Observation of Convergent Oscillations of the Flux Line Lattice as a Result of Magnetic Flux Jumping in Hard Superconductors

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We have monitored new peculiarities of the dynamics of catastrophic avalanches of the magnetic flux in superconducting Nb, Nb-Ti, and YBaCuO samples: i) convergent oscillations of the magnetic flux; ii) a threshold for entering the huge flux avalanches in the shielding experiments; iii) a threshold for the exit of a residual flux in the trapping experiments. The observed phenomena are interpreted in terms of a theoretical model which takes into account the inertial properties of the vortex matter.

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Recent studies of the marginally stable Bean critical state determined by a balance between intervortex repulsion and pinning by defects in type II superconductors have brought out a number of astonishing phenomena associated with spatiotemporal dynamic properties, vortex avalanches of many scales, self-organized criticality and memory effects in vortex matter (for example, [1]).

Our experiments identify flux avalanches as nonlocal processes propagating rapidly over the distance comparable with the size of the sample. Earlier thermal effects in massive rods of niobium caused by giant flux jumps were observed in [2]. Some observations of the behavior of the flux jumps and its structure were presented in [3]. These data show that there exists the exact correlation between the jumps in the resistivity and the collapse of magnetization. One of the recent investigations [4] of magnetic field screening by the superconductors in the vortex state revealed "negative vortices" whose penetration leads to the expulsion of a magnetic field.

In this paper we report about the observation of two distinct magnetic phenomena in the vortex state of superconductors: i) a threshold for entering the huge flux avalanches in the shielding experiments (in other words, the increase in the screening properties of a superconductor before the flux jump). We have also found a threshold for the exit of a residual flux in the trapping experiments; ii) convergent oscillations of the magnetic flux arising from flux jumping.

The latter result is of a particular interest since collective modes in a fluxoid system are very difficult to observe [5]. In addition, due to a large vortex viscosity, the displacement waves in a vortex lattice do not propagate.

The observed oscillations in the vortex system can be interpreted as a result of the existence of a definite value of the effective vortex mass, i.e. this phenomenon can be considered as displaying the inertial property of the vortex matter.

We have studied the structure of the flux jumps by means of a miniature Hall probe sensor. It was placed in the center of the sample (Fig. 1) and measured the surface induction $B_0$. We have examined the Hall sensor voltage directly by the transient recorder (model TCC-1000, Riken Denshi Co., LTD). In our experiment a flux avalanches are detected in real time ($t_{real} > 10^{-6}$ s) without distortion. In the shielding experiments, the zero field cool mode (ZFC) was used. The trap field mode was implemented by increasing the external magnetic field up to the values exceeding the critical magnetic field $H_{c2}$. The data presented in this study were obtained from Nb-Ti(at% 50) samples, polycrystalline Nb plates, and melt-textured YBaCuO slabs. The sizes ($L \times 1 \times 2R$ mm$^3$, see Fig. 1) of the samples were as follows: for Nb-Ti, $15 \times 2.8 \times 3.1$ mm$^3$; for Nb, $11 \times 3.5 \times 5$ mm$^3$; for YBaCuO, $6 \times 2 \times 3.5$ mm$^3$.

Fig. 1(a-c) shows the temperature and temporal dependence of the surface magnetic induction $B_0$ for the first and the second flux jumps in a shielding mode for the Nb-Ti sample. The structure of the jump essentially differs from a simple step. Some of the principal differences are clearly seen in Fig. 2(a).

The development of the thermomagnetic instability can be divided into three stages (see Fig. 1(b) and Fig. 2(a)). The flux jump is preceded by a certain phenomenon under which the field on a superconductor sur-
FIG. 1: Above - geometry of the experiment. Main frames: the temporal evolution of the surface magnetic induction $B_0$ for the first flux jump (a, b) and for the second flux jump (c). Inserts: Hysteresis loops, $B(H)$.

