Measurements of microwave vortex response in dc magnetic fields in Tl$_2$Ba$_2$CaCu$_2$O$_{8+x}$ films

N. Pompeo, Senior Member, IEEE, H. Schneidewind, E. Silva, Senior Member, IEEE

Abstract—There is a renewed interest in superconductors for high-frequency applications, leading to a reconsideration of already known low-$T_c$ and high-$T_c$ materials. In this view, we present an experimental investigation of the millimeter-wave response in moderate magnetic fields of Tl$_2$Ba$_2$CaCu$_2$O$_{8+x}$ superconducting films with the aim of identifying the mechanisms of the vortex-motion-induced response. We measure the dc magnetic-field-dependent change of the surface impedance, $\Delta Z_s(H) = \Delta R_s(H) + i\Delta X_s(H)$ at 48 GHz by means of the dielectric resonator method. We find that the overall response is made up of several contributions, with different weights depending on the temperature and field: a possible contribution from Josephson or Abrikosov-Josephson fluxons at low fields; a seemingly conventional vortex dynamics at higher fields; a significant pair breaking in the temperature region close to $T_c$. We extract the vortex motion depinning frequency $f_p$, which attains surprisingly high values. However, by exploiting the generalized model for relaxational dynamics we show that this result comes from a combination of a pinning constant $k_p$ arising from moderate pinning, and a vortex viscosity $\eta$ with anomalously small values. This latter fact, implying large dissipation, is likely a result from a peculiar microscopic structure and thus poses severe limits to the application of Tl$_2$Ba$_2$CaCu$_2$O$_{8+x}$ in a magnetic field.

Index Terms—Pinning, Surface impedance, Microwaves.

I. INTRODUCTION

The need for pushing further the performances of superconductor-based high-frequency devices, such as accelerating cavities [1] or electromagnetic screenings [2] has given rise to a reexamination of the temperature and magnetic field dependences of the surface impedance in both conventional and high-$T_c$ superconductors (HTS). Well-known superconductors, such as Nb$_3$Sn, are being investigated with respect to the field–dependent surface impedance [3], and NbTi cavities for dark matter search are being tested in mid-to-high magnetic fields [4]. HTS have been studied for longtime, but Tl-based HTS have been dismissed in early times due to their inferior performances with respect to YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO). However, some Tl-based compounds are now under scrutiny for selected large-scale applications [5]. It is then a useful contribution to investigate the microwave properties in magnetic field of other superconductors. Clarifying the main mechanisms of the dissipation is the main step in order to ascertain the usefulness of a material for selected applications.

E. Silva and N. Pompeo are with the Department of Engineering, Università Roma Tre, 00146 Roma, Italy. Corresponding author: E. Silva; e-mail: enrico.silva@uniroma3.it.

H. Schneidewind is with the Leibniz Institute of Photonic Technology, Albert-Einstein-Straße 9, D-07745 Jena, Germany.

Manuscript received October 30, 2018.

Since the microwave response in a dc magnetic field is of interest here, one has to deal with losses mainly due to fluxon motion [6]. However, other sources of dissipation cannot be ruled out: weak–links, and related “strange fluxons” such as Josephson or Abrikosov-Josephson fluxons [7], and quasiparticle excitations. It should be noted, however, that weak–links phenomena can be reduced or avoided with proper material engineering, and quasiparticle excitation is an intrinsic detrimental effect that arises -for what concerns applications- only close to $T_c$ or $H_{c1}$. It is then useful to give more detail on the main source of dissipation, that is the fluxon motion. The response of the system of flux lines to an ac field is given by the vortex complex resistivity $\rho_{em}$ [8], [9], [10]:

$$\rho_{em} = \rho_{em1} + i\rho_{em2} = \frac{\Phi_0 B \chi + i\frac{f}{f_0}}{\eta + i\frac{f}{f_0}}$$

where $\Phi_0 \approx 2.07 \times 10^{-15}$ Tm$^2$ is the flux quantum, $\eta$ is the so-called vortex viscosity, $B \approx \mu_0 H$ (in the London limit) is the magnetic induction field, and $\chi$ is a dimensionless creep factor that takes into account the thermal activation phenomena, with $\chi \in [0, 1]$. This expression simplifies when no thermal effects are relevant, in which case $\chi = 0$ and $f_0 \rightarrow f_p$, where $f_p = k_p/(2\pi\eta)$ is the so–called depinning frequency, and one writes down the well–known result by Gittleman and Rosenblum [11]:

