crystals of the iron-based superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$.

2. Experiments
Optimally-doped single crystals Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ were grown by using a self-flux method [9]. The crystal batch studied here has a critical temperature $T_c$ ~24 K and self-field critical current density $J_c$ ~8×10$^7$ A/cm$^2$ at 5 K. We present here data on one single crystal which was cleaved and cut to dimensions 490 × 345 × 20 µm$^3$. Qualitatively similar results were also obtained for two other crystals. MO imaging was performed in a flow-type cryostat. During MO imaging a Bi-doped
A ferrimagnet garnet film is placed over the surface of the sample to be studied. The incident polarized light undergoes a Faraday rotation and the resulting two-dimensional intensity map can be converted to a map of the local values of the axial component of magnetic induction $B_z(x,y)$ [1].

3. Results and discussion

For remagnetization studies, the sample was first cooled from above $T_c$ in a field of +300 Oe to the desired temperature. Subsequently, the external field was swept to zero and increasing negative fields were applied and MO images were captured. Figures 1 (a)-(c) shows a representative set of MO images captured at different temperatures after reversing the field to -150 Oe. These images were captured with crossed microscope-polarizers. In this setting, the bright intensity regions correspond to Faraday-rotated values signifying finite $|B_z|$ values and the dark band ($B_z = 0$) represents the remagnetization flux front. The sample edges are outlined by the thin bright bands where the expelled flux concentrates. The development of the flux turbulence with increasing temperature is evident from these panels: At 10K, when the front is close to the sample edges, we observe a wiggling remagnetization front. These small wiggles are also observed on a virgin flux penetration front and hence could be related to the local distribution of pinning centers in the crystal. At 15 K and 20 K, the remagnetization flux front exhibits considerable swirling as it moves further inside the sample in contrast to virgin penetration fronts that are smooth at high temperatures. This observation constitutes the main feature of the flux turbulence.

![Figure 1. MO images after remagnetization with -150 Oe at different temperatures.](image)

Further evidence for the turbulent flux penetration is presented in figure 2. In these figures (captured with polarizers oriented slightly away from the crossed position) after cooling the crystal to the desired temperature in zero field, +800 Oe field is applied followed by a reversal to -500 Oe field. Then the images are captured while again reversing the applied field to positive values. Figures 2(a)-(d) show the MO images at four different temperatures after the final field reversal to +200 Oe. In figure 2(b) the arrows locating the positions 1, 2, and 3 represent the flux fronts corresponding to the virgin penetration, first reversal, and second reversal, respectively. The undulating nature of the remagnetized front is observed to be more pronounced after the second reversal.

To get quantitative local $B_z$ values with the correct sign, we recapture MO images as in figures 1 (a)-(c) but with the polarizers away from crossed position. Figure 1 (d) shows the MO image in figure 1 (b) with this setting. Here dark and bright refer to negative and positive values of $B_z$, respectively, and the boundary between them represents the remagnetization front. Figures 3 (a)-(c) show the $B_z$ profiles obtained across the dashed line in figure 1(d) at 10, 15 and 20 K after field reversal ranging from 0 to -300 Oe. The profiles at 10 K (figure 3 (a)) are smooth as the induction changes from the positive values in the sample center (due to the initially applied +300 Oe field) to the negative values.
at the sample edges (due to the remagnetized field). However at higher temperatures (figure 3 (b)-(c)) a definite change in the slope is apparent around $B_z = 0$. (Note: The clarity of the profiles near the left edge in figure 3 is diminished due to inhomogeneties on the sample or slightly larger distance of the garnet film from the sample across this edge). The location of the breaks in slopes is represented by the pairs of horizontal arrows in panels (b) and (c). To get more accurate values of the difference in local induction between the locations of the change in slope we subtract an averaged linear slope across $B_z = 0$. Figure 4 shows the resulting $\Delta B_z$ curve obtained for the remagnetized profile at 20 K for $H = -100$ Oe near the right edge in figure 3 (c) after this procedure. The induction step (~55 G) across the $B_z = 0$ position is evident in this plot. The induction step arises due to excess surface-like currents that flow around the $B_z = 0$ regions of the sample. We note here that such excess current strings around $B_z = 0$ were observed in YBa$_2$Cu$_3$O$_7$ and Bi$_2$Sr$_2$CaCu$_2$O$_8$ single crystals upon remagnetization [2,4]. In Bi$_2$Sr$_2$CaCu$_2$O$_8$ the associated flux steps were found to match the expected step-height in the modified Bean model which takes into account a finite $H_{c1}$ [4].

We now compare and contrast our results with turbulence in the 123-type superconductors. Initially turbulence was observed in optimally doped YBCO single crystals [2]. It was believed that the large anisotropy factor ($\gamma \sim 6$) and presence of twins have some influence on the turbulent behaviour. Turbulence was seen to be suppressed in the presence of a high density of crossing twin boundaries in the 123-superconductors. Flux turbulence has since been observed in underdoped YBCO single crystals as well as in optimally-doped NdBCO [5]. These observations suggested that the presence of vortices and antivortices in any superconductor should lead to turbulent behavior. Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ has a smaller anisotropy factor ($\gamma \approx 3$) and twin boundaries associated with a tetragonal to orthorhombic structural transition are not present in optimally-doped crystals [12]. Hence, we believe, our observations reinforce that flux turbulence is a basic feature associated with remagnetization of type-II superconductors. In the cuprate superconductors, turbulence is observed at high temperatures (above 40 K). Similarly, in Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ crystals the flux turbulence is easily visualized above ~15 K. This could be due to increased flux motion at elevated temperatures associated with diminished effective pinning strength. Another point of contrast between the turbulent behaviour in Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ crystals in comparison to the 123-type crystals is the time evolution

**Figure 3.** Local $B_z$ profiles across the dashed line in figure 1(d) at different temperatures with increasing remagnetization field. The vertical lines denote sample edges.

**Figure 4.** Representative plot illustrating the induction step after subtracting an average linear slope around $B_z = 0$. $\Delta x = 0$ corresponds to the location of $B_z = 0$ near the right edge in figure 3.
of the remagnetization flux front. In our samples after switching the field we observe definite flux front motion which nearly stabilizes within ~25-30 s. In YBCO after switching field reversal the motion of the turbulent front stabilizes in $\approx 3$ s [7] whereas in NdBCO the flux front dynamics is more pronounced with the fronts reaching the sample centre in $\approx 250$ s [5]. The time-duration of the development of the turbulent instability seems to be influenced by the strength and distribution of pinning centers. Finally, we comment on the relevance of our results to the observed low-field anomaly in the magnetic relaxation rate $S(= d \ln M/d \ln t)$ in $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$. Studies have shown that there is a sharp suppression of $S$ at low fields in pristine samples which occurs when the applied field is lower than the self-field of the sample [13]. The presence of Meissner holes in the sample interior with the associated formation of closed vortex loops could significantly hamper the thermally-activated motion of vortices. The motion of the remagnetization flux front after field reversal could help to shed more light on this. The field- and temperature-dependence of such temporal measurements needs to be investigated and compared with conventional magnetic relaxation measurements.

4. Conclusion
In summary, we have described the observation of turbulent nature of the remagnetization flux front in single crystals of optimally-doped $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$ via magneto-optical imaging. The nature of this instability for single- and double-reversal of field is revealed as a swirling of the flux-front boundary. The local magnetic induction profiles across the sample show distinct steps at the remagnetization front which are related to the values of lower critical field. We compare our results with flux turbulence in the cuprate superconductors. Our results show that flux turbulence can, in principle, be observed for all type-II superconductors.

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