Thickness dependence of dendritic flux avalanches in $YBa_2Cu_3O_{7-x}$ films

To cite this article: E. Baruch-El *et al* 2018 *J. Phys.: Conf. Ser.* **969** 012042

Thickness dependence of dendritic flux avalanches in $YBa_2Cu_3O_{7-x}$ films

E. Baruch-El[1], M. Baziljevich[2], T.H. Johansen[2,3], A. Shaulov[1] and Y. Yeshurun[1]

[1] Department of Physics, Institute of Superconductivity and Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 52900, Israel
[2] Department of Physics, University of Oslo, P.O. Box 1048, Blindern, N-0316 Oslo, Norway
[3] Institute for Superconducting and Electronic Materials, University of Wollongong, NSW 2522, Australia

Abstract. By implementing a unique magneto-optical system with ultrafast magnetic-field ramping-rate capability (up to 3 kT/s), we have been able to routinely generate and image dendritic flux instabilities in $YBa_2Cu_3O_{7-x}$ films. In the present work we study the effect of the film thickness on the dendritic instability. Dendritic avalanches in 50 - 600 nm thick films were magneto-optically imaged at 7 K, after ramping the magnetic field from zero to 60 mT at different rates. The data reveal a remarkable change in flux morphologies between the thin and the thicker films. While the former (50-250 nm) display well-developed dendritic patterns, the latter (350-600 nm) exhibit few avalanches with favored branch directions parallel to the film's edges. Several possible explanations for this behavior are discussed.

1. Introduction

Dendritic flux instabilities have been observed in superconducting films such as MgB_2 [1-3], Nb [4], NbN [5], and a-MoSi [6], after exposing them to an external perpendicular magnetic field. The phenomenon, explained in several theoretical works [7-9], reflects a thermomagnetic runaway. It occurs when thermal fluctuations locally release some vortices out of their pining sites, enabling the vortices to move and heat the superconductor, which in turn further reduces the pinning and increases vortex motion. If the heat generated in the film is not dissipated quickly enough into the substrate, a thermomagnetic runaway occurs, resulting in a dendritic flux avalanche pattern in the film.

Experiments have demonstrated that high-temperature superconductors, such as $YBa_2Cu_3O_{7-\delta}$ (YBCO), are very stable, preventing the formation of dendritic avalanches. In fact, it was shown that local laser-heating of the films was necessary to generate such avalanches [10, 11]. Nevertheless, we recently found that YBCO films become thermomagnetically unstable when applying fast ramping-rate of the external field [12-14]. Exploiting this technique, we investigated different parameters that control the dendritic penetration. In a recent publication we studied the effect of the magnetic field ramp rate, identifying the threshold rate for generating avalanches at different temperatures [13]. In the present work we focus on how the film thickness influences the avalanche behavior. Our results display dendritic avalanches in all the studied YBCO films. However, the thin (50-250 nm) films and the thicker (350-600 nm) ones show significantly different dendritic patterns. In contrast, the threshold ramp rate values do not show any clear trend as the film thickness varies.

2. Experimental

YBCO films (4x4 mm^2) with thickness in the range 50-600 nm were epitaxially grown by thermal reactive coevaporation [15] on yttrium stabilized zirconia (YSZ) substrate, resulting in films with the *c* axis perpendicular to the surface. The low thermal conductivity of YSZ facilitates the generation of dendritic avalanches [14]. Magnetic measurements, using a commercial Quantum Design magnetometer, reveal a transition temperature, $T_c \approx 87$ K. All the magneto-optical imaging (MOI) measurements described in the next sections were done using our custom-made MOI system that enables real-time imaging at rates up to 70,000 frames per second. Furthermore, the magnetic field in this MOI system can be ramped up to a field of 60 mT at rates up to 3 kT/s [16].

