Flux cutting in YBa$_2$Cu$_3$O$_7$–δ single crystals: experiment and phenomenological model.

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Abstract

We measured the current induced loss of vortex correlation in YBCO crystals using the pseudo DC flux transformer geometry. We find that the current $I_{cut}$ at which the top and bottom voltage drops differ is a linear function of temperature independent of pinning. Although the vortex correlation length at $I_{cut}$ coincides with the sample thickness, the experimental data show that $I_{cut}$ is sample thickness independent. The observed behavior with temperature, magnetic field and thickness is described by a phenomenological model.

74.40.+k, 74.60.Ge, 74.60.Jg
The laminar structure of the high temperature superconductors has important influence on the vortex behavior in the mixed state. This laminar structure and the presence of thermal fluctuations yields an extremely rich $H-T$ phase diagram. Recent experiments, using a DC flux transformer contact configuration, have shown that the correlated vortex motion can be destroyed by either thermal fluctuations or the application of large driving forces. The non-homogeneous current distribution induced in electrical transport measurements in YBCO(123) single crystals, in the DC-transformer configuration, has been used to determine the correlation length of the vortices in the direction of the applied field (c crystallographic direction). It was shown that there is a well defined temperature, $T_{th}(H)$, above the irreversibility line $T_i(H)$, where the correlation of the vortex velocity across the sample is lost. This has been interpreted as a decoupling of the vortices nucleated in the Cu-O planes. Since this decoupling takes place in the linear current-voltage response regime it is concluded that at that temperature the vortex correlation length in the direction of the applied field coincides with the thickness, $d$, of the sample. As a consequence the transport measurements in samples of different thicknesses have been used to determine the temperature dependence of the correlation length in the c direction at different fields. On the other hand transport measurements in the linear regime using a Montgomery type analysis have led to the conclusion that the transport properties of the vortex liquid phase has a non-local character. The non-local character of the electrodynamics induces an enhancement of the apparent anisotropy of the resistance of the vortex liquid in the DC transformer configuration.

In this paper we concentrate our interest in the study of the I-V characteristics for $T < T_{th}$ and temperatures above and below the reversibility line, defined as the temperature $T_i(H)$ where the resistance of the $ab$ planes tends to zero. For $T > T_i(H)$ the I-V characteristics show a linear regime at low currents and become non linear at higher currents. For $T < T_i(H)$ the response is non linear for all currents. It is shown that for $T < T_{th}$ flux cutting is induced by a current $J_{cut}(H,T,d)$, in the non-linear response regime.

The experimental results are consistent with a current distribution flowing near the sample surface. This allowed us to extend the model developed by J. Clem et al. to explain our results obtained using a non-homogeneous current distribution. The results of the model provide a qualitative comprehension of the field, temperature and sample thickness dependence of $J_{cut}(H,T,d)$. It also shows that the understanding of the thickness dependence of $T_{th}$ goes beyond the assumptions made by the model and requires the analysis of the contribution of thermal fluctuations in the vortex transport properties.

The YBCO single crystal was prepared as indicated in Ref. 5. The results presented in this paper were obtained using the same samples and contact configuration described in Refs. 5 and 6.

In Fig. 1 we plot typical I-V characteristics for temperatures above (1a) and below (1b) $T_i = 89.7K$ at a field of 10kOe. In this case the sample thickness is $d = 20\mu m$. The experiment was made injecting current through contacts 1 and 4, $I_{14}$, and measuring the voltages $V_{23}$ and $V_{67}$, see insert in Fig. 1. At low currents $V_{23} = V_{67}$ indicating that the vortices move correlated across the sample. Increasing the driving current, $V_{23}$ becomes different from $V_{67}$ at a well defined current $I_{cut}$ (arrows in Fig. 1) where flux cutting is induced.

Figure 2a shows the cutting current density defined as $J_{cut} = I_{cut}/(d \times w)$ (where $w$ is...
the width of the sample) as a function of temperature for samples of different thickness. The data show that $J_{cut}$ decreases linearly with temperature vanishing at $T_{th}$. For a given temperature, $J_{cut}$ decreases when increasing the thickness. In Fig. 2b we show the same data but scaled by the sample thickness. It is clearly seen that $J_{cut} \times d$ becomes thickness independent. This result indicates that flux cutting is induced by a force that can be associated with a surface current density given by $I_{cut}/w$. That is, the transport current should be considered as flowing in a region close to the surface in a thickness much smaller than d, in agreement with the suggestion made in ref. 7 and with the experimental results obtained in the linear response regime.

It is interesting to point out that the data above and below $T_i(H)$ fall on the same straight line. This is demonstrated in Fig. 2a where $T_i$ ($T_i/T_{th} = 0.985$) is indicated by the arrow for the sample with $d = 48 \mu m$. Thus, flux cutting should be related to the properties of the flux structure, independently of the presence of effective pinning centers. That is, the dynamic vortex correlation length in the field direction is not modified by the introduction of pinning.

