Nonconventional short-time dc magnetometer for superconducting films

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A nonconventional technique for the measurement of magnetic relaxation in superconducting films at short times ($\sim 10^{-5}$ s) is described. This technique combines the application of a pulsed magnetic field and a synchronized high-energy pulsed laser. Remanent magnetic relaxation in (Y;Gd)$Ba_2Cu_3O_{7-\delta}$ thin films is reported over five decades time at reduced temperatures above 0.8. © *1998 American Institute of Physics.* [S0034-6748(98)00701-1]

I. INTRODUCTION

Thermally activated flux creep in high-temperature superconductors is one of the most intensively studied properties of the vortex state, which, once understood, may be the basis for a new variety of superconducting devices. Magnetic relaxation measurements yield essential information about the underlying physics of vortex behavior.[1] A detailed description requires monitoring magnetization over the widest possible time window. In conventional techniques, the response and initial data-acquisition times are both of the order of ten seconds and, therefore, the study of magnetic relaxation usually implies time consuming experiments that need long-time thermal and magnetic-field stability.[1] Moreover, the strong magnetic relaxation at intermediate and high temperatures,[1,2] where most applications are desirable, together with the slow time response of conventional techniques, have led in the past to the study of flux dynamics far from the critical state, where the metastable current density j is small compared with the critical current density j_c.

In an effort to reduce the experimental time scale, different techniques have been developed as, for example, a custom made pulse magnetometer for bulk ceramic samples[3] and a custom made dc SQUID magnetometer for single crystals,[4] where the lower limit of the accessible time window has been reduced down to 10^{-4} and 10^{-2} s, respectively.

Recently, short flux motion signals ($\sim$ ns) across voltage leads in thin $YBa_2Cu_3O_{7-\delta}$ films following the absorption of short pulses of laser radiation were reported.[5] These experiments form the basis for new methods of studying vortex dynamics at the microsecond time scale and below.[6]

In this article we present a nonconventional technique that combines a pulsed magnetic field and a synchronized pulsed laser to measure magnetization in superconducting films at times of the order of 10^{-5} s.

Results of remanent magnetization relaxation in (Y;Gd)$Ba_2Cu_3O_{7-\delta}$ films over a five decade time window are presented.

II. EXPERIMENT

The experiment is performed as follows. The critical state is induced by applying and removing the magnetic field at a high rate ($\dot{H} = \pm 1000$ T/s) to reduce the uncertainty of the time origin of the relaxation process. After a controlled delay t_d, a short laser pulse (~ 10 ns) is triggered producing a rapid optical heating of the sample to the normal state. The unstable distribution of vortices at t_d completely relaxes, and the resulting flux variation is detected with a pick-up coil. The time integrated signal thus obtained is proportional to the magnetization at t_d, $M(t_d)$. The experiment is repeated at different t_d's to study the time dependence of the remanent magnetization. The very short measuring and starting times of this technique ($\sim 10^{-6}$ and $\sim 10^{-5}$ s) allow covering five decades in time window in a few minutes when measuring magnetic relaxation.

This technique also opens the possibility for other short time magnetization experiments as it avoids the instrumental integration times that usually restrict measurements in most conventional magnetometers.

Figure 1 shows the experimental array. A copper-saphire sample support is attached to the cold finger of a liquid-nitrogen cryostat equipped with an optical window. The coil system includes a 38-turn primary coil and a coaxial 75-turn secondary coil of 1.6 and 1.8 cm diameter, respectively. The sample is glued to the saphire at the center of this coil system as shown in the inset of Fig. 1. Both primary and secondary coils are thermally decoupled from the sample. They are attached independently to the cold finger of the cryostat so they are kept at fixed temperature. The primary produces a 25 Oe/A magnetic field perpendicular to the film surface with a radial variation of about 5% over the sample. The primary and secondary were wound with 100 and 60 μm diameter copper wire, respectively. Single-layer coils were used to minimize the stray capacitance of both primary and secondary coils.

