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CRITICAL CURRENT RELAXATION IN EPITAXIAL THIN YBaCuO FILMS IN CHANGING AND CONSTANT FIELD.

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The magnetic hysteresis loop (MHL) amplitude increases with the sweep rate of the external magnetic field B_e. Each MHL recorded with a sweep rate dB_e/dt can be labeled with an "effective" time t_{M_o} which represents the time needed for the relaxation at constant B_e of magnetic moment M from the critical state M_c to the value M_o of a given MHL. The dependence of M on dB_e/dt provides essentially the same information as magnetic relaxation experiments at constant B_e. The determination of t_{M_o} from a general dependence of M on sweep rate dB_e/dt or on rate of relaxation dM/dt is described and applied to experimental data obtained for an epitaxial $YBa_2Cu_3O_7$ thin film. In comparison with conventional relaxation at constant magnetic field MHL experiments make it possible to drastically extend the time window of relaxation processes towards shorter times (down to $10^{-2}s$ or less). Combination of both methods enables more precise tests of existing models on vortex motion in layered superconductors.

1. Introduction

Very large relaxation of the critical current j is a characteristic feature of all known high temperature superconductors (HTSC) and it presents a limit for some technical applications. Relaxation of the magnetic moment is by many orders of magnitude larger in HTSC than in conventional superconductors. This effect is determined by the easy depinning of vortices in actual HTSC materials [1]. The current density j (determined through Maxwell's equations by the distribution and shape of vortices in the material) is closely related to the magnetic moment M, [2], induced in a superconductor by a change of the external magnetic field B_e. In a thin film the density of flux lines is approximately constant and the current j is carried mainly by the curvature of vortices. Therefore the investigation of M is of direct relevance for the study of vortex motion and of j.

The giant relaxation in HTSC is believed to be caused mainly by thermally activated motion of vortices similarly to that in conventional superconductors [3]. An essential parameter is the activation energy U which is generally a non-linear function of j. As a consequence, pronounced non-logarithmic relaxation has been observed especially in HTSC's with low activation energies, such as Bi-based materials [6, 7, 8] while a linear $U(j)$ dependence (following from the simple Anderson-Kim's model [3]) yields purely logarithmic relaxation as is usually observed in conventional superconductors.

Several models have been proposed to explain non-logarithmic relaxation [4, 16, 17, 18, 19]. Most attention has been paid to the modified model of vortex glass [9, 16] and, in particular, to the theory of collective pinning [6, 9, 18]. For the determination of the current dependence $U(j)$ it is necessary to monitor relaxation over the widest possible time window as a function of temperature and field (thus not only at zero B_e as in refs.[6] and [9]).

For samples with a large demagnetizing factor, magnetic relaxation experiments at constant B_e are difficult to perform since the transition from a fast sweep-rate of the external field B_e to the constant B_e regime can induce uncontrolable current patterns in the sample which perturb considerably the subsequent relaxation process. Following the work of Půst et al [12] we show that information on fast relaxation at short times can actually be derived from magnetic hysteresis loop (MHL) measurements at high sweep rates by associating an effective time t_{M_o} to each sweep rate.

On the basis of a phenomenological model these authors suggested that data on the sweep-rate dependence of the magnetic moment (i.e. $M(dB_e/dt)$), determined from direct measurements of MHL's could be translated into magnetic relaxation data $M(t_{M_o})$ by defining an appropriate effective time t_{M_o}. In this way the time window of relaxation experiments could be markedly extended on the short time side (down to typically $10^{-2}s$).

2. Experimental

In this paper we illustrate the above mentioned method with new data measured by means of a vibrating sample magnetometer on a $YBa_2Cu_3O_{7-y}$ epitaxial thin film grown by dc sputtering on $CaNdAlO_4$ substrate. The magnetic moment M was measured by a vibrating sample magnetometer with magnetic field applied along the c-axis. A set of MHL's measured with B_e sweeping at different rates dB_e/dt ranging from 88.8 to 1 mT/s was recorded to obtain MHL relaxation data (Fig.1). The measured MHL's were numerically corrected for the finite time constant of the VSM electronics. Besides MHL experiments we also carried out conventional relaxation taking special care to prevent any overshoot of B_e. It was preceded by field sweep at the rate $dB_e/dt = 29.45$ mT/s. As indicated in Figure 1. the sweep rate dB_e/dt decreased during a transition time interval after stopping field ramp continuously to zero. All measurements were performed at T = 26.0 K.

