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Dendritic instability in $YBa_2Cu_3O_{7-\delta}$ films triggered by transient magnetic fields

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Superconducting films of $YBa_2Cu_3O_{7-\delta}$ are shown to become thermomagnetically unstable when experiencing a time-varying perpendicular magnetic field. Using magneto-optical imaging and ramping the applied field at rates up to 3000 T/s, dendritic flux avalanches were observed in two different films, one grown by evaporation on sapphire and one by laser ablation on $SrTiO_3$. The unstable behavior occurs over a wide temperature range limited by an upper threshold value of 40 K for the film on sapphire, and 20 K for the one on $SrTiO_3$. At 7 K for the same films, the threshold ramping rates are 1000 T/s and 3000 T/s, respectively. The avalanches are causing permanent damage by leaving a micron wide track where the superconductor melted during the thermomagnetic runaway. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4887374]

When type-II superconductors are considered for applications, it is crucially important that the material shows electromagnetic stability and predictable behavior when exposed to time-varying magnetic fields. These conditions are met in the majority of situations, where the magnetic flux distributes essentially according to the critical-state model.[1] However, below a threshold temperature, superconducting films can behave quite differently, where the penetration of flux consists of large-scale avalanches forming dendritic structures. Using magneto-optical imaging (MOI) this dramatic behavior has been observed in a number of materials[2] such as Nb, MgB_2, and NbN.

It is widely agreed today that the phenomenon is a thermomagnetic breakdown of the superconductor.[3] This may occur when a fluctuation weakens the pinning of some vortices, causing them to move and locally heat the material, thus reducing the pinning even further. If the film and substrate are unable to dissipate the heat, a runaway will take place with lightning-like characteristics.[4]

While such abrupt flux jump events are commonly found among superconductors, it is a surprising fact that films of the key material $YBa_2Cu_3O_{7-\delta}$ (YBCO) show an unusual degree of stability. So far, avalanches in YBCO films seem to require active local triggering, e.g., by exciting the edge with a hot spot generated by a pulsed laser, as reported by Leiderer *et al*.[5] Interestingly, for YBCO films there exists also one singular observation of a spontaneous avalanche event,[6] the cause of which remains unclear. Thus, it is today an open question where the boundaries for stable behavior of YBCO films lie with respect to transient magnetic fields.

In this work, we report a systematic investigation of thermomagnetic avalanches in YBCO films exposed to fast ramping of transverse magnetic fields at different temperatures. The observations were made using a specially designed MOI system,[7] that allows very high ramping rates to be applied to the sample, which is mounted on a sapphire cold finger to minimize eddy currents. The threshold temperature where YBCO films lose stability is determined for ramping rates up to 3000 T/s. We find that different from other materials, the avalanches in YBCO often leave an imprint of their path, even making permanent damage to the superconducting film.

YBCO films of thickness 150 nm were produced by thermal reactive co-evaporation on r-cut sapphire substrates.[8] The films have a transition temperature of $T_c = 87\,\mathrm{K}$, and a critical current density of $j_c = 3.8\,\mathrm{MA/cm^2}$ at 77 K. They were epitaxially grown, with the c-axis perpendicular to the surface. One film was cut using a precision saw into a square with 4 mm sides. The size is well fitted for MOI measurements, where a Bi:YIG indicator plate is placed on top of the sample. The large Faraday effect in such ferrite garnets[9] allows imaging of the global flux dynamics in the superconducting film using polarized light microscopy.[10]

Figure 1(a) shows, as initial reference, a magneto-optical image of the sample in a field $B_a = 5\,\mathrm{mT}$ applied slowly after initial zero-field cooling to 7 K. The field is perfectly screened by the superconductor, as one sees a sharp outline of the film edge, where the expelled flux piles up. Evidently, the sample edge is free of major defects. To prepare for a high ramping rate experiment, the flux trapped at the sample rim was removed by warming up above T_c. After re-cooling in zero field to 7 K, the magnetic field was ramped to 60 mT at the rate of 3000 T/s. As seen from Fig. 1(b), showing an image recorded at $B_a = 60\,\mathrm{mT}$, the resulting flux penetration pattern is typical for stable critical state behavior. The slight striations in the pattern are due to minor edge roughness, whereas the overall image demonstrates a high uniformity of this YBCO film.

