Penetration of ac magnetic field into bulk high-temperature superconductors: Experiment and simulation

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To determine the magnetic field inside a superconductor, we have measured the distribution of the ac magnetic field in a narrow gap between two BSCCO superconducting cylinders with a set of Hall probes. Numerical simulations showed a close agreement between the magnetic field distributions inside the superconductor and the gap. Bean's model was used for setting the current density distribution inside the superconductor. It was found that at low currents, the field distribution inside the superconductors could be described by Bean's model. Marked difference observed at higher currents can be explained by flux creep and flux flow. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1667423]

I. INTRODUCTION

The analysis of the operation of superconductors in electric devices requires the study of the magnetic field penetration in the bulk of a superconductor. The magnetic field distribution in a superconductor is usually calculated using various models of the critical state, in particular, Bean's model. However, pronounced deviations from these models for high-temperature superconductors are observed at the operation in ac fields even of low frequencies. For more correct description of the magnetic properties, other models were developed which were based on experimental electric field versus current density ($E-J$) characteristics obtained under dc conditions.[1–3] The experimental verification is usually based on measurements of the integral characteristics: ac losses, susceptibility, trapped magnetic flux, shielding properties, etc. These measurements have shown that the models based on $E-J$ characteristics have also the restricted field of the application. Therefore, the study of the magnetic field distribution inside superconductors under dynamic conditions is very important for correct modeling magnetic properties of high-temperature superconductors. In this article we propose a method of the experimental study of the magnetic field distribution inside a superconductor via the measurement of the field in a narrow gap between two superconducting cylinders. Using a computer simulation, we analyze the adequacy and accuracy of this method.

II. EXPERIMENTAL SETUP

The main part of the experimental setup, shown schematically in Fig. 1(a), constitutes an open core transformer. A 400-turn primary coil, 36 mm in height and 22 mm in outside diameter, made out of a 0.3 mm cooper wire and two hollow superconducting 2212 BSCCO cylinders are centered on a $10\times12\ \mathrm{mm}^2$ cross-section ferromagnetic core. The BSCCO cylinders were fabricated using the melt cast technology developed by Hoechst.[4] The obtained casts were machined into 15 mm height, 35 mm outside diameter, and 5 mm wall thickness cylinders. The study of $E-J$ characteristics of the cylinders was performed using the method de-

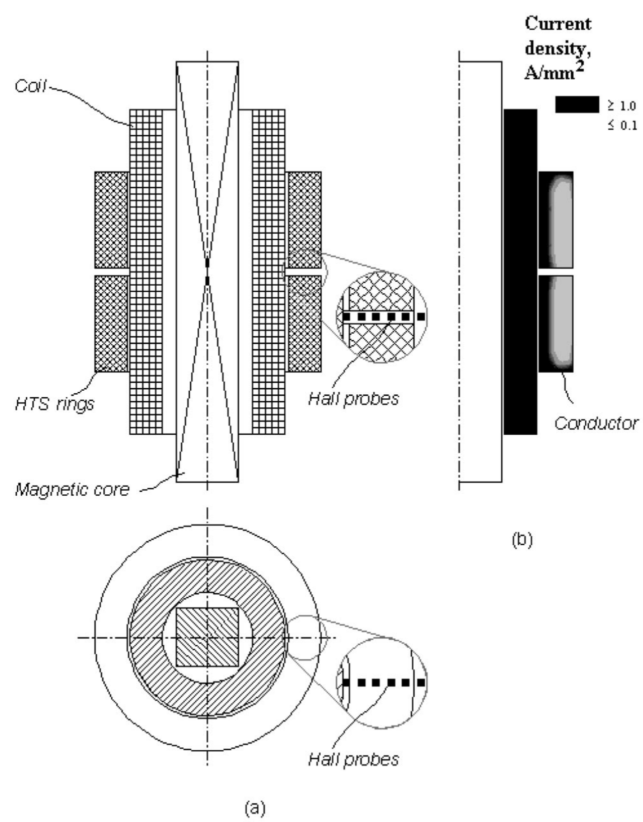

FIG. 1. (a) Experimental setup; (b) distribution of current in the almost perfect (10^{10} S/m) conductive ring (numerical simulation for 1 A/mm^2 primary current density and 50 Hz frequency).

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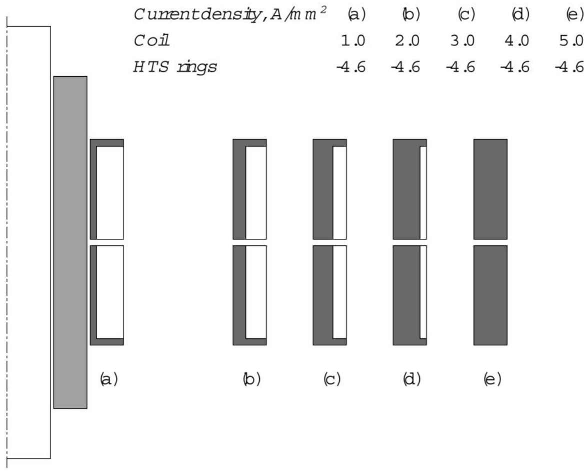

FIG. 2. The chosen current distribution in the superconducting cylinders for numerical simulations. (Magnetic coupling between the primary and the secondary is 0.7.)