With the results and considerations made before we present now a simple model which enables to rationalize the observed field and temperature dependence of $I_{cut}$. The model also explains why $I_{cut}$ is independent of pinning whereas the voltage $V_{cut}$ at the cutting does depend on pinning.

Consider a stack of N superconducting layers with vortex pancakes moving in these layers. The equation of motion for vortex number $i$ in layer number $\nu$ (see Fig. 3a) is given by:

$$\eta v_{i,\nu} = \delta_{1,\nu} f - f_{i,\nu}^{P} + f_{i,\nu}^{v} + (1 - \delta_{1,\nu}) f_{i,\nu}^{\nu-1} - (1 - \delta_{N,\nu}) f_{i,\nu}^{\nu+1}$$

where $\eta$ is a friction coefficient which for convenience we put equal to 1. The terms $f_{i,\nu}^{P}$ denote the total pinning force on vortex $(i, \nu)$. The term $f_{i,\nu}^{v}$ is the force from all the vortices in layer $\nu$ on vortex $(i, \nu)$ and $f_{i,\nu}^{\nu+1}$ denotes the interlayer forces between the vortices. We assume that the effect of the external current is to give rise to a driving force $f$, which is confined to the top layer. This assumption is consistent with the experimental observation as discussed above. It is also in accordance with the phenomenological viscous hydrodynamics of Huse and Majumdar. However, it should be mentioned that Huse and Majumdar work in the limit of linear resistance, whereas the cutting by current always occur in the non-linear region.

We want to determine the average velocity in layer $\nu$: $v_{\nu} = \langle v_{i,\nu} \rangle$, since the voltage drop over that layer is proportional to $v_{\nu}$. We consider the situation where the average velocity is the same in each layer, i.e., $v = v_1, v_2, \ldots, v_N$, thus $V_{top} = V_{bottom} (V_{23} = V_{67})$. Assuming that the average of the pinning force over vortices and time is independent of the layer number, we obtain the following equation:

$$v = \delta_{1,\nu} f - f^{P} + (1 - \delta_{1,\nu}) f_{\nu}^{\nu-1} - (1 - \delta_{N,\nu}) f_{\nu}^{\nu+1}$$

This set of equations is readily solved to give:

$$f_{\nu}^{\nu+1} = \frac{N - \nu}{N} f$$
The largest stress is between the two top layers. The driving force at which the velocities in layer 1 and 2 starts to differ is given by:

\[ f_{\text{cut}} = \frac{N}{N-1} f_{1,\text{max}}^{2} \simeq f_{\text{max}} \]  

(4)

where \( f_{\text{max}} \) is the maximum force which the bonds between pancakes in adjacent layers can sustain. Notice that \( f_{\text{cut}} \) is independent of the pinning forces. In contrast, the velocity (or voltage) at cutting does depend on the pinning. By substituting Eq. 4 into the equation for the average velocity one obtain \( v_{\text{cut}} = f_{\text{max}}/(N-1) - f_{p} \). Thus if one knows the friction coefficient \( \eta \) one can determine the intrinsic property \( f_{\text{max}} \) together with the extrinsic pinning force \( f_{p} \) by a combined measurement of the voltage and the current at cutting.

To estimate \( f_{\text{max}} \) is like to estimate the yield strength of a material. It is not easy. Let \( \Delta x_{\text{max}} \) denote the displacement of vortices in layer 2 at which plastic slip sets in (see Fig. 3b and 3c). Let \( \Delta E \) denote the associated increase in the energy due to the deformation. We estimate

\[ f_{\text{max}} = \frac{\Delta E}{\Delta x_{\text{max}}} \]  

(5)

Slip will occur when \( \Delta x_{\text{max}} \) reaches some fraction of \( a_{o} \), the distance between the vortices. For small \( a_{o} \) (Fig. 3b), i.e. large magnetic field, we expect \( \Delta E = \kappa_{1} \Delta x^{2} \) where \( \kappa_{1} \) will be a short wave length tilt modulus. For lower fields (Fig. 3c), \( a_{o} \) increases and so do \( \Delta x_{\text{max}} \). In this case we should rather connect \( \Delta E \) with the energy of the Josephson vortex running in between the planes connecting the vortices in the two layers. This suggest that \( \Delta E \) becomes linear in \( \Delta x \) for low fields: \( \Delta E = \kappa_{2} \Delta x \). Both constants \( \kappa_{1} \) and \( \kappa_{2} \) will scale with the superfluid density \( |\psi|^{2} \). The maximum force will behave like

\[ f_{\text{max}} \simeq |\psi|^{2} G(B), \]  

(6)

where \( G(B) = 1 \) for low fields and \( G(B) \sim B^{-1/2} \) for high fields.

