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Anomalous magnetic hysteresis loops and small H_{c1} values in high T_c superconductors

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Abstract. We have studied the hysteresis loops of $RBa_2Cu_3O_7$ (R = Gd, Ho and Y) and detected anomalies in some of them. The observed anomalies support a recent prediction by Ravi Kumar and Chaddah based on an extension of Bean's model. The anomalies indicate low H_{c1} values and we have confirmed this by studying the onset of low-field hysteresis in less than 10 Oe at 77 K for these high T_c superconductors.

Keywords. High T_c superconductors; lower critical field; AC methods; magnetization curves.

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The lower critical field H_{c1} is a basic physical parameter of a hard superconductor. It is most often identified as a field value at which virgin M versus H curve deviates from linearity. H_{c1} values thus obtained from high field magnetization data of high T_c superconductors are of the order of 1000 Oe at 4·2 K, decreasing to about 100 Oe at 77 K (Cava *et al* 1987; Dinger *et al* 1987; Mcguire *et al* 1987; Murakami *et al* 1987; Nagarajan *et al* 1987; Umezawa *et al* 1987; Worthington *et al* 1987). In a recent preprint, Ravi Kumar and Chaddah (1987) argue that it is inappropriate to estimate H_{c1} in the above manner. They show that the shape of the virgin M versus H curve, including the deviation from linearity, is governed by factors other than H_{c1}, for example by the field dependence of the critical current density and geometrical parameters like the size and shape of the superconducting grains. However, in the framework of their model calculations which are based on an extension of the model originally proposed by Bean (1962, 1964), H_{c1} manifests itself as an anomalous dip in magnetization values in the region $|H| < H_{c1}$ in the subsequent M versus H traces. In view of the reported absence of such an anomaly for $|H| < 100$ to 1000 Oe in the magnetization data published so far, they have conjectured that H_{c1} in the high T_c superconductors may be considerably lower. In such a case, either the anomaly may be absent or may escape detection in measurements in which the magnetic field is varied in discrete steps higher than H_{c1}. The recent observation (Gammel *et al* 1987) of uniform hexagonal magnetic flux lattice in a single crystal specimen of $YBa_2Cu_3O_7$ in a field of 13 Oe at 4·2 K is ample proof that H_{c1} in that specimen is < 13 Oe at 4·2 K. Two of us (AKG and CRK) had, however, observed some months ago anomalies near $H = 0$ in the AC magnetic hysteresis loops in a peak field of the order of 1 kOe at 77 K in a few of the $RBa_2Cu_3O_7$ (R = rare earth) specimens synthesized by one of us (GVS). This unpublished work has now been repeated. We report, in this note, probably the first low (< 10 Oe) and high field (100 to 1000 Oe) magnetic hysteresis loops obtained by AC methods. We may mention that the general features of our data are similar to the low and high field DC magnetic hysteresis loops obtained for $La_{1\cdot 85}Sr_{0\cdot 15}CuO_4$ and $YBa_2Cu_3O_7$ specimens by Senoussi *et al* (1987a, b). However, they did not observe the expected anomaly.

The $RBa_2Cu_3O_7$ (R = Gd, Y and Ho) samples used in the present study are of a high quality. All of them attain zero resistance state above 90 K and the 10% to 90% widths of the diamagnetic transition in the AC susceptibility data, recorded in a peak field of 0·5 Oe at 320 Hz, are < 2 K. The high (Radhakrishnamurty *et al* 1971) and the low field (Likhite and Radhakrishnamurty 1966) techniques used for the present purpose were developed originally for the rapid study of the superparamagnetic aspects of rock samples. The high T_c sample, in the form of a thin pellet 8 mm in diameter and 2 mm in thickness, is enclosed in a teflon capsule with a hole. The capsule is immersed in a liquid nitrogen bath to precool it to 77 K and then quickly transferred into the sample holder of the apparatus. The liquid N_2 trapped inside the capsule maintains the temperature of the sample at 77 K for about a minute. The current value of the field coil is preset to the desired value before the insertion of the sample. The hysteresis loops displayed on the oscilloscope screen are photographed at 77 K and at various stages during the rapid warm up cycle. The low (up to 8 Oe) and high (100 to 1650 Oe) field traces were obtained at frequencies of 317 Hz and 50 Hz respectively. Some of the representative loops obtained in peak fields of 1650 Oe, 500 Oe, 8 Oe and 4 Oe for $GdBa_2Cu_3O_7$ and $YBa_2Cu_3O_7$ specimens are displayed in figures 1 and 2. The loops of Ho specimen are similar to those of Gd specimen but the anomaly near H = 0 is somewhat less perceptible in the high field loop.

