# Collapse of superconducting current in high-$T_c$ ceramics in alternating magnetic field

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We have investigated theoretically and experimentally a new effect – the formation of a transport current cord in a longitudinal ac magnetic field. The sizes of the cord diminished with field amplitude. When the current density in a cord reaches a critical value, the sample transits to a resistive state.

**1.** The electromagnetic properties of HTSC ceramics are known [1–3] to be described perfectly by a critical state model [4,5] in a wide range of magnetic fields $H \leqslant 10^2$ Oe. In accordance with the papers mentioned above, the magnetic induction $\boldsymbol{B}$ in a sample is defined from the following critical state equations,

$$c \operatorname{rot} \boldsymbol{B} = 4\pi\mu \boldsymbol{j} , \quad (1)$$

$$\boldsymbol{j} = j_c(B) \boldsymbol{E}/E . \quad (2)$$

Here $\boldsymbol{E}$ is the electric field; $\boldsymbol{j}$ is the current density averaged over a volume containing a large number of grains; $j_c(B)$ is the critical current density; $\mu$ is the magnetic permeability of the ceramics without intergranular links; $c$ is the speed of light.

The critical state model initially was proposed and usually was used for analysis of the situations when the supercurrent flows everywhere along one of the coordinate axes only. For instance, in ref. [1] the distribution of the transport current in the cross section of cylindrical samples (the current was directed along the cylindrical axis $z$) was investigated. The magnetization curves in a longitudinal magnetic field were also studied in that paper. In the latter case only the azimuthal component of the current, $j_\varphi$, was not equal to zero.

The other, more complicated, situation takes place when the supercurrent has several components. For example, if the cylindrical sample carrying the transport current is inserted in an external magnetic field parallel to the $z$-axis, both an axial current $j_z$ and an azimuthal current $j_\varphi$ will appear. As a matter of fact, in similar cases some questions arise with respect to the applicability of eq. (2). However, analyzing the processes of critical state installation, we came to the conclusion that eqs. (1), (2) hold true for the multicomponent situation. A consideration similar to that in refs. [4,5,1] led us to the result that due to the electric field the critical current density becomes parallel to the $\boldsymbol{E}$ direction in a short time.

All conclusions of this paper are based on eqs. (1) and (2). It will be noted that all results concern not only HTSC ceramics but also other superconductors in the critical state, in particular, the usual "cold" superconductors.

**2.** Important consequences connected with the current and magnetic induction distributions in a superconductor follow from formulae (1) and (2). Let us consider the situation when a fixed direct transport current $I$ flows along the $z$-axis of a cylindrical sample with radius $R$. If the current $I$ is less than the critical current $I_c$ the distribution of the current density versus coordinate $r$ has the form shown schematically in fig. 1a. Let a magnetic field parallel to the $z$-axis be switched on. In such a case an azimuthal electric field $E_\varphi$ arises in the surface layer of the superconductor according to the Faraday law. This electric field produces a current $j_\varphi$ that will screen an external field $H(t)$. It is extremely important that there is a $\varphi$-component of the electric field in the sample only. The field $E_z$ will be equal to zero as long as the transport current density will not exceed its critical value $j_c$ anywhere. As consistent with formula (2), an azimuthal current $j_\varphi$ exists in the whole region where the external magnetic field has penetrated while the current component $j_z$ is absent here. This means that the part of the transport current that has flown in this region in the initial state is displaced to deeper layers of the superconductor (see fig. 1b).

The collapse of the transport current will continue until the external magnetic field achieves its threshold value $H_t$. At this moment the current density $j_z$ becomes nonzero on the axis of the cylinder (fig. 1c). At $H(t)>H_t$ the transport current density becomes higher than the critical one and the sample transits into the resistive state. The appearance of a homogeneous electric field $E_z$ in a sample leads to a transport current flow through the whole cross section of the sample. Following (2) the current density is described by

$$j_z \approx \frac{E_z}{(E_z^2+E_\varphi)^{1/2}} . \tag{3}$$

3. In the framework of the critical state model one can calculate the dependence of the magnetic field $H_t$ on the transport current. Using the Kim–Anderson relation [6,7] which takes into account the dependence of the critical current density on the magnetic induction in the form

$$j_c(\boldsymbol{B}) = \frac{j_0}{1+|B|/B^*} , \tag{4}$$

we obtain the following relations,

$$\begin{aligned} H_t &= H_p\,[1-0.5(I/I_c)^{2/3}] , \quad I \ll I_c , \\ &= H_p \times 3^{-1/2}(1-I/I_c) , \quad I_c - I \ll I_c . \end{aligned} \tag{5}$$

Here $H_p$ is the value of the external magnetic field when a magnetic flux reaches the cylinder axis in the absence of the transport current. In the model (1)–(3) this field is equal to

