

Article

Pinning Energy and Evidence of Granularity in the AC Susceptibility of an $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ Superconducting Film

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Featured Application: This work concerns the study of the granular nature of an $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconducting film, whose expertise can be useful in understanding the temperature and the DC and AC field application ranges of these materials with non-optimized fabrication properties, which are typically found in superconducting wires and power cables.

Abstract: The study of granularity in superconducting films by using AC susceptibility has a crucial role in the development of and improvement in the ReBCO-coated conductors, which are a constantly evolving reality in the modern power applications of superconductivity. Specifically, the study of the granularity is essential because the ReBCO superconducting wires and tapes are far from the regularity of a single crystal while they often present an inter- and intragranular contribution to the critical current density. On the other hand, the AC susceptibility is a key part of the characterization of a granular sample because this technique is very sensitive to the presence of granularity in the superconductors and, moreover, the study of its first harmonic allows for determining pivotal properties such as the pinning energy as well as the dissipation processes acting in the sample. The pinning energy values and the granularity of an YBCO thin film have been studied by means of AC susceptibility measurements as a function of the AC amplitude, temperature, and DC field. In particular, the first harmonic imaginary component of the AC susceptibility χ''_1 related to the dissipation processes of the sample has been studied. First, starting from the Brandt approach, the critical current density J_c and the pinning energy U of the sample have been extracted at 77 K by using the χ''_1 measurements as a function of the AC amplitude at different AC frequencies and DC fields. From these measurements, a first signal of granularity appears. In order to confirm it, the temperature dependence of the χ''_1 at different DC fields has been studied and a contribution deriving from the inter- and intragranular part of the sample has emerged. By taking the temperature corresponding to the crossover between the two contributions at the different DC fields, the intergranular and intragranular response has been separated. Successively, the temperature has been fixed to 77 K, together with an AC frequency equal to 1597.9 Hz, and the χ''_1 as a function of the DC field at different AC amplitudes has been analyzed showing a clear presence of granularity in all the curves. By drawing the contour plot of the χ''_1 with the DC and AC values, it was possible to determine the best parameters to put at 77 K in order to exploit the material for applications.

Keywords: AC susceptibility; magnetic measurements and characterization; pinning energy; critical current density; granularity; inter-grain and intra-grain contributions; vortex dynamics; high- T_c superconductors; superconducting film; superconductivity and magnetism



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1. Introduction

Since its discovery in 1911 by Kamerlingh Onnes [1], the phenomenon of superconductivity has undergone an intense theoretical and experimental investigation due to its unique characteristics, such as zero electrical resistance and the complete expulsion of the magnetic field from the material when it is cooled below a certain characteristic temperature, which is known as the critical temperature. The discovery of high- T_c superconductors in 1986 by Bednorz and Müller [2] was a paradigm shift, revealing materials that conduct electricity without resistance at temperatures significantly higher than the previously known superconductors. This discovery has expanded our understanding of quantum physics and revolutionized the development of superconductive applications. In fact, the major part of the high- T_c superconductors is characterized by their ability to exhibit superconductivity at temperatures above the boiling point of liquid nitrogen [3,4], making them more practical for real-world applications compared to their low-temperature counterparts. On the other hand, the BCS theory [5] governing the low-temperature superconductors is not applicable to the high- T_c ones. Despite the significant advancements, the mechanism behind high- T_c superconductivity remains one of the most intriguing puzzles in condensed matter physics. The cuprates family is the most well-known class of high- T_c superconductors, with critical temperatures reaching up to 135 K [6]. Among the cuprates, YBCO (Yttrium Barium Copper Oxide) is one of the most studied cuprate compounds and it is historically considered the first compound to become superconducting above the boiling point of liquid nitrogen (77 °K), at about 92 °K [7]. This remarkable property opened the door to potential various technological applications, such as clean energy area power applications [8,9], Magnetic Levitation Trains (Maglev) [10,11], the Superconducting Quantum Interference Device (SQUID) [12], Magnetic Resonance Imaging (MRI) [13,14], and Superconducting Power Transmission Cables [15,16]. More recently, superconductors have been essential to the development of quantum computing [17,18]. It is worth noting that in order to use YBCO for the aforementioned applications, samples in the form of coated conductors or thin films are usually exploited [19,20] because of their high critical temperature and high upper critical field [21,22]. In this framework, granularity is a strong performance barrier because the intergranular current density is highly dependent on the adjacent grains' misorientation angle [23]. This implies that even with a moderate misalignment, the angles correspond to a significant reduction in the macroscopic critical current density [24,25]. On the contrary, large-angle boundaries also form excellent Josephson junctions [24]. Moreover, it has been demonstrated that the intergranular current density controls the current transport at low fields, while at fields in the Tesla range, the critical current inside the grains (intragranular) dominates the current transport [24]. So, it is clear that the understanding of the granular structure and its impact on superconductivity is crucial for the development of practical applications that could revolutionize energy systems and electronic devices. This work deals with the AC magnetic response of an YBCO thin film by studying the imaginary component of the AC susceptibility. The choice to perform and measure the AC susceptibility derives from the fact that this technique is very sensitive to the presence of granularity in the superconductors because it can reveal the complex electromagnetic properties of the granular structure of materials [26–35]. In particular, the AC susceptibility has been studied as a function of the AC amplitude $\chi_1''(h_{AC})$, the temperature $\chi_1''(T)$, and the DC magnetic field $\chi_1''(H_{DC})$. From the $\chi_1''(h_{AC})$ curves performed at different AC frequencies and DC fields, the critical current density together with the pinning energy have been obtained, evidencing the first signals of granularity inside the sample. From the $\chi_1''(T)$ and the $\chi_1''(H_{DC})$ curves performed at different DC fields and AC amplitudes, respectively, the granularity has been revealed and, by means of a contour plot of the χ_1'' with the temperature, DC field, and AC amplitudes, the inter- and intragranular regions have been highlighted and separated.

2. Materials and Methods

The film was grown by Pulsed Laser Deposition (PLD) on a 5 mm × 5 mm SrTiO₃ (STO) single-crystal substrate using a KrF excimer laser with a 248 nm wavelength with a pulse duration of 30 ns, repetition rate of 3 Hz, laser energy density of 1.5 J/cm², laser energy of 266 mJ, and target–substrate distance of 5 cm, with the laser having a scanning beam. The system has a multi-target carousel; the two targets used for this sample being YBa₂Cu₃O_{7-x} doped with 4% at. BaZrO₃ (YBCO/BZO) and metallic Ag. The substrate temperature was 800 °C and the oxygen partial pressure during deposition was 450 mTorr. After the deposition, the film was cooled down in a partial oxygen atmosphere of 450 Torr at the rate of 8 °C/min. The sample is a 4 µm thick bi-layer, with Ag nano-islands decorating the substrate and with the same architecture of the Ag nano-islands between the two YBCO/BZO layers. Silver nano-islands on the substrate and in the quasi-layer were grown by 15 laser pulses at 400 °C in vacuum. The AC magnetic susceptibility was measured using a Quantum Design PPMS-9 T equipped with an ACMS option. In particular, the AC susceptibility measurements as a function of an applied AC field were performed at T = 77 K, with the H_{DC} ranging from 0 T up to 9 T, AC amplitude h_{AC} up to 12 Oe, and AC field frequency ν between 177 Hz and 9997 Hz. Concerning the AC susceptibility measurements as a function of temperature, they were performed by applying the magnetic fields parallel to the c crystal axis at a fixed AC amplitude h_{AC} = 10 Oe and AC frequency ν = 508.94 Hz, both with and without a DC field applied parallel to the AC one and ranging from 0 T up to 9 T. To avoid any possible effects on the sample response [36], the residual trapped field inside the PPMS DC magnet was reduced below 3 × 10^{−4} T before each measurement, according to the protocol described in a previous paper [37]. After that, the sample was cooled to 10 K in the absence of a magnetic field and allowed to stabilize thermally for at least half an hour in order to reach thermal equilibrium. Subsequently, the fields were activated, and information was gathered at a sweep rate of 0.1 K min^{−1} for temperature increases reaching 100 K. In conclusion, an analysis of the AC susceptibility at T = 77 K was conducted, considering varying AC field amplitudes (h_{AC} = 0.5, 1, 2, 4, 8, and 12 Oe) and a constant frequency of ν = 1597.9 Hz. Specifically, the sample was thermally stabilized and cooled to 77 K in the zero field. Following the fields' activation, the data were collected using a DC field increment of 0.05 T within the range of 0 T to 9 T.

