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Field and temperature dependence of intergranular hysteresis in $YBa_2Cu_3O_7$

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Abstract. We have studied the variation of low field magnetization hysteresis in $YBa_2Cu_3O_7$ as a function of the maximum magnetic field applied during a hysteresis cycle ($1\,G < H_{max} < 7{\cdot}3\,G$) and also as a function of temperature ($77\,K < T < 95\,K$). The remnant magnetization is studied as a function of H_{max} and T and the measured dependences are explained using the extended critical state model. The potential of this technique as a contactless method of probing the temperature dependence of J_c is discussed.

Keywords. High temperature superconductors; remnant magnetization; critical current density.

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1. Introduction

Sintered pellets of the ceramic high T_c superconductors are not homogeneous but consist of superconducting grains coupled by intergranular links. The much lower critical current density (J_c) seen in transport measurements on the sintered pellets, as compared to that in single crystal samples, is identified as due to these intergrain links. The isothermal magnetization hysteresis of these sintered pellets shows a low field loop, which disappears on powdering the pellets, and is again attributed to the intergrain links (Grover *et al* 1988; Chaddah *et al* 1989a; Calzona *et al* 1989). The imaginary part (X'') of the susceptibility also shows two peaks as a function of temperature (Chen *et al* 1988; Calzona *et al* 1989) and the low temperature peak disappears on powdering. We have earlier explained the hysteresis of sintered pellets in terms of an extended critical state model (Grover *et al* 1988; Chaddah *et al* 1989a), and related it to the transport J_c and the dimensions of the pellet (Mishra *et al* 1988; Radhakrishnamurthy *et al* 1989).

In this paper we present low field hysteresis measurements on sintered pellets of $YBa_2Cu_3O_7$, as the temperature is varied between 77 K and 90 K and the maximum applied field, H_{max}, varied between 1 G and 7·3 G. The variation of temperature causes a variation in the intergrain transport J_c and thus in the parametric field of the critical state model. This parametric field for a pellet is defined as $H_p^* = \mu_0 J_c D/2$, where D is the dimension of the pellet perpendicular to the field and μ_0 is the permeability of free space. In § 2 we present the experimental details and results, while in § 3 we explain

these results in terms of a model (Grover *et al* 1988; Chaddah *et al* 1989a). In §4 we discuss the possibility of using such measurements to estimate the temperature dependence of the zero-field J_c in sintered pellets.

2. Experimental set up and results

The hysteresis curves are measured using an AC(317 Hz) susceptibility instrument (Likhite and Radhakrishnamurthy 1966) coupled with a flow type liquid nitrogen cryostat. Figure 1 shows a schematic of the flow type liquid nitrogen cryostat. The $YBa_2Cu_3O_7$ samples were prepared by the conventional sintering route. The sample and a copper constantan thermocouple are encapsulated in a nylon sample holder which is filled with thermally conducting Apiezon N grease. The sample holder rests in a glass tube which is inside a double walled glass tube. The double walled glass tube passes through the secondary coils of the susceptibility instrument. The position of the sample is adjustable with respect to the secondary coils. Temperature is varied in the range of $T = 77$ K to 95 K with $\Delta T = \pm 0{\cdot}5$ K by controlling the rate of flow of the