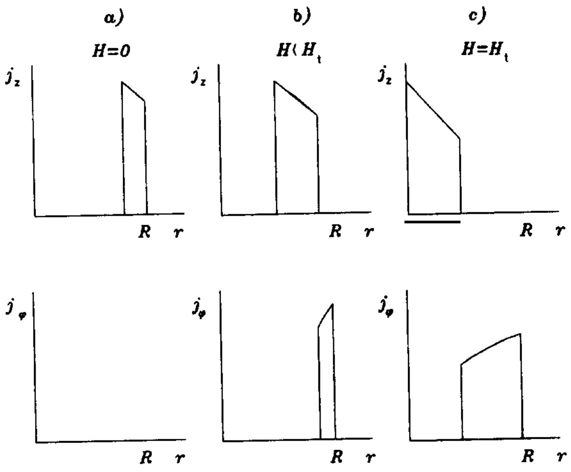


Fig. 1. Schematic distributions of currents $j_z(r)$ and $j_\varphi(r)$ in a sample when the magnetic field has been switched on before the transport current. (a)–(c) are for different values of the current, changing from $I=0$ to $I=I_c(\boldsymbol{H})$.

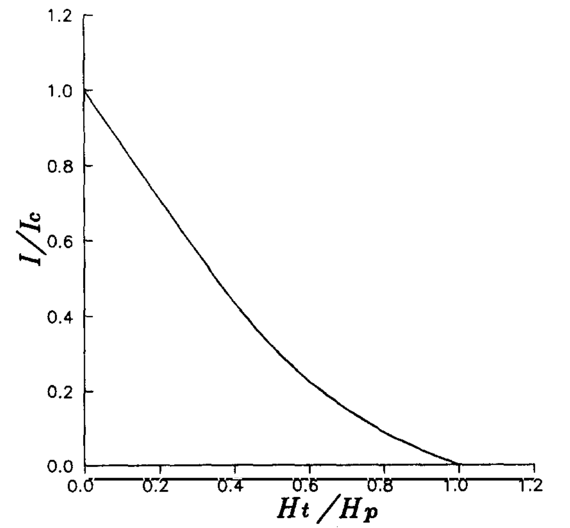


Fig. 2. Calculated dependence of the dimensionless threshold current $I_t/I_c$ on the dimensionless magnetic field $H_t/H_p$.

$$H_p = (8\pi j_0 B^* R / c\mu)^{1/2} , \qquad (6)$$

and the critical current value is given by the formula

$$I_c = (2\pi j_0 B^* c R^3 / 3\mu)^{1/2} . \qquad (7)$$

The plot of $H_t/H_p$ versus $I/I_c$ is presented in fig. 2.

**4.** From the above consideration it follows that the space distribution of the transport current in the presence of the longitudinal magnetic field $H_z$ has to depend on the order of their switching on. If one applies the magnetic field to a zero field cooled sample before the transport current, the current distribution will correspond to fig. 3. Let us note that when the supercurrent $I \leqslant I_c$ is put into a sample, the screening current $j_\varphi$ is located near the cylinder axis only and becomes zero at $I = I_c$. In the other order of switching on $I$ and $H_z$ the distribution will have the form shown in fig. 1. In the last case the appearance of the screening current on the surface layer of the cylinder is followed by a displacement of the transport current deep into the superconductor.

In spite of all our expectations, the results of the measurements of the $z$-component magnetic moment by the vibration magnetometer appeared to be independent of the order of switching on current and field. The critical value of the transport current defined by the four-probe method at a fixed magnetic

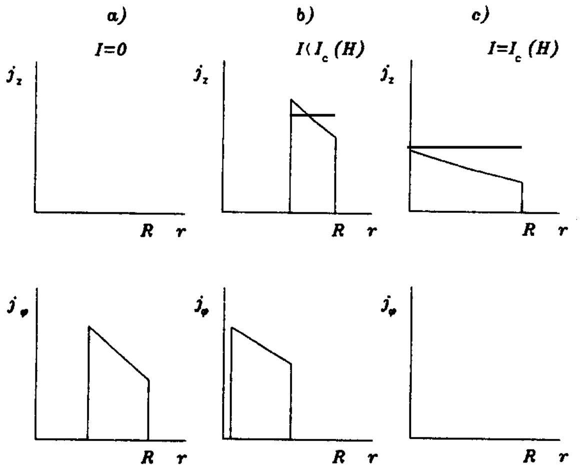


Fig. 3. Schematic distributions of current components $j_z$ and $j_\varphi$ when the current has been switched on before the longitudinal magnetic field. (a)–(c) are for different stages of the field from $H=0$ to the threshold value $H=H_t$.

field does not depend on the pre-history either. The reason of such a distinct contrast between experiment and theory one can understand taking into account the nonequilibrium nature of the superconductor's critical state. Let us, for example, first switch on the transport current and then the magnetic field; the correspondent distributions of currents $j_z$ and $j_\varphi$ are shown in figs. 1b, 1c. The small fluctuations of the electric field $E_z$, which exist always in the nonequilibrium state of superconductors, lead to the appearance of the surface current $j_z$ in correspondence with (2). This means that in the fixed current regime a re-distribution of currents takes place in a short time. So the distributions shown in fig. 1 transform to those shown in fig. 3.

