

## Dendritic magnetic instability in superconducting MgB<sub>2</sub> films

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**Abstract.** – Magneto-optical imaging reveal that below 10 K the penetration of magnetic flux in MgB<sub>2</sub> films is dominated by dendritic structures abruptly formed in response to an applied field. The dendrites show a temperature-dependent morphology ranging from quasi-1D at 4 K to large tree-like structures near 10 K. This behaviour is responsible for the anomalous noise found in magnetization curves, and strongly suppresses the apparent critical current. The instability is of thermo-magnetic origin, as supported by our simulations of vortex dynamics reproducing the variety of dendritic flux patterns.

The new superconductor [1], MgB<sub>2</sub>, has already proved to be a promising candidate for technological applications due to success in fabrication of thin films [2] and wires [3] with high current carrying capabilities. At the same time, such films and wires, as well as polycrystalline MgB<sub>2</sub> are reported to show exceptional magnetic behaviour displaying numerous and “noise-like” jumps in the magnetization as a function of applied field [3–5]. Magnetization jumps in type-II superconductors are usually associated with a thermo-magnetic instability of the flux lines (vortices) penetrating the material. Motion of vortices is accompanied by a heat dissipation, which reduces flux pinning and facilitates further motion, eventually leading to a large-scale avalanche invasion of depinned flux [6]. In high-temperature superconductors (HTSs) the flux jumps have been observed only in bulk materials, where the first jump occurs typically at applied fields of 1 Tesla, and with subsequent ones coming nearly periodically as

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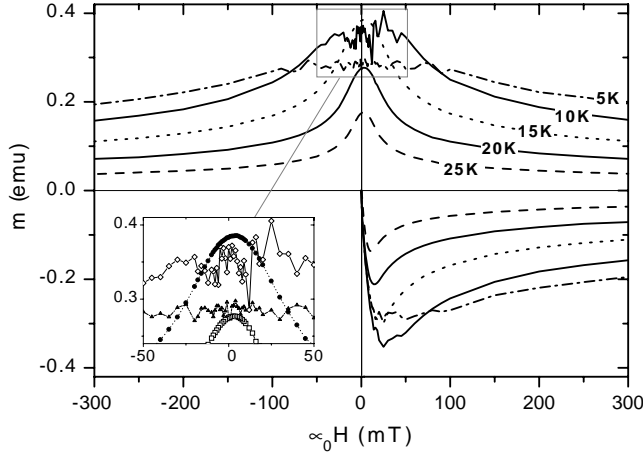


Fig. 1 – Magnetization hysteresis loops for a  $\text{MgB}_2$  thin film. The measurements were done after zero-field cooling down to different temperatures using a SQUID magnetometer (Quantum Design MPMS). Pronounced fluctuations in the magnetization are evident at  $T = 10$  and  $5$  K, while only regular behaviour is seen at the higher temperatures. The fluctuations indicate that numerous flux jumps are taking place. Their magnitude as well as the accompanying effect of cutting off (flattening) the central peak vary with the temperature.

the field increases. In  $\text{MgB}_2$  the jumps are omnipresent, with the first one occurring already at a few milliTesla, and with subsequent jumps coming at random. Thus,  $\text{MgB}_2$  appears not only far more susceptible to thermal runaways than HTSs, but the jumps exhibit also qualitatively new features. In this work we show, using magneto-optical (MO) imaging, that the magnetic noise in  $\text{MgB}_2$  films originates from an abrupt penetration of dendritic flux structures. Similar dendritic patterns have been observed earlier in films of niobium [7–9] and  $\text{YBa}_2\text{Cu}_3\text{O}_7$  [10–12]. Our space-resolved measurements revealed a characteristic temperature dependence in the dendrite morphology, which ranges from quasi-one-dimensional at  $4$  K to large tree-like structures near  $10$  K. Above  $10$  K the dendrites are never observed. Our vortex dynamics simulations of the thermo-magnetic instability in thin films reproduce the formation of flux dendrites and their temperature-dependent morphology.

