

# Harmonic susceptibilities and pinning properties of $\text{MgB}_2$ bulk superconductors

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## Abstract

The fundamental and third harmonics of the ac magnetic susceptibility have been studied on  $\text{MgB}_2$  bulk superconductors, obtained by reactive liquid infiltration. In particular, measurements performed as a function of temperature, dc magnetic field, ac field amplitude and frequency have been compared with susceptibility curves obtained by means of numerical simulations of the non-linear diffusion equation for the magnetic field. The experimental frequency dependence of the  $\chi'_1(T)$  and  $|\chi_3|(T)$  peak amplitude cannot be explained by frequency dependent critical state models. On the contrary, we have shown that the measured curves are correctly derived using a diffusion coefficient dominated by a creep process within the framework of the vortex glass approach.

*Key words:* ac susceptibility,  $\text{MgB}_2$ , flux dynamics

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## 1. Introduction

The discovery of superconductivity in magnesium diboride,  $\text{MgB}_2$ , with a critical temperature  $T_c$  close to 39 K, has raised enormous interest in this simple binary system [1]. The intrinsic properties of  $\text{MgB}_2$  make this material very promising for applications, although the rapid decrease of the critical current density  $J_c$  with the magnetic field actually determines a restraint for its potential uses. The study of the pinning properties as well as the vortex dynamic represent therefore a basic means to understand the mechanisms governing the magnetic irreversibility and to overcome the actual limits.

Magnetic measurements using ac fields are recognized as an important tool to check the pinning models [2]. One of the main advantages offered by this ac technique is the possibility to change the effective time

window in which the dynamical phenomena are observed simply by changing the frequency of the driving field. In addition, temperature, dc magnetic field, ac field amplitude can be varied allowing the study of the flux line system in different regimes.

In this paper we present fundamental and third harmonics susceptibility studies on  $\text{MgB}_2$  bulk samples. Measurements are compared with numerical simulations of the magnetic flux diffusion equation in presence of an external ac field [3,4], where the diffusion process is determined by the the residual resistivity due to the vortex motion.

## 2. Experimental results and discussion

The ac susceptibility measurements has been performed on  $\text{MgB}_2$  bulk samples prepared by reactive liquid infiltration [5], whose dimensions are  $20 \times 2.9 \times 0.4 \text{ mm}^3$ . The temperature dependencies of both the fundamental and the third harmonics have been mea-

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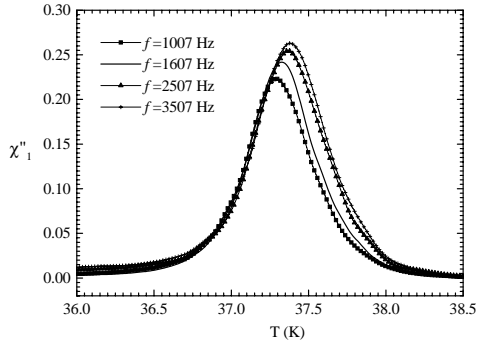


Fig. 1. Temperature dependence of  $\chi''_1$  measured at  $H_{AC} = 4G$  and  $f = 1007, 1607, 2507, 3507$  Hz.

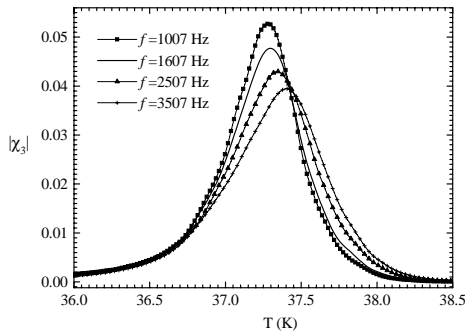


Fig. 2. Temperature dependence of  $|\chi_3|$  measured at  $H_{AC} = 4G$  and  $f = 1007, 1607, 2507, 3507$  Hz.

sured changing the temperature from 4.2 K to 45 K, with a rate  $\Delta T/\Delta t = 0.4$  K/min., using different ac field amplitudes (1, 4, 8, 16 G) in the frequency range 27–3507 Hz, with a dc field  $H_{DC}$  ranging from 0 to 200 G. Both the dc and ac fields are parallel to the length of the sample and it exhibits a quite sharp transition with a  $T_c = 38.8$  K, evaluated by the real part of  $\chi_1$  measured for  $H_{AC} = 1$  G and  $f = 3507$  Hz; the transition width, estimated by the 10%–90% criterion, is about 1 K.

The main feature of the measured  $\chi''_1(T)$  curves reported in Fig.1 is the increase of both the peak temperatures and amplitudes with the frequency. Also in the third harmonic measurements (Fig.2) a pronounced frequency dependence appears. In fact, the experimental data show that not only the position of the peak moves toward higher temperatures, but also its height decreases by increasing the frequency. This is visible also in the curves measured at lower frequencies (from 27 to 1007 Hz), not reported here. The peak shift in temperature is related to the increase of the current induced by an higher ac field frequency and could be explained within a critical state picture by introducing an increasing  $J_c(\omega)$  dependence. Shatz et al.[6] have given

a comprehensive analysis of the harmonic response of a type-II superconductor: in the framework of the critical state description, the ac response is shown to be determined by a single parameter which is the ratio between the full penetration field and the amplitude of the ac field. However, in this picture, the peak heights of the harmonic susceptibilities result to have defined and constant values, also assuming a frequency dependent current density. Since the experimental curves have a clear frequency dependence, the critical state description is not suitable and numerical solutions of the non-linear diffusion equation for the magnetic field are necessary. In particular, by this approach it is clear that the increase of the amplitude of  $\chi''_1(T_p)$  with the frequency is a signal of the reduction of the non-linear behaviour of the I-V characteristic driven by the increased electric field; in fact the predicted value for  $\chi''_1(T_p)$  in the critical state picture is 0.24, whereas for a pure resistance it is 0.42 [3]. Moreover, the reduction of the non-linearity for increasing frequency can be ascribed either to a passage from flux creep to flux flow regime in a Kim-Anderson scenario (with  $U(J) = U_0[1 - J/J_c]$ ) or to a faster decrease of the  $U(J)$  dependence typical of the vortex glass approach. By modelling our samples as an infinite slab in parallel field, we have numerically computed the frequency dependence of the peak amplitude of the third harmonic modulus, both in the framework of the previously described Kim-Anderson model and of the collective pinning vortex glass (CPVG) picture [4,7]. In particular, the CPVG choice corresponds to a dependence of the thermal activation energy  $U$  on the current density in the form  $U(J) = U_0[(J_c/J)^\mu - 1]$ , where  $\mu \in (0, 1)$  is regarded as an universal exponent. The simulated curves within the Kim-Anderson approach show that, in the passage from creep to flow, the peak amplitude of  $|\chi_3|(T)$  first increase than decrease for increasing frequency. On the other side the CPVG simulations well agree with the experimentally found monotonous decrease of the peak amplitude of  $|\chi_3|(T)$  suggesting that the vortex glass scenario might be considered for the understanding of the pinning properties in  $MgB_2$ .

## References

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