MSU-chem 95

Weak gravitation shielding properties of composite bulk $YBa_2Cu_3O_{7-x}$ superconductor below 70 K under e.m. field.

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Abstract

A high-temperature $YBa_2Cu_3O_{7-x}$ bulk ceramic superconductor with composite structure has revealed weak shielding properties against gravitational force in the state of levitation at temperatures below 70 K. A toroidal disk was prepared using conventional ceramic technology in combination with melt-texture growth. Two solenoids were placed around the disk in order to initiate the current inside it and also to provide rotation about its central axis. Samples placed over the rotating disk demonstrated a weight loss of 0.3-0.5%. When the rotation speed was slowly reduced by changing the current in the solenoids, the shielding effect became considerably higher and reached 1.9-2.1% at maximum.

74.72.-h High-T_c cuprates.

1 Introduction.

The behavior of high-temperature ceramic superconductors under high-frequency magnetic field is of great interest for practical applications. Crystal structure seems to be the key factor determining all physical properties of bulk superconductors, and the interaction of this structure with external and internal e.m. fields might result in quite unusual effects. Despite a large number of studies [1, 2, 3] the nature of these interactions still remains unresolved.

Our recent experimental work [4] clearly indicated that under certain conditions single-phase bulk dense $YBa_2Cu_3O_{7-x}$ revealed a moderate shielding effect against gravitational force. In order to obtain more information about this unusual phenomenon, a new installation was built which allowed to operate with magnetic fields up to 2 T and frequencies up to 10^8 Hz at temperatures from 40 to 70 K. A new experimental technique was applied to modify the structure of the ceramic superconductor. All these efforts yielded a larger value of the shielding effect (up to 2%) and provided good hopes for technological applications.

A gravitational shielding effect of this strength has never been previously observed and its theoretical explanation presents serious difficulties (see [11] for references and an analysis of some hypotheses). Thus great attention was devoted to the elimination of any possible source of systematic errors or of spurious non-gravitational effects. The small disturbances due to air flows pointed out by some authors [9, 10] were eliminated weighing the samples in a closed glass tube (see Section 2.2). The entire cryostat and the solenoids were enclosed in a stainless steel box. But probably the best check for the truly gravitational nature of the effect is the observed independence of the weight reduction (in %) of the mass and of the chemical composition of the tested samples (Section 3).

According to public releases, the NASA group in Huntsville, Alabama, is presently "cloning" our experiment. This is a difficult task, especially for the sophisticated technology involved in the construction of the large ceramic disk and in the control of its rotation. We are also aware, though still at un-official level, of other groups working at the experiment with smaller disks.

2 Experimental.

2.1 Construction of the disk.

The shielding superconducting element was made of dense, bulk, almost single-phase $YBa_2Cu_3O_{7-x}$ and had the shape of a toroidal disk with the outer diameter of 275 mm, the inner diameter of 80 mm, and the thickness of 10 mm. The preparation of the 123-compound consisted of mixing the initial oxides, then calcining the powder at 930^0 C in air, grinding, pressing the disk at 120 MPa and sintering it in oxygen at 930^0 C for 12 hours with slow cooling down to room temperature. After that the disk was kept in a furnace at 600^0 C and the upper surface was quickly heated to 1200^0 C using a planar high-frequency inductor as shown in Figure 1. During this last heating the gap between the sample and the inductor was chosen precisely to provide only the heating of the upper 2 mm-thick layer of the disk, though the high heat conductivity of the material caused the heating of some part of the material below this layer. Finally the disk was slowly cooled down to room temperature in a flow of oxygen and treated mechanically in order to obtain good balance during rotation. A thin (1 mm) metal foil of magnetic material was attached to the upper surface of the disk using plastic glue in order to provide the disk rotation as described below. Table 1 summarizes the disks construction procedure.

The phase and crystal structure of the superconductor were studied using X-ray diffraction analysis (XRD) and a scanning electron microscope (SEM) equipped with an energy dispersive spectral (EDS) analyzer. The samples were cut layer by layer from the bulk ceramic disk.

