Microwave-induced instability observed in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ in a static magnetic field

Y. De Wilde$^1$, H. Enriquez$^1$, N. Bontemps$^1$ and T. Tamegai$^2$

$^1$ Laboratoire de Physique de la Matière Condensée, Ecole Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05, France
$^2$ Department of Applied Physics, The University of Tokyo
Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

(Received 4 December 2000; accepted 5 January 2001)

PACS. 74.25.Nf – Response to electromagnetic fields (nuclear magnetic resonance, surface impedance, etc.).
PACS. 74.72.Hs – Bi-based cuprates.
PACS. 74.50.+r – Proximity effects, weak links, tunneling phenomena and Josephson effects.

Abstract. – We have measured the microwave dissipation at 10 GHz through the imaginary part of the susceptibility, $\chi''$, in a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystal in an external static magnetic field $H$ parallel to the $c$-axis at various fixed temperatures. The characteristics of $\chi''(H)$ exhibit a sharp step at a field $H_{\text{step}}$, strongly dependent on the amplitude of the microwave excitation $h_{\text{ac}}$. The characteristics of $h_{\text{ac}}$ vs. $H_{\text{step}}$, reveal the behavior expected for the magnetic-field dependence of Josephson coupling.

Vortex physics on high critical temperature superconductors (HTSC) has driven a lot of interest over the past few years [1]. Because of the short coherence length of these systems, some HTSC such as $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO) have to be described as stacks of intrinsically Josephson-coupled superconducting planes [2], rather than as superconductors with a high effective mass anisotropy. In a magnetic field, DC transport measurements [3–5] and thermodynamic [6–8] studies have shown that melting of vortices is a first-order process. In Josephson-coupled HTSC, it is still not clear if melting goes along with total decoupling of the superconducting planes, or if instead decoupling is only achieved beyond the melting transition. Experimental studies of the Josephson plasma resonance (JPR) have been performed to investigate the temperature and magnetic-field dependence of Josephson coupling [9–12]. The results point to a drop of Josephson coupling at the vortex melting [11,12]. Other JPR experiments on BSCCO have shown the possible occurrence of nonlinear effects driven by a microwave field [13].

We have recently presented a detailed study of melting of vortices in a BSCCO single crystal via microwave dissipation measurements [14] at 10 GHz. While a careful study of vortex melting requires current densities as small as possible, and hence low microwave excitations, in this paper we focus on what happens when the amplitude of the microwave field $h_{\text{ac}}$ is progressively increased. We observe a novel feature which shows up as a sharp step in the
characteristics of dissipation vs. magnetic field at fixed temperature. In contrast with vortex melting, whose field position, \( H_m \), only depends on the temperature, the field value at which the step occurs, \( H_{\text{step}} \), drastically depends on \( h_{ac} \), which we argue is closely related to the Josephson interlayer phase coherence \( \langle \cos \phi \rangle \).

The experimental set-up that we use to measure the 10 GHz microwave dissipation has been described elsewhere [15]. The sample is placed in a TE\(_{102}\) resonant cavity (resonance frequency \( \omega /2\pi = 9.6 \) GHz) of an Electron Spin Resonance spectrometer, at the maximum of the microwave magnetic field, \( h_{ac}(\omega) = h_{ac} \cos \omega t \), and in zero electric field. The external static magnetic field \( H \) is applied parallel to the \( c \)-axis of the crystal, while \( h_{ac}(\omega) \) is oriented within the \( ab \)-plane. The microwave field \( h_{ac}(\omega) \) induces surface currents in the sample, which in this geometry flow within the \( ab \)-plane and along the \( c \)-axis. The surface currents are responsible for an energy dissipation which is measured through the imaginary part of the susceptibility \( \chi'' \). With a small \( h_{ac} \), in the range of a few mOe, melting of the vortex solid in BSCCO shows up as an increase of dissipation in the characteristics of \( \chi'' \) vs. \( H \) recorded at a fixed temperature [14].

The BSCCO single crystal used in the experiments is a rectangular platelet with dimensions \( 2 \times 0.8 \times 0.03 \) mm\(^3\). For this sample, the critical temperature \( T_c = 84 \) K, with a transition width \( \Delta T_c \approx 0.4 \) K, as measured at 10 GHz. An attenuator placed between the source and the cavity enables a step-by-step variation of the microwave power in the cavity, with an attenuation of 1 dB between each step. An attenuation of 1 dB corresponds to a reduction of \( h_{ac} \) by a factor 1.12. Figure 1 shows a typical \( \chi'' \) vs. \( H \) characteristic obtained at \( T = 65 \) K with an input power of 0.8 mW, corresponding to \( h_{ac} \approx 60 \) mOe. Here melting occurs around \( H_m = 315 \) Oe and shows up as a small jump and a change of slope in \( \chi''(H) \). There is no influence of the input power on the value of \( H_m \) measured at 10 GHz with our technique. Good agreement is found between the \( H_m(T) \) phase diagram measured at 10 GHz and that obtained from DC SQUID measurements on the same sample [14]. The small jump in \( \chi'' \) at \( H_m \) is analogous to the sharp onset of resistivity observed in DC transport measurements [3].