Thin films of  $\text{MgB}_2$  were fabricated on  $(1\bar{1}02)$   $\text{Al}_2\text{O}_3$  substrates using pulsed laser deposition. An amorphous B film was first deposited, and then sintered at high temperature in a Mg atmosphere. Details of the preparation are reported elsewhere [2]. Typical films had a sharp superconducting transition ( $\Delta T_c \approx 0.7$  K) at  $T_c = 39$  K, and a high degree of  $c$ -axis alignment perpendicular to the film plane.

Magnetic characterization of films with dimensions  $400 \text{ nm} \times 5 \text{ mm} \times 5 \text{ mm}$  was first done by measuring the magnetization *vs.* perpendicular applied field (fig. 1). The vertical width of such major hysteresis loops represents the integral magnetic moment of the shielding currents, and is to a good approximation proportional to the critical current density  $J_c$ . The magnetization was measured at various temperatures from  $25$  K and below, and as expected, the loop becomes wider the lower the temperature. Furthermore, peaks are present at  $H \approx 0$ , in accordance with critical-state considerations for thin samples [13], and imply an enhancement of  $J_c$  at low fields.

At  $10$  K the behaviour evidently changes character as distinct “noisy” features start to appear in the central part of the  $M$ - $H$  curves. The fluctuations are also accompanied by a cutoff of the central peak, thereby decimating the favorable low-field value of  $J_c$ . The

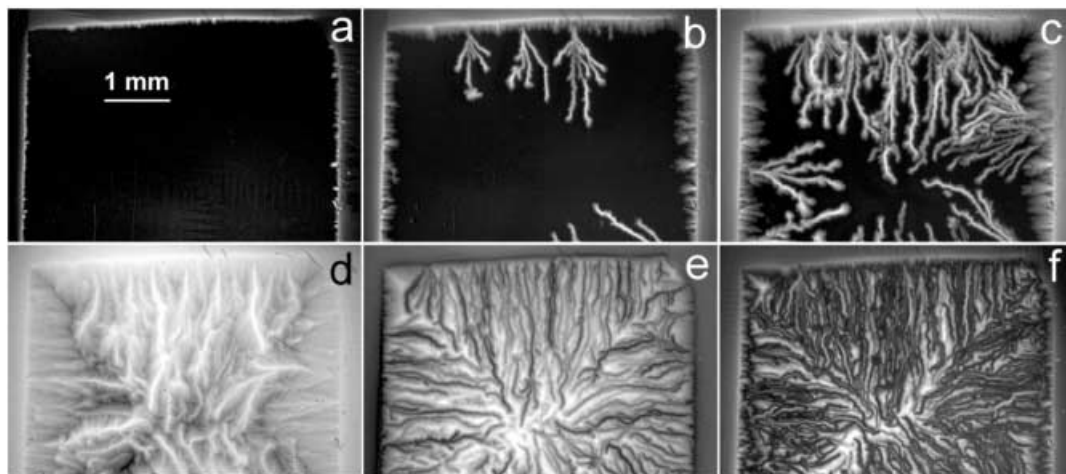


Fig. 2 – MO images of flux penetration into the virgin state at 5 K (image brightness represents the flux density). a)-d) Images taken at applied fields (perpendicular to the film) of 3.4, 8.5, 17, 60 mT, respectively. e), f) Images taken at 21 and 0 mT during the subsequent field reduction. Except for an initial stage, the flux penetration is strongly dominated by the abrupt appearance of dendritic structures nucleating at seemingly random places at the sample edge. The behaviour is essentially independent of the field sweep rate.

amplitude of the fluctuations is found to be largest near 10 K, while the peak cutoff is more severe at lower temperatures. To reveal the details of this most unexpected behaviour, found to be typical for such films, we performed space-resolved magnetic measurements.

Shown in fig. 2 is a sequence of MO images taken during a field cycle at 5 K. Immediately, one sees that the magnetic behaviour of the MgB<sub>2</sub> film differs totally from the usual critical-state type of smooth flux penetration patterns. The images for increasing field a)-d) show that the flux instead penetrates in dendritic structures which, one after the other, invade the entire film area. The dendrites nucleate at seemingly random places near the film edge, and grow to their final size in less than 1 ms (the time resolution of our CCD system). Moreover, it is found that once a dendrite is formed its size remains constant although the applied field continues to increase. When the field is subsequently reduced e), f), the flux redistributes in the same abrupt manner leading to a remanent state with an overlapping mixture of two types of dendrites —one containing trapped flux of initial polarity and one with antflux due to penetration of the reverse return field of the trapped vortices. From these images, which may be directly compared to the 5 K curve in fig. 1, it is clear that the irregular features in the  $M$ - $H$  data stem from the formation of flux dendrites.

