

Microwave measurements to assess the properties of superconducting materials for applications.

Enrico Silva^{1,2}, Nicola Pompeo¹, Kostiantyn Torokhtii¹

¹*Dept. of Engineering, University Roma Tre, via della Vasca Navale 84, 00146 Roma, Italy*

²*enrico.silva@uniroma3.it*

Abstract – Establishing with minimum effort the performances of coated conductors (superconducting-based tapes) in terms of maximum current density is a crucial issue in the optimization of the superconducting material. Methods with minimum requirements in terms of sample preparation (nondestructive) are maximally sought. In this work we review the potential of a contactless microwave technique based on the use of resonators. The technique exploits the intrinsic processes at the heart of the dissipation of a superconductor in order to assess a first, go/no-go quality test for the superconducting material. We discuss the limitations and the advantages of the proposed method as well as the requirements for the microwave setup. Finally, we compare the microwave results to the directly measured dc features of several superconducting samples of interest for coated conductors.

I. INTRODUCTION

Superconducting materials are the essential core of many high-power devices. Due to the favourable cryogenic requirements, the use of ceramic high- T_c superconductors (HTS) such as, e.g., $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO, transition temperature $T_c \simeq 90$ K) raised a strong interest for power [1] applications (while other HTS, such as $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_{8+x}$ -TBCCO, $T_c \simeq 110$ K, have been proven useful in telecommunications [2]). Superior performances are obtained only by appropriate engineering of the superconducting material in order to overcome the formation of weak links between grains and to raise the maximum current bearable (critical current density, J_c). The ceramic nature and complex crystal structure of HTS make conventional cables unfeasible. The so-called coated conductors (CCs) are the present response to this issue: a metal tape, sufficiently flexible in order to be wound in coils, covered by a complex series of buffer layers and finally by the HTS thin film (typically YBCO, with thickness of the order of $1 \mu\text{m}$, as compared to $50\text{-}100 \mu\text{m}$ for the metal tape). Such a material is now commercially available by several sources [3, 4], but the improvement of the performances of CCs is a continuous challenge. Beside the increase of YBCO grain connectivity, J_c can be significantly engineered [5, 6] with the appropriate insertion of suitably shaped defects in the superconducting matrix,

such as nanoshaped BaZrO_3 (BZO) inclusions, that hinder the dissipative motion of magnetic flux lines. In fact, $J_c \sim 1 \text{ MA cm}^{-2}$ are now reachable. Thus, an important challenge is a reliable and quick test of the performances of a superconducting planar material, to the least at the level of “go/no-go” evaluation during material optimization, in terms of grain connectivity and pinning capability. A local test is particularly desired, since one of the major issues is the uniformity of the performances of the superconducting materials.

In this work we show that, by exploiting the physical processes responsible for the dissipation in superconductors, a microwave measurement can act as a reliable, non-destructive material test for HTS on laboratory-sized samples (typically $25\text{-}100 \text{ mm}^2$), as well as on commercial portions of CCs, giving reliable results on areas of $\sim 2 \text{ mm}^2$. This test is a valuable tool in the path toward optimization of the superconductor, both as a raw material (laboratory sample) and when incorporated in a CC.

II. PHYSICAL PRINCIPLES OF THE METHOD

The subject of interest is the performances of a superconducting flat sample in a magnetic field. Under such conditions, two main sources of dissipation exist: dissipation due to weak-links, and dissipation due to the motion of quantized flux (“fluxons”, $\Phi_0 = 2.07 \cdot 10^{-15} \text{ Tm}^{-2}$). Weak links arise from weakly connected superconducting grains, that give rise to local depressions of the superconducting properties. Fluxon motion losses arise because a current density J exerts a force on fluxons and, unless “pinned” to suitable defects, they move and a finite resistance arises. Thus, the existence of weak-links is basically a matter of better connection between the superconducting grains, while hindering fluxon motion requires material engineering at the nanoscale with the aim of raising the maximum (“critical”) current density $J_c(H, T)$ bearable without dissipation, the ultimate limit to the application of superconductors in a magnetic field (including the self-field). The detrimental effect of both phenomena require different material engineering, so it is important to identify the responsible for the losses. A dc investigation has two main drawbacks. First, the role of weak-links might be difficult to isolate clearly, since “short-circuit” paths along well-connected regions would mask the effect. Second, a clear