3. Results

MOI experiments using slow field ramping yield images with a smooth flux penetration front, consistent with the Bean model [17], see Figure 1. As the number of pinning sites increases with film thickness, the effective critical current also increases with thickness. Consequently, thinner films exhibit deeper flux penetration.

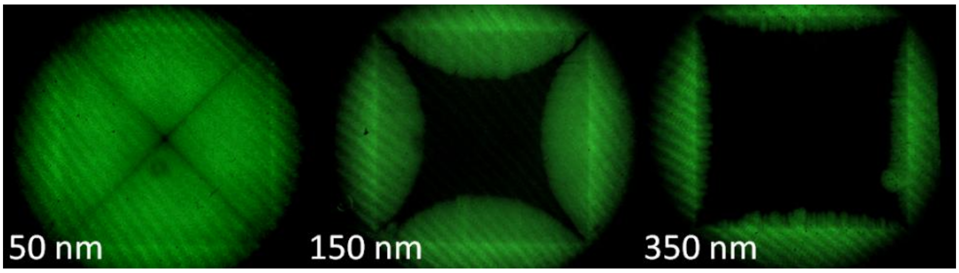

Figure 1. MO images of the YBCO films. The films were zero-field-cooled to 7 K and then exposed to a 60 mT magnetic field increased at a rate of several mT/s.

Repeating the same experiments with a fast field ramp rate (3 kT/s) produced dendritic patterns, as shown in Figure 2 and 3 for the thin (50 – 250 nm) and thicker (350 – 600 nm) YBCO films, respectively.

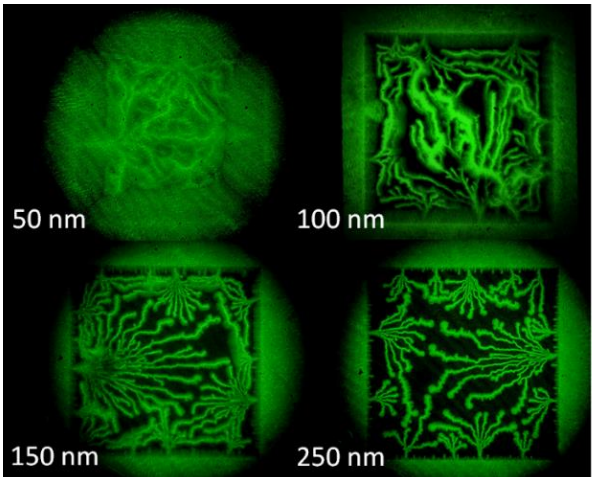

Figure 2. Dendritic avalanches in the thin YBCO films. The films were zero-field cooled to 7 K and then exposed to magnetic field ramped from zero to 60 mT at 3 kT/s.

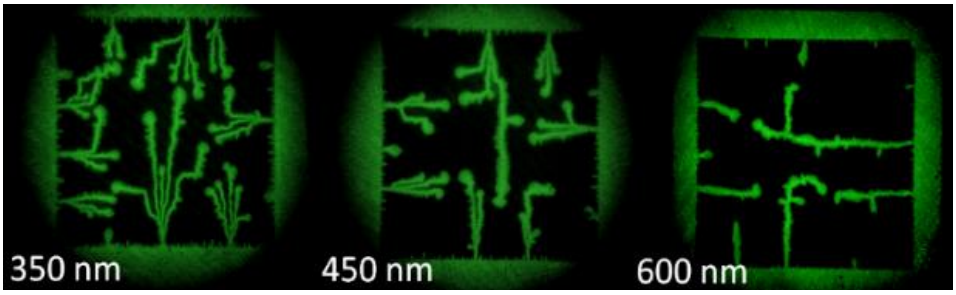

Figure 3. Dendritic avalanches in the thicker YBCO films. The films were zero-field cooled to 7 K and then exposed to magnetic field ramped from zero to 60 mT at 3 kT/s.