In accordance with this consideration, it takes a rather quick change of $H(t)$ to observe the scenario of transport current collapse stimulated by a magnetic field and described in the sections 1–3. In other words, the induced electric field responsible for the displacement of the current $I$ deep into a cylinder has to exceed considerably the fluctuating electric fields. In fact, the collapse of the transport current is experimentally observed when an ac magnetic field $H(t)$ oscillates with a frequency of about several hertz.

In the present paper we studied the critical state experimentally on cylindrical samples of yttrium HTSC ceramics. The samples were 0.5 cm in diameter, had a length of 4–5 cm and were cooled by liquid nitrogen. For every fixed $I$ we determined the value of $H_0$ which corresponds to the resistive state transition.

In fig. 4 this dependence is shown by asterisks. It is practically insensitive to the field frequency in the range $10$–$10^4$ Hz. In fig. 4 the theoretical dependence $I$ versus $H_0$ is presented also. In order to plot the theoretical curve we must know the parameters $H_p$ and $I_c$, which are defined by eqs. (6) and (7). However, we do not know well the Kim–Anderson parameters $j_0$ and $B^*$ suited for our samples. In addition it is well known that eq. (4) does not describe the critical current density dependence on induction in high-$T_c$ ceramics satisfactory. So, we took the parameter $H_p$ from the experiment. The value $H_p = 50$ Oe was defined by the method described in ref. [8] (see also ref. [9]). The value of $I_c$ in the theoretical calculations is chosen in such a manner that the cal-

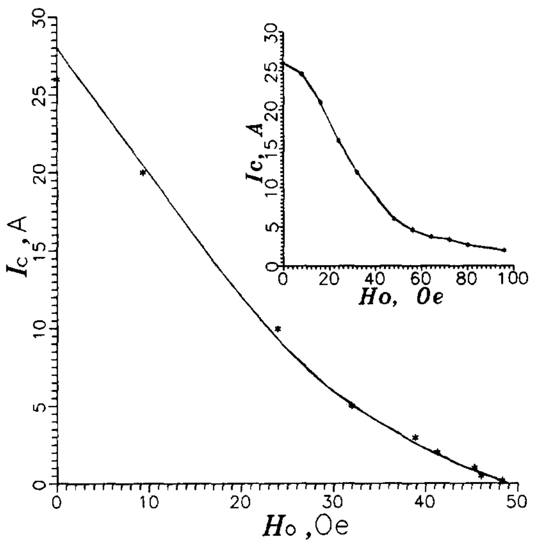


Fig. 4. The current corresponding to the resistive state transition versus the ac magnetic field amplitude: (•) experimental, (——) calculated data. The curve on the insert represents the dependence $I_c(H)$ in static conditions.

culated curve should pass near the experimental points in the region of large field $H_0$. As shown in fig. 4, the theoretical curve lies near the experimental points in a wide range of amplitudes $H_0$. The most noticeable deviations take place at high values of the current in the region of the critical one. We cannot give preference to any definite physical reason which should cause this difference. So here we mention some possible reasons. At first, we had not taken into account in the theory the existence of a surface barrier [10] which prevents magnetic flux penetration into the superconductor, especially at a small amplitude $H_0$. We did not pay attention either to the magnetic flux creep, which is very important near $I_c$. Due to these reasons we cannot determine the real value of $I_c$ in experiment. Therefore the parameter $I_c$ for the calculated curve is taken as adjusted.

The experimental dependence $I$ versus $H$ in static conditions in a wide range of the magnetic field is presented in the insert of fig. 4. The dependence $I(H)$ is similar to the behaviour of the critical current in an ac magnetic field. The main differences are as follows: (1) the values of $I(H)$ exceed the corresponding values of $I(H_0)$ elsewhere in the region $0<H$, $H_0<H_p$; (2) the main difference is observed when $H$, $H_0>H_p$. Here, due to the collapse in an ac field, the transport current equals zero, while in static conditions the superconducting transport current exists even in a field higher than 10 kOe.

So one can understand the observed suppression of the critical current by an ac magnetic field, in the framework of the critical state model. The ac magnetic field displaces the transport current deep into the sample. As a result, a current cord has formed, of which the radius decreases with increase of the amplitude $H_0$. The sample transits into a resistive state, when the critical current density in the cord reaches its critical value at $H=H_t$.

It will be noted in conclusion that a great number of papers are devoted to the problem of interaction between the transport current and external ac magnetic fields (see, for example, refs. [11–16]). However, another geometry was studied in these papers – the external magnetic field was oriented perpendicular to the current. As consistent with this, the treatment was stated in one-dimensional form.

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