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# Effect of flux re-distribution on resistivity in granular YBCO

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**Abstract**

Dc resistivity of a zero-field cooled YBCO was previously studied as a function of angle between applied field and transport current. The resistivity followed a $\sin^2\theta$ variation that was understood as a consequence of Lorentz force like effect. The resistivity deviated from the harmonic curve giving a minimum at low angles before following the true $\sin^2\theta$ behavior. The angle corresponding to minimum voltage $\theta_{min}$ has been thoroughly studied in this paper as a function of applied field, transport current and temperature. $\sin^2\theta$ behavior of resistivity is not affected by the fields below Hc1 at their respective temperatures. The angle $\theta_{min}$ reduces with increasing fields and vanishes at about fields of 8 kOe for 77K. $\theta_{min}$ also decreases with increasing values of current and temperature when studied under constant externally applied field. The data are explained as a consequence of Lorentz force-mediated flux re-distribution in the inter- and intragranular regions which further support the idea of controversial Lorentz force-like dissipation.

**Key Word:** Polycrystalline YBCO, dc resistivity, angular dependence, Lorentz force-like effect.

## 1. Introduction

The different superconducting nature of intra- and inter-grain regions in type II high $T_c$ granular superconductors in the presence of external applied field is still not completely understood. The grains have large critical currents and fields [1] whereas intergrain regions have much smaller values [2] of the same. The structure of the vortex in the intra grain region is some how well defined and subjected to much stronger pinning while the structure of vortices in the intergrain regions i.e. depressed superconducting regions is still under discussion. However, these vortices are much weakly pinned. The movement of vortices in a flux flow like dissipation is dominant [3] by the intergrain fluxons which is true in particular at smaller values of J and B, while at fields H $\gg$ $H_{c1}$ one may expect contributions to the dissipation from both inter- and intragrain components. The effect of Lorentz force on the dynamics of vortices and hence on the dissipation of energy is also controversial. There are reports both in favor of [4-6] and against [7, 8]. Following the discussion of Lorentz independent force dissipation, Kes et al [7] have argued that the flux line is no longer a straight line in the sample, resulting in the formation of vortex pancakes on the superconducting $CuO_2$ plane connected by the kinks and Josephson vortices between the $CuO_2$ plane. A $\sin^2\theta$ variation of the angle dependent dissipation has been reported [4, 6, 9] in a number of reports, a typical signature of the Lorentz-like force-mediated voltage. In previously reported works [6, 10] we also observed a $\sin^2\theta$ variation of resistivity, but with a anomalous deviation of dissipation from $\sin^2\theta$ variation at low angles before following the pure $\sin^2\theta$ behavior. In this report we have thoroughly studied this anomalous feature of resistivity as a function of various operating parameters and have argued that this feature is also a consequence of Lorenz force like effect.

## 2. Experimental

A bar shaped $YBa_2Cu_3O_{7-y}$ (YBCO) polycrystalline sample with $T_c$ of 92K and $H_{cl}$ of 75Oe was used for these studies as well. Standard four probe dc resistivity method was used for these studies. The sample had dimensions of (2.4x1.5x12) mm$^3$ for all the data, unless otherwise mentioned for some specific tests. The angle dependence of the dissipation $\rho(\theta)$, where $\theta$ is the angle between the applied field H and current density J, were performed with the sample zero field cooled in the $\theta = 0°$ position. The sample was rotated in such an arrangement so that H, J and the sample remained in the same plane. Angular resolution of 1° was obtained. The rotation was performed continually without bringing $\theta$ back to zero, before proceeding to the next angle. An adequate time was taken to ensure that eddy currents or relaxation like changes in the voltage accompanying the rotation had died out.