A salient new feature in fig. 1, is the sharp step which corresponds to a sudden increase of dissipation at a field \( H_{\text{step}} \approx 200 \) Oe. The curves shown in the inset of fig. 1 were obtained at a temperature of 65 K, with \( h_{ac} \approx 47 \) mOe, when sweeping the magnetic field up and down successively. A hysteretic behavior of the step is observed. The amplitude of the hysteresis loop at 65 K is of the order of 10 Oe.

Figure 2 shows a series of characteristics of \( \chi'' \) vs. \( H \) recorded at 65 K, where the input power has systematically been attenuated by 2 dB between subsequent recordings. In contrast with \( H_m \), the field \( H_{\text{step}} \) strongly depends on the input power. At 20 dB, which corresponds to \( h_{ac} \approx 95 \) mOe, the step occurs in the solid phase, \( H_{\text{step}} \) well below \( H_m \approx 315 \) Oe, and shifts to higher fields as the attenuation is increased, i.e. as \( h_{ac} \) is reduced. The step survives in the liquid phase beyond \( H_m \), where it presents significant broadening. Increasing the microwave power shifts \( H_{\text{step}} \) to lower values, and eventually to \( H_{\text{step}} = 0 \); beyond this limit, the characteristics of \( \chi'' \) vs. \( H \) start with nonzero dissipation at \( H = 0 \). Similar observations of a step with 10 GHz dissipative measurements were done on other BSCCO samples, showing the intrinsic origin of the feature.

In our geometry, \( h_{ac}(\omega) \) tends to tilt slightly the field on the sample away from the \( c \)-axis. In tilted magnetic fields, vortices in samples such as BSCCO adopt a tilted structure made of vortex pancakes linked by Josephson vortex segments [16,17], or may even form a two-component structure with coexistent Abrikosov and Josephson vortex systems, orthogonal to each other [18,19]. While the density of pancake vortices depends on the static field component \( H \), the density of Josephson strings, regardless of the details of the vortex structure, is driven by the field component parallel to the superconducting CuO\(_2\) planes, here \( h_{ac}(\omega) \). The step
amplitude in $\chi''(H)$ is proportional to the microwave input power and independent of the static field component. This points to a dissipation process related to Josephson strings induced by the microwave field and not to pancake vortices.

We have thoroughly investigated the temperature and power dependence of the step between 75 K and 30 K, changing the temperature by steps of 5 K between each series of recordings, and the attenuation of the microwave excitation by steps of 1 dB. Figure 3 shows two series of plots of $h_{ac}$ vs. $H_{step}$, which cover the entire temperature range of our studies. The arrows in these plots indicate the melting transition at $H_m$, whenever observed. Figure 3 shows that $h_{ac}$ is a decreasing function of the static field. Down to about 45 K, the characteristics of $h_{ac}$ vs. $H_{step}$ exhibit a fairly distinct drop which in each case coincides with the melting transition. The dependence of $h_{ac}$ vs. magnetic field is qualitatively the same as that expected for the interlayer Josephson coupling. The additional phase difference $\phi$ due to the presence of pancake vortices in a perpendicular static magnetic field $H$ produces a loss of interlayer phase coherence $\langle \cos \phi \rangle$, and so reduces the average Josephson coupling energy (or equivalently, the average Josephson current) when $H$ increases [20]. Extra decoupling of the layers seems to occur at melting, producing a sudden drop of $\langle \cos \phi \rangle$. Experimental observation of this drop has been reported in the organic superconductors $\kappa$-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br and, recently, in BSCCO in measurements of the magnetic-field dependence of the JPR frequency $\omega_{pl}$ [11, 12]. Note that at $T = 40$ K and below, melting could not be resolved in our measurements, neither in the characteristics of $\chi''$ vs. $H$, nor via magnetization measurements with a SQUID magnetometer. Below 40 K, the drop in the characteristics of $h_{ac}$ vs. $H_{step}$ does not seem to be present in fig. 3 as well, in contrast with recent JPR data in which a drop in $\omega_{pl}^2$ vs. $H$ was still observed below the critical point [12].

