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Magneto-thermal oscillations in a granular YBCO superconductor

L. Legrand[a], I. Rosenman[a], R.G. Mints[b], G. Collin[c], and E. Janod[d]

[a] Groupe de Physique des Solides, Universités Paris 6 et Paris 7, 75251 Paris Cedex 5, France

[b] School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

[c] Laboratoire Léon Brillouin, CEN-Saclay, 91191 Gif-sur-Yvette Cedex, France

[d] DRFMC, CENG, 17 rue des Martyrs, F-38054 Grenoble Cedex 9, France

It is shown that in a granular superconductor magneto-thermal oscillations precede a series of subsequent flux jumps. We study these oscillations experimentally in three YBCO samples at temperatures $3\,\mathrm{K} < T < 7\,\mathrm{K}$ and field sweep rates $10\,\mathrm{G/s} < \dot{B}_e < 45\,\mathrm{G/s}$. We find that the frequency of the oscillations is a linear function of the magnetic field sweep rate and is inversely proportional to the square root of the heat capacity.

1. INTRODUCTION

Bean's critical state model [1] successfully describes the irreversible magnetization in type-II superconductors with a strong pinning potential for vortices by introducing the critical current density j_c. In the framework of Bean's model the value of the slope of the stationary magnetic field profile is less or equal to $\mu_0 j_c$.

The stationary critical state becomes unstable under conditions when the local vortex avalanches result in a global flux jump driving the system to the normal state [2]. In many cases a flux jump is preceded by a series of magneto-thermal oscillations [3]. These oscillations of temperature, electric and magnetic fields have been reported earlier [4, 5, 6]. However, no systematic experiments accompanied by an adequate theory have been made.

In this paper we treat both experimentally and theoretically the dependence of the frequency of magneto-thermal oscillations on the temperature and magnetic field sweep rate in case of a granular superconductor.

2. THEORY

We begin with a theoretical consideration and propose a one-dimensional model of a granular superconductor treating it as a stack of superconducting slabs having the width $2b_i$ ($i = 1, 2, 3, \ldots, N$) randomly distributed with a certain mean value b. We assume that: (a) there is no electrical contact between the slabs and there is an ideal thermal contact between them; (b) the external magnetic field $\mathbf{B}_e(t)$ is parallel to the sample surface and the sweep rate $\dot{B}_e$ is constant; (c) the critical state arises simultaneously in the entire superconductor, *i.e.*, in each of the slabs simultaneously arise the magnetic, $B_i(t)$, and electric, $E_i(t)$, fields. We suppose also that close to the instability threshold most of the slabs are saturated, *i.e.*, B_e is higher than Bean's saturation field $B_p = \mu_0 j_c b$.

The critical state is stable if the heat release, δQ, arising in the process of development of small perturbations of electric field and temperature is less than the heat flux to the coolant. The value of δQ depends on both $\dot{B}_e$ and B_e for the unsaturated grains and only on $\dot{B}_e$ for the saturated grains. In our experiments most of the grains are saturated in the magnetic field region corresponding to the magneto-thermal oscillations. Therefore, the heat release in the unsaturated grains, δQ_u, is small compared with the heat release in the saturated grains, δQ_s. However, the term δQ_u is the only magnetic field dependent term in the heat balance equation and, thus, it determines the value of the global flux jump field B_j. In other words, the relatively small heat release in the unsaturated grains is tuning the superconducting state in a granular superconductor to the instability.

We use the heat diffusion and Maxwell equations to determine the frequency ω of small amplitude magneto-thermal oscillations. In the case when the