## 3. Results and discussion

Figure 1 introduces the general features of the $\rho(\theta)$ measurements, showing the variation of resistivity as a function of $\theta$, the angle between H and J. The data had been obtained in zero field cooled (ZFC) conditions at 79.3K in 2 kOe field and 100mA current. The data points for increasing and decreasing angles are indicated. Several features are immediately obvious from the figure, which essentially represents the general behavior for all fields expect the deviation at low angles. This anomalous feature will be our prime focus in the following figures. The above data show both angle-independent and angle-dependent parts. The angle independent dissipation is larger compared to the angle dependent part at this specific field, current and temperature. The relative magnitudes of these two parts are found to be field, current and temperature dependent [10]. The data is fit to the expression

$$\rho(\theta) = a + bsin^2\theta. \tag{1}$$

The harmonic behavior of the data is apparent from the good fit (solid line in Figure 1) to the $\sin^2\theta$ function. It is clear from the data that on increasing $\theta$ from 0°, the dissipation first decreases, goes through minimum at an angle $\theta_{min}$ , before rising again to join the $\sin^2\theta$ curve. This feature is absent in the data for decreasing angles indicating the hysteric nature of this deviation. This lack of reversibility around $\theta = \theta_{min}$ suggests that the initial decrease in the voltage could be due to one of the following reasons: a) expulsion of the part of the flux from the sample when it is rotated from $\theta = 0°$. This flux expulsion could obviously result in lowered dissipation. b) A re-arrangement of the flux between grains and the inter grain regions, subsequent to the rotation could also lead towards a less dissipative distribution. Another doubt could be an experimental artifact related to the sense of rotation. This was checked by rotating the sample both ways i.e. clockwise and counterclockwise. Figure 2 shows the V($\theta$) behavior when sample was rotated both ways. The data was obtained at 77K in the field of 1kOe by applying transport current of 150 mA. A mirror image of the curve at $\theta_{min} \cong 18°$ was observed. The sample was taken above $T_c$ and was again zero field cooled prior to making each of the tests, to erase any magnetic history. We also checked whether the hypothesized flux redistribution was actually determined by the angle between J and B, or whether the angle simply referred to a rotation with respect to any starting condition. On initiating the experiment at a perpendicular orientation of J and B, i.e. $\theta = 90°$, we observed a smooth $\sin^2\theta$ variation with a maximum at $\theta = 90°$ and no anomalous decrease was observed. This is to be expected if the flux movement is Lorentz force mediated, since on initiating the measurements at $\theta = 90°$, the $J \times B$ force is maximum and complete flux redistribution (between inter- and intragrain regions) has already taken place, and subsequent rotation makes no difference to the flux arrangement.

To test hypothesis (a) we checked the zero field cooled magnetization at fields of 250 Oe and 500 Oe as a function of angle with respect to initial direction i.e. M($\theta$). If any flux depinning were to take place at low angles this would be evident as increased diamagnetism [11, 12]. However no flux depinning was observed in these tests, (though it was clearly seen under field cooling conditions at 1 kOe). Hence flux expulsion cannot account for the effect. However, it is possible that the flux redistributes itself without leaving the sample i.e. without changing the total magnetization. Such redistribution would of course not be measurable in our magnetization measurements as they only measure the total magnetic moment and are insensitive to such fine redistribution. This redistribution is most probably between the grains and the inter grain region between them. The flux re-distribution effect can be understood by observing that on zero field cooling at ($\theta = 0°$), the flux is concentrated more in the intergrain regions while the