$$\rho_{em} = \frac{\Phi_0 B}{\eta} \frac{1}{1 - i\frac{f}{f_p}}$$

where it is clear that $f_p$ is the crossover frequency that separates the low frequency, vanishing dissipation (Campbell) regime [12] from the high-frequency dissipative (flux–flow) regime. The depinning frequency has been recognized as a fundamental parameter to assess the microwave properties of superconductors [11], [13], since it gives a rough measure of the weight of the losses at a certain frequency: the dimensionless parameter $r = \rho_{em2}/\rho_{em1} \approx f_p/f \leq 1$ is the crossover mark between Campbell and flux–flow regime (one has however to bear in mind that the crossover region extends for a decade in frequency [11]).

The aim of this paper is to report on the microwave surface impedance of thin Tl$_2$Ba$_2$CaCu$_2$O$_{8+x}$ (TBCCO) films in a moderate magnetic field $\mu_0 H \leq 0.8$ T, in order to identify the main dissipative mechanisms and to give information on some of the relevant parameters to assess the high–frequency performances, with particular attention to the depinning frequency and to its dependence on the temperature and magnetic field. We will compare the results to typical results obtained in YBCO and in conventional superconductors.
II. Samples and Method

Measurements are performed on two TBCCO thin films (thickness $t_s=240$ nm), labelled as TS2 and TS5, grown by conventional two-step method in the c-axis direction over CeO$_2$ buffered R-plane sapphire substrates, 2 inches in diameter and 0.5 mm thick. Preparation details and additional characterization are available elsewhere [14, 15]. The samples were cut from a wafer in the shape of $10 \times 10$ mm$^2$ squares. The film thickness is $t_s \approx 240$ nm. Since both samples give analogous results, we report here data obtained on sample TS2, where inductive measurements yielded $T_c \approx 104$ K, which compares well to the maximum $T_c \approx 110$ K in very clean samples [16], and $J_c(77 \text{ K}, H=0) = 1.0$ MAcm$^{-2}$.

The microwave surface impedance is measured by means of a cylindrical sapphire resonator [18] used within the surface perturbation method. The resonator is operated in reflection in the TE$_{011}$ mode, with the resonance frequency $f_{res} \approx 47.7$ GHz. The measuring frequency is much smaller than the gap, estimated in the tens of meV (40 meV, equivalent to approximately 10 THz, as measured in the infrared range [17]. Microwave patterns induced on the sample are planar and circular, so that only the $ab$ plane response is measured. The unloaded $Q$ factor and the resonance frequency $f_{res}$ yield the surface impedance [18]. Taking into account the thickness of the film [19], one can write down the following relation between the measured $Q$, $f_{res}$, the effective surface impedance shift $\Delta Z_s(H)$ and the microwave complex resistivity $\tilde{\rho}$:

$$
\Delta Z_s(H) \approx \frac{\Delta \tilde{\rho}(H)}{t_s} = \frac{\Delta \rho_1(H) + i \Delta \rho_2(H)}{t_s} = G_s \left( \frac{1}{Q(H)} - \frac{1}{Q(0)} - 2i \frac{f_{res}(H) - f_{res}(0)}{f_{res}(0)} \right)
$$

where $G_s$ is a calculated geometrical factor.

Using a solid/liquid nitrogen cryostat we vary the temperature between $T \approx 60$ K and $T_c$. A moderate magnetic field $\mu_0 H \leq 0.8$ T is applied perpendicularly to the sample surface (i.e. parallel to the superconductor $c$-axis).

A typical measurement is shown in Figure 2(a), where we show the raw data for $Q$ and $f_{res}$ vs. $H$ (Fig 2a) and the resulting surface impedance shift $\Delta \tilde{\rho}(H)$ (Fig 2b). Figure 2c shows an enlargement of the low-field region, illustrating the wide dynamic range of the measurements.