Figure 3 shows that in the liquid phase $h_{ac}$ can be fitted with a $1/H^\alpha$ dependence. Down to 50 K, the fits give $\alpha \approx 0.8$. Approaching 40 K, and below, $\alpha$ progressively increases and is of order 1.2 around 30 K. Koshelev [20] has predicted that in the particular case of
Fig. 3 – Double-logarithmic plot of the amplitude of the input excitation, $h_{ac}$, vs. the field at which the step in dissipation occurs, $H_{\text{step}}$, recorded (a) between 75 K and 50 K, and (b) between 50 K and 30 K. The arrows locate the melting transition, whenever observed (see text). (c) Data corresponding to $T \geq 45$ K plotted on a normalized scale, with $h_{ac}$ and $H_{\text{step}}$ divided by their values at melting. The dashed line corresponds to $h_{ac} \propto 1/H_{\text{step}}$.

a vortex liquid, $\langle \cos \phi \rangle$ should exhibit a $1/H^\alpha$ dependence, with $\alpha$ close to unity, and be proportional to the square of the JPR frequency $\omega_{pl}^2$; these predictions have been confirmed in JPR studies [10–12]. An increase of $\alpha$ is expected for $\langle \cos \phi \rangle$ as a consequence of disorder in the pancake arrangement along the $c$-axis [21], due, for instance, to an increase of pinning at low temperature. Figure 3 shows that the relation between $h_{ac}$ and $H$ found in BSCCO is very close to that expected for $\langle \cos \phi \rangle$ in the liquid phase. It suggests that $h_{ac}$ provides a direct measure of the interlayer phase coherence, being nearly proportional to $\langle \cos \phi \rangle$, in a
similar way as \( \omega^2_{pl} \). This is supported by the close similarity existing between the normalized characteristics of \( h_{ac} \) vs. \( H_{step} \), shown in fig. 3c, and the JPR data presented in ref. [12]. Within this scenario, the fact that \( h_{ac} \) still has a substantial nonzero value right beyond \( H_m \) in fig. 3 indicates that phase coherence is not completely lost when the vortices enter the liquid phase. It is only at higher fields that vanishingly small \( h_{ac} \)’s probe almost totally decoupled layers. In the characteristics of \( \chi'' \) vs. \( H \) shown in fig. 2, the step progressively broadens in the liquid phase, suggesting that the phase difference between the superconducting layers becomes less and less homogeneous over the sample thickness as the static field is increased beyond \( H_m \).

The step observed in figs. 1 and 2 indicates that a new dissipation process sets in at once when \( H \) reaches a threshold value \( H_{step}(h_{ac}) \). When a large-area Josephson junction is subject to a small in-plane magnetic field \( h \), the penetration of Josephson strings is prevented if the supercurrent density circulating at the junction periphery, over a thickness given by the London penetration depth \( \lambda \), is smaller than the Josephson critical current density \( j_c \) [22]. This defines the lower Josephson critical field \( h_{c1} < j_c \lambda \) below which \( h \) is screened. Similarly, a stacked structure of Josephson junctions such as a BSCCO single crystal should expel in-plane microwave fields of amplitude \( h_{ac} \) smaller than \( h_{c1} \) over a length scale \( \lambda_c \). An estimate of \( h_{c1} \) can be obtained from \( h_{c1} = \Phi_0/(4\pi\lambda_{ab}\lambda_c)[\ln(\lambda_{ab}/d)+1.12] \), where \( \Phi_0 \) is the magnetic-flux quantum, \( \lambda_{ab,c} \) is the London penetration depth associated with current flow parallel (or perpendicular) to the layers, and \( d \) is the distance between adjacent layers [23]. For BSCCO, \( d \approx 15 \text{ Å} \). Taking into account the temperature variation of \( \lambda_{ab,c} \) [24, 25], at 65 K \( \lambda_{ab} \) is of the order of 0.4 to 0.6 \( \mu \text{m} \) and \( \lambda_c \) is of the order of 80 to 200 \( \mu \text{m} \) [2, 12, 24–27]. This gives values of \( h_{c1} \) in the range of 94–333 mOe. At the same temperature, we measure \( H_{step} = 0 \) when the attenuation of the microwave field is 17 dB, which corresponds to \( h_{ac} \approx 133 \text{ mOe} \). This estimate shows that the values of \( h_{ac} \) and of \( h_{c1} \) are comparable in our experiments.