A striking change in the morphology of the flux patterns was observed when MO imaging was carried out at different temperatures (fig. 3a-c). At the lowest temperature of 3.3 K the number of dendrites is large, and each dendrite has only a few branches. With increasing temperature the degree of branching grows, as seen in the image taken at 9.9 K, where a large tree-like structure was formed in one single burst of flux motion. These results reveal why the fluctuations in the magnetization data changed from numerous small jumps at low temperatures to fewer but larger jumps at 10 K. MO imaging showed also that above 10 K the dendrite formation never occurs and is replaced by a regular behaviour, also this fully consistent with the  $M$ - $H$  data.

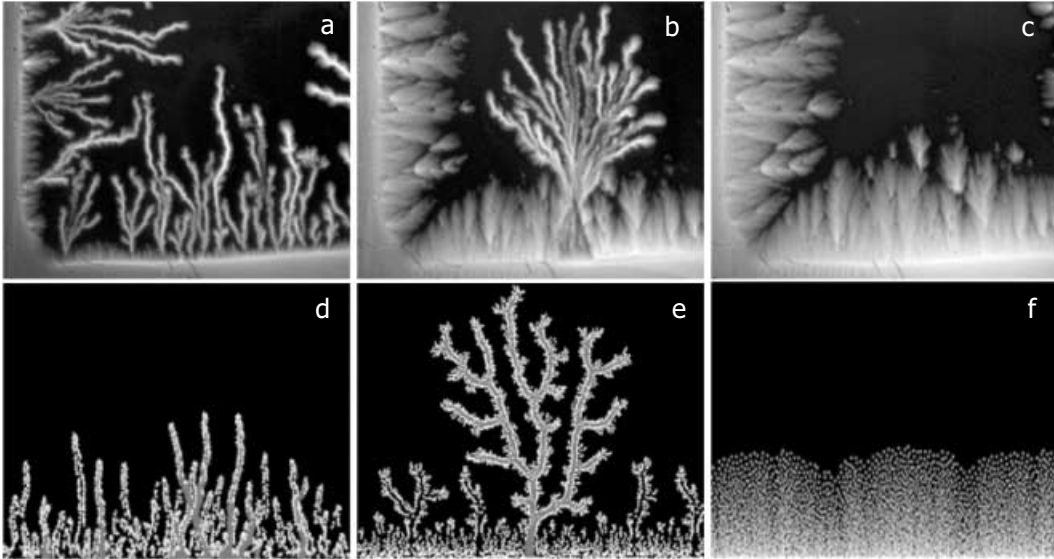


Fig. 3 – Different types of flux pattern morphology at various temperatures. a)-c) MO images taken for  $T = 3.3, 9.9$  and  $10.5$  K at applied fields of 13, 17 and 19 mT, respectively. At low  $T$  the dendrites are numerous and with few branches, while just below 10 K only large tree-like structures are formed. Above 10 K the film behaves traditionally according to the critical-state model. d)-f) Results of computer simulations largely reproducing the observed types of flux penetration patterns. Individual vortices are indicated by white dots, and gray indicate elevated temperature due to heat dissipated by the most recent vortex motion.

This remarkable complexity in the flux dynamics suggests that an instability is taking place in  $\text{MgB}_2$  films. The fact that unstable conditions exist only at the lowest temperatures points towards one of thermo-magnetic origin. It is well known that the heat released by vortices in motion causes a local temperature rise (large at low  $T$  since the specific heat is small), which facilitates further flux motion that in turn can trigger an avalanche-like invasion. We have used this mechanism as basis for vortex dynamics simulations, where aspects particular for films in a perpendicular field are taken into account.

