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GEOMETRIC BARRIER EFFECTS ON TRI-DIMENSIONAL SUPERCONDUCTING STRIPES WITH RANDOM PINNING

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ABSTRACT

We study the behavior of tri-dimensional driven vortex lattices in highly anisotropic superconducting materials such as BSCCO with random distribution of impurities (pinning centers). We consider a narrow stripe, finite in the transversal direction and infinite in the longitudinal one, composed by a stack of bi-dimensional layers. Our numerical simulations are made using molecular dynamics techniques with periodic boundary conditions in the direction the stripe is infinite and a surface barrier in the direction it is finite. The equation of motion includes in-plane and inter-plane pancake vortex interactions, vortex interaction with the screening current, vortex images, transport current and random distributed pinning centers. We could distinguish among three different dynamical regimes as observed in previous works, but with differences in the vortex trajectories and an increase in the critical current due to the geometric barrier effects.

1. INTRODUCTION

It is known that in highly anisotropic superconductors such as BSCCO, the 3D vortex lattice can be described by a stack of superconducting layers with 2D pancake vortices, which is a set of vortices located in only one of the layers [1]. In 2D systems the vortex lattice can be dynamically reordered by an applied driven current [2-4], but in layered systems it strongly depends on the interaction between layers. It was found that above the depinning current, the system shows a sequence of dynamical regimes [2-6], initially passing through plastic flow [4], then upon increasing drive a new dynamic regime sets in where the vortices form elastic channels known as smectic flow regime [2,5]. At higher currents different kinds of order are possible, depending on pinning strength and dimensionality. A crystal-like structure is only possible in 3D systems, in 2D or in 3D with intermediate currents, a transverse glass is expected [5,6]. These previous works in 3D simulations have analyzed the problem on infinite systems and almost nothing has been done to understand the effects of the geometric barrier in samples with size comparable with the London penetration depth. In this work, using molecular dynamics technique we solve Langevin equations for the vortex system and we study the geometric barrier effects on vortex lattice regimes in two-dimensional correlated planes, simulating a three-dimensional layered high-T_C superconducting stripe. We consider the long-range magnetic interactions between all the pancakes, neglecting Josephson coupling [1]. This model is adequate when the interlayer periodicity d is much smaller than the in-plane penetration depth λ [1,5].

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2. METHOD

The dynamics of the vortex lattice can be simulated using the Langevin differential equation of motion. In the present case we write the equation of motion of a vortex at the position $\mathbf{R_i}=(r_i, z_i)$ as:

$$\eta \frac{dR_i}{dt} = \sum_{j \neq i} f_v(r_{ij}, z_{ij}) + f_H(r_{xi}) + \sum_p f_p(r_{ip}) + F \quad (1)$$

where $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ and $z_{ij} = |\mathbf{z}_i - \mathbf{z}_j|$ are the in-plane and inter-plane distances between the vortex pancakes, r_{xi} is the position of the pancake i in the **x** direction, $r_{ip} = |\mathbf{r}_i - \mathbf{r}_p|$ is the in-plane distance between the vortex i and a pinning site at $\mathbf{r}_p$, η is the Bardeen-Stephen viscous friction. The magnetic interaction between pancakes $f_v(r,z)$ is given by [1,5]:

$$f_v(r,0) = \frac{A_v}{r}\left[1 - \frac{\lambda}{\Lambda}(1 - e^{-r/\lambda})\right] \quad (2)$$

$$f_v(r,z) = -\frac{\lambda}{\Lambda}\frac{A_v}{r}\left[e^{-|z|/\lambda} - e^{-Z/\lambda})\right] \quad (3)$$

where $Z = (z^2 + r^2)^{1/2}$ and $\Lambda = 2\lambda^2/d$ is the 2D thin film screening length. The force generated by the geometric barrier is given by the screening current generated by the external field H plus the vortex self-energy [7]:

