

# Stable and Metastable vortex states and the first order transition across the peak effect region in weakly pinned 2H-NbSe<sub>2</sub>

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## Abstract

The peak effect in weakly pinned superconductors is accompanied by metastable vortex states. Each metastable vortex configuration is characterized by a different critical current density  $J_c$ , which mainly depends on the past thermomagnetic history of the superconductor. A recent model [G. Ravikumar *et al*, Phys. Rev. B **61**, R6479 (2000)] proposed to explain the

history dependent  $J_c$  postulates a stable state of vortex lattice with a critical current density  $J_c^{st}$ , determined uniquely by the field and temperature. In this paper, we present evidence for the existence of the stable state of the vortex lattice in the peak effect region of  $2H - NbSe_2$ . It is shown that this stable state can be reached from any metastable vortex state by cycling the applied field by a small amplitude. The minor magnetization loops obtained by repeated field cycling allow us to determine the pinning and "equilibrium" properties of the stable state of the vortex lattice at a given field and temperature unambiguously. The data imply the occurrence of a first order phase transition from an ordered phase to a disordered vortex phase across the peak effect.

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## I. INTRODUCTION

In the presence of strong pinning, the vortex state of type II superconductors is usually characterized by the critical current density  $J_c(H, T)$  which decreases monotonically with increasing field  $H$  or temperature  $T$ . In the weakly pinned superconductors, on the other hand, the interplay between the intervortex interaction and the flux pinning produces an anomalous peak in  $J_c$ , as a function of both field and temperature [1] just below the normal state boundary (usually designated as the peak effect or PE). Within the collective pinning description [2], this signifies that the vortex phase undergoes a transition/crossover from an ordered state to a disordered state [1,3–5]. The detailed nature of this transition, e.g., whether it is a thermodynamic phase transition or not, remains a subject of considerable debate.

One of the key issues is the detection of an anomaly in the thermodynamic quantities, such as, specific heat or equilibrium magnetization  $M_{eq}$ .  $J_c$  and  $M_{eq}$  can be estimated from the measured irreversible magnetization data of a superconducting sample [6–8] using the relations,

$$J_c(H) = [M(H \downarrow) - M(H \uparrow)]/2g\mu_0R, \quad (1a)$$

$$M_{eq}(H) = [M(H \uparrow) + M(H \downarrow)]/2, \quad (1b)$$

where  $M(H \uparrow)$  and  $M(H \downarrow)$  are the magnetization in the increasing (forward) and decreasing (reverse) field cycles respectively,  $\mu_0 = 4\pi \times 10^{-7}$  W/A.m,  $R$  is the sample dimension transverse to the applied field and  $g$  is a factor which depends on the sample geometry. Eq. 1 implicitly assumes that  $J_c$  is history independent and is thus uniquely determined by the local induction  $B$ . However, across the peak effect region, the above equations are not valid due to a strong history dependence in  $J_c$  [3,9–17]. Recently, considerable efforts have gone into ascertaining the equilibrium magnetization across the peak effect region, where an order-disorder transition occurs in the vortex matter. However, these efforts have met with ambiguous and somewhat conflicting results. For example, the construction

of the equilibrium magnetization from the hysteresis loop by using two different kinds of minor magnetization curves [16,18,19], results in apparently different conclusions. In one case, a jump [16,19] in  $M_{eq}$  could be found at the onset of the PE, while the other case shows no increase at all [18]. These differences apparently originate from the difficulties in establishing an unambiguous and reproducible vortex state due to a strongly history dependent configuration of the vortex matter in the PE region. The different procedures proposed to obtain  $M_{eq}$  shall be discussed in section II.

In Sec. III, we briefly discuss a recent phenomenological model [20], which addresses the issue of the history dependent  $J_c$  and the metastability in the vortex state through an extension of the Bean's critical state model [6]. In Sec. IV, we present an experimental method based on the ideas of the model [20] to obtain a unique "stable" vortex state in the PE region, which is independent of the past magnetic history. We propose that this state, in effect, is the "stable" or "equilibrium" state and evaluate the critical current density and  $M_{eq}$  of this state. We further demonstrate that, a sharp change in the equilibrium magnetization (albeit smeared) occurs across the PE region. These results imply that an underlying first order phase transition, presumably driven by a competition between elastic and pinning energies in a situation where thermal fluctuations are weak, marks the peak effect.

## II. MINOR CURVES AND THE EQUILIBRIUM MAGNETIZATION ACROSS THE PEAK EFFECT

In the peak effect region, the critical current density in the increasing field cycle  $J_c(H \uparrow)$  is less than that ( $J_c(H \downarrow)$ ) in the decreasing field cycle [9,10,14] for  $H < H_p$ , where  $H_p$  is the field where  $J_c$  is maximum. However, well below the onset of the PE and at  $H > H_p$ ,  $J_c$  is independent of the magnetic history. One of its consequences is the peculiar behavior of the minor magnetization curves, which can not be reconciled within the critical state model [6]. For instance, a typical minor magnetization curve (type I) initiated from a field  $H < H_p$  in the PE region *saturates without meeting* the reverse magnetization curve [14,16,17], as shown

in Fig. 1(a). On the other hand, the minor curves (type II) measured by increasing the field from different points on the reverse magnetization curve *overshoot* the forward curve [14,18] as shown in Fig.1(b). The two types of anomalous behavior may be contrasted with the conventional behavior for the minor curves starting at (a)  $H > H_p$  and (b)  $H < H_{pl}$ , i.e., for fields well below the PE region. The latter categories of minor curves meet the magnetization envelope, constituted by the forward and reverse curves, as expected from the Bean's critical state model.