3. Results and Discussion

3.1. AC Susceptibility as a Function of AC Field Amplitude: $\chi''_1(h_{AC})$

We want to determine the pinning potential U values of the sample. It is known that there are several methods to accomplish this task: One of them is by performing DC relaxation measurements, which consist of measuring the DC magnetization as a function of time at a fixed temperature and DC field [38]. In particular, by taking the slope of the normalized magnetization as a function of the natural logarithm of time, it is possible to directly obtain the creep rate and thus the pinning energy values [39]. Another method to determine the pinning potential values is by considering the slope of the Arrhenius plots, which allows for directly determining the pinning potential values as a function of the DC and AC fields [40]. Another way to find the pinning potential in superconducting materials by means of AC measurements is to measure the frequency-dependent out-of-phase (imaginary) AC susceptibility χ''_1 as a function of the AC field amplitude h_{AC} at fixed temperatures and fixed DC fields [41,42]. The critical current density of the sample can be correlated with the $\chi''_1(h_{AC})$ dependence at a given temperature for different H_{DC} values. This dependence may show a peak in the experimental window of measurements at a given temperature, with its position h* representing the AC field of full penetration of the perturbation in the center of the sample [43]. We are going to use this last method in order to obtain the pinning potential values as a function of the DC field at a fixed temperature equal to 77 K, which is of particular interest in the framework of the power application of superconductivity. In Figure 1, at H_{DC} = 0 T, $\chi''_1(h_{AC})$ shows an evident peak at all the AC frequencies ascribable to the full penetration of the AC field in the center of the sample.

Then, it is clear that by increasing the DC field (up to 2 Tesla), there is a disappearance of the peak, which would induce one to think that the χ_1'' values are going toward zero with the increasing in the DC field due to the transition of the sample to the normal state. On the contrary, by further increasing the DC field, the χ_1'' values start to increase again with h_{AC} .

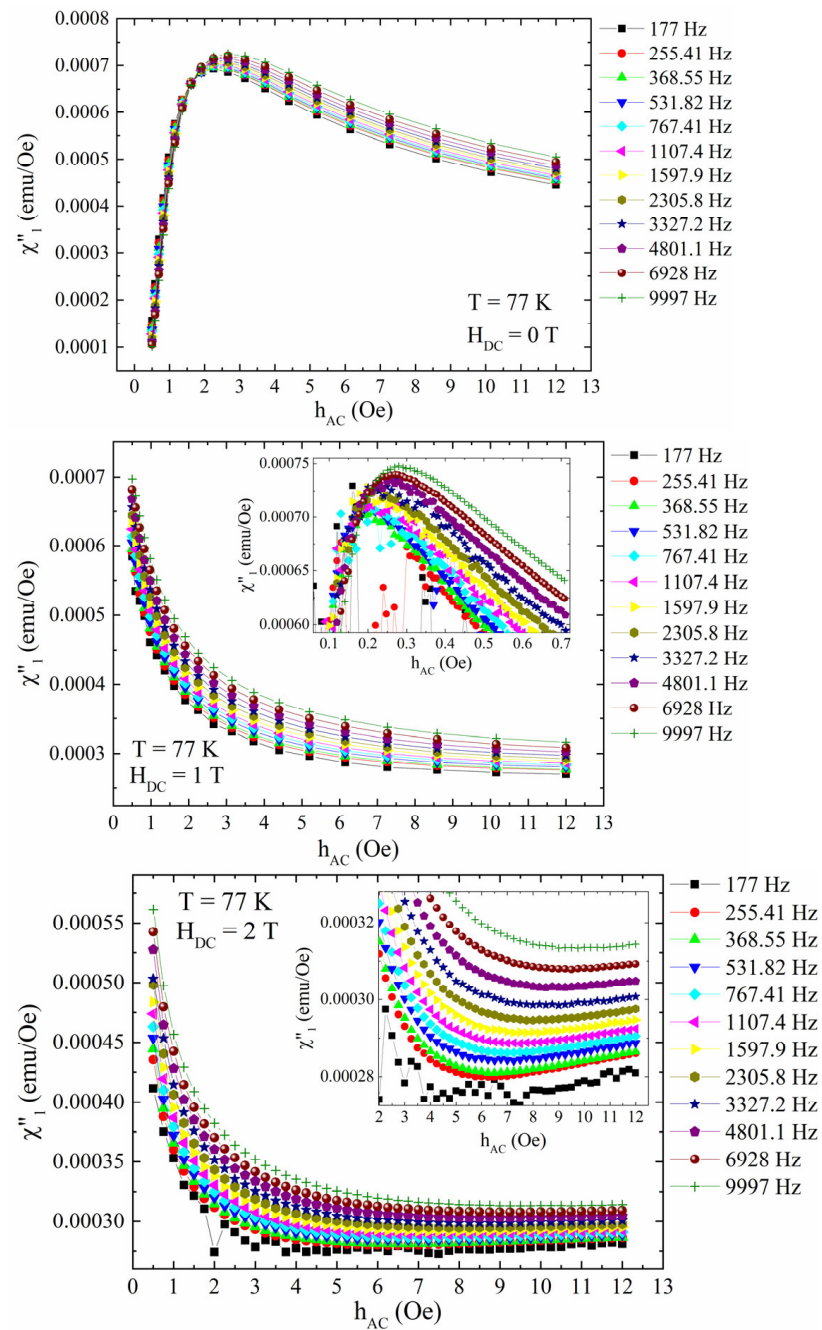


Figure 1. Cont.