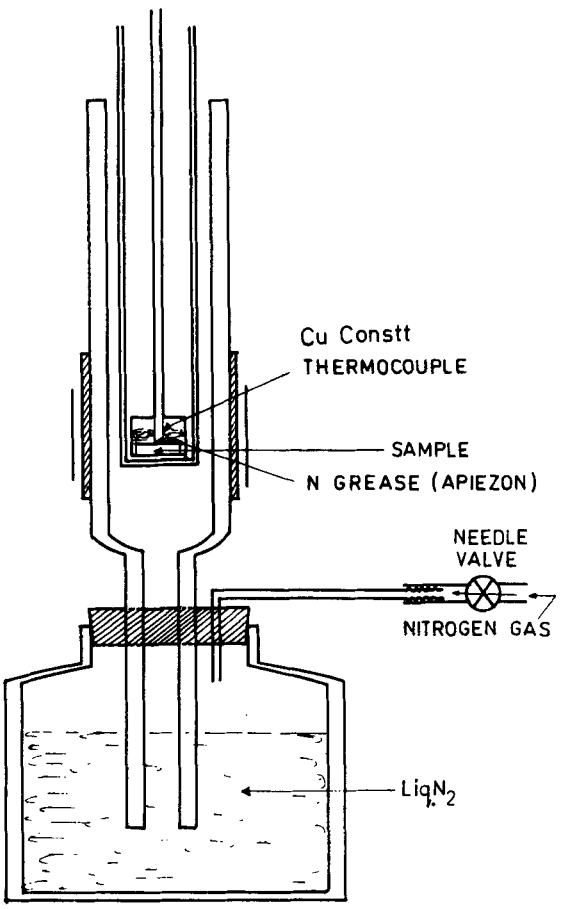

Figure 1. Schematic of flow-type liquid nitrogen cryostat.

nitrogen gas through liquid nitrogen. Samples in the pellet geometry are used in this study. The maximum cycling field, H_{max}, is varied between 1 and 7·3 G.

Figures 2 and 3 show the hysteresis loops, (for sample 1), for $H_{max} = 2$ G and 7·3 G respectively, at various temperatures. We observe that the remnant magnetization (M_r) which is proportional to the opening in the hysteresis loop at $H = 0$, increases to a maximum and then decreases as the sample is cooled from $T = 90$ K to 77 K. This opening at $H = 0$ is measured directly from the oscilloscope at various temperatures. The relative magnitude of opening at different temperatures is shown in figure 4 for another sample (sample 2) in the range of $H_{max} = 1$ to 6 G.

We make the following observations:

a) For each $H_{max} = H_m$ there exists a temperature $T = T_m$, at which the remnant magnetization (M_r) is maximum. If we now make measurements with the temperature fixed at T_m and vary H_{max}, we find that M_r decreases as H_{max} is reduced below H_m. But as H_{max} increases beyond H_m, M_r stays constant. This feature is clear from figure 4, where the solid line yields this saturation value of M_r for various temperatures.
b) The maximum in M_r shifts to low temperatures for higher H_{max}. The maximum is broader for higher $H_{max}(> 3$ G).

In the next section we shall explain these results.

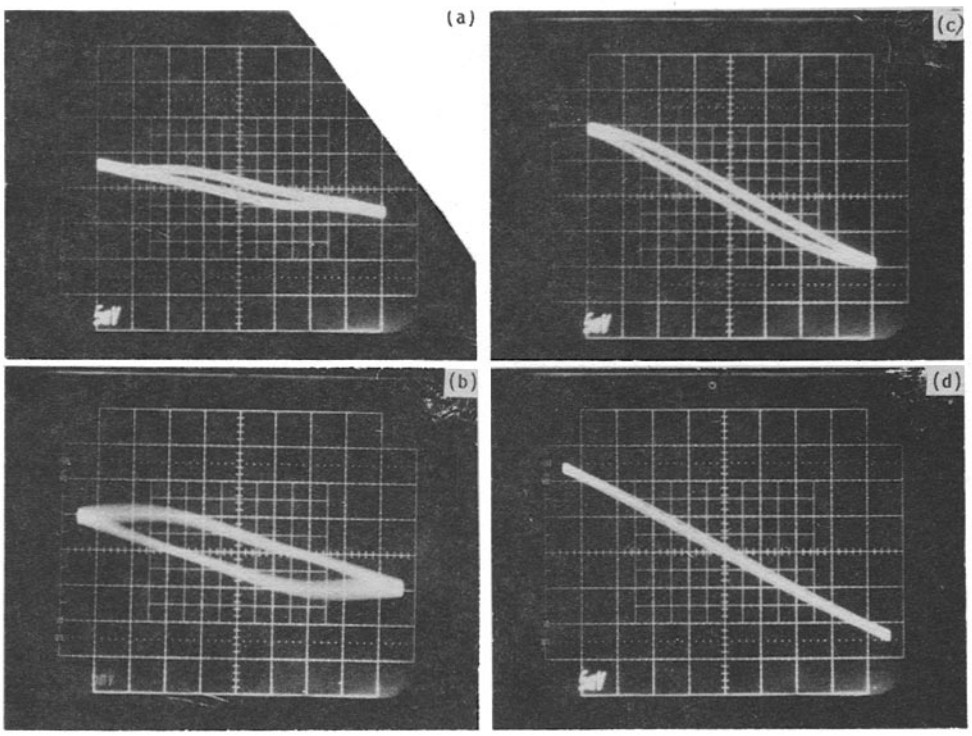

Figure 2. Magnetization hysteresis loops for a $YBa_2Cu_3O_7$ sintered pellet (sample 1) at different temperatures for $H_{max} = 2$ G. The temperatures are (**a**) 88·0 K; (**b**) 87·5 K; (**c**) 86·5 K and (**d**) 80·0 K.

