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Linear and non-linear aspects of the field-dependent microwave losses in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals

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Résumé.- Nous avons mesuré la résistance de surface sous champ magnétique statique, entre 0 et 2 T, à température fixe, inférieure à T_c . Nous comparons nos résultats avec ceux que nous obtenons par modulation du champ, et les discutons dans le cadre des théories existantes.

Abstract.- We have measured the surface resistance in a static magnetic field, between 0 and 2 T, at a fixed temperature below T_c . We compare the results with those using a modulation field, and discuss them within existing theories.

1. Introduction.

The knowledge of the surface resistance R_s of HTSC at microwave frequencies, besides its technological interest (development of microwave circuits, using films with known, low, losses), is helpful in the understanding of the dynamics of vortices, when R_s is measured in the presence of a static magnetic field. However, while a lot of results have been reported upon the field-dependent losses in HTSC, using conventional ESR equipments with modulating magnetic field and lock-in detection, the question of what is exactly measured is still controversial. We have developed a method needing no field-modulation, and compared the results with those we get from the same samples with the conventional field-modulation technique, which informs directly upon the non linearities of the system.

2. Experimental method and conditions.

All the present results were obtained at 9.4 GHz. In measurements without magnetic field modulation, we use a single-klystron heterodyne spectrometer. First, in (nominally) zero field, we measure R_s at a reference temperature ($T_r = 200$ K), and at successive lower temperatures down to 10 K [1]. Then, at a given temperature T , we measure $R_s(T, H)$ in a static field, by adapting the method used for zero-field measurements: $R_s(H=0)$ replaces $R_s(T_r)$, and $R_s(H)/R_s(H=0) = 1 + \gamma \cdot Q_s(H=0)/Q_2(H=0)$. The cavity, critically coupled when $H=0$, has a reflection coefficient Γ when the field is H , and $\gamma = 2\Gamma/(1-\Gamma)$. The quality factors of the cavity are Q_1 (without sample) and Q_2 (with sample), $1/Q_s = 1/Q_2 - 1/Q_1$, and $Q_s(H=0) / Q_2(H=0) = \mu_0 \omega I/J$ (I : integral of the

square of H_t , the tangential part of the rf field, over the cavity volume; J : the corresponding integral over the sample surface). We used a TE_{104} rectangular cavity regulated around 300 K, an ESR9 Oxford gas-flow cryostat, and a styrofoam sample-holder. In experiments with field-modulation we used homodyne spectrometers (Bruker ESP300 -1.5 KHz-100KHz- and Varian E112 -33 Hz-100 KHz-) and a silica sample-holder. The modulation-field was then colinear to the slowly varying field. In all cases the microwave field was perpendicular to the static or quasi-static field. The samples were mineralization-grown $YBa_2Cu_3O_7$ single crystals (for more precisions upon them, see [2]).

3. Experimental results

The R_s increase observed below T_c at a given temperature when the sample is submitted to a static field H_0 is shown in figure 1, for $\vec{c} // \vec{H}_0$. The effect is weak near T_c (1a: 81.5 K), then increases (1b: 76.5 K; 1c: 71.6 K) and decreases (1d: 67.5 K; 1e: 62 K). Above roughly 0.5 T, R_s increases linearly with the applied field. This R_s increase is anisotropic, has displayed in figure 2: it is highest when θ , the angle between the applied field and the $\vec{c}$ axis, is zero, and the weakest when θ is nominally $\pi/2$.

Fig. 1. - Dependence of R_s upon applied magnetic field for an $YBa_2Cu_3O_7$ single crystal at fixed temperatures (9.4 GHz)

Fig. 2. - Field dependence of R_s at $T = 67.5$ K, for three values of θ , the angle between H_0 and the $\vec{c}$ axis. (same crystal as in Fig.1).

When a slowly-varying field and a modulation field are both applied, one hopes to detect dR_s/dH . Comparison of the results with modulation (Fig.3) and without modulation (Fig.1) unambiguously shows that this is not the case, as the signal obtained using a modulation field has not a constant amplitude above 0.5 T. The system is not linear versus the modulation field. Moreover, while this signal is the same for increasing and decreasing fields below but near T_c (for instance at $T=82$ K, (with a 2 mT_{pp} , 100KHz modulation field, signal unshown) a large remanence is observed at lower temperatures, and the shape of the signal depends upon the modulation amplitude (Fig.3), as already observed in [3][4] for instance. One has therefore a direct confirmation that the signal observed in modulation experiments is not the derivative dR_s/dH_0 . The signal has the same shape at 35 Hz and 100KHz (Fig.4), while we observed no remanence in static field measurements, even after several hours (one Γ measurement at a given field takes roughly 10 mn). This suggests that the remanence effects correspond to changes in the critical state, with a characteristic time between 10^{-2} and 10^2 s. One can then hope that the interpretation of static field measurements is less complex than that for results with modulation.