We have \( |\psi|^{2} \simeq (1 - T/T_{c})(1 - B/B_{c2}(T)) \). Furthermore, \( f_{\text{max}} = \phi_{o} J_{\text{cut}} l \), where \( l \) denotes the thickness of the layer (\( l \ll d \)) that carries the transport current which gives rise to the Lorentz force. In the model \( J_{\text{cut}} = I_{\text{cut}}/(l \times w) \), therefore

\[ I_{\text{cut}} \simeq (1 - T/T_{c})(1 - B/B_{c2}(T))G(B), \]  

(7)

independent of \( l \).

Using \( B_{c2}(T) = (1 - T/T_{c})B_{c2}(0) \) we finally obtain

\[ I_{\text{cut}} \simeq (1 - T/T_{c} - B/B_{c2}(0))G(B). \]  

(8)

According to this expression, \( I_{\text{cut}} \) depends linearly on the temperature. As \( B \) is increased the intersection of \( I_{\text{cut}}(T) \) with the \( x \)-axis decreases linearly in \( B \). The slope of \( I_{\text{cut}}(T) \) is independent of \( B \) for small \( B \). For large \( B \) the slope decreases as \( B^{-1/2} \). This is in qualitative agreement with the experimental results shown in the inset of Fig. 2b. For a quantitative analysis of the results, more data at higher fields are necessary.
As was discussed above, the experimental results shown in Fig. 2a prove that $I_{\text{cut}}$ is independent of pinning. This agrees with our model, as shown by expression (4), where $f_{\text{cut}}$ is found to be pinning independent despite pinning is included in the equations of motion (see equation [4]). Thus, expression (8) describes the experimental temperature and field dependence of $I_{\text{cut}}$ and shows that $I_{\text{cut}}$ is an intrinsic property of the flux structure, in agreement with the data of Fig. 2a.

We have restricted our discussion to purely mean field considerations neglecting thermally induced vortex fluctuations. We now want to turn our attention to the field dependence of $T_{\text{th}}$. As shown in Fig. 4 one finds experimentally that $T_{\text{th}}$ depends linearly on the magnetic field. In accordance with the definition of $T_{\text{th}}$, it appears natural to associate this temperature with the temperature where vortex-antivortex pairs thermally activated in the superconducting planes unbind. The unbinding in zero field happens when the ratio $T/|\psi|^2$ achieves a certain invariant value [11]:

$$\frac{T_{\text{ub}}}{|\psi(T_{\text{ub}})|^2} = \text{const.}$$  \hfill (9)

It has previously been suggested [12] that the effect of the external magnetic field on the unbinding transition in a first approximation can be obtained simply by including the mean field dependence on $B$ in $|\psi|^2$ in Eq. (4).

This leads to

$$\frac{T_{\text{ub}}(B)}{T_{\text{ub}}(0)} = 1 - \frac{B}{B_c(T = 0)}. \hfill (10)$$

The linear field dependence of $T_{\text{ub}}$ and the decoupling of the layers [13] at $T_{\text{ub}}$, strongly suggest that $T_{\text{ub}}$ is identical to $T_{\text{th}}$. The dependence of $T_{\text{th}}$ on thickness arises then as an effect of the correlation length (in the field direction) connected with the unbinding transition becoming equal to the sample thickness [14].

We have been able to show that flux cutting in YBCO(123), using the DC transformer configuration, is induced by currents flowing at the sample surface, in strong agreement with the suggestion made in ref. 7 and the previous results of ref. 2, obtained in the linear response regime. This has allowed us to formulate a simple model which disregarding the effect of thermal fluctuations, describes qualitatively the results in the non-linear response regime. The temperature dependence is correctly described by the model, assuming that the coupling between planes has its origin in a Josephson energy.

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FIGURES

FIG. 1. $V_{23}$ and $V_{67}$ as a function of driving current $I_{14}$ for two different temperatures: a) 89.9K and b) 89.4K. Also shown is $\Delta V = V_{23} - V_{67}$. The sample geometry is shown in the inset. The arrows show the current, $I_{cut}$, where $V_{23}$ and $V_{67}$ start to differs.

FIG. 2. a) Temperature dependence of $J_{cut} = I_{cut}/(d \times w)$ for different sample thickness, for an applied field of 10kOe. The arrow shows the corresponding $T_{i}$ for the sample with $d = 48\mu m$. The solid lines are linear fit to the data. b) Same data of Fig. 2a scaled by the sample thickness $d$: $(J_{cut} \times d)$ as a function of temperature. In the inset is shown the temperature and field dependence of $I_{cut}$ for the sample with $d = 32\mu m$. The data were fitted using expression (8)(solid lines).

FIG. 3. Schematic diagram showing the velocity of the pancakes vortices in different superconducting layers (see text). Sketch of the vortex configuration in adjacent layers for large (b) and small (c) fields. $\Delta x$ is the relative displacement between vortices in adjacent layers due to the external current.

FIG. 4. Phase diagram showing the temperature $T_{i}$ and $T_{th}$ for a sample with $d = 20\mu m$. The solid line is a linear fit and the dotted one is a guide to the eye.