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Flux-cutting in $YBa_2Cu_3O_{7-\delta}$ revisited

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Abstract

In this paper we present an analysis of the response of the vortices in $YBa_2Cu_3O_{7-\delta}$ to different configurations of applied driving forces. The use of inhomogeneous current allows us to induce vortex cutting. We determine the maximum current injected in different electrical contact distributions which preserves vortex integrity, and we show that vortex cutting cannot be explained by a single vortex picture. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

The mixed state of high temperature superconductors has been a subject of extensive theoretical and experimental studies [1]. It was early recognized, both theoretically [2] and experimentally [3] that thermal fluctuations melted the vortex lattice into a liquid, characterized by linear resistivity in the *ab* plane, that is, the vanishing of the critical current. Thermal fluctuations can also induce vortex cutting and reconnection in the liquid phase. The problem of longitudinal vortex velocity coherence in the liquid was addressed by several works using the dc-transformer configuration [4]. Using this technique it was shown that in $YBa_2Cu_3O_{7-\delta}$ samples with twin boundaries there is a well defined temperature $T_{th}(d)$ above the melting temperature, where the correlation across a sample of thickness d is lost. Among the consequences of this finite correlation length is the nonlocal character of the resistivity tensor measured in this type of samples [5,6].

At temperatures below T_{th}, the injection of inhomogeneous currents is a controlled way of inducing cutting strains to probe vortex longitudinal coherence. In Ref. [7], the current induced vortex loss of correlation was studied experimentally, and a phenomenological model for vortex cutting was used to explain the results. They used a modified version of Giaver's flux transformer geometry [4], in which the intrinsic anisotropy of the high T_c superconductors is used to achieve an inhomogeneous distribution of the current in the direction perpendicular to the magnetic field. The result is that a single vortex experiences Lorentz forces which are different in different regions of the sample. In this way a shear strain proportional to the current shear stress is exerted upon the

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vortices. When the current is raised above some threshold current, I_{cut}, the strain induced upon the vortices is such that the vortices cut. They subsequently studied the temperature and field dependence of this cutting current I_{cut}.

In this paper we revisit the problem of current-induced vortex cutting. We first consider a trivial extension of the phenomenological model used in Ref. [7] to take into account different current configurations. Next we consider the experimental results obtained in this configurations and show the inadequacy of this model to explain our results. Finally we propose a different criteria for vortex cutting which proves to be more successful.

2. Theory

Flux cut experiments have been explained in terms of a model introduced by Ekin and Clem [9] and generalized in Ref. [7], which we (trivially) extend to the case of different top and bottom currents. The material is modeled as an array of N superconducting layers, each one containing a number of vortex segments. Each segment in a layer is subject to forces due to interaction with its nearest neighbours, pinning, and an external force which can be different in each layer. In this situation, the equation of motion for the vortex i in the layer v is given by the array

$$\begin{aligned} \eta v_{i,1} &= f(1) + f_{i,1}^{1} + f_{i,1}^{2} - f_{i,1}^{\mathrm{P}} \\ &\vdots \\ \eta v_{i,v} &= f(v) + f_{i,v}^{v} + f_{i,v}^{v-1} + f_{i,v}^{v+1} - f_{i,v}^{\mathrm{P}} \\ &\vdots \\ \eta v_{i,N} &= f(N) + f_{i,N}^{N} + f_{i,N}^{N-1} - f_{i,N}^{\mathrm{P}}, \end{aligned} \tag{1}$$

where η is the friction coefficient (which will be taken unity for simplicity) and all forces are assumed parallel to the layer. The (arbitrary) function $f(v)$ is the external force applied to the vortices in layer v, $f_{i,v}^{\mathrm{P}}$ is the pinning force acting upon vortex i in layer v, $f_{i,v}^{v}$ is the force exerted upon (i,v) by neighbouring vortices in the same layer, and $f_{i,v}^{v\pm1}$ denotes the force between the vortex i in layer v and the same vortex in layers immediately above and below. The relation $f_{i,v}^{v+1} = -f_{i,v+1}^{v}$ must hold.

