Metastability and Transient Effects in Vortex Matter Near a Decoupling Transition

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We examine metastable and transient effects both above and below the first-order decoupling line in a 3D simulation of magnetically interacting pancake vortices. We observe pronounced transient and history effects as well as supercooling and superheating between the 3D coupled, ordered and 2D decoupled, disordered phases. In the disordered supercooled state as a function of DC driving, reordering occurs through the formation of growing moving channels of the ordered phase. No channels form in the superheated region; instead the ordered state is homogeneously destroyed. When a sequence of current pulses is applied we observe memory effects. We find a ramp rate dependence of the V(I) curves on both sides of the decoupling transition. The critical current that we obtain depends on how the system is prepared.

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Vortices in superconductors represent an ideal system in which to study the effect of quenched disorder on elastic media. The competition between the flux-line interactions, which order the vortex lattice, and the defects in the sample, which disorder the vortex lattice, produce a remarkable variety of collective behavior [1]. One prominent example is the peak effect in low temperature superconductors, which appears near $H_{c2}$ when a transition from an ordered to a strongly pinned disordered state occurs in the vortex lattice [2–8]. In high temperature superconductors, particularly BSCCO samples, a striking “second peak” phenomenon is observed in which a dramatic increase in the critical current occurs for increasing fields. It has been proposed that this is an order-disorder or 3D to 2D transition. [9–13]

Recently there has been renewed interest in transient effects, which have been observed in voltage response versus time curves in low temperature superconductors [5–7,14–17]. In these experiments the voltage response increases or decays with time, depending on how the vortex lattice was prepared. The existence of transient states suggests that the disordered phase can be supercooled into the ordered region [21], producing an increasing voltage response, whereas the ordered phase may be superheated into the disordered region, giving a decaying response. In addition to transient effects, pronounced memory effects and hysteretic V(I) curves have been observed near the peak effect in low temperature materials [2,4–7,16–20]. Memory effects are also seen in simulations [22]. Xiao et al. [7] have shown that transient behavior can lead to a strong dependence of the critical current on the current ramp rate. Recent neutron scattering experiments in conjunction with ac shaking have provided more direct evidence of supercooling and superheating near the peak effect [23]. Experiments on BSCCO have revealed that the high field disordered state can be supercooled to fields well below the second peak line [24]. Furthermore, transport experiments in BSCCO have shown metastability in the zero-field-cooled state near the second peak as well as hysteretic V(I) curves [25], and magneto optic imaging has revealed the coexistence of ordered and disordered phases [26]. Hysteretic and memory effects have also been observed near the second peak in YBCO [27–29].

The presence of metastable states and superheating/supercooling effects strongly suggests that the order-disorder transitions in these different materials are first order in nature. The many similarities also point to a universal behavior between the peak effect of low temperature superconductors and the peak effect and second peak effect of high temperature superconductors.

A key question in all these systems is the nature of the microscopic dynamics of the vortices in the transient states; particularly, whether plasticity or the opening of flowing channels are involved [6]. The recent experiments have made it clear that a proper characterization of the static and dynamic phase diagrams must take into account these metastable states, and therefore an understanding of these effects at a microscopic level is crucial. Despite the growing amount of experimental work on metastability and transient effects in vortex matter near the peak effect transition [5–7], these effects have
In this work we numerically study magnetically interacting pancake vortices driven through quenched point disorder. As a function of applied field, temperature, or interlayer coupling the model exhibits a sharp 3D (coupled, ordered phase) to 2D (decoupled, disordered phase) transition, consistent with theoretical expectations [12,13], that is associated with a large change in the critical current [30]. Near the disordering transition, we find strong metastability and transient effects. A metastable state is a thermodynamic state that is out of equilibrium, which persists for a time longer than the characteristic relaxation time of the system at equilibrium [33]. By supercooling or superheating the ordered and disordered phases, we find increasing or decreasing transient voltage response curves, depending on the amplitude of the drive pulse and the proximity to the disordering transition. In the supercooled transient states a growing ordered channel of flowing vortices forms. No channels form in the superheated region but instead the ordered state is homogeneously destroyed. We observe memory effects when a sequence of pulses is applied, as well as ramp rate dependence and hysteresis in the $V(I)$ curves. The critical current we obtain depends on how the system is prepared.

