Vortex Softening: Origin of the second peak effect in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Transverse ac permeability measurements in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals at low fields and temperatures in a vortex configuration free of external forces show that the decrease of the critical current as measured by magnetization loops at the second peak effect is an artifact due to creep. On the other hand, the increase of critical current at the second peak is due to a genuine softening of the tilting elastic properties of vortices in the individual pinning regime that precedes the transition to a disorder state.

The existence of the second peak in the low field low temperature magnetization of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) as well as the peak effect observed in the critical current $J_c$ of low (LTS) and high temperature superconductors are manifestations of instabilities of the vortex structure (VS) in the presence of pinning potentials. Since the first explanation by Pippard and the theoretical description by Larkin and Ovchinnikov there have been several other alternatives have been proposed, including order disorder thermodynamic phase transitions.

The most remarkable manifestation in both phenomena is that $J_c$ goes through a maximum when increasing field. Thus, most experiments studying the anomaly are based in measurements of $J_c$ and consequently describe the properties of a non equilibrium thermodynamic state. In particular, in the case of the second peak in Bi2212, $J_c$ determined by magnetization loop measurements is strongly affected by time dependent phenomena. As a result, it has been suggested a possible explanation of the second peak effect as due to different relaxation rates of the vortex system in a non homogeneous field distribution induced by the critical state. Other suggestion supporting the dynamical origin of the phenomenon has been introduced from local magnetization loops induced in short time scales. This is in contrast with other experiments in Bi2212 where a thermodynamic phase transition is claimed to be associated with the second peak.

In this paper we compare experimental results obtained by different techniques in order to distinguish the possible dynamical contribution to the second peak from that caused by genuine changes in the elastic response of the VS in the presence of pinning potentials. We have compared magnetization loop measurements in the critical state with results obtained from ac transverse permeability measurements of vortex configurations free of bulk magnetic gradients. With this last constrain we have been able to detected an enhancement of the intrinsic pinning potential of the vortex lattice in a region of fields where the second peak is detected. The observed behavior is due to a softening of the elastic properties of vortices that might be considered a precursor of a phase transition.

The Bi2212 single crystals used in this work were grown using the self flux technique and they have typical dimensions 2x1x0.02 mm$^3$. We have made measurements of the field cooled, FC, ac transverse permeability in the Campbell limit, where the VS remains pinned under the perturbation induced by the ac field. A sketch of the experimental configuration with the applied field $H_a$ in the $c$ direction can be seen in the insert of Fig. 1 and details in ref. 10.

The ac permeability in this configuration is given by

$$\mu = \frac{2 \lambda_{ac} d}{d} \tanh\left(\frac{d}{2 \lambda_{ac}}\right)$$

where $d$ is the thickness of the sample and the ac penetration depth $\lambda_{ac}$ in the Campbell limit follows expression

$$\lambda_{ac}^2 = \lambda_{ac}^2(H_a = 0) + \lambda_C^2,$$

where $\lambda_C$ is the Campbell penetration depth. The Campbell limit is achieved when the ac response is characterized by vortices locked in a pinning potential, linear frequency independent response to ac excitations and a very small dissipation due to the displacement of the vortex core within the effective pinning potential. The Campbell penetration depth is given by

$$\lambda_C^2(H_a, T) = \frac{c_{44}}{\alpha_L(H_a, T)}$$

The elastic constant $c_{44}$ determines the vortex response to the tilting force induced in the transverse configuration. The Labusch parameter $\alpha_L(H_a, T)$ is the effective pinning potential responding to the ac excitation.

It has been demonstrated that the pinning barrier is a function of the force acting on the vortices. When the only external force applied to the VS is that of the perturbation induced by the ac field the elastic response in the Campbell limit is determined by the curvature at the bottom of the effective pinning potential. This requires the
electromagnetic force induced by the ac field to be much smaller than the critical one to remove vortices from the pinning sites. Basically, the VS localized at the bottom of the Labusch potential represents a free force VS in thermodynamic equilibrium with the pinning potential. In practice, the true equilibrium state for a given external field and temperature can not be reached. On the other hand, the structure obtained by freezing the FC vortex system through the liquid solid-first order transition is essentially a vortex free force configuration down to temperatures where the individual pinning vortex limit is achieved [13]. In this configuration the pinning barrier is maximum [13] and in the individual vortex pinning limit \( \alpha_L(H_a,T) \) becomes field independent. In this limit, the field dependence of \( \lambda_{ac}^2 \) is given by the field dependence of \( c_{44} = H_a \phi_0/4 \pi \). Typically, when the field is increased the vortex-vortex interaction becomes relevant and a crossover to the collective pinning regime takes place. Then \( \alpha_L(H_a,T) \) decreases, and the Campbell penetration depth increases.

