Physica C: Superconductivity and its applications 532 (2017) 40–43

Contents lists available at ScienceDirect

Physica C: Superconductivity and its applications

journal homepage: www.elsevier.com/locate/physc

# Stop of magnetic flux movement in levitating superconductor

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ARTICLE INFO

*Article history:*
Received 29 September 2016
Accepted 30 November 2016
Available online 1 December 2016

*Keywords:*
Magnetic relaxation
High-temperature superconductors
Levitation

ABSTRACT

A phenomenon of magnetic relaxation stopping in a levitating superconductor was studied. It was experimentally shown that magnetic flux creep (diffusion of flux lines to regions with lower vortex density) is absent in magnetic suspension of the superconductor. Magnetic relaxation arises, when a rigid constraint that fixes a position of the superconductor relative to a magnet is imposed on a levitating object. It is assumed that oscillations of magnetic structure, which is due to free oscillations of the levitating superconductor, stop magnetic relaxation.



## 1. Introduction

Strong magnetic relaxation (magnetic flux creep) breaks supercurrents in high-temperature superconductors (SC) [1]. It destructively influences on characteristics of superconducting devices. For example, a main parameter of a magnetic bearing system, levitation force, has to decrease with time. At present there are great numbers of experimental studies [2–11], where an interaction force between a SC sample and permanent magnet (PM) was measured as a function of time. The *force-in-time* experiments pointed to the fact that the magnetic force decreased as a logarithmic time law with a rate close to a flux creep rate in a SC. It is believed that the results of these experiments need to take into account in practice of superconducting magnetic bearings [12]. However, it was experimentally found in the work [13] that the lift force did not change with time when only the magnetic force acted on the object of levitation; relaxation of this force developed during fixation of the levitating object position, when a rigid constraint is imposed on this object. The question arises why the constancy of the force acting on the levitating SC due to flux creep stop, i.e. levitation stop the decay of supercurrents in the magnetized SC? It is known [14,15] that the magnetic force could remain unchanged for a long time when the magnetic flux is redistributed in the SC sample but does not leave it (the so-called internal magnetic relaxation). There are no experiments with investigations of magnetic relaxation in fact, i.e. magnetic flux movement in levitating SC. The present paper fills this gap.

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http://dx.doi.org/10.1016/j.physc.2016.11.013
0921-4534/

## 2. Experiment

Fig. 1 shows a low-temperature part of an experimental setup for measuring a relaxation rate of induction on a superconductor surface. The experiments were performed using a disk-shaped sample of melt-textured YBCO ceramics (with a diameter of 10 mm and a height of 3.5 mm) and a ring-shaped SmCo magnet (30 × 18 × 8 mm). The SC sample with a heater and load container formed a levitating object (a floater) of total weight $G$, which could freely move in an evacuated glass tube immersed in liquid nitrogen. A float detent placed above the floater could move inside the tube in vertical direction. A thermocouple and Hall probes having an active zone of 1.5 × 0.5 mm with sensitivity of 90 $\mu$V/mTл were situated on the surface of the detent. The glass tube passed through the ring magnet that could be moved along the tube by draw rods. The SC/PM system had an azimuthal symmetry relative to a vertical axis ($z$).

The system was set in an initial state before each experiment: the floater was put on a support and pressed from above by the detent; then the ring magnet was moved down below the SC sample at a certain distance from the SC (a height of cooling $H_{fc}$). In this position, the sample was heated up to ∼ 110 K (to eliminate remanent magnetization) and cooled once again to 77 K. As a result, the system of levitation returned to the initial state before magnetization of the SC. The experiment can be split into two stages.

*Stage 1. Levitation height*

The floater was freed by rising the detent, and the ring magnet was moved up by micrometric feed of the draw rods. As a result, the SC sample was magnetized and experienced a magnetic force F that increased during the PM approached the SC. When F became equal to a levitation force $F_{lev} = G$, the floater left the support. On further movement of the magnet, the distance between the