Fig. 3. - Non resonant absorption in a slowly varying field (H_0), for several modulation amplitudes. ($F_{mod} = 100$ KHz, $\vec{c} \perp \vec{H}_1$, $\vec{c} // \vec{H}_0$; same crystal as in Fig.1)

Fig. 4. - Non resonant absorption in a slowly varying field (H_0), for several modulation frequencies (2 mT peak-to-peak amplitude; crystal used in Fig.1)

4. Discussion.

We will focus upon $\Delta R_s = R_s(H) - R_s(H=0)$, which is linear above 0.5 T (Fig.1). R_s describes microwave losses, and the sample is in a place of minimum rf electric field). R_s depends therefore upon the rf magnetic field or upon the corresponding current density. This, and the angular dependence of $R_s(H)$ (Fig.2) suggest that these extra losses are due to the microwave motions of vortices under the Laplace force. If these motions were ideal (viscous force, but no pinning center), the motion of the unit length of vortex would obey $m \dot{V} + \eta V = J \Phi_0$ (Φ_0 : flux quantum, J : supercurrent density) and would induce an electric field $\vec{E} = -\dot{V} \wedge \vec{B}$, whence, in stationary regime a flux flow resistance $\rho_f = \frac{E}{J} = \frac{B \Phi_0}{\eta}$. This is true if angular frequency ω and relaxation time $\tau = \frac{m}{\eta}$ verify $\omega \tau < 1$. Using $\eta = \frac{\sigma}{\pi} \left(\frac{\Phi_0}{\xi}\right)^2$, with $\sigma_{ab} = 2 \times 10^5 (\Omega m)^{-1}$ [1], $\xi_{ab} = 15 \text{ \AA}$, one gets $\eta \simeq 1.2 \times 10^{-7} \text{ kg/m.s}$. There is a large uncertainty about m : Suhl [5] found $m/m_e \simeq 4 \times 10^5/m$ (his approach, with $n_0 \simeq 10^{21} / \text{cm}^3$, $\Delta/E_F \simeq 2 \times 10^{-3}$ gives presently 4×10^4), while Gittleman et al [6] use $2 \times 10^{10}/m$. However, even with the highest m value $\omega \tau \ll 1$ at 10 GHz. The associated surface resistance is then, as $\epsilon \omega \rho_f \ll 1$, $R_s = \sqrt{\frac{\mu \omega}{2}} \rho_f \propto \sqrt{B}$. Gittleman described the pinning with an effective potential creating a restoring force $-kx$ (linearization) upon bundles of vortices moving as a whole. It is generally thought that at 10 GHz $\eta \omega \gg k$. Then, at 10 GHz the pinning is unefficient [6], the previous results for ρ_f and R_s still apply. Portis [3] has reexamined this question, considering that the rf electric field is the sum of the induced and applied fields, and found a complex resistivity $\rho \simeq i\omega\lambda + f\rho_f$ ($\lambda = \mu_0 \lambda^2$: London constant, induced field $-fV B$; Portis proposes $f \simeq 0.1$). In this approach, $R_s = X_0 [(1+b^2)^{1/2} - 1]^{1/2} / \sqrt{2}$, with $X_0 = \mu_0 \lambda \omega$ and $b = \frac{f\rho_f}{\omega\lambda} = \frac{f\Phi_0 B}{\eta\omega\lambda}$, and it is therefore predicted that when $b \ll 1$, $R_s \propto B$, while when $b \gg 1$ then $R_s \propto \sqrt{B}$. Taking $\lambda = 0.1 \text{ }\mu\text{m}$, one finds that $b = 1$ for $\mu_0 H = 0.46 \text{ T}$. This value should not be taken too seriously, remembering the various approximations made. It should not be compared to the experimental value 0.5 T above which R_s increases linearly with the field, since in Portis approach $R_s \propto \sqrt{B}$ then. On the whole it seems difficult to explain our results even with Portis model. The correction suggested by Stewart [7] does not seem to be able to improve the situation, as it plays a role on the high field side only, and an explanation of this discrepancy remains to be found.

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