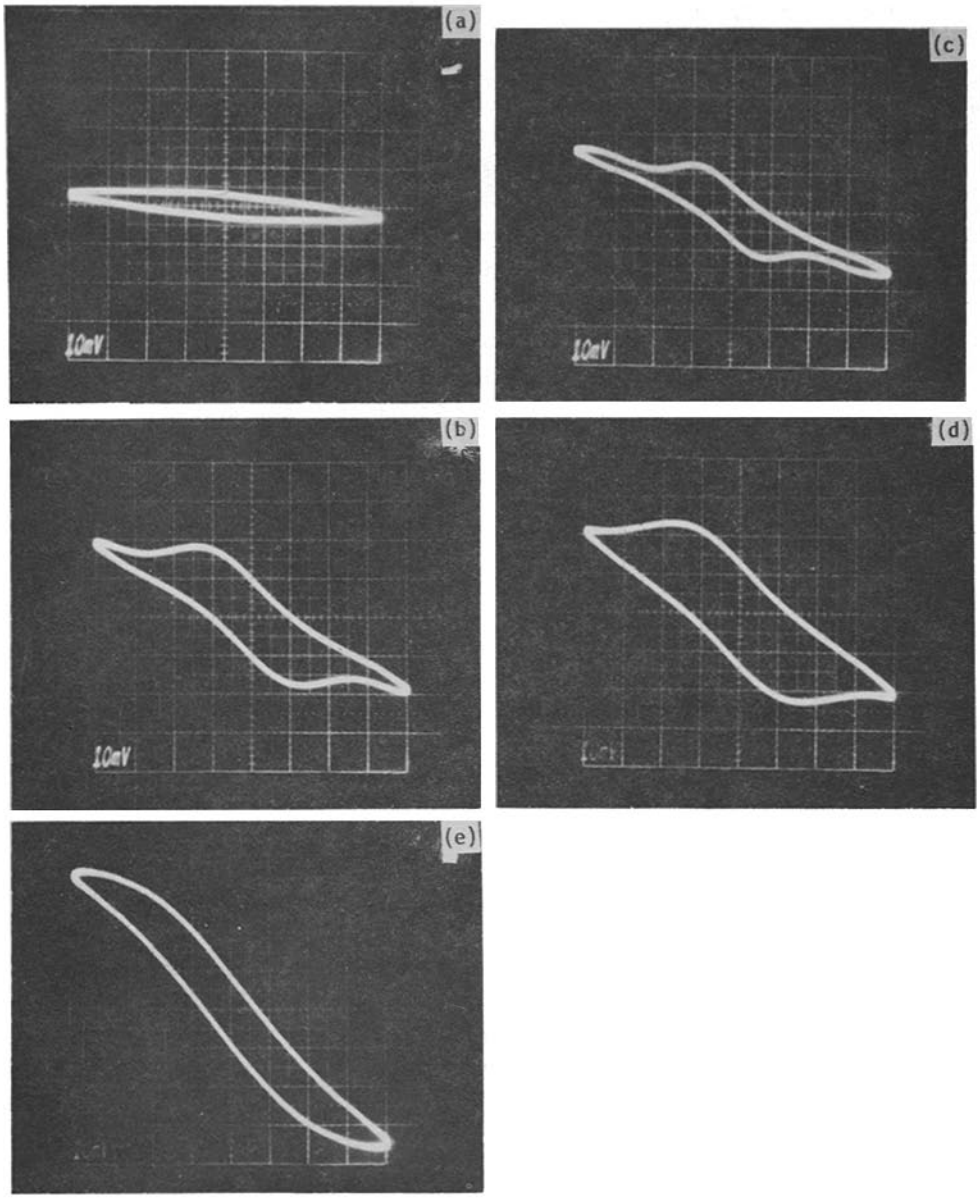

Figure 3. Magnetization hysteresis loops for a $YBa_2Cu_3O_7$ sintered pellet (sample 1) at different temperatures for H_{max} of 7·3 G. The temperatures are (**a**) 89·0 K; (**b**) 85·0 K; (**c**) 86·5 K; (**d**) 84·0 K and (**e**) 78·0 K.

