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Vortex lattice mobility and effective pinning potentials in the peak effect region in YBCO crystals

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Abstract. The peak effect (PE) in the critical current density in both low and high temperature superconductors has been the subject of a large amount of experimental and theoretical work in the last few/several years. In the case of YBCO, crucial discussions describing a dynamic or a static picture are not settled. In that region of field and temperature the mobility of the vortex lattice (VL) is found to be dependent on the dynamical history. Recently we reported evidence that the VL reorganizes and accesses to robust VL configurations (VLCs) with different effective pinning potential wells arising in response to different system histories. One of the keys to understand the nature of the PE is to investigate the VL behavior in the vicinity of the various VLCs in the region of the PE. The stability of these VLCs was investigated and it was found that they have distinct characteristic relaxation times, which may be related to elastic or plastic creep processes. In this paper we review some of these results and propose a scenario to describe the PE in YBCO crystals

Keywords. Peak effect; YBCO; AC susceptibility.

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1. Introduction

The peak effect (PE) in the critical current density (J_c) in both low and high temperature superconductors has been the subject of intensive experimental and theoretical work in the last decade. The phenomenon refers to a non-monotonous dependence of J_c with both temperature and magnetic field. An anomalous increase is observed above an onset field B_{on} or temperature T_{on}, until J_c reaches a maximum at B_p (or T_p) above which a fast decrease in the measured critical current density occurs, just before reaching either the melting or the upper critical field line.

The origin and nature of these phenomena are still controversial issues. Since the first description of the PE by Larkin and Ovchinnikov [1], a diversity of theoretical pictures have been proposed. The role of dislocations in the vortex lattice (VL) dynamics near the PE particularly was highlighted by Higgins *et al* [2,3]. Alternative scenarios have described the origin of the PE as the manifestation of a first order thermodynamic transition from a quasi ordered Bragg glass to a disordered VL, and recently unified phenomenological descriptions using the Lindemann criterion have been published [4]. Very recently, a purely dynamic picture in the absence of a phase transition has been proposed [5] while other authors [6] claim that a change in the pinning regime is the main ingredient of the VL response in the PE region. Probably, the large collection of proposed models are a consequence of the different nature of the PE in the various materials, as is becoming clear from the increasing amount of experimental evidence.

Interestingly, VL history effects are concurrently observed in the PE region in a wide range of superconducting materials, and are probably closely related to the same kind of phenomena. In fact, in the vicinity of the PE, both the mobility of the VL and the measured $J_{\rm c}$ are found to be dependent of the dynamical history of the sample in both low $T_{\rm c}$ [7,8] and high $T_{\rm c}$ [9–11] materials.

In the particular case of YBCO crystals, the first observations of the PE was made more than 10 years ago [12]. However, at the present time the role of disorder and twins in the occurrence of the PE is controversial, and not completely understood [11,13], and key discussions describing a thermodynamic [14] or a dynamic picture are not settled.

In AC susceptibility experiments, the PE is observed as an anomalous increase in shielding capability or an anomalous decrease in losses also usually interpreted as an anomalous decrease in VL mobility. In recent experiments in YBCO crystals, it was shown that the mobility of the VL increases after assisting the system with a symmetric ac field (or current) [10] with moderate amplitude [15]. On the other hand, when vortices are assisted by an asymmetric ac field, the VL becomes less mobile [10]. This salient feature indicates that these effects cannot be ascribed to an equilibration process, but have their origin in the oscillatory character of the vortex dynamics.

In a recent work [16,17] the solid VL in YBCO single crystals was prepared with different dynamical histories and was explored using a very small AC field to measure AC susceptibility. In that way vortices oscillate inside their effective pinning potential wells without modifying the configuration of the system. Results show that oscillatory dynamical history not only determines the degree of mobility, but also directly modifies the effective pinning potential wells.

Therefore, we have proposed [17,18] as one of the keys to understand these complex phenomena to investigate the VL behavior in the vicinity of the various VL configurations (VLCs) acquired immediately after assisting it with a specific dynamical history in the region of the PE.

In this paper we review some of our recent results [16–19] and propose a scenario to describe the PE in YBCO crystals.

2. Experimental

The samples were twinned $YBa_2Cu_3O_7$ single crystals with $T_{\rm c} \approx 92$ K and $\Delta T_{\rm c} \approx 0.3$ K. AC susceptibility measurements were carried out with the usual mutual inductance technique. The AC field is parallel to the c-axis. The static magnetic field H, provided by an electromagnet, was tilted by $\theta = 20^\circ$ away from the twin planes to avoid the Bose glass phase. The assisting AC field was applied with the primary measuring coil that was fed by a waveform generator to provide different waveforms.

