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# Investigation of the Critical Current Density of YBaCuO high-temperature Superconductor Ceramic

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## Abstract

The method of high harmonics is used to investigate penetration of low magnetic fields within the  $Y_1Ba_2Cu_3O_7$  high-temperature superconductor ceramic. Given experimental results are explained by the modal dependencies between the value of critical current density and the magnetic induction  $B$ :

$$j_c(B) = j_c(0) \frac{B_0^2}{B_0^2 + B^2}.$$

**Key Words:** High-temperature superconductors, critical current density, low magnetic field, high harmonics.

## 1. Introduction

Grain superconductors, to which belong high-temperature superconductor ceramics, have a peculiarity associated with the existence of superconductivity in every grain, that the parameters are characteristic of bulk monocrystals. Adding to this, between the grains there are weak Josephson junctions determining the superconducting properties of the system on the whole. One of the clear manifestations of high-temperature superconductor ceramics as a Josephson junction medium is the penetration of low magnetic fields of order  $10^{-3}$  Oe less than the first critical field of grains into this medium.

In  $h > H_{c1}$  fields there are formed macroscopic vortices with  $\lambda_{eff} \gg a$ , where  $a$  is the grain size. In such cases, as in common II type superconductors, the superconducting current results from the pinning of vortices on inhomogeneities of the system. It is well known that the behavior of the system is fully determined by the dependence of the pinning force on magnetic field. The pinning force is proportional to the  $j_c$  current density [1].

## 2. The problem formulation

The critical current density is one of the main parameters of superconductors determining the possibilities of their practical application. The analysis of magnetic measurements for high-temperature superconductors is also complicated as the exact dependence of  $j_c$  on  $B$  is not known. The model dependence  $j_c(B) = j_c(0)/(1-B/B_0)$ , which qualitatively agrees with the experimental data, has been used in [2]. In a series of articles [3,4]  $j_c(B) = j_c(0)/(1+B/B_0)$  dependence is used. Other investigators have used the following dependencies:  $j_c(B) \sim B^{-1/2}$  [5],  $j_c(B) \sim B^{-3/2}$  [6],  $j_c(B) \sim B^{-n}$  [7]. For YBaCuO, the dependencies  $j_c(B) = j_c(0)\exp(-B/B_0)$  [8,9] and  $j_c(B) = j_c(0)/1 + B^2/B_0^2$  [10,11] are used. From this it is seen that

there is no unified opinion of the choice of  $j_c(B)$ . In this connection the magnetic measurements of the high-temperature superconductor  $Y_1Ba_2Cu_3O_7$  was carried out in the low fields regions.

### 3. Experimental

In order to study the behavior of the critical current density in low magnetic fields we used the method of high harmonics. The main point of this method is the following: if we act on the nonlinear system by harmonic excitation and study the response to this excitation, the response signal, most likely, will not be harmonic. At the same time, the spectrum of the response can be represented as a sum of elemental harmonic signals (harmonics), a Fourier composition.

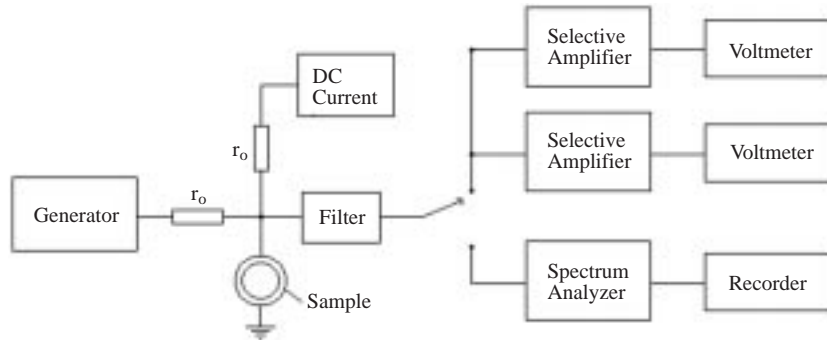
In our experiment we discuss the case when collinear constant and variable fields  $H(t) = H + h_0 \cos \omega t$  are applied to the sample. In response,  $B(t)$  can be expanded into a Fourier series:

$$B(t) = \frac{a_0}{2} + \sum_n (a_n \cos \omega t + b_n \sin \omega t). \quad (1)$$