We show the M versus H (figures 1a and 1b) and $\mathrm{d}M/\mathrm{d}H$ versus H loops (figures 1c and 1d) for Gd and Y specimens in a peak field of 1650 and 500 Oe respectively. It is interesting to note that the anomaly predicted by Ravi Kumar and Chaddah (1987) appears as a pair of kinks symmetrically located about H = 0 in the M versus H loop (figure 1a) of Gd specimen (the oscilloscope trace has been deliberately off-centered to make the kinks visible clearly). The manifestation of this anomaly can be seen more clearly in the $\mathrm{d}M/\mathrm{d}H$ versus H loop (figure 1c). The kinks of figure 1a correspond to the pair of spikes in figure 1c. The kinks and the corresponding spikes are also seen in the loops of the Ho sample. However, this anomaly is not detectable for the Y specimen (see figures 1b and 1d).

Figure 2 shows the low field hysteresis loops of Gd specimen in two different fields and at three different temperatures. It should be mentioned that these loops in low field, especially those in 4 Oe, have been photographed close to the sensitivity limit of the apparatus and hence the oscilloscope trace is very thick due to the noise level. However, the magnetic behaviour of the sample could be deciphered adequately from these loops. It may be pointed out that the phase of the magnetization signal in figure 2 has been reversed to avoid overlapping of the trace with the luminous scale indications in left top corner of the oscilloscope screen. Figure 2a shows that at 77 K M versus H is almost linear and reversible in a field of 4 Oe. We note that at 77 K the nonlinearity and irreversibility set in at a field value of about 5·5 Oe, which may be taken as an estimate of H_{c1} at that temperature. Figures 2b and 2c show that nonlinearity and irreversibility can set in even in a field of 4 Oe as the sample warms

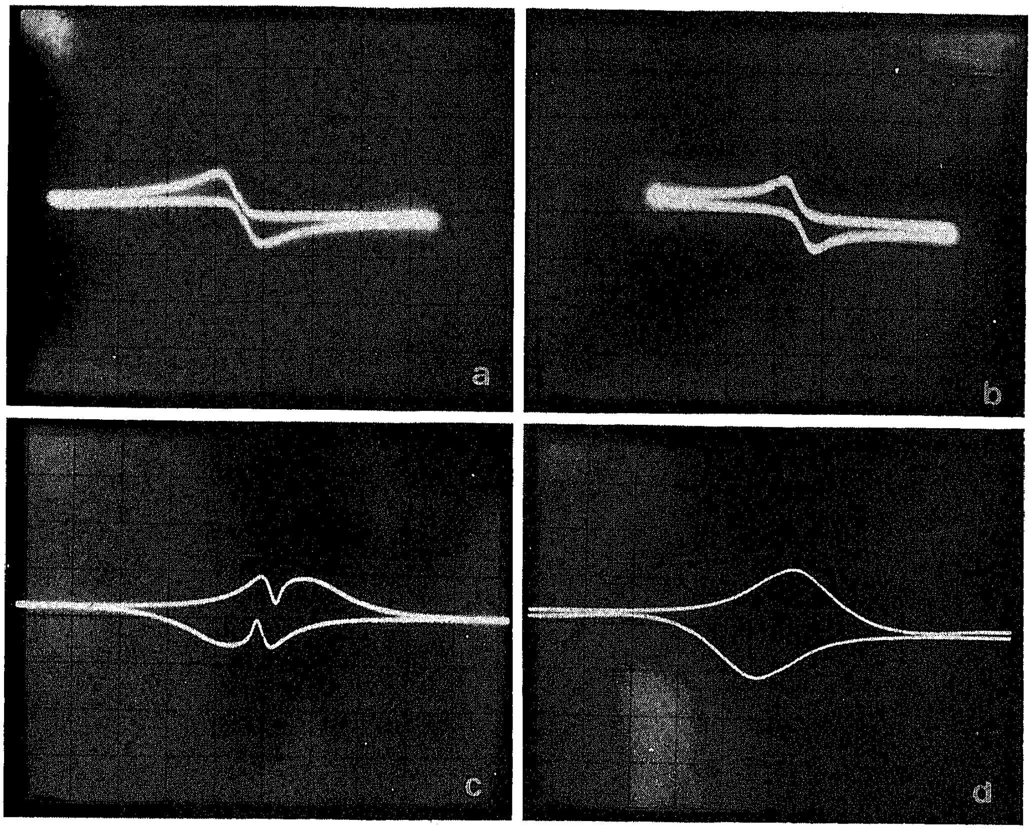

Figure 1. High field hysteresis loops for $GdBa_2Cu_3O_7$ and $YBa_2Cu_3O_7$ superconductors at 77 K. **a** and **b** are M versus H loops in a peak field of 1650 Oe at 50 Hz for Gd and Y specimens respectively. **c** and **d** are dM/dH versus H loops in a peak field of 500 Oe for the same specimens. Vertical scale is arbitrary for all the loops.

