



## Dendritic flux avalanches in superconducting Nb<sub>3</sub>Sn films

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### Abstract

The penetration of magnetic flux into a thin superconducting film of Nb<sub>3</sub>Sn with critical temperature 17.8 K and critical current density 6 MA/cm<sup>2</sup> was visualized using magneto-optical imaging. Below 8 K an avalanche-like flux penetration in form of big and branching dendritic structures was observed in response to increasing perpendicular applied field. When a growing dendritic branch meets a linear defect in the film, several scenarios were observed: the branch can turn and propagate along the defect, continue propagation right through it, or “tunnel” along a flux-filled defect and continue growth from its other end. The avalanches manifest themselves in numerous small and random jumps found in the magnetization curve.

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The conventional superconductor Nb<sub>3</sub>Sn belongs to the family of A15 materials characterized by a high value of the critical temperature and upper critical field, and is therefore widely used for various technological applications [1]. One of the central issues is then the material's stability with respect to flux jumps, an avalanche process resulting in a thermal runaway. Such a dramatic event occurs because flux motion dissipates heat leading to a local temperature rise, which in turn reduces the flux pinning, and thereby gives a positive feedback to the process [1–3].

As the critical current density  $J_c$  in Nb<sub>3</sub>Sn is constantly being improved [4], the stability criteria for flux jump, e.g. the critical filament width, need to be reconsidered [5,6]. Moreover, there are still open questions related to flux jumping in general, namely, that samples often appear more stable experimentally than predicted by theories [1]. In investigations of such avalanche events, one can benefit significantly by using thin-film samples, where one can visualize the development of the instability by monitoring spatial distributions of the magnetic flux. In this work we used magneto-optical

(MO) imaging to study flux penetration in films of Nb<sub>3</sub>Sn, which revealed a new type of instability in this material.

Films of Nb<sub>3</sub>Sn were deposited on 0.5 mm thick sapphire substrates using magnetron sputtering [7]. The films had thickness of 0.1–0.15 μm. The critical temperature and the width of the resistive transition measured by a four-probe method were  $17.8 \pm 0.1$  K. Critical current densities as high as 6 MA/cm<sup>2</sup> were measured at 4.2 K in a magnetic field of 1 T. For fields below 0.5 T, the critical current density could not be determined accurately, pointing to possible instabilities [8]. The presence of flux instabilities becomes evident from the magnetization curve, Fig. 1, showing numerous and random jumps. The typical jump amplitude here,  $\Delta m \sim 0.1$  m, is much larger than the sensitivity of the measurements,  $3 \times 10^{-5}$  emu.

The spatial distributions of magnetic flux were visualized using the MO imaging technique [9] based on the Faraday effect in ferrite-garnet indicator films, see Ref. [10] for more details on the set-up. The sample, with the indicator film placed directly on top, was glued to the cold finger of an optical cryostat using vacuum grease. The sample was initially cooled to liquid helium temperature in zero magnetic field. Then, an applied field was turned on perpendicular to the film.

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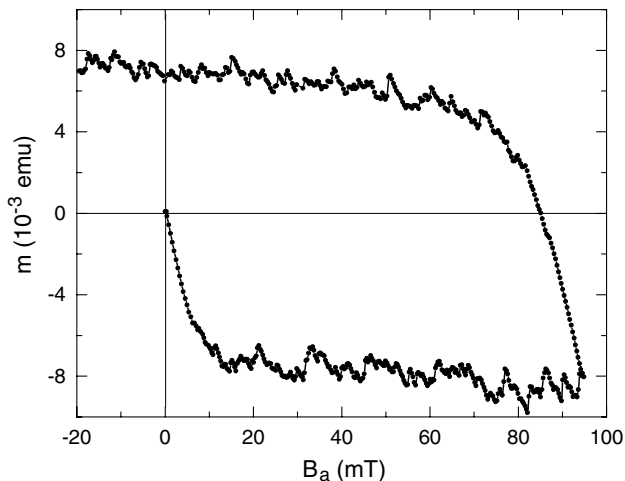


Fig. 1. Magnetic moment of a  $\text{Nb}_3\text{Sn}$  film at 4.2 K as a function of perpendicular applied field. The noisy behavior is indicative of local flux instabilities. The measurements were taken with a vibrating sample magnetometer PARC, with a field ramp rate of 0.15 mT/s.

