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EXPLOSIVE INSTABILITY IN TYPE II SUPERCONDUCTORS

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Abstract. *A theoretical study of the development of thermomagnetic instability such as a magnetic flux jump in a type II superconductor located in a flat semi-infinite sample was carried out within the framework of the Wien critical state model. An expression for thermomagnetic instability in the sample is determined.*

Key words: *thermomagnetic instability, magnetic flux jump, superconductor critical state*

Introduction

The main reason limiting high-precision technical applications of superconductors is the sudden accidental destruction of their critical state. It is expressed in the loss of the main property of a superconductor - the absence of resistance to the flow of electric current. Such phenomena are called thermomagnetic instabilities of superconductors. They manifest themselves in the form of giant jumps in the properties (resistance, temperature, speed of sound, magnetic flux, magnetization, etc.) of the material. In this case, all the gigantic accumulated energy of the current or magnetic field is released inside the superconductor within microseconds. This often simply leads to the melting of its individual sections and to irreversible consequences. The problem of giant magnetic instabilities in hard superconductors is more than thirty years old [1]. The study of thermomagnetic instabilities has become even more relevant after the discovery of high-temperature superconductivity (HTSC) [2-5]. Interest has increased due to the shift in operating conditions of new superconducting materials 100 degrees closer to room temperature without loss of quality technical parameters. This significantly reduces operating costs .

Therefore, the central issue in the search for the prevention of catastrophic phenomena in materials due to thermomagnetic instabilities is to clarify the mechanisms of their origin, to establish the determining driving forces during their development and ways to prevent such events. Giant instabilities, as a physical phenomenon, have many similarities with theoretical models of catastrophes. In recent years, much attention has been paid to the study of the metastable state of a superconductor, caused by the balance of intervortex repulsion forces and flow pinning at defects. A significant number of unusual phenomena associated with spatiotemporal dynamic properties were observed : vortex avalanches of various scales, self-organized criticality and memory effects in the vortex structure [3]. These studies are focused on analyzing the causes and patterns of the occurrence of small triggering fluctuations - flux jumps (from tens to hundreds of thousands of magnetic flux quanta) inside the material, which can develop into giant magnetothermal instabilities. Such small flux jumps always accompany, for example, the process of penetration of a magnetic flux (in the form of a vortex structure) into the superconductor under pressure, a magnetic field that increases over time.

Thermomagnetic instability such as a magnetic flux jump in superconductors is caused by the interaction of thermal and electromagnetic small disturbances. Such a jump, as a rule, leads to the transition of the superconductor to the normal state [1]. The phenomenon of thermomagnetic instability of a critical state or a jump in magnetic flux was discovered in both low-temperature [1-3] and high-temperature superconducting samples [2]. The general concept of stability of the critical state in type II superconductors was developed in the literature [4]. The purpose of this work is to theoretically study the dynamics of the spatial and temporal distribution of thermal and electromagnetic disturbances in a superconductor in the flux creep mode.

Basic Equation

To describe the flux jump instability in Superconductor slab, the sample is placed in a parallel magnetic field, H. When this magnetic field is applied in the direction of the z-axis, the screening current j and the electric field E are induced inside the slab along the y-axis. For this geometry (Fig 6), the current J and magnetic field contributions in the sample (flux penetrated region ($0 < x < 1$) are described by the following Maxwell equation,

$$\mathrm{rot}\mathbf{B} = \mu_0 \mathbf{J}, \tag{1}$$

$$\mathrm{rot}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{2}$$

Where the common approximation $\mathbf{B} = \mu_0 \mathbf{H}$ is used because $H_{c1} = 0.$

$$\nu \frac{dT}{dt} = \kappa \frac{d^2T}{dx^2} + \mathbf{j}_c\mathbf{E}. \tag{3}$$

where $\nu=\nu(T)$ and $\kappa=\kappa(T)$ are the heat capacity and thermal conductivity coefficients of the sample, respectively. $a=j_0/(T_C-T_0)$; j_0 is the equilibrium current density, T_0 and T_C are the initial and critical temperature of the sample, respectively [6]. In the flux creep mode, the current-voltage characteristic of superconductors is essentially nonlinear, caused by the thermally activated motion of the vortices. The dependence $j(E)$ in creep flow 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 $j = j_C$ [1]; the constant parameter n depends on the pinning mechanisms. In the case when n =1, relation (4) describes the viscous flow of the flow. For sufficiently large values of n, the last equality determines the Bean critical state $j \propto j_c$. When 1< n <∞, relation (4) describes the nonlinear flow creep [3]. In this case, the differential conductivity is determined by the equality

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

According to equality (5), differential conductivity increases with increasing background electric field E_B and significantly depends on the value of the rate of change of magnetic induction according to the equality $E_B \propto \dot{B}_E x$. For such a geometry, the spatial and temporal distributions of small thermal $\delta T(x,t)$ and electromagnetic disturbances $\delta E(x,t)$ are described by the following equations

$$\nu \frac{d\delta T}{dt} = \kappa \frac{d^2\delta T}{dx^2} + \vec{j}_C\vec{E}, \tag{6}$$

$$\frac{d^2\delta E}{dx^2} = \mu\left[\frac{j_C}{nE_b}\frac{d\delta E}{dt} - \frac{dj_C}{dT}\frac{d\delta T}{dt}\right]. \tag{7}$$

Note that the system of differential equations (6), (7) quite fully describes the dynamics of the evolution of thermal and electromagnetic disturbances in a superconductor in the flux creep mode. A detailed discussion of the conditions for the applicability of the system of equations (6) - (7) to describe the dynamics of the development of thermomagnetic disturbances is quite well described in the literature [4]. Let us represent the solution to 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 of the problem to be determined. From the last system of equations it is clear that the characteristic time of development of thermal and electromagnetic disturbances is of the order of - t_0/γ.