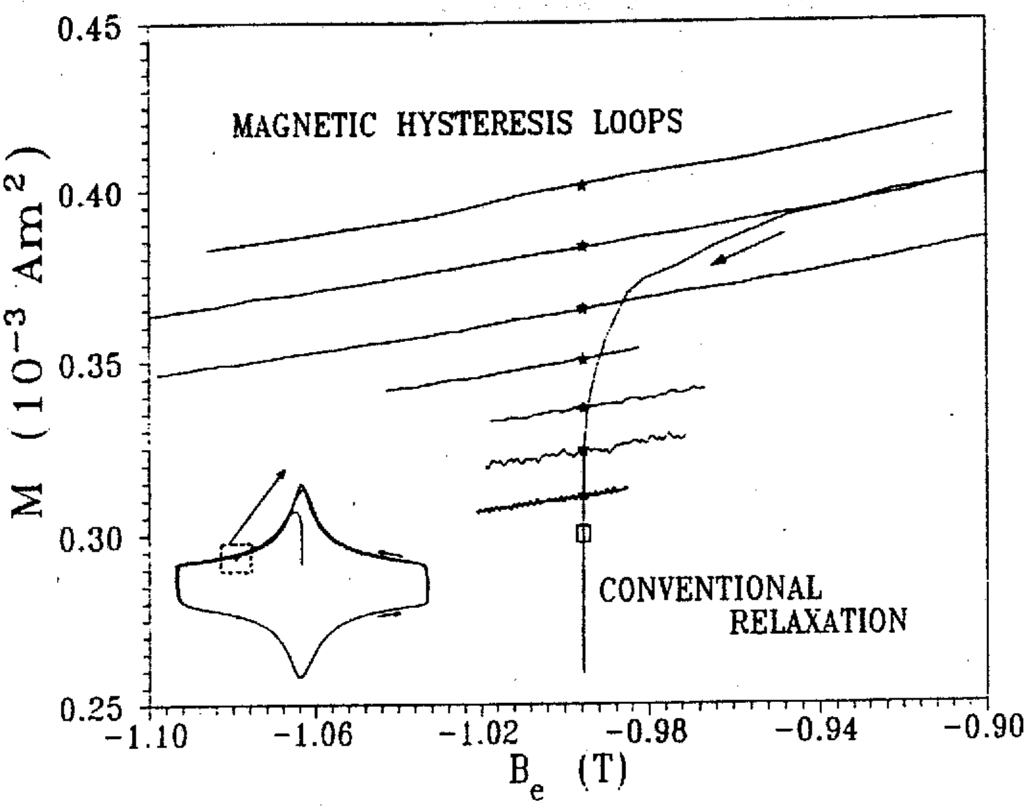

Figure 1. Parts of magnetic hysteresis loops measured at sweep rates dB_e/dt = 88.8, 29.45, 8.96, 3.1, 1.03, 0.309, 0.103 mT/s (going from the upper to the lower curves) in vicinity of the magnetic field value B_e = -0.9957 T at which "conventional" relaxation was also measured. The insert shows the analyzed part of the whole MHL set. The arrow indicates sense of the MHL run. There is also shown the transition between MHL- and constant-B_e- regimes preceding the "conventional" relaxation measurement. Sign □ indicates the point at which B_e got constant and from which downwords the "conventional" relaxation was analyzed. Stars indicate the points on MHL's taken for analysis of MHL relaxation. Measurements were carried out at $T = 26$ K.