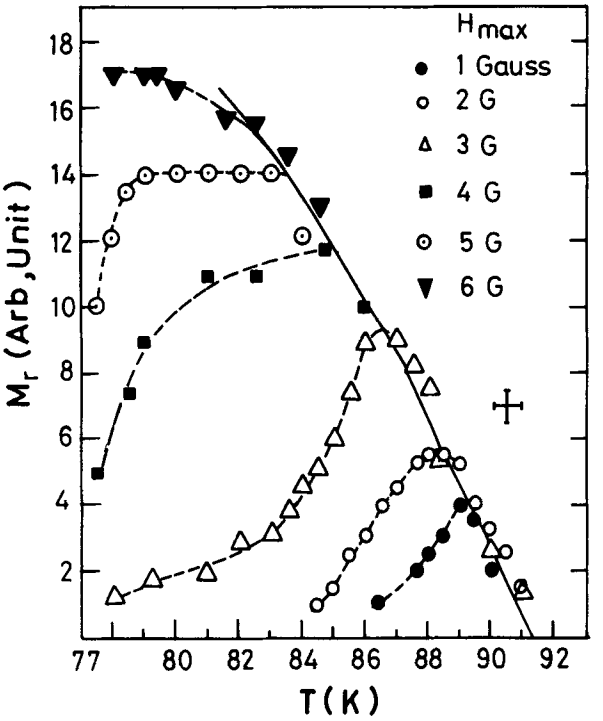

Figure 4. Remnant magnetization (M_r) as a function of temperature for $H_{max} = 1$ G to 6 G of $YBa_2Cu_3O_7$ sample 2. The error bar is indicated. The solid line corresponds to $H_m(T)$ (see text).

3. Extended critical state model

It has been shown earlier (Grover *et al* 1988; Chaddah *et al* 1989a) that the observed low field hysteresis is due to intergranular links when the applied field, H_{max}, is small compared to a parametric field, H_g^*, for a grain. H_g^* depends upon the intragrain critical current density J_{cg} and the grain dimensions and its magnitude is more than 200 G at 77 K in sintered pellets measured by us. We thus note at any given temperature $H_g^* > H_p^*$, and both of them tend to zero, at different rates, as $T \to T_c$ (Radhakrishnamurty *et al* 1989). Thus, for a fixed H_{max}, there is a temperature above which $H_{max} > H_g^*$ and the hysteresis loop has a contribution from intragrain hysteresis also. This is clearly visible in the data in figures 3(a) and 3(b). The complete loop in figure 3(a) and the narrow tail in figure 3(b) are due to intragrain hysteresis.

Figure 5 shows the qualitative evolution of the hysteresis loop as the temperature is lowered. Once the hysteresis curve shows the shape of figure 5c, the hysteresis is due only to intergrain links. As the temperature is lowered further (for a fixed H_{max}) the observed hysteresis is solely intergranular in origin. The observations (a) and (b) are at such temperatures and will now be explained in terms of the variation of the intergranular transport critical current with temperature. The response of the intergrain regions is characterized by the parametric field

$$H_p^*(T) = 1/2\,\mu_0 J_c(T,0)D \tag{1}$$

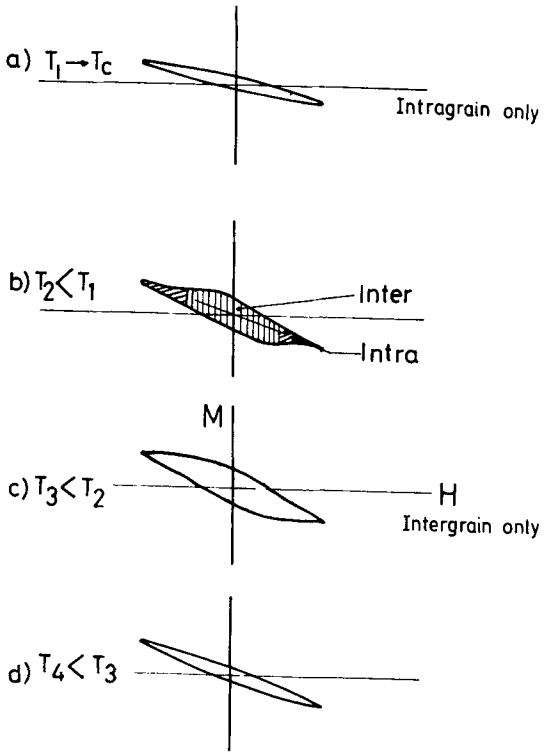

Figure 5. Schematic hysteresis loops as a function of temperature.