Three different protocols or dynamical histories were followed to obtain the various VLCs. In all cases, the sample is cooled in DC magnetic field avoiding bulk magnetic gradients, but in each protocol the applied assisting AC field has a different waveform. The first case is a DC field cool process without any assisting AC field (zero AC field cooled, $\mathrm{ZF_{AC}}$ C). A less mobile VLC [10], that we call Asy, is obtained assisting the VL with an *asymmetric* (sawtooth) AC field (3.5 Oe at 30 kHz) for 30 sec. once the sample has been DC-field cooled to the destination temperature. The assisting AC field is then turned off and the measurement begins. A more mobile VLC [10], that we call Sy, is obtained applying a *symmetrical* (sinusoidal) AC field (3.5 Oe and 30 kHz) for 30 s. following the complete Asy protocol. The sinusoidal shaking field is turned off and the measurement begins. Linear Campbell regime was measured at an amplitude two orders of magnitude lower (0.04 Oe) and frequency $f = 30$ kHz.

3. Results and discussion

Pinning potentials corresponding to different VLCs were explored measuring the linear real penetration depth λ_{R} in the Campbell regime [20], for small AC field amplitudes. In fact, assisted by large enough ac fields, vortices perform inter-valley motion and the non-linear penetration depth is directly related to the measured critical current density, while for the lower amplitudes, intra-valley motion dominates and the shape of the effective pinning potential well is probed when losses are negligible.

In a general case, the linear AC response is determined by the complex frequency dependent penetration depth $\lambda_{\mathrm{AC}}(f) = \lambda_R + i\lambda_{\mathrm{I}}$ [21]. The function $\chi(\lambda_{\mathrm{AC}})$ depends on the sample geometry. In the particular case of the Campbell regime vortices oscillate inside their effective pinning potential wells without modifying the configuration of the system. The imaginary penetration depth $\lambda_{\mathrm{I}} << \lambda_{\mathrm{R}}$ and dissipation is very small. In this regime, the curvature of the pinning potentials or Labusch constant α_{L} may be estimated by measuring the linear real penetration depth λ_{R}. Moreover, in this limit, the inductive component of the AC susceptibility χ' is only determined by the experimental geometry and a dimensionless parameter λ_{R}/D where D is the characteristic length of the sample

To evaluate the real penetration depth λ_{R} in the Campbell regime, we approximated our experimental geometry by a thin disk of radius R and thickness δ in a transverse AC magnetic field. We used the numerical solution developed by Brandt [22,23], in which χ is determined by the adimensional parameter λ_{AC}/D, where $D = (\delta R/2)^{1/2}$. In the Campbell regime $\lambda_{\mathrm{R}} = (\lambda \mathrm{L}^2 + \lambda_{\mathrm{C}}^2)^{1/2}$, where λ_{L} and $\lambda_{\mathrm{C}} = (\phi_0 B/4\pi\alpha_{\mathrm{L}})^{1/2}$ are the London and Campbell penetration depths respectively and ϕ_0 and B are the flux quantum and the magnetic induction [21]. When the phase $\varepsilon = \lambda_{\mathrm{I}}/\lambda_{\mathrm{R}} << 1$, to first order in ε, we obtain

$$\chi' + i\chi'' = -1 + f(\lambda_{\mathrm{R}}/D) + i\ \varepsilon\ g(\lambda_{\mathrm{R}}/D),$$

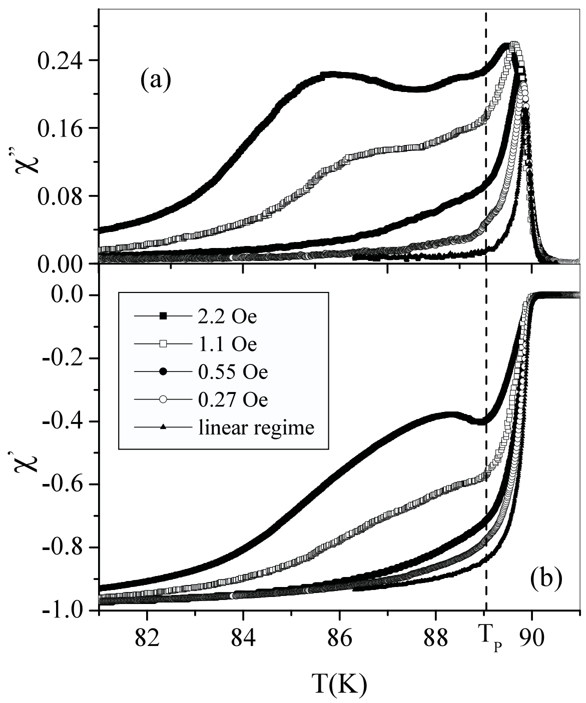

Figure 1. Curves of $\chi''(T)$ (a) and $\chi'(T)$ (b) for various h_{a}. For high amplitudes (squares) a clear PE with a minimum of χ' at the temperature T_{P} (dashed line) is displayed. Below T_{P}, for the lower amplitudes (triangles), a linear Campbell response holds and no PE is observed.

