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PHYSICA A

On the possibility for flux penetration into a Campbell regime near the onset of irreversibility in high temperature superconductors

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The onset of dissipation and of harmonic generation in response to an ac magnetic field of high temperature superconductors are used for the identification of the irreversibility line below which dissipation occurs due to flux motion in the sample. We demonstrate, however, that in the presence of a static magnetic field and for low amplitude ac fields, the penetration close to the onset may occur into the Campbell regime in which the vortex motion induced by the ac field occurs inside the pinning potential well.

1. Introduction

The experimental determination of the magnetic irreversibility line (IRL) of high temperature superconductors (HTS) is still a challenging task. In early experiments two types of identification of IRL were used: (1) loss of ergodicity, which is observed as a split of the zero-field-cooled (ZFC) from the field-cooled (FC) magnetization [1] and (2) a peak of dissipation [2] in the ac susceptibility (χ''). Both methods suffer serious limitations. The ZFC–FC split of the dc magnetization corresponds to some finite shielding current related to instrumental resolution, typically of the order of 10–1000 A/cm^2. The ac magnetic field method presents a great interest because it provides the possibility of probing the frequency dependence of the IRL. However, the identification of the IRL from the peak of χ'' is even more controversial. At the high frequency limit, the skin depth effect is a likely origin of the χ''-peak [3] and at the low frequency limit the peak position depends on the amplitude of the applied ac magnetic field and on the sample geometry. For these reasons the onset of nonlinearity, most conveniently observed by third harmonic measurements, was recognized as a more realistic fingerprint of the IRL [4]. The use of the third harmonic onset for the identification of the IRL also rules out the skin depth artifact because this effect is essentially linear and does not produce harmonics.

While the use of third harmonic onset (T_0^{3h}) for identification of the IRL induces a growing interest, it is worthwhile to examine its meaning in the context of different regimes of flux penetration. In the critical state, the ac field penetration is characterized by a field gradient and flux jumps over the pinning sites. In the Campbell regime [13] the ac flux penetration is characterized by the oscillations of flux lines inside their potential wells. In the latter case the harmonic generation results from the anharmonicity of the potential well. It is the purpose of the present paper to discuss the experimental conditions that lead to the different regimes of flux penetration. We argue that close to the IRL, for small single crystals and small ac amplitudes, the ac field penetration in the presence of a dc field occurs in the Campbell limit.

2. Experimental

A typical set-up for the measurement of low frequency harmonic susceptibility is presented in fig. 1. This set-up is a simple modification of the local Hall probe magnetometer (LHPM) used previously for measurements of dc magnetization [5]. The sample is mounted on top of a miniature ($100 \times 80\ \mu m^2$) Hall probe, in the center of an ac magnetic field excitation coil. The set-up is placed on a temperature controlled sample-holder inside a coil which produces a dc magnetic field. Two major differences with respect to the conventional ac susceptibility set-up should be pointed out:

(1) The area of the investigated sample can be as small as the active area of the Hall probe, which allows measuring of extremely small (<10 μg) samples. The thickness of the sample defines the set-up sensitivity in terms of shielding current J_s. For a typical InSb Hall probe with sensitivity of 50 μV/G and a detection lock-in resolution of 10 nV, the product of the sample thickness t and minimal detectable shielding current J_s^0 gives rise to a detectable signal of

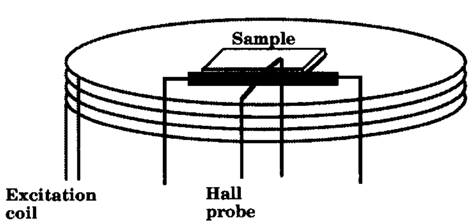

Fig. 1. Schematic representation of the experimental set-up.

order $tJ_s^0 = 25 \times 10^{-5}$ A/cm. For a typical 20 μm thick sample J_s^0 is of the order of 0.1 A/cm^2.

(2) The system sensitivity is frequency independent. This allows the exploration of low (≈1 Hz) frequencies.