up. This is understandable as H_{c1} decreases on approaching T_c. Figure 2d shows a hysteresis loop in field of 8 Oe at 77 K. Figures 2e and 2f show that the loop becomes wider before collapsing on approaching T_c. The shape of the loop in figure 2f, namely the irreversible nature near the origin superimposed on the reversible linear portion at higher values of field, is reminiscent of some of the traces reported by Senoussi *et al* (1987a, b) in high T_c specimens. The H_{c1} values estimated by the low field hysteresis method in Ho and Y specimens are $\sim 3{\cdot}5$ Oe and $\sim 3{\cdot}0$ Oe respectively at 77 K. Low field response of Ho and Y specimens is similar to that in Gd specimen.

As stated above, H_{c1} at any temperature is easily ascertained from the low field hysteresis data by varying the peak field. The anomaly in the high field hysteresis curve occurs at $|H| < H_{c1}$ and a typical calculated curve (Ravi Kumar and Chaddah 1987) is shown in figure 3. The extent of this anomaly depends, however, on both H_{c1} and a parametric field H^* which depends directly on the critical current density J_c and the grain dimensions D. The anomaly will become less perceptible as H_{c1} reduces, or as the sample becomes less homogeneous. The latter causes a distribution in H^* because of a distribution in either D or J_c, and this may cause a smudging of the anomaly. The onset of low field hysteresis with increasing peak field on the other hand, is a direct measure of H_{c1} irrespective of any distribution in D and/or J_c. Thus any sample which shows an anomaly in the hysteresis curve must provide a measurable low field hysteresis, while the converse need not be true. The absence of the anomaly

