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# Local flux intrusion in HTS annuli during pulsed field magnetization

V S Korotkov<sup>1</sup>, E P Krasnoperov<sup>1,2</sup> and A A Kartamyshev<sup>1</sup>

<sup>1</sup> National Research Center “Kurchatov Institute”, Kurchatov Square 1, 123182, Moscow, Russia

<sup>2</sup> Moscow Institute of Physics and Technology, Institutskiy Pereulok, 9, 141700, Dolgoprudniy, Russia

E-mail : [vasmephi@mail.ru](mailto:vasmephi@mail.ru)

**Abstract.** During pulsed field magnetization of melt-grown HTS flux jumps can occur and the shielding current falls by 10-20 times. As the duration of pulse is shorter than the temperature relaxation time ( $\ll 1$  s), the circular current remains small during the field falling. The residual trapped field in the hole of the annulus has a direction opposite to that of the pulsed field. Small circular current and high critical current density are explained by the fact that flux moves through narrow regions of the annulus body. The angle of the sector with “soft flux” (i.e. a low  $J_c$  region) is estimated to be  $\sim 7$  deg.

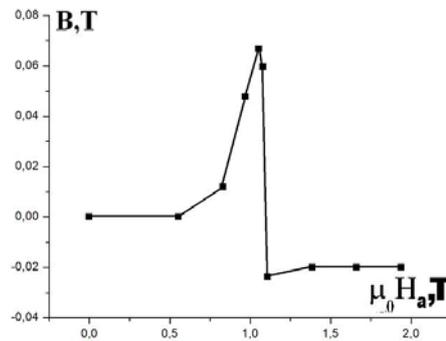
## 1. Introduction

Flux jumps in hard superconductors are extensively studied. At low temperatures in the conditions of the slow magnetization (the isothermal limit) flux jumps arise due to the thermo-magnetic instability [1]. High-temperature superconductors (HTS) have high heat capacity and the thermo-magnetic instability is usually not observed at  $T > 40$  K [2]. At high temperature flux jumps arise in conditions of large disturbances, in particular, fast variation of the magnetic field. The study of flux jumps in HTS during pulsed field magnetization (PFM) is of interest because this process is useful for industrial and power applications.

## 2. Experimental setup

The dynamics of the flux jumps in melt-grown HTS were studied in liquid nitrogen ( $T = 78$  K). We measured the evolution of the induced current and the magnetic field during the pulsed field magnetization. After the magnetization the average critical current density was determined. Four annuli with outer diameter  $2a_1 = 36$  mm, inner diameter  $2a_0 = 17$  mm and thickness  $2b \approx 11$  mm were studied. The annuli were cut from melt - grown Y-Ba-Cu-O discs which were prepared as described in ref. [3]. Critical temperatures of annuli were approximately identical; the critical current densities differed by 10-20 %. The trapped fields were  $B_{tr} \approx 0.4$  T at  $T = 78$  K. The magnetizing field was generated by copper coils located outside annuli. The current source allowed generating pulses with a peak field up to 3.5 T and a duration up to 40 ms. The magnetic field was measured by a Hall probe which was connected in parallel to the digital oscilloscope and to the DC micro-voltmeter. This setting allowed us to measure the field evolution during the pulse and field value after the magnetization with high accuracy. For the measurement of circular shielding current a Rogowski belt was used.





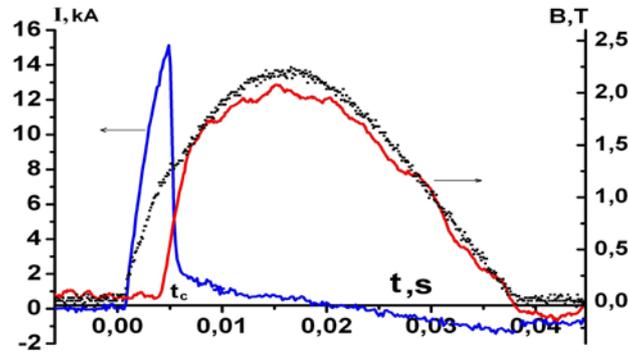
**Figure 1.** The trapped field in center of annuli as a function of external field peak.

### 3. Results and Discussion

In figure 1 the dependence of trapped field in the center of annuli versus the external field peak is shown. After each magnetization the annuli were heated above  $T_c$ . At low pulse peak ( $\mu_0 H_a < 0.5$  T) the trapped field is absent ( $B_{tr} \approx 0$ ). At these conditions circular currents screen the external field. With increasing the field peak  $B_{tr}$  appears and rises quickly. At some critical field peak  $\mu_0 H_a \approx 1.0$  T the trapped field has a maximum and then falls sharply and changes the direction (sign). The sharp drop of  $B_{tr}$  and reversing its direction is a signature of a flux jump. Obviously, the field drop happens as a result of partial or full destruction of the shielding current circulating around the hole.