We consider a 3D layered superconductor containing an equal number of pancake vortices in each layer, interacting magnetically. We neglect the Josephson coupling, which is a reasonable approximation for highly anisotropic materials. The overdamped equation of motion for vortex $i$ at $T = 0$ is

$$f_i = -\sum_{j=1}^{N_v} \nabla_j U(\rho_{ij}, z_{ij}) + f_i^{\text{pp}} + f_d = \eta v_i.$$  

The total number of pancakes is $N_v$, and $\rho_{ij}$ and $z_{ij}$ are the distance between vortex $i$ and vortex $j$ in cylindrical coordinates. We impose periodic boundary conditions in the $x$ and $y$ directions and open boundaries in the $z$ direction. The magnetic interaction energy between pancakes is [34,35]

$$U(\rho_{ij}, 0) = 2d\epsilon_0 \left(1 - \frac{d}{2\lambda} \ln \frac{R}{\rho} + \frac{d}{2\lambda} E_1\right),$$  

$$U(\rho_{ij}, z) = -s_m d^2 \epsilon_0 \lambda \left(\exp(-z/\lambda) \ln \frac{R}{\rho} + E_2\right),$$  

where $E_1 = \int_\rho^\infty d\rho' \exp(-\rho'/\lambda)/\rho'$, $E_2 = \int_\rho^\infty d\rho' \exp(-\sqrt{z^2 + \rho'^2}/\lambda)/\rho'$, $R = 22.6\lambda$, the maximum in-plane distance, $\epsilon_0 = \Phi_0^2/(4\pi\lambda)^2$, $d = 0.005\lambda$ is the interlayer spacing as in BSCCO, $s_m$ is the coupling strength, and $\lambda$ is the London penetration depth. The viscosity $\eta = B_2\Phi_0/\rho N$, where $\rho N$ is the normal-state resistivity. Time is measured in units of $\eta/f_0^*$. For example, in the case of a BSCCO sample 2 $\mu$m thick, taking $\lambda = 250$ nm, $\xi = 1.8$ nm, and $\rho_N = 2.8$ m$\Omega$ cm gives the value of a single time step as 0.4 ns. We model the pinning as $N_p$ short range attractive parabolic traps that are randomly distributed in each layer. The pinning interaction is $f_i^{\text{pp}} = -\sum_{j=1}^{N_v} (f_p/\xi_p) (r_i - r_j^{(i)}) \Theta((\xi_p - |r_i - r_j^{(i)}|)/\lambda)$, where the pin radius $\xi_p = 0.2\lambda$, the pinning force is $f_p = 0.02 f_0^*$, and $f_0^* = e_0/\lambda$. We fix the temperature $T = 0$. To vary the applied magnetic field $H$, we fix the number of vortices in the system and change the system size, thereby changing the vortex density $n_v$. The pin density remains fixed. We use $L = 16$ layers throughout this work, and except where mentioned, we focus on a system that ranges from $12.9\lambda \times 12.9\lambda$ to $14.8\lambda \times 14.8\lambda$, with a pin density of $n_p = 1.0/\lambda^2$ in each of the layers. We have also studied a sample with stronger, denser pinning of $\xi_p = 0.1\lambda$, $f_p = 0.08 f_0^*$, and $n_p = 8.0/\lambda^2$, of size $5.1\lambda \times 5.1\lambda$ to $6.9\lambda \times 6.9\lambda$. In each case there are $N_v = 80$ vortices per layer, giving a total of 1280 pancake vortices.

For sufficiently strong disorder, the vortices in this model show a sharp 3D-2D decoupling transition as a function of coupling strength $s_m$, vortex density $H$ [30,36], or temperature [36,37]. A dynamic 2D-3D transition can also occur [30]. There are actually two disordered transitions that occur in the model: a decoupling transition from 3D to 2D, and an in-plane disordered transition. In our studies, we find that these two transitions always coincide, and appear as a single transition from a 3D state that is ordered in the plane and coupled between planes, to a 2D state that is decoupled and disordered in the plane. We denote the magnetic field at which the static 3D-2D transition occurs as $n_v^c$, and the coupling strength at which the transition occurs as $s_m^c$. For the main system considered here, a transition from ordered 3D flux lines to disordered, decoupled 2D pancakes occurs at $s_m^c = 1.2$ with $n_v = 0.3/\lambda^2$ or at $n_v^c = 0.38$ with $s_m = 0.7$. The coupling/decoupling transition occurs twice as a function of field $[8]$, once at low

![FIG. 1. Critical current $f_c$ (filled squares) and interlayer correlation $C_s$ (open circles) for varying $s_m$ in a system with 16 layers, $n_v = 0.3/\lambda^2$, and $f_p = 0.02 f_0^*$, showing the sharp transition from coupled behavior at $s_m \leq 1.2$ to decoupled behavior at $s_m > 1.2$.](image-url)
fields when the vortex lines form as the effective pinning strength begins to decrease away from the single vortex pinning regime, and a second time at higher fields when the magnetic interactions among vortex pancakes in a given plane cause the pancakes in different planes to decouple. We examine the higher field transition in the sample with strong, dense pinning, where \( n^e \) = 3.0 at \( s_m = 0.7 \). The same effects described here also appear on either side of a temperature-induced 3D-2D transition.