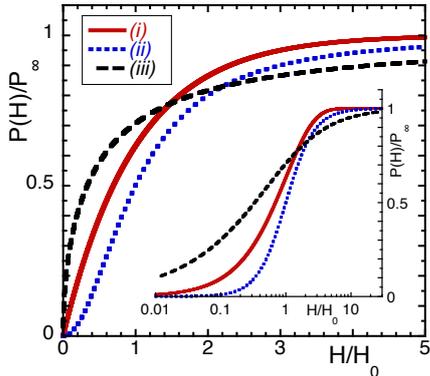


Fig. 1. Normalized microwave power dissipation in a granular superconductor P/P_∞ vs. H/H_0 , the normalized field, for different models: [7] (i), [8] (ii), [10] (iii). The qualitative field dependence is the same.

observation of fluxon motion would require large currents, in excess of $J_c \sim 1 \text{ MA cm}^{-2}$. In relatively large samples this task is not trivial [11], and several technical problems must be overcome: the need to pass large currents in a cryogenic environment; the need to pattern the sample in a proper shape; the difficult control of the temperature when large dissipation is induced in the sample. By contrast, tests on small-scale samples require patterning in the proper shape, and this further manipulation can be undesirable in the process of optimization of the material. In many cases one needs only an indication whether a sample presents suitable performances for further investigations, or for the approval of a growth process, so that simpler “quality tests” might prove useful. A microwave investigation can be very useful in these respects, as we explain in the following.

At microwave frequencies (1-100 GHz), the electromagnetic field probes a volume of the sample across a thickness of the order of the London penetration depth $\lambda \sim 200 \text{ nm}$ (in HTS at the temperatures of interest), and all processes are detected altogether even at low magnetic fields. In particular, “shaking” of fluxons gives a well detectable signal even at subcritical currents. The key to discriminate between the two processes is the very different *qualitative* magnetic field dependence: the dissipation due to weak links increases fast and then saturates, while the fluxon motion increases steadily, quasi-linearly. Despite the many possible loss mechanisms acting in weak links (e.g.: field [7] and thermal [8] dephasing of Josephson junctions between grains, motion of Josephson [9] and Abrikosov-Josephson fluxons [10]), the field dependence always gives a steep rise of the dissipation, followed by a saturation: $P(H) = P_\infty \times p(H/H_0)$, as reported in Fig. 1, where P_∞ is the high-field saturation, and H_0 the characteristic dc field for the initial increase of $P(H)$. By contrast, fluxons subjected to ac currents of frequency ν ex-

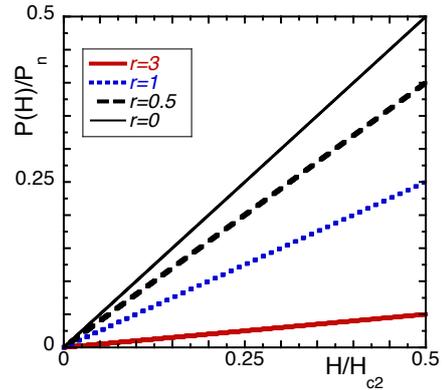


Fig. 2. Plot of the fluxon motion microwave power dissipation normalized to the normal state P/P_n vs. H/H_{c2} in a thin superconductor, due to the motion of fluxons, with different r values. $r = 0$ corresponds to Pinning-free flux flow.

hibit a field-variation of the complex resistivity analogous to a massless particle elastically bound (“pinned”) to the position of equilibrium and subjected to a viscous drag¹ [12, 13]:

$$\rho_1 + i\rho_2 = \rho_{ff} \frac{1}{1 - i\nu_p/\nu} \quad (1)$$

where $\rho_{ff} \sim H$ is the free-flow resistivity (zero pinning) and the so-called depinning frequency ν_p is a measure of the balance between losses and reactive energy. Often, in the context of rf performances of superconductors, one introduces the r parameter [9] defined as:

$$r = \rho_2/\rho_1 = \nu_p/\nu \quad (2)$$

where the first equality is a definition, and the second equality derives from Eq. 1. We show below that r is correlated to J_c . Thus, the information of interest for power applications is within r , and requires the measurement of both ρ_1 and ρ_2 (see Fig. 2).