where f and g are functions of the dimensionless variable λ_{R}/D [22,23]. Therefore, in this limit, the inductive component of the AC susceptibility χ' is determined by the experimental geometry and the adimensional parameter λ_{R}/D.

The general behavior of the PE when varying the applied AC field is depicted in figure 1, where curves of $\chi''(T)$ (figure 1a) and $\chi'(T)$ (figure 1b) are shown for various h_a. For high amplitudes a clear PE with a minimum in χ' at the temperature T_{p} is displayed. Below T_{p}, for the lower amplitudes, a Linear Campbell response holds with a very small dissipation. As can be observed, in this regime, no PE is observed. The PE appears in the non linear curves with high dissipation, where vortices perform inter-valley motion and an important influence of thermal creep in the response is expected. This fact has been reported in other works [11], but no explanations were provided. We consider that this is a key factor for the understanding of the nature of peak effect in YBCO crystals.

As was pointed out in the introduction, above the onset of the PE a more disordered (and more pinned) VL is expected. Changes in the number and distribution of dislocations may affect both the static and dynamic properties. However, results of figure 1 indicate that, if there were an increase in the number of dislocations with temperature about the onset of the PE, it would not be reflected in the pinning static properties, but only in the VL dynamics.

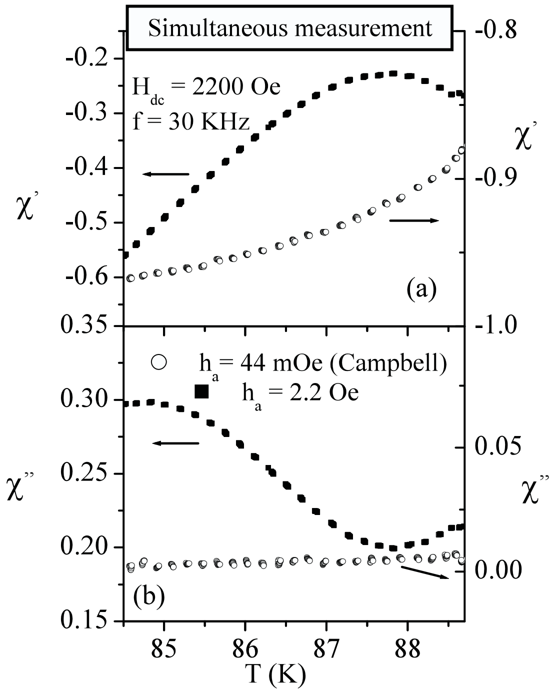

Figure 2. Linear (right axis, hollow circles) and non-linear (left-axis, black squares) curves of $\chi''(T)$ (**a**) and $\chi'(T)$ (**b**) in an unique warming process switching alternatively from high to low measuring h_a. Although the VL is allowed to move at high h_a, the Campbell response does not show any anomaly.

A possible first explanation for the observed behavior could be the nature of the Campbell regime. Vortices remain oscillating around a pinning position and cannot perform large excursions; therefore most of the VLCs are not accessible. To test this possible explanation, we have performed simultaneous measurements in the linear and non-linear regime.

In figure 2, curves for $\chi''(T)$ and $\chi'(T)$ in a unique warming process switching alternatively from high (non-linear) to low (linear) measuring h_a amplitudes, are shown. The PE in the non linear response (left axis in the figure) is shown. Although the VL is allowed to move, the Campbell response (right axis in the figure) does not show any anomaly.

A second possible argument to explain the absence of the PE in the linear response is the fact that measurable changes in the non linear regime could be related to very small changes in the Labusch constant, undetectable with our experimental technique. We rule out this possibility: We have shown [16] that we are able to measure changes in λ_R (i.e. in α_L) that can only have their origin in a different VLC (i.e. a change in the number or distribution of dislocations). In the following we show results of the study of the stability [17] of these different dynamic-modelled VLCs in the region of the PE.