These equations can be easily solved in the case when vortices maintain integrity ($v_{i,v} = v$) and the pinning force is homogeneous ($f_{i,v}^{\mathrm{P}} = f^{\mathrm{P}}$). Then the force between layers is

$$f_{v}^{v+1} = \frac{v}{N}\sum_{i=1}^{N} f(i) - \sum_{i=1}^{v} f(i), \tag{2}$$

independent of f^{P}. It is assumed that a vortex will cut when the force between two elements reaches some threshold $f^{\max}$.

To apply this model to the flux transformer, we recall that it has been shown [7] that in this configuration, the applied currents are confined to a surface layer much thinner than the sample thickness. Thus we can set all external forces to 0 except in the top and bottom layers, and consider $N \to \infty$. This defines the effective thickness of each layer. As discussed below, the vortex cut current cannot be directly determined experimentally when the top and bottom currents are equal. Instead, several measurements are done with a difference Δf between currents, and the result is extrapolated to $\Delta f \to 0$. So we are interested in the case when the external forces are

$$f(v) = \begin{cases} f^{\mathrm{t}} & \text{if } v = 1 \\ f^{\mathrm{b}} & \text{if } v = N \\ 0 & \text{all other layers} \end{cases} \tag{3}$$

The interlayer force is

$$f_{v}^{v+1} = f^{\mathrm{b}}\left(\frac{2v - N}{N}\right) + \Delta f\left(\frac{v}{N} - 1\right), \tag{4}$$

where $\Delta f = f^{\mathrm{t}} - f^{\mathrm{b}}$. This has a maximum for $v = 1$,

$$f_{1}^{2} = f^{\mathrm{b}}\left(\frac{2 - N}{N}\right) + \Delta f\left(\frac{1 - N}{N}\right). \tag{5}$$

The cut is assumed to happen when f_1^2 reaches the threshold current.

With no bottom current ($f^{\mathrm{b}} = 0$), we obtain for the cutting current

$$f_{\mathrm{cut}} = \frac{N}{N-1} f^{\max}. \tag{6}$$

In the case when $f^{\mathrm{t}} = f^{\mathrm{b}}$, the cutting force (which we call $f_{\mathrm{cut}}^{\mathrm{b=t}}$ in this case) is

$$f_{\rm cut}^{\rm b=t} = \frac{N}{N-2} f^{\max}, \tag{7}$$

which in the limit $N \to \infty$ is identical to the $f_{\rm b} = 0$ case. Finally, using Eqs. (5)–(7) we can write for the general case

$$\Delta f_{\rm cut}(f^{\rm b}) = f_{\rm cut} - f^{\rm b} \frac{f_{\rm cut}}{f_{\rm cut}^{\rm b=t}}, \tag{8}$$

where $\Delta f_{\rm cut}$ is the current difference between top and bottom layers needed to cut a vortex at fixed $f^{\rm b}$.

3. Experimental

Several $YBa_2Cu_3O_{7-\delta}$ crystals were picked with a high density of singly oriented twin boundaries, as revealed by polarised light microscopy. They were prepared as indicated in Ref. [4]. In a first stage electrical contacts were put in the configuration of Giaver's flux transformer [4] (see Fig. 1). In some crystals the wiring was later modified, as described below, in order to allow for an homogeneous current to be injected in addition to the flux transformer driving current.