III. MICROWAVE MEASUREMENTS AND COMPARISON WITH J_C

Measurements of the microwave complex resistivity in a dc magnetic field are easily and relatively quickly performed with the use of cavity [14] or dielectric resonators [15, 16]. We focus on the latter.² Bearing in mind that a primary requirement is to deal with unpatterned (pristine) samples, and that the test is intended for optimization of the material, typical “laboratory” scale samples should be examined, of size ranging between $5 \times 5 \text{ mm}^2$ to 15

¹We treat here only the increase of the resistivity due to an external, dc magnetic field. We also neglect thermally induced creep of flux lines.

²Other methods, such as stripline resonators or Corbino disk setups, while powerful, are either too complex for the purpose, or they require patterning of the samples.

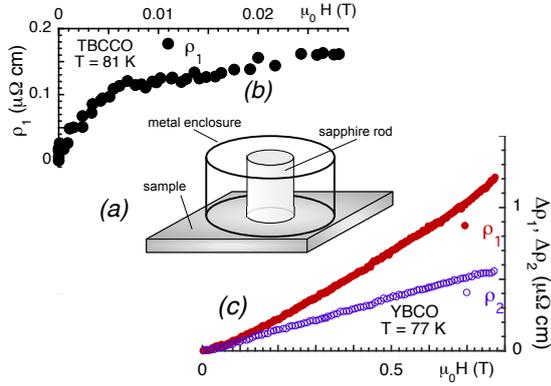


Fig. 3. (a) Sketch of the resonator. (b) Field-induced dissipation [here, $\rho_1(H)$] in TBCCO: weak links clearly show up. (c) Typical curves for $\rho_1(H)$, $\rho_2(H)$ in a YBCO sample without weak-links, and fluxon motion dominates.

$\times 15 \text{ mm}^2$. Second, microwave frequencies not too low should be used: to have maximal sensitivity, one should work around $r \simeq 1$ (see Eq.s 1 and 2). Since ν_p is in the $\sim 10 \text{ GHz}$ range [17], and experiments should be directed to samples for power application (with large r , see below), operating frequencies $\nu = 30 \div 50 \text{ GHz}$ are good candidates. Moreover, high operating frequencies imply small dimensions of the resonator and of the area probed.

We employ here a dielectric resonator consisting of a single crystal, very-low-losses sapphire rod in the Hakki-Coleman configuration [18], optically polished, of dimensions $(2.918 \pm 0.002) \text{ mm}$ (height), $(1.748 \pm 0.004) \text{ mm}$ (dia.), enclosed in a metal radiation shield of 9 mm diameter. The sample under study is placed as a base of the resonating structure. Changes in the Q factor and in the resonant frequency ν_0 with the applied field directly yield the changes in the complex resistivity of the film [19]:

$$\rho_1(H, T) = G_s d \left[\frac{1}{Q(H, T)} - \frac{1}{Q(0, T)} \right] \quad (3)$$

$$\rho_2(H, T) = -2G_s d \left[\frac{\nu_0(H, T) - \nu_0(0, T)}{\nu_0(0, T)} \right] \quad (4)$$

where G_s is a geometrical factor [19] and $d < \lambda$ is the film thickness [20]. We note that the determination of the relevant parameter r is independent on complex calibrations of the setup, and it is given by directly measured quantities, Q and ν_0 . The resonator operates at 47.5 GHz in the TE_{011} mode, with induced currents parallel to the surface of the sample. The assembly is placed in a cryostat that operates down to 50 K. Cryogenic, non magnetic coaxial cables connect the room temperature microwave source and the low temperature inset. The sensitivity and the accuracy increase with increasing Q factor [16, 21]. Here, Q is in the range $(0.2 \div 1.2) \times 10^4$. In Fig.3a we present sample measurements in a TBCCO film [13] showing typical weak-links response at low fields: from this simple qualitative

