

February 15, 1990

## Effects of dc transport current on low-field microwave-absorption in ceramic superconducting YBCO samples

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### Recommended Citation

How, H.; Karim, R.; Seed, R.; Widom, A.; Vittoria, C.; Balestrino, G.; and Paroli, P., "Effects of dc transport current on low-field microwave-absorption in ceramic superconducting YBCO samples" (1990). *Electrical and Computer Engineering Faculty Publications*. Paper 37. <http://hdl.handle.net/2047/d20002207>

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Citation: *J. Appl. Phys.* **67**, 2182 (1990); doi: 10.1063/1.345561

View online: <http://dx.doi.org/10.1063/1.345561>

View Table of Contents: <http://jap.aip.org/resource/1/JAPIAU/v67/i4>

Published by the [American Institute of Physics](http://www.aip.org).

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## Effects of dc transport current on low-field microwave absorption in ceramic superconducting YBCO samples

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(Received 7 April 1989; accepted for publication 7 November 1989)

The effects of dc transport current on low-field microwave absorption have been investigated systematically on bulk ceramic  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  samples. At a fixed temperature  $T$ , the critical current  $I_c(T)$  at which the electron paramagnetic resonance (EPR) signal vanishes varies linearly with  $T$ . The EPR absorption characteristics obey a scaling rule in accordance with the flux creep model. A revised version of the flux creep model is also presented.

Low-field microwave absorption experiments are considered to be useful in providing information concerning the dissipation mechanism of a type-II superconductor in a perturbing microwave field. In previous work it was suggested that electron paramagnetic resonance (EPR) losses were due to the circulation of supercurrents through a network of Josephson junctions.<sup>1,2</sup> We report in this communication a systematical analysis of the loss mechanism in a bulk ceramic superconducting  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) sample as a function of temperature. EPR absorption techniques and dc transport currents were applied simultaneously to the sample during the measurements. We find that the experimental results can be described by a flux creep model that has not been reported previously in EPR-type measurements.

Low-field differential microwave absorption signals were measured utilizing modified EPR equipment operating at 9.33 GHz and 0.2 mW levels in a  $\text{TE}_{102}$  cavity. The modification<sup>3</sup> included a pair of Helmholtz coils to null the residual fields in the magnet. Polycrystalline YBCO samples, with a  $T_c(R=0)$  of approximately 85 K, were used in the experiment with typical size of  $0.1 \times 0.1 \times 0.5 \text{ mm}^3$ . Silver paint was used to make contact between the sample and the gold-plated alumina substrate. Contact resistance of the bond was about 1  $\Omega$  at room temperature. The whole assembly was immersed in the center of the cavity with liquid helium flowing at a rate of about 2  $\ell/\text{h}$ . In a test run a silicon diode thermosensor mounted in contact with the sample showed a temperature change of about 5 K at the highest current (1 A) passed through the sample. Temperature was measured using a gold-ferric aluminum thermocouple. A modulating

field of amplitude 2 Oe and frequency 100 kHz was employed parallel to the applied dc field for the phase-lock technique in taking the differential microwave absorption data.<sup>3</sup>

We have measured for each fixed temperature the differential EPR signals for various applied dc currents sweeping a dc magnetic field from  $-1$  to 1 kOe. Figure 1 shows the observed derivative absorption curves for the temperature held at 40 K. For each dc current value the differential EPR signal first rises from the origin to a peak value at a field strength equal to  $H_{c1}$ ;<sup>3</sup> it then declines and reaches a constant value at very large fields [ideally up to the field  $H_{c2}^*(I)$  discussed later]. In Fig. 2 the peak-to-peak values of the differential EPR signal are plotted as function of the transport dc currents with the temperature treated as a parameter. One observes that for each temperature the amplitude of the differential microwave absorption signals increases with the dc current before a rapid falling down to zero near a critical value of the current  $I_c(T)$ . In addition,  $I_c(T)$  decreases with increasing  $T$ . The rising parts of the curves in Fig. 2 satisfy the scaling rule proposed in Eq. (1) below, and the dependence of  $I_c$  on  $T$  can be explained by a flux creep model.