$$f_H(r_x) = \sqrt{A_v}H\frac{sinh(r_x - L_x/2\lambda)}{\cosh L_x/2\lambda} + \\ + A_v\frac{8\pi}{L_x}\frac{sin(\pi r_x/L_x)\cos(\pi r_x/L_x)}{4sin^2(\pi r_x/L_x) + (\pi\xi/L_x)^2} \quad (4)$$

where L_x is the width of the stripe and ξ is the coherence length. We consider a random distribution of attractive pinning centers interacting with vortices by $f_p(r)=-2A_p exp(-(r/a_p)^2)r/a_p^2$ [5], where a_p=0.2 is the pinning range. The last term on Eq. (1), $\mathbf{F}=\phi_0/c(\mathbf{J}\times\mathbf{z})$, is the driven force associated to the in-plane transport current **J**. We normalize length scales by λ, energy scales by $A_v = \phi_0^2/4\pi^2\Lambda$, and time is normalized by $\tau = \eta\lambda^2/A_v$.

The system is formed by a stack of 3 rectangular $L_x \times L_y$ layers, with N_v=48 pancake vortices and N_p=96 random distributed pinning centers. We consider a pinning strength of A_p/A_v=0.2, a box with $L_x/L_y=\sqrt{3}/2$, a vortex density of n_v=0.12 and pinning density n_p=0.24, and we take $d \approx \xi$. We use periodic boundary conditions in the y direction, with periodicity L_y, a surface barrier in the x direction and integrate using a time interval Δt = 0.01τ. Instead of the Abrikosov triangular lattice used as initial configuration for the infinite system, we obtain the initial vortex configuration for the finite system relaxing the vortices without a transport current.

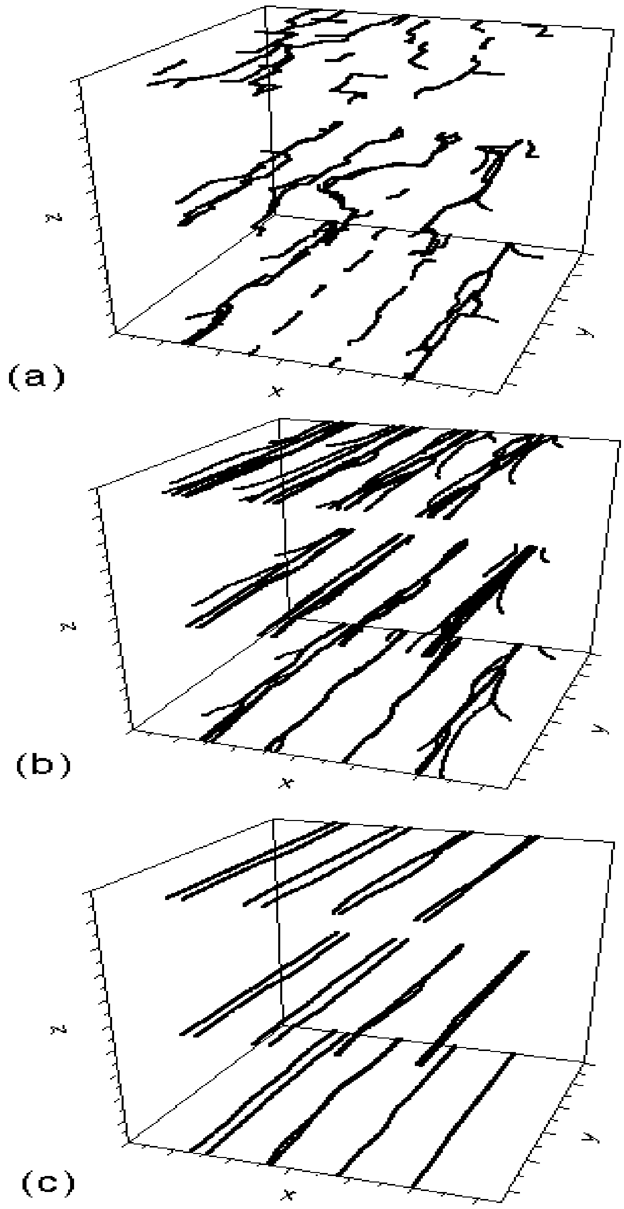

Figure 1 - Vortex trajectories for 500 time steps and for F=0.8 (a), F=2.0 (b) and F=6.0 (c).

