The role of demagnetizing factors in the occurrence of vortex avalanches in Nb thin films

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Abstract. Under specific circumstances, magnetic flux penetrates into superconducting thin films as dendritic flux jumps. The phenomenon has a thermomagnetic origin, where flux motion generates heat that suppresses flux pinning and facilitates further flux motion. We have studied the thickness influence on the flux stability for very thin Nb films, 20, 40, 60, and 80 nm, through dc-magnetometry. The thicker the film; the higher is the threshold field where instabilities first take place. Due to the demagnetizing factor in a perpendicular geometry, the effective magnetic field at the border of the film is largely amplified. For thin specimens, a linear dependence between the threshold field and the thickness is expected and has been actually observed. When normalized by the sample aspect ratio, the effective threshold magnetic field is nearly the same for all specimens studied.

1. Introduction
Just after the discovery of superconductivity [1], its great potential for applications was soon realized [2]. However, this was only rendered [3] with the advent of superconductors that admit penetration of magnetic flux, in order to decrease their free energy – as was comprehended by Abrikosov in his anthological paper [4], where the classification of this second group of superconductors was first mentioned. During almost one hundred years of research, superconductivity was discovered in several elements and compounds. Spanning from conventional low temperature superconductors (LTS); to high temperature superconductors (HTS); through the intermetallic MgB\textsubscript{2} [5]; and the recently discovered FeAs compounds [6], all type II materials have an inherent problem, i.e., the vortex motion, which can depress to zero the bulk critical current density. Nevertheless, real materials have defects and inhomogeneities, which act as pinning centers for vortices. Emerging from this scenario, other features have been observed in these materials, mainly in HTS, which have unveiled quite intricate phase diagrams [7]. Hence, the knowledge of Vortex Matter properties in type II superconductors is highly desirable, most especially for the appropriate use of these materials for applications.

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1.1. Flux avalanches
Further than just movement, vortices can show an undesirable kind of behavior, called a flux jump [8], which means that a large amount of flux moves abruptly into the sample. This has been ordinarily detected as sharp variations on curves of the isothermal magnetization versus applied field. In the frame of a critical state model, the current and/or magnetization current densities adjust themselves to maximum amplitude, the so-called “critical current density”. Under these circumstances, the Lorentz \( F_L \) and the pinning \( F_p \) forces, along with the force due to the “magnetic pressure” \( F_m \), balance each other, creating a metastable equilibrium. When the field is slightly increased, \( F_p \) holds vortices in place until the sum \( F_L + F_m \) overcomes it. As a result, vortices – or bundles of them – jump away from their pinning centers and move. The flux distribution can be catastrophic or not, depending on the relative importance of magnetic and thermal diffusion [9]. When the magnetic diffusion is slower than thermal, heat developed in a certain region spreads away in a smooth dynamic process. On the other hand, when magnetic diffusion is faster than thermal, the system will not have enough time to redistribute the heat generated by vortex motion and flux jumps take place under an essentially adiabatic condition. A good explanation for catastrophic avalanches of vortices due to thermomagnetic instabilities, has been discussed by Mints & Brandt [10]. In short, vortex motion generates heat which suppresses flux pinning and facilitates further vortex motion.

1.2. Avalanches in superconducting films
In particular, flux jumps in films exhibit a characteristic dendritic form, as has been largely observed by magneto-optical imaging (MOI) experiments. Different specimens in the perpendicular geometry have shown this fingering abrupt penetration of magnetic flux. Among them are LTS as Nb [11, 12], Nb₃Sn [13] and NbN [14]; HTS as YBCO [15]; and MgB₂ [16]. A close parity was observed between dendritic flux penetration images and jumps on the isothermal dc-magnetization (DCM) measurements for the MgB₂ case [17], which also qualifies this latter technique as an efficient tool to detect flux instabilities as they occur in films. Thus, one can make use of DCM to map the region of “dendritic-instabilities” on the field-temperature (HT) phase diagram, as previously done for MgB₂ [17] films.

Some models have dealt with specific conditions which lead to the appearance of thermomagnetic instabilities in the form of dendrites [18-21]. Among them, Denisov et al. [21] have found that thin films are most unstable than bulk superconductors, and a linear dependence between the threshold field for the first instability and the film thickness was predicted. In this work we have carried out experiments with Nb films of different thicknesses, which allowed verifying this linear dependence that emerges from their model. Other features of the models have been demonstrated [22], which have shown good agreement between both theory and experiments.