Magnetization loops were also measured using a commercial Quantum Design SQUID magnetometer. From these measurements \( J_c \) was extracted using the expression [15]

\[
J_c = \frac{3}{2} c \Delta M R
\]  

where \( \Delta M \) is the difference in magnetization for a given field and \( R \) is a typical dimension of the sample. Equation (4) gives \( J_c \) only when creep effects can be disregarded. In this case, \( J_c \propto \alpha_L (H_a,T) \). The measurements were taken in time scale of few minutes.

In Fig. 1 we show the field dependence of \( \lambda_{ac}^2 \) at 15K, normalized by the thickness of the sample. The dotted line is a linear fit to the data. Insert at the lower right: Imaginary part of the permeability vs T at \( H_a = 600 \) Oe. Insert at the upper left: Experimental configuration.

The field independent Labusch coefficient can be extracted from the slope of the data or from each experimental value using the expression

\[
\alpha_L = \frac{H_a \phi_0}{4 \pi} (\lambda_{ac}^2(H_a,T) - \lambda_{ac}^2(0,T))
\]  

In principle, \( \lambda_{ac} (0,T) \) is the London penetration depth \( \lambda_L \). However, it is often found [16] that \( \lambda_{ac}(0,T) \) obtained from the extrapolation of the linear field dependence is larger than \( \lambda_L \). In our case \( \lambda_{ac}(0,T) \approx 3 \lambda_L \). This is due to a rapid increase of the penetration depth in the low field range, \( H_a \leq 30 \) Oe, of unknown origin, followed by the linear increase shown in Fig. 1. The rapid increase is incorporated in \( \lambda_{ac}^2 (0,T) \) as a fitting parameter for the linear field dependence of \( \lambda_{ac}^2 \) (\( H_a,T \)). The slope of \( \lambda_{ac}^2 \) (\( H_a,T \)) determines \( \alpha_L \) (\( H_a,T \)), plotted as a full line in Fig. 2 together with the corresponding values obtained from expression (5).
The current density $J_c$, obtained from (4) is also plotted in Fig. 2. It is interesting to point out that the $J_c$ field independent region (individual pinning regime) is limited to fields one order of magnitude smaller than those where $\alpha_L$ is seen to remain constant. As mentioned before $J_c \propto \alpha_L(H, T)$, when $J_c$ is the true critical current. Creep measurements [17] in the critical state made in the time scale of the same order of that used in the magnetization measurements show that the decrease of $J_c$ as seen in Fig. 2 can be taken into account by creep effects. Equivalent measurements in the FC structure [17] show undetectable creep in agreement with the results of decoration experiment [14] and with the observed constant $\alpha_L(H_a, T)$ plotted in Fig. 2.

Fig. 3 depicts the field dependence of $\lambda_{ac}^2$ for other three higher temperatures. The frequency independence of the results and the low dissipation ($\mu'' < 0.04$) verifies that the Campbell limit is obeyed up to 750 Oe where dissipation is detected to increase rapidly with field (shadowed region in the figure). The slope of $\lambda_{ac}^2(H_a, T)$ for the three temperatures is seen to be independent of field (indicated by the dotted line with slope 1) for $H_a < 200$ Oe. It is interesting to remark the relative decrease of $\lambda_{ac}^2(H_a, T)$ with field as compared to that of the individual pinning limit (followed by an increase at higher fields [18], shadowed region in the figure). It is surprising that the increase of the effective pinning potential (better shielding) with $H_a$ takes place within the individual Campbell pinning limit. This is clearly seen in Fig. 4 where we have plotted $\alpha_L(H_a, T)$ from the data in Fig. 3, for two temperatures. The increase of the pinning potential with field strongly suggests an anomalous softening of the elastic constant $c_{44} = (H_a, T)$ at low fields and temperatures.

Critical currents extracted from magnetization loops for $T = 25$K and $T = 35$K together with the corresponding $\alpha_L(H_a, T)$ from permeability measurements are shown in Fig. 4. As observed at lower temperatures, the decrease of $J_c$ in the region of fields where $\alpha_L$ is field independent is also due to creep effects. Thus, the decrease in $J_c$ with $H_a$ should not be considered as an increase of the pinning correlation volume with field due to collective pinning effects and consequently should not be associated with the second peak effect. This is further supported by a close inspection of the data in Fig. 4, showing that the enhancement of $\alpha_L(H_a, T)$ above the individual pinning limit takes place at the field where the decreasing $J_c(H_a)$ shows an inflexion point, as marked in the figure with an arrow. At this field a new mechanism that increases $\alpha_L(H_a, T)$ is switched on and, consequently, slows down the creep rate. This anomalous behavior of the pinning potential could be considered a precursor of the second peak effect.