In figure 2 the evolutions of the shielding current and magnetic fields during flux jump are presented. The right axis relates to the external field of  $\mu_0 H_a \approx 2$  T (dots) and the field in the center of the annuli (solid curve). The left axis relates to the shielding current evolution curve  $I(t)$ . Up to  $t = t_c$  the current rises and then falls sharply by a factor of 10. On the increasing part of current, the resulting field is equal to 5-7 % of the external field. The sharp drop in the shielding current opens free way for the magnetic flux to penetrate into the hole of annuli. This is the flux jump. The Hall probe shows that starting with this moment of time the field in the center becomes nearly the same as the external field. The current drop is described by the exponential function  $I = I_c \exp(-t/\tau_f)$ , where  $\tau_f = L/R_{flow}$ , ( $L$  – the inductance,  $R_{flow}$  – the flux flow resistance). The  $I_c$  characterizes the critical current. The characteristic time of current drop is  $\tau_f = 0.36$  ms. This time remains practically the same for the magnetic field up to 5 T and for pulse duration down to 10 ms. In order to determine the  $R_{flow}$ , the current damping time was measured in pure aluminum annuli having identical sizes. It turned out that for Al (at  $T = 78$  K) the decay time of the current is order of magnitude higher and is  $\tau_{Al} = 3.6$  ms. Since the resistivity of Al at  $T = 78$  K is  $\rho_{Al} = 0.2 - 0.3 \mu\Omega \cdot \text{cm}$  [5], the resistance of the Al annuli is  $R_{Al} = 2\pi \cdot \rho_{Al} \cdot (b \cdot \ln(a_1/a_0))^{-1} = 2.5 \mu\Omega$ . Accordingly, the flux flow resistance in the superconductor is  $R_{flow} = R_{Al} \cdot \tau_{Al} / \tau_f = 25 \mu\Omega$ .

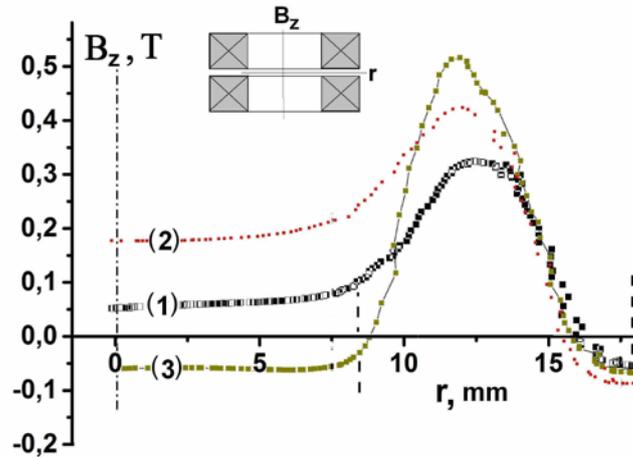
During the decrease of the external field the shielding current remains small and the field in the hole is nearly equal to the external field. The low current value after the flux jump and the low rate of current variation is explained by the high temperature rise, which is supported by a high heat capacity and low heat conductivity of HTS. The thermal relaxation time in our samples is  $\tau_{th} \approx 1$  s [6], explaining why the flux dynamics remain high and the difference between the external and the internal field is practically absent during the pulse.



**Figure 2.** The evolution of current and field. Left axis – the current in annuli –  $I(t)$ . Right axis – external field (dots) and field in the opening (solid curve).

The destruction of the critical current and the flux jump, as it is well-known, is caused by the overheating. In the experiment (figure 2) the critical current falls by 10 times. By using the linear temperature approximation of current  $I(T)$ , the heating on  $\Delta T_j \approx 10$  K is required. The heat dissipated during the jump is  $q_j = \int I^2 \cdot R_{flow} dt \approx 1.28$  J. If this heat were dissipated over the whole volume of the annulus, the average temperature rise  $\langle \Delta T \rangle = q_j / (C_\Omega \cdot \Omega)$  (where  $C_\Omega$  is the volumetric heat capacity [7]) would be less than 0.2 K. But this low heating does not correspond to the observed current drop during the flux jump.

