

# Memory effects in the dynamics of the vortex lattice in YBCO crystals: the role of correlated disorder

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*Memory effects (ME) in the solid vortex lattice (VL) are observed in a wide range of superconducting materials. Experiments in twinned  $YBa_2Cu_3O_7$  (YBCO) crystals in a DC magnetic field tilted respect to the twin planes indicate that ME in these samples cannot be ascribed to an equilibration process. However, how extensive is this behaviour, has not been explored so far. In this work we study the role of correlated defects in ME by performing angular ac susceptibility measurements in YBCO crystals. We conclude that, when uncorrelated disorder prevails, either in twinned or untwinned samples, ME have their origin in the oscillatory character of the vortex dynamics.*

*Keywords: superconductivity; vortex dynamics; memory effects; ac susceptibility.*

*Los efectos de memoria (EM) en la fase sólida de la red de vórtices (RV) se observan en una amplia gama de materiales superconductores. Experimentos en monocristales de  $YBa_2Cu_3O_7$  (YBCO) maclados con el campo magnético inclinado respecto de los planos de maclas indican que, en estas muestras, los EM no pueden adjudicarse a un simple proceso de equilibración. Sin embargo, hasta el momento no se ha investigado cuan extensivo es este tipo de mecanismo. En este trabajo estudiamos el rol que juegan los defectos correlacionados en los EM a través de mediciones angulares de susceptibilidad alterna en cristales de YBCO. Concluimos que, cuando prevalece el desorden al azar, tanto en cristales maclados como en los sin maclas, los EM tienen su origen en la propia dinámica oscilatoria de los vórtices.*

*Descriptores: superconductividad; dinámica de vórtices; efectos de memoria; susceptibilidad alterna.*

## 1. Introduction

The complex dynamical behavior of the vortex lattice (VL) in type II superconductors has been subject of continuous efforts in the last fifteen years. Particular attention has been directed towards understanding driven lattices in the vicinity of the peak effect (PE) which refers to an anomalous non-monotonous dependence of the critical current density  $J_c$  with both temperature and magnetic field [1]. In this region memory effects (ME) are observed in low [2] and in high  $T_c$

materials (HTSC) [3–5].

A general feature of the observed driven dynamics is the increased mobility of the VL after assisting it with a temporarily symmetric (e.g. sinusoidal) ac field [2–5]. Among the various proposed mechanisms, the most invoked is an equilibration process assisted by the ac magnetic field [6, 7].

However, experiments in twinned YBCO single crystals with the DC field tilted out of the twin boundaries (TB) indicate that, in these samples, this framework does not apply. It has been shown [5] that a VL free from bulk field gradients

assisted by an asymmetric ac field (e.g. sawtooth - although a small asymmetry is enough) becomes less mobile. Moreover, mobility is also reduced if a temporarily symmetric ac field forces vortices into large excursions [8]. These striking features indicate that these effects have their origin in the oscillatory character of the vortex dynamics. Defects (e.g. dislocations), their creation or annihilation controlled by the different driven histories, might play a major role in the bulk VL response to an applied force [9]. A plausible picture is that the repeated interactions between vortex neighbors facilitates the healing of topological defects, while temporarily asymmetric ac fields or large vortex excursions promote their creation [10]. Moreover, in a recent work we have shown evidence that the PE in YBCO crystals originates from a drastic change in the dynamics of the VL [11]. How extensive is this behaviour is an open issue that has not been explored so far. Strong correlated disorder as that produced by columnar defects may suppress history effects [12]. In this framework, the role that extended TB play in the ME of YBCO crystals has been subject of controversies until now and similar studies in other materials have to be addressed.

In this work we studied the role that correlated defects as TB and CuO planes play in the ME of YBCO single crystals. With this scope, angular ac susceptibility measurements in untwinned and twinned YBCO crystals have been performed. In each case, the picture presented in the paragraph above has been tested.

