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Absence of the Role of Temperature and Size of Pinning Sites on the Occurrence of the Dip Effect

I. M. Obaidat*, F. Hamed, M. Benkraouda and U. Al Khawaja

Department of Physics, United Arab Emirates University, Al-Ain 17551, United Arab Emirates
**Author E-mail: iobaidat@uaeu.ac.ae*

Abstract

The properties of the critical current density in high temperature superconductors were investigated. Molecular dynamic simulations based on periodic square arrays of vortices and pinning sites were carried out. The variables in the simulations were the vortex density, the temperature, the pinning strength, the size of pinning sites. An interesting *dip* was found to occur in the critical current density but only at zero temperature and specific values of pinning strength. The properties of the *dip* were found to depend strongly on the initial positions of the vortices with respect to the positions of the pinning sites. The formation of one dimensional linear channels of moving vortices in the direction of the applied current was found to take place at the *dip* and no where else. The occurrence of the observed dip is attributed to the channel formation. *Corresponding*

Keywords: Critical current density; Dip effect; Simulations

Introduction

High temperature superconductors (HTSCs) are type II superconductors. It is known that an applied magnetic field (H) penetrates type II superconductors in the form of quantized magnetic vortices and any transport current will have to contend with the presence of such vortices. Superconductors are characterized by critical current density (J_c) above which superconductivity cease to exist. This critical current density is greatly affected by the motion of the magnetic vortices unless they are pinned down. It is crucial that J_c is made as high as possible if HTSCs are to be considered for any practical applications. Great efforts have been devoted to understand the dynamics of the magnetic vortices in HTSCs in hopes of making J_c optimal [1-3].

The name of the game is pinning i.e. pinning forces capable of preventing the vortices form moving. Increasing the applied magnetic field (i.e. increasing the number of vortices) or the temperature (i.e. increasing the thermal energy) was found to suppress the pinning forces which in turn lowered J_c [1]. However a sharp enhancement of J_c with increasing the applied magnetic field was reported for some superconductors. Such anomalous behavior has been termed the peak effect (or the fish-tail). This peak effect has been observed in conventional superconductors [4] as well as many HTSCs [5-19]. The peak effect has attracted a great deal of attention for the obvious reason of J_c optimization and the underlying mechanism for the vortex phase diagram. The competition between the repulsive vortex-vortex interactions and the attractive vortex-pin interactions have resulted in this striking effect. As the peak appears, a new pinning mechanism becomes activated and the strength of this pinning increases with increasing H. In HTSCs, the peak effect was found to occur in the solid phase of the H-T phase diagram, well below H_{c2}. This suggests that the peak effect might be associated with the softening of the shear modulus [20].

It was also proposed that the peak effect is associated with a crossover from elastic to plastic depinning forces [21], vortex melting, or the possibility of a two to three-dimensional transition [1]. The order-disorder transition from proliferation of dislocation at the stability line seems to be one of the most promising models [22]. There has been a general consensus that the occurrence, location, strength, and width of the peak depend on the size [23] and strength [24] of the pinning sites. Numerical studies of the effect of the strength of the pinning sites on the peak effect in superconductors with random distribution of pinning sites were conducted [25], it was found that the peak effect is more pronounced in the weak pinning limit and progressively diminishes with increasing pinning strength. Reichhardt *et al*. have carried out simulations on systems of square arrays of pinning sites [26] and showed that the occurrence, location and height of the peak depend on the size of pinning sites.

While numerical studies [27] on systems with small number of pinning sites showed that the occurrence of the peak and its height depend on the distribution of the pinning sites. In the case of square array of pinning sites, the occurrence of the peak was found at most matching and fractional matching of the first applied magnetic field. While the peak was found to be absent in the systems with random distribution of pinning sites at all fields.

In both of the above studies [26, 27], the peak in the critical current occurred at those matching fields where the interstitial vortices can form a highly ordered lattice. This result was confirmed in HTSCs with square pinning arrays by direct imaging techniques such as Lorentz microscopy [28] and scanning Hall probes [29].