In figure 3 the evolution of λ_{R}/D during a very slow (≈ 2 h) warming–cooling process (W–C) for the different VLCs is shown. In figure 3a the result of a W–C excursion of approximately 1.3 K after preparing the VL in the Sy and Asy VLCs at $T \approx$ 87.3 K are compared. It can be seen that the Sy VLC has an initial fast accommodation and after that it remains reversible for the whole measured temperature range. This initial relaxation is difficult to measure with a good temporal resolution, because of the large lock-in amplifier integration time required to detect such small signals. On the contrary, the more pinned Asy VLC relaxes slowly during the warming process. In figure 3b the Asy evolution is compared with that corresponding to a usual FC ($\mathrm{ZF_{AC}C}$) VLC. The FC VLC is practically reversible, although it seems to slightly relax towards the Sy curve. In fact, all the evolutions seem to get closer to a unique AC penetration depth.

We then performed a series of tests to investigate the nature of such a relaxation. We repeated the same W–C process without applying the small measuring AC field, and obtained the same final state. This is an indication that relaxation is dominated by a thermal activated process, and it is supported by the fact that in an inverse cooling–warming process, beginning at the same temperature, no relaxation is observed. Note that the time scale of this relaxation process is larger than the time-scale of vortex motion in Campbell response, contributing to negligible AC losses at 30 kHz.

As another test to confirm the thermal origin in the relaxation of the Asy VLC, we repeated the same procedure in another temperature range. In figure 4, evolutions of λ_{R}/D in similar W–C excursions are shown. Vertical axis are shifted for clarity, but the scale used in all the panels is the same. In panel (a) the Asy VLC excursion shown in figure 3 is plotted again in a broader temperature range. In panels (b) and (c) the Asy VLC was prepared at a lower temperature. In panel (b) the sample was warmed to $T_{\max} = 87.5$ K and the response is reversible. However, if the same process is carried out up to a higher temperature (panel (c)), the irreversibility reappears.

A possible scenario to explain the above results is the following: plastic vortex creep in a dislocated vortex solid, has been shown to have higher exponents for the power-law divergence of the creep barriers than elastic vortex creep occurring in an elastic medium free of topological defects [3]. A further insight was provided from molecular dynamics simulations that have shown that a temporarily symmetric solicitation promotes a more mobile VLC that is more ordered, i.e. presents a lower density of topological defects, while an asymmetric solicitation promotes a less mobile VLC characterized by a greater number of topological defects or dislocations [24].

On the other hand, Campbell regime is characterized by very small AC losses, probably related to small thermal creep [21]. The characteristic time scale for creep is much larger than the AC field period, and consequently, the VL is observed to slowly adapt to a more stable (or less stressed) VLC with very low losses.

In this framework, the fast initial relaxation in the Sy VLC could be associated to a small elastic creep where vortices only slightly adapt better to the pinning potential without modifying the structure of the VL. In contrast, the slow thermal relaxation in the defective Asy VLC can be due to plastic creep, where the number of dislocations slowly decreases and the system evolves towards a less strained (and

