Eva Y. Andrei[1], Z.L. Xiao[1], W. Henderson[1,2], M. J. Higgins[3], M. Shuk[4], M. Greenblatt[4]

[1] Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08855
[2] Department of Physics, University of California, Los Angeles, California 90024-1547
[3] NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540
[4] Department of Chemistry, Rutgers University, Piscataway, New Jersey 08855

Abstract We report on a novel form of organization of magnetic vortices in a superconductor driven by a current. By following the vortex motion with fast transport measurements we show that the current enables the system to escape out of metastable states and explore its energy landscape. At low fields and temperatures the system relaxes into an ordered vortex lattice while just below H_{c2} it is in a disordered state. In the intermediate region the vortex state can be controlled by an external driving current. In this regime the critical current can be either increased or decreased with an appropriate driving current.

1. INTRODUCTION

Recent experiments on the dynamics of vortices in type II superconductors have revealed a number of unusual and surprising phenomena such as strong metastability, nonlinear response, frequency memory , logarithmic time scales and glassy dynamics [1-6]. These are most prominent in the so called peak effect region- a strip in the *H-T* phase diagram marked by a rise in the critical current, I_c , as H_{c2} *(T)* is approached. The peak in I_c , which can be as much as one order of magnitude above the low temperature value, is attributed to the formation of a disordered vortex state as softening of the vortex interactions close to H_{c2} facilitates vortex pinning on randomly distributed material defects [7]. The peak effect region separates an ordered vortex state which is stable at low *T* and *H,* from a disordered glassy state above it..

The degree of order of a vortex system is the outcome of the competition between vortex-vortex interactions, pinning and thermal fluctuations. When thermal fluctuation are negligible compared to pinning, the vortex state is determine by the pinning strength: the stronger the pinning the more it is disordered and the higher the critical current density $J_{c.}$ As was shown by Larkin and Ovchinikov [7] and more recently by small angle neutron scattering experiments [8], J_c is inversely proportional to the size of an ordered domain and therefore it is frequently used, as was done in the experiments described below, to quantify the degree of vortex order.

When the vortices move the vortex state depends on the velocity as well. At high velocities fluctuations of the pinning potential are averaged out leading to a more ordered state [9]. As the velocity is reduced the competition between pinning, vortex interactions and thermal fluctuations sets in. Our experiments show that in the presence of strong metastable states the vortex velocity is the crucial factor in driving the system towards equilibrium by enabling it to explore the energy landscape. In principle it may be possible to reach thermodynamic equilibrium if the vortex velocity is increased adiabatically so that at all times it is too low to cause averaging of the pinning potential but yet allows access to nearby configurations.

2. EXPERIMENTAL RESULTS

2.1 Metastability

The existence of strongly metastable vortex states below the peak region was demonstrated in transport experiments on low T_c superconductors [1,4,6]. For example if the system is prepared by field cooling, FC, whereby the sample is cooled through T_c in the presence of a field, the resulting state is completely disordered. By contrast if the system is prepared by zero field cooling, ZFC, the vortex state is ordered having the lowest possible critical current for a given field and temperature. Both types of preparation can lead to a metastable state: the ZFC state is metastable in the peak region and the FC state is metastable below it. If thermal fluctuations are small compared to the pinning potential such metastable states could live indefinitely. The metastability effects can be significantly enhanced by introducing strong pinning centers. In $NbSe_2$ doping with Fe leads to strong metastability without appreciable deterioration of sample quality (superconducting transition width is unchanged). This is illustrated in Fig. 1 showing the H-T phase diagram