The surface decreases (see Fig. 2(a) for Nb-Ti, Fig. 3(a) for Nb, and Fig. 4 for YBaCuO). The value of the negative peak in the experiment with Nb is 16% of the total value of the flux jump. This is the first stage of the process. The second stage is in fact the avalanche-like penetration of the flux. Finally, at the last stage the relaxation of thermal and conductive properties of the superconductor occurs. In the most cases, this is a nonmonotonic process. Let us analyze it for the Nb-Ti sample.

As is shown in Fig. 2(a), after the avalanche had penetrated the sample, the induction $B_0(t)$ in the center of the sample was higher than that of the external magnetic field by $\Delta B_{\text{comp}}$. Recently it was found by Nowak [6], that the large avalanches are most likely system-spanning; as a result after avalanche a significant fraction of the Nb film has magnetic induction large than the applied field. Apparently, Coffey [7] observed such a compression of the vortex lattice by measuring the distribution of the induction inside the sample after the flux jump. Next, in the background of a relaxation curve the damped oscillations with a characteristic frequency $\nu \simeq 2.5$ kHz were observed.
FIG. 3: Structure of the avalanche jumps for (a) shielding and (b) trapping regimes for Nb. Inserts show $B_0(H)$.

The effect of the compression of the magnetic flux caused by avalanche passing is particularly pronounced in the YBaCuO samples as well. In order to check this effect we measured the difference $B_0 - \mu_0 H$ using two Hall probes where $H$ is the external magnetic field, $\mu_0$ is the permeability of vacuum. Fig. 4 shows that this difference changes its sign after the avalanche has passed. The difference $\Delta B_{comp}$ is about the value of the penetration field $H_p$.

Now, let us consider peculiarities of the structure of the thermomagnetic avalanche for the case of magnetic flux trapping. For Nb, (Fig. 3(b)) a positive peak $B_0(t)$ is observed which precedes the development of the instability. It is of the same origin as the negative peak $B_0(t)$ in the case of the shielding mode (Fig. 3(a)).

The above-described peculiarities of the flux jumps are not sensitive to the change in the rate $dH/dt$ of the external magnetic field sweeping in the range of $0.05 - 2 \text{T/s}$.

Now we would like to scrutinize the observed phenomena. In our opinion the most striking effect is the compression of the magnetic flux after the avalanche has passed through the sample. It is very important to emphasize that the magnetic induction in the middle of the sample can exceed the value of the external magnetic field. In this case, some of the vortices move in the direction from the area with low vortex density towards the area with the vortex surplus, against the total repulsion force. This means that these vortices move in spite of all the forces acting in the direction opposite to this motion. Such a motion is possible only due to the existence of some effective vortex mass. There are plenty of papers dealing with the theoretical attempts to estimate the mass of the Abrikosov vortex. Experimental data on microwave field attenuation contain information on the inertial properties of a vortex.

To explain the observed oscillatory phenomena, we suggest the following mechanism which takes into account the inertial properties of the vortex system. Prior to the jump, the mixed state of superconductors is characterized by nonuniformly distributed magnetic induction localized near the surface. As a result of the avalanche, the flux rushes from either sides of the sample towards the center. Two fronts of the penetrating flux collide in the center of the sample and, owing to the existing vortex mass, give rise to the local surplus density of the magnetic flux that exceeds the value of the external magnetic field. The repulsion force in the vortex structure at the center of the sample that have resulted from its compaction, initiates the wave of the vortex density of the inverse direction of propagation. Upon reaching the surface, this wave is reflected from it. This results in the oscillations in the vortex system. The limitation of the number of oscillations observed is caused by the existence of damping. One succeeds in observing the oscillation of the vortex density only owing to a strong compression of the vortex structure as a result of the giant avalanche-flux. But for the second jump (Fig. 1(c)), a smooth descending slope in the curve $B_0(t)$ is noted and the oscillatory mode is not observed.