We briefly comment on Fig.s 2 and 2b. The sample data have been selected at a rather high temperature in order to highlight all three regimes that showed up in the measurements. First, at very low fields (Fig 2a) a small “step” in the surface impedance appears, with a trend to saturation at a few mT. Second (Fig 2b), a rapid increase (first linear, then superlinear) of both $\Delta R_s$ and $\Delta X_s$ is observed, followed by a field region where $\Delta X_s$ only drops quickly. For reasons that will be clarified later, we label these regimes as AJF, VM, QP, respectively. We anticipate that the discussion will be focused on the intermediate, VM region. All the regions here depicted have different extension (i.e., field range) depending on the temperature. In particular, at low $T$, below $\approx 85$ K, the QP region cannot be observed.

III. Experimental Results and Discussion

We report a series of measurements at selected temperatures in Fig 3. It can be seen that, at all temperatures, $\Delta X_s > \Delta R_s$. [This sentence is not clear and might need to be revised or rephrased.]
This is usually a manifestation of very strong pinning: the elastic energy stored in the fluxon system is larger than the dissipated energy per oscillation due to the flux–flow mechanism. The customary parameter to quantify the strength of the pinning is, at microwaves, the parameter \( r = \Delta X_s/\Delta R_s \). Making reference to Eq. (2) and to Eq. (3), it is seen that, should the field–increase of the surface impedance be due to vortex motion only, one would have \( r = \Delta \rho_{vm2}/\Delta \rho_{vm1} \). In the present case, as anticipated in Sec.II, several mechanisms are present so that a preliminary data elaboration is needed.

First, we note that the field region where \( \Delta X_s \) decreases with the field is a clear manifestation of quasiparticle (QP) motion, and it is directly measured as \( \Delta Z_s = \Delta Z_{sym} + \Delta Z_{AJF} + \Delta Z_{QP} \). We are interested in the derivation of the vortex–motion parameters present in \( \Delta Z_{sym} \) through Eq. (2). We then remove the contribution of \( \Delta Z_{QP} \) by simply avoiding to examine the data where \( \Delta X_s \) decreases with the field (this is why some of the following data will be cut above a certain field). We then remove the \( \Delta Z_{AJF} \) contribution by estimating the height of the saturation value of the first, low field increase of \( \Delta Z_s \) (as an example, in Fig.2 we estimate \( \Delta Z_{AJF} \approx 8 \text{ m} \Omega + i12 \text{ m} \Omega \), and we subtract it from the data. We note however that \( \Delta Z_{AJF} \) is negligible with respect to the overall \( \Delta Z_s \), so that we expect small additional errors in the derivation of the vortex motion (VM) parameters. After the subtraction, and the field limitation if required, we analyse the data with Eq. (2). A consequence of the need to remove the other contributions is that the parameters obtained from the analysis are not reliable below \( \sim 0.2 \text{ T} \), so that the following plots will report the data in the range 0.2 T – 0.8 T only.

We use the procedure described with great detail in [10] to derive the vortex parameters. Here, the parameters are derived from the data in Fig.3 by using Eq. (2). We refer the reader to [10] for the estimates of the uncertainties and of the statistical confidence intervals.

The first important parameter is the depinning frequency \( f_p \). We report such data in the form \( r = \Delta \rho_{vm2}/\Delta \rho_{vm1} \) in Figure 4a. As it can be seen, the data show very high values \( r > 1 \). Bearing in mind our operating frequency, \( f \approx 48 \text{ GHz} \), our values for \( r \) would give a huge \( f_p \approx 200 \text{ GHz} \) at low temperature. This is a surprisingly large value: the depinning frequency attains values of \( \sim 10 \text{ GHz} \) (at \( \sim T_c/2 \)) in YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) (YBCO) single crystals [22], and in the range 30–70 GHz for temperatures between 60 K and 80 K in nanostructured YBCO with BaZrO\(_3\) nanorods [23], [24], [25]: low-\( T_c \) Nb thin films exhibit depinning frequencies in the 5–20 GHz range [26], [27]. Although it was reported that very thin films show increased \( f_p \), e.g. [27], we do not believe that this is the case, since the thickness of our TBCCO films (also as compared to the London penetration depth) is not significantly different from other cuprates investigated [23], [24], [25]. We stress that the parameter \( r \), hence \( f_p \), is not affected by calibrations and geometrical factors: looking at Eqs. (2) and (3), it is easy to see that \( r \) is directly measured from \( Q \) and \( f_{res} \).

A high depinning frequency is usually considered the necessary condition for the operation of a superconductor at high frequency in dc magnetic field. However, a more complete analysis shows that for the compound under study this is not sufficient.