A Q-switched Nd:YAG laser furnished with a second-harmonic generating crystal provides 10 ns FWHM pulses at 532 nm. The spatial profile of the pulse is Gaussian providing a uniform illumination of the sample. The laser com-

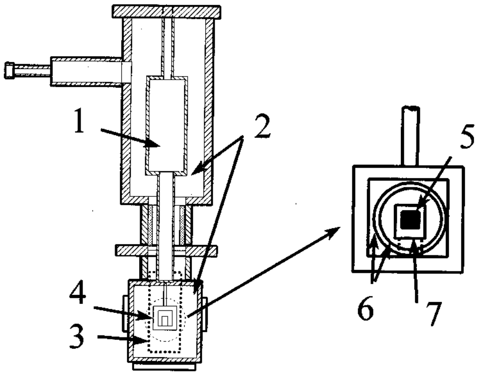

FIG. 1. Schematic diagram for the cryostat: (1) liquid nitrogen, (2) vacuum jacket, (3) radiation shield, (4) sample support. The inset shows the sample support: (5) sample, (6) primary and secondary coils, (7) sapphire.

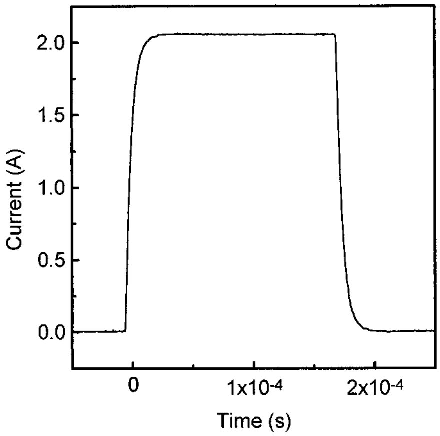

FIG. 3. A 150 μs, 2 A current pulse in the primary coil.

pletely illuminates the film with normal incidence and a fluence of 2 mJ/cm^2. Calculations of the heating in a 300 nm YBCO film following the absorption of the laser radiation[5] shows that a 20 K temperature rise in the whole film occurs in approximately 1 μs establishing a measuring time of the same order of magnitude or below. This temperature rise is enough to drive the sample above T_c if the initial temperature T is higher than $0.8T_c$.

A trigger device synchronizes the buildup of the critical state and the heating of the sample. As displayed in Fig. 2, the falling edge of a 0.7 Hz square wave pulse oscillator activates two independent variable delay generators that fix t_d. The first one (0–5 ms) controls a variable width pulse generator (0–0.5 ms) that feeds a pulsed voltage source connected to the primary coil. The second one (0–1.2 s) triggers the pulsed laser.

It was verified that, at this repetition rate (0.7 Hz), the sample had enough time to cool down to the initial state between laser shots.

The current (magnetic-field) decay of the primary coil has been studied by measuring the voltage across a 0.1 Ω series resistor (Fig. 3). The response time τ is about 5 μs and there are no current oscillations when the voltage supply is switched on/off.

A 100 MHz 200 MS/s Le-Croy LS-140 oscilloscope and a 300 MHz bandwidth SR445 SRS preamplifier are used to acquire the transient pick-up coil signal. A 10 Ω bypass resistor is connected in parallel to the pick-up coil in order to avoid oscillations.

Figure 4 shows typical pick-up coil signals as a function of time for different t_d, which have been plotted with a common time origin for clarity. The signal time dependence is in accordance with the response of an L-R circuit to the delta voltage excitation of the laser heating induced flux motion. The L-R circuit is analogous to a ballistic galvanometer. Numerical integration of each curve provides $M(t_d)$.

As explained below, the experimental setup presented here can also be used to measure magnetization as a function of magnetic field in zero field cooled samples, just by heating the sample at a fixed time t_d following the applied magnetic-field rising edge without removing the field. It could also be used to measure the spatial variation of the local induction B as a function of time by means of an array of coils (or contacts) distributed over the sample.