The transition temperature T_c was determined from the resistive transition in a variable temperature cryostat, under zero magnetic field, using an AC current and sputtered golden contacts. The critical current density was measured for samples cut from the top and from the bottom of the superconducting disk. Measurements of J_c were carried out at 75 K using an AC current, four-probe method and direct transport measurements.

The analysis of the cross-section of the ceramic $YBa_2Cu_3O_{7-x}$ disk revealed the existence of two zones with different crystal structure. The upper part of the disk (6-7 mm of thickness) had an orthorhombic structure typical of the quench and melt growth process [5, 6] and consisted mainly of single-phase orthorhombic 123-compound. The material was dense and had pure and hardly visible grain boundaries. The grains had the size of less than 2 μm and were oriented (75%) with c-axis parallel to the surface of the disk. The transition temperature for the material as defined by direct measurements was 94.2 K.

The lower part of the disk which was in close contact with the water-cooled base during the high-frequency heat treatment had a structure with randomly oriented grains and average grain size from 5 to 15 μm. The porosity of this zone varied from 5 to 9%. The transition temperature T_c was equal to 60.5 K and the material contained about 40% of the tetragonal phase.

Crystal lattice parameters for these two layers as calculated from XRD are listed below, the values being given in nm:

Upper layer: a=0.381; b=0.387; c=1.165;

Lower layer: a=0.384; b=0.388; c=1.170.

a=0.387; c=1.183.

The first (upper) layer was quite homogenous with even distribution of elements in the volume of all the samples. EDS analysis showed the presence of small inclusions of Y_2BaCuO_5 in the lower layer.

2.2 Operation of the apparatus.

Two identical solenoids were placed around the superconductor using fibreglass supports as shown in Figures 2, 4, 5. The gaps between these solenoids and the disk were large enough for it to easily move about 20 mm in each direction. The toroidal disk was placed inside a cryostat equipped with a set of three coils (Fig. 3) which could keep it levitating when it reached the superconducting state. A blocks scheme of the electrical connections is shown in Fig. 6. High-frequency electric current (10^5 Hz) was first sent to the two main solenoids around the toroidal disk, initiating the current inside the ceramics at room temperature. Then the system was slowly cooled down to 100 K by liquid nitrogen and then quickly cooled by liquid helium vapors to the temperature of 65-70 K so that the disk became superconducting (Fig. 7). The main solenoids were switched off. After that the current (10^5 Hz) was sent to the coils below the disk and the superconductor raised up (about 15 mm) because of the Meissner effect. Then a small current (10^5 Hz) was sent to the main solenoids and the disk began to rotate counter-clockwise with increasing speed. The rotation speed was increased up to 5000 rpm. At this moment the measurements of weight for various objects were taken (Fig. 8).

Finally the rotation speed was slowly reduced by changing the current in the main solenoids (Fig. 9). The rotation speed was controlled by means of a laser beam reflected by a small piece of plastic light-reflecting foil attached to the disk. The measurements of weight were taken constantly during this period, too.

The frequency of the e.m. field was varied from 10^3 to 10^8 Hz. Samples made of various materials were tested, including metals, glass, plastic, wood and so on. All these samples were placed over the cryostat hanging on a thread connected to a sensible balance. The distance from the samples to the cryostat varied from 25 to 1500 mm in the first run and up 3 meters in the second run. The weight of the samples was typically from 10 to 50 grams. Every precaution was taken to avoid any possible disturbance including induced magnetic fields and air flows. The samples were placed inside a closed vertical glass tube in order to eliminate the influence of air flows.

3 Results.

The levitating disk revealed a clearly measurable shielding effect against the gravitational force even without rotation. The values of the weight loss for various samples were within the range of 0.05-0.07% in this case. As soon as the main solenoids were switched on and the disk began to rotate in the vapors of liquid helium, the shielding effect increased, and at the speed of 5000 rpm the air over the cryostat began to raise slowly up to the ceiling. The particles of dust or smoke made the effect clearly visible. The boundaries of the flow could be seen clearly and corresponded exactly to the shape of the toroid.