Shown in Fig. 2 is a series of MO images taken in a slowly increasing field. Bright and dark regions correspond here to high and low flux densities, respectively. In (a), which was taken at 5.5 mT, one can see that the

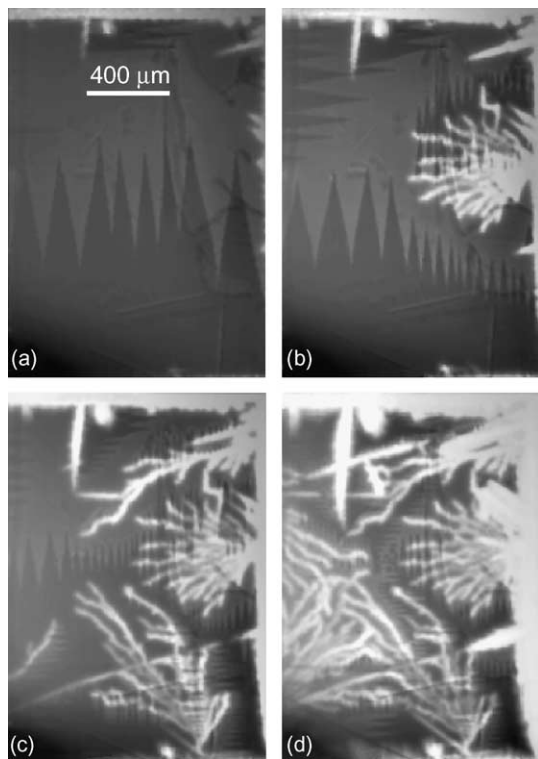


Fig. 2. MO images of the flux distribution in a  $\text{Nb}_3\text{Sn}$  film at 3.5 K for increasing magnetic field of 5.5 (a), 8.5 (b), 14.5 (c), and 26.3 mT (d). The image brightness represents the magnitude of the local flux density. The flux penetrates abruptly in the form of branching dendritic patterns. Zigzag lines are artifacts caused by domains in the MO indicator.

film is completely shielding the applied field. A few exceptions are seen near the edge, where due to imperfections a small amount of flux penetrates in a needle-like manner. By increasing the field to 8.5 mT an abrupt event occurs, with the flux entering in the form of a branching dendritic structure. This contrasts the conventional scenario of flux penetration where a smooth flux front is gradually advancing in from the edges [9]. When the field is increased further, one finds that many new flux dendrites are abruptly formed, and eventually cover most of the sample area, as seen in (c) and (d).

The observed behavior is similar to the dendritic instability found earlier in films of a few other superconducting materials: Nb [11–13],  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (when triggered by a laser pulse) [14,15], and the recently discovered  $\text{MgB}_2$  [16–18]. The common features are that the dendrites are formed at seemingly random places along the edge, from where they develop extremely fast (less than 1 ms), and remain afterwards “frozen”, i.e., the grown dendritic structure is not affected by the subsequent field increase. Furthermore, when new dendrites propagate, they tend to avoid the already existing ones, as seen in Fig. 2(c). If the field is later decreased, new dendrites are formed showing that also the exit of flux from the film takes place via dendritic avalanches. When the experiment is repeated at higher temperatures, the number of the dendritic structures goes down, and we find in  $\text{Nb}_3\text{Sn}$  that they disappear completely above 8 K.

It is clear now that the dendritic flux avalanches are responsible for the small random jumps in magnetization seen in Fig. 1. Remarkably, the field when the first dendrite is formed, 8.5 mT, is in a very good agreement with the field of the first jump on the virgin branch of  $m(H)$ . The critical current density determined from such  $m(H)$  curve appears significantly reduced compared to its “true” value that it would take in the absence of instabilities. The reduction can be as high as 50% as demonstrated for  $\text{MgB}_2$  films [16], where similar noisy magnetization curves have been measured in a wide range of  $T$  and  $H$  [19]. The dendritic avalanches can also be induced by pulses of transport current [17], which threatens high-current applications. The thermo-magnetic origin of the dendritic instability is supported both by experiments [18] and computer simulations [20,16].