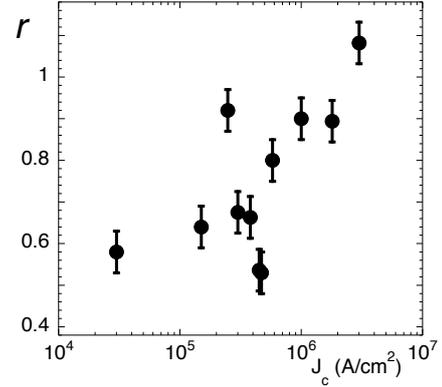


Fig. 4. Correlation between the r parameter and the dc critical current density J_c , independently measured, in different sample types and operating temperatures.

measurement, one immediately concludes that weak-links are present in the sample, with no need for any complex interpretation. In Fig.3b we report measurements of $\rho_1 + i\rho_2$ in a YBCO thin film [6], whence r . Once one has determined on qualitative grounds that the pinning properties of the samples can be assessed by microwave contactless measurements, a direct comparison between the measured r and dc J_c is desirable. To this aim, we have analyzed several samples of YBCO thin films, at different temperatures ($83 \text{ K} \geq T \geq 62 \text{ K}$), with and without BZO defects, grown on different substrates, by different methods and from different sources, including commercially available portions of coated conductors. When only one sample of a certain type was available, the sample was first measured at microwave frequencies, and then patterned for J_c measurements. Otherwise, twin samples (grown at the same time) were used. We have selected samples where no trace of weak-links could be detected. In all cases, we compared J_c measurements taken at $\mu_0 H = 1 \text{ T}$, and r taken at $\mu_0 H = 0.5 \text{ T}$ at the same temperature. This was made on purpose, to compare a typical dc figure of merit (J_c at 1 T, after the typical low-field steep drop) with the r factor measured in “easy” conditions (use of a conventional electromagnet). Fig.4 reports a plot of r vs. J_c . It is apparent that a correlation exists between the microwave and dc parameters. This fact is even more striking taking into account that the microwave measurements are performed firmly in the linear regime, while J_c is inherently a nonlinear property. Obviously, the reason for the correlation resides in the common origin -pinning- of both properties. Nevertheless, correlation over two decades in J_c is a remarkable feature.

As a final consideration, we recall that fluxon dynamics is a complex field: a qualitative assessment of the properties of a superconducting material can be performed in the high-frequency, linear regime measurements, but the final check on the finite assembly will require dc measurements.

IV. CONCLUSIONS

Microwave measurements in a moderate dc magnetic field can be a useful tool to assess the quality of laboratory-scale samples during the path for optimization of the pinning properties of superconductors. By exploiting the features of the physical processes, we have shown that weak-links can be easily detected on the basis of qualitative field-dependences of the losses, and we have reported sample measurements where weak-links show up. In samples without weak-links, we have shown that measurement of the complex resistivity yield the pinning-related parameter, the r ratio. We have experimentally shown that r is directly correlated to the critical current density J_c . Thus, when a nondestructive, contactless evaluation of the properties of a superconducting material is required, measurements at microwave frequencies can be performed.

ACKNOWLEDGMENTS

We acknowledge support from EURATOM. N.P. acknowledges support from Regione Lazio. We thank G. Celentano, A. Augieri, V. Galluzzi at ENEA-Frascati for the YBCO samples and for useful discussions.