Fig. 2 shows a typical I–V characteristic of the flux transformer current configuration (see Fig. 1(a)) at a fixed temperature $T < T_{\rm th}$. $T_{\rm th}$ is the temperature at which the velocity correlation length becomes of the order of the sample width. For small currents the top and bottom voltages are equal, indicating that the vortices move correlated across the sample. For higher currents, the voltages start to differ as the inhomogeneous current induces vortex cuttings and re-connections. This is better seen through the difference, $\Delta V = V_{\rm top} - V_{\rm bot}$, plotted semi-logarithmically in the inset. The current at which ΔV vanishes below our experimental resolution is what we define as $I_{\rm cut}$. Fig. 3 shows a comparison between the I–V curve corresponding to the flux transformer configuration ($I^{\rm b} = 0$) and the one corresponding to a configuration in which an additional constant current of $I^{\rm b} = 5$ mA is injected through the bottom surface. The applied external field is 1 T and the temperature is 88.38 K. The current ΔI is defined as the difference between that injected in the top and

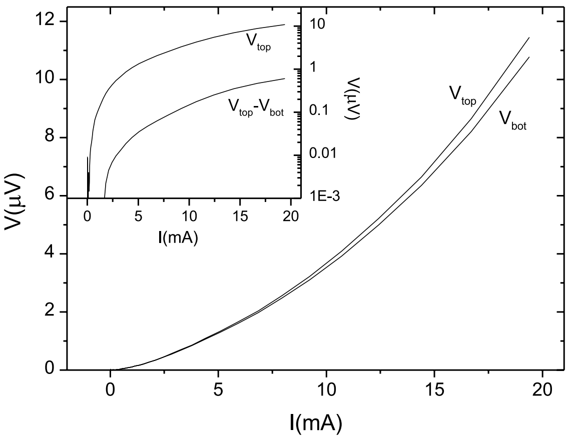

Fig. 2. Top $V_{\rm top}$ and bottom $V_{\rm bot}$ voltages as a function of the current at a fixed temperature of $0.99T_{\rm th}$ and at an applied external magnetic field of 1 T. In the inset the top voltage and the difference $\Delta V = V_{\rm top} - V_{\rm bot}$ on a semi-logarithmic scale.

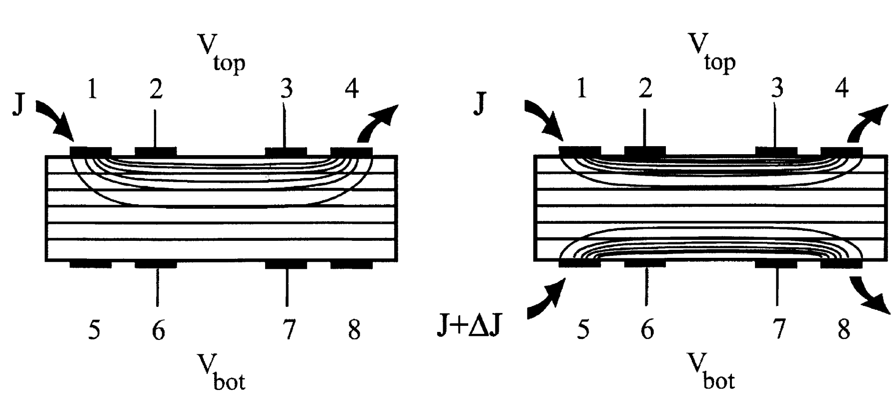

Fig. 1. Schematic drawing of the contact configuration and current distributions used in the experiments: (a) usual flux transformer configuration, used to determine the cutting current $I_{\rm cut}$ and (b) configuration used to determine $I_{\rm cut}^{\rm b=t}$.

