DYNAMICS OF THE FLUX JUMPS IN SUPERCONDUCTORS

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Abstract.*In this work, the spatial and temporal distributions of small thermal and electromagnetic perturbations in a plane semi-infinite superconducting sample are studied. Based on a system of equations for temperature, magnetic induction, and vortex motion, a dispersion relation was obtained that determines the growth (or decay) increment of small perturbations. It was shown that, under certain conditions, depending on the values of the parameters of the system, flux jumps of the magnetic flux are observed.*

Key words: *superconductors, small perturbations, flux jumps, vortex, critical state.*

Introduction

Thermomagnetic avalanches, which lead to a sudden failure of the critical state, are the major factor limiting the high current technical applications of bulk superconductors. The total magnetic flux in the superconductor changes with the increase in the applied field. This will induce a dissipation of heat, and thus, the shielding ability of the magnetic field is reduced in the superconductor [1]. The reduction of shielding ability will also lead to the motion of magnetic flux and more heat. This positive feedback can trigger thermomagnetic instability, further causing flux jump [1-3].

We investigated the stability of the critical state in superconducting sample against the small perturbations of temperature, magnetic and electric field. Based on the system of equations for temperature, magnetic induction, and vortex motion, a criterion stability relation was obtained that determines the growth (or decay) increment of small perturbations. It is shown that, under certain conditions, depending on the values of the parameters of the system, explosive patterns of the magnetic flux can be observed.

Basic equations

The distribution of magnetic induction, electric field, and transport current in the superconductor are determined by the following equation

$$\mathrm{rot}\,\vec{B} = m_0 \vec{j}. \tag{1}$$

$$\mathrm{rot}\,\vec{E} = \frac{d\vec{B}}{dt}. \tag{2}$$

Accordingly, the temperature distribution in the sample is determined by the heat conduction equation

$$\nu(T)\frac{dT}{dt} = \nabla[\kappa(T)\nabla T] + \vec{j}\vec{E}, \tag{3}$$

where ν and κ are the coefficients of heat capacity and thermal conductivity of the sample, respectively. Addiction $j = j_C(T,B,E)$ is determined by the following critical state equation

$$j = j_C(T,B) + j(E).$$

We will use the Bean model $j_C = j_C(B_e,T) = j_0 - a(T_C - T_0)$, where B_e is the value of the external magnetic induction; $a = \dfrac{j_0}{T_C - T_0}$; j_0 - equilibrium current density, T_0 and T_C - initial and critical temperature of the sample, respectively [1-3]. In the flow creep mode, the current-voltage characteristic of superconductors is nonlinear, due to thermally-activated motion of vortices [4]. The dependence j (E) in the flow creep mode is described by the expression

$$j = j_C \left[\frac{E}{E_0} \right]^{1/n}, \tag{4}$$

where E_0 is the value of the electric field strength at $j = j_C$; the constant parameter n depends on the pinning mechanisms. In the case when n =1, relation (4) describes a viscous flow [1]. For sufficiently large values of n, the last equality defines Bean's critical state $j \propto j_c$. When 1< n <∞, relation (4) describes the nonlinear creep of the flow [4]. In this case, the differential conductivity is determined by the equality

$$\sigma = \frac{d\vec{j}}{d\vec{E}} = \frac{j_C}{nE_B}. \tag{5}$$

The results and discussions

According to equation (5), the differential conductivity increases with increasing background electric field E_B and essentially depends on the value of the rate of change of magnetic induction according to the equality $E_B \propto \dot{B}_E x$. Let's present the basic equations describing the dynamics of the development of thermal and electromagnetic disturbances for a simple case - a superconducting flat semi-infinite sample (x >0) [5]

$$\nu \frac{d\Theta}{dt} = \kappa \frac{d^2\Theta}{dx^2} + j_c \varepsilon, \tag{6}$$

$$\frac{d^2\varepsilon}{dx^2} = \mu_0 \left[\frac{j_c}{nE} \frac{d\varepsilon}{dt} - \frac{dj_c}{dT} \frac{d\Theta}{dt} \right]. \tag{7}$$

We represent the solution of system (6), (7) in the form

$$dT(x,t) = (T_c - T_0) Q(z) e^{\frac{\gamma t}{t_0}}, \tag{8}$$

$$dE(x,t) = E_c \varepsilon(z) e^{\frac{gt}{t_0}}. \tag{9}$$

where γ is the eigenvalue problem to be determined. It can be seen from the last system of equations that the characteristic time for the development of thermal and electromagnetic perturbations of the order of - t_0/γ [6]. Here we have introduced the following dimensionless parameters and variables

$$\beta = \frac{\mu j_c^2 L^2}{\nu (T_c - T_0)}, \quad t_0 = \frac{\mu j_c L^2}{E_c}, \ z = \frac{x}{L}, \quad \tau = \frac{t}{t_0}, \ . \ e = \frac{\delta E}{E_c}, \ t_0 = \frac{\sigma \nu (T_c - T_0)}{j_c^2}, l = \frac{\nu (T_c - T_0)}{\mu_0 j_c^2}$$

$$\gamma = \frac{1-n}{n}.$$

Let's consider the problem within the adiabatic approximation, when $\tau << 1$, i.e. [6], the diffusion of the magnetic flux occurs faster than the thermal diffusion. Then, we obtain the following equation in the quasi-stationary approximation

$$\frac{d^2Q}{dz^2} - zQ = 0. \tag{10}$$

Since, when deriving the last equation, we neglected thermal effects, only the electro dynamical boundary should be put in (10)

$$Q(1,t) = 0, \qquad \frac{dQ(0,t)}{dt} = 0. \tag{11}$$

The stability criterion of the magnetic flux jumps is determined by the values of $\mathrm{Re}\,\gamma \le 0$. Then, using the second boundary condition $Q(1) = 0$, we obtain the following equation for determining the parameter γ

$$J_{2/3}(a_n) = J_{-2/3}(a_n).$$

A nontrivial solution of the last equation, taking into account the boundary conditions (10), exists only for certain values

$$a_1 = \rho^{2/3}\gamma .$$

where a_1 are the roots of the characteristic Bessel function. After simple transformations, we obtain the following stability criterion for the flux jumps

$$B_c = \frac{4\pi j_c}{c}\sqrt{\frac{k(T_c - T_0)}{j_c n \dot{B}_e}} . \tag{12}$$

It is easy to see that the threshold value of B_c flux jump stability mainly depends on the type of background electric field initiated by a change in external magnetic induction $E_b \approx \dot{B}_e$ [6]. The value of B_c decreases monotonically with increasing of the external magnetic field induction rate in the sample.

Conclusion

Thus, based on a system of equations for temperature, magnetic induction, and vortex motion, a dispersion relation was obtained that determines the growth (or decay) increment of small perturbations. It was shown that, under certain conditions, depending on the values of the parameters of the system, flux jumps of the magnetic flux may be observed.

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