We shall now explain the data in terms of the flux creep model. If the flux creep model is applicable to the high- $T_c$  sample, the absorbed microwave power shall be proportional<sup>4</sup> to the volume fraction of the normal region  $V_n$ , or

$$V_n/V \cong B/H_{c2}^*(I), \quad (1)$$

where  $V$  is the total volume and  $H_{c2}^*(I)$  denotes the field predicted by the Landau-Ginsberg theory and is larger than

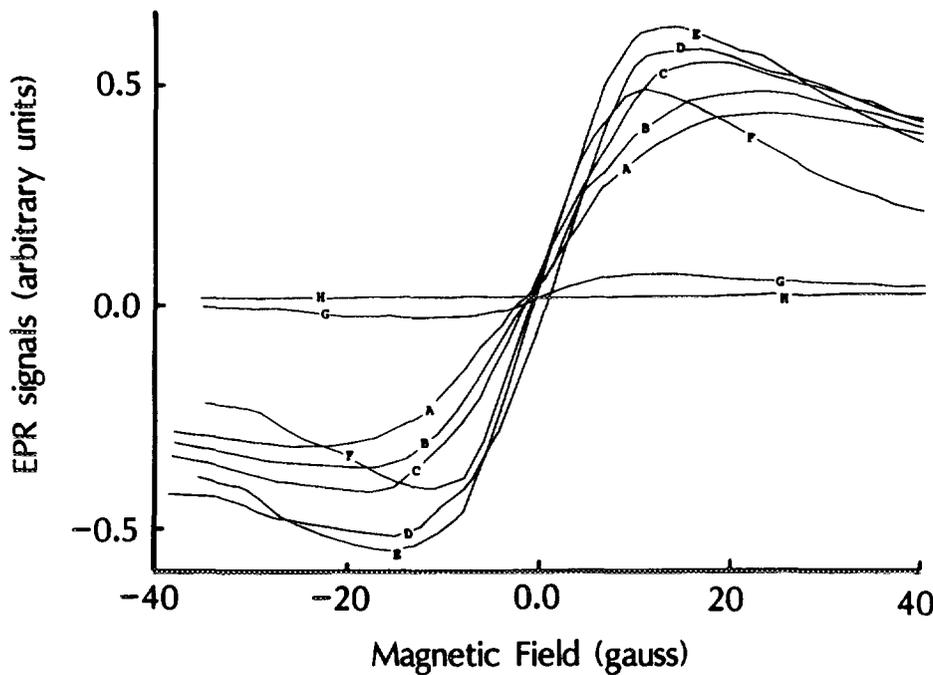


FIG. 1. Differential EPR signals for various imposed dc currents,  $I$ , at  $T = 40$  K.  $I = 0$  mA for curve A, 100 mA for curve B, 150 mA for curve C, 200 mA for curve D, 250 mA for curve E, 300 mA for curve F, 350 mA for curve G, and 400 mA for curve H.

the conventionally observed upper critical field  $H_{c2}(I)$  due to the so-called "paramagnetic effect."<sup>5</sup> For  $H_{c1} \ll H$ ,  $H \approx B$ . The linear relation between  $V_n$  and  $B$  in Eq. (1) holds for all values of  $I$ . According to the flux creep model the application of a dc current will lower the barrier height of a pinning center, and so it is equivalent to the addition of thermal energy. The increase of the derivative EPR signal with  $I$  is related to the increase in slopes of the  $V_n/V$ -vs- $B$  curves, as depicted by Eq. (1). That is, the observed differential EPR signals for  $H_{c1} \ll H \approx H_{c2}$  is inversely proportional to  $H_{c2}^*(I)$ . Denote this large-field absorption derivative signal as  $V_\infty$ . We shall show here that  $V_\infty$  is directly proportional to the observed low-field derivative signal at  $H = H_{c1}$ , denoted as  $V_p$ . This is done by using a relationship connecting the magnetic induction  $B$  within the sample and the externally applied field  $H$  as<sup>6</sup>

$$H = B + H_{c1} \left( 1 - \frac{\ln[(B + H_{c1})/H_{c1}]}{\ln(H_{c2}/H_{c1})} \right). \quad (2)$$

