

Mesoscopic flux jumps in MgB₂ films visualized by magneto-optical imaging

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Abstract

We report on the first spatially resolved observation of mesoscopic flux jumps in superconducting films. Magneto-optical imaging was used to visualize the flux penetration in MgB₂ films subjected to a slowly varying perpendicular field. Below 10 K, flux jumps with typical size 10–20 microns and regular shape are found to occur at random locations along the flux front. The total number of vortices participating in one jump is varying between 50 and 10,000. Simultaneously, big dendritic jumps with dimensions comparable to the sample size (10⁶–10⁸ vortices) are also found in this temperature range. We believe that both types of jumps result from thermo-magnetic instability.

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Magnetic flux often penetrates type-II superconductors via discrete jumps or avalanches where a few or many vortices hop at once from one position to another. Sometimes these jumps are small, with <100 vortices taking part in one event, and the avalanche size distribution is close to power law [1]. Sometimes macroscopic flux jumps take place accompanied by abundant heat dissipated during the flux motion that gives essential positive feedback to the avalanche development [2]. Such thermal flux jumps have been found in MgB₂ films where they lead to a peculiar dendritic and highly branching patterns of magnetic flux [3]. These dendritic flux structures start entering the zero-field-cooled (ZFC) film after applying a perpendicular field exceeding some threshold value of 2–10 mT. In the present work we use

magneto-optical (MO) imaging to study flux penetration below this threshold field, i.e. in the absence of dendritic jumps. Surprisingly, here we find flux jumps too, only now on a much smaller scale.

Films of MgB₂ were fabricated on Al₂O₃ substrates using pulsed laser deposition [4]. Two samples, 400 nm thick with lateral dimensions 5×5 mm², were studied and showed similar behaviour. The films had the critical temperature of 39 K, and the critical current density of ~10⁷ A/cm². The flux density distribution was visualized using MO imaging based on the Faraday effect, for a review, see Ref. [5].

A ZFC film at 4 K was placed in a perpendicular applied field slowly increasing in time with rate of 6 μ T/s. Shown in Fig. 1(a) is the flux density distribution, $B(\mathbf{r}, 7.1 \text{ mT})$, near the film edge that coincides with the bottom of the image. The flux front separating the flux-free interior (black) from the flux-penetrated region near the edge is highly non-uniform. By observing the dynamics of flux penetration in the MO microscope, one could immediately see numerous small jumps taking place along

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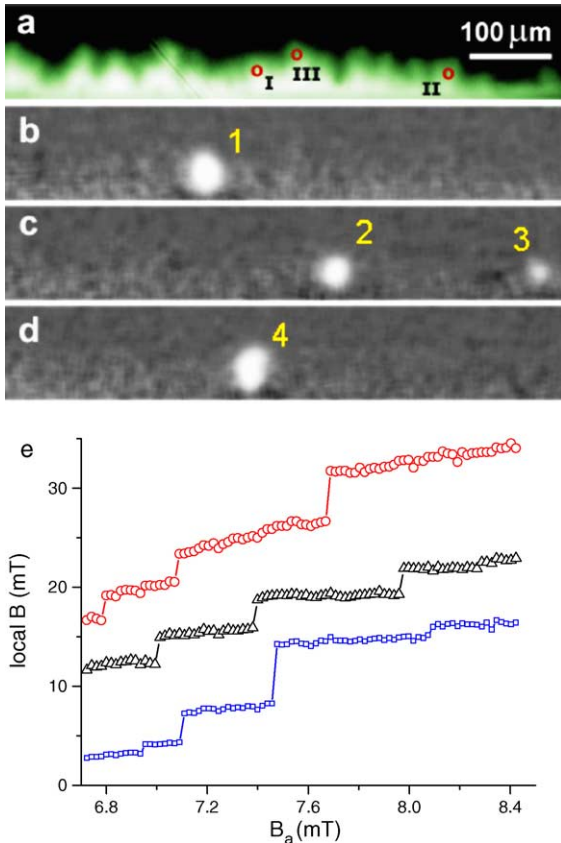


Fig. 1. (a) Magneto-optical image of flux distribution $B(\mathbf{r})$ near the edge of MgB₂ film in applied field $B_a = 7.1$ mT. (b)–(d) Change in $B(\mathbf{r})$ due to increase of B_a by 0.01 mT as found by subtracting subsequent MO images. The white spots indicate where localized flux jumps occurred (the contrast is enhanced). The total amount of incoming flux found by integrating $B(r)$ over the jump area was 1900 (1), 1200 (2), 300 (3), and $2100\Phi_0$ (4). (e) Local flux density as a function of applied field for three regions of $10 \times 10 \mu\text{m}^2$ size indicated by circles on the MO image (a). Steps in $B(B_a)$ correspond to flux jumps.

the flux front. The jumps seem instantaneous, thus their duration is smaller than 0.1 s. To analyse the jumps quantitatively, we took a series of MO images with field interval of 0.01 mT, and subtracted every two subsequent images. Fig. 1(b) shows the difference image, $B(\mathbf{r}, 7.11 \text{ mT}) - B(\mathbf{r}, 7.10 \text{ mT})$, where the gray color corresponds to unchanged flux density, while the white indicates increase in B . One can see that B has increased only in one rather small region. By integrating the change in flux density over this region, we find that the total flux arrived here equals to $1900\Phi_0$, Φ_0 is the flux quantum. Subsequent difference images (c) and (d) show similar jumps but in other places along the flux front. The first jump with the smallest size resolved by our setup, $50\Phi_0$, was detected at $B_a = 4$ mT. As B_a increases, the average

jump size increases too, the largest jumps being around $10,000\Phi_0$. At $B_a = 9$ mT the first macroscopic jump of dendritic shape [3] takes place with size exceeding $10^6\Phi_0$. The small jumps continue to occur for $B_a > 9$ mT, but they only slightly affect the overall $B(\mathbf{r})$ which is governed now by the dendritic jumps.

To imitate Hall-probe measurements [1] we plot in Fig. 1(e) local flux density B averaged over $10 \times 10 \mu\text{m}^2$ area as a function of applied field. Clear steps dominate the $B(B_a)$ dependence with only little growth of B between them. The steps on different curves corresponding to three distinct areas are seemingly uncorrelated. Moreover, when the whole experiment is repeated, the flux distribution $B(\mathbf{r})$ turns out to be well reproduced, however the sequence of flux jumps is every time unique.

Two types of jumps different in the jump size were earlier found in Nb film, and argued to have different physical mechanisms [6]. In our studies both the small jumps and the macroscopic dendritic jumps disappear above the same threshold temperature 10 K. This suggests that both types have the same mechanism—thermo-magnetic—and disappear at higher T due to fast increase of the specific heat. We explain existence of two types of jumps by an additional positive feedback mechanism due to strong demagnetization effects in thin films. When a jump exceeds some critical size, bending of current lines around the jump area enhances the local field, and thus accelerates the jump development which is then limited only by the sample dimension.

In summary, the flux penetration in MgB₂ film below 10 K proceeds via abrupt flux jumps on all spatial scales. The thermal origin of the jumps implies that the apparent critical current density is determined here by thermal parameters such as specific heat rather than by the pinning strength.

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