In the present paper we follow up on our previous study [30] on the appearance of a “dip” effect in the critical current density and its properties. In our previous report [30] we have found that pinning strength and vortex initial positions have an influence the occurrence and properties of the dip effect. The dip effect was observed only at zero temperature for specific values of pinning strength and specific pinning site size. The dip effect was found to occur only at nearly 0.4 fraction of first matching field for all values of pinning strength. We have also found that at the dip the moving vortices form linear channels along the direction of the driving force. Here we investigate whether or not the temperature and size of pinning sites have a role on the occurrence of the dip effect.

Simulations

We consider a *2D* transverse slice (in the *xy*-plane) of an infinite *3D* slab containing rigid vortices and columnar defects, all parallel to both the sample edge and the applied field $\mathbf{H} = H\hat{z}$. These vortices attain a uniform density n_v, allowing us to define the external field $H = n_v \phi_\circ$, where $\phi_\circ = hc/2e$. This model is most relevant to superconductors with periodic arrays of columnar defects or thin-film superconductors where the vortices can be approximated by *2D* objects. We model the vortex-vortex force by a modified Bessel function of the first kind, $K_1(r \setminus \lambda)$, where λ is the penetration depth [2, 3]. For the vortex-pin interaction, we assume the pinning potential well to be parabolic [2, 3]. The pinning range (i.e., the radius of the parabolic well) is r_p. For computational efficiency the vortex-vortex interaction can be safely cut off at 6λ since the Bessel function decays exponentially for r grater than λ. We use finite temperature overdamped molecular dynamics simulations in two dimensions. The overdamped equation of motion for each vortex is given by:

$$\mathrm{f}_\mathrm{i}^{\mathrm{tot}} = \mathrm{f}_\mathrm{i}^{vv} + \mathrm{f}_\mathrm{i}^{vp} + \mathrm{f}_\mathrm{i}^{T} + \mathrm{f}_d = \eta \mathrm{v}_i, \tag{1}$$

where $\mathrm{f}_\mathrm{i}^{\mathrm{tot}}$ is the total force on vortex *i*, $\mathrm{f}_\mathrm{i}^{vv}$ is the vortex-vortex force, $\mathrm{f}_\mathrm{i}^{vp}$ is the vortex-pin force, f_d is the driving force in the *x*-direction corresponding to the Lorentz force, and the thermal fluctuations are accounted for by a stochastic term that has the properties $\langle f_i^{\,t} \rangle = 0$ and $\left\langle f_i^T(t) f_j^T(t') \right\rangle = 2\eta k_B T \delta(t-t')\delta_{ij}$, where f_i^T is the thermal force given by $f_\mathrm{i}^\mathrm{T} = Af_\circ$, and *A* is the number we tune to vary *T*.

In this manner the temperature is given by $T = 1/(2\eta k_B)(Af_\circ)^2 \Delta t$, where Δt is the time step used in the numerical simulation [2, 3]. The total force on each vortex, due to all other vortices and pinning sites can be expressed as follows:

$$\boldsymbol{f}_i = \sum_{j=1}^{N_v} f_\circ K_1\left(\frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{\lambda}\right)\hat{r}_{ij} + \sum_{k=1}^{N_p} \frac{f_p}{r_p}\left|\boldsymbol{r}_i - \boldsymbol{r}_k^p\right| \Theta\left(\frac{r_p - \left|\boldsymbol{r}_i - \boldsymbol{r}_k^p\right|}{\lambda}\right)\hat{r}_{ik} \tag{2}$$

