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The Structure of Thermomagnetic Avalanches in Superconducting Disc of NbTi

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We investigated dynamics of giant flux jumps, caused by thermomagnetic avalanches, in superconducting disc of conventional NbTi-50% superconductor. We studied surface magnetization, as well as changes of magnetic flux in the superconducting sample and in the area around it. The influence of the magnetic history on the flux jumps structure was investigated. The most complex structure of the flux jumps was found during sample remagnetization. The comparison between dynamic changes of the magnetic flux in the sample and in the area around it shows that, at the last stage of the thermomagnetic avalanche, a process of magnetic flux redistribution in the superconductor's volume occurs. This process is not accompanied by an entrance of additional flux lines into the superconductor's volume.

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1. Introduction

Thermomagnetic instability, manifesting itself as magnetic flux jump, is one of the phenomena commonly observed in hard superconductors [1–5]. Local heating, due to flux motion, reduces the pinning force and facilitates further flux motion, which may lead to an avalanche-like process accompanied by a substantial temperature rise. This phenomenon is characterized by a strongly nonlinear dependence of the electric field versus the current density. In this work we report new experimental data of electrodynamics of the mixed state of hard superconductors at the flux jump runaway process. We studied the avalanche dynamics of magnetic induction in a disc shape NbTi (50at.%) superconductor during a slow

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sweep of external magnetic field, H_{ext} (critical current density $j_{\mathrm{c}}(4.2\ \mathrm{K})$ is about $10^9\ \mathrm{A/m^2}$). We investigated the magnetic flux avalanche dynamics, both inside the superconductor and outside it (it means the dynamics of the magnetic stray field), during the remagnetization process, in a wide range of magnetic fields, up to 12 T. Our investigations reveal an unconventional behavior of the stray field at the initial and at the final stage of the flux jump process.

2. Experiment

In our studies, we used a disc of conventional NbTi-50% superconductor with the diameter of 14 mm and height of 4 mm. The measurements of the local surface induction were performed by using a miniature Hall probe. The sensitivity of the Hall probe (n-InSb thin film, doped with Sn) was about 100 μV/mT. The probe measured local surface induction, B_{surf}, in the center of sample surface. Second, similar Hall probe measured induction of the external magnetic field, B_{ext}. The difference between the signals taken from both Hall sensors was proportional to a local surface magnetization, $M_{\mathrm{surf}} = B_{\mathrm{surf}} - B_{\mathrm{ext}}$. A thermocouple thermometer (Cu–CuFe) attached to the sample monitored its temperature.

Flux dynamics inside superconductor was investigated by a pick-up coil (coil 1). This coil was wound directly on the superconducting disc and consisted of 10 turns of copper wire (see Fig. 1). We also investigated the changes of the magnetic flux around the sample. To this aim, we used the outside pick-up coil (coil 2), whose cross-section embraced some area around the disc and consisted of 5 turns of copper wire (see Fig. 1). This coil detected the changes of the stray field. The avalanche of the magnetic flux induced a voltage ($U \sim \mathrm{d}\Phi/\mathrm{d}t$, Φ — magnetic flux, t — time) on both pick-up coils. This voltage was registered by a transient recorder with memory (model TCC-1000 Riken Denshi Co., Ltd.). Our investigations were performed in a 12 T superconducting magnet with variable temperature insert. The rate of the external magnetic field sweep was $\mathrm{d}H_{\mathrm{external}}/\mathrm{d}t \propto 0.6$ T/min.

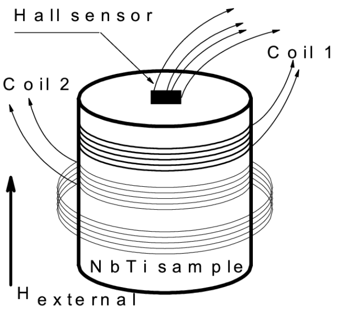

Fig. 1. The geometry of the experiment. The position of the Hall probe and the shapes of two pick-up coils are shown.