where $J_c(T,0)$ is the transport current density in zero field and D is the diameter of the pellet. $J_c(T,H)$ is known to be sharply decaying with field (see Mishra *et al* 1988), and we approximate this decay by

$$J_c(T,H) = J_c(T,0)\exp(-|H|/H_0(T)) \tag{2}$$

where H_0 is an experimental constant that decreases with increasing temperature.

To understand observations (a) and (b), we make the following observations for a general form of $J_c(H)$ that decreases with increasing $|H|$. For a given sample at a constant temperature (i.e. fixed H_p^*), M_r increases up to a certain field H_{II}. When H_{max} increases beyond this H_{II}, the profile of the remnant field in the sample is dictated only by H^* and the H-dependence of J_c, and M_r is independent of H_{max}. This is depicted in figure 6 by drawing schematic field profiles of the remnant field, for various values of H_{max}. These field profiles are obtained by demanding curl $H = J_c$, with the sign of curl H being determined by the sign of the last field change (Chaddah and Ravikumar 1989). H_{II} is the lowest H_{max} for which the remnant field profile peaks at the centre of the sample, and for $J_c(H)$ given by (2) H_{II} is obtained as (Chaddah and Ravikumar 1989).

$$H_{II}(T) = H_0(T)\log[1 + 2H^*(T)/H_0(T)]. \tag{3}$$

This explains our observation (a) and we can identify $H_m(T) = H_{II}(T)$.

To explain observation (b) we note that for a given H_{max}, our above identification corresponds to $H_{max}(T_m) = H_{II}(T_m)$. As H_{max} is held fixed and the temperature is

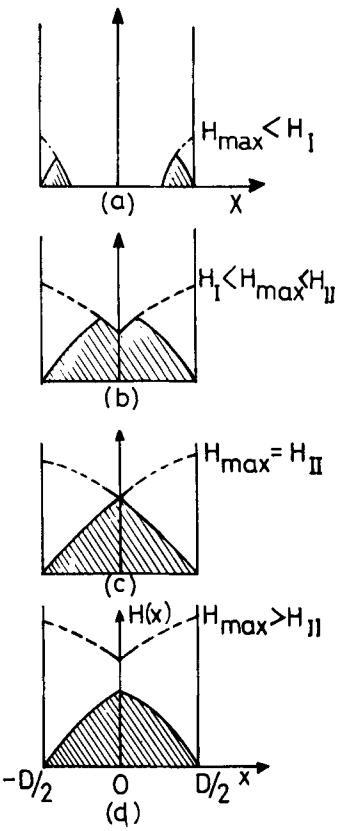

Figure 6. We show (by the dashed lines) the local remnant field profiles ($H(x)$) as the applied field is raised to H_{max} and by the solid lines the field profiles when this field is lowered to zero. The value of M_r is directly proportional to the area of the hatched region for a sample in the shape of a slab. (**a**) to (**d**) corresponds to various values of H_{max}. The curves are schematic corresponding to a $J_c(H)$ that decreases with increasing H. H_I is the value of H_{max} at which the flux first penetrates the entire sample, while H_{II} is defined in the text.

raised, H^* (or $J_c(0)$) is lowered, the hysteresis curve corresponds to the regime $H_{max} > H_{II}$. As depicted in figures 6(d) and 7(b), M_r decreases with decreasing $J_c(0)$. As the temperature is lowered below T_m, $J_c(0)$ and thus H^* increases, and we are now in the regime $H_{max} < H_{II}$. As is schematically depicted by comparing figures 6(a) and 7(a), M_r will decrease in this regime with increasing $J_c(0)$. We thus find that M_r will decrease as temperature is varied on either side of T_m (for fixed H_m) and we can identify $H_{II}(T_m) = H_{max}$. We should mention that the sharpness of the maximum in M_r depends on T_m since H_0 varies with temperature.