The measurement set-up was based on a two-channel synthesizer which generates the ac signal at the fundamental frequency and a reference signal for lock-in detection at the harmonic frequency [6].

Measurements of fundamental and harmonic susceptibilities were performed on two $YBa_2Cu_3O_7$ crystals: an as grown sample (AGS) and an irradiated sample (IRS). The samples ($200 \times 200 \times 20\ \mu m^3$) were cut from the same single crystal. One was used as a reference sample and the other was irradiated with 5.8 GeV Pb ions[#1]. This kind of irradiation is known to produce amorphous columnar tracks, crossing the sample side by side [7]. The transmittivity presentation ($T' = 1 + \mu_0\chi'$, $T'' = \mu_0\chi''$) which was used in our previous work [8] was adopted also here. Note that the transmittivity and the third harmonic data throughout this paper are already normalized to the ac field amplitude.

Typical results of T'' and of the absolute value of the third harmonic transmittivity are presented in fig. 2 as a function of temperature for the AGS. Similar results obtained for the IRS are presented in fig. 3. All experiments presented here were performed in field-cooled mode, typically in 20 mK steps every 10 s.

The onset of $|T_{H3}|$ and T'' coincide and are independent of H_{ac}. The striking feature is *the absence of amplitude dependence* on the high temperature side of the peak of $|T_{H3}|$ and T''. The maximum of $|T_{H3}|$ and of T'' can be identified as the full penetration of ac magnetic field ripple. The narrower peaks of $|T_{H3}|$ and of T'' in the IRS reflect the pinning enhancement by columnar defects [9]. Note that for sufficiently low amplitudes the AGS behaves as a linear system and the third harmonic signal disappears.

Fig. 4 illustrates the effect of static magnetic fields on the temperature dependence of the third harmonic signal. In the AGS, the third harmonic peak broadens and eventually splits, exhibiting two distinct maxima. The onset of the third harmonic signal shifts to lower temperature with increasing dc magnetic field. The resulting variation of the irreversibility point with temperature is smooth, contrary to recently reported sudden collapse of the IRL determined from the peak of dissipation [10]. The dissipation peak position vs. temperature of our data exhibits such an anomaly, but the collapse coincides with the splitting of the third harmonic peak. As we argue below, this can be identified as a crossover between two regimes of flux penetration.

[#1] Irradiation realized at GANIL Caen, France.

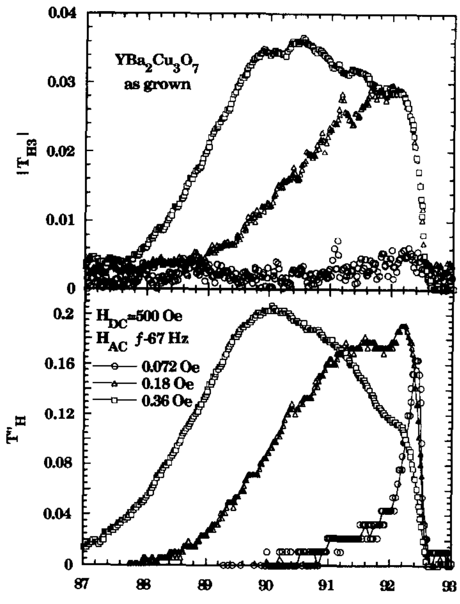

Fig. 2.

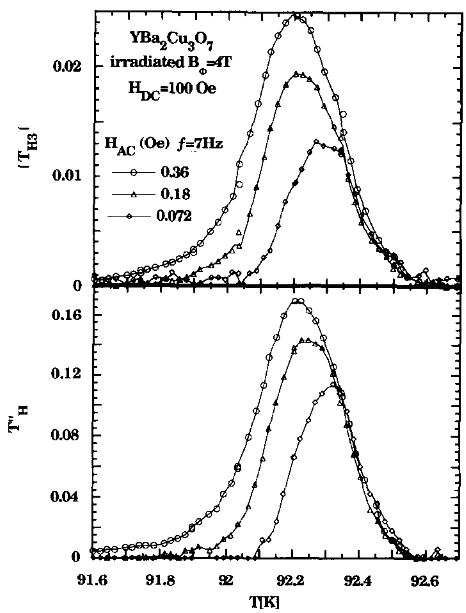

Fig. 3.