In Figure 4b we report the vortex viscosity \( \eta \) as a function of the dc magnetic field. Although the determination of the absolute value of \( \eta \) depends on the determination of the film thickness, a 30% uncertainty on the determination of
Thus, we are led to the important conclusion that the huge values of \( f_p \) do not come from some kind of strong pinning. Instead, recalling that \( f_p = k_p/(2\pi\eta) \), we must ascribe this very high value for \( f_p \) to an anomalously small value for \( \eta \). The reasons for this behavior are not clear at present, and they resides in the very fundamental nature of the superconducting state in TBCCO: the vortex viscosity is a lumped parameter that contains the details of the microscopic processes governing the dissipation in the flux–flow state, and it is unlikely to be controlled by some kind of material engineering. Thus, although a direct measure of the depinning frequency yields huge values, a more complete study shows that the peculiar (albeit not known) microscopic state gives rise to exceedingly high losses even in a moderate dc magnetic field.

### IV. Conclusions

In order to assess the possible use of Tl\(_2\)Ba\(_2\)CaCu\(_2\)O\(_{8+x}\) for microwave applications in a dc magnetic field, we have measured the magnetic field dependence of the complex surface impedance in thin TBCCO films. We have found that a rich variety of processes exists, even in our moderate fields. In particular, an extrinsic contribution due to grain boundaries or weak links has been identified at low fields. The intrinsic quasiparticle increase process is much more present than in other HTS, thus increasing significantly the dissipation even at 15 K below \( T_c \) in moderate fields (below 1 T). The most important finding resides in the huge depinning frequency. However, by performing a complete analysis with a general model for vortex motion, we have shown that the huge values for the depinning frequency are not due to some kind of exceptional pinning (that would increase the interest for applications). Instead, it results from the combination of a pinning constant which is weaker than in YBCO, and a vortex viscosity that is more than an order of magnitude smaller than in, e.g., YBCO. The latter finding is very hard to reconcile with the present understanding of HTS. Although it cannot be excluded that the depinning frequency could be increased further by acting on, e.g. artificial defects, it has little effect on the practical applications of TBCCO, since it does not reduce the anomalous dissipation.