As well known,[11] a sizable indentation at the film edge will amplify the local external magnetic field significantly. Thus, to test the stability of the YBCO film at higher effective ramping rates, a 0.5 mm long and 80 μm wide slit was cut normal to one edge near its midpoint. To verify its amplifying effect, the field was again slowly increased to

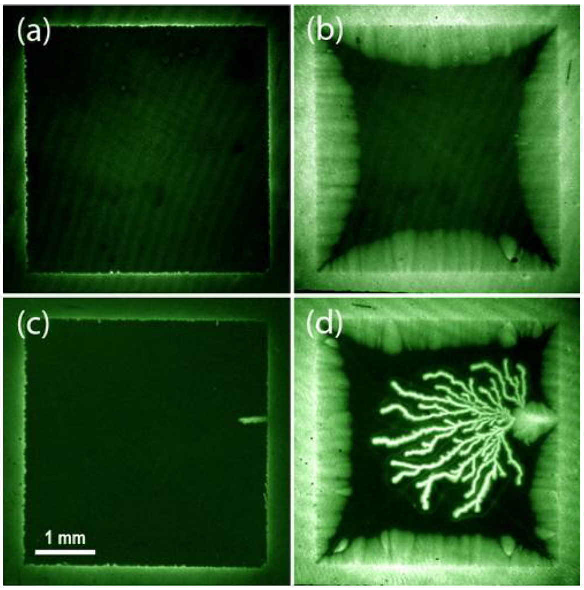

FIG. 1. Magneto-optical images of the YBCO film at 7 K. Darkest contrast corresponds to zero flux density, and increasing brightness represents higher flux density. (a) shows an image after slow ramping of the applied field to 5 mT, while in (b), the field was ramped to 60 mT at a rate of 3000 T/s. (c) and (d) show the flux distribution after a cut was made from the right edge. In (c), the field was applied as in (a), and in (d), the same ramping as in (b) was applied, creating an avalanche.

$B_a = 5$ mT after zero-field cooling to 7 K. The resulting MOI contour of the sample, see Fig. 1(c) resembles that of Fig. 1(a), with the tip of the slit showing enhanced contrast corresponding to a field amplification near 100%.

Repeating the fast ramping experiment, the resulting flux distribution changed dramatically, see Fig. 1(d). Now, the final flux pattern includes one large dendritic structure, rooted at the tip of the slit. From there it spreads out over a large portion of the sample. Repeated runs, all starting with the film in the virgin state, and using the same experimental parameters, produced similar avalanche structures. However, they had substantial differences in the branching details, reflecting the stochastic nature of the phenomenon. The overall behaviour found in this sample is quite similar to avalanche characteristics reported for films of other superconductors.[2]

To determine the temperature range where the instability occurs in the YBCO film, several similar experiments were performed up to 42 K. Each time the flux-free sample was cooled to the target temperature, and then the field was increased from zero to 60 mT at the rate of 3000 T/s. Shown in Figs. 2(a)–(e) is the resulting flux distribution at the respective temperatures 13, 20, 30, 40, and 42 K. The avalanche activity stops after reaching 40 K, which defines the threshold temperature at this ramping rate.

From Fig. 2, it is evident that the avalanche patterns show systematic changes. With increasing temperature, the individual branches become wider, thus following the trend displayed by the general flux penetration from the main edges. This is an expected result of the flux pinning decreasing with larger temperature. There is also variation in the number of branches, but the trend is not fully systematic. Actually, it deviates from what has been reported, e.g., for films of MgB_2.[12] There, it was found that the dendritic structures have a lot more branches near the threshold temperature than far below. In the present sample, it is opposite. A possible reason is that the avalanche at 40 K occurs at a stage where the flux-free central region available for an avalanche is significantly reduced, thus limiting its size and degree of branching.