It is interesting to point out similarities and differences between the peak effect close to $H_{c2}(T)$ in LTS [19], and the second peak in Bi2212 at low fields and temperatures. In LTS, $J_c$ decreases with field down to a minimum at $H_{onset}$, then pinning increases to reach a maximum at $H_{peak}$. It is shown [19] that $H_{onset}$ is situated in the field region where collective pinning is described by a three dimensional Larkin volume. For $H_a > H_{onset}$ the correlation volume decreases until a crossover from the collective to the individual pinning limit takes place at $H_{peak}$. The previous description implies that $\alpha_L(H_a, T)$ decreases down to a minimum at $H_a = H_{onset}$. The enhancement of $\alpha_L(H_a, T)$ for $H_a > H_{onset}$ indicates a reduction of the correlation volume induced by a softening of the VS. Agreement between theory and experiment is found [19] only if the pinning correlation volume is calculated taking into account the lattice softening induced by the dispersive nature of $c_{44}(k)$. This is important close to $H_{c2}$ where the typical interaction length $\lambda_H = \lambda_L/1-b$ ($b = H / H_{c2}$) becomes comparable to the relevant elastic distortion of wave vector $k$ of the VS.
FIG. 4. $J_c$ from magnetization loops and Labush coefficient $\alpha_L$ from equation (5) as a function of the applied magnetic field for (a) $T=25 K$ and (b) $T=35 K$. The individual pinning region (field independence) deduced for both magnitudes is indicated. The arrow marks the inflection point of $J_c(H_a)$. The shadowed region corresponds to a dissipative regime.

In the extreme anisotropic Bi2212, pinning is also detected to increase with field at the second peak. However, in this case $\alpha_L(H_a,T)$ shows no minimum, it increases from a field independent value at low fields, as shown by penetration depth measurements. Thus the reduction of the vortex pinning correlation starts from the already individual Larkin volume, characterized by a one dimensional vortex length, $L_c$. In this limit $J_c$ is given by

$$J_c = J_0(T)\left(\frac{\xi(T)}{L_c(T)\gamma}\right)^2$$

where $J_0(T)$ is the depairing current, $\xi$ is the superconducting coherence length, $\gamma$ is the anisotropy and $L_c$ is the Larkin correlation length in the field direction. Previous measurements of $J_c$ and $\alpha_L(H_a,T)$ have shown a field independent temperature induced crossover from one to zero dimensional pinning behavior at $T_{0D} \simeq 20 K$, where $L_c$ becomes equal to the CuO interspacing $s$.

In Fig. 5 the temperature dependence of $\alpha_L(H_a,T)$ in the individual vortex limit is depicted. The transition to the zero dimensional limit, $T = T_{0D}$, is evident. At this temperature the minimum pinning correlation volume (maximum $\alpha_L(H_a,T)$ for a given temperature) is achieved. For $T > 20 K$ the pinning is one dimensional with $L_c = s$. Thus, the increase of $\alpha_L(H_a,T)$ with field, described in this paper, should be due to a decrease of $L_c$ induced by a softening of the elastic vortex properties. Following the previous discussion the maximum value that $\alpha_L(H_a,T)$ can take is for $L_c = s$. We have plotted in Fig. 5 the maximum values of $\alpha_L(H_a,T)$ at different temperatures within the Campbell limit (maximum $H_a$ in Fig. 4 before the shadowed area). The linear extrapolation (dotted line) of the data below 20 K to higher temperatures strongly supports the picture discussed previously.

FIG. 5. Temperature dependence of $\alpha_L(H_a,T)$ in the individual vortex limit. Full symbols: Field independent $\alpha_L$. Open symbols: maximum value of $\alpha_L$ in the Campbell limit. The full line is an extrapolation of the low temperature (below $T_{0D}$) evolution. The insert is a similar result for a sample with lower defects concentration.

It is seen from Fig. 5 that the increase of $\alpha_L(H_a,T)$ and the corresponding increase of $J_c(H_a,T)$ at the second peak is due to a softening of the elastic properties of the vortices in a region of fields where its integrity along the field is assured: individual pinning limit in the Campbell regime. When $H_a$ is further increased $J_c$ and the effective $\alpha_L(H_a,T)$ are seen to decrease rapidly but the rapid increase of dissipation in $\mu$ indicates a crossover to a non equilibrium state. The large dissipation is associated with currents flowing in the $c$ direction as mentioned in ref. 10, indicating a loss of vortex integrity in transport properties.

We have made measurements in two other samples with similar results: thermal crossover to zero dimensional pinning below $T_{0D} \simeq 20 K$, and a magnetic softening of the VS above $T_{0D}$. However, it is interesting to remark that the field where dissipation marks the end of the Campbell limit depends on each sample. In particular we see in the insert of Fig. 5 results equivalent to those
in the main frame. However, in this sample (that by all indications seems to be cleaner) the dissipation appears at values of $\alpha L (H_a, T)$ well below that corresponding to the zero pinning limit behavior. This result is in agreement with a possible influence of point disorder on a first order transition associated with the loss of coherence in the $c$ direction.

We have shown that the increase of $J_c$ in the second peak effect is due to a genuine softening of the elastic properties in the individual pinning regime. Whether it is a manifestation of a phase transition is a subject that deserves more theoretical and experimental work. As mentioned in ref. [20] we have not detected the second peak effect below 20K neither by permeability nor by $J_c$ measurements. Why the thermal induced transition to a zero dimensional pinning limit precludes the vortex softening with field remains as an open question.

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