REFERENCES

- [1] W.H. Fietz, R. Heller, S.I. Schlachter, W. Goldacker, "Application of high temperature superconductors for fusion", *Fusion Eng. Des.*, vol. 86, 2011, pp. 1365-1368.
- [2] H. Schneidewind, M. Manzel, G. Bruchlos and K. Kirsch, "TlBaCaCuO-(2212) thin films on lanthanum aluminate and sapphire substrates for microwave filters", *Supercond. Sci. Technol.*, vol. 14 no. 4, pp. 200-212.
- [3] SuperPower, inc., www.superpower-inc.com
- [4] AMSC, www.amsc.com
- [5] B. Maiorov, S. A. Bailly, H. Zhou, O. Ugurlu, J. A. Kennison, P. C. Dowden, T. G. Holesinger, S. R. Foltyn, and L. Civale, "Synergetic combination of different types of defect to optimize pinning landscape using BaZrO₃-doped YBa₂Cu₃O₇", *Nature Mater.*, vol. 8, 2009, pp. 398-404.
- [6] A. Augieri, V. Galluzzi, G. Celentano, A. Armenio Angrisani, A. Mancini, A. Rufoloni, A. Vannozi, E. Silva, N. Pompeo, T. Petrisor, L. Ciontea, U. Gambardella, S. Rubanov, "Transport Property Improvement by Means of BZO Inclusions in PLD Grown YBCO Thin Films", *IEEE Trans. Appl. Supercond.*, vol. 19, 2009, pp. 3399-3402.
- [7] M. Giura, R. Fastampa, R. Marcon, E. Silva, "Effects of the magnetic and thermal history in granular samples of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O: Experimental evidence of a sharp transition into a frozen state at low temperature", *Phys. Rev. B*, vol. 42, 1990, pp. 6228-6232.
- [8] J. Wosik, L. M. Xie, J. Halbritter, R. Chau, J. C. Wolfe, V. Selvamanickam and K. Salama, "Measurements of Surface Resistance of Grain-Aligned Bulk Material as a Function of dc Magnetic Field: Weak Link Study", *IEEE Trans. Appl. Supercond.*, vol. 3, 1992, pp. 1432-1435.
- [9] J. Halbritter, "Granular superconductors and their intrinsic and extrinsic surface impedance", *J. Supercond.*, vol. 8, 1995, pp. 691-695.
- [10] A. Gurevich, "Nonlinear dynamics of vortices in easy flow channels along grain boundaries in superconductors", *Phys. Rev. B*, vol. 65, 2002, art. no. 214531.
- [11] A. Ballarino, G. Montenero, P. Arpaia, "Transformer-based Measurements of Critical Currents in Superconducting Cables: Tutorial 51", *Instrumentation & Measurement*, vol. 17 no. 1, 2014, pp. 49-55.
- [12] J. Gittleman, B. Rosenblum, "Radio-Frequency Resistance in the Mixed State for Subcritical Currents", *Phys. Rev. Lett.*, vol. 16, 1966, pp. 734-736.
- [13] N. Pompeo and E. Silva, "Reliable determination of vortex parameters from measurements of the microwave complex resistivity", *Phys. Rev. B*, vol. 78, 2008, art. no. 094503.
- [14] E. Silva, A. Lezzerini, M. Lanucara, S. Sarti, R. Marcon, "A cavity system for the measurement of the surface resistance at 48 GHz in high-T_c superconductors", *Meas. Sci. Technol.*, vol. 9, 1998, pp. 275-282.
- [15] J.Krupka, "Contactless methods of conductivity and sheet resistance measurement for semiconductors, conductors and superconductors", *Meas. Sci. Technol.*, vol. 24, 2013, art. no. 062001.
- [16] N. Pompeo, K. Torokhtii, E. Silva, "Dielectric resonators for the measurements of the surface impedance of superconducting films", *Meas. Sci. Review*, vol. 14, 2014, pp. 164-170
- [17] M. Golosovsky, M. Tsindlekht, and D. Davidov, "High-frequency vortex dynamics in YBa₂Cu₃O₇", *Supercond. Sci. Technol.*, vol. 9, 1996, pp. 1-15.
- [18] B. W. Hakki, P. D. Coleman, "A dielectric resonator method of measuring inductive capacities in the millimeter range", *IEEE Trans. Microwave Theory Tech.*, 1960, vol. 8, pp. 402-410.
- [19] L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan, V. K. Varadan, "Microwave Electronics: Measurement and Materials Characterization", John Wiley & Sons, Ltd, 2004.
- [20] E. Silva, M. Lanucara, R. Marcon, "The effective surface resistance of superconductor/dielectric/metal structures", *Supercond. Sci. Technol.*, vol. 9, 1996, pp. 934-941.
- [21] J.Mazierska, C.Wilker, "Accuracy Issues in Surface Resistance Measurements of High Temperature Superconductors Using Dielectric Resonators (Corrected)", *IEEE Trans. Appl. Supercond.*, vol.11, 2001, pp. 4140-4147.