Fig. 2. Temperature dependence of the normalized third harmonic signal $|T_{H3}|$ (upper panel) and the dissipative component of the fundamental susceptibility T'' (lower panel) recorded for as grown $YBa_2Cu_3O_7$ crystal.

Fig. 3. Temperature dependence of the third harmonic signal $|T_{H3}|$ (upper panel) and the dissipative component of the fundamental susceptibility T'' (lower panel) for $YBa_2Cu_3O_7$ crystal irradiated with 5.8 GeV Pb ions to the fluence of 2×10^{11} ions/cm^2.

In the IRS the broadening of the third harmonic peak under dc magnetic field is much less pronounced. The amplitude of the peak is slightly depressed but the shape remains the same. The shift of the onset of the third harmonic signal under dc magnetic field is much less important than in the AGS, in agreement with an earlier report of an upward shift of the irreversibility line after introduction of columnar defects [9].

Close to the onset, the frequency dependence of the third harmonic signal is very weak. As shown in fig. 5 for the IRS, it is below the resolution of our thermometry (20 mK) over $2\frac{1}{2}$ decades of frequency.

The polar plot of the out-of-phase vs. the in-phase components of the third harmonic response for both AGS and IRS, is presented in fig. 6. This plot was obtained from the temperature dependence of the in-phase and out-of-phase third harmonic signal recorded at a 100 Oe dc magnetic field superposed with a 0.36 ac field at a frequency of 7 Hz. On cooling, the points move clock-wise starting from 0. This plot differs essentially from the apple-shape plot expected

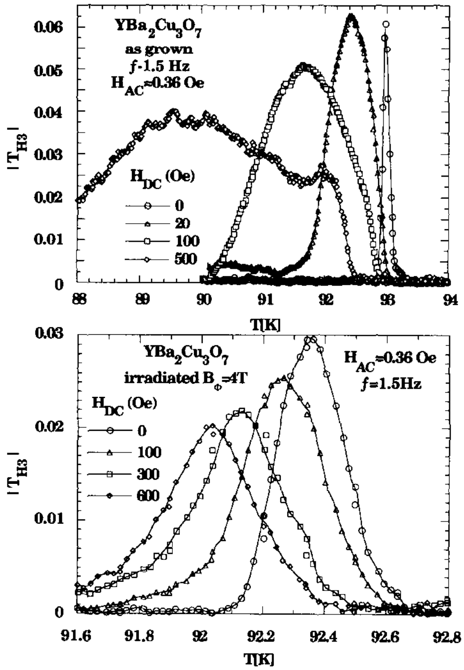

Fig. 4. Third harmonic signal vs. temperature for the AGS (upper panel) and for the IRS (lower panel) at various dc magnetic fields.

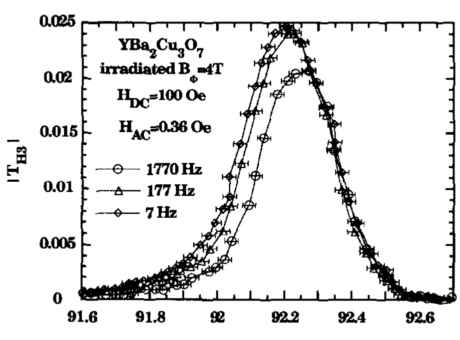

Fig. 5.

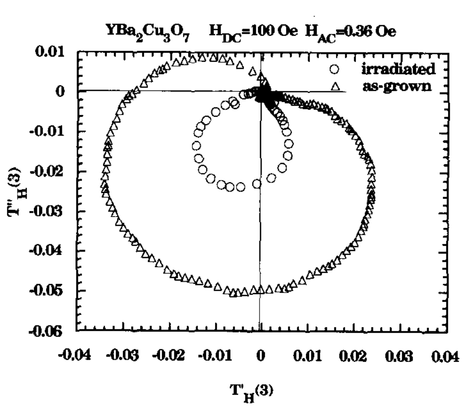

Fig. 6.