An additional static field component \( H \) perpendicular to the Josephson stacks produces pancake vortices in the superconducting planes, which result in an extra loss of interlayer phase coherence and hence in a decrease of \( h_{c1}(H) \). In each characteristic of \( \chi'' \) vs. \( H \) shown in figs. 1 and 2, \( h_{ac} \) is kept at a constant value during the sweeps of \( H \). Sweeping up the static field \( H \) results in a decay of \( h_{c1}(H) \). When \( H \) is such that \( h_{c1}(H) > h_{ac} \), no microwave-induced Josephson strings penetrate the sample. A further increase of \( H \) leads to the reversed situation, \( h_{c1}(H) < h_{ac} \); Josephson strings enter and then leave the sample at the microwave frequency, giving rise to an extra contribution to the dissipation. This process is expected to occur at a threshold field such that \( h_{c1}(H) = h_{ac} \), producing a step in the characteristics of \( \chi'' \) vs. \( H \) like that observed experimentally at \( H = H_{step} \). Hence, a possible explanation for the step could be that it is associated with the lower Josephson critical field \( h_{c1} \) below which penetration of Josephson strings is prevented at 10 GHz.

An important consequence of this scenario is that the diagram of \( h_{ac} \) vs. \( H_{step} \) should permit to explore how Josephson coupling evolves in a static perpendicular field \( H \), provided that the relation between \( h_{ac} \) and \( \langle \cos \phi \rangle \) is known. As a first guess, we take \( j_c \propto h_{ac}/\lambda_c \), which is justified at the step, since we suppose \( h_{c1}(H_{step}) = h_{ac} \) in each characteristic of \( \chi'' \) vs. \( H \). As in ordinary Josephson junctions, we also assume [22] that \( \lambda_c \propto j_c^{-\frac{1}{2}} \propto \langle \cos \phi \rangle^{-\frac{1}{2}} \). Combined with the \( 1/H \) dependence of \( \langle \cos \phi \rangle \) in the decoupled liquid phase predicted by Koshelev [20], one should then expect a \( 1/H^{1/2} \) dependence for \( h_{ac} \). The experimental data in fig. 3 show instead a \( 1/H^\alpha \) behavior with \( \alpha \) close to 1. On the other hand, the losses in the liquid phase should then exhibit a \( H^{1/2} \) dependence [28]; instead, the results presented in ref. [14] show a
behavior closer to linear in $H$. These discrepancies point to some difficulty essentially related to the field dependence of $\lambda_c$. The main reason might be the lack of knowledge about either the effective thickness $\lambda_{c\text{eff}}$ of the layer through which the microwave surface currents flow, or its magnetic-field dependence. The microwave loss data from ref. [14] suggest that $\lambda_{c\text{eff}}$ weakly depends [28] on $H$, which would then be consistent with the experimentally observed $1/H$ variation of $h_{ac}$. More realistic models [29], taking into account the influence of effects such as surface defects on $\lambda_{c\text{eff}}$, might be able to reconcile the experimental observations with theory.

Recent JPR experiments of Hanaguri et al. on BSCCO have shown nonlinear effects induced by microwave power [13]. The nonlinearities of the JPR were qualitatively explained with the perturbed sine-Gordon equation for the Josephson phase. It predicts a lowering of the resonance frequency and the appearance of a hysteretic bistable regime at high microwave current, consistent with the experimental JPR data [13,30]. Figure 3 shows that, at a fixed value of the static magnetic field, the step occurs at lower temperature when $h_{ac}$, and the associated microwave current, is increased. This behavior is similar to that observed in ref. [13] for the nonlinear JPR. Hence, another possible interpretation for the step is that it might correspond to the switching between two stable solutions of the perturbed sine-Gordon equation. A theoretical estimate of the range of existence of each solution of the sine-Gordon equation predicts [30] $h_{ac} \propto \langle \cos \phi \rangle^{1/2}$. This is the same analytical dependence as that predicted in the scenario involving the lower critical field $h_{c1J}$. It should result in a $1/H^{1/2}$ dependence of $h_{ac}$ in the liquid phase, whereas the experimental data exhibit a behavior closer to $1/H$. A deeper comparison of our data with the nonlinear JPR data [13] requires the knowledge of the currents which flow across the superconducting layers in both experiments. Such data are presently not available in the JPR experiment.

In summary, the characteristics of $h_{ac}$ vs. $H_{\text{step}}$, recorded at various fixed temperatures, qualitatively reveal the behavior expected for the magnetic-field dependence of Josephson coupling; the characteristics exhibit a drop at $H_m$, which points to substantial (but not yet full) decoupling at the melting transition. We propose that the step is either related to the lower Josephson critical field $h_{c1J}$ in BSCCO, or to nonlinear JPR.

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We are grateful to A. E. Koshelev for stimulating discussions. This work is supported by CREST and Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan.

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