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Nanosecond magneto-optic study of a new instability in thin $YBa_2Cu_3O_{7-x}$ films

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We have investigated the dynamics of flux penetration into thin superconducting $YBa_2Cu_3O_{7-x}$ films using a magneto-optic technique with nanosecond time resolution. For films carrying large shielding currents an instability in the magnetic flux distribution is discovered, which can be triggered by a local perturbation, e.g., by a focused laser pulse. The instability develops in the form of fine ramified flux structures, with a propagation speed of the flux front on the order of 5×10^4 m/s.

Magnetic flux penetration into a superconductor has many practical implications, e.g., for the performance of superconducting coils or the shielding of magnetic fields. Related is the fact that a superconducting sample carrying the critical current density j_c is in a state close to being unstable: Even a small local perturbation may hence rapidly quench the superconducting state over a major portion of the sample and can in this way give rise to an "explosive" penetration of flux into formerly well-shielded regions. We report here the first observations of the development of such an instability in thin HTSC films exposed to an external magnetic field in the 0.1 T range. It is found that under certain circumstances the flux distribution in the sample evolves into delicate ramified structures. The magnetic instability can occur as a spontaneous event, but can also be nucleated by heating the sample locally. Owing to the pronounced structure in the magnetic flux distribution, this phenomenon is not only relevant for the magnetic behavior of superconductors, but is of interest also from the general point of view of pattern formation in unstable systems.

Our specimens were thin epitactic $YBa_2Cu_3O_{7-x}$ films with an area of 1×1 cm^2 and a thickness of several hundred nm. The external field B_{ext} was applied perpendicular to the film plane. Starting from a sample cooled in zero field below the critical temperature T_c, a gradual increase in B_{ext} leads to the induction of currents which shield the central part of the sample and thus keep it in the so-called "Meissner state." Due to the small film thickness and the film geometry (characterized by a large demagnetization factor) the current densities are then of the order of j_c over large portions of the film, extending even into the magnetically shielded area.

A sketch of our experimental setup is shown in Fig. 1. In order to visualize the magnetic field distribution an EuS film was used as the magneto-optically active element, as described by Kirchner.[1] The EuS was evaporated onto a glass plate and covered by a highly reflecting aluminum film. This sandwich was then placed directly in front of the HTSC sample and immersed in an optical ^{4}He cryostat, equipped with a superconducting magnet. Due to the large Faraday effect in EuS at low temperature, light incident onto the detector film and reflected by the aluminum is rotated in its plane of polarization in proportion to the local magnetic field. A fraction of it can therefore pass a crossed polarizer, thus yielding an image of the magnetic field distribution at the sample surface with a spatial resolution of a few μm. Using a 1 mW He-Ne laser ($\lambda=633$ nm) as a light source, the intensity is sufficiently high that magneto-optic pictures can be recorded with a sensitive video camera with a temporal resolution of some 20 ms (for a better time resolution, see below).

This technique has proven as very efficient for characterizing samples with respect to the pinning of magnetic flux, the critical current density, sample inhomogeneities, influence of sample geometry, etc.[2-6] For HTSC films of square shape it was found, e.g., that the field preferentially penetrates from the edges (and not from the corners) of the sample, thus leaving a well-shielded region essentially centered along the sample diagonals.[2] For an epitactic 1×1

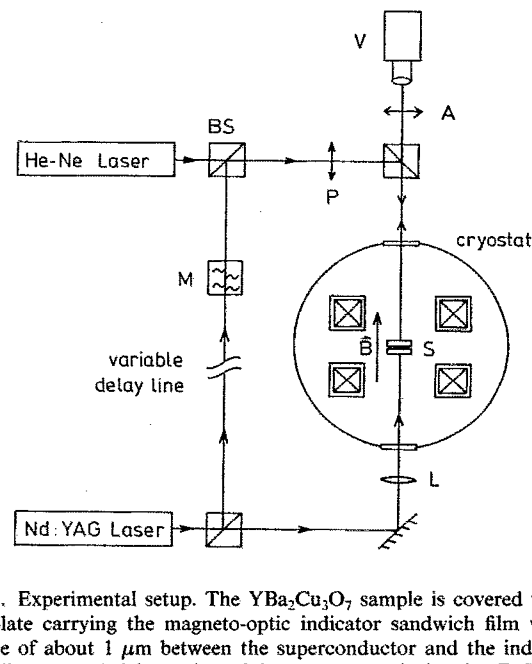

FIG. 1. Experimental setup. The $YBa_2Cu_3O_7$ sample is covered with a glass plate carrying the magneto-optic indicator sandwich film with a distance of about 1 μm between the superconductor and the indicator. The indicator sandwich consists of the magneto-optical active EuS layer, which is covered with an aluminum film to increase the reflectance. The direction of the magnetic field B is perpendicular to the sample plane. BS: beam splitter; S: sample; P: polarizer, A: analyzer; V: video camera; L: lens; M: methanol cell for stimulated Raman scattering. The *variable* delay line is used for magneto-optic recording with high temporal resolution.