3. Model and Discussion

In actual experiments the constant magnetic field B_e at which the mag- netic moment relaxation $M(t)$ is to be studied cannot be reached in an infinitely short time and finite sweep rate dB_e/dt leads to a "sub-critical" state. Moreover, there is always a transition period between the field-sweep ($dB_e/dt = const$) and constant-field ($B_e = const$) modes of operation of the magnet. To avoid these problems many authors analyze their magnetization data after a waiting time of 10 to $10^2 s$ in order to get rid of transients. As pointed out in [5, 12, 15], magnetic hysteresis loop experiments at various magnetic field sweep rates give essentially the same information as relaxation data. For example, in the Kim-Anderson approximation where the activation energy $U(j)$ for thermally activated vortex motion depends linearly on j, i.e. $U(j) = U_c(1 - j/j_c)$, the current density j induced in a superconducting cylinder of radius a by sweeping the external field parallel to the cylinder axis at a constant rate dB_e/dt is given by

$$j(B_e, dB_e/dt) = j_c \left[1 - \frac{kT}{U_c} \ln \left(\frac{v_o B_e}{a\, dB_e/dt}\right)\right] \quad . \tag{1}$$

where v_o is the velocity of flux-lines when $U = 0$, i.e. when $j = j_c$. After a stop of the field sweep at a given value B_e the current decays following a logarithmic law

$$j(t) = j(0) - j_c \frac{kT}{U_c} \ln \left(1 + \frac{t}{\tau_i}\right) \tag{2}$$

where

$$\tau_i = \frac{\mu_o a^2 j_c kT \exp\left[(U_c/kT)\left(1 - j(0)/j_c\right)\right]}{v_o B_e U_c} \tag{3}$$

The similarity between the relaxation and the MHL measurements at various sweep rates results directly from the structure of the flux creep equation [5, 15]

$$\mu_o \frac{dM}{dt} = \Delta v_o B_e \exp\left(-\frac{U(j)}{kT}\right) - \chi_o \frac{dB_e}{dt} \tag{4}$$

which is derived from Maxwell's equation $\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$ with $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$ after integration over the cross-section of a sample. The external magnetic field is H_e and $B_e = \mu_o H_e$, the vortex velocity $v = v_o \exp(-U(j)/kT)$, the differential susceptibility χ_o and the geometric factor Δ depend on the size and shape of the sample. The magnetic moment M of the sample is then directly proportional to the current density j [5, 15]

$$M = -\Omega j \tag{5}$$

The minus sign is due to our convention for the current direction. Ω depends also on the sample shape. For a thin slab of thickness $2a$, width b and length c, with B_e in the slab plane

$$\chi_o = 2abc, \quad \Delta = bc, \quad \Omega = a^2 bc \tag{6}$$

while for a disk we have

$$\chi_o = \frac{\pi^2 a^3}{3\mathcal{L}}, \quad \Delta = \frac{2\pi^2 a^2}{3\mathcal{L}}, \quad \Omega = \frac{\pi}{3} a^3 D \tag{7}$$

where a is the radius, D the thickness, and $\mu_o a \mathcal{L}$ the self-inductance of the disk. We can solve eq. (4) formally for $U(j)$:

$$U(j) = kT \ln \left[\frac{B_e \Delta v_o}{(\mu_o\, dM/dt + \chi_o\, dB_e/dt)}\right] \tag{8}$$

An interesting property of eq. (8) is that for a given value of B_e, the current j has the same value during a sweep and a relaxation, if $[\mu_o\, dM/dt + \chi_o\, dB_e/dt]$ is constant. Of course, during a MHL measurement at a given field sweep rate $dB_e/dt \neq 0$, $dM/dt = 0$, while during a relaxation experiment $dB_e/dt = 0$ and $dM/dt \neq 0$. However, if we make a graph of j versus $[\mu_o\, dM/dt + \chi_o\, dB_e/dt]_S$ for a sweep (S), the relaxation curve (R) fits in the same graph, if one represents j as a function of $[\mu_o\, dM/dt]_R$. This means that the function $U(j)/kT$ can be determined up to an additive constant by plotting $-\ln[\mu_o\, dM/dt + \chi_o\, dB_e/dt]$ as a function of j, irrespectively of the type of measurement (MHL at various sweep rates or magnetic relaxations at constant B_e). From this graph it is then possible to determine completely $\partial U/\partial j$ by simple differentiation and to compare these experimental data with the predictions of theoretical models. To do that, we need to determine the current density experimentally.