Fig. 5. Temperature dependence of the third harmonic signal for the IRS at 100 Oe for various frequencies.

Fig. 6. Polar plot of the out-of-phase T''_{H3} vs. the in-phase T'_{H3} components of the third-harmonic transmittivity for the AGS and for the IRS. Data taken on cooling the sample in a 100 Oe dc magnetic field with a 0.36 Oe, 7 Hz ripple.

in the critical state [8,11]. Only for low temperatures (left half-space of fig. 6) for the AGS, one can find this characteristic feature.

3. Discussion

The fingerprints of various regimes of ac field penetration were discussed recently in the context of ac magnetic susceptibility measurements [11,12]. The Campbell regime [13], in which the vortex displacements are confined to the bottom of a single potential well, exhibits frequency independence and linear amplitude dependence of dissipation. This regime is usually expected at low amplitudes and low temperatures (i.e. strong pinning). We will now examine the applicability of the Campbell regime description for flux penetration to the region close to the onset of irreversibility.

The main criterion for the distinction between the Campbell regime and the critical current regime (in which vortices jump several minima of the pinning potential) is the comparison of vortex displacement with the size of the potential well. Let us consider an ideal 200 μm diameter disk shaped sample that is slowly cooled from above T_c in the presence of superposed dc and ac magnetic fields. In the absence of pinning, the application of the ac field results in a compression of the vortex lattice. The effective displacement of the vortices is much higher on the perimeter of the disc than in the center. This displacement can be calculated simply from the variation of the vortex lattice parameter: $\Delta x \approx \frac{1}{2} r\, \Delta B / B$ where r is the radial position of the vortex, ΔB the amplitude of magnetic field ripple and B is the dc magnetic field.

When the sample is cooled below the irreversibility line, some pinning arises, and this effective displacement should be compared with the size of the potential well d. If d is much larger than the displacement of the vortices, the quasi-elastic limit of the pinning is an appropriate description of flux penetration. This problem was originally treated by Campbell [13] for flux lines parallel to the surface. The penetration of the ac magnetic ripple corresponds to the propagation of compression waves in the vortex lattice, with penetration depth $\lambda_c = \sqrt{c_{11}/\alpha_L}$. Recently this elastic pinning description was extended by Brandt [14] to fields perpendicular to the surface.

Let us consider two extreme examples of pinning: (1) weak pinning centers with a pinning mechanism described by the collective pinning theory [16], and (2) columnar defects that are induced by heavy ion irradiation. These two pinning mechanisms are related to pinning in the AGS and the IRS respectively. In the case of single vortex pinning, the size of the potential well is of the order of coherence length ξ. As ξ grows with increasing temperature close to T_c, it is likely that the condition $\Delta x < \xi$ will be fulfilled before reaching the irreversibility line close to T_c.

The data presented in fig. 2 for the AGS can be interpreted as follows. Close to the high temperature onset of $|T_{H3}|$ and T'', the condition for the Campbell limit of flux penetration, $\Delta x < \xi$, is fulfilled. By decreasing the ac amplitude, the vortices' oscillations become elastic and the third harmonic signal disappears. Therefore, for a true IRL detection one must be aware of this elastic regime. The weak H_{ac} amplitude dependence of T'' close to the onset (fig. 2) also demonstrates that the conventional Bean model for flux penetration is inappropriate here. As discussed in ref. [8] the transmittivity in this case depends upon a single variable $j_c \times t/H_{ac}$, where t is the thickness of the (flat) sample. The absence of $1/H_{ac}$ dependence demonstrates that this is not the appropriate description of ac field penetration, and it supports our assertion that we have reached the Campbell regime.