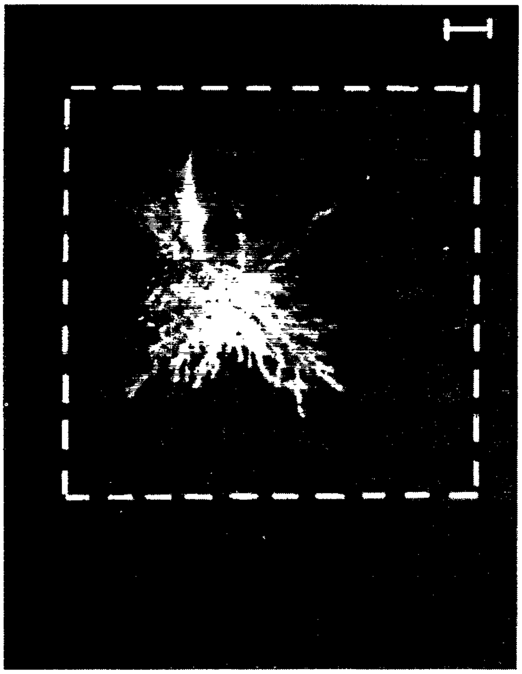

FIG. 2. Flux pattern in an epitactic thin $YBa_2Cu_3O_{7-x}$ film (1×1 cm^2, thickness 150 nm), resulting from a spontaneous instability in an external magnetic field of 0.1 T at a temperature of 2 K (after Ref. 3). The background distribution presented in the sample before the occurrence of the instability is subtracted by means of image processing. The dashed lines mark the edges of the sample, the scale bar represents 1 mm.

cm^2 YBCO film with a critical current density of 2×10^7 A/cm^2 at 2 K this shielded region typically amounts to several 10%s of the sample area in an applied field of 0.1 T. It was under these conditions that on one occasion a *spontaneous* instability of the magnetic flux distribution was observed, which gave rise to a momentary penetration of the field into the formerly shielded part of the film.[3] The resulting flux pattern is depicted in Fig. 2 (the flux already present in the sample before the occurrence of the instability is subtracted by image processing in this case). Strikingly the field penetrated not in a homogeneous way, but rather in the form of fine "dendritic" branches.

We have tried to generate this instability deliberately by a perturbation of the Meissner state, focusing a short frequency-doubled Nd:YAG laser pulse (pulse width 7 ns, $\lambda=532$ nm) onto a small spot of the sample, thereby locally heating it above the critical temperature. The finite electrical resistivity in this area then leads to dissipation and a redistribution of the shielding currents. The results presented here demonstrate that indeed the instability can be nucleated in this way, which manifests itself in an avalanchelike propagation of flux into the originally shielded area.

An example of the laser-induced instability generated in this way is given in Fig. 3. Shown are two video pictures taken immediately before and after the laser shot. As in the spontaneous event mentioned above, the flux penetrates into the Meissner region in the form of fine ramified structures, which in their shapes are reminiscent of crystal dendrites or "Lichtenberg patterns" observed upon dielectric