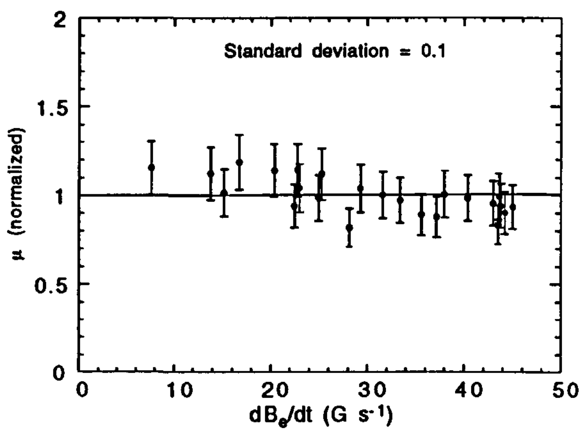

Figure 1: The ratio μ for the samples S0, S1, and S2 as a function of the sweep rate for different temperatures T_0 from the range $3\,\mathrm{K} < T_0 < 7\,\mathrm{K}$. The values of μ are normalized by the mean value of their distribution. The error bars are 13%

critical current density j_c is a linear function of T and $\delta Q_u \ll \delta Q_s$ we end up with the formula

$$\omega \approx Const \frac{\dot{B}_e}{\sqrt{\mu_0 C(T_0)(T_c - T_0)}}, \quad \text{if} \quad \dot{B}_e > \dot{B}_0, \tag{1}$$

where $C(T)$ is the heat capacity, T_c is the critical temperature, T_0 is the coolant temperature, and $\dot{B}_0$ is the minimum ramp rate below which the critical state is stable against the flux jumps.

3. EXPERIMENT

We study the magneto-thermal oscillations in a textured $YBa_2Cu_3O_{7-\delta}$ superconductor grown from the melt and heat treated after the preparation [7]. First, we do the measurements using the original sample (S0) with the size of $8\times9\times5.5$ mm^3. Next, we cut this sample in two approximately equal parts (S1 and S2) and we measure the magneto-thermal oscillations in S1 and S2. In this way we check the independence of the oscillations frequency on the size of the sample.

We perform the magnetic characterization of the samples by DC and AC measurements in a Quantum Design SQUID magnetometer using the sample S3 with a size of $0.3\times0.5\times0.8$ mm^3 (the sample S3 is cut from the sample S2). We find that the critical current density decreases linearly in the range $2\,\mathrm{K} < T_0 < 6\,\mathrm{K}$, the onset temperature at zero magnetic field is equal to $T_c \approx 88\,\mathrm{K}$ and the AC susceptibility transition has the width $\Delta T \approx 5\,\mathrm{K}$.

We measure the magneto-thermal oscillations at temperature T_0 in the range $3\,\mathrm{K} < T_0 < 7\,\mathrm{K}$ and the field sweep rates within the interval $10\,\mathrm{G/s} < \dot{B}_e < 45\,\mathrm{G/s}$. At low values of the magnetic field $B_e(t)$ there is a slow temperature increase due to the small vortices avalanches establishing the critical state. Above a certain magnetic field value, the sample temperature oscillations appear with a period τ in the range $10\,\mathrm{s} < \tau < 70\,\mathrm{s}$ and an amplitude increasing in time. These magneto-thermal oscillations we mainly explore and analyze. A flux jump occurs close to the Bean field accompanied by a temperature rise up to about 12 K with a characteristic time of the order of 1 s.

We show in Fig. 1 the dimensionless ratio $\mu = \omega\sqrt{C(T_0)(T_c - T_0)}/\dot{B}_e$ normalized by its mean value as a function of the magnetic field sweep rate $\dot{B}_e$ for the samples S0, S1, and S2 for different temperatures T_0 from the interval $3\,\mathrm{K} < T_0 < 7\,\mathrm{K}$. In order to calculate the value of μ the dependence $C(T)$ was measured for the sample S0. We see in Fig. 1 that the ratio μ is a constant within the accuracy of our experiments as predicted by Eq. (1). The minor slope that can be seen in Fig. 2 is related to the fact that Eq. (1) is valid only for high values of $\dot{B}_e$.

4. CONCLUSIONS

We show theoretically that in a granular superconductor the magneto-thermal oscillations precede to a flux jump. We study these oscillations experimentally in a granular YBCO samples at temperatures $3\,\mathrm{K} < T < 7\,\mathrm{K}$ and field sweep rates $10\,\mathrm{G/s} < \dot{B}_e < 45\,\mathrm{G/s}$. We find both experimentally and theoretically that the frequency of the magneto-thermal oscillations is a linear function of the magnetic field sweep rate and is inversely proportional to the square root of the heat capacity.

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