The weight of various samples decreased no matter what material they were made of. Samples made of the same material but with different masses lost the same fraction of their weight. The weight loss depended on the shape and the position of the sample. The maximum loss of weight could be reached when the sample was parallel to the surface of the disk, so that its projection had the maximum area. The best measurement gave a weight loss of 0.5%, while typical values were from 0.3 to 0.5%. The areas close to the inner edge of the toroid (5-7 mm from the edge) gave lower values of shielding, from 0.1 to 0.25% only.

During the time when the rotation speed was decreased from 5000 to 3500 rpm using the solenoids as braking tools, the shielding effect reached maximum values and the weight loss of the samples was from 1.9 to 2.1%, depending on the position of the sample with respect to the outer edge of the disk. These peak values were measured during 25-30 seconds as the speed decreased rather quickly. Because of considerable vibration of the disk at the rotation speed of 3000-3300 rpm, further braking was done very quickly in order to avoid unbalanced rotation and the weight measurements could not be carried out.

Remarkably, the effect of the weight loss was the same when the samples together with the balance were moved upwards to a distance of 3 m, within the projection of the toroidal disk. No weight loss at all was observed below the cryostat.

The maximum shielding properties were observed for maximum current inside the superconducting disk. According to preliminary measurements the upper layer of the disk was able to carry over 15000 A/cm^2. The maximum weight loss of the samples was observed only at high frequencies of the magnetic field in the interval from 3.2 to 3.8 MHz.

The shield decreases slightly the gravitational force within the vertical projection of the disk and creates a kind of vertical cylindrical tunnel in the air with slightly reduced air pressure. (The observed effect also works in various gases and liquid media.) The difference between the atmospheric pressure over the cryostat and the pressure below it was measured with high precision using a mercury barometer. It was equal to 8 mm for the maximum shielding effect. Such a pressure difference produces a lifting force on the cryostat, which in the present case is however of no practical interest (of the order of 10^2 Kg/m^2).

4 Discussion.

The interaction of a superconducting ceramic body with the gravitational field is a complicated process and cannot be characterized by one single law or physical phenomenon. Also, an overwhelming explanation of the mechanism of high-temperature superconductivity has not been found yet. Still these facts do not make the observed phenomenon less interesting.

In our previous work [4] the loss of weight of the sample over the levitating superconductor was smaller and varied from 0.05 to 0.3%. At that time it was difficult to exclude entirely any influence of the radio-frequency field because the sample was separated from the disk and the magnets by a thin plastic film. Now the superconductor was situated in a stainless steel cryostat and the influence of non-gravitational factors causing levitation should be negligible.

The modification of the crystal structure of the superconductor allowed to obtain a composite body with a dense and oriented upper layer and a porous lower layer with random orientation of the grains. The upper layer is able to carry high J_c current under considerable magnetic field while the lower layer cannot conduct high currents and is not resistant to the external magnetic field. The lower part of the disk with wide intergrain boundaries is also a source of a great number of Josephson junctions and is responsible for the direct and reverse, primary and secondary Josephson effect. The presence of tetragonal non-superconducting phase allows interaction with the external magnetic field.

The combination of two different crystal structures with different behavior under magnetic field creates a composite ceramic body with new properties. According to Faraday law the placement of a normal conductor in a magnetic field causes electric current inside it. Usually during levitation the magnetic field does not penetrate into a superconductor for more than a penetration depth, thus the interaction with the field is extremely small. But in the described experiment the superconductor also carries high frequency electric current modified by Josephson effect. It is possible to admit that some interaction between the composite ceramic body and the external magnetic field takes place. This interaction depends on the coherence length, the flux pinning, the field frequency and the field force, the penetration depth and the parameters of the crystal lattice. These characteristics are interrelated in a complex way. According to the experimental data (compare also [10], where only a static field was applied) the ceramic superconductor kept at the temperature below 70 K does not reveal any unusual shielding if it has no contact with the AC magnetic field.