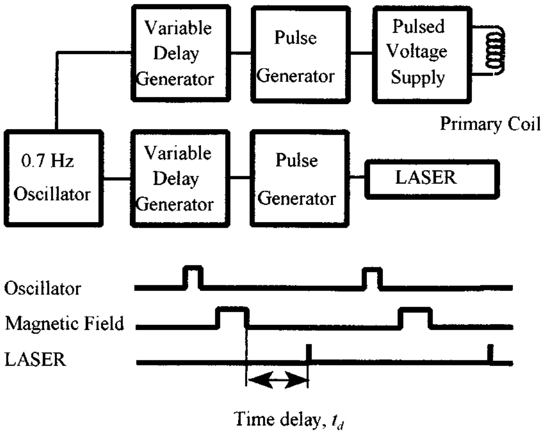

FIG. 2. Control electronics to synchronize the application of the pulsed magnetic field and the laser pulse. Schematic temporal sequence for remanent magnetization measurements.

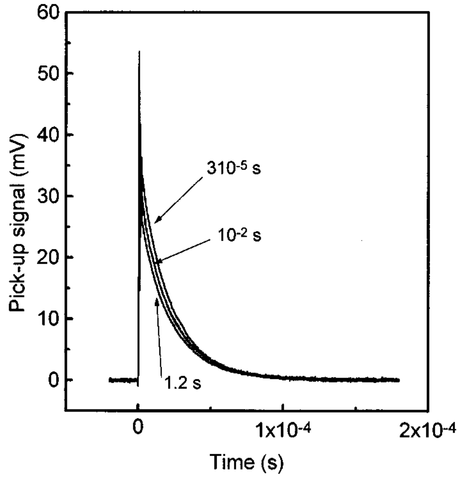

FIG. 4. Measured pick-up signals at the indicated delay times t_d for an YBCO film at 84 K.

III. VORTEX DYNAMICS AT THE MICROSECOND TIME SCALE

With this technique, we investigated the low field virgin magnetization and the magnetic relaxation of two c-axis oriented epitaxial $R\mathrm{Ba}_2\mathrm{Cu}_3\mathrm{O}_{7-\delta}$ films for magnetic field H_a perpendicular to the CuO_2 layers: a $0.5\times0.7\ \mathrm{cm}^2$ 300-nm-thick $\mathrm{YBa}_2\mathrm{Cu}_3\mathrm{O}_{7-\delta}$ film deposited on SrTiO by laser ablation of bulk targets;[7] and a $0.5\times0.5\ \mathrm{cm}^2$ film 300-nm-thick $\mathrm{GdBa}_2\mathrm{Cu}_3\mathrm{O}_{7-\delta}$ deposited on (100) MgO by magnetron dc sputtering.[8] Both films were characterized by ac susceptibility measurements, showing sharp transitions at T_c equal to 90.3 and 88.5 K, respectively.

A. Virgin magnetic moment

We first investigated the virgin magnetic moment of the samples as a function of the applied magnetic field at fixed temperature. To do so, the sample was heated at $t_d = 100\ \mu\mathrm{s}$ following the magnetic field rising edge without removing the field. A second laser pulse was shot after the field was removed to leave the film in a clean state ($B=0$) before performing the next measurement (at a higher magnetic field).

We analyzed our data in the framework of the modified Bean's model for a circular film; to our best knowledge, there is no published theory that provides an exact solution for our geometry.

According to Ref. 9, the virgin magnetic moment of a circular film in a transverse magnetic field can be written as

$$M=-\frac{8R^3}{3}H_aS(x),$$

$$S(x)=\frac{1}{2x}\left[\arccos\left(\frac{1}{\cosh x}\right)+\frac{\sinh x}{\cosh^2 x}\right], \tag{1}$$

where $x=H_a/H_d(T)$, $H_d(T)=j_c(T)d/2$ is a characteristic field, R the film radius, and d its thickness.

