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Inductive braking of thermomagnetic avalanches in superconducting films

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Abstract
The stabilizing effect of placing a normal metal layer adjacent to a thermomagnetically unstable superconducting film is investigated. By solving the coupled Maxwell and heat transfer equations numerically it is shown that the metal, via inductive braking of the rapidly propagating flux avalanches, strongly reduces their impact. It is found that with increasing thickness and/or electrical conductivity of the metal layer, the number of avalanche events increases, while the amount of flux involved in each avalanche is strongly reduced, resulting in an overall more stable thermomagnetic system. The numerical results provide detailed insight into the braking process, and explain both previous dc magnetometry measurements and new magneto-optical imaging results obtained for a superconducting NbN film coated with a Cu-layer.

Keywords: superconducting films, thermomagnetic instability, dendritic flux avalanches, metal coating

(Some figures may appear in colour only in the online journal)

1. Introduction

The smooth penetration of magnetic flux in type-II superconductor films subjected to a gradually increasing transverse applied magnetic field is occasionally interrupted when, suddenly, large amounts of flux rush in from a point along the edge. From there, the avalanche invades an area that grows into a dendritic structure. The residual flux patterns from such events have been observed in many materials, e.g., Pb [1, 2], Sn [3], Nb [4, 5], YBa₂Cu₃O₇₋ₓ [6, 7], MgB₂ [8–10], Nb₅Sn [11], YNi₂B₃C [12], NbN [13], and a-MoGe [14]. Theory suggests that these avalanches are nucleated by a thermomagnetic instability, where a fluctuation-induced increase in temperature facilitates uncontrolled penetration of magnetic flux [15, 16]. Recent numerical simulations have confirmed that in thin films this instability gives rise to ultra-fast thermomagnetic avalanches [17, 18], which can display a wide variety of complex morphologies [19].

For practical applications, the occurrence of such avalanches can represent dramatic perturbations, and it is therefore important to find ways to avoid them. Experimental works using magneto-optical imaging (MOI) have shown that by covering a superconducting film with a layer of normal metal, the avalanche activity can be suppressed [20–23]. Originally, this effect was attributed to the metal layer’s ability to absorb and redistribute the heat generated by the flux motion, and thus cause thermal shunting [20]. However, it was realized that another mechanism could also in principle be responsible for suppression of the avalanches, namely induction of eddy currents in the adjacent metal. The role of this electrodynamic process, analogous to conventional magnetic braking, was later investigated by measuring magnetization hysteresis loops for a superconducting film mounted near, but not in contact with, a metal plate [24]. The experiments showed unequivocally that an adjacent metal layer suppresses the avalanche activity and the effect increases as the metal–superconductor distance is reduced.
Although this way of improving the thermomagnetic stability of superconducting films is simple and powerful, essentially no theoretical work has so far provided physical insight into the braking effect. Actually, a recent theoretical study [25] found that electromagnetic braking is not expected to play a role in the nucleation of thermomagnetic avalanches. In this initial stage only the thermal shunting can prevent such a runaway from developing. It is first during the propagation stage of an avalanche that the electrodynamic interaction with the metal becomes important. This second stage is very hard to treat analytically, and theoretical works addressing the full process of inductive braking of thermomagnetic avalanches in superconductors are lacking.

In this work we performed numerical simulations to explore in detail the role of inductive braking of thermomagnetic avalanches in superconducting films with an adjacent metal layer. The calculations determine the electrodynamics of the combined system coupled with the production of heat in the course of an avalanche. To isolate the effect of inductive braking, the model ignores the thermal contact between the superconducting film and the metal layer. In the simulations we follow the protocol often used in MOI and magnetization experiments, where the sample is initially zero-field-cooled, before a transverse magnetic field is gradually applied. Differently from [25], we focus here on simulating the whole dynamical process of the flux penetration, starting from the initial zero-field-cooled state. Moreover, we here consider a square sample, allowing us to compare the simulation results with new MOI observations. We also calculate the magnetic moment of the sample as a function of applied field, explaining previous magnetization measurements. The paper is organized as follows. Section 2 describes the physical model and outlines our numerical simulation method. Section 3 presents the results of the simulations and discusses their interpretation, while section 4 reports MOI measurements made on a film of NbN partly coated with a thin Cu-layer, and finally a summary is given in section 5.