3. Results and discussion

Figure 2a (middle part) shows the hysteresis loop of the surface magnetization $M_{\mathrm{surf}}(H_{\mathrm{ext}})$, taken at 4.2 K. In this figure one can see giant jumps of surface magnetization, caused by thermomagnetic avalanches. Figure 2a (upper and lower parts) also presents typical impulses of the voltage on the pick-up coil 1, induced by the changes of the magnetic flux in the superconductor. Impulses of the voltage induced by stray field jumps, on the pick-up coil 2, are presented in Fig. 2b.

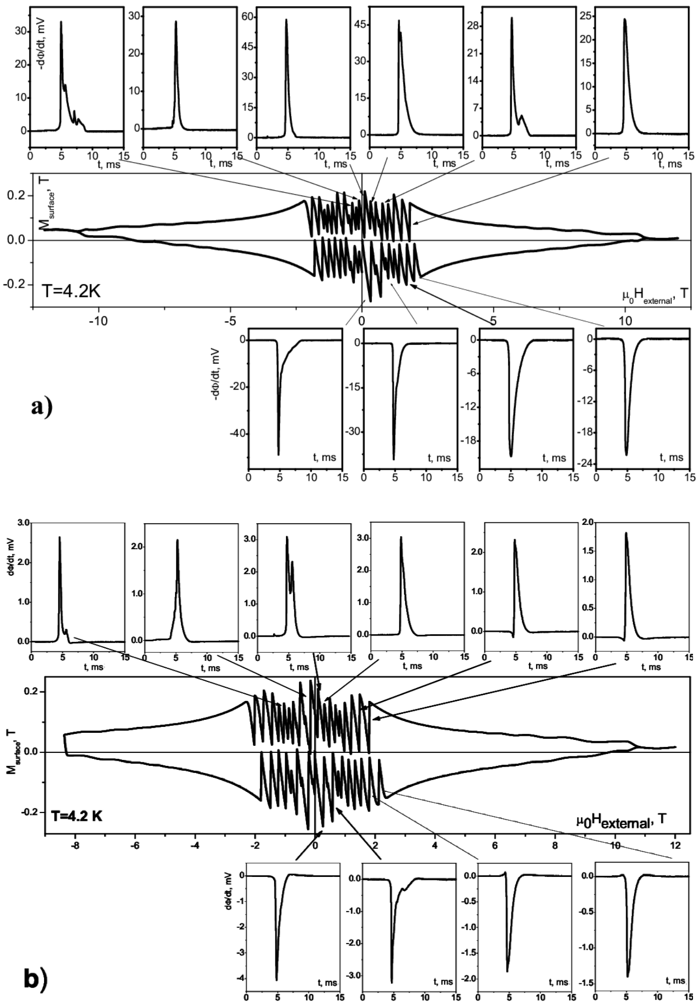

Fig. 2. Surface magnetization hysteresis loops and the signals taken from the pick-up coils during the following flux jumps at 4.2 K. (a) Changes of the magnetic flux in the superconductor's volume — signal taken form coil 1. (b) Changes of the magnetic flux of the stray field — signal taken from coil 2.

Most of the observed voltage impulses have simple (single peak) structure. The complex structure of the flux jumps was observed in remagnetization area and also in the small area before it (see Fig. 2a, Fig. 2b). In this area of the $M_{\text{surface}}(H)$ loop, each signal taken from any of our pick-up coils, during a flux jump, consists of several peaks. Such behavior may be caused by the presence of antivortex phase, which increases the instability of nonuniform mixed state [6, 7] or by the presence of the so-called Meissner holes [8–10].

The structure of the stray field jumps, which was registered by coil 2 (Fig. 2b), is more complex than the structure of the flux jumps in the superconductor's volume, registered by coil 1 (Fig. 2a). Typical structure of a stray field jump is shown in Fig. 3a. Let us analyze the structure of stray field jumps during an increase in the external magnetic field (the lower branch of the magnetization hysteresis loop). Before the flux jump magnetization of the superconductor is negative. During a flux jump magnetic flux enters rapidly into the superconductor volume and the absolute value of the negative moment of the sample decreases. During this process the stray field around the superconductor decreases, which corresponds to the large peak registered by coil 2. However, except for the large peak in Fig. 3a, one can also recognize two other processes, which are marked in Fig. 3 as stages I and II. During these stages of the flux jump the voltage on the pick-up coil changes its sign, which corresponds to an increase in the stray field. The first stage of the stray field jump occurs at its initial stage, however, not for all jumps registered in our experiment. The stage of the stray field jump marked as II occurs at the final stage of each jump registered in our investigations. Figure 3b shows the signal from the coil 2 after integration. The stages I and II of the stray field jumps also occur during decrease in the external magnetic field (the upper