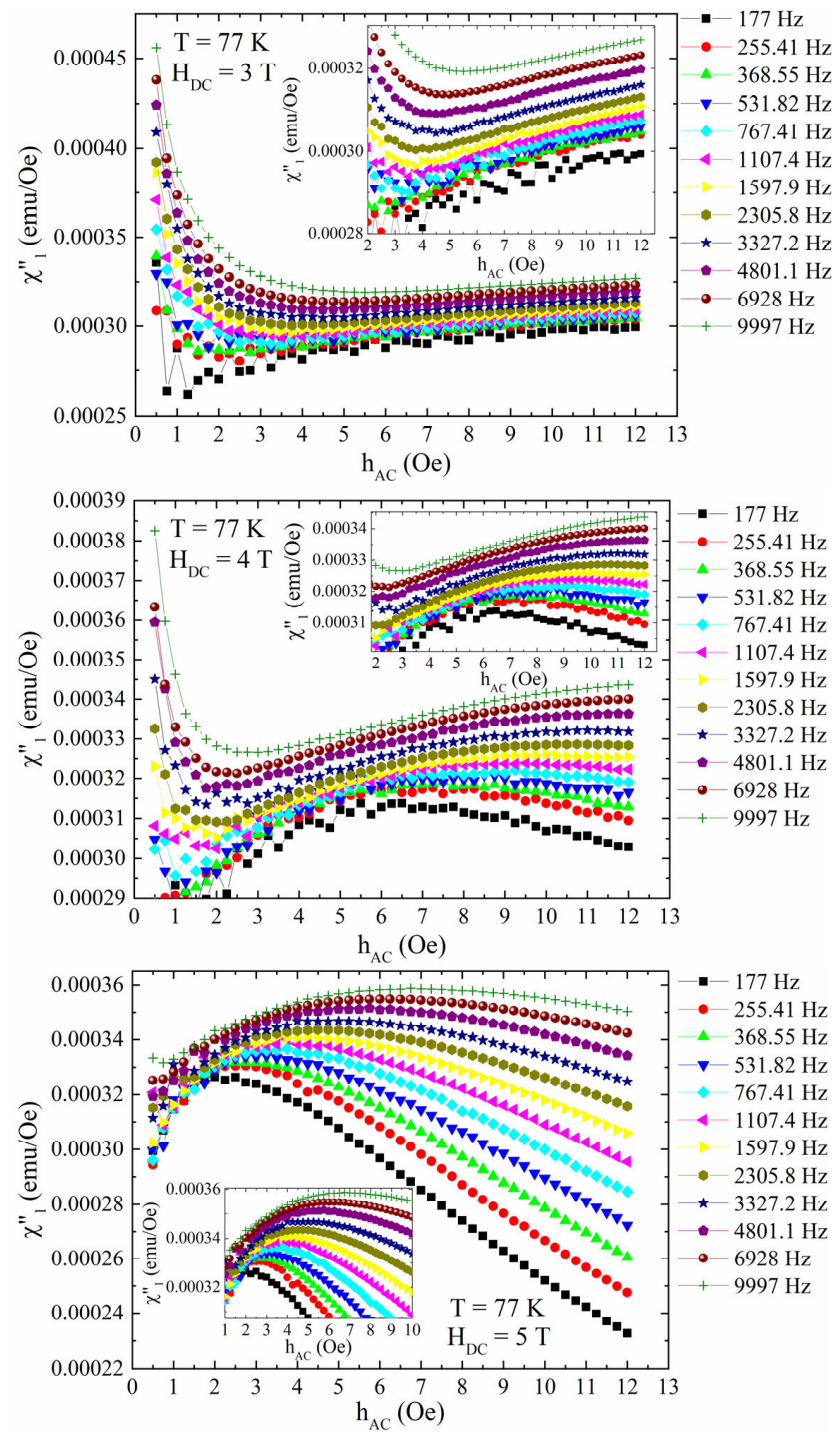


Figure 1. Cont.

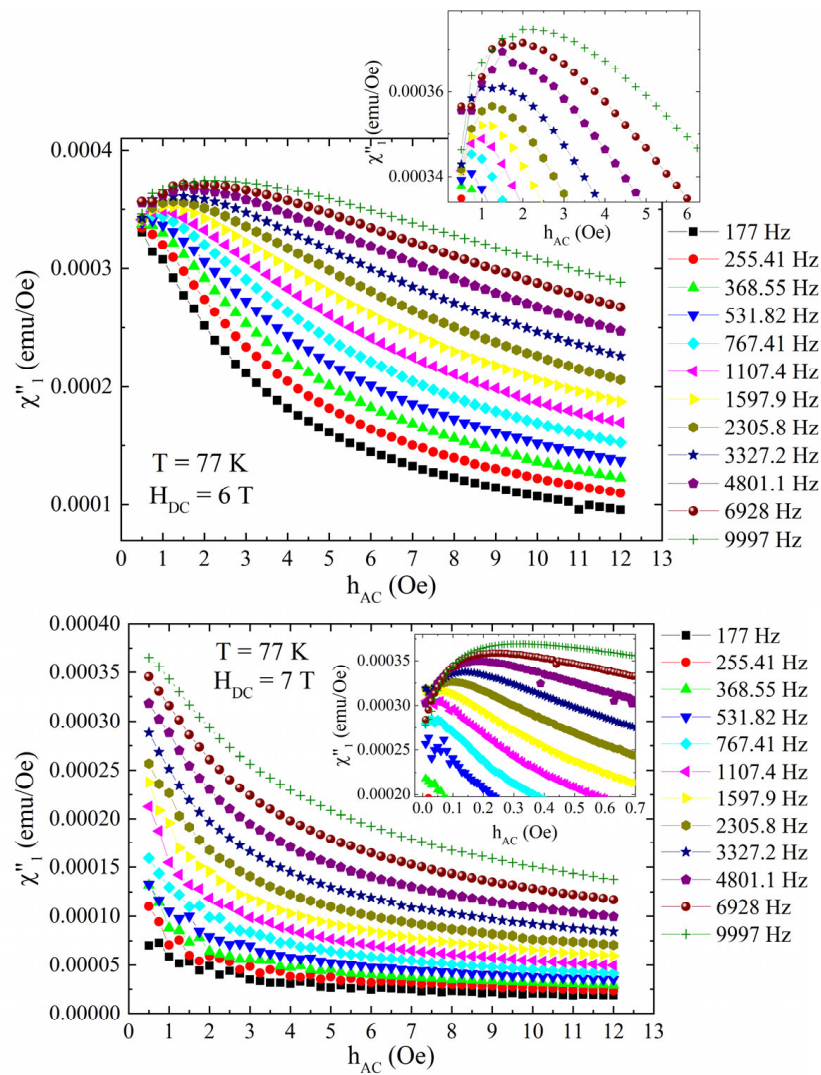


Figure 1. χ''_1 as a function of the AC field amplitude at $T = 77$ K for different DC fields and AC field frequencies.

This could be due to a granular conformation of the sample and therefore to inter-grain and intra-grain contributions to the whole signal [44–46]. In particular, the first peak at low DC fields, which quickly disappears, is associated with the inter-grain link among the grains, while the second peak, which develops at higher DC fields, can be ascribed to the contribution deriving from the single grains. We will look at this in more detail in the next subsections. Now, even after the discovery of the granularity in the sample, we want to focus on the possibility of extracting the pinning energy values starting from the curves of Figure 1 and, in particular, by taking the h^* values at the different AC frequencies and DC fields. Because the thickness of our sample is much smaller than the other two dimensions, it is possible to use the Brandt approach [47], which links the location of the maximum h^* in the $\chi''_1(h_{AC})$ dependency to the critical current density:

$$J_c = h^* / \gamma d \quad (1)$$

where $\gamma \approx 0.9$ is a coefficient that varies slightly with the geometry and d is the thickness of the sample equal to 4 μm . So, the critical current densities at different frequencies, at 77 K, and in multiple DC applied fields have been estimated from the h^* . The dependence of J_c (in logarithmic scale) on $\ln(f_0/f)$ is displayed in Figure 2, where f_0 is the macroscopic attempt frequency, which is approximately 10^6 Hz. It is worth noting that the J_c values

decrease up to 3 T, while an increase in J_c is observed with further increasing the magnetic field. This can be associated with the intergranular and intragranular contributions already noted in Figure 1, respectively. The behavior of the experimental dependence of J_c as a function of $\ln(f_0/f)$ provides insight into the suitability of different pinning models [42]: the Anderson–Kim model of pinning is represented by a downward curvature [48], the collective pinning model is represented by an upward curvature [49], and the suitability of a logarithmic dependence of the pinning potential on the current density is indicated by a straight line [50], which is the case with our data. For the latter case, as was shown in ref. [42], the pinning potentials for each DC applied field, $U_0 = k_B T(1 + 1/b)$, can be estimated thanks to the slope b of the straight lines in Figure 2.