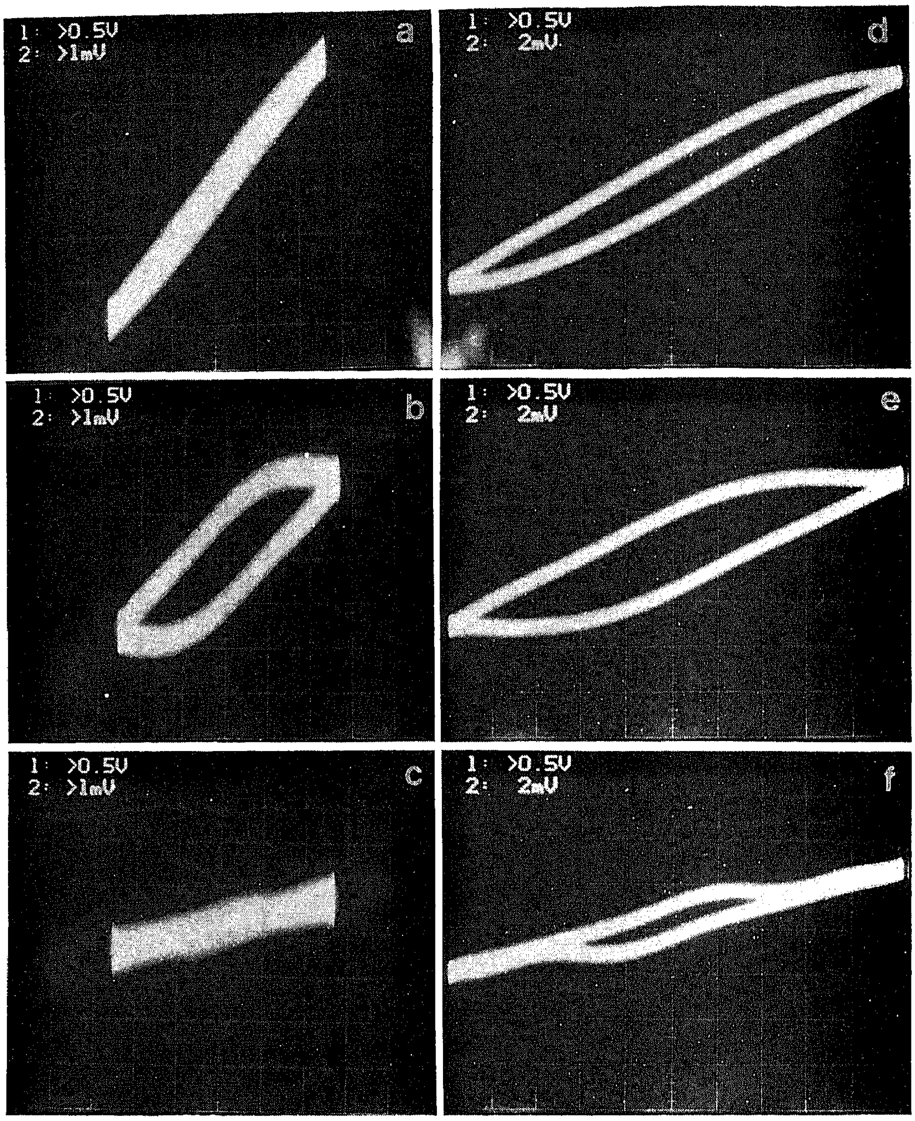

Figure 2. Low field hysteresis loops for Gd superconductor in peak fields (317 Hz) of 4 Oe (**a** to **c**) and 8 Oe (**d** to **f**) at various temperatures. **a**. 77 K. **b**. 77 K $< T < T_c$. **c**. $T \rightarrow T_c$. **d**. 77 K. **e**. 77 K $< T < T_c$. **f**. $T \rightarrow T_c$. Vertical scale is arbitrary for all the loops. It may be noted that the phase of the magnetization signal has been reveresed for convenience (see text).

in our $YBa_2Cu_3O_7$ sample could be due to a smudging caused by a distribution of H^*. It could also be due to its H_{c1} being lower than that of $GdBa_2Cu_3O_7$ and $HoBa_2Cu_3O_7$.

An outcome of the present work is the fact that the fast AC methods can be used to study the onset of low field hysteresis as well as to detect any anomalies in the magnetic behaviour present in high field hysteresis curves of the high T_c superconductors. It may be cautioned that AC and DC methods are not expected to give identical results because of some additional losses in AC fields.

To conclude, we have shown that H_{c1} in high T_c superconductors is very low. The values of $\sim$ 5 Oe at 77 K appear to be consistent with the observation of Gammel *et al* (1987) of homogeneous flux penetration at 4·2 K in a field of 13 Oe. Theirs was a single crystal sample and the flux has penetrated the bulk of the material. It is our

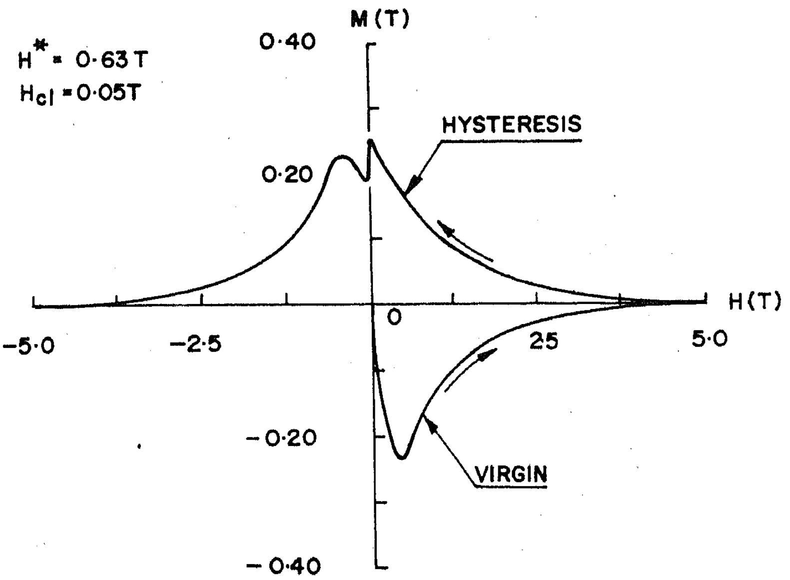

Figure 3. Calculated M versus H curve for $H_{c1} = 0{\cdot}05$ Tesla, $H^* = 0{\cdot}63$ T and $H_0 = 1{\cdot}0$ T. Only half of the symmetric hysteresis loop has been plotted. For meaning of H^*, H_0 and other details see Ravi Kumar and Chaddah (1987).

contention that the hysteresis seen by us in less than 10 Oe at 77 K corresponds to flux penetrating within the grains and the low H_{c1} is intrinsic to high T_c superconductors.

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