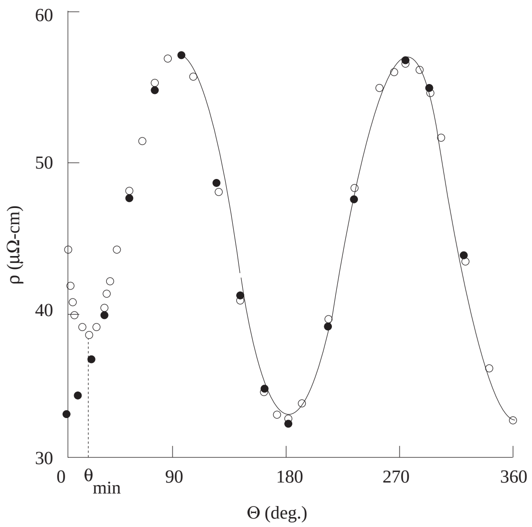


**Figure 1.** The angular dependence of zero field cooled resistivity at 79.3 K for H = 2 kOe and I = 100 mA of YBCO sample. The open circles (o) are for data taken in increasing and closed circles (•) for decreasing angles. The solid line represents the best fit to Eq. 1. Note the local minimum in resistivity at $\theta_{min}$ and the hysteresis close to $\theta = 0°$.

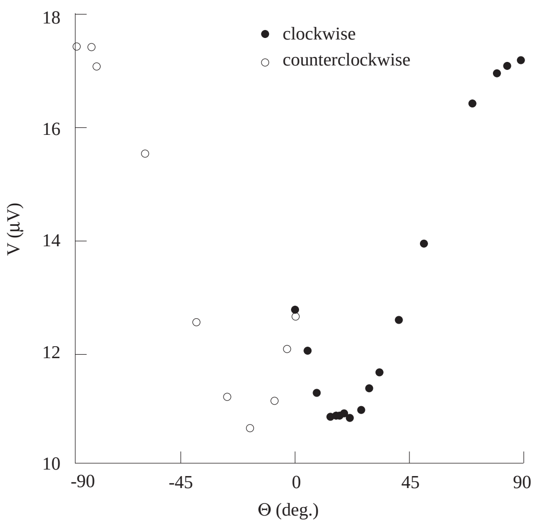


**Figure 2.** Angular dependence of voltage of a zero field cooled YBCO sample at 77 K for H=1kOe and I=150 mA. Note the drop in voltage at $\theta_{min}$ on both sides of $\theta = 0°$.

grains are highly flux-excluding. This has been reported in a number of similar works [3, 13] and is attributed to the large difference between the $H_{c1}$ of the grains and the intergrain regions as well as the respective pinning strengths. When $\theta$ increases, the Lorentz force pushes the vortices into the grains provided H > $H_{c1}$ between the grains. The reduced flux density in the intergrain region leads to a reduced value of the phase slip component. With increase of $\theta$, the flux flow part $\sin^2\theta$ also begins to get significant. Finally, the decreasing trend is overcome by the increasing flux flow part, at $\theta_{min}$ . This redistribution probably does not increase the flux density within the grains to any significant extent, thereby ensuring that the overall effect of the redistribution is to decrease the dissipation. This feature is supported by the observations at low fields, e.g. H $\approx$ 40 Oe where we do not observe low angle anomaly. Here, the field being less than $H_{c1}$ in the grains, does not permit flux entry into the grains on rotation. Thus with increasing $\theta$, the flux flow part of resistivity increases. At higher fields, H $\gg$ $H_{c1}$, flux distribution between inter and intra grain regions is more uniform and the effect of redistribution of flux is expected to be small. This is consistent with data at higher fields where the low angle anomaly is much weaker, and eventually vanishes at a temperature dependent field.

To check our hypothesis further we studied the field-cooled resistivity. The idea here was that in the field-cooled state, there is already a significant amount of flux trapped within the grains and therefore the flux distribution is expected to be more uniform [13]. Hence on rotation there should be smaller redistribution effects. The field cooled (FC) resistivity data taken for YBCO showed that the voltage increases immediately as we rotate the sample without giving any trace of a dip. This trend was expected due to presence of uniformly distributed flux in the intra grain regions as initial rotation of sample (hence current) could not push the inter grain flux into the intra grain region to decrease dissipation. (A small amount of hysteresis in the low angle region was visible, consistent with the flux depinning that occurs in field cooled samples, on rotation of M with H).

All these observations led us to the conclusion that the effect was due to the redistribution of flux between inter and intra grain regions. Immediately after zero field cooling the field is highly concentrated in the inter grain regions which on rotation, due to a finite $J \times B$ force ($\theta \neq 0°$), is driven into the grains themselves.