A driven force is increased from F=0.0 to F=6.0 in steps of ΔF=0.05 in 10000 integration steps after 2000 iterations for equilibration.

3. RESULTS AND DISCUSSION

We start showing the vortex trajectories, Fig. 1, for typical values of increasing drive F by plotting the positions of the pancakes in 3 layers for a wide range of time steps. We found that the geometric barrier push the vortices towards the center of the sample. The transport current is applied in the x direction so the force F is in the y direction. In Fig. 1(a) the driven force is weak, F=1.0, so some of the vortices are trapped in pinning centers and others move in paths without any correlation to each other, showing an intricate structure of channels, characteristic of the plastic motion. For F=2.0, Fig. 1(b), vortices move in elastic channels almost parallel to the y axis, but there is a transverse motion that consists of vortex jumps from one channel to another, what is called smectic flow [2]. And in Fig. 1(c) for F=6.0, vortices align in linear channels parallel to the driven force that are totally uncoupled. Then we have a transverse glass.

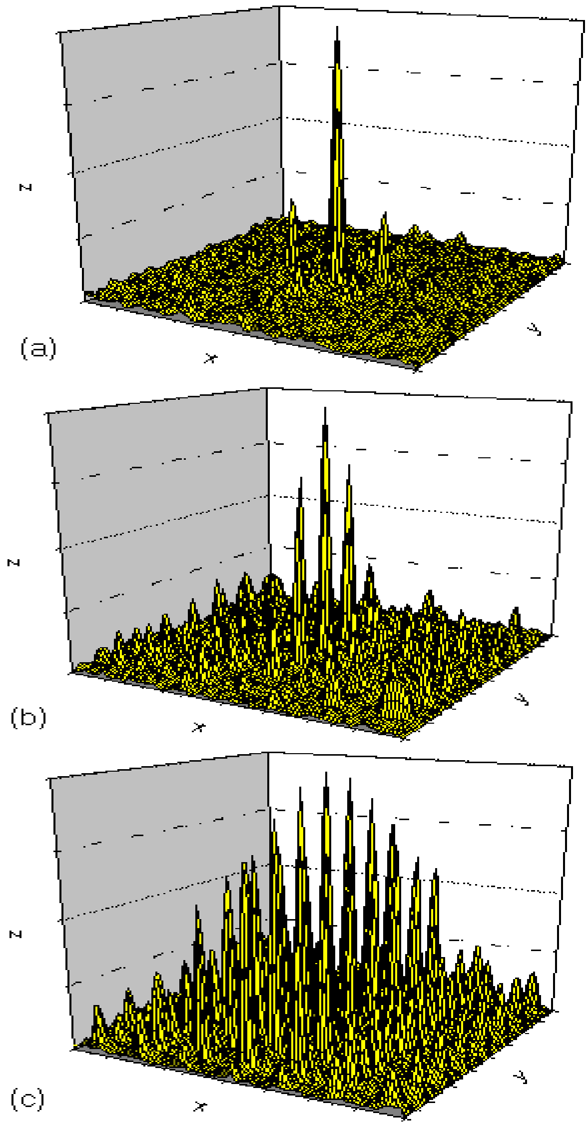

Figure 2 - Averaged structure factor of the trajectories of Fig. 1 for F=0.8 (a), F=2.0 (b) and F=6.0 (c).