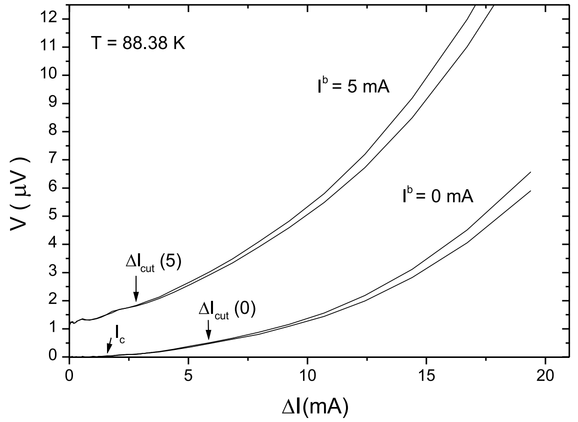

Fig. 3. Top V_{top} and bottom V_{bot} voltages against the current difference between top and bottom faces. The temperature is 88.38 K and the external magnetic field is 1 T. The measurement was done using configuration (b). In the lower curve, the applied current on the bottom face of the crystal is $I_b = 0$ mA; while in the upper curve $I^b = 5$ mA.

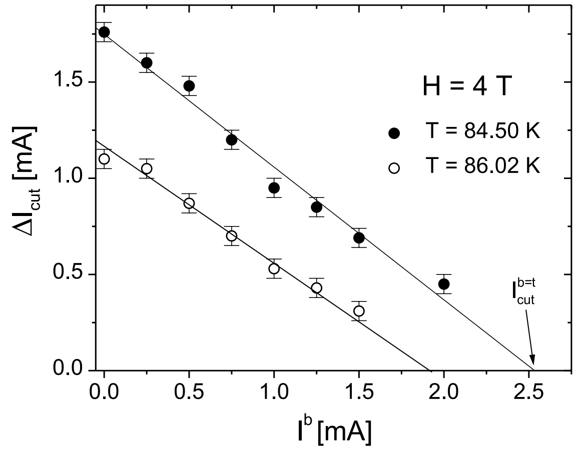

Fig. 5. Same as in Fig. 4 for external field $H = 4$ T.

bottom surfaces; $\Delta I = 0$ in this case corresponds to the situation in which a current of 5 mA is being injected through both surfaces. It can be seen that the differential cutting current $\Delta I_{cut}(5)$ is smaller than $\Delta I_{cut}(0)$, as expected from Eq. (8).

Figs. 4 and 5 show the dependence of the differential cutting current as a function of the base current. It can be seen that the results follow a linear dependence in I^b to a good extent, as predicted by Eq. (8). Extrapolation to $\Delta I_{cut} = 0$ gives an experimental way of determining $I_{cut}^{b=t}$, that is, the cutting current when the applied top and bottom currents are equal. However, contrary to the model's prediction, see Eqs. (6) and (7), $I_{cut}^{b=t}$ is found to be larger than I_{cut}. This difference increases with increasing field.

Fig. 6 condenses the results obtained so far; the different characteristic currents are shown as a function of the normalised temperature T/T_{th}. The data for external field of 1 and 4 T are qualitative the same. Experiments at intermediate values of

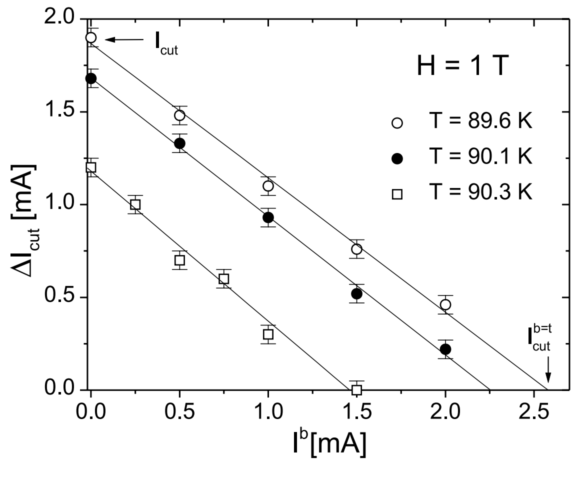

Fig. 4. Differential cutting current ΔI_{cut} as a function of I^b for three different temperatures at $H = 1$ T. The linear extrapolation determines $I_{cut}^{b=t}(H, T)$.