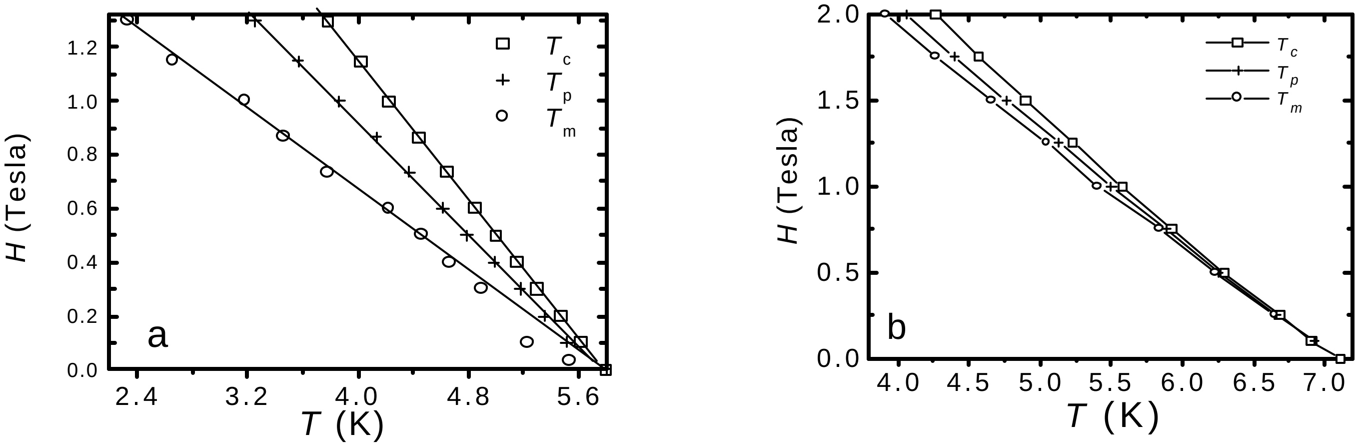

Figure 1: *H-T* phase diagram for two 2H-$NbSe_2$ samples. The peak effect region is bracketed by $T_p(H)$ and $T_m(H)$ –the temperatures of the peak and minimum in critical current . a) Doped sample Fe (200ppm). b) Undoped sample.

Here we describe experiments on doped 2H-$NbSe_2$ (Fe-200ppm) samples which illustrate the role played by the current in driving the system towards or away from equilibrium and the unusual vortex dynamics associated with these processes. Fast transport measurements were used to study the vortex dynamics in response to an applied current step or ramp, as described in [2]. The vortex response is monitored through the longitudinal voltage drop V. Both accessible transport quantities, the voltage and the applied current, are global in nature: $I=\int J(x)dx$ is the weighted average of the current density and $V=vBd$, is a measure of the average vortex current, with v the mean vortex velocity weighted over the vortex density, B the applied field and d the distance between the voltage leads.

Fig. 2 – illustrates the metastability. The temperature dependence of I_c at 0.4T is plotted for two states, one prepared by FC and the other by ZFC, showing that for the same field and temperature the system can exist in different states depending on its history. Below temperatures corresponding to the peak in I_c, the ZFC state has a significantly lower critical current, and therefore is more ordered than the FC state. At the peak and above it, I_c is independent of history and its value corresponds to a completely disordered state (domain size is comparable to inter-vortex spacing). The decrease in I_c on approaching H_{c2} is due to the onset of thermal creep.

The difference between the two states can be understood as follows: in the FC case, during the cool-down process the vortices evolve from a homogeneous field distribution above T_c through a region of large overlapping vortex cores which can easily adapt to the local pinning potential creating a disordered state. Upon further cooling, if thermal fluctuations are too weak compared to the pinning potential, the vortices remain trapped in the disordered state even when the ordered state has a lower energy. In the ZFC case the sample is already superconducting when the field is turned on. As the field increases so do the Meissner shielding currents until vortex penetration occurs when they exceed J_c. The vortices enter the sample with large velocities which leads to an ordered state.

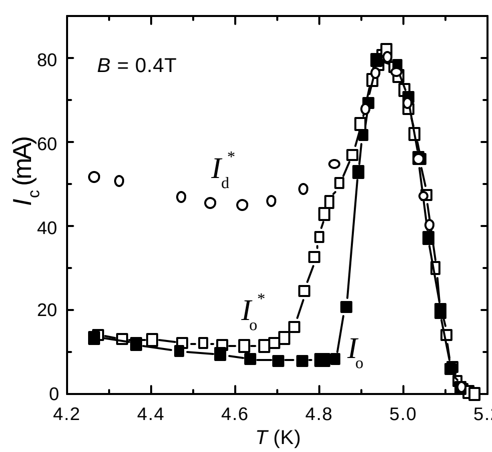

Figure 2: Temperature dependence of critical current. ❍ FC state measured by SCR. ⊡ ZFC state measured by SCR. ■ ZFC statte measurent by FCR .

The critical current of the ZFC state was obtained by measuring the voltage response to two extreme current ramps:

a slow current ramp (SCR)- 10^{-3} A/s and a fast current ramp (FCR) - 200A/s. The SCR curve, I_o^*, merges with the FCR curve, I_o, at low temperatures. Just below the peak I_o^* is significantly higher than I_o indicating that during the SCR the vortex state rearranges and settles into a more strongly pinned state. The critical current of the FC state shown in the figure was obtained with an SCR and is labeled as I_d^* . The corresponding FCR curve (not shown) lies is slightly weaker [4, 11].