To find out the distribution of the current in the superconducting annuli the radial field distribution  $B_z(r)$  was measured in the central plane  $z = 0$ . For the measurements two identical annuli with 2 mm gap were used. A Hall probe was moved along the radial direction. In this geometry the axis component of the field was measured. From these data we can estimate the current density using the expression  $J = \mu_0^{-1} dB_z/dr$ . In figure 3 the flux density distribution  $B_z(r)$  in the gap between annuli is shown for different magnetization conditions. The curve (1) corresponds to the single pulse magnetization with field peak of  $\mu_0 H_a = 0.9$  T. The curve (2) corresponds to the multi-pulse magnetization (10 pulses). The curve (3) shows the field distribution after the flux jump at  $\mu_0 H_a = 2.0$  T.



**Figure 3.** The radial field distribution  $B_z(r)$  at the different conditions: (1) – after the single pulse of  $\mu_0 H_a = 0.9$  T; (2) – after 10 pulses with peak field  $\mu_0 H_a = 0.9$  T; (3) after the flux jump  $\mu_0 H_a = 2.0$  T. The dotted line corresponds to the inner and outer annuli radii.

Currents in the region of  $dB_z/dr < 0$  produce the field in the direction of the magnetizing field while the internal currents ( $dB_z/dr > 0$ ) produce the field with the opposite direction. As shown in figure 2 when the current falls magnetic flux penetrates into the hole. When the external field is reduced, the flux trapping can be observed if  $I_c$  is high. Otherwise (if  $I_c$  is small) the flux escapes the hole and low field will be trapped. In the experiment the trapped field is low and has a direction opposite to that of the applied field. On the other hand from the figure 3 it follows that the critical current density  $J_c = \mu_0^{-1} dB_z/dr$  is high enough 15 kA/cm<sup>2</sup>. In fact it is order of magnitude higher than what remains after the flux jump. The high critical current density corresponds to the relatively low ( $< 0.5$  K) heating as it is observed in the experiments [6,8]. Low critical current after the field jump corresponds to high heating, no less than  $\Delta T_j \approx 10$  K. It is possible only in the case if the heat is dissipated not in all volume but only in the region of low pinning force. The volume of region occupied by the moving fluxoid at the flux jump can be estimated from the relation

$$\Omega_{flow} = q_j / (C_\Omega \cdot \Delta T_j) \quad (1)$$

From the symmetrical considerations this region is reasonable to imagine as the sector of annulus. Thus we can obtain that sector angle is of  $\varphi = 2\pi \cdot \langle \Delta T \rangle / \Delta T \approx 7$  deg.

The local heat dissipation in the narrow sector during the flux jump is explained by the azimuthal inhomogeneity of the critical current. In the melt-grown Y-Ba-Cu-O the critical currents in the (ab) plane have angle anisotropy which manifests itself in the anisotropy of trapped magnetic field in discs [8]. This inhomogeneity of the critical current is related to the technology of the HTS growth. Even if the anisotropy is low (10–15 %) due to the high exponent of HTS current-voltage curve ( $E \sim J^N$ , here  $N > 25$  [9]), the heating temperature in this so-called “soft flux” region would exceed the heating temperature of region with higher  $J_c$ . Thus, the most of energy will be dissipated in the narrow sector of annuli.

Knowing the volume of soft flux region we can estimate the dynamical resistance of the flux motion. As the resistive region occupies the narrow sector of the annuli

$$\rho_{flow} = (2\pi/\varphi) \cdot \rho_{Al} \cdot (\tau_{Al} / \tau_f) \approx 100 \mu\Omega \cdot \text{cm} \quad (2)$$

This value is approximately two times lower than the resistivity in ab plane at the normal state [7].

Due to the short pulse duration compared to the thermal relaxation time the region of flux motion remains at the high temperature after the flux jump. The rest of the annulus temperature is lower and  $J_c$  maintains high. Falling field magnetizes the body of annuli as in case the annulus has a slit. When the external field is switched off, the residual magnetization exhibits a maximum in the body of the annulus and low negative value near its internal and external edges. The symmetrical configuration of magnetic field shown in figure 3 creates the negative value in the center of the annulus when the radius of the annulus is comparable to its thickness. Similar distributions of  $B_z(r)$  were observed in annuli with slit after the field cooling process and field removal [11].

#### 4. Conclusion

During the pulsed field magnetization of melt-grown HTS annuli, the circular currents are destructed and a flux jump takes place. Because of the slow thermal processes vortices retain high mobility and the magnetic flux is not trapped in the hole of the annulus. The low value of the induced current and high value of critical current density in the body of the annulus indicates that: (1) during the flux jump the magnetic field gets into the hole through a “soft flux” region (i.e. with low  $J_c$ ) of the annulus, (2) the soft flux region is the narrow annulus sector where the pulse heating is at least one order of magnitude higher than average heating.

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