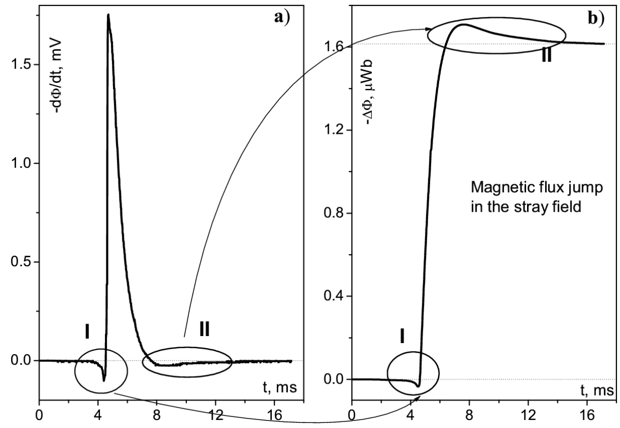

Fig. 3. Typical structure of the stray field jumps. Two characteristic stages of the jump are shown. (a) Signal from the pick-up coil. (b) Signal from the pick-up coil after integration.

branch of the magnetization hysteresis loop). However, in this case the voltage induced on the coil 2 has opposite sign.

Figure 4 presents the influence of the magnetic history on the flux jump duration. In order to study the flux jumps dynamics in more detail, we have divided each of the investigated flux jumps into two characteristic time intervals. The first interval, with the length of t_{bm} (before maximum), begins at the beginning of the flux jump and comes to its end at the point, where the signal from the pick-up coil reaches its maximum. The second interval, with the length of t_{am} (after maximum), begins at this maximum and finishes at the end of the flux jump. Figures 4a and b show the lengths of these two time intervals. Figure 4c presents the total lengths of the following flux jumps — $t_{\mathrm{full}} = t_{\mathrm{bm}} + t_{\mathrm{am}}$. In each figure we present the characteristic times of the impulses registered by both coil 1 (On Sample Coil), which measured the changes of the magnetic flux in superconducting disc, and coil 2 (External Coil), which measured the changes of the flux of the stray field. In Fig. 4c one can see that the jumps of the stray field are approximately twice longer than the jumps registered by the coil wound around the investigated sample. The first time interval, t_{bm}, of both investigated signals is approximately

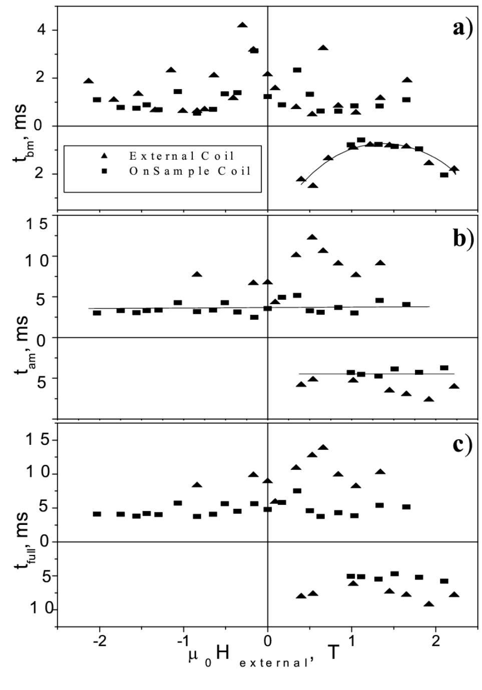

Fig. 4. The influence of the magnetic history on the flux jump duration. Flux jumps registered by both coil 1 (On Sample Coil) and coil 2 (External Coil) are shown. (a) The length of the first time interval, t_{bm}. (b) The length of the second time interval, t_{am}. (c) Total length of the flux jump, $t_{\mathrm{full}} = \mathrm{t_{bm}} + \mathrm{t_{am}}$.

the same (see Fig. 4a). The second interval, t_{am}, is longer in the case of the jumps of the stray field. Moreover, the investigated two time periods change in different way with the external magnetic field. The interval t_{am} is, practically, magnetic field independent, while the interval t_{bm} changes with the external magnetic field. This experimental fact tells us that the physical mechanisms of the two processes investigated in our experiment are different. The signal taken from the coil 1 tells us about the amount of magnetic flux entering, in a time unit, into the superconductor. However, this signal does not tell us anything about the magnetic flux distribution in the superconductor's volume. On the other hand, the magnetic stray field depends strongly on the magnetic field distribution in the superconducting sample. The difference in lengths of the jumps registered by two coils used in our experiment enables us to make the following conclusion.

