Glass-Collective Pinning and Flux Creep Dynamics Regimes in $\mathrm{MgB_2}$ Bulk

Daniele Di Gioacchino, Paolo Tripodi, and Jenny Darja Vinko

***Abstract*—Superconducting dynamic response in zero field cooling (ZFC) of $\mathrm{MgB_2}$ bulk has been analyzed using high harmonic ac susceptibility measurements (χ_n). The driving external ac magnetic field is in the frequency range $[107\ \mathrm{Hz} < f < 2070\ \mathrm{Hz}]$, the driving external dc magnetic field is in the range $[0\ \mathrm{T} < \mathrm{H_{dc}} < 5\ \mathrm{T}]$and the temperature has been varied in the range $[15\ \mathrm{K} < \mathrm{T} < 38\ \mathrm{K}]$. These responses are characterized from the critical states that decay in glass states via creep processes. In this analysis different frequency values at fixed $\mathrm{H_{dc}}$ investigate different current levels. This way, different pinning regimes as single vortex, small bundle, large bundle are studied. Using this approach some parts of the $\mathrm{MgB_2}$ three-dimensional phase diagram H-T-J can be described.**

***Index Terms*—Flux pinning regimes, high harmonic magnetic ac susceptibility measurements, magnesium-boron compound.**

I. Introduction

THE flux dynamic response in a superconductor is determined by the extrinsic properties namely by the pinning effects due to quenched disorders present in the material [1]. The statistic sum in the collective weak pinning theory and the creep pinning vortex dynamic are typical tool for the analysis of experimental data. The complexity of analysis is mainly due to a large number of parameters: coherence length ξ that describes the core of the weak pinning potential in a disordered state; inter-vortex distance $\mathrm{a_0}$ leading to the pinned vortex bundle formation; λ defining the flux extension range and the elastic properties of flux lattice; mean thermal displacement $\langle \mathrm{u} \rangle$ of the flux vortex that contributes to the vortex interaction, leading to the flux melting transition and finally to the hysteretic response. The interaction of these scale lengths conducts to the presence of different pinning flux motion regimes [2] resulting in well defined critical current $\mathrm{J_c(B,T)}$ and pinning energy $\mathrm{U_p(BT)}$ dependence. Their presence has also an influence in the different collective creep processes occurring in the flux motion trough the glass parameter μ [3] present in this approach. In the phenomenological tri-dimensional phase B-T-J diagram, the current can be considered the time variable through the relation $\mathrm{J(time)} \approx [\ln(\mathrm{t}/\mathrm{t_0})]^{-1/\mu}$ that probes various pinning regimes. Moreover the ac multi-harmonic susceptibility is powerful and better tool used to study the dynamic response of superconductors. In fact the frequency of exciting magnetic field becomes the time axes in the B-T-J space. At fixed state in the B-T-J diagram the frequency probes the flux dynamics behavior in time.

In this paper we analyze the third harmonic modulus of ac magnetic susceptibility as a function of the applied ac magnetic field frequency, temperature and applied dc magnetic field. These analysis render information on the different vortex dynamic regimes in the Collective-Glass pinning (CG) framework [1], [3]. The E-J non linearity, described by the curvature K, is strictly connected with the ac magnetic susceptibility third harmonic modulus [4]–[6]. We will describe how the superconducting pinning can be classified by single vortex (sv) or small bundle (sb) or even large bundle (lb) as a function of the ac applied magnetic field frequency for fixed dc magnetic field and temperature. The theoretical E-J curvature K(J), in various pinning CG regimes, have been calculated for YBCO because all the involved parameter are well known in respect to the $\mathrm{MgB_2}$. Moreover, the mathematical K(J) slopes for different CG pinning regimes have general validity for superconductor described with CG pinning theory. Finally these slopes will be used to explain the experimental ac magnetic susceptibility third harmonic modulus for a $\mathrm{MgB_2}$ sample.