Our measurements are on samples of non-zero demagnetization factor N, while the above discussion had assumed $N = 0$. We thus have to make the identification

$$H_{max} = (1 - N)H_{II}(T_m) \tag{4}$$

Since H_{max} and T_m are experimentally determined, $H_{II}(T_m)$ can be obtained from our data provided we can estimate N.

For a sample in the disc geometry, the demagnetization factor N can be

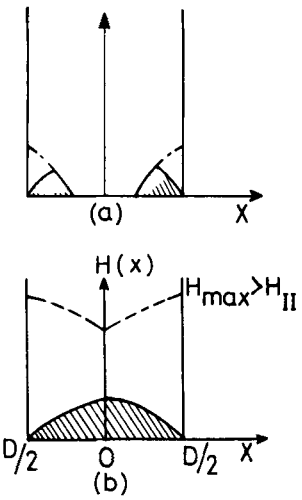

Figure 7. Same as figure 6 but $J_c(0)$ is assumed to be smaller. By comparing 6(**a**) with 7(**a**) we note that M_r rises for $H_{max} < H_{II}$, but a comparison of figures 6(**d**) and 7(**b**) shows that M_r decreases for $H_{max} > H_{II}$.

experimentally estimated using the following relation (Grover *et al* 1988)

$$N = (2M_1 - M_2)/(2M_1 + M_2) \tag{5}$$

where M_1 is the magnetization for a fixed applied field perpendicular to the plane of the pellet and M_2 is the magnetization for the same field applied parallel to the plane of the pellet. The applied field is small (1 G at $T = 77$ K) such that there is no hysteresis in the $M - H$ curve. For the sample of volume = 0·40 cm^3 and diameter 0·86 cm, we obtain the value of $N \simeq 0{\cdot}72$ when the field direction is perpendicular to the plane of the pellet.

4. Discussion

We have experimentally determined $H_{II}(T)$, and this is depicted in figure 8. By measuring D we can obtain estimates of $J_c(0)$ provided we know the H-dependence of $J_c(H)$ or the parameter $H_0(T)$. By using (3), we can get the inequality

$$H_{II}(T) < 2H^*(T) \tag{6}$$

where the inequality becomes weaker as $H_0 \to \infty$. H_0 can be determined from the extent of hysteresis at large fields (Chaddah *et al* 1989b), one can then use (1) to estimate $J_c(0)$ at various T. While this can provide a contactless method of estimating $J_c(0)$ as a function of temperature, we have here only confirmed that (1) is consistent with the directly measured $J_c(0)$.

A direct V-I measurement on this sample yields $J_c(0) = 38$ A/cm^2 at 77 K. Substituting the pellet dimensions ($D = 8{\cdot}6$ mm) we get $H^*(77\text{ K}) = 20$ G while our magnetization data shows $H_{II}(77\text{ K}) = 21{\cdot}5$ G. These values satisfy the inequality (6) and provide further justification of our analysis in § 3. They correspond to $H_0 \simeq 20$ G at 77 K, an estimate consistent with our earlier direct measurements (Mishra *et al* 1988).

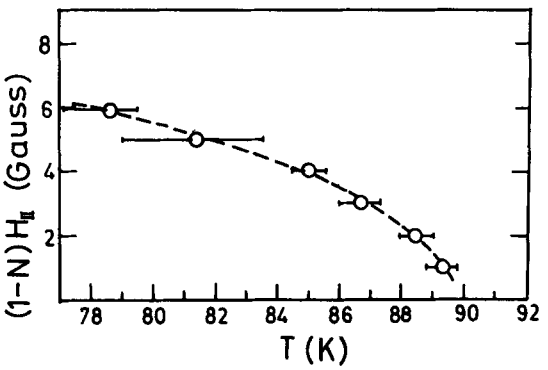

Figure 8. $(1 - N)\,H_{II}$ versus temperature for the sintered $YBa_2Cu_3O_7$ pellet no. 2 as inferred using the data of figure 4. See text for details.

To conclude, we have measured low field hysteresis in $YBa_2Cu_3O_7$ as a function of temperature and cycling field. We have explained this as a response from the intergranular regions and correlated it with the transport J_c.

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