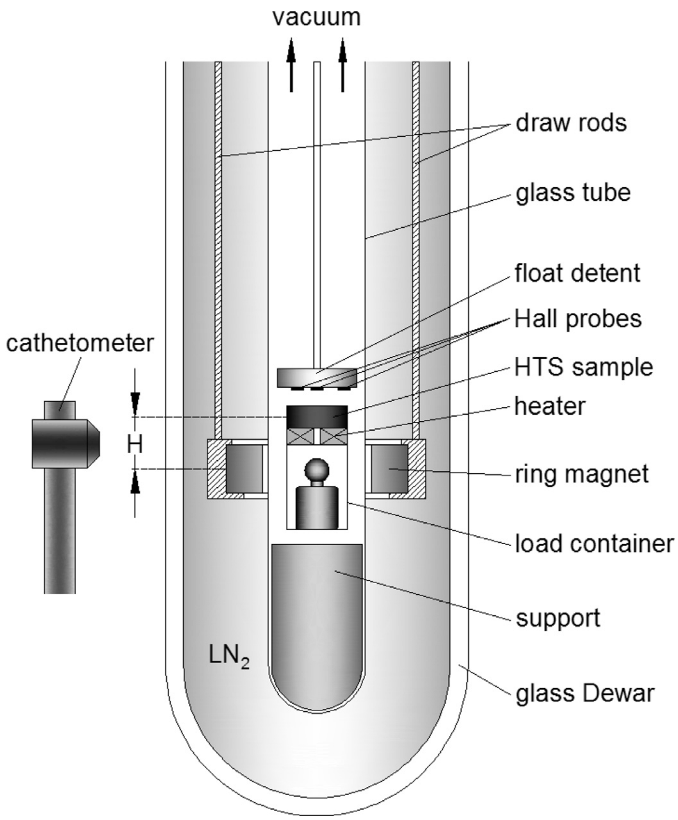


**Fig. 1.** A diagram of the experimental setup.

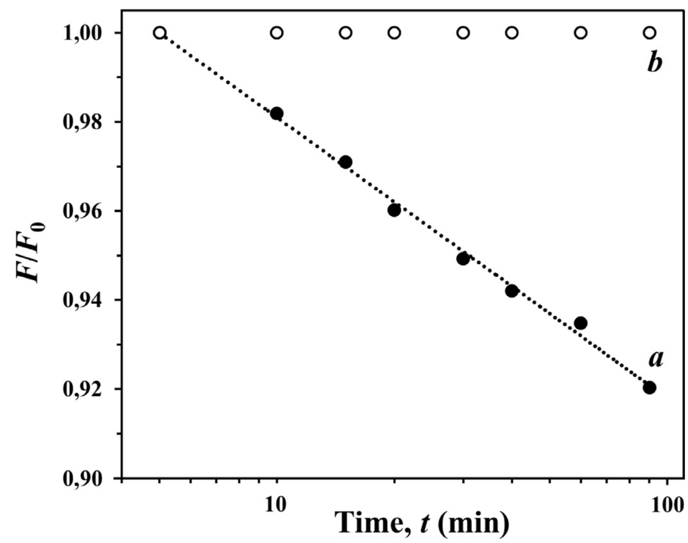


**Fig. 2.** Normalized magnetic force vs. time for the fixed SC (dependence *a*) and for the levitating SC (*b*) initial force $F_0 = F(t_0) = 240$ mN, $t_0 = 5$ min. This figure illustrates the results of [13].

magnet and levitating floater did not change. A levitation height $H_{lev}$ was determined as a distance between centers of the SC sample and ring magnet. It was measured by a cathetometer with an error of 0.01 mm. The $H_{lev}$ value did not change with time and well reproduced in repeated experiments with the same weight load G.

*Stage 2. Magnetic relaxation*

In order to measure the magnetic relaxation rate in the fixed SC, the floater was pressed down to the support by the detent. The SC sample, which was at the $H_{fc}$ distance from the PM, was magnetized by approaching the magnet at the $H_{lev}$ distance. In this position, the sample had the same magnetization and distribution of induction as in levitation, and the magnetic force was equal to G. Sensitive zones of the Hall probes were at a distance of ~0.8 mm from the SC surface. Positions of the probes are shown in Fig. 3. The probes registered a component of induction normal to the sample surface. Induction B was measured simultaneously in three points on the surface of the sample as a function of time. Hereinafter, an index of normal at B is omitted.

To obtain relaxation dependences B(t) in the case of levitation, the following procedure was used. The detent was placed above the floater and the magnet was moved close to the superconductor in order to set up levitation of the floater. Then the magnet was raised to press the floater to the detent by the magnetic force, i.e. to fix the SC sample position. In this case, the distance between the centers of the SC and PM (a height of fixation $H_{fix}$) was less than the levitation height $H_{lev}$, the magnetization was more than in levitation, and the magnetic force F correspondingly exceeded G. Since the magnetic force decreases with time in the system with fixation of the object of levitation (see Fig. 2, *a*-dependence), so the magnetic force pressing down the floater decreased to the value $F_{lev} = G$ after some period of time, i.e. the floater started to levitate. The magnetic force did not change with time in levitation (Fig. 2, *b*), so the distance between the sensitive zones of the probes and the surface of the levitating SC did not change with time as well. A separation of the floater from the detent meaning levitation was almost invisible in observation. In order to register a transition from fixing position to levitation, a central Hall probe was connected to the computer through an AD converter, and a frequency spectrum of induction oscillations was measured.

## 3. Calculation of critical state

Distributions of induction and current density in a magnetized superconductor were calculated by a finite element method. It was used a numerical scheme with field-formulation of equations, which describe a process of critical state propagation in a superconductor [16]. A model of Bean's critical state was employed in the calculation. The following parameters of power law $J(E)$ were used: $J_c = 2.4 \times 10^7$ A/m$^2$, $E_c = 10^{-4}$ V/m, $n = 21$ (a creep component).

A numerical calculation procedure corresponded to the experimental technique of magnetization. The sample having a temperature $T > T_c$ placed 10 mm above the magnet (cooling height $H_{fc} = 10$ mm). In this position, the sample was cooled and transited into a superconducting state. Then it was magnetized by approaching the magnet to the superconductor. (It was assumed that the sample practically had no magnetization after field-cooling. A critical state with current density $J_c$ arises only when the cooled sample (i.e. the superconductor) moves relative to the magnet.) A field-cooled regime was modeled by setting appropriate boundary and initial conditions. A ring magnet field was calculated by an equivalent solenoids method. The process of magnetization was described as an approach of the solenoids with current to the SC. The movement of the solenoids was stopped at a distance $H_{lev} < H_{fc}$. The induction and current density distributions in the SC were determined in this position.

## 4. Results and discussion

Fig. 3*a* shows the results of the critical state calculation in the superconducting disk. The magnetic field configuration corresponds to the magnetization whereby the magnetic force acting on the sample equals to floater weight *G*. It is an initial induction distribution, which should undergo magnetic relaxation. Radial and axial gradients of induction produce azimuthal currents of density