2. Model

Consider a superconducting film of thickness \(d_s\), and shaped as a square of lateral size \(2a\), see figure 1. Close to the superconductor, but not in thermal contact, is a normal metal layer of thickness \(d_m\). The superconductor is in thermal contact with the substrate, which is kept at constant temperature \(T_0\). Both the superconductor and metal layer are thin, with \(d_s, d_m \ll a\). In the simulations we assume that the current is uniformly distributed over the thickness of the normal layer. This is the case when the normal metal layer is thin compared to the characteristic skin depth, \(d_m \ll \lambda_{sk}\). With a typical duration of the thermomagnetic process of \(~\approx\) ns [7, 26], we estimate for a Cu film that \(\lambda_{sk} \sim 5 \mu m\), whereas in the present experiments described in section 4, \(d_m \approx 1 \mu m\).

In this limit, the superconductor and metal can be treated as an effective medium obeying the material relation [25, 27]
\[
\mathbf{J} = (d_s + d_m)\sigma \mathbf{E},
\]
where \(\mathbf{J}\) is the sheet current and \(\mathbf{E}\) is the electric field. The effective conductivity \(\sigma\) is defined as for a normal resistor and a superconductor connected in parallel,
\[
(d_s + d_m)\sigma = d_s\sigma_s + d_m\sigma_m.
\]

Here, \(\sigma_m = 1/\rho_m\) is the conductivity of the normal metal and \(\sigma_s\) is the conductivity of the superconductor. The latter is strongly nonlinear, and in the flux creep state the resistivity is commonly approximated by a power law [28],
\[
\frac{1}{\sigma_s} = \frac{1}{\sigma_{sn}} \begin{cases} (J/J_c)^{\eta-1}, & T < T_c \text{ and } J < J_c, \\ 1, & \text{otherwise}, \end{cases}
\]
where \(J_c = d_s J_c\) is the critical sheet current, \(\sigma_{sn}\) is the normal-state conductivity of the superconductor, and \(\eta \gg 1\) is the creep exponent. For simplicity, we use in (3) the total sheet current rather than the part flowing in the superconductor. This is a good approximation when \(d_m\sigma_{sn}E \ll J_c\), like during the regular flux penetration, and in the very initial stage of an avalanche. During the propagation stage of an avalanche the \(E\)-field is large, and our simplification leads to underestimation of the magnetic braking effect.

In the present calculations, and for the subsequent analysis, it is convenient to introduce a dimensionless braking parameter \(S\), defined as
\[
S = \frac{d_m\sigma_m}{d_s\sigma_{sn}}.
\]
For \(S \gg 1\), i.e., when the conductance of the metal is much larger than that of the superconductor in the normal state, one expects a large braking effect.

The magnetic flux dynamics is governed by the Maxwell equations
\[
\nabla \times \mathbf{E} = -\mathbf{B}, \quad \nabla \times \mathbf{H} = \mathbf{J} \delta(z), \quad \nabla \cdot \mathbf{B} = 0,
\]
with \(\mu_0\mathbf{H} = \mathbf{B}\) and \(\nabla \cdot \mathbf{J} = 0\). The transport of heat in the superconductor is described by the equation
\[
c \frac{\partial T}{\partial t} = \kappa \nabla^2 T - h (T - T_0)/d_s + \sigma_s E^2,
\]
where \(c\) is the specific heat and \(\kappa\) is the thermal conductivity of the superconductor. The last term represents the Joule heating, and the coefficient \(h\) characterizes the heat transfer to the substrate. Due to the thermal isolation between the

\[\text{Figure 1. Sketch of the system configuration. A square superconducting film of thickness } d_s \text{ and lateral size } 2a \text{ is covered by a normal metal layer of thickness } d_m. \text{ The superconductor is in thermal contact only with the substrate.} \]
superconductor and the metal, the thermal properties of the metal do not enter. The temperature dependence of the material parameters is taken as [29]

\[ J_c = J_{c0} (1 - T/T_c), \quad n = n_1 T_c/T, \] (7)

and

\[ \kappa = \kappa_0 (T/T_c)^3, \quad c = c_0 (T/T_c)^3, \quad h = h_0 (T/T_c)^3, \] (8)

where \( J_{c0}, n_1, \kappa_0, c_0 \) and \( h_0 \) are constants.