This expression was used to fit the normalized time-integrated pick-up coil signal with $H_d(T)$ as the only fitting parameter. The results for the YBCO film are shown in Fig. 5 as a function of $H/H_d(T)$. They are normalized by their corresponding saturation values and plotted with the fitting curve (full line). The experimental data for all temperatures follow very well the theoretical prediction for the transverse Bean's model. This seems to imply that surface barriers[10] have a secondary effect when compared with bulk pinning and also that we are working in the single vortex pinning regime.[11]

The inset of Fig. 5 shows the temperature dependence of the critical current density obtained from $H_d(T)$ and the thickness of the film $[j_c(T)=2H_d(T)/d]$. If we assume $j_c=j_c(0)(1-T/T_c)^{3/2}$ as in Ref. 12 (full line), we obtain $j_c(0)=3.2\times10^7\ \mathrm{A/cm}^2$ as an estimate of the critical current density at $T=0\ \mathrm{K}$ in agreement with previously reported values.[12] Similar results were obtained with the GBCO film.

It should be pointed out that the field rate $\dot{H}$ varied in almost two orders of magnitude for $H_{\min}<H<7H_d$ (where $H_{\min}\sim2$ Oe was the lowest applied field) with no systematic departure of our data from calculations. Moreover, we changed the response time τ by a factor 2 and no change in the remanent magnetization was detected. From these estimations we concluded that self-heating of the sample due to transient induced currents was negligible.

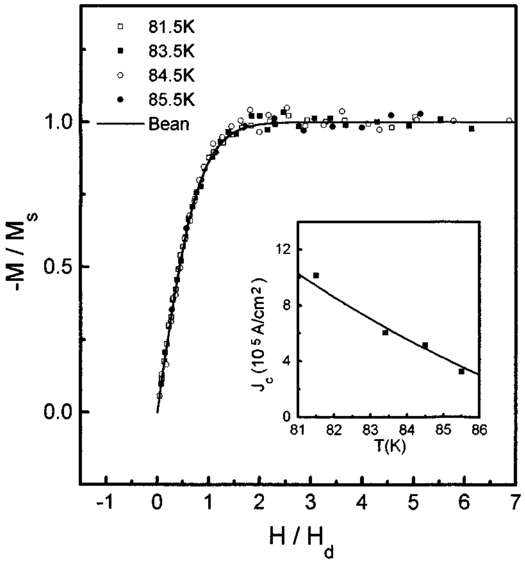

FIG. 5. Normalized time-integrated pick-up coil signals for different temperatures as a function of $H/H_d(T)$. The measurements were performed 100 μs after applying the magnetic field. The values of $H_d(T)$ were obtained by fitting these measurements to Eq. (1). The continuous line shows the normalized fit. The inset shows j_c vs T obtained from the fitting parameter $H_d(T)$. The continuous line is given by $j_c(0)(1-T/T_c)^{3/2}$ ($T_c=90.3\ \mathrm{K}$). The value of the critical current density at $T=0\ \mathrm{K}$ is estimated to be $j_c(0)=3.2\times10^7\ \mathrm{A/cm}^2$.

The above analysis in the framework of the Bean model also shows that the integrated pick-up coil signal and the magnetic moment of the sample are proportional. From this relation we estimated an overall resolution of 10^{-3} emu (a resolution that, for the present configuration, would be equivalent to those reported for most Hall probes).

B. Magnetic relaxation

Figure 6 shows a semilog plot of remanent magnetization versus time for the YBCO film at high reduced temperatures t_r, with $t_r=T/T_c>0.8$. Similar results for the GBCO film were obtained. The measurements were performed for the maximum remanent magnetization state at different temperatures, by applying a pulsed field $H_a>4H_d$ in all cases. In preliminary experiments we verified that the sample was being left in a clean state between shots, by shooting a second laser pulse between measurements. Results in Fig. 6 were analyzed in the framework of the collective pinning and creep models[13] and fitted (full lines in Fig. 6) to the expression:

$$M(t)\sim(1+t/t_0)^{-1/\sigma}, \tag{2}$$

where t_0 is an intrinsic diffusion time scale and $1/\sigma=(T/U_0)$ the relaxation rate.