Here Θ is the Heaviside step function, $\boldsymbol{r}_i$ is the location of the i^{th} vortex, $\boldsymbol{r}_k^p$ is the location of the k^{th} pinning site, $\hat{r}_{ij} = (\boldsymbol{r}_i - \boldsymbol{r}_j)/|\boldsymbol{r}_i - \boldsymbol{r}_j|$, $\hat{r}_{ik} = (\boldsymbol{r}_i - \boldsymbol{r}_k^p)/|\boldsymbol{r}_i - \boldsymbol{r}_k^p|$, f_p is the pinning strength, N_v is the number of vortices, and N_p is the number of pinning sites. We measure all forces in units of $f_\circ = \phi_\circ^2/8\pi^2\lambda^3$, fields in units of $\phi_\circ/\lambda^2$, lengths in units of λ, temperature in units of $\lambda f_\circ/k_B$, and the velocity in units of $f_\circ/\eta$. We take $f_\circ = k_B = \eta = 1$. Our system has a size of $36\lambda \times 36\lambda$. The pinning sites are distributed over this area in a square array with a density $n_p = 0.74\lambda^{-2}$.

Initially, we place the vortices in a perfect lattice subject to a uniform driving force f_d in the positive *x*-direction (which would correspond to a Lorentz force due to an applied current). For each value of the driving force F_d, the average velocity $\bar{v}_x$ of all vortices is calculated after the steady-state is reached:

$$\bar{v}_x = \frac{1}{N_v} \sum_{i=1}^{N_v} v_i \cdot \hat{x}, \tag{3}$$

The average velocity $\bar{v}_x$ versus the force f_d curve corresponds experimentally to a voltage-current, $V(I)$, curve. The critical depinning force F_d^c corresponds to the critical current density marking a transition from the pinned to the moving vortex phase. In the present work, we investigate the vortex dynamics in the low current driven region where $f_d < F_d^c$.

We used the Euler method to solve the equations of motion. The time step used is $\Delta t = 0.02$. we found that the maximum time needed for the vortices to reach a steady state is 2×10^4 for all of our calculations.

Results and discussion

In this part, we present results and discussions on the outcomes of our simulations. Figure 1 shows the average velocity $\bar{v}_x$ versus the driving force f_d calculated at different temperatures and for $N_p = 961$, $N_v = 625$, $f_p = 2.0$ and $r_p = 0.2$. At zero temperature, the average velocity remains zero up to the value of the critical depinning force F_d^c. Above F_d^c, the vortices are depinned and flow. As the temperature is raised, F_d^c becomes lower due to the extra thermal energy gained by the vortices.

A careful examination of the dynamics of these results at low temperature reveals two distinct phases, a plastic phase where a small number of vortices are depinned and an elastic phase where all the vortices are depinned. The transition from the plastic phase to the elastic phase is smeared out as the temperature is raised and it disappears completely at high temperatures where pinning cease to exist. Similar results were obtained when the size of the array, the density of pinning sites, the strength of pinning and the size of pinning sites are varied.

In our previous report [30], we reported on an anomaly of the critical current density during the course of our simulations, we termed it the “dip effect” in analogy to the well known “peak effect

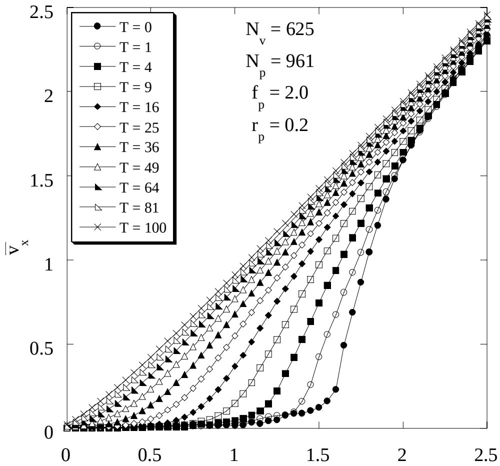

Figure 1: The average velocity $\overline{\mathrm{v}}_x$ versus the driving force f_d calculated at different temperatures and for $N_p = 961$, $N_{\mathrm{v}} = 625$, $f_p = 2.0$ and $r_p = 0.2$.