## 2. Experimental

Twinned YBCO crystals from two different sources have been used [13, 14]. The untwinned sample was detwinned with the same method used in Ref. [15]. All the samples were  $YBa_2Cu_3O_{7-\delta}$  single crystals with  $91K < T_c < 92K$  in accordance with slightly underdoped crystals [16]. Results shown in this work correspond to a twinned sample with a critical temperature (defined as the middle point of the linear ac susceptibility transition at 0 dc field)  $T_c = 91K$  and an

untwinned crystal with  $T_c \sim 91.6K$

Global ac susceptibility measurements  $\chi' + i\chi''$  were carried out with the usual mutual inductance technique. The measuring ac field is parallel to the crystal  $c$  axis. A cryostat with the static magnetic field  $H$  provided by a magnet was used, so that  $H$  could be rotated relative to the sample. All the measurements have been made at the same frequency  $f = 30kHz$ . Curves were normalized to a total step  $\Delta\chi' = 1$  between the normal and superconducting response with  $H_{dc} = 0$ .

In ac susceptibility experiments, a larger VL mobility corresponds to a larger ac penetration depth (i.e. a larger  $\chi'$ ). To test ME, various protocols or dynamical histories have been performed, where the sample is cooled in dc magnetic field avoiding bulk magnetic gradients, but each case differs in the applied assisting ac field.

An Asy protocol consists in shaking the VL with an asymmetric (sawtooth) ac field of large amplitude ( $\sim 4Oe$ ) once the sample has been dc-field cooled whereas a Sy protocol consists in applying a symmetrical (sinusoidal) large ac field ( $\sim 4Oe$ ) after a complete Asy protocol. In both cases the shaking field is turned off and the measurement begins.

Moreover, ZFCW protocol corresponds to a dc field cool process without any assisting ac field, followed by a warming measurement. Finally, a FCC protocol is a cooling measurement during a dc field cool process assisted by the measuring ac field ( $\sim 1Oe$ ).

## 3. Results and discussion

As has been reported in past work [4], in twinned YBCO crystals, ME are clearly observed when  $H$  is tilted away from the  $c$  axis (i.e. from the TB) in an intermediate angle  $\theta$ . In fact, 4 angular regions with qualitative different ac response are found. These regions agree with those reported in Ref. [15] identified by means of Bitter decoration.

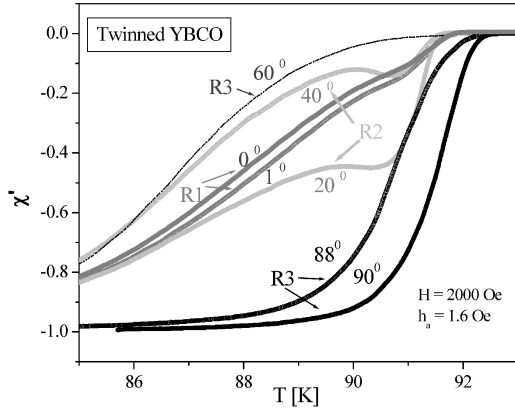


Fig. 1: Inductive component of the ac susceptibility  $\chi'$  measured at different orientations of the DC field  $H$ .  $\theta$  indicates the angle between  $H$  and the  $c$  axis. 4 angular regions with qualitatively different ac response are identified with different color lines.

The characteristic FCC  $\chi'(T)$  at various  $\theta$  corresponding to the 4 angular regions (R1, R2, R3 and R4) are shown in Figure 1. A broad PE develops in R2 (light gray curves in the figure) ( $10^\circ \lesssim \theta \lesssim 50^\circ$ ), where the predominance of correlated pinning due to TB is expected to decrease. Approaching the TB planes (R1, dark gray curves) the shape of the curves is very different and the PE diminishes. At  $\theta \sim 60^\circ$  (R3, dashed curve), a softening of the VL occurs and PE disappears. Finally, in R4 (black curves), when  $\theta$  approaches  $90^\circ$ , the pinning is enhanced due to the CuO planes and mobility drastically diminishes.

In Figure 2a, ZFCW and FCC curves for the same sample are shown. It can be seen that ME are well visible in R2 whereas approaching the TB planes (R1) they become inappreciable within our resolution. In R4 ME completely disappear due to the strong dominating correlated pinning of CuO planes.

In Figure 2b, analogue experiments are shown in an untwinned crystal. In this particular sample a PE develops at DC fields greater than 3000 Oe. In that case the  $\chi'(T)$  curves in regions R1 and R2 are very similar, and ME are well visible at  $\theta \sim 0^\circ$ .