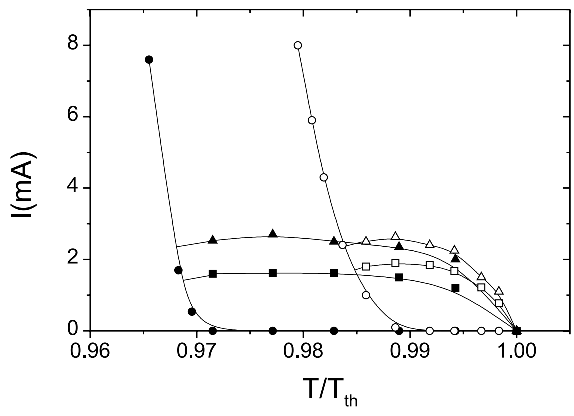

Fig. 6. Critical current (circles), cutting currents I_{cut} (squares) and $I_{cut}^{b=t}$ (triangles) as a function of the normalized temperature T/T_{th} for applied magnetic fields of 1 T (open symbols) and 4 T (full symbols).

the field yielded similar results, which are not shown. It can be seen that I_{cut} is a decreasing function of the temperature, and vanishes at T_{th}, where thermal fluctuations are big enough to induce vortex cutting in the absence of any injected current. It is also seen that the difference between I_{cut} and $I_{cut}^{b=t}$ has a weak temperature dependence, except close to T_{th}, and therefore cannot be simply attributed to thermal fluctuations, which were not considered in the model. The field dependence of this difference, on the other hand, is seen to be significative.

In the case when the top and bottom currents are equal, vortex begin to cut at a higher total current density. It might be thought, consequently, that neglected effects such as the washing out of point-like disorder could account for the difference. To check the correctness of this line of reasoning, we performed the following experiment. We took some of the samples for which I_{cut} and $I_{cut}^{b=t}$ had been measured, and added two current contacts at the sides, in order to be able to inject an homogeneous current (see Fig. 7). We repeated the previous experiments with an extra homogeneous current between 0 and 20 mA (our experimentally available range). We observed no changes in either I_{cut} or $I_{b=t}^{cut}$.

The weakest point in the phenomenological model we revised and extended above is the condition for vortex cutting: it is a simple maximum stress criterion, as would hold in a solid. Vortices, however, are different in that a vortex line cannot

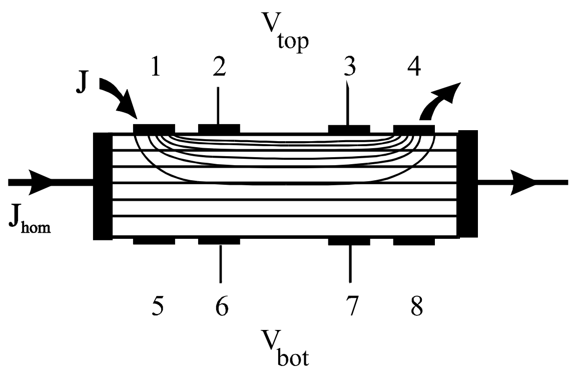

Fig. 7. Schematic drawing of the contact configuration used for applying an homogeneous current simultaneous to the flux transformer measurement of I_{cut}.

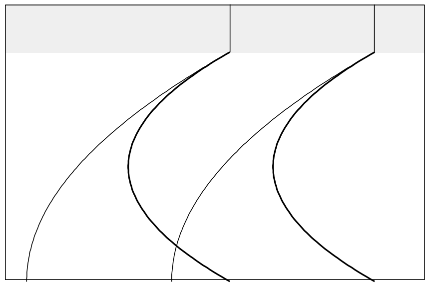

Fig. 8. Plot of the vortex profile as obtained from the continuous model for an applied force of 0.2 at the top surface only (thin lines) and at the top and bottom surfaces (thick line). A second vortex is plotted to allow a comparison of the minimum distance between neighbouring vortices in the two current configurations. The gray region is that where the top current is flowing.