II. Experimental Set-Up

$\mathrm{MgB_2}$ bulk samples with dimension $(1 \times 2 \times 5.6\ \mathrm{mm^3})$ have been cut from the bar produced by high-pressure reaction sintering method [7], [8]. Zero resistance critical temperature of these samples is about 38 K. High harmonics response has been measured in the LNF-INFN susceptometer with a double pick-up coil, surrounded by the driven coil. The sample is set on sapphire holder which is fitted in the pick-up coil in series and in opposition, one strongly, the other weakly coupled to the sample. The coil assembly is cooled in zero field cooling (ZFC) in a thermally controlled He gas flow cryostat provided with an 8 Tesla superconducting magnet. The ac driving magnetic field frequency range is $61 < \mathrm{f(Hz)} < 2070$ with 6 G amplitude. The induced signal has been measured by multi-harmonic lock-in amplifier. The presented susceptibility data is the result of the subtraction between the signal with sample and without it, for each frequency, ac and dc magnetic field and temperature.

III. Methods

The calculated E-J characteristic is based on the $\mathrm{J_c(B,T)}$ and $\mathrm{U_p(B,T)}$ functions in various pinning regimes as single vortex (sv) in (1), small bundle (sb) in (2) and large bundle (lb) in (3) [2]:

$$J_c^{sv}(B,T) \propto B_{sb} J_c(t_{sb})$$
$$U_p^{sv}(B,T) \propto U_{po}(t_{sb}) \qquad \left(t_{sb} = \frac{T}{T_{dp}^{sb}}\right) \tag{1}$$

Manuscript received October 5, 2004.
D. Di Gioacchino is with the National Institute of Nuclear Physics-National Laboratory of Frascati (INFN-LNF), 00044 Frascati, Italy (e-mail: daniele.digioacchino@lnf.infn.it).
P. Tripodi and J. D. Vinko are with the Hydrogen Energy Research Agency (H.E.R.A.), 00049 Velletri, Italy.
Digital Object Identifier 10.1109/TASC.2005.848861

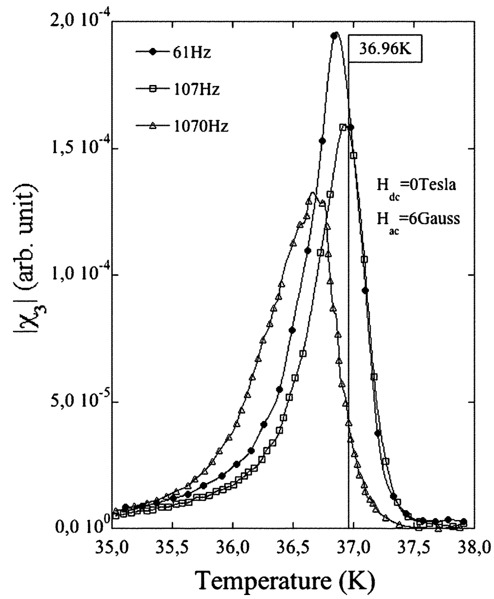

Fig. 1. Modulus of the third harmonic of ac magnetic susceptibility with external dc magnetic field of 0 T and ac magnetic field of 6 Gauss. Fixing the temperature at $T = 36.96$ K it is evident that increasing the frequency of ac magnetic field a decrease of the modulus occurs.

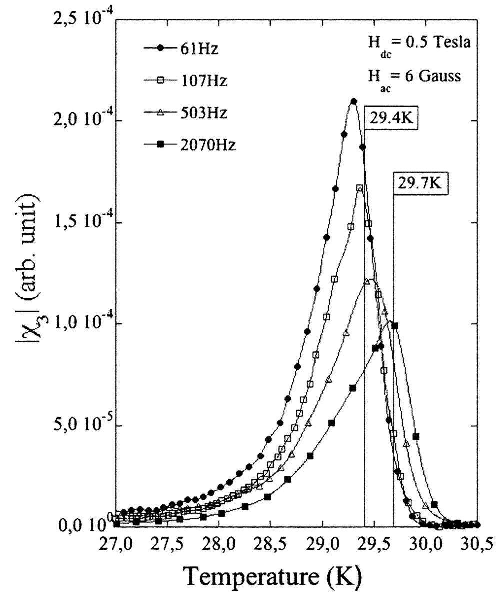

Fig. 2. Modulus of the third harmonic of ac magnetic susceptibility with external dc magnetic field of 0.5 T and ac magnetic field of 6 Gauss. Fixing the temperature at $T = 29.4$ K it is evident that increasing the frequency of ac magnetic field a decrease of the modulus occurs. While at $T = 29.7$ K the contrary occurs.