### 3.1 $\theta_{min}$ as a function of H and I

We extended the experiment to further verify and explore the variation of $\theta_{min}$ with applied magnetic field and current at constant temperature. We performed the $\rho(\theta)$ experiment in fields greater than $H_{c1}$ that included 0.5 - 8 kOe. The temperature was kept at 77K for field dependent $\rho(\theta_{min})$ experiments whereas the value of current was kept at 100 mA. The variation of $\theta_{min}$ as a function of applied field over the entire range of field is plotted in Figure 3a. We see a rapid decrease in the value of $\theta_{min}$ up to 2 kOe, and a comparatively slow drop after that field, with $\theta_{min}$ vanishing somewhere close to 8 kOe. Such a trend was expected from the argument of flux redistribution. As in field cooled conditions, or at higher fields, the flux density in inter- and intragrain regions is much more homogenous [3], the vanishing of the effect indicates that the low angle behavior is important when the flux densities in the two regions are very different. The reduction in $\theta_{min}$ and hysteresis with increasing fields is in accordance with our earlier discussion which support the flux redistribution in inter and intra grain regions. At higher fields the flux present inside the grains is already uniformly distributed and only a small amount of new flux may be pushed inside by the driving force resulting in reduction of $\theta_{min}$ value with increasing fields.

We also investigated the current dependence of this effect, since any effect related to the Lorentz like force is expected to vary with the current. The temperature was fixed at 77K while the field was kept at 2 kOe. Data for $\rho(\theta_{min})$ behavior were taken in the current range of 20 mA $\leq$ l $\leq$150 mA. It is clear from the (Figure 3b) that $\theta_{min}$ (the angle upto which the voltage decreases) decreases with increasing current. $\theta_{min}$ was as large as 25° for I = 20 mA, became 18° for 50 mA and was finally reduced to 10° for 100 mA. However, beyond 100 mA, upto 150 mA, there appeared to be no change in $\theta_{min}$. The value of $\theta_{min}$ decreases slowly for the initial increase in current values and at large values it became even slower. This trend is in contrast to the rapid drop in the value of $\theta_{min}$ observed at low and increasing fields. The decrease in $\theta_{min}$ with increasing J implies that the driving force $J \times B = JB$ sin$\theta$ becomes sufficiently large at relatively smaller angles, so as to be able to move the vortices into the grains. The constancy of the angle $\theta_{min}$ (at $\cong$ 10°) for higher currents (I > 100 mA) is not surprising since the flux redistribution requires a finite $J \times B$ force, i.e. a significant angle $\theta$. The next point about the $\rho(\theta)$ behavior is the hysteresis between increasing and decreasing angles. Here, we compare the data for $\theta$ increased upto $2\pi$ and then decreased back from $2\pi$ to zero. The data for 50 mA current are shown in Figure 4 shows hysteresis between zero and 90°. For higher currents I=75 mA this range is reduced to about 45° while for I=150 mA this hysteresis extends only up to 20°. Thus the irreversible behavior of $\rho(\theta)$ diminishes as we move towards higher currents. In all cases the hysteresis follows the same pattern viz. the dissipation in decreasing angle is less than the corresponding values in increasing angles. The hysteresis indicates firstly, that flux distribution effects between inter- and intragrain persist beyond $\theta_{min}$, up to 90° for the smaller currents. Secondly, the angular extent up to which the flux distribution produces the hysteresis, depends upon the driving current. The higher the driving current the earlier the flux distribution completes itself. Thus this effect gives clear evidence of the current dependence of the flux redistribution tendency. Lower dissipation on the return path, indicative of a reduced flux density in the intergrain, has also been confirmed by $\chi'_{ac}$(H) measurements [14, 15]. While these latter measurements did not vary the angle $\theta$ they clearly showed that in increasing fields the flux density is initially larger in the inter grain regions.