First, in superconducting films where the thickness is of the order of the London penetration depth, or smaller, the extreme demagnetization results in a Meissner sheet current that flows in the entire sample area. For a thin rectangular film the Meissner current flows [14] as shown by the stream lines in fig. 4a, and the Lorentz force  $F_M$  from this current on a vortex is directed as indicated by the arrows. From the overall alignment of the dendrites seen in the MO image (b), it is clear that the Meissner current is a major driving force in their formation. A second aspect included in the simulations is that in thin films the vortex-vortex repulsion  $F_{ij}$  is long range [15], and we use here the asymptotic  $r_{ij}^{-2}$ -dependence.

The pinning of the vortices was accounted for by assuming a position-independent pinning energy  $U_{\text{pin}}$ . Uniform pinning was motivated by the observation that when flux penetration experiments are repeated the detailed dendrite pattern is never recurring, *i.e.*, the exact shape and number of dendrites vary at random, thus showing that this flux dynamics is insensitive to local variations in the pinning. The vortices were allowed to enter the superconductor at a discrete number of random positions, as expected for a real film with edge imperfections.

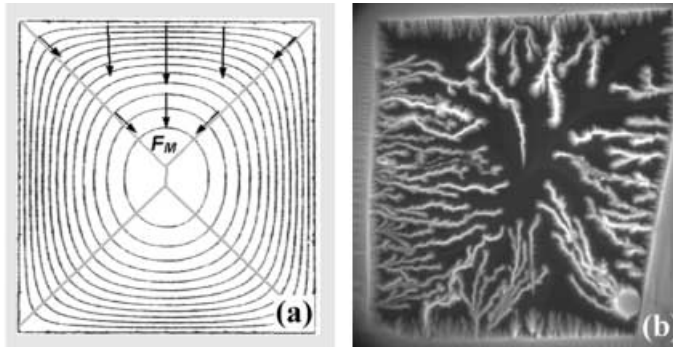


Fig. 4 – (a) Current stream lines in a rectangular thin film superconductor in the Meissner state [14]. The arrows show the Lorentz force  $F_M$  acting on a vortex. (b) MO image of the whole MgB<sub>2</sub> film. The global penetration of dendrites is governed by the Meissner current because i) dendrites nucleate preferably where  $F_M$  is maximum, ii) dendrites grow along the direction of  $F_M$ , and iii) they terminate where  $F_M$  is small, *i.e.*, near the centre or along the diagonals. The MO image is one frame of a VIDEO sequence [16] recorded at 3 K as the field was ramped from 0 to 35 mT.

Vortex-edge interactions leading to a surface barrier were not considered. Finally, it is assumed that a trail of elevated temperature follows the path of every moving vortex. More details of the simulations are given in [17].

Seen in fig. 3 are the results of simulations corresponding to three different temperatures. All the types of penetration pattern observed in the experiments are here reproduced: quasi-one-dimensional dendrites at low  $T$  (d), a single large and highly branching structure at intermediate  $T$  (e), and the conventional smooth flux profile at high  $T$  (f). Also the rapid dynamics is there, since avalanches are triggered by a small incremental step in the applied field, and followed by a fast growth of the full dendrite. Shown gray in (d) and (e) are the regions where the recent bursts of flux motion have increased the temperature. In general,

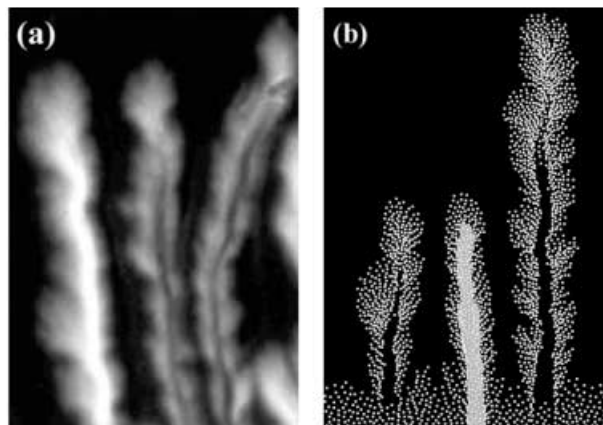


Fig. 5 – Internal structure of dendrite branches. (a) MO image of dendrites where two of them have cores with low flux density. (b) Vortex dynamics simulations reproducing the experimental observation. Shown in gray is the heated core of a growing dendrite. The total number of flux quanta in the MO image is  $10^2$ – $10^3$  times larger than that used in the simulations.