We illustrate the difference in critical current between the coupled and decoupled vortex phases in Fig. 1. As a function of interlayer coupling \( s_m \), we show the critical current \( i_c \), obtained by summing \( v_z = \frac{1}{N_{xy}} \sum v_x \) and identifying the drive \( f_d \) at which \( v_z \) < 0.0005. Also plotted is a measure of the z-axis correlation, \( C_z = 1 - \langle |[r_{xL} - r_{1,L+1}|/a_0/2) \rangle \Theta(a_0/2 - |r_{xL} - r_{1,L+1}|) \), where \( a_0 \) is the vortex lattice constant, and the average is taken over all pancakes in the system. The ordered phase has a much lower critical current, \( f_d^c = 0.0008f_0^*, \) than the disordered phase, \( f_d^{*0} = 0.0105f_0^* \).

To observe transient effects, we supercool the lattice by annealing the system at \( s_m \) < \( s_m^c \) into a disordered, decoupled configuration. Starting from the state, we set \( s_m > s_m^c \) such that the pancakes would be ordered and coupled at equilibrium, and at \( t = 0 \) we apply a fixed drive \( f_d \) for 400000 steps. Application of a driving current is only one possible way in which the equilibrium configuration can be regained. The equilibrium state can also be reached via thermal fluctuations, through gradients in the magnetic field [24], or by applying a rapidly fluctuating magnetic field [31]. In Fig. 2 we show the time-dependent voltage response \( v_z \) for several different drives \( f_d \) for a sample which would be coupled in equilibrium, with \( s_m = 2.0 \), that has been prepared in a decoupled state at \( s_m = 0.5 \). For \( f_d < 0.0053 \pm 0.0001f_0^* \) the system remains pinned in a decoupled disordered state. For \( f_d \sim 0.0053f_0^* \) a time dependent increasing response occurs. \( v_z \) does not rise instantly but only after a specific waiting time \( t_w \). The rate of increase in \( v_z \) grows as the amplitude of the \( f_d \) increases. As shown in Fig. 3(a,b), the z-axis correlation \( C_z \) exhibits the same behavior as \( v_z \), indicating that the vortices are becoming more aligned in the z direction as time passes. If the vortices move in response to thermal activation, a voltage response of the form \( V_z(t) = G_0(1 - e^{-Wt}) \) should appear [15]. Since our simulation is at \( T = 0 \), we would not expect thermal activation to apply. Instead, the response we observe can be fit by an exponential form only at long times, such as \( t \geq 30000 \) in Fig. 3, when \( v_z \) is beginning to saturate. At intermediate times (5000 < \( t < 30000 \) in Fig. 3(a,b)) the increase in \( v_z \) and \( C_z \) is roughly linear with time. As we will show below, this linear increase indicates that an ordered regime is growing at a constant rate. The amount of time required for the system to reach a steady voltage response level is indicative of the fact that we have started the system in a metastable state. If we prepare the lattice in its equilibrium configuration of coupled lines and then apply the same currents shown in Fig. 2, the voltage response reaches its full, steady value within less than 100 steps, whereas in Fig. 2, 10000 to 50000 steps are required.

To determine how the vortex lattice is moving when \( v_z \) is nearly zero (during \( t_w \)), linearly increasing, and saturating exponentially, we show the vortex positions and trajectory images in the supercooled sample in Fig. 4. Here a series of images have been taken from a sample in Fig. 2 with \( s_m = 2.0 \) for \( f_d = 0.007f_0^* \) for different times. In Fig. 4(a) at \( t = 2500 \) the initial state is disordered. In Fig. 4(b) at \( t = 7500 \) significant vortex motion occurs through the nucleation of a single channel of moving vortices. At lower drives the channel gradually appears
Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time. Vortices do not begin to move until the edge of the ordered channel reaches them. Therefore, the linear increase in $V_x$ indicates that the number of moving vortices is also increasing linearly in time.
moving vortices. If we assume that these interactions do not change with $f_d$, since $f_d$ is not being applied in the transverse direction, then $f_{\text{eff}}^T$ remains constant while $f_{\text{dp}}^T$ decreases with increasing applied drive $f_d$. As a result, the ordered front propagates outward more quickly as $f_d$ increases, and the saturation time $t_s$ required for the ordered channel to fill the entire sample decreases. In Fig. 5 the dotted line indicates a fit to