terminate at a point because it is a line of magnetic field. The consequence is that vortex-cutting cannot happen without a subsequent reconnection. The fracture condition, then, should be formulated taking into account the geometry of the vortex *and its neighbours*. A good approximation is to consider that cut and reconnection occurs when the maximum displacement from the equilibrium position equals a fraction of the lattice parameter. In Appendix A we discuss a model in which vortices are considered as continuous elastic rods, from which we can obtain the profile of vortices for the two different current configurations. Fig. 8 shows the profile $c(x)$ of a vortex and its nearest neighbour with current flowing in the top surface only ($F_0 \neq 0$, $F_L = 0$), and with current flowing in both surfaces ($F_0 = F_L \neq 0$). In both cases $\tilde{F} = 0.2$. It is clearly seen how the condition for cut and reconnection would be satisfied first by the vortices being driven only by a force exerted on the top (the situation from where we derive I_{cut}). On the other hand, the successful predictions of the previous model, like the linear dependence of ΔI_{cut} with the base current, are also obtained using this model.

4. Conclusions

In this paper we have analyzed the flux cutting induced by inhomogeneous currents in $YBa_2Cu_3O_{7-\delta}$. By using different current configurations we have been able to show the inadequacy of the vortex cutting criterion commonly used in the literature, i.e., maximum local stress. We propose a different criterion, maximum distortion of a vortex equals a fraction of the lattice parameter, which explains our experimental results.

Appendix A. Continuum model

To consider the geometrical properties of a vortex under stress, we model it as an elastic, massless rod subject to a friction force. Let G note the rods elastic coefficient, A its cross-section and L its length. We take its main axis along the x-axis (see Fig. 9) and call $c(x)$ the displacement of the rod from its equilibrium position at x. If we consider an effective viscosity η of the superconductor, the equation for $c(x)$ can be written

$$AG\frac{\partial^2 c}{\partial x^2} = \eta\frac{\partial c}{\partial t}. \tag{A.1}$$

Here we have neglected the pinning force, inclusion of which would only shift the velocity a constant amount. To solve this equation in the case of vortex integrity we try the ansatz $c(x,t) = c(x) + c(t)$, because the velocity must not depend on x in this case. We straightforwardly get

$$\frac{\partial c}{\partial t} = v, \tag{A.2}$$

$$AG\frac{\partial^2 c}{\partial x^2} = \eta v \tag{A.3}$$

and then for $c(x)$

$$c(x) = \tfrac{1}{2}\alpha x^2 + bx + c, \tag{A.4}$$

with $\alpha = \eta v/AG$. We consider the boundary conditions given by a force F_0 at 0 and F_L at L. Since the stress is given by $S = F/A = G\partial c/\partial x$, the conditions are

$$\begin{cases} c'(0) = -F_0/AG \\ c'(L) = -F_L/AG \end{cases} \tag{A.5}$$

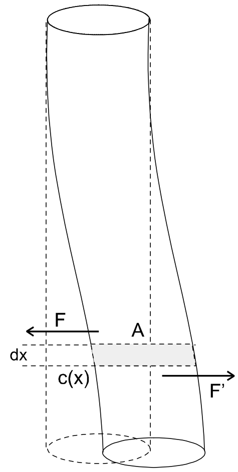

Fig. 9. Definition of $c(x)$, A, FyF'.

and then

$$c(x,t) = \frac{(F_0 + F_L)}{2AGL}x^2 - \frac{F_0}{AG}x + \frac{(F_0 + F_L)}{L\eta}t, \tag{A.6}$$

which using the dimensionless variables $\tilde{c} = c/L$, $\tilde{F}_X = F_X/AG$, $\tilde{x} = x/L$ can be written as

$$\tilde{c}(\tilde{x},t) = \tfrac{1}{2}(\tilde{F}_0 + \tilde{F}_L)\tilde{x}^2 - \tilde{F}_0\tilde{x} + \tilde{v}t. \tag{A.7}$$

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