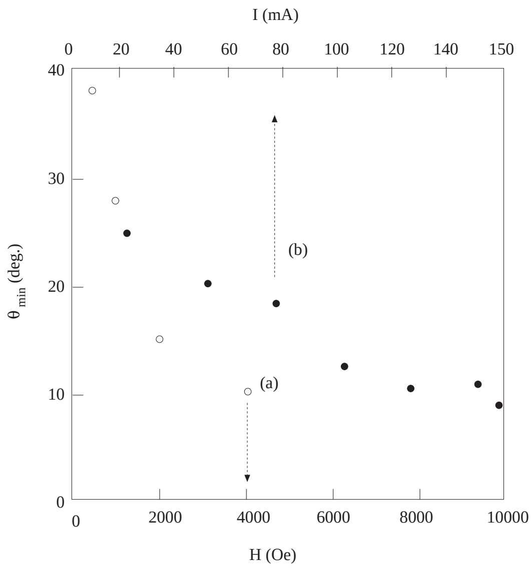


**Figure 3.** The variation of $\theta_{min}$ as a function of a) applied field for I = 100 mA and b) transport current for H = 2 kOe, at 77 K.

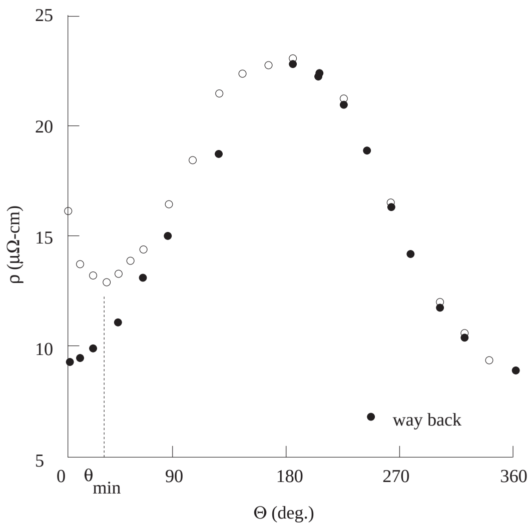


**Figure 4.** The angular dependence of resistivity at 77 K and I = 50 mA in an applied field of 2 kOe. Note the local minimum in resistivity at $\theta_{min}$ , and the hysteresis between increasing and decreasing angles.

### 3.2 $\theta_{min}$ as a function of temperature

We extended our experiments to higher temperatures. The temperature dependence was anticipated since with increasing temperature the decrease in $H_{c1}$ and flux pinning facilitate the flux entry into the sample, and tends to homogenize the flux distribution. In the temperature dependent data the current was fixed at 50 mA while the field was 2 kOe. The data were taken at 77 K, 80.6 K and 86.2 K. Figure 5 shows the variation of dissipation as a function of angle between the field and current at 86.2 K. The value of $\theta_{min}$ at T= 80.6 K is 10°, whereas it was 15° at 77 K. Also that the width of hysteric region at 80 K is close to 60°, while at 77 K this extends upto about 90°. At 86.2 K, (Figure 5) there is a continuous increase in voltage i.e. no minimum in $\rho(\theta_{min})$. The hysteresis is negligible and the differences are within the error at this temperature. This reduction in the value of $\theta_{min}$ with temperature clearly reflects that the occurrence of a minimum depends upon temperature. This behavior is understandable in the sense that with increasing temperature the flux enters the grains with increasing ease. This is enhanced both by virtue of low shielding currents and reduced pinning. Hence the inter and intra grain flux densities tend to become uniform and no redistribution of flux occurs at higher temperatures e.g. at 86.2 K and H=2 kOe, as in Figure 5.