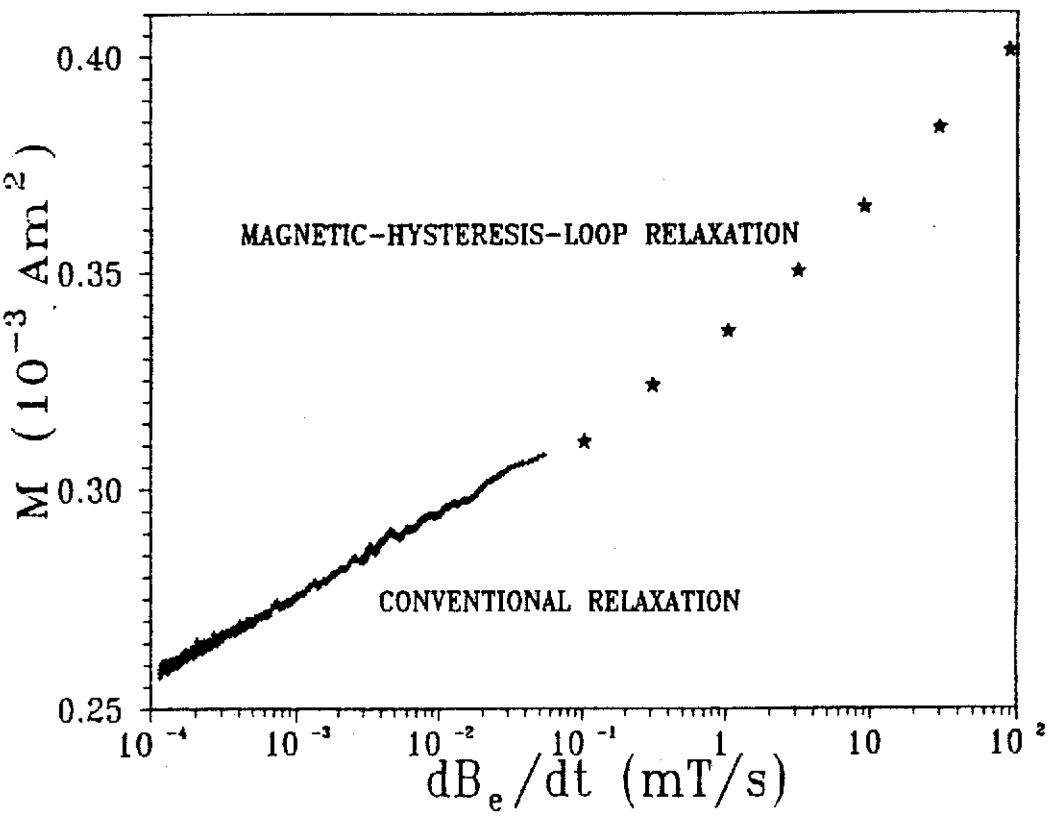

Figure 2. Magnetic moment as a function of dB_e/dt determined i) directly from MHL measurements (★) and ii) from relaxation at constant magnetic field (+) using eq.(11). The susceptibility χ_o required for the conversion of dM/dt data into dB_e/dt was measured after ac demagnetization at zero field (χ_o = 6.4x 10^{-5} m^3).

As discussed in [5, 15] during a MHL experiment $[\mu_o \, dM/dt \ll \chi_o \, dB_e/dt]$ and consequently eq. (8) can be written as

$$U(j) = -kT \ln \left(\frac{\chi_o}{\Delta v_o B_e} \frac{dB_e}{dt} \right) \tag{9}$$

For magnetic moment relaxation we have

$$U(j) = -kT \ln \left(\frac{\mu_o}{\Delta v_o B_e} \frac{dM}{dt} \right) \tag{10}$$

From eqs. (9) and (10) immediately follows that

$$\frac{dB_e}{dt} = \frac{\mu_o}{\chi_o} \frac{dM}{dt} \tag{11}$$

Consequently a plot of e.g. M versus dB_e/dt is identical to a plot of M versus $(\mu_o/\chi_o)dM/dt$, see Figure 2.