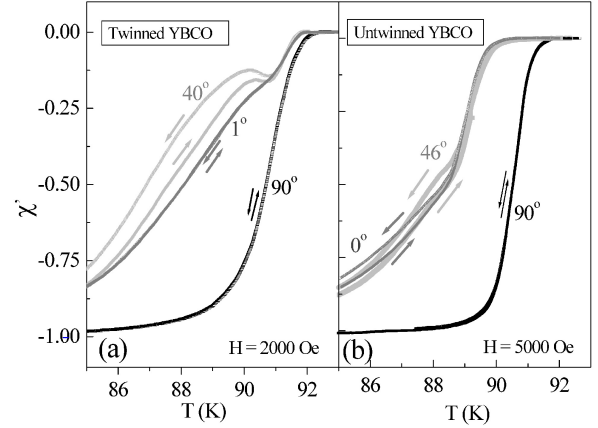


Fig 2:  $\chi'$  curves recorded with ZFCW and FCC protocols (see text) in the various angular regions in a twinned (Fig 2a) and an untwinned (Fig. 2b) sample. Correlated disorder due to TB and CuO planes inhibits ME, whereas in the untwinned sample responses in R1 and R2 are very similar.

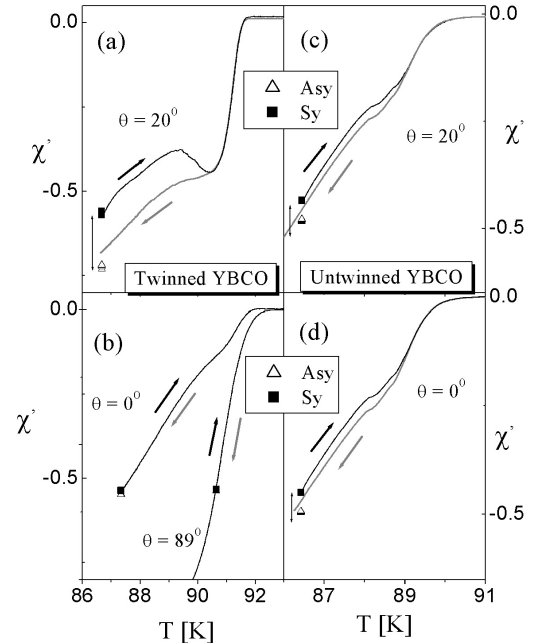


Fig 3: Test probing that whenever ME are relevant, the symmetry of the shaking ac field affects the VL mobility in both twinned (a) and untwinned (c and d) samples. After a FCC (gray curves), Asy and Sy protocols (see text) are apply. Sample is warmed after the last Sy protocol (black curves). In R1 and R4 (b) there is no effect.

Notice that in both samples the VL is more mobile in the FCC curve, indicating that the measuring ac fields assist the VL to attain a more ordered configuration.

Moreover, whenever ME are observed, the symmetry of the assisting ac field plays a mayor role. This fact is illustrated in Figure 3. In all the panels, the twinned and untwinned samples have been measured at various  $\theta$  with the following sequence: The sample was field cooled (gray curve) until a fixed temperature  $T$ . Then the Asy (open triangles) and Sy (black squares) protocols were performed. Both protocols were repeated two or three times at this fixed  $T$ , and finally, after the last Sy protocol, the sample was warmed (black curve). Notice that in the angular regions where ME are not relevant (R4 and R1 in the twinned sample), the Sy and Asy protocol do not produce any change in the VL. On the contrary, in the regions affected by dynamical history, the asymmetric shaking leads to a VL in a less mobile configuration, whereas the symmetric shaking promotes a more mobile VL. These configurations are robust and repetitive.

#### 4. Conclusions:

By means of angular  $\chi_{ac}$  measurements in YBCO crystals, we have observed that for angular regions where correlated disorder prevails (i.e. when the vortex direction is nearly aligned with the twin planes or CuO planes), the peak effect and memory effects diminish and/or disappear.

In the angular regions where uncorrelated disorder prevails, in accordance with previous work, memory effects present a particular phenomenology, where the most salient features are the following: any symmetric assistance of moderate amplitude able to move vortices out of pinnig centers reorganizes the VL in a more ordered and more mobile configuration. On the contrary, an asymmetric shaking promotes a less mobile VL.

In this work we have observed this behavior in crystals coming from different sources, with and without TB. Particular these features hold in untwinned crystals when the

VL is aligned with the c axis. Therefore, we claim that these characteristics are not an artifact produced by twin boundaries, but are intrinsic of vortex matter in this HTSC.

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