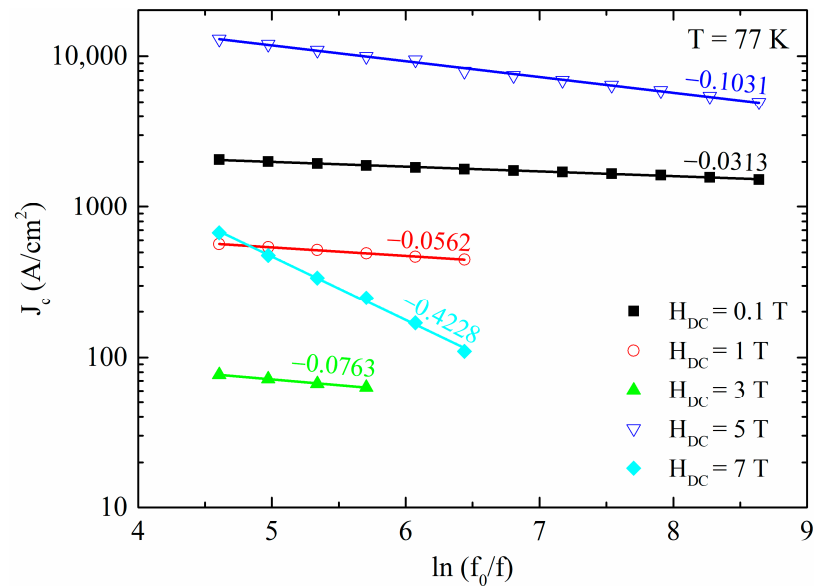


Figure 2. Critical current density as a function of frequency at 77 K at different DC fields. The slopes of the linear fits (their values are reported on the fitting lines) allow for estimating the values of the pinning potential U .

The obtained values of U_0 in K ($k_B = 1$) as a function of the DC field are displayed in Figure 3. It is interesting to note that the two different behaviors of the pinning energy as the field are increased: up to about 4 Tesla, the slope of the U values is low and constant, but as the field further increases, the pinning energy values show a strong decreasing trend. Moreover, the $U(H_{DC})$ curve can be fitted by the power law $U(H) \propto H^{-\alpha}$ where the vortex pinning regime operating in the sample is indicated by the exponent α . Specifically, for a value of $\alpha \approx 0$, we are considering a single vortex pinning regime [49], while for $\alpha > 0.5$, we are in a collective pinning regime [51]. In our case, we have $\alpha = 0.25$ for $0 \text{ T} < H \leq 4 \text{ T}$, indicating a single vortex pinning regime with a very low vortex interaction. For $H > 4 \text{ T}$, α shows a much larger value equal to 3.6, indicating a collective pinning regime with very strong vortex interactions. This is in agreement with the inter- and intragranular hypothesis because, for lower magnetic fields, the interaction among the vortices is low (single vortex) because the number of vortices that can be accommodated in the normal links among the grains is low as well as their interaction, because each vortex is pinned by a defect. For higher fields, the number of vortices increases, forming bundles of vortices predicted in the collective pinning theory [49]. In this case, their interaction is much higher than the single vortex state and, together with the high values of the magnetic field, leads to a fast decrease in the pinning energy as evidenced in Figure 3.

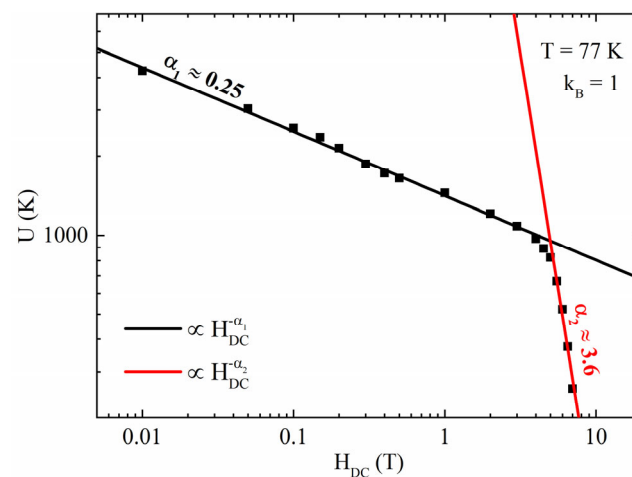


Figure 3. Pinning energy as a function of DC field at 77 K. Solid lines indicate a power law fit $U(H) \propto H^{-\alpha}$. Fit details and results are reported in the text.

3.2. AC Susceptibility as a Function of Temperature: $\chi_1''(T)$

Until now, the sample granularity has just been assumed by looking at the $\chi_1''(h_{AC})$ and J_c behaviors. If this hypothesis is true, we expect to find evidence of granularity in the $\chi_1''(T)$ and $\chi_1''(H_{DC})$ measurements as well. In Figure 4, the $\chi_1''(T)$ curves at an AC frequency $\nu = 508.94$ Hz, an AC amplitude $h_{AC} = 10$ Oe, and for different DC fields have been reported. The main panel of Figure 4 shows the curves ranging from 10 K to 100 K and it is evident they do not follow the standard behavior predicted by the Bean critical state model [43,52], in which usually the $\chi_1''(T)$ has a single peak associated to the full penetration of the AC field in the center of the sample. From these curves, the granular nature of the samples is visible because the presence of a double peak in the imaginary part of the first harmonic is a known feature of a granular magnetic response [53]. In particular, the peaks visible in the inset of Figure 4 can be associated to the contribution given by the individual grains present in the sample (intragranular contribution), which are electrically disconnected from each other. At lower temperatures, the connections between the neighboring grains become superconducting (intergranular contribution) [53]. Because the intergranular part of the $\chi_1''(T)$ curves is very large, this lets us understand that the connection among the grains is weak. Another indication about the weakness of the grains' connection is the fast disappearance of the intergranular peak with the increase in the superimposed DC field. In the inset of Figure 4, the colored arrows indicate the end of the low-temperature peak and the beginning of the high-temperature one, thus individuating T_g [54], i.e., the temperature that marks the transition from a behavior primarily controlled by the intergranular component caused by currents flowing across the grains to a behavior primarily controlled by the intra-grain component caused by currents flowing only inside the grains. In Figure 5, the contour plot of the χ_1'' with the temperature and DC field is shown. In particular, the T_g values at the different DC fields have been reported together, with T_c estimated by taking the first non-zero value of the $\chi_1''(T)$ curves. Both the T_g and T_c field dependencies can be fitted with the power law $H_{DC}(T) = H_{DC}(T = 0 \text{ K})(1 - T/T^*(H_{DC} = 0))^n$ where $T^*(H_{DC} = 0)$ is the characteristic temperature at zero DC field, and n is the exponent. Specifically, $T_g(0) = 86.27$ K, and $n = 1.63$. On the other hand, $T_c(0) = 88.91$ K, and $n = 1.31$. The red line separates the inter-grain region from the intra-grain one while the black line separates the intra-grain region from the normal state of the material. From the contour plot, it is possible to observe how a major part of the dissipation processes occur in the inter-grain region. It is worth noting that from an electric transport point of view, the intergranular region is preferable because the grains are in contact each other and the current is favored to flow inside the grain junctions instead of flowing inside the single grains.