2.2 Current Driven organization

2.2.1 Current driven order

The decrease in critical current of the FC state during the SCR shows that below the peak region the current causes the FC lattice to become more ordered. To directly observe this annealing process we applied a current step to the FC state and monitored the time evolution of the response [4]. For a current step $I< I_d^*$ no measurable response is observed while for $I>I_d$, the response is finite increasing rapidly with time to the value obtained for an ordered phase. For $I_d^* <I<I_d$ shown in Fig. 3, the response is initially zero, followed by a

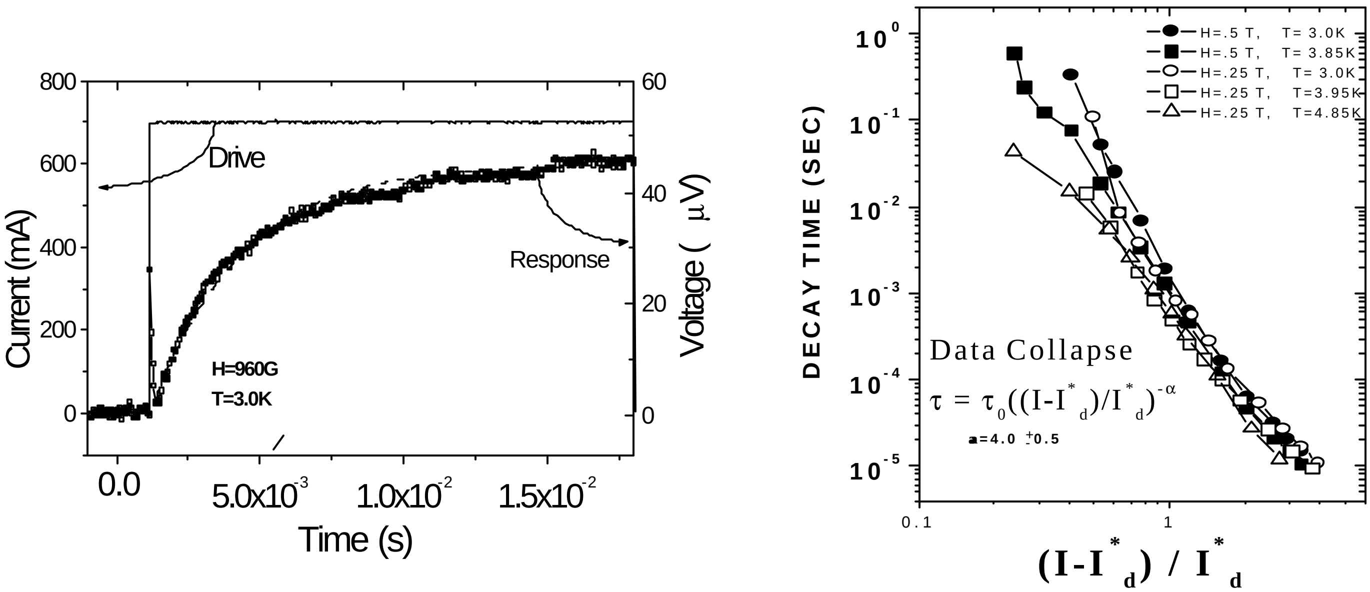

Figure 3: Current driven ordering of vortex state. a) Time dependence of response of an FC sate to a current step in the range $I_d^* <I<I_d$. b) The characteristic time scale for current driven ordering diverges as $I \rightarrow I_d^*$.

gradual increase which saturates at a value close to the response of an ordered lattice $V(t)= V_o(1-\exp(t/\tau))$. The characteristic time scale τ, shown in the inset, diverges as the current approaches I_d^*. The data for all measured temperatures and fields can be collapsed according to $\tau=\tau_o((I- I_d^*)/ I_d^*)^{-4}$. After the response has saturated the critical current is reduced to that of the ordered state. In other words the current lifts the system out of the metastable disordered state and drives it towards the more stable ordered state.

2.2.2 Current driven disorder

The complementary process in the peak region is illustrated Fig. 4. Here a current step applied to a metastable ordered state prepared by ZFC causes it to rearrange into a more disordered state. This process too can be seen directly by monitoring the evolution of the response to a current step. For a current $I> I_o$ the response is initially large followed by a slow decay during which the system becomes gradually more disordered. If $I< I_o^*$ the response decays to zero whereas for $I> I_o^*$ it decays to a finite value. This again shows that the current assists the system in finding a more stable state: in the peak region it is a state that is more disordered than the ZFC state, whereas below the peak it is the same as the ZFC state.