This dip effect was found to occur only at zero temperature. Figure 2 is a plot of the critical depinning force F_d^c as function of B/B_ϕ, where B is the magnetic flux density of the vortices and B_ϕ is a flux density corresponding to the pinning sites. The curves in the plot correspond to different values of the pinning force strength f_p. These curves were obtained for a number of pinning centers $N_p = 961$ and a pinning radius r_p= 0.2. It is seen that F_d^c decreases as the density of vortices is increased; however, a clear dip in this general behavior of F_d^c occurs. We have found that this dip is mostly pronounced for $f_p = 1.0$, $f_p = 2.0$, $f_p = 3.0$, and $f_p = 4.0$ and slowly disappears below and above these values. It is also interesting to note that this dip occurs only at $B/B_\phi \approx 0.4$ (which is just a fraction of the first matching field), corresponding to $d/d_\phi = 3/5$, where d and d_ϕ are the lattice constants of the initial vortex lattice and the pinning centers lattice, respectively.

We have carried out extensive simulations to study the properties of the dip effect further where we investigate the role of temperature and size of pinning sites. Figures 3 shows F_d^c as a function of B/B_ϕ at $T = 0$ and $f_p = 2.0$ for different values of $r_p \leq 0.2$. It is clearly seen that the dip exists only at $r_p = 0.2$ and $B/B_\phi \approx 0.4$. It is seen that the value of F_d^c increases as r_p is increased at any given value of B except at $B/B_\phi \approx 0.4$ and $r_p = 0.2$ where the dip takes place. Figure 4 shows F_d^c as a function of B/B_ϕ at $T = 0$ and $f_p = 2.0$ for different values of $r_p \geq 0.2$. It is also clearly seen that the dip occurs only at $r_p = 0.2$ and $B/B_\phi \approx 0.4$. Figure 5 give plots of F_d^c versus B at different temperatures for r_p= *0.2* and $f_p = 2.0$. As the temperature is decreased the value of F_d^c increases at any given value of *B* except at $B/B_\phi \approx 0.4$ and *T = 0* where a pronounced dip is clearly seen. These results clearly show that the dip effect in F_d^c takes a place only at *T = 0*, r_p= *0.2* and $B/B_\phi \approx 0.4$ i.e. at the same vortex density for different values of pinning strength f_p. Size of pinning sites and high temperatures were found to have no effect on the dip effect.

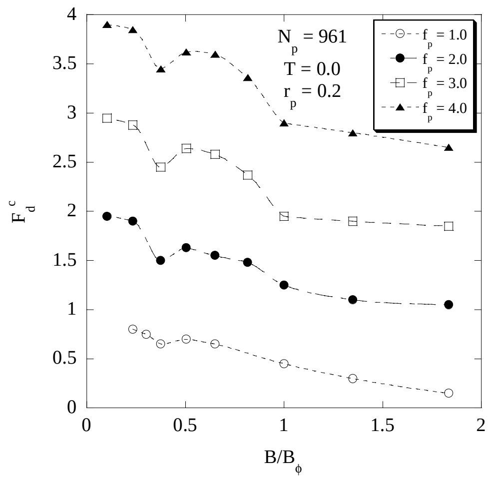

Figure 2: The critical depinning force F_d^c as a function of B/B_ϕ calculated for different values of pinning force f_p at zero temperature and a pinning radius r_p= *0.2*.

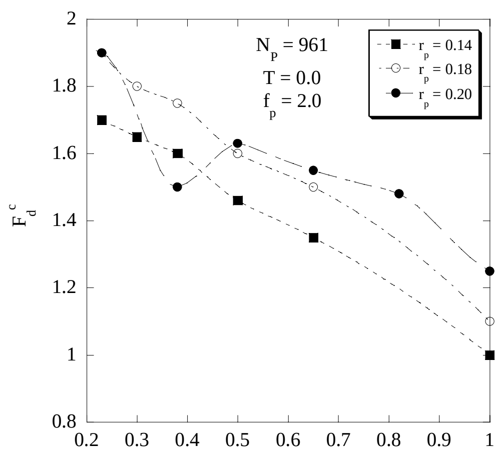

Figure 3: The critical depinning force F_d^c as a function of B/B_ϕ calculated for different values of $r_p \le 0.2$ at zero temperature and for $f_p = 2.0$.