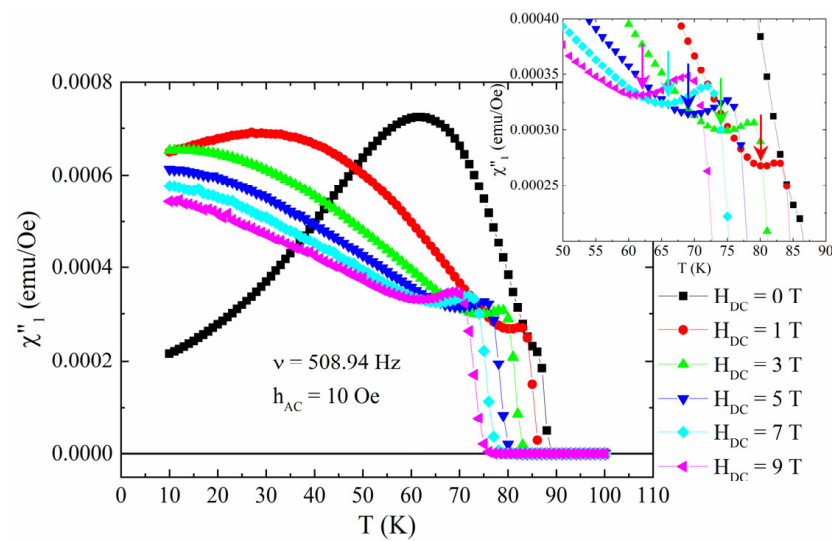


Figure 4. χ''_1 as a function of the temperature at different DC fields, fixed frequency $\nu = 508.94$ Hz, and AC amplitude $h_{AC} = 10$ Oe. Inset: the arrows indicate the local minimum of the curves corresponding to the crossover between the inter-grain and intra-grain contributions.

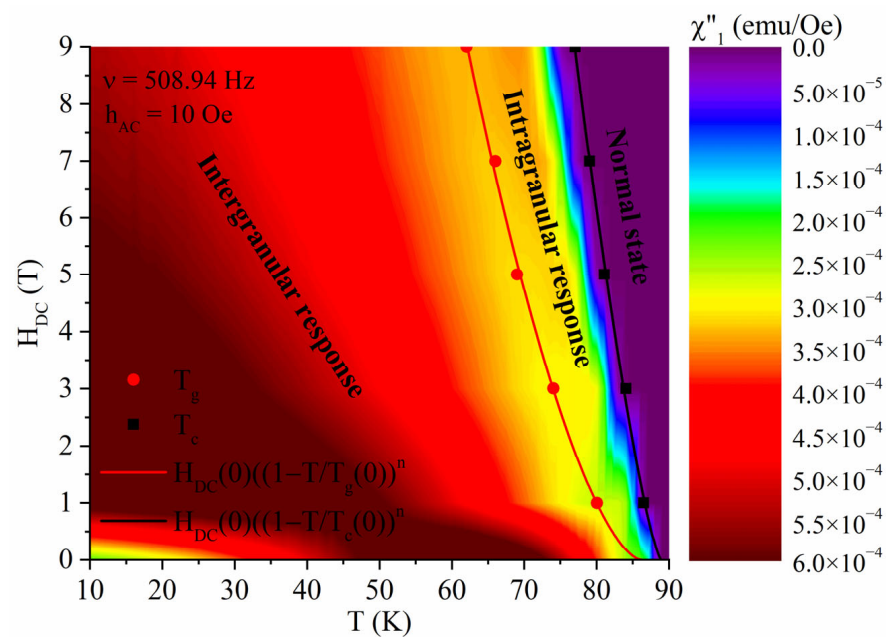


Figure 5. The contour plot of the χ''_1 with the temperature and DC field shows the intergranular and intragranular regions. At this AC frequency and amplitude, the intergranular contribution is much more active than the intragranular one.

An alternative, good way to identify the inter- and intragranular response and the associated T_g of a sample is by using the fundamental harmonic Cole–Cole plots consisting of plotting the imaginary part of the fundamental harmonic as a function of the real part. As shown in Figure 6, the fundamental harmonic Cole–Cole plots have been plotted at different DC fields for $\nu = 508.94$ Hz and $h_{AC} = 10$ Oe. Especially for $H_{DC} > 1$ T, the presence of a second peak in the χ''_1 vs. χ'_1 behavior can be noted, indicating the presence of granularity in the sample. Looking at the whole curves, each first harmonic Cole–Cole plot is characterized by two dome-shaped curves. The closed symbols correspond to the inter-grain contributions, while the open symbols correspond to the intra-grain contributions.

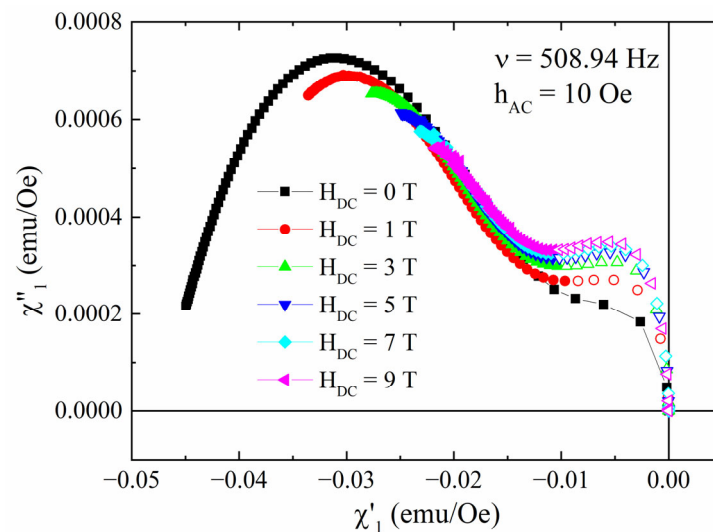


Figure 6. First harmonic Cole–Cole plots at a fixed AC frequency $\nu = 508.94$ Hz and AC amplitude $h_{AC} = 10$ Oe. The two dome-shaped curves evidence the inter-grain (closed symbols) and the intra-grain contributions (open symbols).

3.3. AC Susceptibility as a Function of DC Field: $\chi''_1(H_{DC})$

An interesting approach that can be used to detect the granularity in a sample is to plot the imaginary part of the fundamental harmonic χ''_1 as a function of the DC magnetic field. In the main panel of Figure 7, χ''_1 vs. H_{DC} curves at different AC amplitudes, at a fixed temperature equal to 77 K and fixed frequency equal to 1567.9 Hz, have been reported. The presence of an anomalous trend of the curves is evident because usually these curves are characterized by the presence of a standard dome-shaped curve [33]. In our case, after the anomalous initial decrease in the χ''_1 signal [33] due to the inter-grain contribution, a peak at high DC fields is present for all the reported curves and can be ascribable to the intra-grain contribution. The crossover between the two contributions is identifiable by considering the minimum of the curves as indicated by the colored arrows in the inset of Figure 7.