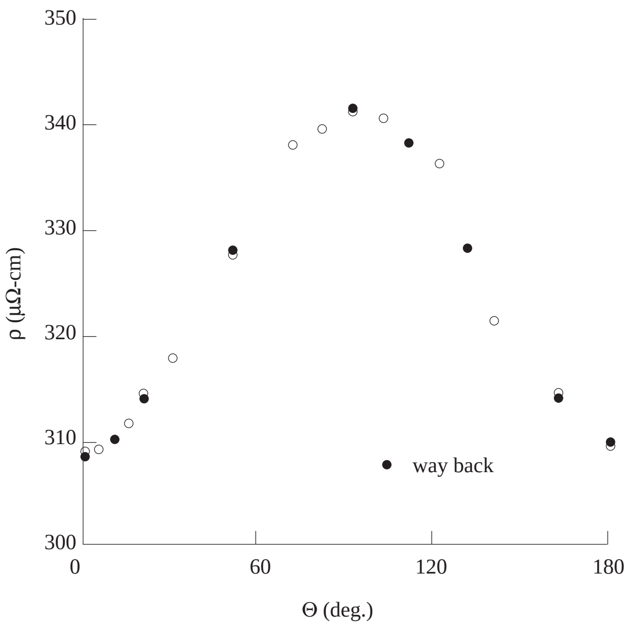


**Figure 5.** The angular dependence of resistivity at 86.2 K and I = 50 mA in an applied field of 2 kOe. Note the absence of minima in resistivity and the hysteresis between increasing and decreasing angles.

## 4. Conclusion

The deviation from $\sin^2\theta$ behavior and the hysteresis at low angles in resistivity are attributable to a Lorentz force mediated flux redistribution between inter and intra grain regions. Increasing fields, temperature, currents and field cooling conditions homogenize the flux distribution in intra grain regions and reduce such effects. We understand that these studies further support the Lorentz force like flux flow behavior.

## References

[1] P. Chaudhari, R.H. Koch, R.B. Laibowitz, T.R. McGuire, and R.J. Gambino, *Phys. Rev. Lett.* **58**, (1987) 2684.

[2] D. Shi, D.W. Capone II, G.T. Goudey, J.P. Singh, N.J. Zaluzec, and K.C. Goretta, *Mater. Lett.* **6**, (1988) 217.

[3] L. Ji, M.S. Rzchowski N. Anand, and M. Tinkham, *Phys. Rev.* **B 47**, (1993) 470.

[4] H.A. Blackstead, D.B. Pulling, and C.A. Clough, *Physica* **C 175**, (1991) 6955.

[5] Y. IYE, A. Watanabe, S. Nakamura, and T. Tamegai, Physica C 167, (1990) 278; D. Lopez, R. Decca, and F. De La Cruz, *Supercond. Sci. Technol.* **5**, (1992) S276.

[6] S.K. Hasanain, and M.M. Asim, *Int. J. Mod. Phys.* **B 8**, (1994) 4007.

[7] K. Kadowaki, Y. Songliu, and K. Kitazawa, *Supercond. Sci. Technol.* **7**, (1994) 519.

[8] P.H. Kes, J. Aarts, V. M. Vinokur, and C.J. Van der Beek, *Phys. Rev. lett.* **64**, (1990) 1063.

[9] H.A. Blackstead, D.B. Pulling, D.G. Keiffer, M. Sanakararaman, and H. Sato, P*hysics Letters* **A 170**, (1992) 130.

[10] M.M. Asim, and S.K. Hasanain, *Supercond. Sci. Technol.* **9**, (1996) 461.

[11] A. Mumtaz, H. Athar, S.K. Hasanain, and J.A. Khan, *Solid State Commun.* **79**, (1991) 601.

[12] Y. Wolfus, Y. Yeshurun, and I. Felner, *Phys. Rev.* **B 37**, (1988) 3667.

[13] D. Lopez, R. Decca, and F. De La Cruz, *Solid State Commun.* **79**, (1991) 959.

[14] S.K. Hasanain, S. Shahzada, A. Mumtaz, and G.S. Bhatti, *Physica* **C 269**, (1996) 149.

[15] K.N.R. Taylor, J. Wang, G.J. Russel, *Mod. Phys. Lett.* **B 7**, (1993) 83.