### References

[1] H. Padamsee, “The science and technology of superconducting cavities for accelerators,” Supercond. Sci. Technol., vol. 14, no. 4, pp. R28R51, 2001.
[2] L. J. Tavian, “Cryogenics Future Circular Collider Study Kickoff Meeting”, University of Geneva, Switzerland, Feb. 2014. [Online]. Available: http://indico.cern.ch/event/282344/contributions/1630775/
[3] A. Alimenti et al., “Surface impedance measurements on Nb\(_3\)Sn at high magnetic fields”, IEEE Trans. Appl. Supercond., submitted for publication.
[4] D. Di Gioacchino et al., “Microwave losses in a dc magnetic field in superconducting cavities for axion studies”, presented at 2018 Applied Superconductivity Conference, presentation ILOr1A-01, and IEEE Trans. Appl. Supercond., submitted for publication.
[5] S. Calatroni et al., “Thallium-based high-temperature superconductors for beam impedance mitigation in the Future Circular Collider,” Supercond. Sci. Technol., vol. 30, p. , Oct. 2017, Art. no. 075002.
[6] R. Marcon, R. Fastampa, M. Giura, and E. Silva, “Vortex-motion dissipation in high-Tc superconductors at microwave frequencies,” Phys. Rev. B, vol. 43, no. 4, pp. 2940-2945, Feb. 1991.
[7] A. Gurevich, “Nonlinear viscous motion of vortices in Josephson contacts,” Phys. Rev. B, vol. 48, no. 17, pp. 12857–12865, Nov. 1993.
[8] M. W. Coffey and J. R. Clem, “Unified theory of effects of vortex pinning and flux creep upon the rf surface impedance of type-II superconductors,” Phys. Rev. Lett., vol. 67, no. 3, pp. 386–389, Jul. 1991.
[9] E. H. Brandt, “Penetration of magnetic ac field into type-II superconductors,” Phys. Rev. Lett., vol. 67, no. 16, pp. 2219–2222, Oct. 1991.
[10] N. Pompeo and E. Silva, “Reliable determination of vortex parameters from measurements of the microwave complex resistivity,” Phys. Rev. B, vol. 78, no. 9, Sep. 2008, Art. no. 094503.
[11] J. I. Gittleman and B. Rosemblum, “The pinning potential and high-frequency studies of type-II superconductors,” J. Appl. Phys., vol. 39, no. 6, pp. 2617–2621, May 1968.
[12] A. M. Campbell, “The response of pinned flux vortices to low-frequency fields,” J. Phys. C Solid State Phys., vol. 2, no. 8, pp. 1492–1501, 1969.
[13] S. Calatroni and R. Vaglio, “Surface resistance of superconductors in the presence of a dc magnetic field: frequency and field intensity limits,” IEEE Trans. Appl. Supercond., vol. 27, no. 5, p. 3500506, 2017.
[14] H. Schneidewind, M. Zeisberger, H. Bruchlos, M. Manzel, T. Kaiser, Institute of Physics Conf. Series, vol. 167, p. 383, 2000.
[15] H. Schneidewind, M. Manzel, G. Bruchlos, and K. Kirsch, “TiBaCaCuO-(2212) thin films on lanthanum aluminate and sapphire substrates for microwave filters,” Supercond. Sci. Technol., vol. 14, no. 4, p. 200, 2001.
[16] C. W. Chu, “High-temperature superconducting materials: a decade of impressive advancement of Tc,” IEEE Trans. Appl. Supercond., vol. 7, no. 2, June. 1997, pp. 80–89.
[17] N. L. Wang, P. Zheng, J. L. Luo, Z. J. Chen, S. L. Yan, L. Fang, and Y. C. Ma, “Strong electron-boson coupling effect in the infrared spectra of Tl2Ba2CaCu2O8–δ,” Phys. Rev. B, vol. 68, no. 5, Aug. 2003, Art. no. 54516.
[18] N. Pompeo, K. Torokhtii, and E. Silva, “Dielectric resonators for the measurements of the surface impedance of superconducting films,” Meas. Sci. Rev., vol. 14, no. 3, pp. 164–170, 2014.
[19] N. Pompeo, K. Torokhtii, and E. Silva, “Surface impedance measurements in thin conducting films: substrate and finite-thickness-induced uncertainties,” in IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC), Turin, Italy, 2017, pp. 1–5.
[20] A. Gurevich and L. D. Cooley, “Anisotropic flux pinning in a network of planar defects,” Phys. Rev. B, vol. 50, no. 18, May 1994, Art. no. 214531.
[21] A. Gurevich, “Nonlinear dynamics of vortices in easy flow channels along grain boundaries in superconductors,” Phys. Rev. B, vol. 65, Jun. 2002, Art. no. 214531.
[22] Y. Tsuchiya et al., “Electronic state of vortices in YBa2Cu3O6.9 investigated by complex surface impedance measurements,” Phys. Rev. B, vol. 63, no. 18, Apr. 2001, Art. no. 184517.
[23] N. Pompeo et al., “Reduction in the field-dependent microwave surface resistance in YBa2Cu3O7–δ with submicrometric BaZrO3 inclusions as a function of BaZrO3 concentration,” J. Appl. Phys., vol. 105, no. 1, Jan. 2009, Art. no. 013927.
[24] K. Torokhtii et al., “Microwave measurements of pinning properties in chemically deposited YBCO/BZO Films,” IEEE Trans. Appl. Supercond., vol. 27, no. 4, Jun. 2017, Art. no. 8000405.
[25] N. Pompeo, K. Torokhtii, E. Silva, “Extraction of the complex resistivity and pinning parameters from microwave surface impedance measurements of coated conductors,” IEEE Trans. Appl. Supercond., vol. 28, no. 4, Jun. 2018, Art. no. 9000505.
[26] E. Silva, N. Pompeo, and S. Sarti, “Wideband microwave measurements in Nb/Pd0.4Ni0.6/Nb structures and comparison with thin Nb films,” Supercond. Sci. Technol., vol. 24, no. 2, Jan. 2011, Art. no. 024018.
[27] D. Janjićević, M. S. Grbić, M. Požek, A. Dulčić, D. Paar, B. Nebendahl, and T. Wagner, “Microwave response of thin niobium films under perpendicular static magnetic fields,” Phys. Rev. B, vol. 74, no. 10, Sep. 2006, Art. no. 104501.