In the case of pinning by columnar defects, the size of the potential well is the spacing between columns and is controlled by the irradiation dose. In the case of the sample of concern here, irradiated by a fluence of 2×10^{11} ions/cm^2, the average spacing is ≈200 Å. This distance should be compared with Δx. For an ideal 200 μm diameter disc shaped sample the condition $\Delta x < d$ will be fulfilled in the whole sample volume for $\Delta B/B < 4.4 \times 10^{-4}$. It should be noted that for the ac magnetic field perpendicular to the sample surface for any values of $\Delta B/B$ and d, the Campbell limit of flux penetration will apply to the central part of the sample. For the particular case of the Pb ion irradiated sample exposed to a 0.36 Oe (RMS) ac field ripple on a background of a dc magnetic field of 100 Oe, one can estimate that the maximal displacement of the vortices on the sample periphery would be 1270 Å. This value exceeds the spacing between columnar defects. However, even in this regime, the Campbell limit for flux penetration seems to apply (fig. 3). The delocalization of the flux lines close to T_c leads to collective pinning of a single vortex by many columnar defects [17]. This may be the origin of the increase of the effective size of the potential well.

The generation of the third harmonic signals is a fingerprint of nonlinearity of the ac magnetic field response. Such nonlinearity implies that the normalized fundamental response should be amplitude dependent. But, the experimental data that exhibit amplitude independence are in disagreement with this expectation. A possible explanation to this apparent contradiction is that two distinct regions of the sample contribute to the ac magnetic response in different regimes of the flux penetration. Namely, in the central part of the sample, the elastic Campbell-like regime of flux penetration will apply with no third harmonic generation, while in the outer region the anharmonicity of the pinning potential or critical current regime will produce the third harmonic response. The increase of the H_{ac} amplitude will shrink the region in which the elastic limit of flux penetration will apply.

Finally we would like to relate our ac measurements to transport measurements. From the frequency and amplitude dependence of the magnetic susceptibility it is a priori possible to extract the form of the *I–V* curve of a superconducting sample [11]. Using simple electrodynamics arguments, one can find that the frequency variation at a given amplitude is equivalent to probing the electric field while the change of amplitude at a fixed frequency is equivalent to current density variation. In the region close to the onset of shielding, the ac magnetic field penetration depth in any of the penetration regimes is much larger than the sample size. Thus the frequency independent shielding corresponds to the *I–V* curve exhibiting a vertical drop-off at low current densities. In order to compare the *I–V* curve derived from the ac measurements with electrical transport measurements, we can use the estimate of the shielding current close to the onset given in section 2, namely currents of the order of 0.1–1 A/cm^2. The corresponding electrical field developed in the sample can be found from Maxwell equation $\partial B/\partial t = -\nabla \times E$. Let us consider a 1 Oe amplitude magnetic field perpendicular to the ideal 200 μm diameter sample, oscillating at 1 Hz. The electrical field at the sample periphery will be of the order of 50 pV/cm. This means that the sample resistivity at the onset of shielding of low frequency magnetic field is extremely low, of the order of 10^{-11} Ωcm. In order to explain the frequency independent onset of shielding in our experimental conditions, *the portion of the I–V curve at extremely low electrical fields should exhibit an almost vertical drop*. This reminds us of a recent observation of similar sharp features on *I–V* curves in ion-irradiated samples [18].

To summarize, the main motivation of this paper was the need for a reliable interpretation of the onset of the third harmonic in the response of HTS to an ac field. Because of the finite size of the sample, the Campbell regime is close to the IRL. Potentially, this can lead to a shift of T_0^{3h} to lower temperatures in respect of the onset of pinning. In the case of extremely low AC amplitudes it might lead to the disappearance of the third harmonic signal (see fig. 2). However, the experimental coincidence of the onset of shielding at fundamental frequency (at low frequencies) with T_0^{3h} demonstrates that for the samples under investigation here this misfit is negligible and the onset T_0^{3h} demonstrates that for the samples under investigation here this misfit is negligible and the onset T_0^{3h} does indeed represent the IRL.

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