2. Material and methods
The specimens employed in this work are very thin Nb films, with thicknesses ranging from 20 nm to 80 nm. All samples have the same transverse area, 3x3 mm², and were deposited on (100) Si substrates. The growth technique was e-beam evaporation, where the thickness was monitored using a quartz crystal, which provides a resolution up to one nanometer. The films were grown in a UHV system with a base pressure better than 10⁻⁹ mbar. The evaporation pressure was better than 10⁻⁶ mbar. Magnetic measurements were performed in a Quantum Design PPMS-6000 magnetometer. Before running experiments, the remnant field of the superconducting magnet was appropriately reduced to a value of the order of Earth’s field. Several magnetization isothermals, \( m(H) \), were performed at different temperatures after a zero field cooled procedure.
3. Results and discussions

The linear dependence, as a function of the film thickness, of the threshold field for the first jump, is shown in the main panel of figure 1 for three temperatures. The method used to select the values from $m(H)$ curves was discussed in a previous publication [23], where the region of instabilities in a HT diagram was mapped for a thicker Nb film. Below the dashed line, inserted as a guide to eye, no flux jumps occur. Above this limit, thermomagnetic instabilities take place, as detected through jumps on the $m(H)$ curve. As one can see, the results are in excellent agreement with the linear theoretical prediction done by Denisov et al. [21]. The absence of a linear coefficient gives a supplementary validation for the comparison, since it is reasonable to expect a null limit for the threshold field as the thickness goes to zero.

At the imminence of the first flux avalanche, only an outlying frame of the sample is filled with flux [16]. Hence, in these circumstances the demagnetization factor correction is relevant in order to determine the effective magnetic field, $H_{\text{eff}}$, at the sample outer border. For a superconducting film submitted to a field slightly higher than its $H_{\text{c1}}$ and considering an oblate ellipsoid of revolution [24], i.e., flattened in the $x$, $y$-plane, with $c << a$, where $c$ is the thickness and $a$ the lateral dimension, the effective field assumes the form: $H_{\text{eff}} \sim (2a/\pi c)H$. Since the superconductor is thin, its edge is subjected to an extremely high field. Values of the effective field, obtained using the above expression, are shown on the inset of figure 1. Regardless of the thickness, there is a nearly constant threshold $H_{\text{eff}}$, revealing that the avalanches occur when the field reaches this value.

![Figure 1. Linear dependence of the threshold field as a function of the thickness for Nb thin films. The inset shows a nearly constant value for the effective magnetic field. The straight lines are guides to the eye.](image-url)

Another compelling evidence that $H_{\text{eff}}$ is the field that has to be reached to trigger the first avalanche, emerges from results published by Denisov et al. [22]. They have measured, using MOI, a set of MgB$_2$ stripe-shaped samples with 3 mm length, 300 nm thickness, and widths ranging from 0.2 mm to 1.6 mm. When the above referred expression for $H_{\text{eff}}$ is applied to the threshold field, a constant value is also found.
Thermomagnetic avalanches in films is an intricate issue. The existing models [18-21] deal with several parameters to describe the phenomenon, which certainly are significant in the occurrence of flux instabilities. However, the evidences compiled in this work show that the aspect ratio (width/thickness) has a particularly important influence on the occurrence of flux avalanches, which is correlated to the effective magnetic field at the outer border of the sample.

4. Conclusion

We have shown the linear dependence of the threshold field for the first jump, as a function of the film thickness, which was constructed from isothermal dc-magnetization experiments. The thicker the film, the higher is the threshold field where instabilities first take place. The linear behavior predicted by a theoretical model is actually observed. When corrected by the sample aspect ratio, stemming from a non-negligible influence of the demagnetization factor on the local field at the border of a thin film, the effective magnetic field is enormously amplified. The thickness-independence of the value of the effective threshold field suggests that the occurrence of flux avalanches in thin films is a characteristic of the composed system - superconducting film and substrate - regardless of the specific dimensions of the sample. Crucial roles are played by thermal and magnetic diffusion, as well as by pinning forces and critical currents, in the process of triggering flux avalanches into the superconducting film.

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