In Fig. 2 we show the time averaged in-plane structure factor:

$$S(k) = \left\langle \left| \frac{1}{N_v} \sum_i \exp\left[ik \cdot r_i(t)\right] \right|^2 \right\rangle, \tag{5}$$

which allow us to measure the order in the different dynamical regimes. Initially there is just one pronounced peak in the center so there is no order in any direction. As the force is increased to higher values the structure factor shows additional peaks in the transverse direction which means that the vortices are "frozen" in this direction and there is quasi long-range order.

In Fig. 3 we plot the average vortex velocity:

$$V = \left\langle V_y(t) \right\rangle = \left\langle \frac{1}{N_v} \sum_i \frac{dy_i}{dt} \right\rangle, \tag{6}$$

in the direction of the driven force as a function of F and its corresponding derivative dV/dF (differential resistance). Initially, as expected, the average velocity is zero because the vortices are pinned.

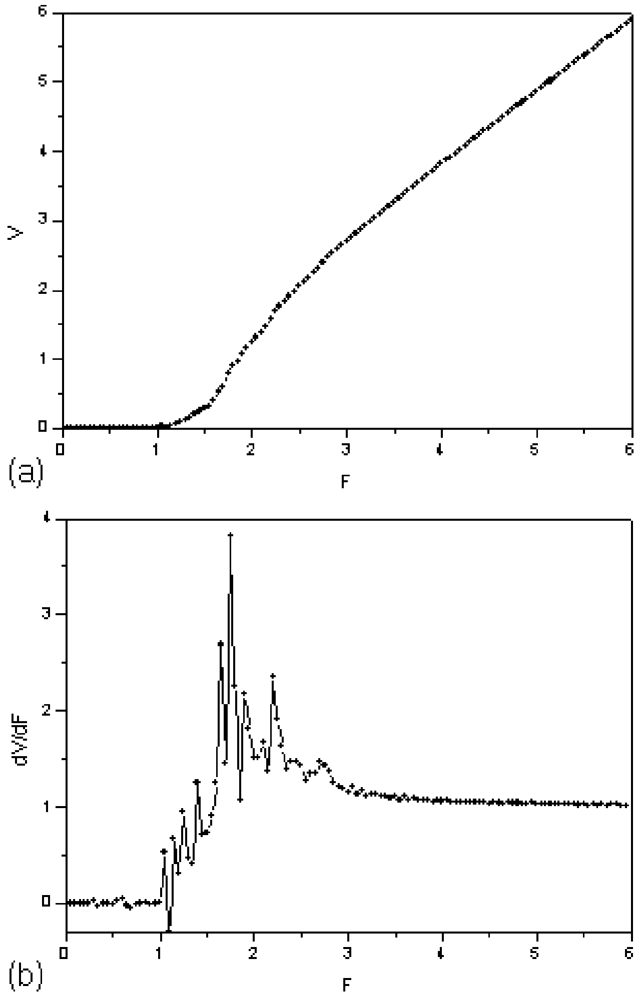

Figure 3 - (a) Vortex velocity-force curve and (b) differential resistance (dV/dF).

For increasing drive, vortices start to move until there is a peak in differential resistance, Fig. 3 (b), i.e. we have the maximum variation in the vortex velocities. For higher values of force the differential resistance decays until reach a stationary value which corresponds to the linear part of the average velocity curve.

We analyze the average quadratic displacements of vortices in both directions from their center-of-mass position ($X_{cm}(t)$,$Y_{cm}(t)$), averaged in time and as a function of current force. These results are shown in Fig. 4. We calculate the transverse diffusion coefficient D_x, Fig. 4 (a), using:

$$D_x t \approx \frac{1}{N_v} \sum_i \left[x_i(t) - X_{cm}(t) - x_i(0) + X_{cm}(0)\right]^2 \tag{7}$$

and the drift from the center of mass of longitudinal displacements, Fig. 4 (b), using:

$$\left\langle \left[\Delta y(t)\right]^2 \right\rangle = \left\langle \left[y_i(t) - Y_{cm}(t) - y_i(0) + Y_{cm}(0)\right]^2 \right\rangle, \tag{8}$$

We find that for low values of force the diffusion coefficient is very low and it oscillates. This occurs because many vortices are still pinned and other are not so the average in time has no preferential value. Probably if we increase the number of vortices and time steps we should get a more stable curve, but it will require a long computational time.