For a comparison of experimental data on $U(j)$ and theoretical models the procedure described in the previous section based on the analysis of the relaxation rate dM/dt is sufficient in itself. For a deeper understanding of the relationship between MHL sweeps and magnetic relaxation it is, however, useful to convert MHL measurements to the time domain. This means that we need to associate an "effective" time to each MHL carried at a given sweep rate dB_e/dt, i.e. to each value of M on MHL. To define this effective time we proceed as follows.

To a given value of j, or equivalently, to a given value of the magnetic moment M correspond definite values of dM/dt and dB_e/dt. Consequently a plot of e.g. M versus dB_e/dt is identical to a plot of M versus $(\mu_o/\chi_o)dM/dt$ as is shown in Fig. 2. By combining MHL experimental data with conventional relaxation data it is thus possible to construct point by point the function relating M to dM/dt, or vice versa

$$\frac{dM}{dt} = g(M) \tag{12}$$

This differential equation for M can be formally integrated to give

$$t = \int_{M_o}^{M} \frac{dM'}{g(M')} \tag{13}$$

which describes a relaxation process starting at $t = 0$ with a magnetic moment $M(\text{t=0}) = M_o$ in the form $t = t(M)$. By inversion of this function one can calculate $M(t) = f_{M_o}(t)$ where the index M_o is added to indicate clearly that t starts at the initial state M_o.

By means of eq. (13) it is possible to calculate the relaxation process from any initial state, i.e. even from states for which a relaxation experiment cannot be performed in an actual experiment because it would require an abrupt and controlled stopping of the magnetic field sweep. Among the many possible initial states one is of special interest as it allows to associate to each sweep rate dB_e/dt an effective time. To show this we consider a field sweep $(dB_e/dt)_c = v_o \Delta B_e/\chi_o$

for which $U(j) = 0$, i.e. for which the sample is in a critical state with $j = j_c$. The corresponding magnetic moment is $M_c = -\Omega j_c$. The relaxation time from this critical state is similarly to eq. (13) given by

$$t' = \int_{M_c}^{M} \frac{dM'}{g(M')} \tag{14}$$

The corresponding relaxation function is $M(t') = f_{M_c}(t')$. The two time scales t and t' are simply related to each other by

$$t' = t + t_{M_o} \tag{15}$$

with

$$t_{M_o} = \int_{M_c}^{M_o} \frac{dM'}{g(M')} \tag{16}$$

Remembering that the initial state with magnetic moment M_c is reached by sweeping the field at a rate $(dB_e/dt)_c$ satisfying eq. (9) with $j = M_c/\Omega$ we see that t_{M_o} is related to $(dB_e/dt)_c$ through eq. (16). The physical meaning is the following: t_{M_o} is the time at which magnetic moment relaxing from the critical state $M(\text{t=0}) = M_c$ reaches the value $M(t_{M_o}) = M_o$. From eqs. (13) and (14) follows also that

$$M(t) = f_{M_o}(t) = f_{M_c}(t + t_{M_o}) \tag{17}$$

which implies that all relaxation curves collapse into a single master curve after shifting of their time axis by the time t_{M_o} corresponding to their initial state. This property is closely related to the existence of a "waiting" τ_i in eqs. (2) and (3) as shall be discussed in a forthcoming publication.

A quantitative evaluation of t_{M_o} requires the knowledge of the $g(M)$ function for $M \leq M_c$. Except at low temperatures $M = M_c$ cannot be reached with practically available sweep rates. It is then necessary to extrapolate the measured part of the $g(M)$ function (for $M \leq M_{max}$) between M_{max} and M_c. At sufficiently low temperatures where $|M/M_c - 1| \ll 1$ is satisfied, for the whole class of activation energies given by

$$U(j) = \frac{U_c}{\mu}\left[\left(\frac{j_c}{j}\right)^{\mu} - 1\right] \tag{18}$$

the function $g(M)$ is to first order independent of μ and

$$g(M) \simeq \frac{v_o \Delta B_e}{\mu_o} \exp\left[-\frac{U_c}{kT}\left(1 - \frac{M}{M_c}\right)\right] \tag{19}$$

This implies that a plot of $\ln(g(M))$ (or equivalently $\ln(dM/dt)$) versus M is a linear function for M close to M_c. From a linear extrapolation of a M versus $\ln(dB_e/dt)$ plot to M_c we can determine the corresponding $(dB_e/dt)_c$. M_c was obtained by extrapolation of $M(T)$ to zero temperature. For $T < T_{irr}$ we can safely assume that $M_c(T) = const. = M_c(T = 0)$ which is easily measured. The slope of this extrapolation is equal to kTM_c/U_c from which U_c can be determined.

