

## Study of the Short-time Fast Relaxation of Induced Currents in High $T_c$ Superconductors using Magnetic Hysteresis Loops

L. Püst<sup>a</sup>, M. Jirsa<sup>a</sup>, J. Schneider<sup>b</sup> and R. Wördenweber<sup>b</sup>

<sup>a</sup>Institute of Physics, Academy of Sciences of CR, Na Slovance 2, CZ-180 40 Praha 8, Czech Republic.

<sup>b</sup>Institut für Schicht- und Ionentechnik, KFA Jülich, P.O.Box 1913, D-52428 Jülich, FRG.

Magnetic hysteresis loops measured with various field sweep rates (sometimes called the dynamic relaxation - DR) enables to extend the time scale of observable relaxation of induced magnetic moment  $\mathcal{M}$  to subsecond region even in high magnetic fields and to study fast relaxation processes in vortex system. Relaxation and DR data measured on  $\text{YBa}_2\text{Cu}_3\text{O}_7$  thin film cover the range of relaxation times  $10^{-2}$ - $10^4$  s corresponding to the range of relaxation rates  $dj_s/dt$  over more than 6 orders of magnitude.

Relaxation of superconducting current  $j_s$  and the directly related induced magnetic moment  $\mathcal{M} = -\Omega j_s$ , where  $\Omega$  is a constant, is usually described in terms of time dependencies  $\mathcal{M}(t)$  and/or  $j_s(t)$  measured after a large preceding change of external magnetic field  $B_e$  (the conventional relaxation, CR) [1]. There are some drawbacks of this approach: (i) The available time window is usually limited at short times by the nonzero transition period from the fast field sweep to the regime of constant  $B_e$  [2]. For common power supplies it represents delay of several seconds. This transition time can be significantly shortened if final  $B_e \approx 0$  [3], but vortex system is rather complicated in this case. (ii) The long time measurements are sometimes affected by temperature instability of the experimental set up. (iii) There is always a considerable uncertainty in the time scale origin.

Due to these limitations CR is not very suitable for direct study of the interesting range of initial fast relaxation processes in vortex systems. More straightforward physical approach to relaxation processes is based on the analysis of the relation between current  $j_s(B_e, T)$  and the rate of current relaxation  $(dj_s/dt)(B_e, T)$  [4]. Because  $dj_s/dt$  is equivalent to the electric field  $E$  we can combine CR with transport measurements where  $j(E)$  dependence is recorded directly. While CR covers range of low  $E$ , we measure much higher  $E$  by the transport measurements. The intermediate range of electric fields can be studied using transformed data from magnetic hysteresis loops recorded with various rates of field sweep  $dB_e/dt$  [5,6]. This method

(called also the dynamic relaxation, DR) extends the range of relaxation rates by a few orders of magnitude in comparison to the CR. The  $j_s(E)$  or  $dj_s/dt$  data obtained from transport or DR experiments can be transformed finally into an equivalent time dependence and compared with the CR data.

In this paper we present new DR data  $j_s(dB_e/dt)$  and describe the way the data are transformed into the time dependence  $j_s(t)$ . After the transformation the DR data cover a short time range, typically between  $10^{-3}$  and 10 s. In the following we will use function  $g(j_s)$  to depict the time derivative of the superconducting current  $g(j_s) = |dj_s/dt|$ , [5]. This simple differential equation can be integrated as

$$t_i(j_s) = t_r + \int_{j_s}^{j_r} \frac{dj_s'}{j_s' g(j_s')} \quad (1)$$

where  $j_r = j_s(t_r)$ . The integration constant  $t_r$  will be discussed later. This definition of the "integral" time  $t_i$  can be modified into form more suitable for practical calculations as  $g$  usually varies by several orders of magnitude

$$t_i(g) = t_r + \int_{\ln(g)}^{\ln(g_r)} \frac{S_{dif}}{g'} d \ln(g') \quad (2)$$

where  $S_{dif} = |dj_s'/d \ln(g')|$  and  $g_r = g(j_r)$ .

In the special case of the purely logarithmic relaxation of the Anderson-Kim type [7]  $S_{dif} = const.$  and we obtain

$$t_i(g) = S_{dif}/g + (t_r - S_{dif}/g_r) \quad (3)$$

Though we may use in general any value of  $t_r$ , only the special choice of the integration constant  $t_r =$

$S_{diff}/g_r$  yields a simple relation between time  $t_i$  and the relaxation rate  $g=|dj_s/dt|$  as  $t_i = S_{diff}/g$  [6]. This choice of  $t_r$  naturally yields the simple dependence linear in  $\ln t$  as  $j_s(t) = j_{s1} - S \ln t$ , where  $j_{s1}$  and  $S = dj_s/d \ln t$  are constants. Moreover, only for such choice of  $t_r$  we have  $S_{diff} = S$ , which also means that  $t_i = t_d$ , where  $t_d$  is defined as  $t_d = S/g$ .