In the thinnest film (50 nm) the avalanches were superimposed on a Bean-like penetration profile, where most of the film was penetrated by magnetic flux. The Bean-like profile covers less of the area as the film thickness increases, virtually disappearing altogether at 150 nm. The 150 and 250 nm films exhibit similar avalanche morphology though it seems that the number of branches of each trunk reached a maximum at the 150 nm film. As discussed above, thicker films have more pinning sites and, therefore provide a stronger resistance against flux penetration; this may explain the slightly less developed trees in 250 nm film.

As shown in Figure 3, the thicker films (350-600 nm) have much different avalanche patterns. In those films, the penetrated flux appears to follow some preferred directions, parallel and perpendicular to the sample edges. Moreover, the avalanches do not here develop into tree-like structures.

We also made an effort to identify experimentally the effect of the film thickness on the minimum ramp rate $\dot{B}_{th}$ required for the appearance of the first avalanche [13]. In these experiments, the film was first zero-field-cooled (ZFC) to 15 K and then a perpendicular field, $B_a=60$ mT, was applied. The measured $\dot{B}_{th}$ values were fluctuating between 0.2 and 0.8 kT/s with no clear trend for the film thickness dependence. Additional efforts with different fields at different temperatures were made, giving essentially the same result.

4. Discussion

In the theoretical analysis of the thermomagnetic runaway, a 'stability parameter', $\tau=t_m/t_h$ is defined [7-9]. This parameter signifies the ratio between the magnetic (t_m) and thermal (t_h) diffusion times. A film with a smaller τ has higher tendency for the occurrence of an avalanche. The time t_m is predicted to increase with the film thickness, d, consistent with the fact that the number of pinning sites is larger in thicker films. An indirect evidence for the increase of t_m with the film thickness was found by dendritic velocity measurements, showing that the flux front velocity of the dendrite decreases as the film thickness increases [11]. The direct dependence of t_m on d implies an increase of τ with d. Thus, thicker films are expected to show better resistance to dendritic flux avalanches.

Our MO images, Figures 2 and 3, are consistent with the above prediction, as the avalanches in the thicker films are less developed and a larger part of these films remain superconducting. The above arguments lead also to an expectation for an increase of $\dot{B}_{th}$, the threshold field ramp rate, as the film thickness increases. However, as indicated above, we could not detect a clear trend for $\dot{B}_{th}$ as the film thickness varied. We believe that the absence of a clear thickness dependence results from local damages created during the generation of the dendritic avalanches [12]. Such damage often forms permanent gaps in the film, which in turn amplifies the local field, and has a significant impact on the following instabilities, perturbing the effect of the film thickness on $\dot{B}_{th}$.

We turn now to discuss the origin of the preferred directions for the dendritic branches in the thicker films (Figure 3). A possible origin may be traced to oriented cracks or similar defects in these films. Such defects, however, should also affect smooth flux entry. To test this possibility we performed extensive measurements at temperatures above the dendritic threshold temperature, where there is no dendritic instability [13]. In these experiments, the thick films were ZFC to 55 K, then exposed to an external magnetic field increased at various rates. In all these experiments, the flux penetration was smooth and homogeneous, and no indication for guiding defects was found. Additionally, those films were checked with scanning electron microscope (SEM) and no sign of such defects was found. It is important to note that the YBCO crystalline a-b-axes are aligned at 45 degrees with respect to the film edges, and although thicker films have a higher tendency to crack (as there is more elastic energy in the films), those cracks would also be oriented 45 degrees with respect to the edge of the film [18]. In light of the above, we conclude that defects cannot be responsible for the observed preferred direction of dendritic branches.