To illustrate the process of current driven evolution toward a more disordered state we monitored the critical current during the decay. This can be done by taking advantage of the metastability: removal of the current causes the vortices to freeze in place, retaining its prior configuration[1,2]. Thus if the driving current is removed during the decay the state of the vortex system at that moment can be deduced by measuring the critical current with an FCR. The result is shown in the inset of Fig 4 where we plot I_c at various times during the decay. As long as $I_o <I<I_o^*$, I_c increases with time saturating at a value that is equal to the driving current. But once $I> I_o^*$ the critical current drops sharply to a value close to that of the ordered state.

lattice is relatively soft, a small but finite vortex velocity can cause an initially ordered lattice to distort and adapt itself to a pinning center thus lowering its energy. The higher value of J_c in such a locally disordered region leads to current depletion outside this region causing vortices to slow down and thus become more prone to pinning and to slow down even more. As time progresses the system becomes more disordered and the critical current keeps increasing until the motion comes to a halt when $I_c=I$. The saturation value of I_c continues to grow with increasing I until $I= I_o^*$ at which point a path becomes available along which the vortex velocity is sufficiently large to traverse the sample without getting pinned [10]. In such a channel the moving vortices become ordered, leading to the sharp drop in the observed critical current. It is thus possible to prepare a vortex state with any desired critical current in the range between I_o and I_o^* by applying a dc current to a ZFC state.

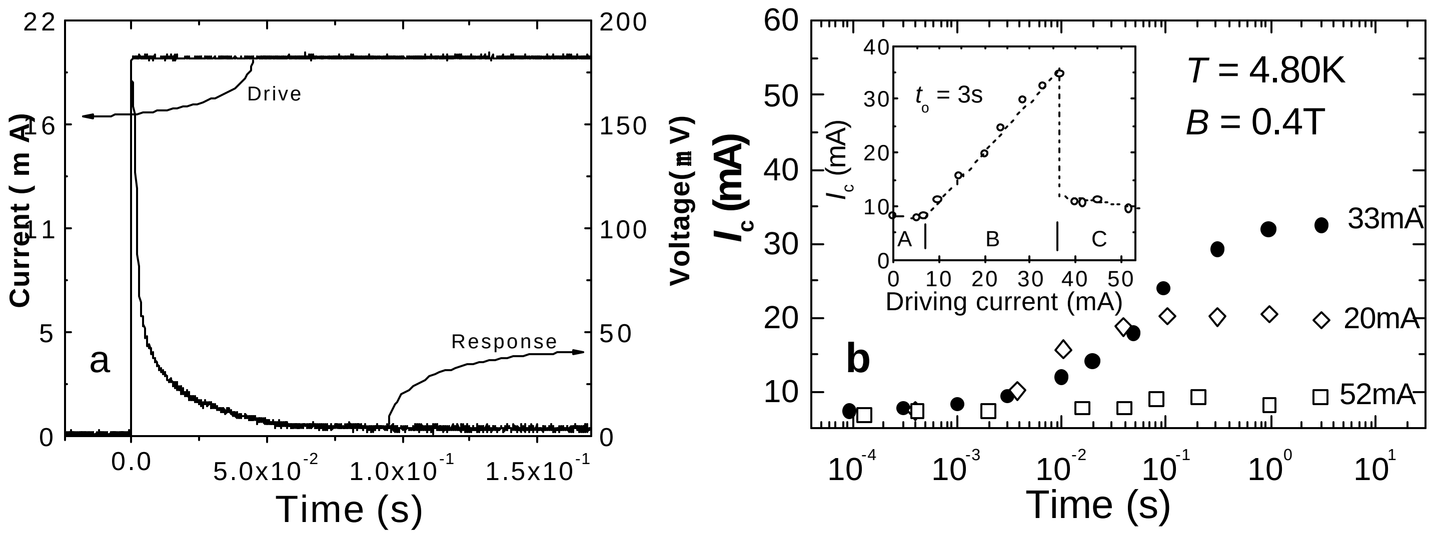

Figure 4: Current driven organization of vortex state: response of a ZFC sate to a dc current step in the range $I_o^* < I < I_o$.
a) Time dependence of response during current step. b) Evolution of critical current during current steps of various amplitudes.
Inset - Saturation value of critical current vs. driving current amplitude.

