Dynamics of the dendritic flux instability in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films

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Abstract. – We have studied the dynamics of magnetic-flux avalanches in superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films by means of a fast magneto-optic pump-probe technique. Two regimes of propagation are found: in regime I, directly after the nucleation of the avalanches by a femtosecond laser pulse, the velocity v of the flux dendrites depends strongly on the magnetic field, and values of v up to 180 km/s are observed. Within some ten nanoseconds after nucleation regime II is reached, where the propagation velocity has dropped by one order of magnitude and is nearly independent of sample temperature and magnetic field. Comparison with previous experiments on flux jumps in superconductors shows good qualitative agreement.

Introduction. – When a magnetic field is applied to a superconductor, the resulting flux pattern in the material does in general not correspond to the equilibrium distribution, but rather to a metastable state due to magnetic pinning. The system is therefore prone to avalanche-like flux jumps, *i.e.* a redistribution of the flux which is closer to the equilibrium state, resulting from an external perturbation or some intrinsic fluctuation in the superconducting sample. The first spatially resolved observation of such flux jumps was already reported in 1967 by Wertheimer *et al.* [1], who investigated superconducting Nb discs with a thickness of several tenths of a millimeter by means of a magneto-optic technique. These authors found finger-like flux fronts with a typical width of 1 mm which propagated with a typical speed between 5 and 100 m/s, depending on the sample thickness, the thinnest samples displaying the highest flux front velocity. Later investigations of thin superconducting Nb and $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films showed a similar flux jump phenomenon, most often resulting in a dendritic flux pattern, both when the avalanche developed spontaneously [2–4] and when it was triggered by local heating of the sample with a short laser pulse [5, 6]. For $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ with a film thickness of 300 nm, the width of the flux branches was about 0.1 mm, and their speed of propagation was determined to be on the order of $5 \cdot 10^4$ m/s [6]. That dendritic flux avalanches are a rather general phenomenon in thin superconductors was corroborated recently by similar observations in MgB_2 films [7].

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Fig. 1 – Experimental setup. For details see the text.

A first explanation for the high speed of the flux branches was given by Maksimov [8], who considered the propagation of a thermomagnetic shock wave. As in an earlier work on magnetic flux jumps by Mints [9], he assumed the thermal diffusion coefficient to be much smaller than the magnetic one [8, 10] and derived a velocity around 10^4 to 10^5 m/s, close to the experimentally observed values. Attempts to explain the formation of dendritic flux structures were presented by several groups [7, 11, 12], and qualitatively the phenomenon could be accounted for, but a quantitative theory does not exist yet. This might be ascribed, at least partly, to the fact that experiments on this subject are sparse, in spite of its relevance also for applications of thin superconducting films.

In order to provide necessary experimental information which can serve as a basis for more detailed theoretical work, we have carried out a systematic study of the development and propagation of flux avalanches in YBCO films [13]. In this letter we will focus on the temporal behavior of this phenomenon. Other aspects like the shape of the dendrites, their spatial distribution or the stability diagram will be the subject of a separate paper.

Experiment. – Due to the high velocity of the flux dendrites in thin films a temporal resolution in the sub-nanosecond regime is required to register the development of flux avalanches with sufficient accuracy. We have used a magneto-optic technique, with a Bi-doped Yttrium Iron Garnet (YIG) film on Gadolinium Gallium Garnet as the sensor layer [14], which was mounted on top of the superconductor [15]. The spatial resolution was on the order of a few μm . To achieve a high temporal resolution, a pump-probe technique was applied in combination with a Ti:sapphire pulse laser ($t = 150$ fs) as an illuminating source. A sketch of the

Fig. 2 – A sequence of magneto-optical images of an YBCO film at 10 K and in an external magnetic field of 20.6 mT. Regions of high magnetic field appear bright. The picture size is 4×2.5 mm. a) The superconductor before the perturbation pulse is applied. One can clearly notice the enhancement of the field at the sample edge (left-hand side of the picture). b) Double-exposure picture. The exposures were taken 37.6 ns and 43.3 ns after nucleation of the dendrite. c) Final state of the dendrite (picture taken after 30 s).