The coupled thermal and electromagnetic equations are solved starting from an initial state zero-field-cooled to \( T_0 \), and then increasing the applied magnetic field at a constant rate, \( \dot{H}_a \). The boundary conditions are complicated due to the nonlocal electrodynamics of films in transverse applied fields [28]. We handle this by a hybrid real-space—Fourier-space iterative method, as described in previous works [18, 30].

The following parameters, typical for films of MgB\(_2\) [18, 29], are used in the calculations: \( T_c = 39 \) K, \( \kappa_m = 1.4 \times 10^7 \) S m\(^{-1}\), \( \dot{J}_{c0} = J_{c0}/d_s = 1.39 \times 10^{11} \) A m\(^{-2}\), and \( n_1 = 40 \). The thermal parameters are chosen as \( c_0 = 35 \) kJ K\(^{-1}\) m\(^{-3}\), \( \kappa_0 = 160 \) W K\(^{-1}\) m\(^{-1}\), and \( h_0 = 10^5 \) W K\(^{-1}\) m\(^{-2}\). The sample dimensions are \( a = 2 \) mm and \( d_s = 225 \) nm. The applied magnetic field is ramped at the rate \( \mu_0 \dot{H}_a = 1.16 \) T s\(^{-1}\), and the substrate temperature is kept constant at \( T_0 = 0.15 T_c \). The system is discretized on a \( 512 \times 512 \) equidistant grid.

A random disorder is added in \( J_{c0} \) with average magnitude \( \langle \Delta J_{c0} \rangle / (J_{c0}) = 2\% \).

By introducing the braking parameter, \( S \), there is no need to specify the metal layer resistivity and thickness separately. Note, however, for reference, that in order to have \( S = 10, 100 \) and 1000, using a gold layer with \( \sigma_m = 7 \times 10^9 \) S m\(^{-1}\), its thickness must be \( d_m = 0.045, 0.45 \) and 4.5 \( \mu \)m, respectively.

3. Results and discussion

As the applied magnetic field starts to increase, flux gradually penetrates from the edges and builds up a critical Bean-state with constant \( J = J_c \). The perpendicular flux density, \( B_z \), has a peak at the edges and falls to zero at the steadily advancing penetration front. When the applied field reaches the threshold value \( \mu_0 H_a = 1.6 \) mT, a thermomagnetic instability is nucleated at a random location along the edge. If the superconductor is not covered with metal, the instability develops into an avalanche which propagates into the sample in a time span of approximately 100 ns. During this interval the avalanche delivers a large amount of flux while it grows into a dendritic pattern, which in its final form remains frozen after the self-driven event terminates. When the magnetic field increases further, similar avalanches are triggered at new edge positions and with irregular time intervals.

Figure 2 displays the flux density distribution when the applied field has reached \( \mu_0 H_a = 6.1 \) mT, and many avalanche events have already occurred. The four panels show the result for samples with braking parameters \( S = 0, 10, 100 \) and 1000. In the uncoated superconductor \((S = 0)\) one sees eight large dendritic structures, rooted along the edge. In the coated samples \((S > 0)\) there are signatures of even more numerous avalanche events, although the dendritic morphology is here much less developed. Note from the figure that for \( S = 10 \) and 100 the avalanches are clearly separated from each other, while at \( S = 1000 \) they are very dense, giving the impression of making only a moderate roughening of a critical state model flux front [31].

Qualitatively, one concludes from figure 2 that with increasing \( S \), the number of avalanche events increases, whereas their size, both in terms of the amount of flux entering and the area covered by each avalanche, is decreasing. This shows that the inductive braking does not prevent nucleation of avalanches, but rather prevents them from growing to full size. The effect becomes increasingly pronounced as the braking parameter \( S \) increases.

To better resolve the individual avalanches, figure 3 presents for all four samples the increment in flux density, \( \Delta B_z \), as the field increases from \( \mu_0 H_a = 5.7 \) to 6.1 mT, i.e., during a small interval preceding the state seen in figure 2. The upper left panel shows that in the uncoated superconductor one large avalanche took place starting from the edge on the right side of the sample. In the coated films, with \( S = 10, 100, \) and 1000, one finds that 7, 17, and 29 avalanches, respectively, occurred in the same field interval. Note that these events were the last to occur among all the numerous avalanches seen in the corresponding panels of figure 2.