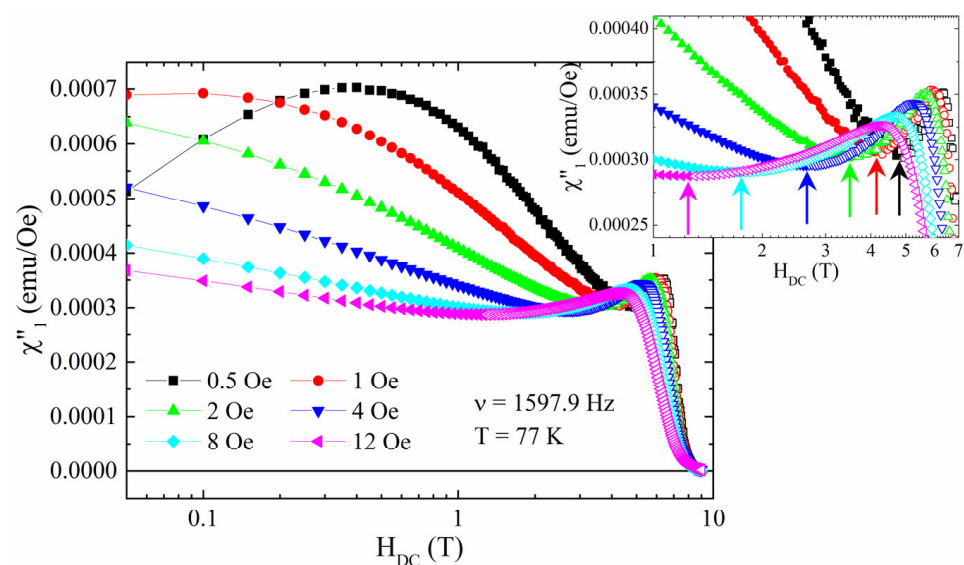


Figure 7. χ''_1 as a function of the DC field at different AC amplitudes, a fixed frequency $\nu = 1597.9$ Hz, and $T = 77$ K plotted on a semi-log field scale. Inset: the arrows indicate the local minimum of the curves corresponding to the crossover between the inter-grain and intra-grain contributions.

The detected points, named H_{DC}^g , are reported as a function of the AC amplitude in the contour plot of the χ_1'' (see Figure 8). The obtained curve can be fitted with the power law $H_{DC}^g(h_{AC}) = H_{DC}^g(0) + bh_{AC}^c$ where $H_{DC}^g(0)$ is the contribution separation when $h_{AC} = 0$ Oe, b is a coefficient, and c is the exponent. Particularly, $H_{DC}^g(0) = 10.4$ T, $b = -6.24$ T/Oe, and $c = 0.16$. In Figure 8, the black solid line separates the intergranular and the intragranular regions in the case of having $T = 77$ K, which can be interesting for different superconducting applications. It is important to note that at 77 K, the intragranular response is dominant, especially at high AC amplitudes, which makes this material interesting for several types of applications, including, among others, energy transmission [55], signal filtering [56], and magnetic confinement fusion [57].

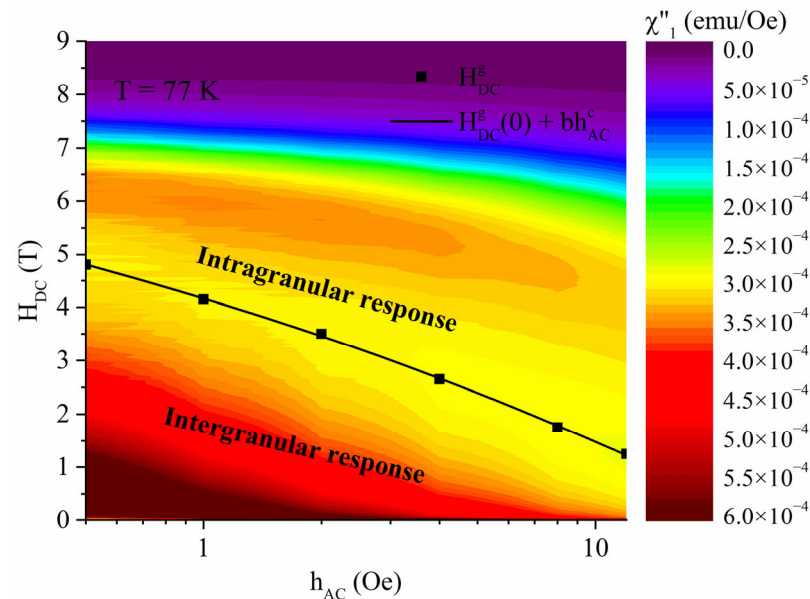


Figure 8. The contour plot of the χ_1'' with the DC field and AC amplitudes is evidence of the intergranular and intragranular regions of the sample. At this temperature, 77 K, and at this AC frequency, the intragranular contribution is much more active than the intergranular one.

4. Conclusions

An YBCO film superconductor has been studied by means of AC susceptibility measurements as a function of the AC amplitude, temperature, and DC field. The first harmonic imaginary component of the AC susceptibility χ_1'' related to the dissipation processes of the sample has been measured initially as a function of the AC amplitude at different AC frequencies, DC fields, and at 77 K in order to obtain the critical current density J_c and, consequently, the pinning energy U values. From these curves, the presence of a double peak with increasing DC fields has been noted, indicating the presence of granularity inside the sample. In particular, the inter-grain link between the grains is responsible for the first peak at low DC fields, which quickly vanishes, while the contribution from individual grains is responsible for the second peak, which forms at higher DC fields. From the position of the peaks, the U values have been extracted and graphed as a function of the DC field, showing a crossover from a single vortex pinning regime to a collective one. After that, the temperature dependence of the χ_1'' at different DC fields has been studied, revealing a double-peak structure correlated with the granularity of the sample. By taking the temperature corresponding to the minimum between the two peaks, a contour plot of the χ_1'' with the temperature and DC field values has been drawn, allowing for separating the inter- and intragranular response of the sample. Finally, the temperature has been fixed to 77 K, in view of the possible applicability of the material for power applications, together with an AC frequency equal to 1597.9 Hz, and the χ_1'' as a function of the DC field at different AC amplitudes has been analyzed. At this temperature, the granularity

is strongly present at all the AC amplitudes even if the intragranular response is wider than the intergranular one. This aspect can be important when the sample is studied by applying a magnetic field instead of probing the sample with transport measurements because the creation of the superconducting currents due to the applied field are favored to form inside the grains rather than among the grains' weak links. This aspect makes this material interesting for several types of applications, such as energy transmission, signal filtering, and magnetic confinement fusion.

Author Contributions: Conceptualization, A.G. and A.C.; methodology, A.G. and A.C.; software, A.G., A.M.I. and A.L.; validation, A.C. and I.I.; formal analysis, A.G. and A.C.; investigation, A.G.; resources, G.G. and M.P.; data curation, A.G., A.C. and A.M.I.; writing—original draft preparation, A.G.; writing—review and editing, A.C., A.M.I., I.I. and A.L.; visualization, A.L., G.G. and M.P.; supervision, G.G. and M.P.; project administration, G.G. and M.P.; funding acquisition, A.C., G.G. and M.P. All authors have read and agreed to the published version of the manuscript.