In the case of low fields, where  $h_0 \ll H$ , we obtain the expression for  $a_n$  and  $b_n$  coefficients [12]:

$$\begin{aligned} a_0 &= 2\mu_{eff}H, & a_1 &= \frac{\mu_{eff}h_0^2}{4\pi j_c(H)d}, \\ a_{2k+1} &= 0, & k \geq 1; & b_{2k+1} = -\frac{\mu_{eff}h_0^2}{8\pi^2 j_c(H)d} \cdot \frac{1}{(k^2 - \frac{1}{4})(k + \frac{3}{2})}; \\ a_2 &= \frac{\mu_{eff}h_0^3}{32\pi d} \frac{d}{dH} \left\{ \frac{1}{j_c(H)} \right\}, & a_{2k} &= 0, \quad k > 2; \\ b_{2k} &= \frac{\mu_{eff}h_0^3}{16\pi^2 d} \frac{d}{dH} \left\{ \frac{1}{j_c(H)} \right\} \frac{k}{(k^2 - \frac{1}{4})(k^2 - \frac{3}{2})}. \end{aligned} \quad (2)$$

The schematic diagram of the measuring system of high harmonics is presented in Fig. 1. The variable voltage source had a coefficient of nonlinear distortion that did not exceed  $10^{-6}$ . At the input of the amplifier was placed a selective filter that dampened the base frequency by a factor of  $10^{-3}$ . Two such selective amplifiers were used to measure the second and third harmonics  $C_2$  and third  $C_3$ . The variation of harmonics was measured by a spectrum analyzer. The amplifiers had a noise level of about  $0.1-0.2 \mu V$ . Then the amplitude of the measuring signal was less than  $0.2 \mu V$  the precision of measurement was 2%, but did not exceed 0.5 % at the upper amplitudes.



**Figure 1.** Schematic diagram of the measuring system.

For the investigation a  $YBa_2Cu_3O_7$  sample was chosen. In order to remove the effect of demagnetization connected with the form, the sample was formed in the shape of a torus with 10 mm outer and 5 mm inner diameters. The sample was wrapped with a single layer coil, which was used both to induce variable  $h_0 \cos \omega t$

and constant  $H$  fields and for measurements. The sample was located in a thermostat allowing us to carry out the investigation in the temperature interval of 70-300 K. The system of temperature stabilization allowed us to maintain a constant temperature with accuracy to  $10^{-3}$  K. The thermometer was a KD-102 type silicium diode having high sensitivity of 2.5 mV/K. The voltage drop allowed us to measure the temperature variation with resolution of 0.001 K. The magnetic field of the Earth in the block of samples was less than  $10^{-3}$  Oe, which was obtained by means of the permalloy screens. The measurements were carried out at the frequency of 20 kHz.

#### 4. Experimental Results and Discussion

In order to show clearly that the grain superconductors are really nonlinear systems in low fields we measured the spectrum of harmonics experimentally when  $h_0=0.1$  and  $H=2.5$  Oe (Fig. 2). As it is seen from the figure, the amplitudes decreased with increase of the harmonic numbers. Therefore, for the investigation, we used the second and third harmonics,  $C_2$  and  $C_3$ .

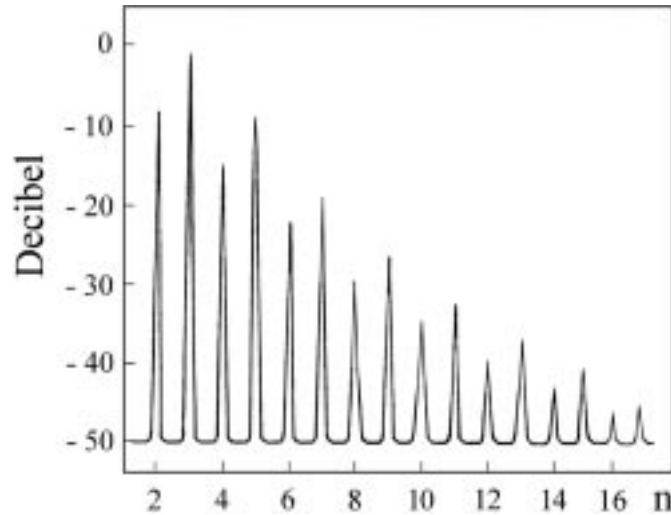


Figure 2. Spectrum of high harmonics.  $T=89$  K,  $h_0=0.1$  Oe,  $H=2.5$  Oe.