Another possible origin for the flux direction preference may be related to the square geometry of our films. Screening currents along the film edges apply on the penetrating flux a Lorentz force directed perpendicular to these edges (see, e.g., Figure 4 of Ref. [1]). To test this possibility, we etched (with Argon plasma) few of the 600 nm thick YBCO films, preparing the different geometries (trapezoid and circle) displayed in Figure 4. The films were field cooled (FC) with -60 mT to 7 K, then exposed to a 60 mT field ramped up at a rate of 3 kT/s. The FC procedure facilitates the triggering of more avalanches, due to extra heating from vortex-antivortex annihilation. As is apparent from the MO images of Figure 4, even though the sample geometries have been changed, the preferred directions of the avalanche branches still remain as they were in the case of the square sample (see Figure 3), i.e. parallel and perpendicular to the original square film edges. We thus conclude that also the film geometry cannot be causing the directed flux entry. Thus, the physical mechanism behind the different avalanches morphologies remains unresolved.

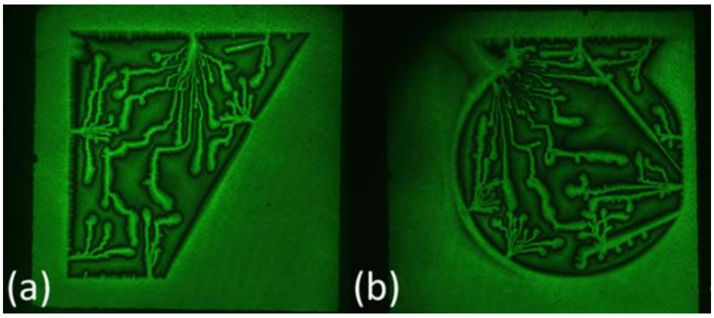

Figure 4. Flux avalanches in 600 nm YBCO films etched to form different geometries: (a) trapezoid, and (b) circle. The films were cooled to 7 K in the presence of -60 mT and the MO images were taken while ramping up the field to 60 mT at a rate of 3 kT/s. (The two long diagonal lines in the right edge of the circle sample are mechanical scratches in the YBCO).

Finally, we present preliminary results of fractal analysis of the different dendritic morphologies. Using the 'box-counting' method [19], the images were covered with a grid, and the number of boxes occupied with magnetic flux was counted. A graph of the number of occupied boxes versus the box size was then plotted. The slope of this graph represents the fractal dimension of the studied image. The above procedure was done for the 150 nm – 600 nm YBCO samples. The 50 nm and 100 nm films were not included in this study because of the significant Bean-like penetration that adds complexity to the fractal dimension analysis. The results of this analysis showed a monotonic decrease of the fractal dimension from 1.85 for the 150 nm film to 1.36 for the 600 nm film. The calculated fractal dimension may be used as a quantifying parameter of the films stability against dendritic avalanches. More experimental work combined with fractal analysis is needed to substantiate such a conclusion.

5. Summary

MO images of YBCO films exposed to an ultra-fast magnetic field ramp, revealed different dendritic morphology for the thin and thicker films. Specifically, we observed a change from dense, well-developed tree-like avalanches in the thin films, to avalanches with few branches penetrating along favored directions in the thicker ones. The origin of this change in the morphology is still unclear. The fractal dimension of the dendritic avalanches is suggested as a quantifying parameter of the sample stability against the flux avalanches. Quantifying the parameters governing the dendritic avalanches is also important for application of high-temperature superconducting films, as such thermomagnetic avalanches limit their potential use and may even cause permanent damage [12].

Acknowledgments

The authors thank Dr. Robert Semerad for preparation of the films and for helpful discussions. We also acknowledge a financial support from the Israel Science Foundation (ISF-164/12) and the Norwegian Research Council.