One can directly show that

$$\frac{V_p}{V_\infty} = \left( 1 - \frac{1}{2 \ln \kappa} \right) - 1, \quad (3)$$

where  $\kappa = \lambda/\xi$  denotes a fundamental parameter of the superconducting sample. Therefore the ratio of  $V_p$  to  $V_\infty$  is determined through the intrinsic properties of the sample rather than extrinsic parameters like temperature and current. The advantage of using  $V_p$  instead of  $V_\infty$  in analyzing the data is in the improvement in the resolution of detecting the low-field peak-to-peak amplitudes of the EPR derivative signals. We conclude that the peak-to-peak values of the microwave absorption signals are "inversely" proportional to  $H_{c2}^*(I)$ .

In Fig. 3 we plot, as function of temperature, the inverse of the peak-to-peak EPR signal values up to the maximum values of  $I$ , denoted as "1/p.p." We notice in Fig. 3 that 1/p.p. scales linearly with temperature, and all the curves have the same slope. Therefore we conclude that the scaling rule, and hence the flux creep model that predicts Eq. (1), can adequately describe the observed microwave absorption data on a bulk ceramic YBCO sample. Note that in Fig. 3  $H_{c2}^*(I)$  scales quite well with  $[T_c^*(I) - T]$  with the extrapolated  $T_c^*(I)$  being larger than the true observed critical temperature  $T_c(I)$  due to the paramagnetic effect.<sup>5</sup>

As it has been recently proposed by Yeshurun and Mazlumoff,<sup>7</sup> the flux creep mechanism is responsible for the magnetization relaxation processes in a single crystal YBCO. We propose here that the flux creep mechanism also applies to polycrystalline YBCO samples. We plot in Fig. 4 the critical current  $I_c(T)$  observed in Fig. 2 versus temperature, and the result yields a linear relationship. Recalling in a flux creep model that<sup>4,8</sup>

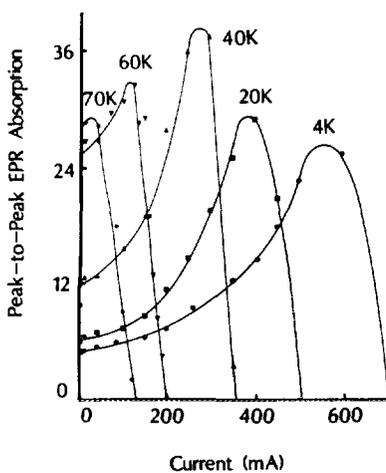


FIG. 2. Peak-to-peak values of the differential microwave absorption signals measured as function of current at various temperatures. The accuracy on the peak-to-peak microwave signal measurements is  $\pm 2.5\%$ .

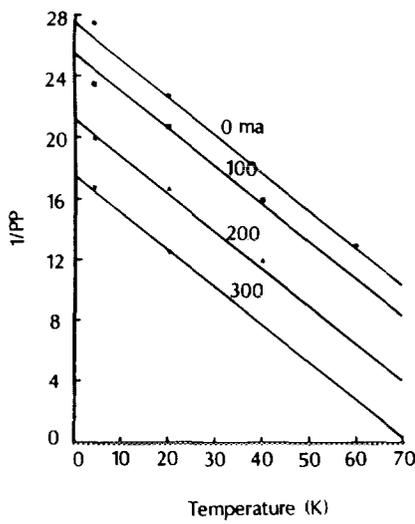


FIG. 3. Plots of  $1/p.p.$  vs temperature for various imposed dc currents: a linear scaling relation.

$$I_c(T) = I_c(0) \left[ 1 - \frac{k_B T}{U} \ln \left( \frac{BvLd}{cE_c} \right) \right], \quad (4)$$

we can immediately interpret the experimental data in terms of the flux creep theory. In Eq. (4)  $B$  is the field induction,  $v$  the vibrational frequency of the fluxoid within a pinning position,  $d$  the separation distance between two pinning positions,  $L$  the length of the sample,  $E_c$  a minimum voltage assigned in measurements, and  $U$  the potential depth of a pinning center. In the experiment we have monitored the rate of change of fluxoid volume, which is related to the creep motion of the fluxoid in and out of the superconductor with a rate faster than the applied modulation frequency (100 kHz).