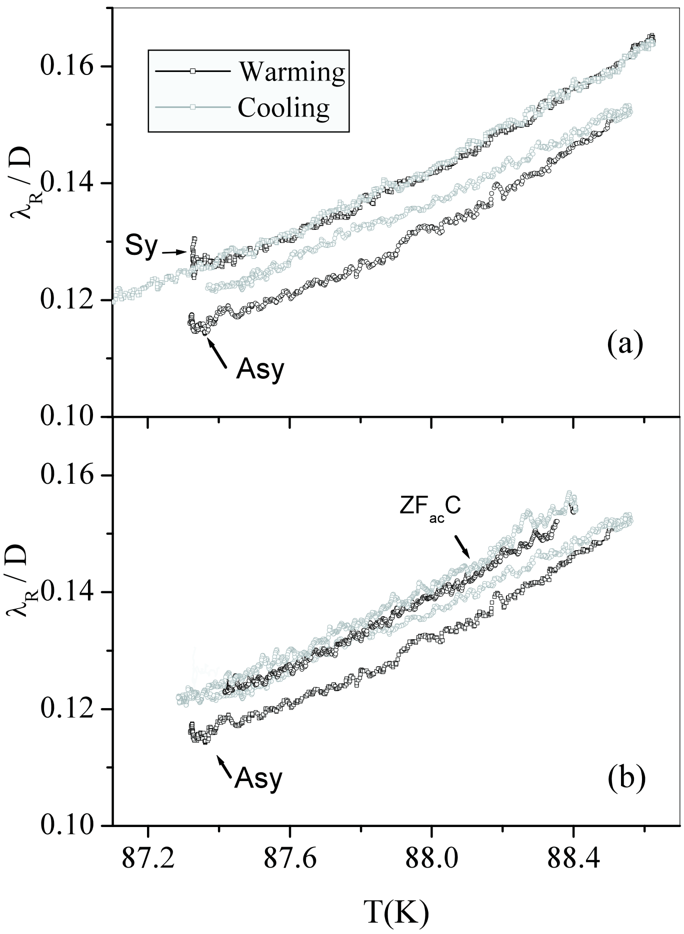

Figure 3. Evolution of λ_{R}/D during a warming (black symbols) followed by a cooling (gray symbols) process, after preparing different VLCs. In (**a**) the evolution of Sy and Asy initial VLCs are shown. The Sy VLC has an initial fast accommodation after which it remains reversible for all the measured temperature range. The more pinned Asy VLC decays during the slow warming process. In (**b**) the evolution for the Asy initial VLC is compared with that corresponding to a $\mathrm{ZF_{AC}C}$ VLC.

less pinned) configuration. It seems that the protocol that creates the Asy VLC promotes more dislocations than the existing number in the stable configuration.

Finally, as a result of thermal annealing, all the prepared VLCs seem to relax to final static VLCs with a degree of pinning similar to the one observed for the Sy VLC. It seems that the protocol creating the Asy VLC, promotes more dislocations than the existing number in the stable configuration even at these high temperatures. A possible scenario is that such a high number of dislocations modifies the correlation volume of the VL. However, the intrinsic increase of dislocations with

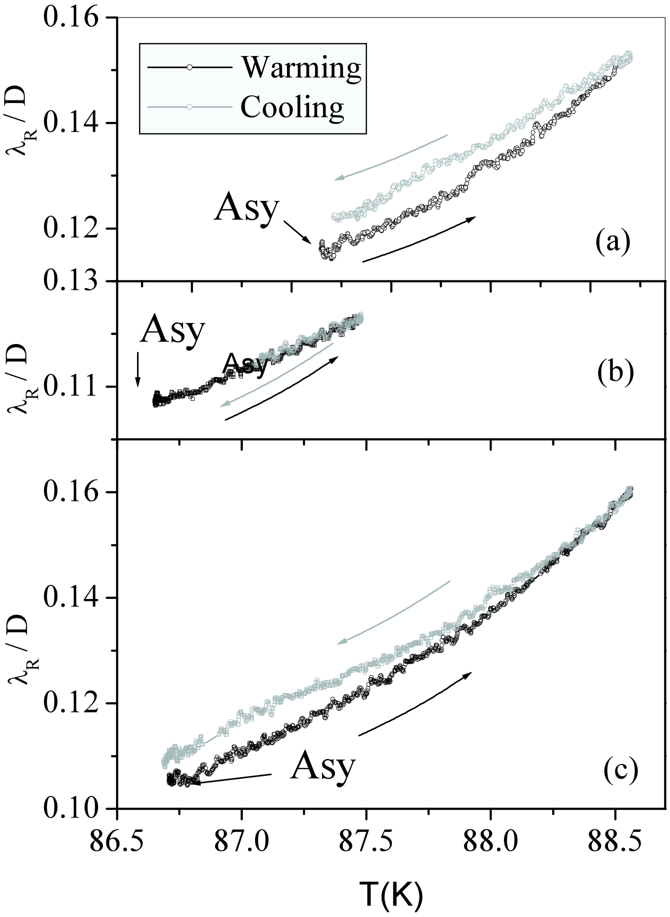

Figure 4. (**a**) Evolution of λ_R/D for the Asy VLC in the same procedure shown in figure 3. (**b**) A similar procedure as in figure 3 but done in a lower temperature range: the response is reversible. (**c**) The same process carried up to a higher temperature: irreversibility emerges. Vertical axis-scales are shifted for clarity.

temperature at the PE is only reflected in a dynamic change. The temperature-induced defects seem to have a distinct nature, that makes them different from the ones created by the shaking AC fields, but the details are still unknown

The scenario we have described above has been further confirmed in a recent work [19] where the linear and non-linear behavior for different DC fields and AC measuring frequencies were compared. From these observations, we conclude that the PE in YBCO crystals results from a drastic change in the dynamics of the VL. This dynamic change, however, is correlated with a genuine modification in the dependence of the Labusch constant with magnetic field, probably due to an increase in the amount of dislocations that do not generate an anomalous temperature dependence in the Campbell regime.

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