$$J_c^{sb}(B,T) \propto B \cdot e^{-b_{lb}^{1.5}} J_c(t_{sb}) \qquad \left(b_{lb} = \frac{B}{B_{dp}^{lb}}\right)$$

$$U_p^{sb}(B,T) \propto U_{po}(t_{sb}) \cdot b_{lb} \cdot e^{b_{lb}^{1.5}} \qquad \left(t_{lb} = \frac{T}{T_{dp}^{lb}}\right) \qquad (2)$$

$$J_c^{lb}(B,T) \propto B^{-3} J_c(t_{lb}) \qquad \left(b_{lb} = \frac{B}{B_{dp}^{lb}}\right)$$

$$U_p^{lb}(B,T) \propto b^{\frac{3}{2}} b_{lb}^2 U_p(t_{lb}) \qquad \left(t_{lb} = \frac{T}{T_{dp}^{lb}}\right) \qquad (3)$$

where B_{sb} and B_{lb} with t_{sb} and t_{lb} are the cross-over field and temperature for the vortex pinning regimes.

The characteristic E-J function in the Collective-Glass approach is as follows in (4) [9]:

$$E(J)_{creep} = \rho_{ff} J_c(B,T) e^{\{[-U_p(B,T)/\mu KT][(J_c(B,T)/J)^{\mu}-1]\}} \qquad (4)$$

where ρ_{ff} is the flux-flow resistivity: $\rho_{ff} = \rho_n B/B_{c2}(t)$.

It is evident that the $E^{sv,sb,lb}(J)$ behavior is common for any superconducting material in the given state. The curvature function K of the E-J characteristic is calculated as follows in (5):

$$K = \frac{\frac{d^2E(J)}{dJ^2}}{\left\{1 + \left[\frac{dE(J)}{dJ}\right]^2\right\}^{\frac{3}{2}}} \qquad (5)$$

As previously published [4] the nonlinearity in the E-J characteristic produces a non harmonic signal in the magnetic susceptibility giving rise to the presence of higher harmonics not null in the Fourier Series of the ac magnetic susceptibility. Through the curvature K of the E-J characteristic to describe its non linearity, jointly with the ac magnetic susceptibility modulus of the third harmonic, in the framework of C-G, we describe a way to classify the flux pinning dynamics regimes as a function of dc magnetic field and frequency of the applied ac magnetic field.

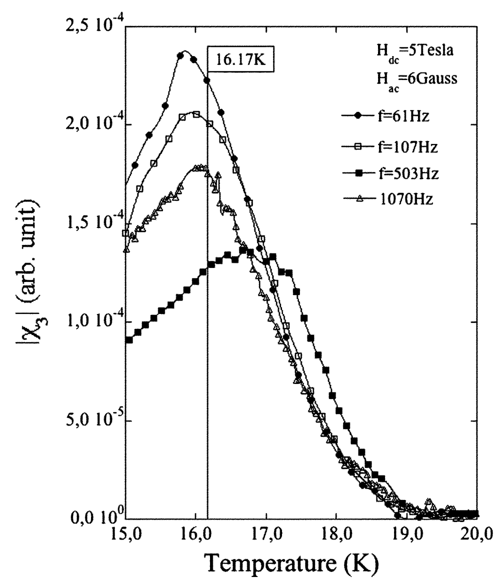

Fig. 3. Modulus of the third harmonic of ac magnetic susceptibility with external dc magnetic field of 5 T and ac magnetic field of 6 Gauss. Fixing the temperature at $T = 16.17$ K it is evident that increasing the frequency of ac magnetic field an increase of the modulus occurs.

IV. Results and Discussions

In Figs. 1, 2, 3 some behaviors of the third harmonic ac susceptibility modulus for an MgB_2 sample are shown as a function of the temperature, external ac magnetic field frequency and external dc magnetic field. The frequency has been varied in the range $[60 < f(\mathrm{Hz}) < 2070]$ while the external dc field was