A specific feature of our  $\text{Nb}_3\text{Sn}$  sample is the presence of linear defects which serve as channels of easy flux penetration (see Fig. 2). These straight bright lines in the MO images represent regions of suppressed superconductivity, and are probably related to defects in the substrate created by imperfect polishing. Normally, we find that the flux penetration into these defects proceeds gradually. For example, the vertical-line defect appearing near the middle of the top edge clearly grows in size as the field increases, see Fig. 2(a)–(d). However, this gradual penetration is sometimes disturbed by an abrupt invasion of a dendrite. Conversely, also the propagation of the

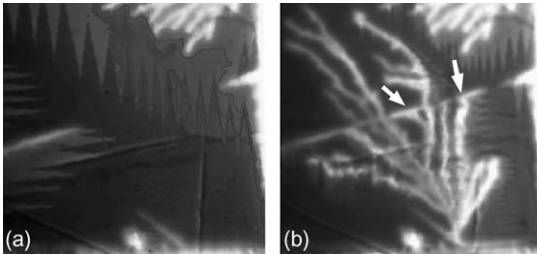


Fig. 3. MO images showing penetration of a flux dendrite into a region with a linear defect. The dendrite was abruptly formed as the field increased from 14 mT (a) to 14.5 mT (b). Some of dendritic branches (marked by arrows) are stopped by the defect, while others penetrate right through.

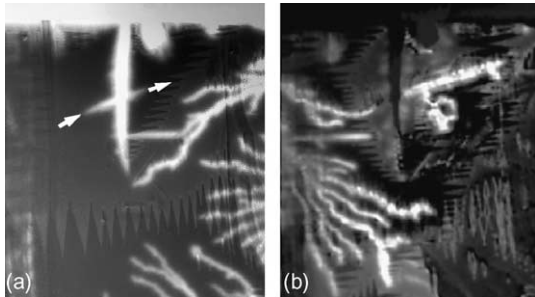


Fig. 4. Dendrite propagation mediated by a linear defect: (a) MO image taken at an applied field of 20 mT, (b) the difference between images taken at 20.7 and 20 mT. In (b), where the newly formed dendrite appears bright, one of its branches is disconnected. The flux penetrated into the isolated branch through the linear defect, as shown by arrows in (a).

dendrite then becomes perturbed by the defect, and this interesting interplay is illustrated in Figs. 3 and 4.

The MO image in Fig. 3(a) was taken just before a dendritic avalanche entered the lower part of the film. Clearly seen is a linear defect, which is here only partly penetrated by magnetic flux from the right and the left edges. The image (b) shows the same region right after the dendrite had entered. We see here two types of behavior when the dendritic branches reach the defect. Some branches (marked by arrows) suddenly terminate their propagation at the defect, and pump it with flux. Hence, we find here the same tendency as for conventional penetration, namely, that flux prefers to propagate along defects. On the other hand, some branches of the dendritic structure actually cross the defect as if it was not there. Based on this, we suggest that the different branches of the same dendritic tree do not grow simultaneously. First, those of the terminating type reach the defect and fill it with flux. Eventually, this makes the defect unattractive for the later arriving branches which simply run it over.

Another kind of dendrite-defect interaction is illustrated in Fig. 4, where image (a) shows the flux density distribution at 20 mT. By increasing the field by 0.7 mT, a large dendritic structure penetrated from the left. The

change in the flux distribution is presented in (b), which was obtained by subtracting two subsequent MO images. Surprisingly, the bright regions, which show where the flux arrived, seem disconnected. This raises the question of how the flux did enter the isolated area seen in the upper half of image (b). By comparing (a) and (b) it appears that the isolated part is connected to the main dendritic structure through a linear defect as indicated by arrows. We believe that this defect served to mediate the propagation of this long dendritic branch. All the flux contained in the isolated part has evidently passed through the defect. At the same time, the flux density in the defect itself was not affected by this process since it appears black in the difference image.

In conclusion, macroscopic dendritic flux avalanches were found in Nb<sub>3</sub>Sn films subjected to a varying applied field. These avalanches destroy the critical state and can be a threat for applications using this material. We also demonstrate that when a growing flux dendrite meets a flux-free linear defect, it tends to propagate along the defect. If the defect is already filled with flux, the dendrite can cross the defect or “tunnel” through it and continue growth at the other end.

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