References

[1] Johansen T H, Baziljevich M, Shantsev D V, Goa P E, Kang W N, Kim H J, Choi E M, Kim M-S and Lee S I 2002 Dendritic magnetic instability in superconducting MgB_2 films *EPL (Europhysics Letters)* **59** 599
[2] Baziljevich M, Bobyl A V, Shantsev D V, Altshuler E, Johansen T H and Lee S I 2002 Origin of dendritic flux patterns in MgB_2 films *Physica C: Superconductivity* **369** 93
[3] Albrecht J, Matveev A, Djupmyr M, Schütz G, Stuhlhofer B and Habermeier H-U 2005 Bending of magnetic avalanches in MgB_2 thin films *Applied Physics Letters* **87** 182501
[4] Duran C, Gammel P, Miller R and Bishop D 1995 Observation of magnetic-field penetration via dendritic growth in superconducting niobium films *Physical Review B* **52** 75
[5] Yurchenko V V, Shantsev D V, Johansen T H, Nevala M R, Maasilta I J, Senapati K and Budhani R C 2007 Reentrant stability of superconducting films and the vanishing of dendritic flux instability *Physical Review B* **76** 092504
[6] Colauto F, Motta M, Palau A, Blamire M G, Johansen T H and Ortiz W A 2015 First observation of flux avalanches in a-MoSi superconducting thin films *IEEE Transactions on Applied Superconductivity* **25** 1
[7] Aranson I S, Gurevich A, Welling M S, Wijngaarden R J, Vlasko-Vlasov V K, Vinokur V M and Welp U 2005 Dendritic flux avalanches and nonlocal electrodynamics in thin superconducting films *Physical review letters* **94** 037002
[8] Denisov D V, Rakhmanov A L, Shantsev D V, Galperin Y M and Johansen T H 2006 Dendritic and uniform flux jumps in superconducting films *Physical Review B* **73** 014512
[9] Dvash E, Shapiro I and Shapiro B Y 2009 Dendritic instability of the magnetic flux in thermally anisotropic type-II superconductors *Physical Review B* **80** 134522

IOP Conf. Series: Journal of Physics: Conf. Series **969** (2018) 012042 doi:10.1088/1742-6596/969/1/012042

[10] Leiderer P, Boneberg J, Brüll P, Bujok V and Herminghaus S 1993 Nucleation and growth of a flux instability in superconducting $YBa_2Cu_3O_{7-x}$ films *Physical review letters* **71** 2646
[11] Bolz U, Biehler B, Schmidt D, Runge B-U and Leiderer P 2003 Dynamics of the dendritic flux instability in $YBa_2Cu_3O_{7-\delta}$ films *EPL (Europhysics Letters)* **64** 517
[12] Baziljevich M, Baruch-El E, Johansen T H and Yeshurun Y 2014 Dendritic instability in YBCO films triggered by transient magnetic fields *Applied Physics Letters* **105** 012602
[13] Baruch-El E, Baziljevich M, Shapiro B Y, Johansen T H, Shaulov A and Yeshurun Y 2016 Dendritic flux instabilities in $YBa_2Cu_3O_{7-x}$ films: Effects of temperature and magnetic field ramp rate *Physical Review B* **94** 054509
[14] Baruch-El E, Baziljevich M, Johansen T and Yeshurun Y 2015 Substrate Influence on Dendritic Flux Instability in YBCO Thin Films *Journal of Superconductivity and Novel Magnetism* **28** 379
[15] Utz B, Semerad R, Bauer M, Prusseit W, Berberich P and Kinder H 1997 Deposition of YBCO and NBCO films on areas of 9 inches in diameter *Applied Superconductivity, IEEE Transactions on* **7** 1272
[16] Baziljevich M, Barness D, Sinvani M, Perel E, Shaulov A and Yeshurun Y 2012 Magneto-optical system for high speed real time imaging *Review of Scientific Instruments* **83** 083707
[17] Schuster T, Kuhn H, Brandt E H, Indenbom M V, Kläser M, Müller-Vogt G, Habermeier H U, Kronmüller H and Forkl A 1995 Current and field pattern in rectangular and inhomogeneous superconductors *Physical Review B* **52** 10375
[18] Semerad R private communication
[19] Feder J 2013 *Fractals* (Springer Science & Business Media)