Fig. 3 – a) Average lengths s of the dendrite branches for a 330 nm YBCO sample at 10 K in an external field of 17.3 mT. The straight line corresponds to a velocity v of 18 km/s. b) Data points: propagation velocity v as determined by the double-exposure technique. Horizontal line: equivalent to the straight line in a).

experimental setup is shown in fig. 1: One part of the laser pulse is used to trigger a flux avalanche, whereas a second part is fed through an optical delay line of up to 150 ns and is then used to take a magneto-optic snapshot of the flux distribution, as is illustrated in fig. 2. (In some experiments the delayed imaging pulse was additionally split into two, one being delayed with respect to the other by only a few nanoseconds, in order to provide a double exposure from which not only an averaged, but also the momentary dendrite velocity could be determined. This technique has been used for obtaining the data in fig. 3b.) The limit in temporal resolution with this setup is given by the response time of the YIG film, which was found to be 200 ps in our case [13]. The samples were $10 \times 10 \text{ mm}^2$ YBCO thin films on strontium titanate deposited by the PLD technique. Each data point was obtained by the following procedure: The sample was zero-field cooled below T_c , and after reaching a stable temperature a magnetic field B_{ext} was applied perpendicular to the film. The thin-film geometry leads to an enhancement of the field at the sample edges, from where the magnetic flux penetrates partly into the superconducting film, analogous to the Bean state in 3 dimensions. It has to be pointed out, however, that in a thin film due to the 2-dimensional character shielding currents flow also in those areas of the film which are still in the Meissner state, *i.e.* the B -field is zero [16]. The resulting metastable field distribution was then disturbed locally at the sample edge by the focused laser pulse, and for sufficiently strong perturbations this triggered a magnetic-flux avalanche. We estimate that the YBCO film was heated above T_c in the focal spot of some $50 \mu\text{m}$ in diameter, but an actual temperature measurement has not been carried out. The heating was subtle enough, however, not to modify or even destroy the film locally, as tested by reversibility measurements.

Results. – Previous investigations of flux avalanches have suggested that a relevant parameter which affects the propagation speed is the sample thickness d . Other interesting parameters which might shed light on the avalanche mechanism are the temperature T and the externally applied magnetic field B_{ext} . The dependence of the propagation speed v on these quantities will be described below. First of all, we will discuss the variation of v as the avalanche propagates towards the center of the sample from the spot where it was nucleated.

A typical example for the length s of the dendrites, determined by a sequence of snapshots taken at different delay times t , is shown in fig. 3a. The film thickness was 330 nm in this case, the temperature 10 K, and the applied field 17.3 mT. It is obvious from this plot that

Fig. 4 – Dependence of the momentary penetration velocity on the external field. For these data the double-exposure technique has been applied. Δt is the time interval between the two illuminating pulses. One can distinguish between regime I ($t < 10$ ns) where a strong correlation is observed, and regime II ($t > 10$ ns) where the velocity is constant and nearly independent of the applied field.

the velocity is much larger in the beginning (which we will call regime I) than at the later stages. This can qualitatively be ascribed to the fact that the driving force for the dendrite is expected to be largest in the region of high field gradients, *i.e.* close to the sample edge. After about 10 ns, corresponding to a dendrite length of about 0.6 mm, the slope and hence the velocity becomes more or less constant at a value of $(18 \pm 2) \cdot 10^3$ m/s (regime II). The velocity $v(t)$ derived from fig. 3a is plotted in fig. 3b, together with data points obtained by the double-exposure technique mentioned above. Apparently, the two methods lead to comparable results, although the scatter of the data is relatively large.

The data shown in fig. 3 should be compared with the already mentioned earlier publication [6], where an average velocity of $5 \cdot 10^4$ m/s was reported for a 300 nm thick YBCO film. The time resolution of these measurements was distinctly lower, therefore the high values of $v(t)$ in the initial stage could not be resolved. If we take an average over the first 30 to 50 ns, as in the previous experiments, the data in fig. 3 are consistent with the earlier results for a comparable film thickness.

The final stage of the avalanche development, where the dendrite tip eventually comes to a stop, is not easily accessible in a systematic way by the snapshot technique. Yet we can conclude from the available data that the velocity does not display a gradual decrease, but drops to zero rather rapidly.