The observed process of damping oscillations can be described in terms of the following theoretical model. We
use the continuity equation for the dimensionless variables,
\[ \dot{b} + (bv)' = 0 \]  
where \( b = B/H_p = Bc/2\pi J_c(0)d \) is the normalized magnetic induction, \( d \) is the sample thickness, \( J_c(0) \) is the critical current density at the initial temperature (before the avalanche has passed), the dot denotes the derivative with respect to the time \( \tau = t/t_0 = t\Phi_0 H_p/4\pi d^2\eta \), \( \Phi_0 \) is the flux quantum, \( \eta \) is the viscosity coefficient, the sign prime denotes the derivative with respect to the coordinate \( \xi = x/d \), \( v = V/V_0 = Vt_0/d \) is the hydrodynamic vortex velocity. The second equation of the model describes the motion of the vortex system under the action of the Lorentz, pinning, and viscosity forces,
\[ \mu\theta' + \mu v = -b' - 2\text{sign}(v)f(\theta) - v. \]  
Here \( \mu = m/m_0 = m\Phi_0 H_p/4\pi d^2\eta^2 \) is the normalized vortex mass, \( \theta = 4\pi C\Delta T/H_p^2 \), \( C \) is the specific heat, \( \Delta T = T - T_0 \) is the deviation of the temperature from its initial value \( T_0 \) before the flux jump, the function \( f(\theta) \) describes the temperature dependence of the critical current, \( J_c(\theta) = J_c(0)f(\theta), \ f(\theta) = \xi \) at \( \theta = 0 \) and \( f(\theta) = 0 \) at \( \theta = T_c - T_0 \) (\( T_c \) is the critical temperature). The temperature change occurs due to the Joule losses. Neglecting the process of thermal conductivity, we can use the following equation of the energy balance:
\[ \dot{\theta} = bv^2 + 2|v|bf(\theta). \]  
This set of equations should be solved within the spatial interval \(-1/2 < \xi < 1/2\) together with the boundary and initial conditions, \( b(1/2, \tau) = b(-1/2, \tau) = H/H_p = \alpha \), \( b(\xi, 0) = \alpha(1 + 2\beta/\alpha)(\xi - 1/2) \), \( \theta(\xi, 0) = \beta \), \( v(\xi, 0) = 0 \). Here \( \beta = J_0/J_c \), \( J_0 \) is the critical current density at the initial time moment. We assume that this value exceeds slightly the value \( J_c(0) \), i.e. \( \beta > 1 \). This supposition is introduced to initiate the onset of an avalanche.

The results of the simulation for \( \alpha = 1 \), \( \beta = 1.01 \), \( f(\theta) = 1 - \kappa\theta \), \( \kappa = H_p^2/4\pi C(T_c - T_0) = 12 \) are presented in Fig. 2(b). It is seen that the curves in this figure describe qualitatively well the behavior of the experimental ones (see Fig. 2(a)).

The suggested mechanism of the oscillations which takes into account the inertial properties of the vortices allows one to interpret the surprising behavior of the vortex system just before the avalanche passage when the magnetic flux near the middle of the sample unexpectedly moves in the opposite-to-avalanche direction (see Figs. 3(a),(b)). The mechanism of this effect may be as follows. Due to the vortex mass, the frozen profile of the magnetic induction after some avalanche has passed can contain a smooth peak in the middle of the sample (see, for example, [10]). This local maximum remains on hand while the external field increases and exists in the initial profile for the subsequent avalanche. The new avalanche can destroy this peak due to the heating effect before the new vortices arrive there. This tends to decrease the vortex density in the middle of the sample.

Finally, we remark that very interesting oscillating phenomena originated by the thermomagnetic avalanches are observed in the vortex matter for both low-\( T_c \) and high-\( T_c \) hard superconductors. These phenomena can be qualitatively interpreted in terms of the theoretical model which takes into account the inertial properties of the vortex system. However, new experimental and theoretical in-depth studies are necessary to elucidate the situation.

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