$$t_s \propto (f_d - f_0)^{-1},$$

with $f_0^d = 0.0053$. For $f_d < 0.0053 f_0^d$, there was no voltage response to the applied current over the time period we considered (indicating that $t_w > 400000$) and the vortices remained stationary in the supercooled state. The apparent discontinuity in $t_w$ from a finite to an unmeasured value arises only because our simulations were performed for a finite amount of time.

We next consider transient effects produced by superheating the lattice. In Fig. 6 we show a superheated system at $s_m = 0.7$ prepared in the ordered state by artificially placing the vortices into perfectly aligned columns at $t = 0$. Here we find a large initial $V_x$ response that decays. With larger $f_d$ the decay takes an increasingly long time. The time scale for the decay is much shorter than the time scale for the increasing response in Fig. 2. As illustrated in Fig. 3(c) and (d), the $z$-axis correlation $C_z$ decays more rapidly than the overall voltage response $V_x$, indicating that vortex motion continues to occur even after the vortex lines have been broken apart into individual pancakes. The form of $V_x$ cannot be fit by any simple function over a significant period of time. The decay of $C_z$, however, is nearly linear with time before saturating at $t \approx 35000$. For $f_d \geq 0.011 f_0^d$ the voltage does not decay completely away to zero, but the vortices continue to move in the disordered state.

The decaying response of the superheated vortex state resembles the yield drop curves observed in crystalline solids, as first noted in low-$T_c$ materials by Good and Kramer [16]. In a yield drop, the stress required to maintain a constant shear strain rate decreases with time. Such a drop occurs when the crystalline solid has a low initial concentration of defects, and the drop is associated with a proliferation of dislocations inside the crystal. In the case of the superheated vortex lattice, a transition from the ordered to the disordered state occurs and the
vortex velocity drops. Good and Kramer find that the total drop in the response of the vortex lattice increases linearly with the applied voltage [16]. To paraphrase their argument, the voltage response of the lattice can be written $V^*$ as it moves until the entire line

dissociates and is pinned. Since all of the vortex lines are pinned at the point pinning as it moves until the entire line

does not repin.

The vortex positions and trajectories for a superheated sample with $s_m = 0.7$ and $f_d = 0.009 f_0^m$. The current is shut off for 400 time steps beginning at $t = 400$, and is turned back on at $t = 800$.

In Fig. 9 we demonstrate the presence of a memory effect by abruptly shutting off $f_d$ at $t = 400$ for 400 time steps. The vortex motion stops when the drive is shut off, and when $f_d$ is re-applied $V_x$ resumes at the same point. We find such memory on both the increasing and decreasing response curves. Since we are at zero temperature, it is the applied current, and not thermal effects, that is responsible for the vortex motion, and thus the vortices cannot adjust their positions in the absence of a driving current. The response curves and memory effect seen here are very similar to those observed in experiments [7,16].

We next consider the effect of changing the rate $\delta f_d$ at which the driving force is increased on $V(I)$ in both superheated and supercooled systems. Fig. 10(a) shows (a): $V(I)$ for a supercooled system at $s_m = 2.0$. Top (light line): slow $\delta f_d$ of 0.0001 $f_0^m$ every 2000 time steps. Bottom (heavy line): $\delta f_d = 0.001 f_0^m$. (b): $V(I)$ for a superheated system at $s_m = 0.7$. From left to right, $\delta f_d =$ (fast) 0.02 $f_0^m$, 0.01 $f_0^m$, 0.005 $f_0^m$, 0.002 $f_0^m$, 0.001 $f_0^m$, 0.0002 $f_0^m$, and 0.0001 $f_0^m$ (slow).

FIG. 10. (a): $V(I)$ for a supercooled system at $s_m = 2.0$. Top (light line): slow $\delta f_d$ of 0.0001 $f_0^m$ every 2000 time steps. Bottom (heavy line): $\delta f_d = 0.001 f_0^m$. (b): $V(I)$ for a superheated system at $s_m = 0.7$. From left to right, $\delta f_d =$ (fast) 0.02 $f_0^m$, 0.01 $f_0^m$, 0.005 $f_0^m$, 0.002 $f_0^m$, 0.001 $f_0^m$, 0.0002 $f_0^m$, and 0.0001 $f_0^m$ (slow).