Figure 3 shows the dependence of the third harmonic  $C_3$  on  $T$  for various values of variable field. In the figure two peaks are observed showing that the ceramic samples represent a network of separate superconducting grains with connection between them. High temperature maximum is due to the field penetration into the grains and low temperature maximum is due to the field penetration into intergranular medium formed by the weak links [13,14].

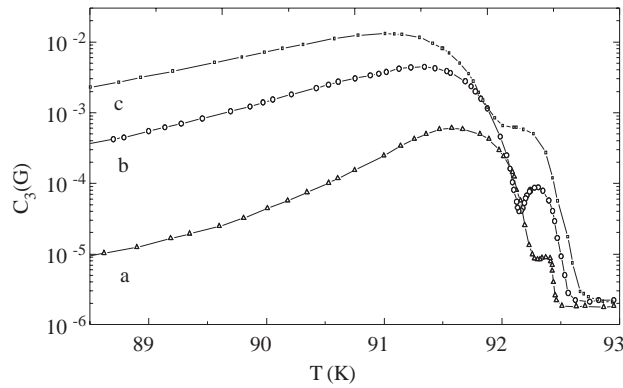
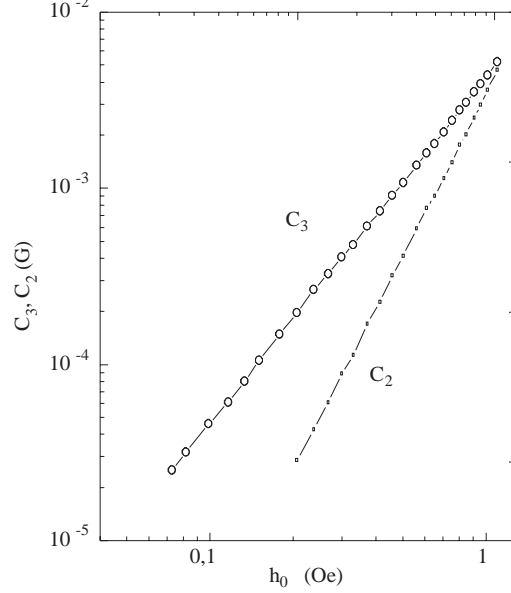


Figure 3.  $C_3(T)$  temperature dependence when  $H=0$ , and with  $h_0$  at various amplitudes: (a)-0.1 Oe; (b)-0.5 Oe; (c)-1 Oe.

Equation (2) shows that in low fields where  $h_0 \ll H$  with increasing of amplitude of variable field, the odd harmonics must increase as  $h_0^2$ , while even harmonics must increase as  $h_0^3$ . In this connection we measured the dependence of the second  $C_2$  and the third  $C_3$  harmonics on the amplitude of the variable field when  $H=2.5$  Oe. The results, in logarithmic scale, are presented in Fig. 4. As the figure shows, the square dependence on the  $h_0$  amplitude of the variable field is observed for  $C_3$  and a cubic relationship for  $C_2$ .



**Figure 4.**  $C_3(h_0)$  and  $C_2(h_0)$  dependencies when  $H=2.5$  Oe,  $T=89$ K.

It should be noted that the square dependence of the third harmonic was observed both in  $H \neq 0$  and  $H=0$  cases. Even harmonics were not observed at  $H=0$ . In Fig. 4  $C_2(h_0)$  and  $C_3(h_0)$  dependencies are presented only for one temperature value, 89 K. Our measurements for the temperature range 80-91 K show that  $C_2(h_0)$  and  $C_3(h_0)$  dependencies are not changed.

In the low field regime even and odd harmonics have dependencies  $C_{2k} \sim \frac{d}{dH} \frac{1}{j_c(H)}$  and  $C_{2k+1} \sim \frac{1}{j_c(H)}$ , respectively. Thus we studied the dependencies of the  $C_2$  and  $C_3$  harmonics on the magnitude of the constant field  $H$  at a fixed values of  $h_0$ , i.e.  $h_0 = \text{const}$ . We found that the amplitude of the second harmonic  $C_2$  depends linearly on  $H$  (Fig. 5a) and, at the same time, the amplitude of the third harmonic  $C_3$  increases as  $H^2$  (Fig. 5b). Observed behavior of third harmonic is explained by the corresponding  $j_c(B)$  dependence which has the form:

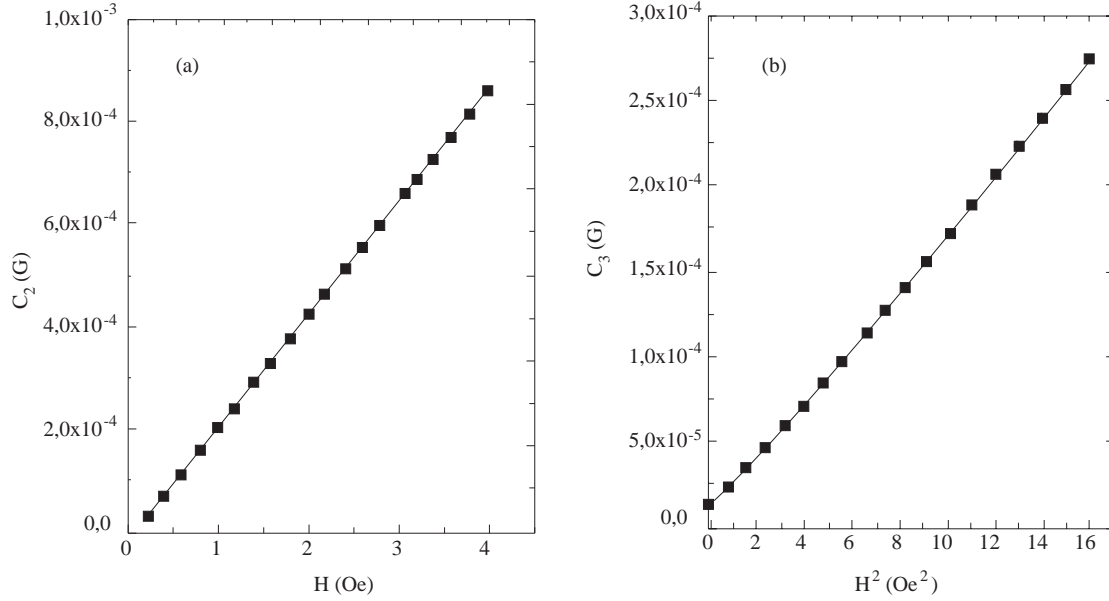
$$j_c(B) = j_c(0) \frac{B_0^2}{B_0^2 + B^2} \quad (3)$$

Taking into consideration the current density dependency on  $C_3$  from (3), we have

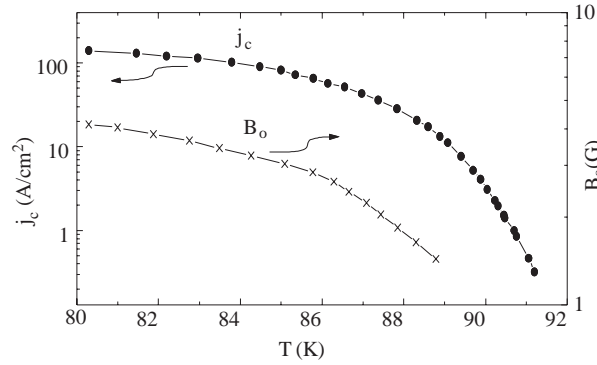
$$\frac{C_3(B)}{C_3(0)} - 1 = \frac{B^2}{B_0^2}, \quad (4)$$

where  $C_3(B)$  is the amplitude of harmonic at  $H \neq 0$  and  $C_3(0)$  is its value at  $H=0$ .

Using Equation (4), it was established that characteristic field  $B_0$  takes values from 4.1 to 1.4 G in the temperature range of 80 - 89 K (Fig. 6).



**Figure 5.** a)  $C_2$  dependence on the  $H$ , b)  $C_3$  dependence on  $H^2$ ,  $T=89$ K,  $h_0=0.1$  Oe.



**Figure 6.** (●)-dependence of the  $j_c(0)$  on  $T$ , when  $h_0=0.1$  Oe,  $H=0$ ; (×)-dependence of  $B_0$  on  $T$ .

We also determined the course of the  $j_c(0)$  curve with dependence of temperature presented in Fig 6. From this Figure it is seen that critical current density is 140 A/cm<sup>2</sup> at 80 K for the investigated sample.

## Summary

Thus, our experiments shows that  $j_c(B) = j_c(0) B_0^2 / (B_0^2 + B^2)$  type modal dependence are realized in the YBaCuO ceramic sample in the low field region where the field only penetrates intergrain Josephson junctions.

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