At the final stage of the flux jump we have no signal from coil 1, but we still register some signal from coil 2, proportional to the changes of the magnetic stray field. It means that at this stage of the jumps no additional flux enters into the superconductor, but the redistribution of the magnetic flux in the superconductor still occurs. In other words, we have found two characteristic stages of the magnetic flux jumps: (1) the stage of magnetic flux entrance, (2) the stage of magnetic field redistribution in the superconductor's volume.

Using our experimental results, taken by coil 1, we can estimate the electric voltage, which induces on the lateral surface of our superconducting disc during a flux jump. To this aim, we used the Maxwell equation: $\mathrm{rot}\boldsymbol{E} = -\mathrm{d}\boldsymbol{B}/\mathrm{d}t$. If one calculates the surface integral of both sides of this equation, one obtains:

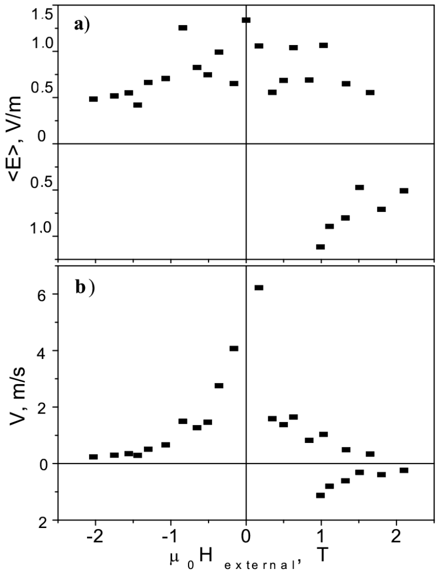

Fig. 5. (a) Average electric voltage induced on the lateral surface of superconducting disc during the following flux jump. (b) Estimated vortex velocity.

$R\oint E_\varphi(\varphi, r=R)\mathrm{d}\varphi = -\mathrm{d}\Phi/\mathrm{d}t$, where E_φ is the azimuth component of the electric field on the lateral surface and R is the radius of disc. Hence, the average electric field on the lateral surface of our sample $\langle E_\Phi\rangle = -\frac{1}{2\pi R}\frac{\mathrm{d}\Phi}{\mathrm{d}t}$. Figure 5a shows magnetic field dependence of $\langle E_\Phi\rangle$, calculated using our experimental data. For each flux jump we took the maximal value of $\mathrm{d}\Phi/\mathrm{d}t$. The electric field, calculated according to the above described procedure, can be used to estimate the average velocity of vortices, which enter, during a flux jump, into the superconductor through its lateral surface: $\langle V\rangle = \langle E_\Phi\rangle/B$. Magnetic field dependence of the estimated vortex velocity is shown in Fig. 5b. One can see in this figure that estimated vortex velocity changes in the range from about 0.1 m/s to about 6 m/s. These values of the vortex velocity agree with those presented in Ref. [11]. In this reference the velocity of vortices, which enter into the superconducting NbTi disc during a thermomagnetic avalanche, was estimated on the basis of magneto-optic investigations.

4. Conclusions

We have studied flux jumps dynamics in a disc of conventional NbTi superconductor. For the first time, we investigated the dynamics of the magnetic stray field around the superconducting sample. The comparison of the dynamics of the stray field with the dynamics of the magnetic flux entering the superconductor's volume shows that the process of the flux jump can be divided into two stages: (1) the stage of magnetic flux entrance, (2) the stage of magnetic field redistribution in the superconductor's volume. We also used our experimental data to estimate the average velocity of vortices entering the superconductor during a flux jump. The results of our estimations agree with the vortex velocities measured by other experimental techniques.

Acknowledgments

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