In fig. 4 we show the dependence of the dendrite velocity on the applied magnetic field, again for a 330 nm thick film and a temperature of 10 K. The various symbols correspond to different times, the straight lines are only a guide to the eye. It is observed that for short times (< 7 ns) there exists a strong (linear) dependence on the magnetic field. For long times ($t > 19$ ns), however, the flux lines propagate essentially independent of the external field with a velocity of about $2 \cdot 10^4$ m/s. A comparison shows that these regimes correspond to the early and late stages in fig. 3. In regime I, where the dendrite propagates still close to the sample edge with high field gradients, the data are in good agreement with a relation $v \propto B_{\text{ext}}$ as predicted by Maksimov [8]. Regime II, on the other hand, where the velocity is nearly constant irrespective of the applied field, mainly corresponds to dendrite propagation in an area where initially no field gradients are present.

We have also investigated how this behavior depends on temperature, and the results are

Fig. 5 – Temperature dependence of the dendrite velocity v . The closed and open symbols correspond to 12.7 mT and 20.6 mT, respectively, the straight lines are guides to the eye. Again regime I and II are clearly separated. For the short ($t = 4.2$ ns) time delays (circles) a strong dependence on the applied field is observed. This is not the case for longer time delays ($t = 37.7$ ns), which are represented by squares.

plotted in fig. 5. The closed symbols represent data for an applied field of 12.7 mT, while the open ones correspond to 20.6 mT, and the circles and squares refer to snapshot times of 4.2 and 37.7 ns, respectively. The roughly linear dependence of v on B_{ext} in regime I and the B -independent velocity in regime II of fig. 4 holds for all temperatures in the investigated range $7.5 \text{ K} \leq T \leq 30 \text{ K}$. What is more, even the absolute values of the velocities do not depend on T within our accuracy.

Finally, the effect of sample thickness d was studied for 4 different films between $d = 100$ nm and 690 nm thickness. In these measurements we applied a slightly different technique, using a line focus instead of a point focus to nucleate the dendrites [17]. The line was placed lengthwise across the quadratic sample to divide it into two rectangles of equal size. This procedure has the advantage that the starting point of the dendrites lies on the line focus in a homogeneous, defect-free sample area and is thus better defined. The data shown in fig. 6a represent regime II, where the velocity is constant and is also independent of the applied

Fig. 6 – a) Time-resolved length s of the dendrite branches for different sample thicknesses. b) Dendrite velocity in regime II, as derived from a) (circles). The line represents a $v \propto d^{-1}$ behavior. Also shown are data by Wertheimer *et al.* (squares) [1].

magnetic field (for the sake of clarity, we show only data points for one magnetic-field value for each thickness). The velocities derived from fig. 6a are plotted in fig. 6b on a double-logarithmic scale, together with data from the previously mentioned work of Wertheimer *et al.* for Nb disks. The straight line corresponds to a dependence $v \propto d^{-1}$. One can see that our data (full symbols) follow this relation with reasonable accuracy, and that in addition also the Nb data (open symbols) seem to fall roughly on the same line. This suggests the same mechanism to govern the spreading of flux avalanches over a wide range of sample thicknesses. Please note the absence of regime I in this case. As indicated above, we ascribe the increased velocity in regime I to the strong gradient in the magnetic field in this region. Hence, if we nucleate dendrites in the interior of the sample, where initially no field gradient is present, regime I is not observed.

Conclusions. – These investigations show for the first time that the dynamics of the dendritic flux instability in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films displays some prominent features: one can distinguish, between two regimes of flux propagation, an early stage, where the dendrite velocity depends linearly on the external field B , and a late stage, where the velocity is nearly constant. In both regimes the velocities are independent of temperature in the investigated range $T \leq T_c/3$. Increasing the film thickness leads to a reduction of the velocity. While the observed B -dependence of v is in agreement with theoretical work by Maksimov, a complete theory for the phenomenon of the dendritic flux instability is not yet at hand. In view of the importance of the effect for applications of HTSC films, where the appearance of such an instability can, *e.g.*, lead to an irreversible destruction of the film [2], we hope that the results presented here will be helpful to contribute information for a deeper understanding of the mechanisms of such instabilities.

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