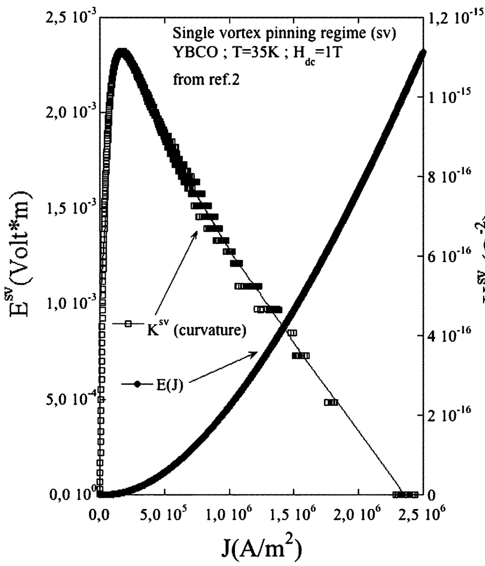

Fig. 4. E-J characteristic of YBCO calculated at $T = 35$ K and $H_{dc} = 1$ T and the correspondent calculated curvature describing the single vortex.

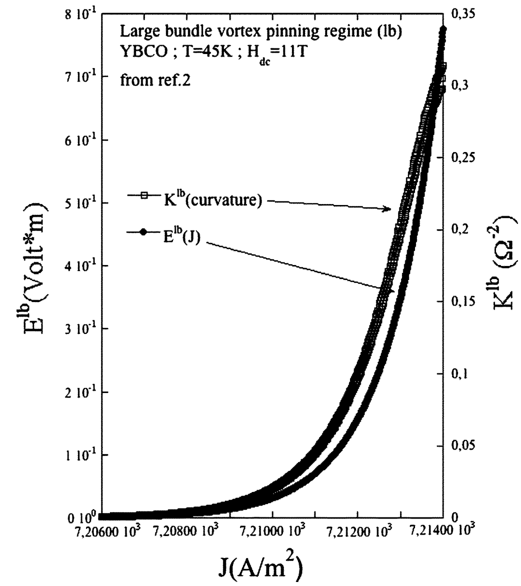

Fig. 6. E-J characteristic of YBCO calculated at $T = 45$ K and $H_{dc} = 11$ T and the correspondent calculated curvature describing the large bundle.

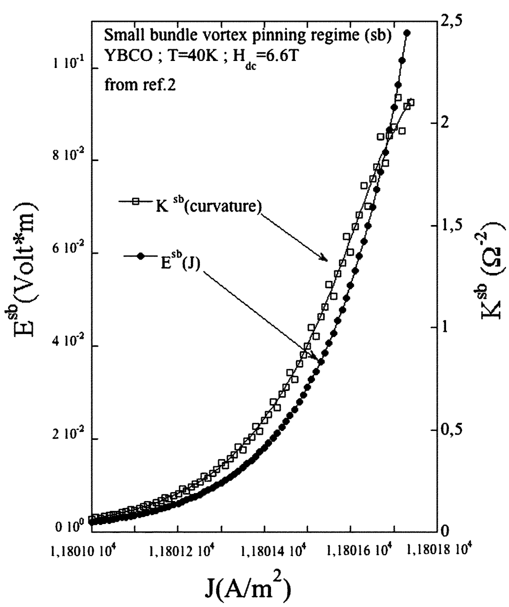

Fig. 5. E-J characteristic of YBCO calculated at $T = 40$ K and $H_{dc} = 6.6$ T and the correspondent calculated curvature describing the small bundle.

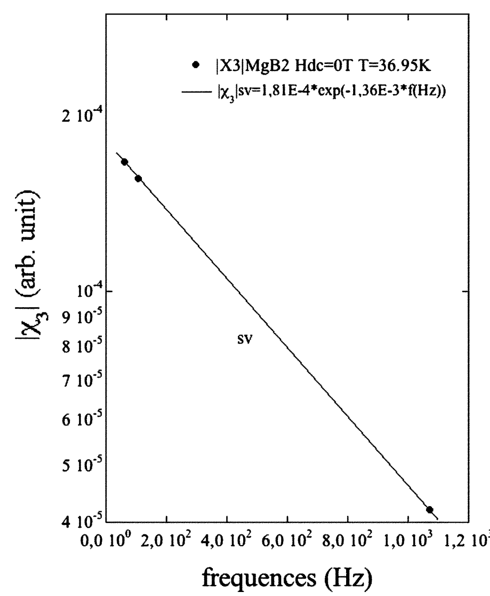

Fig. 7. MgB_2 modulus of ac magnetic susceptibility third harmonic versus frequency at $T = 36.9$ K and $Hdc = 0$ T. The single vortex pinning is present.