We have found $1/\sigma=0.035\pm20\%$ and $t_0=50\ \mu\mathrm{s}\ \pm50\%$ for the studied temperature range. The relaxation rate is in accordance with the usually reported value of 0.03 for single-crystal and ceramic YBCO samples.[1,14] With respect

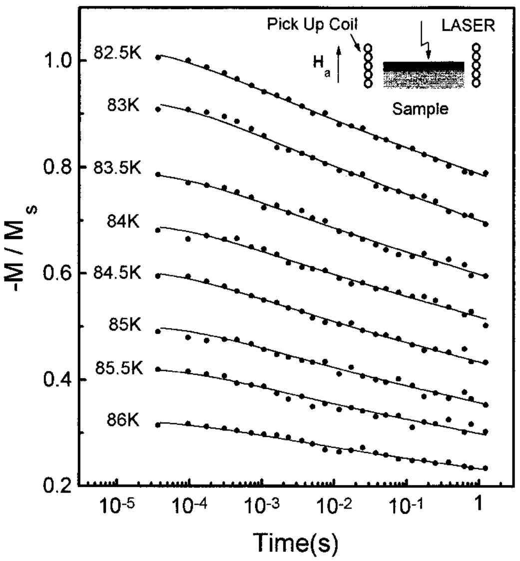

FIG. 6. Remanent magnetization normalized by $M_s = M_{82.5\,\mathrm{K}}(t_s)$ as a function of time in an $YBa_2Cu_3O_{7-\delta}$ thin film at different temperatures. The continuous lines are fits to Eq. (2). From the fit one finds the relaxation rate $1/\sigma$ and the characteristic diffusion time t_0.

to t_0, the results are in agreement with the extrapolated values in temperature from Ref. 15. Further analysis of our data will be presented elsewhere.

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[1] Y. Yeshurun, A. P. Malozemoff, and A. Shaulov, Rev. Mod. Phys. **68**, 911 (1996).

[2] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[3] L. Gao, Y. Y. Yue, P. H. Hov, and C. W. Chu, Physica C **177**, 438 (1991).

[4] M. Nideröst, A. Suter, P. Visani, and A. C. Motta, Phys. Rev. B **53**, 9286 (1996).

[5] T. Puig, P. G. Huggard, G. Schneider, T. P. O'Brien, W. Blau, M. Pont, J. S. Muñoz, and W. Prettl, Phys. Rev. B **46**, 11240 (1992); D. Gupta, W. R. Donaldson, and A. M. Kadin, J. Appl. Phys. **78**, 372 (1995).

[6] T. Puig, Ph.D. thesis, Universitat Autònoma de Barcelona, 1994.

[7] A. I. Golovashkin, F. V. Ekimov, S. I. Krasnosvododtsev, V. P. Martovitsky, and E. V. Pechen, Physica C **162–164**, 715 (1989).

[8] F. Pardo, G. Burmeister, and J. Guimpel, Rev. Sci. Instrum. **67**, 2370 (1996).

[9] P. N. Mikheenko and Yu. E. Kuzovlev, Physica C **204**, 229 (1993).

[10] C. B. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964); M. Konczykowski, L. Burlachkov, Y. Yeshurun, and F. Holtzberg, Physica C **194**, 155 (1992).

[11] H. Ferrari, S. O. Valenzuela, V. Bekeris, J. Guimpel, and F. de la Cruz (unpublished).

[12] M. Wurlitzer, M. Lorenz, K. Zimmer, and P. Ezquinazi, Phys. Rev. B **55**, 11816 (1997), and references therein.

[13] V. M. Vinokur, M. V. Feigel'man, and V. B. Geshkenbein, Phys. Rev. Lett. **67**, 915 (1991).

[14] L. Civale, A. D. Marwick, M. W. McElfresh, T. K. Worthington, A. P. Malozemoff, F. H. Holtzberg, J. R. Thompson, and M. A. Kirk, Phys. Rev. Lett. **65**, 1164 (1990).

[15] Y. Abulafia, A. Shaulov, Y. Wolfus, P. Prozorov, L. Burlachkov, Y. Yeshurum, D. Mayer, E. Zeldov, and V. M. Vinokur, Phys. Rev. Lett. **75**, 2404 (1995).