We have now all ingredients to calculate t_{M_o}. For the fastest sweep rate $(dB_e/dt)_{max}$ corresponding to $M_o = M_{max}$

$$t_o = \int_{M_c}^{M_{max}} \frac{\mu_o}{\chi_o (dB_e/dt)_c} \exp\left[\frac{U_c}{kT}\left(1 - \frac{M'}{M_c}\right)\right] dM' \qquad (20)$$

which can be rewritten as

$$t_o = \frac{\mu_o M_c}{\chi_o (dB_e/dt)_c} \frac{kT}{U_c} \left\{ \exp\left[\frac{U_c}{kT}\left(1 - \frac{M_{max}}{M_c}\right)\right] - 1 \right\} \qquad (21)$$

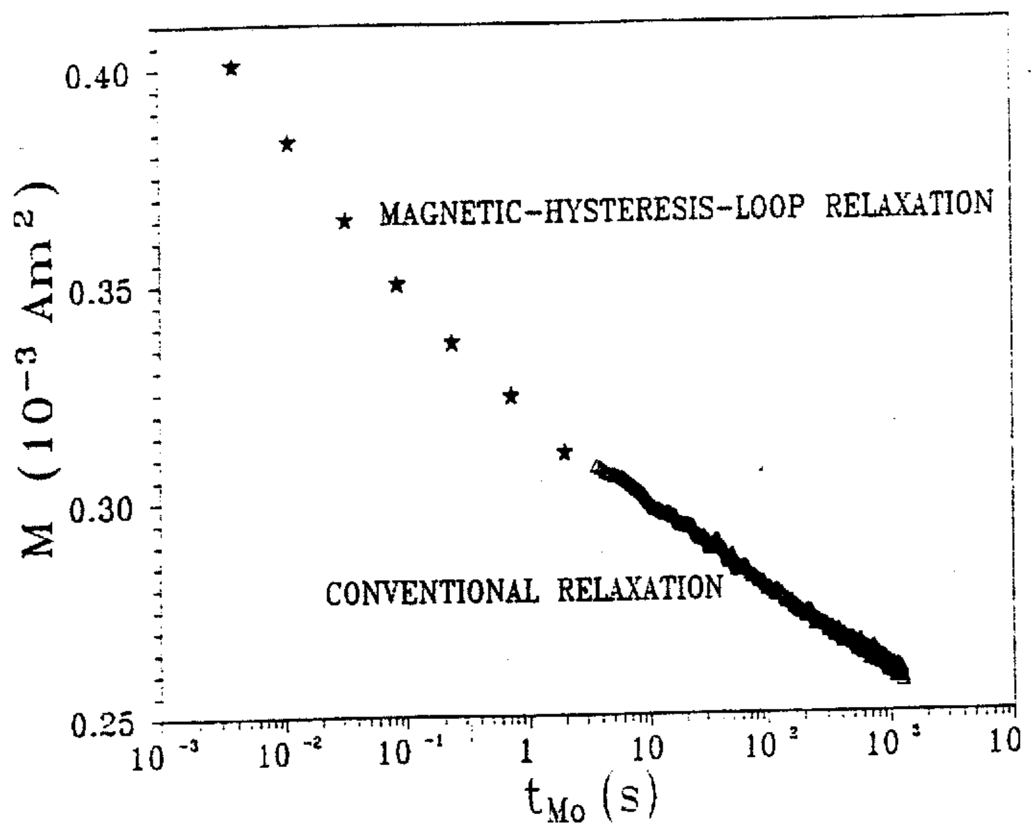

Figure 3. Magnetic moment as a function of the effective time t_{M_o} calculated using eq.(16) for data from Figure 2. Stars correspond to MHL data, triangles to the "conventional" relaxation.