Distinctly different from the footprints of the abrupt events are the traces of the regular penetration of flux in the respective samples. In the differential images in figure 3 one recognizes this as a diffuse ‘aura’ of enhanced brightness around each sample. This increase in flux density is due to (i) the flux entering the sample smoothly during the applied field interval and (ii) the piling up of field outside the edge.
The regular increment of flux inside the superconductor is expected to follow the advancement of a critical state, which for a thin sample in a perpendicular field moves inwards with a curved flux front [31]. Interestingly, in the present samples such curvature is not seen, except near corners. For example, in the uncoated film seen in figure 3, the expected front shape is largely replaced by straight line segments. These lines coincide with the sample edge. This striking feature can be understood as a result of the preceding avalanche activity. Whenever an avalanche takes place, it drains the edge of piled-up external field, as known from both previous experiments and modeling [32, 33]. After that it takes a sizable increase in $\mu_0 H_a$ to restore the edge field. The advancement of the flux front comes to a halt for some period, during which the only change is an increase in $B_z$ around the edge, exactly as our simulations are showing. In the coated samples the inductive braking reduces the size of the avalanches, and hence also the draining of the edge field. Therefore, it takes less increment in the applied field to nucleate new avalanches. As a consequence, the number of avalanche events is expected to increase with increase of the braking parameter $S$. This effect is clearly demonstrated by the present results.

It is interesting to compare the simulated magneto-optical images with the field dependence of the magnetic moment in these samples. The moment is given by [28], $m = \frac{1}{2} \varepsilon \cdot J \times \mathbf{r} \, d\mathbf{x} \, d\mathbf{y}$, and figure 4 shows $m$ plotted in units of $m_0 = a^3 J_c 0$ as a function of increasing applied field. At low fields all the curves coincide and behave smoothly, in full accordance with the critical state model. On reaching the threshold field near $\mu_0 H_a = 3.5$ mT, the moment of the uncoated superconductor shows a pronounced drop, which is the signature of substantial redistribution in shielding currents caused by a large flux avalanche. As the applied field continues to increase to 6.1 mT, there are in total eight such discontinuities in the $m$–$H_a$ curve, one for each dendritic structure seen in the top-left panel with $S = 0$.

For the samples with finite $S$ the $m$–$H_a$ curves continue smoothly to higher magnetic moments than in the uncoated case. However, the smoothness is only apparent. Closer inspection reveals that the curves actually contain numerous minor jumps, all directly related to the small avalanches seen in figure 2. In the field interval from 3.5 to 6.1 mT, there are in total eight, 36, 59 and 103 avalanches taking place in the samples with $S = 0, 10, 100$ and 1000, respectively. At the same time, these four samples demonstrate that the average size of the flux jumps decreases substantially with increase of the braking parameter. We find that the average jump sizes measured in units of $10^{-3} m_0$ are 42, 3.1, 1.1 and 0.27 for $S = 0, 10, 100$ and 1000, respectively. These results are consistent with previous magnetization measurements [21], where metal layers of increasing thickness gave reduction in the size of the flux jumps, and increase in the magnitude of the magnetic moment.

To shed more light on the processes involved in the avalanche activity, figure 5 presents the magnetic moment and maximum local temperature, $T_{\text{max}}$, in the sample as functions of increasing $\mu_0 H_a$. Only an interval of 0.3 mT near the onset of the unstable behavior is included, and graphs for $S = 10, 100$, and 1000 are plotted. Most importantly, this figure shows that every spike in the temperature coincides with a jump in the magnetic moment, thus revealing the thermomagnetic nature of the avalanche events. The increase in $T_{\text{max}}$ is a significant fraction of $T_c$ of the superconductor. Averaged over all avalanche events, we find that $(T_{\text{max}})/T_c = 0.6, 0.47$ and 0.32 for $S = 10, 100$ and 1000, respectively, whereas in the uncoated superconductor $(T_{\text{max}}) = 1.61 T_c$. In other words, the samples with finite $S$ remain superconducting during the whole duration of the avalanche events, whereas this is not
Figure 5. The magnetic moment and the sample’s maximum temperature, $T_{\text{max}}$, for $S = 10$, 100 and 100, in the vicinity of the threshold magnetic field. The magnetic moment is plotted as the deviation, $\Delta m$, from its value at $\mu_0 H_a = 3.4$ mT.