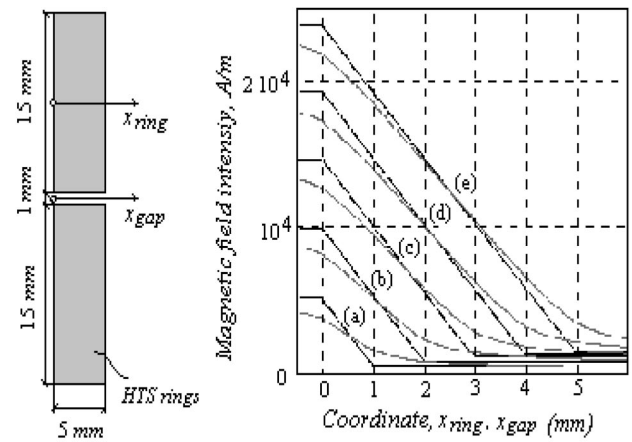

FIG. 3. Magnetic field intensity inside the hollow HTS cylinder wall (the black lines) and air gap (the gray lines).

scribed in Ref. 5. It was shown that these characteristics are well fitted by the power law with the exponent equal to about 8. Characterization of the specimens gave the value of about 460 A/cm^2 for the critical current density at 77 K and the critical temperature of 94 K.

The primary coil is connected with a power supply providing a sinusoidal current of adjustable frequency of 50–500 Hz and effective value up to 3 A. The instantaneous magnetic field distribution in the narrow gap of about 1 mm between two BSCCO cylinders [Fig. 1(a)] was measured by a set of six Hall probes with the active region 0.4×0.12 mm^2 and the sensitivity up to 1400 μV/mT. The Hall probes measured the field component parallel to the axis of the cylinders.

III. NUMERICAL SIMULATION

The purpose of the numerical simulation was to determine to what extent the field measured in the gap between two superconducting cylinders fits the field inside the wall of the hollow cylinder. The simulation was carried out using Maxwell® two-dimensional software manufactured by Ansoft. The magnetic field distribution was calculated in different cross sections perpendicular to the cylinder axis: both in the gap and in the wall of the cylinder. In the first stage of the simulation the superconducting cylinders were replaced by the well conducting ones having the same dimensions. The distribution of the induced current inside the cylinders has been determined at a frequency of 50 Hz [Fig. 1(b)]. In the next stage, using the obtained results, we model the current distribution inside the superconducting cylinders using the Bean model: current density is equaled to the critical value or zero. The thickness of the superconductor zones occupied by the current was calculated with the critical current density equaled to 4.6 A/mm^2 and the magnetic coupling coefficient of 0.7. The value of this coefficient was estimated theoretically and measured with the help of the probe coils modeling the superconducting cylinders. The calculation was performed for different densities of the current in the primary coil (Fig. 2). Here and below the x axis is directed along the radius and $x=0$ corresponds to the inner surface of the superconducting cylinder. The results of the simulation are presented in Fig. 3.

IV. DISCUSSION

The simulation based on the Bean model gives the magnetic field distribution inside the superconductor (black lines, Fig. 3), which can be well fitted by a piecewise-linear function. According to the Bean model, the current does not occupy the whole of the wall of the superconducting cylinders until the external magnetic field is less than the complete penetration value.[2,3] The existence of the nonzero residual field (a few percents of the field at $x=0$) after the sloping part can be explained by an inaccuracy in the determination of the current distribution in the specimen and of the magnetic coupling coefficient. Note that this coefficient depends on the penetration depth of the magnetic field.

Comparing the simulation results for the magnetic field in the gap and cross section of the cylinder (Fig. 3), one can see that the relative difference between them decreases with

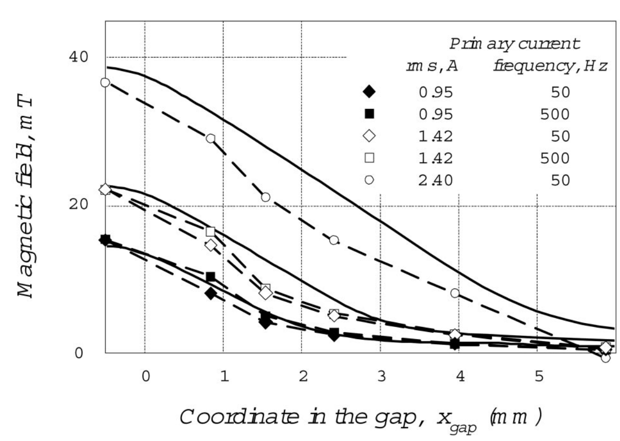

FIG. 4. Comparison between the experimental data and simulation results.

an increase of the applied field. The parameter determining this difference is the ratio of the thickness of the zone occupied by the current and gap thickness.

Let us compare the experimental and simulation results. Figure 4 presents the distribution of the maximum value of the magnetic field in the air gap for different amplitudes and frequencies of the primary current. At low currents (0.95, 1.42 A) there is a good agreement between the theoretical and experimental results. However, at higher currents (2.4 A) a significant difference is observed even at low frequency of 50 Hz. This deviation can be explained by the influence of the flux motion that increases with the induced electric field in the superconductor.[1–3]

The experimental data show clear frequency dependence of the magnetic field in the superconductors. The magnetic field in the center of the gap at 500 Hz is about 20% higher than the field at 50 Hz. The Bean model predicts the frequency-independent distribution of a magnetic field. The frequency dependence is usually associated with the flux creep that is much stronger in high temperature superconductors than in low temperature ones.[1–3] The heating due to ac losses can also be a cause of the pronounced difference between the experimental and calculated data.[3]

In conclusion, our results show that the developed method allows one to determine the distribution of the magnetic field inside a bulk superconductor and to analyze the applicability of various theoretical models. The precision of the method is increased with decreasing the air gap thickness between superconductors.

ACKNOWLEDGMENT

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