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References

- Onnes, K. Further experiments with liquid helium. C. On the change of electric resistance of pure metals at very low temperatures etc. IV. The resistance of pure mercury at helium temperatures. *KNAW Proc.* **1911**, *13*, 1274–1276.
- Bednorz, J.G.; Müller, K.A. Possible high T_c superconductivity in the Ba-La-Cu-O system. *Z. Phys. B Condens. Matter* **1986**, *64*, 189–193. [\[CrossRef\]](#)
- Belala, K.; Galluzzi, A.; Mosbah, M.F.; Polichetti, M. Transport and magnetic properties of Bi(Pb)2212 superconducting ceramics doped by low rate of potassium. *Mater. Sci.* **2021**, *39*, 15–23. [\[CrossRef\]](#)
- Menassel, S.; Galluzzi, A.; Boudjadja, Y.; Altintas, S.P.; Terzioglu, C.; Polichetti, M. Investigation of Cr addition effect on structural, morphological, electrical and magnetic properties of Bi(Pb)-2212 superconductors. *J. Mater. Sci. Mater. Electron.* **2023**, *34*, 1145. [\[CrossRef\]](#)
- Bardeen, J.; Cooper, L.N.; Schrieffer, J.R. Theory of superconductivity. *Phys. Rev.* **1957**, *108*, 1175–1204. [\[CrossRef\]](#)
- Brylewski, T.; Przybylski, K.; Morawski, A.; Gajda, D.; Cetner, T.; Chmista, J. Soft-chemistry synthesis of $\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ precursor and characterization of high- T_c $\text{Hg}_{0.8}\text{Pb}_{0.2}\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+\delta}$ superconductor. *J. Adv. Ceram.* **2016**, *5*, 185–196. [\[CrossRef\]](#)
- Wu, M.K.; Ashburn, J.R.; Torng, C.J.; Hor, P.H.; Meng, R.L.; Gao, L.; Huang, Z.J.; Wang, Y.Q.; Chu, C.W. Superconductivity at 93 K in a new mixed-phase Yb-Ba-Cu-O compound system at ambient pressure. *Phys. Rev. Lett.* **1987**, *58*, 908–910. [\[CrossRef\]](#)
- Busmann-Holder, A.; Keller, H. High-temperature superconductors: Underlying physics and applications. *Z. Naturforschung B* **2019**, *75*, 3–14. [\[CrossRef\]](#)
- Hott, R. Application Fields of High-Temperature Superconductors. In *High Temperature Superconductivity 2*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 35–48.
- Jaiaraman, S.; Madhu, S. Research review on magnetic levitation trains. *Int. J. Appl. Eng. Res.* **2015**, *10*, 26808–26814.
- Jacob, A.; Monteiro, N. A new concept of superelevation in magnetic levitation—Prodynamic. *Transp. Syst. Technol.* **2018**, *4*, 77–111. [\[CrossRef\]](#)
- Swithenby, S.J. SQUID magnetometers: Uses in medicine. *Phys. Technol.* **1987**, *18*, 17–24. [\[CrossRef\]](#)
- Wang, Z.; Van Oort, J.M.; Zou, M.X. Development of superconducting magnet for high-field MR systems in China. *Phys. C Supercond. Appl.* **2012**, *482*, 80–86. [\[CrossRef\]](#)
- Cosmus, T.C.; Parizh, M. Advances in whole-body MRI magnets. *IEEE Trans. Appl. Supercond.* **2011**, *21*, 2104–2109. [\[CrossRef\]](#)
- Hassenzahl, W.V.; Hazelton, D.W.; Johnson, B.K.; Komarek, P.; Noe, M.; Reis, C.T. Electric power applications of superconductivity. *Proc. IEEE* **2004**, *92*, 1655–1674. [\[CrossRef\]](#)
- Malozemoff, A.P.; Yuan, J.; Rey, C.M. High-temperature superconducting (HTS) AC cables for power grid applications. In *Superconductors in the Power Grid: Materials and Applications*; Woodhead Publishing: Cambridge, UK, 2015; pp. 133–188; ISBN 9781782420378.