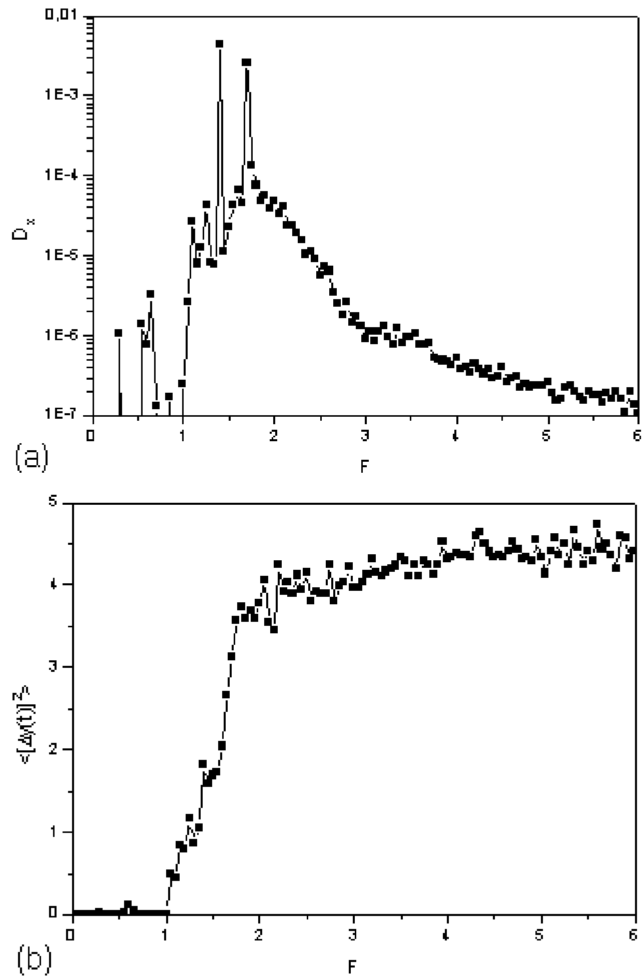

Figure 4 - (a) Diffusion coefficient for transverse motion and longitudinal displacements (b).

We can see that the peak of the diffusion coefficient coincides with the peak in the differential resistance, this implies that for this force the system has a maximum in the number of defects and it is an indication of the regime transition from plastic to smectic flow [2]. In Fig 4 (b) we observe that it increases with the driven force but when it reaches F=2.0 it tends to become constant, what is an indicative that the vortex movement is stationary in the *y* direction.

4. CONCLUSION

The results reported here describe the behavior of 3D driven vortex lattices with a surface barrier in the transverse direction. For this system, vortices remain pinned even at values of currents as high as $F=1.0$. As the force is increased vortices start to move. This behavior is analog to that found in infinite systems [5], with the difference that vortices are pushed by the geometric barrier towards the center of the sample. At these values of force, the system shows an intricate structure of channels, characteristic of the plastic motion. Increasing the force the system shows an almost parallel configuration of channels, and the transverse motion consists of vortex jumps from one channel to another. The rate of these transitions decreases with increasing force. At higher forces, vortices move in straighter and uncoupled channels. So the vortices are “frozen” in the transverse direction and this regime can be called as “frozen transverse solid” [2]. This behavior is analog to that found in infinite systems, when we increase the transport current at constant field, but in this system due to the geometric barrier effects we have an increase in the critical current, as can be seen clearly if we compare the present results of velocity with that of Ref. [5].

5. ACKNOWLEDGEMENTS

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