set at 0 T, 0.5 T, 5 T. In all three cases the third harmonic modulus shows diverse behaviors in respect to the frequency at fixed temperature. This is due to different electrical current magnitude induced in the sample by the ac magnetic field. In other words, the frequency changes the working point on the set E-J knee characteristic. Well known parameters of YBCO in the given set-up (sv, sb and lb) have been used to calculate and correlate the general behavior of high temperature superconductors, like the dynamic flux process and pinning regimes with the E-J characteristics and corresponding curvatures K, using (4) and (5) for weak collective pinning sv, sb, lb. These E-J characteristics are shown in Figs. 4, 5 and 6. The curvature K in Fig. 4 representing the sv behavior, assumes lower values in respect to the other pinning regimes. The curvature K versus electrical current shows an abrupt increase with the consequent exponential decrease. Analysing Figs. 5 and 6 for sb and lb, the curvature shows significantly higher values with a monotonic exponential increase. In case of sb, the parameter K/J, assumes a value of one order of magnitude higher than the lb. This led us to separate the pinning regime. To apply this classification analysis to our experimental data, arbitrary temperatures have been considered. In Fig. 7 the third harmonic modulus versus frequency at $T = 36.96$ K and $H_{dc} = 0$ T is shown (see Fig. 1). It is evident that increasing the ac magnetic field frequency a decrease of the third harmonic modulus occurs. It is obvious that only sv pinning regime has this kind of behavior (Fig. 4). In Figs. 8 and

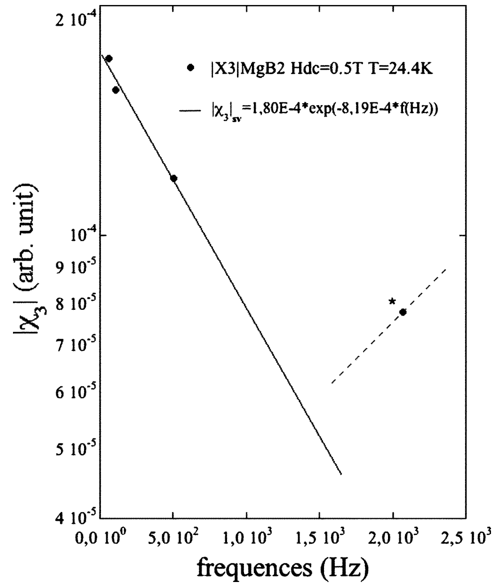

Fig. 8. MgB_2 modulus of ac magnetic susceptibility third harmonic versus frequency at $T = 29.4$ K and $Hdc = 0.5$ T. The transition from single vortex to small bundle pinning is present.

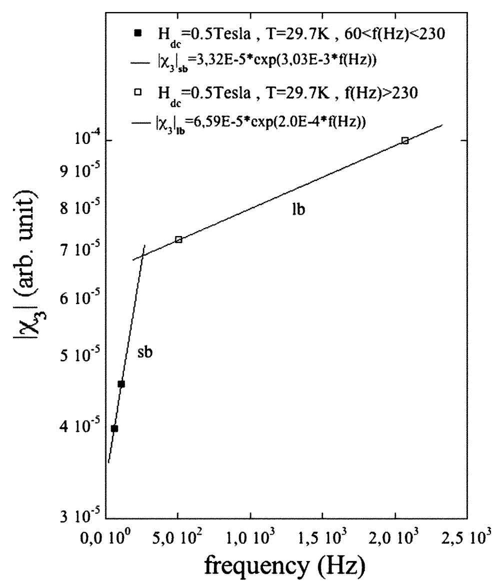

Fig. 9. MgB_2 modulus of ac magnetic susceptibility third harmonic versus frequency at $T = 29.7$ K and $Hdc = 0.5$ T. The transition from small bundle to large bundle pinning is present.