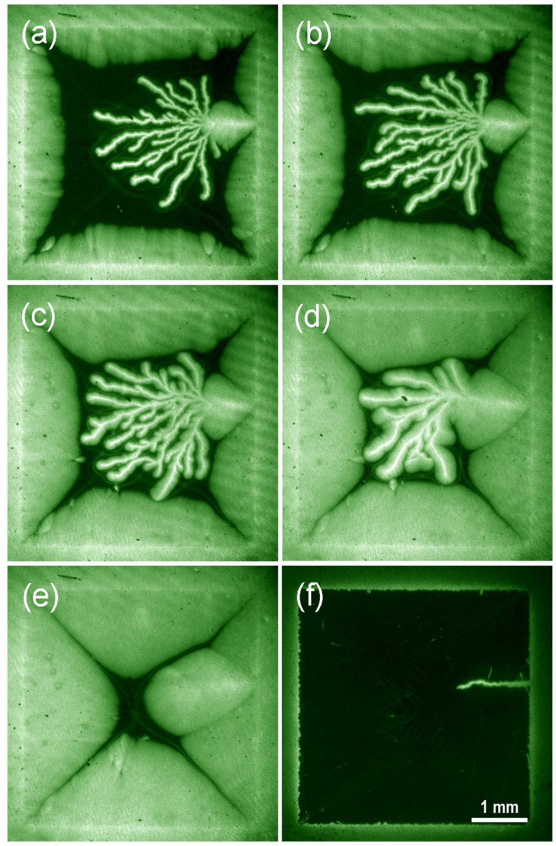

FIG. 2. (a)–(e) Flux patterns in the YBCO film at temperatures 13, 20, 30, 40, and 42 K, respectively. The sample was zero-field cooled to each temperature, and then the applied field was ramped to 60 mT at a rate of 3000 T/s. (f) An image at 7 K and 5 mT applied field, taken after all previous experimental runs, revealing an extended slit.

Another series of experiments were carried out using different ramping rates. After zero-field cooling the sample to 20 K each time, the field was ramped from zero to 60 mT. Fig. 3(a) shows the first result when the ramping rate was 1500 T/s. In this case, there were no dendrites. Increasing the ramping rate to 2000 T/s, the sample becomes unstable and produces a dendritic flux pattern, as shown in Fig. 3(b). Repeating the experiment several times, we find that occasionally the sample produces dendrites also at 1500 T/s.

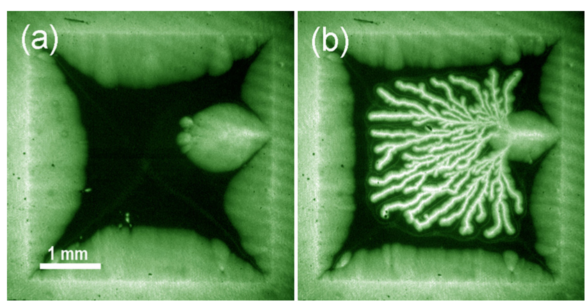

FIG. 3. Dendritic flux patterns in the YBCO film using two different ramping rates. The sample was zero-field cooled to 20 K in both cases. In (a), the applied field was ramped to 60 mT using a ramping rate of 1500 T/s, while in (b), the ramping rate was 2000 T/s.

This was found to be the lowest ramping rate generating an avalanche at 20 K. The corresponding ramping threshold at 7 K was 1000 T/s. The dendritic patterns in Figs. 3(b) and 2(b), and our other experiments, point toward a tendency of increased branching as the ramping rate approaches the threshold value.

While performing the above experiments it became clear that the slit from the sample edge became longer. As evident from Figs. 2(f) and 1(c), its length more than doubled, increasing to approximately 1.2 mm. This modification gradually altered the magnetic response of the film, and shifted the thresholds in temperature and ramp rate. Thus, to continue systematic studies based on this sample became impossible.

Instead, a closer inspection of the extended part of the slit was made using atomic force microscopy (AFM). Measurement of the height profile over a square area of size 5 μm is shown in Fig. 4, and reveals a dramatic impact on the film. Along a linear segment the material had been removed resulting in a sharp groove, while extra height was added on both sides. Inspecting other parts of the extended slit, it was found that the groove typically was 50 nm deep.

The damage seen in Fig. 4 took place at a location corresponding to the main trunk of the dendritic structure. During the avalanche, this is where the traffic of entering flux is highest and thus also where the temperature should be maximum. This has previously been confirmed by numerical simulations,[4] where the peak temperature in the superconducting film increased during a short time interval by an order of magnitude. Very high peak temperature is suggested also from the AFM plot, where one sees that the material added on both sides of the groove has the form of many submicron globules. This suggests that the released heat caused melting of YBCO.