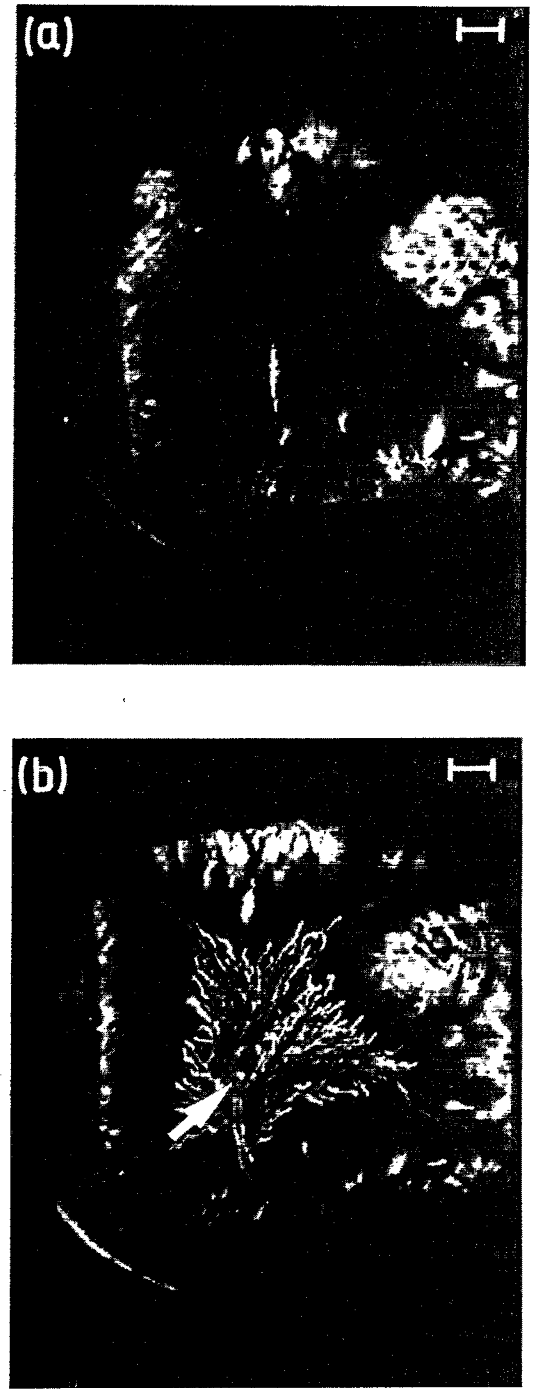

FIG. 3. Laser-induced instability in an $YBa_2Cu_3O_{7-x}$ film (1×1 cm^2, thickness 300 nm). (a) Field distribution in an external field of 60 mT. Flux has entered the sample across the edges, in this case somewhat irregularly due to inhomogeneities of the sample. The large dark area extending in the region around the sample diagonals is in the Meissner state. (b) Flux distribution after locally heating the sample with a short focused laser pulse. The position of the laser spot is marked by an arrow. Both figures are taken without background subtraction. The scale bar represents 1 mm.

breakdown in insulators. This distribution, once formed, turns out to be stable on a time scale of hours.

An obvious question is how fast this instability develops. In the video recording it appeared "instantaneously" from one video frame to the next, setting a first upper limit of 20 ms for the time of formation. In the course of the experiments it turned out that the temporal resolution had to be improved by six orders of magnitude up to the nanosecond level before the spreading of the flux branches could be recorded (see Fig. 1). In order to achieve such a high resolution, the Nd:YAG pulse was split into two parts, one being used to nucleate the instability as before, whereas the other illuminated the whole film for a snapshot recording several tens of nanoseconds later (the He-Ne laser was switched off during this recording). For that purpose, the illuminating pulse was passed through a variable delay line and a cell filled with methanol, where by means of stimulated Raman scattering its wavelength was shifted to 635 nm, close to that of the He-Ne laser for which the magneto-optic setup had been optimized. A related two-pulse technique, yet without a spatial resolution of the flux distribution, has recently been applied for investigating nonequilibrium flux dynamics in a conventional type I superconductor.[7]

As our measurements revealed, the flux branches propagate into the Meissner region at a speed of about 5×10^4 m/s.[8] This value is an order of magnitude larger than the velocity of sound,[9] ruling out an explanation of this phenomenon in terms of a pure thermal instability mediated by phonons; rather it has to be of electrodynamic origin. It should be pointed out that the growth of a flux branch comes to a stop as soon as it gets close to the edge of the Meissner region. So far a formation of branches where some magnetic flux is already present in the form of quantized vortices (the "Shubnikov phase") has *not* been observed.

An understanding of the details of the instability reported here has to await a treatment based on Maxwell's and London's equations, including the thermal properties of the sample. It appears interesting to consider the appearance of the dendritic structure in the general context of pattern formation in systems far from equilibrium. Apart from these theoretical aspects the phenomenon also has consequences for the application of thin superconducting films in high magnetic fields, because—as experiments have shown[3]—the instability not only affects the flux distribution, but may even cause permanent damage of the sample.

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