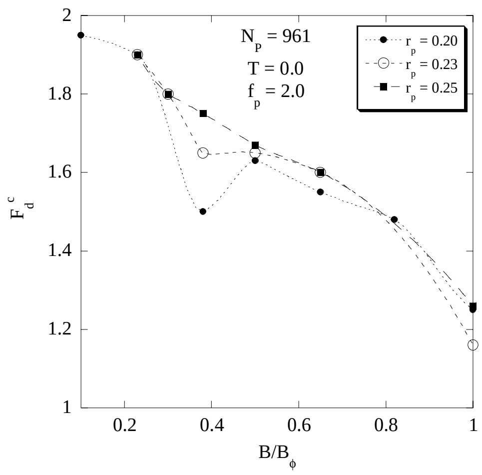

Figure 4: The critical depinning force F_d^c as a function of B/B_ϕ calculated for different values of $r_p \geq 0.2$ at zero temperature and for $f_p = 2.0$.

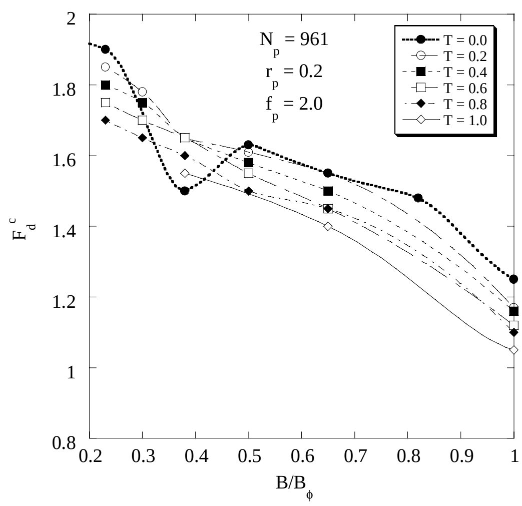

Figure 5: The critical depinning force F_d^c as a function of B/B_ϕ calculated at different temperatures when $r_p = 0.2$ and $f_p = 2.0$.

In our simulations, the vortices were initially distributed in a square lattice over the whole system such that the number of vortices is less than the number of pinning centers. This arrangement gives a few rows of vortices initially located at or near the pinning centers. This initial distribution is mainly responsible for the formation of flow channels. On one hand, the rows of vortices which are initially located at or very close to the pinning centers get pinned with time and eventually form *pinned channels*. On the other hand, rows which are situated close to mid-distance between rows of pinning centers will likely form *flow channels*. The rest of vortices are randomly pinned. The vortex-vortex interaction modifies this picture slightly. The dynamics of vortices at the dip and away from it were investigated. At the bottom of the dip we have found that while many of the vortices are pinned, a considerable number of vortices continue to move in 5 channels. This is responsible for lowering the value of F_d^c giving rise to the dip. Just before reaching the bottom of the dip we have found that the majority of the vortices are pinned and the flow has been suppressed considerably, giving rise to a higher value of F_d^c. We have investigated this behavior further for different values of pinning strength f_p and found that the dip is always associated with the formation of flow channels at $T = 0$ and $B/B_\phi \approx 0.4$.

Conclusion

We have carried out simulations on the behavior of the critical current density in high temperature superconductors in the presence of applied magnetic fields and pinning centers. The variables in our simulations were the vortex density, the temperature, the pinning strength and the size of pinning sites. We have found that a dip in the critical current density occurs only at $T = 0$, $r_p = 0.2$ and $B/B_\phi \approx 0.4$ for different values of pinning strength f_p. Size of pinning sites and higher temperatures were found to have no role on the dip effect. We attribute the occurrence of such dip to the formation of flowing and pinned channels of vortices.

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