To test the general validity of the above results a different YBCO film was investigated. This sample is a 250 nm thick epitaxial film made by laser ablation on a strontium titanate (100) substrate,[13] and has $T_c = 89$ K and $j_c = 2$ mA/cm^2 at 77 K. Originally designed to study the flow of Meissner currents near holes almost 20 years ago,[14] this square film of sides 3 mm was patterned with a set of rectangular slits.

Figure 5(a) shows the sample after zero-field cooling to 7 K, and then applying a 60 mT field at a ramping rate of

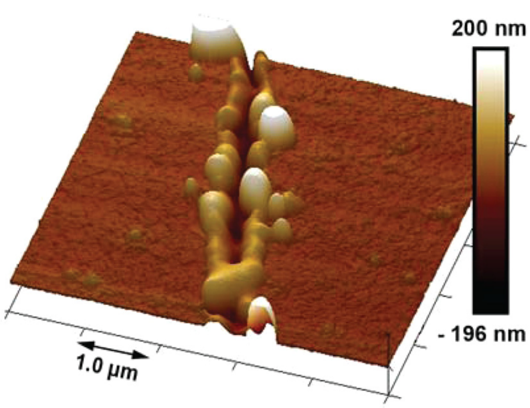

FIG. 4. A height profile plot obtained by AFM measurement of the 150 nm thick YBCO film in an area where the original slit extended its length by the avalanche activity.

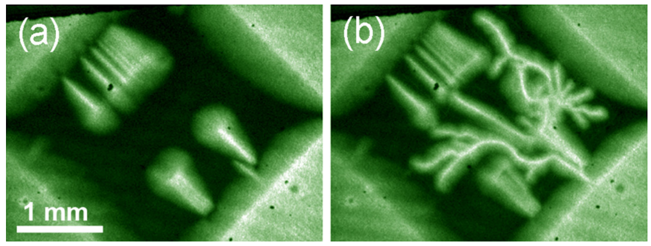

FIG. 5. A comparison of the flux penetration in the 250 nm YBCO film at 7 K, after sweeping the external field to 60 mT using ramping rates of 2400 T/s (a) and 3000 T/s (b), the latter producing a dendritic flux avalanche.

2400 T/s. The contour of the sample is clearly visible, as are the holes appearing as bright internal streaks. At this ramping rate there are no signs of avalanche behavior. However, when the experiment was repeated with ramping rate of 3000 T/s, a large dendritic flux structure was formed from the lower right sample edge, see Fig. 5(b). Thus, although this YBCO film is quite different from the first sample, it displays the same avalanche activity.

Comparing the results obtained for the two films, we find that in the 150 nm thick film the instability occurs up to 40 K at the fastest ramping rate, whereas the 250 nm film is unstable only below 20 K. In the thinner sample, we found that the avalanches repeatedly damaged the superconducting layer. This was not observed in the thicker film. These differences could be due to a number of factors, e.g., the difference in critical current density.[15] Other possible candidates are the differences in the type of substrate and its thermal contact to the film, as well as in the film thickness and microstructure.

Our MOI setup uses intense pulsed laser light as illumination. The incoming light is reflected from a mirror layer deposited on the Faraday rotating plate, and returns into the optical recording system without hitting the sample. However, parts of the laser spot extend outside the indicator plate, and is absorbed by the sapphire cold finger of the cryostat. To rule out that the pulsed laser in any way stimulates triggering of avalanches, tests were performed while completely blocking the beam during field ramping. No difference was found. Thus, the pulsed illumination does not perturb the stability of the superconductor.

In summary, we have made significant progress in demonstrating the generic character of dendritic flux avalanches in films of type-II superconductors. Using MOI and fast ramping of the applied magnetic field, avalanches taking the form of Lichtenberg figures[16] were repeatedly observed in different YBCO films. Unstable behavior was found over a range of temperatures and ramping rates. We find also that the avalanche events frequently cause permanent damage in the films, obviously a result of key importance when designing devices based on YBCO films. Moreover, it has been demonstrated that the patterning of the film plays an essential role, and in particular should narrow slits and other field-focusing shapes be avoided in the film structure.

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