The case for an uncoated superconducting film. Therefore, we identify a second consequence of the metal layer, namely that it significantly reduces the heating of the superconductor during avalanches, even if there is no direct thermal contact with the metal.

From the numerical simulations it is clear that coating a superconducting film with a metal layer does not in general prevent flux avalanches from taking place. The effect of the metal is largely determined by the braking parameter, $S$, which for given materials is the ratio between the products of conductivity and the thickness of the metal layer and the superconducting film. For increasing metal thickness, the jumps in the magnetic moment decrease in amplitude and fall below the resolution of conventional magnetometry.

4. Experiments

To observe flux avalanches in coated superconducting films, we used the MOI technique, where a ferrite-garnet-plate [34] served as a Faraday rotation sensor in a setup described elsewhere [35]. The superconductor was a 170 nm thick NbN film shaped as a 1.5 mm wide rectangle of length 3 mm. One half of the area was covered with a 0.9 $\mu$m thick layer of copper, while the other half was left uncoated. The sample was first zero-field-cooled to 3.7 K, and then an increasing transverse magnetic field was applied.

Figure 6(a) presents the magnetic flux distribution when the field reached $\mu_0 H_a = 3.3$ mT. The brightness in the magneto-optical image represents here the magnitude of the flux density. The Cu layer covers the left half of the sample area. At this field a number of large dendritic avalanches have penetrated the bare superconductor, whereas none have entered the part coated by metal. From the image one sees that several flux dendrites have reached the boundary between coated and uncoated superconductor, but their propagation stops at the interface. Thus, the metal layer is here fully suppressing the avalanche activity. Note, however, that the coated part of the sample shows some flux penetration from the three outer boundaries, most pronounced from the upper edge. This flux pattern is rather fragmented due to imperfections in the NbN film, a feature not uncommon to observe with MOI of superconducting materials [31]. In such cases it is hard to judge from one single image whether flux has entered in a regular way or by avalanches.

To separate avalanches from the regular penetration, we used differential imaging. Panel (b) of figure 6 displays an image showing the flux development as $\mu_0 H_a$ is increased from 5.3 to 5.5 mT. Here, the brightness represents the change in flux density during the field interval, with black indicating no change. Evidently, one large avalanche was triggered at
On moving away from the right corners the draining effect decays, and increasing the applied field causes here regular flux penetration. This behavior is evident in the experimental image, where flux penetrates increasingly deeper as one approaches the coated area. During the present field interval no flux avalanche occurred the uncoated part of the sample.

In the coated part of the sample, the behavior is qualitatively different. Figure 7(b) shows in the left half several protrusions of flux entering perpendicular to the edge, the most pronounced one marked by an arrow. By the linear morphology and small size of these avalanches, they show a striking similarity with the numerically obtained avalanches in the presence of substantial magnetic braking. Based on the panels in figure 3 the morphology of the experimental protrusions compares best with the case $S = 100$.

The braking parameter of the experimental sample was determined by measuring the ratio of resistance in the NbN film and the Cu-layer at room temperature. From this the value $S = 120$ was found, again showing large consistency between the experiment and the theoretical model.

5. Summary

The critical state in superconducting films can be destroyed by the abrupt appearance of thermomagnetic avalanches. In this work we investigated the suppression of such avalanches by placing next to the superconductor a normal metal layer where rapid changes in magnetic flux density induce eddy currents and cause magnetic braking. By introducing the braking parameter, $S$, we could systematically study the braking effect under various conditions. The equations describing the theoretical model were solved numerically, and to isolate the braking effect the two layers had no thermal contact.

The results show that inductive braking does not prevent the nucleation of the avalanches. However, increasing $S$ strongly reduces the impact of avalanches. In particular, samples with large $S$ remain superconducting during the whole duration of avalanche events. In general, this is not the case for an uncoated superconducting film. Thus, an indirect consequence of a metal layer located close to (but not in contact with) a superconductor is to reduce the heat production and thereby significantly increase the stability.

A magneto-optical imaging experiment performed on a partly metal-coated superconducting film confirmed the existence of regions with enhanced flux traffic under the film. The flux penetration patterns seen with MOI and those obtained by the numerical simulations are fully consistent, and show in detail how coating a superconducting film with a metal layer qualitatively alters the flux penetration behavior. All main aspects observed for both the gradual flux penetration and the ultra-fast thermomagnetic avalanche activity could be explained within the present model.

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