Let us consider the process of development of thermomagnetic instability in the adiabatic approximation, which occurs in hard superconductors with low thermal conductivity. The adiabatic nature of the development of instability leads to preferential propagation of magnetic flux diffusion compared to heat diffusion in the sample. This allows us to significantly simplify the procedure for obtaining a solution to the system of nonlinear differential equations (6), (7). In this approximation, the system of equations (6), (7) is reduced to one equation for the distribution of the electromagnetic field

$$\xi \frac{d^2\varepsilon}{d\xi^2} = e^{\gamma} \frac{d\varepsilon}{d\tau} - \beta\varepsilon \tag{10}$$

$\xi = \frac{x}{L}$, $\tau = \frac{t}{t_0}$, $e = \frac{E}{\rho_f j_{c0}}$, $\theta = \frac{T - T_0}{T_c - T_0}$, $\Lambda = \frac{\lambda\mu_0}{\nu\rho_f}$, $\beta = \frac{\mu_0 j_c a^2}{C}\left|\frac{dj_c}{dT}\right|$; where t_0 is a constant parameter characterizing the time of penetration of the magnetic flux deep into the superconductor. Since, when deriving equation (2.23), we neglected thermal effects, only the electrodynamics boundary conditions should be put in (3)

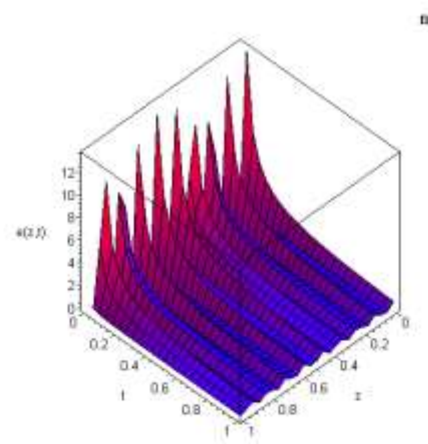
$$\varepsilon(\xi_p, \tau) = 0, \ \frac{d\varepsilon(l,\tau)}{dt} = 0. \tag{11}$$

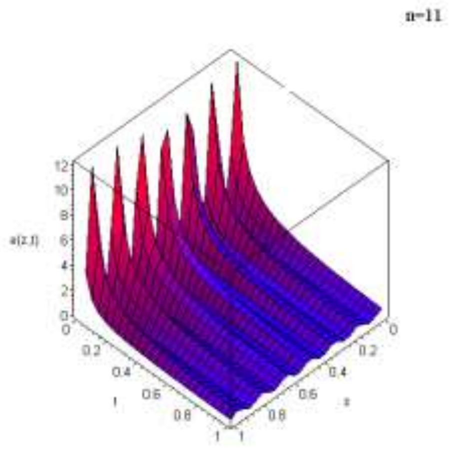
The solution of the last differential equation is obtained using the method of separation of variables [2]. So we may represent the solution of equation (10) in the form

$$\varepsilon(z,\tau) = \left[\frac{B}{\tau_p - \tau}\cos^2\left(\frac{2\pi}{L^*}z\right)\right]^{\frac{n}{n-1}} \tag{12}$$

,.

where τ_p is a constant parameter characterizing the time of penetration of the magnetic flux deep into the superconductor $k=\gamma^{-1}$; $B=\frac{n^2}{1-n^2}\frac{\beta}{2}, \frac{1}{L^*}=\frac{1-n}{4\pi n}\sqrt{\beta}$





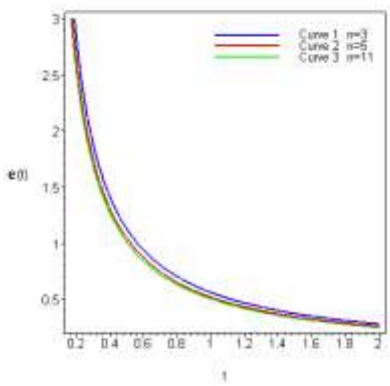


Fig.1. Fig.2. Fig.3.

Fig. 1 and 2. Electric field distribution at $\tau_p=1$, n =3, n =11, $\beta \propto 0.5$.

Fig.3. Temporal evolution of the electric field

Thus, the resulting solution describes the dynamics of the development of thermal and electromagnetic disturbances in a superconductor with a power-law current-voltage characteristic in the magnetic flux creep mode. It is easy to verify that over time, the solution remains localized in a limited interval $x<L^*/2$ [6,7]. The distribution of the electric field $\varepsilon(z,\tau)$ determined from relation (15) is shown in Fig. 1 and 2 for typical parameter values $\tau_p=1$, n =3, n =11, $\beta \propto 0.5$ and $L^* \propto 1$. The time evolution of the electric field is shown in Fig. 13 .

Conclusion

Thus, based on a linear analysis of a system of differential equations for the distribution of temperature and electromagnetic field, it was shown that under certain conditions, explosive instability can occur in a superconductor.

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