For the experimental data presented below $M_{max} = 4.01 \times 10^{-4}\ Am^2$, $U_c/kT \approx 6.1$, $(dB_e/dt)_c \approx 7\text{x}10^4\ T/s$ and $\chi_o = 6.4\text{x}10^{-8}\ m^3$. This leads to $t_o \approx 2\text{x}10^{-6}\ s$ while the time corresponding to the fastest conventional relaxation experiment is in this time scale about $3\ s$ or lower. Here it should be mentioned that at the temperature $T = 26K$ condition $|M/M_c - 1| \ll 1$ is not well satisfied and, therefore.

for the exact determination of t_o integration of dM/dt with a proper value of μ is necessary. In our case $\mu = 1.43$ and correspoding $t_o = 0.005$ s. This shows vividly that MHL measurements make it possible to extend significantly the time window on the short time side down to $10^{-2}s$.

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References

[1] Hagen, C.W. and Griessen, R., in "Studies of High Temperature Superconductors", Vol. III, p.159 (1989), ed. A.V.Narkilar, Nova Science Publishers, New York.

[2] Goldfarb, R.B., Lelental, M. and Thompson, C.A., in "Magnetic Susceptibility of Superconductors and Other Spin Systems", ed. R.A.Hein, T.L.Francavilla, and D.H.Liebenberg, Plenum Press, New York (1992).

[3] Anderson, P.W and Kim, Y.B., Rev.Mod.Phys. 36 (1964) 39; Beasley, M.R., Labusch, R. and Webb, W.W., Phys. Rev. 181 (1969) 682.

[4] Maley, M.P., Willis, J.O. , Lessure, H. and McHenry, M.E., Phys.Rev. B 42 (1990) 2639.

[5] Schnack, H.G., Griessen, R., Lensink, J.G., van der Beek, C.J. and Kes, P.H., Physica C 197 (1992) 337.

[6] Svedlindh, P., Rossel, C., Niskanen, K., Norling, P., Nordblad, P., Lundgren, L., Chandrashekhar, G.V., Physica C 176 (1991) 336.

[7] Li, X.G., Lai, R., Zhao, H., Wang, Z., Chen, L. and Zhang, Y., J.Appl.Phys. 69 (1991) 7339.

[8] Spirgatis, A., Trox, R., Koetzler, J. and Bock, J., submitted to Cryogenics (1992).

[9] Gao, L., Xue, Y.Y., Hor, P.H. and Chu, C.W., Physica C 177 (1991) 438; Xue, Y.Y., Gao, L., Ren, Y.T., Chan, W.C., Hor, P.H. and Chu, C.W., Phys. Rev. B 44 (1991) 12029.

[10] Požek, M., Ukrainczyk, I., Rakvin, B. and Dulčič, A., Europhys. Lett. 16 (1991) 683.

[11] Frait, Z., Fraitová, Z., Pollert, E. and Půst, L., phys. stat. sol. (b) 146 (1988) K119; J.de Physique 49 (1988) C8-2235.

[12] Půst, L., Kadlecová, J., Jirsa, M. and Durčok, S., Proc. Int. Conf. Nature Prop. HTS, Wroclaw (1989), C-7; J.Low Temp. Phys. 78 (1990) 179.

[13] Jirsa, M., Půst, L. and Kadlecová, J., J. Mag. Magnet. Mater. 101 (1991) 105.

[14] Jirsa, M., Půst, L. and Pačes, J., in: High T_c Superconductor Thin Films, ed. L. Correra, Elsevier Sci. Pub., 1992, p. 171.

[15] Jirsa, M., Půst, L., Schnack H. and Griessen R., submitted to Physica C (1992)

[16] Fisher, M.,P.,A., Phys.Rev.Lett. 62 (1989) 1415

[17] Malozemoff, A.,P. and Fisher, M.,P.,A., Phys.Rev.B 42 (1990) 6784

[18] Feigelman, M., V., Geshkenbein, V., B., Larkin, A.,I. and Vinokur, V., M., Phys.Rev.Lett. 63 (1989) 2303; Physica C 167 (1990) 177; Phys.Rev. B 43 (1991) 6263

[19] Yamafuji, K. and Mawatari, Y., Cryogenics 32 (1992) 569