As analyzed in [7] pinning centers with different origins may exist inside the superconducting disk, and fluxes will be trapped at some of them. Fluxes trapped at weak centers will begin to move first while those trapped at strong centers will not move until the Lorentz force exceeds the pinning force. The overall current will be composed of the superposition of flux motions with different speeds. Generally speaking, the quantized fluxes move as a bundle locally formed in a flux lattice by the magnetic interaction between them.

The temperature is also of great importance as it determines the thermodynamic functions and in particular the order parameter and the free energy inside a superconductor. The shielding effect was observed only below 70 K, while the ceramic disk became superconducting already at 94 K.

The electric interactions inside the superconducting body below T_c change under the conditions of the experiment and this might alter the behavior of the whole atomic structure in such a way that the interaction with the gravitational field becomes different. Then, in order to keep a stable level of energy and a stable atomic and crystal lattice structure the superconductor might exchange some energy with the gravitational field and slightly decrease it. There are no grounds to claim that the rotation momentum of the disk interacts with gravitation force, but it seems that fast rotation is favorable for the stabilization of the shielding effect.

According to BCS theory, in weak bond conditions electrons of conductivity and phonons in the crystal lattice interact from time to time: particles collide but they still preserve their individual positions and properties. If we deal with strong bond the interaction takes place all the time and free electrons and phonons exist no longer giving birth to a certain mixture called electron-phonon liquid. This liquid has specific properties and the behavior of the electron-phonon mixture under various conditions is not yet studied. It is possible to admit that this liquid has some properties similar to those which are typical for magnetic liquids, especially if we take into consideration that magnetic hysteresis is characteristic for high T_c compounds. Also the experimental equipment described above has much in common with magneto-hydro-dynamic (MHD) generators.

The first attempt at a theoretical explanation of the effect has been done by G. Modanese [11, 12]. Further investigations that are in progress, will help to prove, change or complete the present understanding of the observed phenomenon.

5 Conclusions.

A superconducting ceramic levitating disk of $YBa_2Cu_3O_{7-x}$ with composite structure demonstrated a stable and clearly measurable weak shielding effect against gravitational force below 70 K and under high-frequency e.m. field. A combination of the high-frequency current inside the rotating toroidal disk and the high-frequency external magnetic field, together with electronic pairing state and superconducting crystal lattice structure apparently changed the interaction of the solid body with the gravitational field. This resulted in the ability of the superconductor to modify the energy of the gravitational force and yielded a weight loss of various samples up to 1.9-2.1% .

Samples made of metals, plastic, ceramic, wood etc. were situated over the disk and their weight was measured with high precision. All the samples showed the same partial loss of weight, no matter what material they were made of. In order to obtain the maximum weight loss the samples should be oriented with the flat surface parallel to the surface of the disk. The overall maximum shielding effect (2.1%) was obtained when the rotation speed and the corresponding centrifugal force were slightly decreased by the magnetic field.

It was found that the shielding effect depended on the temperature, the rotation speed, the frequency and the intensity of the magnetic field. At present it seems early to discuss the mechanisms and to give a detailed analysis of the observed phenomenon as further investigation is necessary. The experimentally obtained shielding value might be of primary interest for scientific and technological applications.

5.1 Acknowledgment.

The author is grateful to the Institute for High Temperatures of the Russian Academy of Sciences for the help in the preparation of the unique superconducting ceramic disks and for the possibility to use their technological equipment. The effect was first observed and studied at Tampere University of Technology.

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FIGURE CAPTIONS.

1. Schematic cross-section of the furnace for high-temperature treatment of the ceramic disk with planar hig-frequency inductors.
2. General magnets and cryostat setup.
3. Typical geometry and position of the disk over supporting solenoids.
4. Schematic design of rotating solenoids. a, b: various configurations.
5. Typical configuration of the tested set-up for the rotating solenoids.
6. Block scheme of the electrical connections.
7. Schematic design of the cryogenic system for the refrigeration of the superconducting disk.
8. General configuration of the equipment for the weight loss measurements.
9. Typical design of the three-point disk-braking system.