2.2.3 Current driven de-pinning

The current step experiments have shown that applying a dc current to a metatstable ordered state in the peak region causes it to become more disordered [1]. This process can be reversed by applying an ac current, as illustrated in Fig. 5. The initial disordered state was prepared by applying a dc current $I^o < I < I^{*o}$

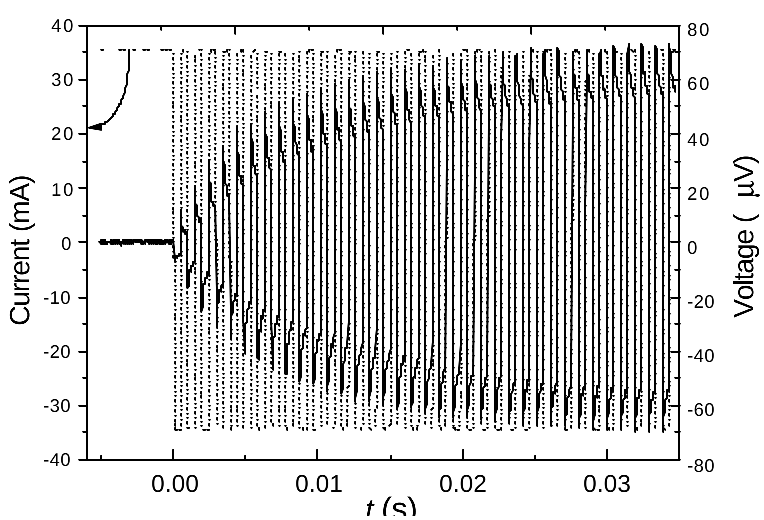

Figure 5. The Fishbone effect: ac current driven ordering.
A square wave of amplitude 35mA (dashed line) is applied to a disordered state as described in text. The response (solid line) grows with every current reversal.

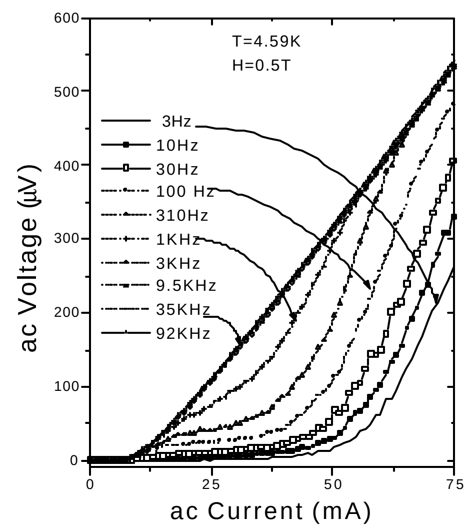

Figure 6. Frequency dependence of I-V curves.
The response increases with increasing frequency saturating to the value of the ordered state.

square wave of amplitude *I* is applied and the time dependence of the voltage response is monitored with a fast amplifier. We note that the response grows with every current reversal starting from the very first kick, and decays somewhat in between. The resulting fishbone pattern keeps growing indicating that the system is becoming more ordered until it saturates at a value that depends on the drive frequency and amplitude. The frequency dependence of the finite frequency *I-V* curves is shown Fig 6. They were recorded with a lock-in amplifier which gives the average value of the saturation response. We note that for sufficiently large frequencies the final state has the same response as the ordered state whereas the low frequency *I-V* approaches that of the disordered state.

The fishbone pattern can be understood as follows: a current reversal requires a field redistribution inside the sample [11] with vortices exiting at one edge and entering at the opposite end. This vortex motion gives an initial surge in response which then decays during the dc part of the drive as vortices find pinning centers and become more disordered. The frequency and amplitude dependence are a result of the competition between the surge of motion during the kick and the slow down in between kicks.

3. MODELS

Our results can be interpreted in terms of current driven thermodynamics and vortex organization. Because in this system thermal fluctuations are negligible compared to pinning the system can be trapped in long lived metastable states from which it can be released only by an applied current. After releasing it from the traps the current enables the system to explore the energy landscape. If the energy scales of pinning, U_p, and that of the current driven motion, $Jf_o l$, are within kT of each other: $U_p - JF_0 l \sim k\ T$ the system can in principle approach thermal equilibrium (here l is the characteristic size of the pinning potential). By using a current step method at various fields and temperatures to drive the system towards equilibrium we obtained a vortex phase diagram which contains an ordered state at low H and T and a glassy disordered state close to $H_{c2}(T)$. Separating these states, is the peak region, in which the degree of order as well as the value of the critical current can be controlled by the applied current.

Two alternative models have recently been proposed to explain these results. One is an elastic network model of overdamped particles moving in a random potential[12]. Simulations using this model reproduce the main features of our results, including the shape of the I-V curves, the metastability, and the response to a current step. The other model [13], assumes that the vortex dynamics is controlled by the injection of disordered vortices through a surface barrier at the sample edge and by their becoming ordered as they move through the sample. This model also reproduces the main features of our results including the frequency dependence of the fishbone pattern and the response to a current step.

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