9 the third harmonic modulus versus frequency at $H_{dc} = 0.5$ T for the two temperatures $T = 29.4$ K and $T = 29.7$ K is shown (see Fig. 2). In Fig. 8 a sv regime is evident for frequency in the range [$60 < f(Hz)$ 1000]. The modulus value at 2 KHz is only explicable if the sb flux dynamics regime is present. In Fig. 9 the exponential increase of the third harmonic modulus is shown. This increase changes the slope at $f = 230$ Hz indicating an evident transition between sb and lb since the slope in sb regime is greater than in lb regime as described above. This enhances the previous conjecture that a change of the frequency is able to give rise to a flux dynamic transition. Fig. 10 shows a flux

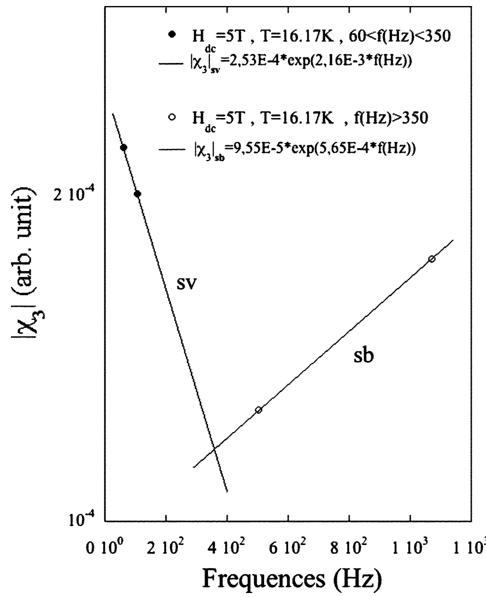

Fig. 10. MgB_2 modulus of ac magnetic susceptibility third harmonic versus frequency at $T = 16.17$ K and $Hdc = 5$ T. The transition from single vortex to small bundle pinning is present.

dynamic transition between sv and sb at $f = 350$ Hz with a different experimental set-up for $H_{dc} = 5$ T.

V. Conclusion

The presented third harmonic ac susceptibility analysis versus external ac magnetic field frequency, is a powerful method to study the flux dynamic regimes in high temperature superconductors around the static working point in the B-T-J space.

References

[1] G. Blatter, M. V. Feigel'man, V. B. Geshknbein, A. I. Larkin, and V. M. Vinokur, "Vortices in high-temperature superconductors," *Rev. Mod. Phys.*, vol. 66, no. 4, pp. 1125–1388, 1994.

[2] ——, "Vortices in high-temperature superconductors," *Rev. Mod. Phys.*., vol. 66, no. 4, pp. 1215–1216, 1994.

[3] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, "Thermal fluctuations, quenched disorder, phase transitions, and transport in type-II superconductors," *Phys. Rev. B*, vol. 43, pp. 130–159, 1991.

[4] D. Di Gioacchino, P. Tripodi, F. Celani, A. M. Testa, and S. Pace, "Frequency dependence of HTS ac harmonic susceptibility in the Kim-Anderson and collective pinning glass models," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, pp. 3924–3927, 2001.

[5] D. Di Gioacchino, F. Celani, P. Tripodi, A. M. Testa, and S. Pace, "Non universal temperature dependences of the low frequency ac magnetic susceptibility in high-Tc superconductors," *Phys. Rev. B*, vol. 59, no. 17, pp. 11 539–11 550, 1999.

[6] D. Di Gioacchino, A. M. Testa, S. Pace, P. Tripodi, and F. Celani, "Field and frequency dependences of ac magnetic measurements as a probe of nonlinear flux diffusion in high-temperature superconductors," *Philos. Mag. B*, vol. 80, no. 5, pp. 997–1001, 2000.

[7] D. Di Gioacchino, U. Gambardella, P. Tripodi, and G. Grimaldi, "Irreversibility line and magnetic field dependence of the critical current in superconducting MgB_2 bulk samples," *Supercond. Sci. Technol.*, vol. 16, pp. 534–537, 2003.

[8] D. Di Gioacchino, P. Tripodi, U. Gambardella, V. Sandu, S. Popa, L. Miu, and D. Vinko, "Third harmonic ac susceptibility measurement in MgB_2 bulk: frequency behavior of IL and 3D glass pinning analysis," *Physica C*, vol. 388–389, pp. 175–176, 2003.

[9] L. F. Cohen and H. J. Jensen, "Open questions in magnetic behaviors of high temperature superconductors," *Rep. Prog. Phys.*, vol. 60, pp. 1602–1608, 1997. See Eq. 3.10.