17. Wright, K.; Beck, K.M.; Debnath, S.; Amini, J.M.; Nam, Y.; Grzesiak, N.; Chen, J.S.; Pisenti, N.C.; Chmielewski, M.; Collins, C.; et al. Benchmarking an 11-qubit quantum computer. *Nat. Commun.* **2019**, *10*, 5464. [\[CrossRef\]](#)
18. Huang, H.L.; Wu, D.; Fan, D.; Zhu, X. Superconducting quantum computing: A review. *Sci. China Inf. Sci.* **2020**, *63*, 180501. [\[CrossRef\]](#)
19. Albiss, B.A.; Obaidat, I.M. Applications of YBCO-coated conductors: A focus on the chemical solution deposition method. *J. Mater. Chem.* **2010**, *20*, 1836–1845. [\[CrossRef\]](#)
20. Obradors, X.; Puig, T. Coated conductors for power applications: Materials challenges. *Supercond. Sci. Technol.* **2014**, *27*, 044003. [\[CrossRef\]](#)
21. Awaji, S.; Badel, A.; Okada, T.; Takahashi, K.; Miyazaki, H.; Hanai, S.; Ioka, S.; Fujita, S.; Muto, S.; Iijima, Y.; et al. Robust REBCO Insert Coil for Upgrade of 25 T Cryogen-Free Superconducting Magnet. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 4300105. [\[CrossRef\]](#)
22. Uglietti, D. A review of commercial high temperature superconducting materials for large magnets: From wires and tapes to cables and conductors. *Supercond. Sci. Technol.* **2019**, *32*, 053001. [\[CrossRef\]](#)
23. Tinkham, M.; Lobb, C.J. Physical Properties of the New Superconductors. *Solid State Phys.* **1989**, *42*, 91–134. [\[CrossRef\]](#)
24. Hilgenkamp, H.; Mannhart, J. Grain boundaries in high-Tc superconductors. *Rev. Mod. Phys.* **2002**, *74*, 485–549. [\[CrossRef\]](#)
25. Durrell, J.H.; Rutter, N.A. Importance of low-angle grain boundaries in YBa₂Cu₃O_{7-δ} coated conductors. *Supercond. Sci. Technol.* **2009**, *22*, 013001. [\[CrossRef\]](#)
26. Chen, D.X.; Nogues, J.; Rao, K.V. AC susceptibility and intergranular critical current density of high Tc superconductors. *Cryogenics* **1989**, *29*, 800–808. [\[CrossRef\]](#)
27. Kunold, A.; Hernández, M.; Myszkowski, A.; Cardoso, J.L.; Pereyra, P. AC susceptibility in granular superconductors: Theory and experiment. *Phys. C Supercond. Appl.* **2002**, *370*, 63–70. [\[CrossRef\]](#)
28. Buchkov, K.; Galluzzi, A.; Mancusi, D.; Nazarova, E.; Pace, S.; Polichetti, M. Harmonic AC magnetic susceptibility analysis of FeSe crystals with composite morphology. *Phys. Scr.* **2019**, *94*, 085804. [\[CrossRef\]](#)
29. Mancusi, D.; Galluzzi, A.; Pace, S.; Polichetti, M. Demagnetization harmonic effects on the magnetization of granular systems on a macroscopic scale: The superconducting case. *J. Phys. Condens. Matter* **2017**, *29*, 425701. [\[CrossRef\]](#)
30. Chen, D.X.; Sanchez, A.; Puig, T.; Martinez, L.M.; Muñoz, J.S. AC susceptibility of grains and matrix for high-Tc superconductors. *Phys. C Supercond. Appl.* **1990**, *168*, 652–667. [\[CrossRef\]](#)
31. Hein, R.; Francavilla, T.; Liebenberg, D. *Magnetic Susceptibility of Superconductors and Other Spin Systems*; Hein, R.A., Francavilla, T.L., Liebenberg, D.H., Eds.; Springer: Boston, MA, USA, 1991; ISBN 978-1-4899-2381-3.
32. Carapella, G.; Sabatino, P.; Barone, C.; Pagano, S.; Gombos, M. Current driven transition from Abrikosov-Josephson to Josephson-like vortex in mesoscopic lateral S/S'/S superconducting weak links. *Sci. Rep.* **2016**, *6*, 35694. [\[CrossRef\]](#)
33. Gömöry, F. Characterization of high-temperature superconductors by AC susceptibility measurements. *Supercond. Sci. Technol.* **1997**, *10*, 523–542. [\[CrossRef\]](#)
34. Nikolo, M.; Goldfarb, R.B. Flux creep and activation energies at the grain boundaries of Y-Ba-Cu-O superconductors. *Phys. Rev. B* **1989**, *39*, 6615–6618. [\[CrossRef\]](#)
35. Ishida, T.; Goldfarb, R.B. Fundamental and harmonic susceptibilities of YBa₂Cu₃O₇. *Phys. Rev. B* **1990**, *41*, 8937–8948. [\[CrossRef\]](#)
36. Galluzzi, A.; Nigro, A.; Fittipaldi, R.; Guarino, A.; Pace, S.; Polichetti, M. DC magnetic characterization and pinning analysis on Nd_{1.85}Ce_{0.15}CuO₄ cuprate superconductor. *J. Magn. Magn. Mater.* **2019**, *475*, 125–129. [\[CrossRef\]](#)
37. Galluzzi, A.; Mancusi, D.; Cirillo, C.; Attanasio, C.; Pace, S.; Polichetti, M. Determination of the Transition Temperature of a Weak Ferromagnetic Thin Film by Means of an Evolution of the Method Based on the Arrott Plots. *J. Supercond. Nov. Magn.* **2018**, *31*, 1127–1132. [\[CrossRef\]](#)
38. Yeshurun, Y.; Malozemoff, A.P.; Shaulov, A. Magnetic relaxation in high-temperature superconductors. *Rev. Mod. Phys.* **1996**, *68*, 911–949. [\[CrossRef\]](#)
39. Galluzzi, A.; Leo, A.; Masi, A.; Varsano, F.; Nigro, A.; Grimaldi, G.; Polichetti, M. Magnetic Vortex Phase Diagram for a Non-Optimized CaKFe₄As₄ Superconductor Presenting a Wide Vortex Liquid Region and an Ultra-High Upper Critical Field. *Appl. Sci.* **2023**, *13*, 884. [\[CrossRef\]](#)
40. Galluzzi, A.; Buchkov, K.; Tomov, V.; Nazarova, E.; Leo, A.; Grimaldi, G.; Pace, S.; Polichetti, M. Mixed state properties analysis in AC magnetic field of strong pinning Fe(Se,Te) single crystal. *Supercond. Sci. Technol.* **2020**, *33*, 094006. [\[CrossRef\]](#)
41. Ionescu, A.M.; Ivan, I.; Crisan, D.N.; Galluzzi, A.; Polichetti, M.; Ishida, S.; Iyo, A.; Eisaki, H.; Crisan, A. Pinning potential in highly performant CaKFe₄As₄ superconductor from DC magnetic relaxation and AC multi-frequency susceptibility studies. *Sci. Rep.* **2022**, *12*, 19132. [\[CrossRef\]](#)
42. Ivan, I.; Ionescu, A.M.; Crisan, D.N.; Andrei, A.; Galluzzi, A.; Polichetti, M.; Mosqueira, J.; Crisan, A. Pinning Potential of the Self-Assembled Artificial Pinning Centers in Nanostructured YBa₂Cu₃O_{7-x} Superconducting Films. *Nanomaterials* **2022**, *12*, 1713. [\[CrossRef\]](#)
43. Bean, C.P. Magnetization of High-Field Superconductors. *Rev. Mod. Phys.* **1964**, *36*, 31–39. [\[CrossRef\]](#)
44. Crisan, A.; Iyo, A.; Tanaka, Y.; Hirai, M.; Tokumoto, M.; Ihara, H. Superconducting properties from AC susceptibility and harmonic generation in CuBa₂Ca₃Cu₄O_y bulk superconductors. *Phys. C Supercond. Appl.* **2001**, *353*, 227–240. [\[CrossRef\]](#)
45. Crisan, A.; Iyo, A.; Kito, H.; Tanaka, Y.; Hirai, M.; Sasase, M.; Okayasu, S.; Ihara, H. AC susceptibility and higher harmonics studies of heavy-ion irradiated CuBa₂Ca₃Cu₄O_y bulk superconductor with highest irreversibility field above liquid-nitrogen temperature. *Phys. C Supercond.* **2002**, *378–381*, 112–117. [\[CrossRef\]](#)

46. Weber, H.W. Critical currents in superconductors. In *Proceedings of the 7th International Workshop*; World Scientific: London, UK, 1994; pp. 1–716.
47. Brandt, E.H. Thin superconductors in a perpendicular magnetic ac field: General formulation and strip geometry. *Phys. Rev. B* **1994**, *49*, 9024–9040. [[CrossRef](#)]
48. Anderson, P.W.; Kim, Y.B. Hard superconductivity: Theory of the motion of abrikosov flux lines. *Rev. Mod. Phys.* **1964**, *36*, 39–43. [[CrossRef](#)]
49. Blatter, G.; Feigel'Man, M.V.; Geshkenbein, V.B.; Larkin, A.I.; Vinokur, V.M. Vortices in high-temperature superconductors. *Rev. Mod. Phys.* **1994**, *66*, 1125–1388. [[CrossRef](#)]
50. Zeldov, E.; Amer, N.M.; Koren, G.; Gupta, A.; Gambino, R.J.; McElfresh, M.W. Optical and electrical enhancement of flux creep in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ epitaxial films. *Phys. Rev. Lett.* **1989**, *62*, 3093–3096. [[CrossRef](#)]
51. Yeshurun, Y.; Malozemoff, A.P. Giant flux creep and irreversibility in an Y-Ba-Cu-O crystal: An alternative to the superconducting-glass model. *Phys. Rev. Lett.* **1988**, *60*, 2202–2205. [[CrossRef](#)]
52. Bean, C.P. Magnetization of hard superconductors. *Phys. Rev. Lett.* **1962**, *8*, 250–253. [[CrossRef](#)]
53. Ozogul, O. Investigation of the ac magnetic field dependence of the first and the third harmonics of the ac susceptibility in a granular Bi-2223 sample. *Phys. Status Solidi Appl. Mater. Sci.* **2005**, *202*, 1793–1798. [[CrossRef](#)]
54. Polichetti, M.; Adesso, M.G.; Zola, D.; Luo, J.; Chen, G.F.; Li, Z.; Wang, N.L.; Noce, C.; Pace, S. Granularity and vortex dynamics in $\text{LaFeAsO}_{0.92}\text{F}_{0.08}$ probed by harmonics of the ac magnetic susceptibility. *Phys. Rev. B* **2008**, *78*, 224523. [[CrossRef](#)]
55. Clem, J.R.; Malozemoff, A.P. Theory of ac loss in power transmission cables with second generation high temperature superconductor wires. *Supercond. Sci. Technol.* **2010**, *23*, 034014. [[CrossRef](#)]
56. Mendes, U.C.; Jezouin, S.; Joyez, P.; Reulet, B.; Blais, A.; Portier, F.; Mora, C.; Altimiras, C. Parametric amplification and squeezing with an ac- and dc-voltage biased superconducting junction. *Phys. Rev. Appl.* **2019**, *11*, 034035. [[CrossRef](#)]
57. Bort-Soldevila, N.; Cunill-Subiranas, J.; Sanchez, A. Complete and robust magnetic field confinement by superconductors in fusion magnets. *Sci. Rep.* **2024**, *14*, 3653. [[CrossRef](#)]

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