Let us now provide here a derivation of the flux creep model based on Faraday's law. The usual flux creep model assumes the fluxoids are held in wells of depth  $U$  and width

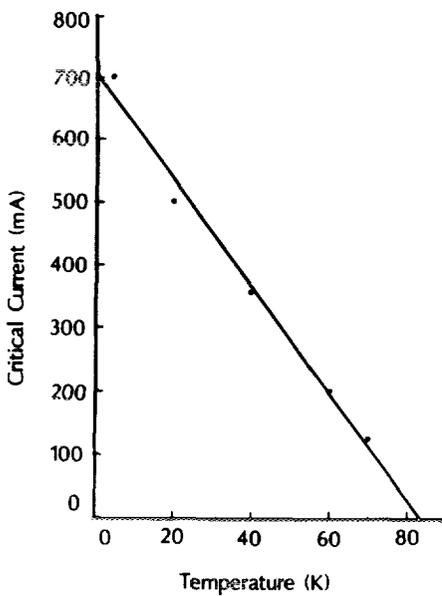


FIG. 4. Plot of critical current vs temperature.

*a.* Upon imposing a current density  $J$  the potential well is, due to the Lorentz force of the current on the fluxoids, reduced to an effective height

$$U_{\text{eff}} = U - BJVa/c,$$

where  $c$  is the speed of light and  $V$  is the volume of the fluxoid line trapped in a pinning center. When there is no thermal energy at  $T = 0$  K,  $U$  is related to the critical current density  $J_c(0)$  at which  $U_{\text{eff}}$  becomes zero. This implies

$$U = BJ_c(0)Va/c, \quad (5)$$

and  $U_{\text{eff}}$  is expressed as

$$U_{\text{eff}} = U \left( 1 - \frac{J}{J_c(0)} \right). \quad (6)$$

In the derivation three defects have been imposed in the above theory. First, the Lorentz force is always perpendicular to the current path and is not able to lower the energy of the potential well. Second, magnetic induction is distributed inhomogeneously in a type-II superconductor.  $B$  is undefined in Eq. (5) according to Ref. 7. Third, the pinning process of the fluxoid was not specified.

A revised version of the flux creep model is provided by explicitly considering the whole pinning process (see Fig. 5). Initially "one portion" of the fluxoid is held by a pinning center. Under thermal excitation the fluxoid jumps from the