DR data are very suitable for such analysis as constant sweep rate  $dB_e/dt$  during MHL recording implies constant relaxation rate [6]

$$g = \frac{dj_s}{dt} = \frac{\chi_0}{\mu_0} \frac{dB_e}{dt} \quad (4)$$

which follows from the equation of motion of  $j_s$

$$\frac{dj_s}{dt} = \frac{\chi_0}{\Omega\mu_0} \frac{dB_e}{dt} - \frac{\Delta v_0 B_i}{\Omega\mu_0} P(j_s, T, B_e), \quad (5)$$

where  $\chi_0$  is the differential susceptibility,  $\Delta$  is a geometric factor and  $P$  is the vortex hopping probability [2.5]. Internal field  $B_i \approx B_e$ .

Measurements of induced magnetic moment were performed on the vibrating sample magnetometer PAR 155 and the superconducting current was evaluated according to the Bean model. MHLs were recorded in  $B_e$  swept up to  $\pm 2$  T. Seven sweep rates  $dB/dt$  ranging from 88 to 0.88 mT/s were used, which correspond according to Eq. 4 to seven values of the relaxation rate  $dj_s/dt$ . In addition we measured CR at constant  $B$ . Both data were first expressed in terms of  $j_s$  and  $dj_s/dt$  and then transformed into the time dependent relaxation using Eq. 2, see Fig. 1. We used the integration constant  $t_r$  equal to  $S_{diff}/g$ , i.e. assuming such time scale that  $dj_s/d \ln t = dj_s/d \ln g$  at the point with highest measured  $j_s$ . We see that the MHL data cover the time scale down to  $t = 30$  ms.

In conclusion, whereas the  $j_s$  vers.  $(dj_s/dt$  or  $E)$  at a given  $T$  and  $B_e$  is an unambiguous function [4.5],  $j_s(t)$  (and in particular the  $j_s(\ln t)$ ) depends very much on the time scale. However, there is one important consequence of Eq. 1. Assuming that we know the  $j_s(E)$  dependence up to very high currents (e.g. from combined magnetic and transport  $j_s$  measurements), we can attribute time  $t_i$  to each  $j_s$  value in the all range of  $j_s$  using Eqs. 1 or 2. The value of the integration constant  $t_r$  is the time corresponding to the highest measured  $j_s$  (by any method, including MHL or a transport measure-

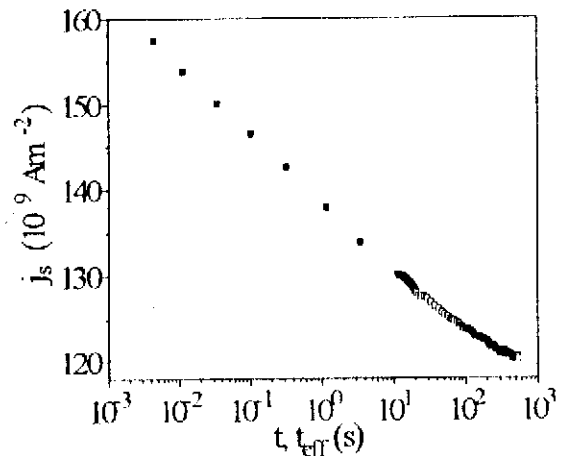


Fig. 1: The time dependent relaxation of  $j_s$  evaluated from both CR and MHL measurements on YBCO thin film at  $T = 6.8$  K and  $B_e = 1$  T.

ment). Though the choice of  $t_r$  is in general arbitrary, there is very advantageous to define time  $t = 0$  to be the time of the vortex state with  $j_s$  equal to the very high critical depinning current  $j_{c0}$ . In such case  $t_r$  would be the time corresponding to (virtual) conventional relaxation between  $j_{c0}$  and the highest measured  $j_s$  value. Then all  $j_s(t)$  dependencies measured at a given  $T$  and  $B_e$  by different methods overlap and we have unambiguous function  $j_s(t)$ . Relaxation in vortex systems is usually close to the logarithmic one and so we can use the value  $t_r = S_{diff}/g_r = (\mu_0/\chi_0) (S_{diff}/(dB/dt))$  deduced for purely logarithmic relaxation. This approach was also used for evaluation of data in Fig. 1.

We are grateful to very stimulating discussions with Prof. R. Griessen. This work was supported by grant GACR.

- [1] A. Gurevich, H. Kupfer, Phys. Rev. B 48 (1993) 6477.
- [2] H. Schmack et al., Physica C 197 (1992) 337.
- [3] L. Gao et al., Physica C 177 (1991) 438.
- [4] A.D. Caplin et al., Supercond. Sci. Technol. 7 (1994) 412.
- [5] M. Jirsa et al., Physica C 207 (1993) 85
- [6] L. Püst et al., J.Low Temp.Phys. 78 (1990) 179
- [7] P.W.Anderson, Y.B.Kim, Rev.Mod.Phys. 36 (1964) 39