FIG. 11. Effect of supercooling on $f_c$. Filled squares: equilibrium $f_c$. Open diamonds: $f_c$ for samples prepared in a disordered, decoupled state.
FIG. 12. Transient voltage response curves $V_x$ versus time.
(a) Increasing response for supercooled state, for $n_v = 2.5$ and $f_d/f_0^* = (bottom) 0.008, 0.009, 0.010, 0.011, 0.012, 0.013, \text{ and } 0.014 \ (top)$. (c) Decreasing response for superheated state, for $n_v = 3.1$ and $f_d/f_0^* = (bottom) 0.0016, 0.0017, 0.00175 \text{ and } 0.0018 \ (top)$.

$V_x$ versus $f_d$, which is analogous to a $V(I)$ curve, for the supercooled system at $s_m = 2.0$ prepared in a disordered state. $V_x$ remains low during a fast ramp, when the vortices in the strongly pinned disordered state cannot reorganize into the more ordered state. There is also considerable hysteresis since the vortices reorder at higher drives producing a higher value of $V_x$ during the ramp-down. For the slower ramp the vortices have time to reorganize into the weakly pinned ordered state, and remain ordered, producing no hysteresis in $V(I)$.

In a superheated sample, the reverse behavior occurs. Fig. 10(b) shows $V(I)$ curves at different $\delta f_d$ for a system with $s_m = 0.7$ prepared in the ordered state. Here, the fast ramp has a higher value of $V_x$ corresponding to the ordered state while the slow ramp has a low value of $V_x$. During a slow initial ramp in the superheated state the vortices gradually disorder through rearrangements but there is no net vortex flow through the sample. Such a phase was proposed by Xiao et al. [7] and seen in recent experiments on BSCCO samples [24]. At the slower $\delta f_d$, we find negative $dV/dI$ characteristics which resemble those seen in low- [14,41–44] and high- [45] temperature superconductors. Here, $V(I)$ initially increases as the vortices flow in the ordered state, but the vortices decouple as the lattice moves, increasing $f_c$ and dropping $V(I)$ back to zero, resulting in an N-shaped characteristic.

To demonstrate the effect of vortex lattice disorder on the critical current, in Fig. 11 we plot the equilibrium $f_c$ along with $f_c$ obtained for the supercooled system, in which each sample is prepared in a state with $s_m = 0.5$, and then $s_m$ is raised to a new value above $s_m^c$ before $f_c$ is measured. The disorder in the supercooled state produces a value of $f_c$ between the two extrema observed in the equilibrium state. Note that the sharp transition in $f_c$ associated with equilibrium systems is now smooth. A similar increase in the critical current when the vortex lattice has been prepared in a disordered state, rather than in an ordered state, has also been observed experimentally as a history effect [15,46–51].

We find the same metastable and history-dependent effects described above on either side of a magnetic-field...
driven disordering transition. To demonstrate this, in Fig. 12(b) we show ordered, coupled vortices as illustrated in Fig. 13. In response is associated with the formation of a channel of ordered vortices followed by an increase in the channel width over time. In the superheated case the ordered phase homogeneously disorders. We also demonstrate that the measured critical current depends on the vortex lattice preparation and on the current ramp rate.

Our simulation does not contain a surface barrier which can inject disorder at the edges. Such an effect is proposed to explain experiments in which AC current pulses induce an increasing response as the vortices reorder but DC pulses produce a decaying response [6,8]. We observe no difference between AC and DC drives.

In low temperature superconductors, a rapid increase in z-direction vortex wandering occurs simultaneously with vortex disordering [23], suggesting that the change in z-axis correlations may be crucial in these systems as well. Our results, along with recent experiments on layered superconductors, suggest that the transient response seen in low temperature materials should also appear in layered materials.

In summary we have investigated transient and metastable states near the 3D-2D transition by supercooling or superheating the system. We find voltage-response curves and memory effects that are very similar to those observed in experiments, and we identify the microscopic vortex dynamics associated with these transient features. In the supercooled case the vortex motion occurs through nucleation of a channel of ordered moving vortices followed by an increase in the channel width over time. In the superheated case the ordered phase homogeneously disorders. We also demonstrate that the measured critical current depends on the vortex lattice preparation and on the current ramp rate.

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