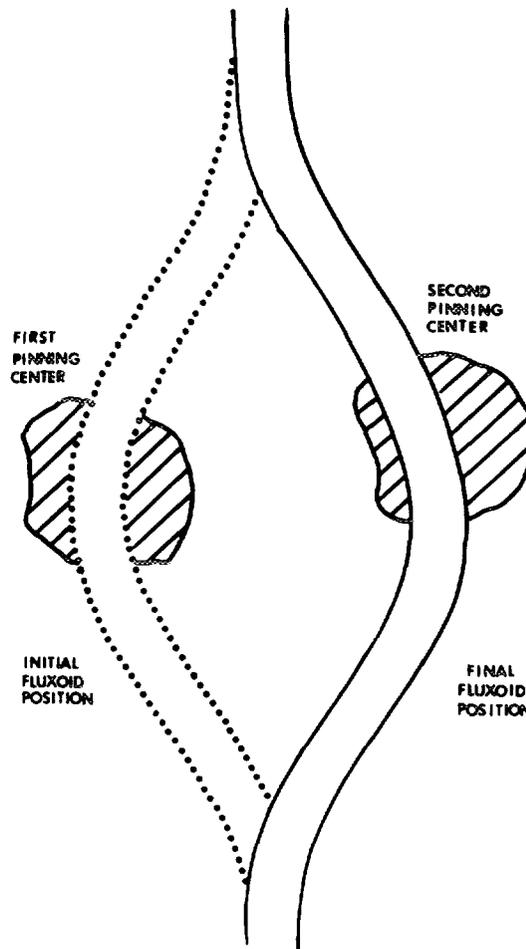


FIG. 5. A revised version of the fluxoid pinning process.

first pinning center to a second one. The energy change accompanying this fluxoid jump can be calculated using "Faraday's law," which yields<sup>9</sup>

$$\Delta U = \frac{\Phi_0}{4\pi} \left( \int_{c_f} \mathbf{H} \cdot d\mathbf{l} - \int_{c_i} \mathbf{H} \cdot d\mathbf{l} \right) \\ = J\Phi_0 A_{\text{eff}}/c.$$

Here  $c_i$  and  $c_f$  denote the initial and final curves that the fluxoid locates,  $\Phi_0$  is the flux quanta, and  $A_{\text{eff}}$  is the effective area enclosed by  $c_i$  and  $c_f$ . Therefore the pinning potential  $U$  can be parametrized as

$$U = J_c(0)\Phi_0 A_{\text{eff}}/c \quad (7)$$

with Eq. (6) still valid. In this way  $U$  is explicitly defined in the new flux creep model and  $A_{\text{eff}}$  can be approximated by  $d^2$ , with  $d$  being the average distance between the pinning centers.

We summarize this communication by concluding that the flux creep model describes very well the loss mechanism

under microwave absorption measurements for a bulk ceramic superconducting YBCO sample, and we have proposed a revised version of the flux creep model through the use of Faraday's law.

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## Current from shock-loaded piezoelectric crystals

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(Received 7 September 1989; accepted for publication 3 November 1989)

Electrical responses of shock-loaded *X*-cut quartz crystals were studied using laser-produced stress pulses. For acoustic transit times that are long compared to the duration of the stress pulse, two short-circuit current signals were observed. The amplitude of the current signal from the rear electrode is predicted to be twice that obtained from the ground electrode using a one-dimensional analysis of the dynamic piezoelectric effect. Experimental observations confirming such predictions are given.

*X*-cut piezoelectric crystals have been extensively used in the past to record transient stress pulses having rise times in the nanosecond range.<sup>1-6</sup> In all these works, the short-circuit current signal from the stress input electrode was related to the stresses at the input electrode for times less than the wave transit time through the thickness of the crystal. No attempts were made to understand or record the nature of the current signal obtained when the stress pulse was reflected from the rear electrode. The purpose of this communication is to explain such current signals and their relation to the stress amplitude using a one-dimensional piezoelectric analysis as proposed by Graham, Neilson, and Benedick.<sup>1</sup> Such studies are necessitated by recent applications of quartz crystals to monitor the behavior of materials under high strain rates. In the usual experiments the specimen is sandwiched between two quartz-crystal gauges, where the

first is used to monitor the input stress pulse and the second to monitor the transmitted stress pulse through the specimen. If the acoustic transit time is long compared to the duration of the stress pulse, it becomes important to understand the current signal from the rear electrode/specimen interface of the first crystal. Such a situation occurred in a study by one of us<sup>7</sup> of the decohesion strength of interfaces where stress pulses produced by laser pulses impinging on the ground electrode of the piezoelectric quartz crystal are being measured. Because the laser fluences used were sufficient to melt a part of the input electrode, it became necessary to record the current signal emitted from the rear electrode for more reliable measurement of the generated stress pulse.

A one-dimensional analysis relating the short-circuit current to the stress at the input electrode has been performed by Graham and co-workers<sup>1</sup> for a piezoelectric shock probe operating under short-circuit condition. They showed that the short-circuit current is given by

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