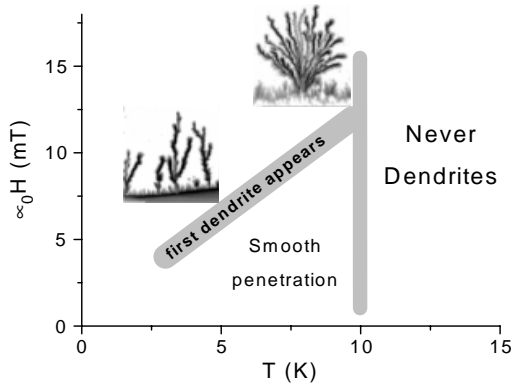


Fig. 6

Fig. 6 – Field-temperature diagram for onset of the flux dendrite instability in the present MgB<sub>2</sub> film. Other films with different thickness showed similar behaviour although the threshold field and temperature varied.

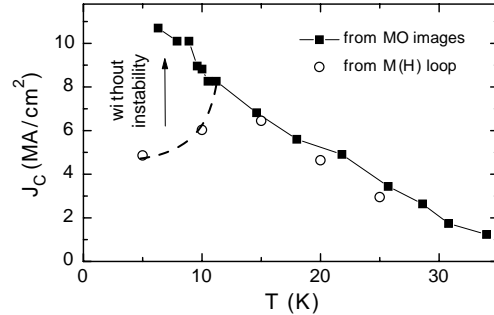


Fig. 7

Fig. 7 – “True”  $J_c(T)$  derived from the flux front position in MO images taken at low fields before dendrites occur, and “apparent”  $J_c(T)$  estimated from the  $M(H)$  curves in fig. 1. The dashed line is a guide to the eye.

the most heated part is the core of a dendrite, reflecting large traffic of vortices. Due to high temperature the vortices move hastily through this region, and finally the core can end up empty of flux, see fig. 5. Remarkably, this prediction could be confirmed experimentally, as our MO imaging was able to resolve several dendrite cores of low flux density.

Figure 6 summarizes our results on flux penetration in MgB<sub>2</sub> films. Dendritic flux structures are formed as  $H$  exceeds a certain temperature-dependent threshold value,  $H_{th}$ , and the dendrite morphology changes with the temperature as indicated. Similar behaviour has been observed earlier in niobium films [7–9], and in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> when triggered by a laser pulse [11,12]. However, an explanation of the phenomenon was hindered because the existing theories for a thermo-magnetic instability [6] were developed only for bulk superconductors, and only flat flux fronts were considered. The instability in thin films is different in two major points: the flux pattern is strongly branched, and the threshold field  $H_{th}$  is much lower. A tendency for branching exists when electro-magnetic processes during the instability are faster than the thermal processes. A branching *temperature* distribution was obtained by simulations of instability in a slab superconductor [18]. In order to simulate the branching patterns of *magnetic flux*, we had to take into account long-range interactions and Meissner currents characteristic for thin superconductors. The threshold field for a thin film is by a factor of  $(\text{width}/\text{thickness})^{1/2}$  less than for a thick superconductor [19]. This factor accounts for the discrepancy between the value  $\mu_0 H_{th} \approx 10$  mT found in the experiment, and the theoretical prediction  $\mu_0 H_{th} \approx 300$  mT [20].

The existence of flux dendrites raises new questions as to how  $J_c$  can be measured correctly. One way is to use the MO images taken at small fields before any dendrite occurs. Shown in fig. 7 by solid symbols is  $J_c$  obtained from images using the position of the flux penetration front, and the Bean-model result for a thin strip [14]. Plotted as open symbols is the *apparent*  $J_c$  obtained from  $M(H = 0)$  on the descending branch of the magnetization loops of fig. 1. Evidently, below 10 K the apparent  $J_c$  is substantially suppressed by the dendritic instability. A challenge for the future is to find practical ways to stabilize the flux behaviour, and re-establish the very high *true*  $J_c$  in films of MgB<sub>2</sub>.

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