A new procedure was proposed by Roy and Chaddah [16] to obtain  $M_{eq}$  from the minor magnetization curves of the type I by the relation,

$$M_{eq}(H) = [M(H + \delta, \uparrow) + M_{ML}(H - \delta, \downarrow)]/2, \quad (2)$$

where  $M(H + \delta, \uparrow)$  is the magnetization at a field  $H + \delta$  (denoted by point A in Fig. 1(a)) from where the minor curve is initiated on the forward curve.  $M_{ML}(H - \delta, \downarrow)$  is the magnetization on the minor curve at a field  $H - \delta$ , where it saturates as indicated by the point B in Fig. 1(a). This procedure is based on the implicit assumption that the vortex state formed on the forward curve is an "equilibrium" state. This assumption is however inconsistent with the experimental observation by Wordenweber, Kes and Tsuei [10], who showed that both current cycling and field cycling processes eventually establish a vortex state with a  $J_c$  higher than that on the forward curve. Such an observation indicates that the vortex state formed on the forward curve is metastable in nature.

Tenya *et al* [18] have preferred a procedure given below, which is very similar to the one described above but using the minor curves of the type II described in Fig. 1(b):

$$M_{eq}(H) = [M(H - \delta, \downarrow) + M_{ML}(H + \delta, \uparrow)]/2, \quad (3)$$

where  $H - \delta$  (point C in Fig. 1(b)) is the field from where the minor curve is initiated on the reverse curve and  $H + \delta$  (point D in Fig. 1(b)) is the field where it saturates.  $M_{ML}(H + \delta, \uparrow)$  is the saturated magnetization value on the minor curve. This procedure too has the

shortcoming similar to that in Eq. 2, viz., the vortex state on the reverse magnetization curve is actually a metastable state [10,14,16]. Moreover, not only are these recipes deficient, they also yield different conclusions, viz., an enhancement in equilibrium magnetization is observed in one case, whereas it is absent in the other. These ambiguities point to the need to evolve a more satisfactory procedure to arrive at a unique and stable vortex state unambiguously and determine the equilibrium magnetization assuming the stable state to be the equilibrium state.

### III. MODEL FOR HISTORY EFFECTS AND METASTABILITY

Ravikumar *et al* [20] incorporated the history dependence in the macroscopic critical current density  $J_c$  by postulating,

$$J_c(B + \Delta B) = J_c(B) + (|\Delta B|/B_r)(J_c^{st} - J_c). \quad (4)$$

where the critical current density  $J_c(B)$  is a macroscopic representation of a particular metastable configuration of the vortex lattice at a field  $B$ . Eq. 4 describes how the vortex state evolves from one metastable configuration to another. An important assumption of this model is the existence of a stable vortex state with a critical current density  $J_c^{st}$ , which is unique for a given field and temperature.  $B_r$  is a macroscopic measure of metastability and describes how strongly  $J_c$  could be history dependent. In the limit of  $B_r$  tending to zero, however, this model reduces to the standard critical state model for which  $J_c (= J_c^{st})$  is independent of the magnetic history. It can be seen from Eq. 4 that a metastable vortex state with  $J_c \neq J_c^{st}$ , can be driven into a stable state by merely oscillating the field by a small amplitude (see Fig. 1 of the Ref. 20). In the PE region, the energy barriers between different metastable vortex configurations are much greater than the available thermal energy. The field cycling allows the vortices to move and explore the energy landscape and thereby rearrange in to a vortex configuration closer to the stable state. In the next section, we will demonstrate this experimentally and show that the stable state obtained is indeed

independent of the magnetic history.

In the limit  $\Delta B \rightarrow 0$ , Eq. 4 can be rewritten in the form,

$$\pm dJ_c/dB = (J_c^{st} - J_c)/B_r, \quad (5)$$

where upper and lower signs are applicable in the cases of increasing and decreasing local field  $B$ , respectively. In each case, the  $J_c(B)$  can be obtained by solving Eq. 5, provided the functional form of  $J_c^{st}(B)$  and  $B_r(B)$  are known. We assume for  $J_c^{st}(B)$  and  $B_r(B)$  the following forms used in Ref. [20] for calculating the minor magnetization curves:

$$J_c^{st}(B) = J_{c1}(1 - B/\mu_0 H_1) + J_{c2}e^{-(B-\mu_0 H_p)^2/2\mu_0 H_W^2} \quad (6)$$

and

$$\begin{aligned} B_r(B) &\approx (B - \mu_0 H_{low})^m (\mu_0 H_p - B)^n \text{ for } H_{low} < B/\mu_0 < H_p \\ &\approx 0 \qquad \qquad \qquad \text{otherwise} \end{aligned} \quad (7),$$

The first term in Eq. 6 is the field dependence of  $J_c^{st}$  well below the peak and the second term reflects the peak in  $J_c^{st}$  vs  $B$ .  $B_r(B)$  in Eq. 7 accounts for the observed history dependence in  $J_c$  in the PE region.  $B_r = 0$  in the field ranges  $H < H_{low}$  and  $H > H_p$  signifies that  $J_c$  is independent of the magnetic history and is always equal to the  $J_c^{st}$ . For the two limiting cases,  $H < H_{low}$  and  $H > H_p$ , the intervortex interaction and the flux pinning are dominant respectively and therefore the stable state is readily accessed by the vortex lattice. The values of the different parameters used in this paper are listed in the caption of Fig. 2.  $J_c(H \uparrow)$  [ $J_c(H \downarrow)$ ] is calculated by numerically solving Eq. 5 with the upper (lower) sign with the initial condition  $J_c(H \uparrow)$  [ $J_c(H \downarrow)$ ] =  $J_c^{st}(H)$  at some field below  $H_{low}$  (above  $H_p$ ). In Fig. 2(a), we present an evaluation of  $J_c(H \uparrow)$  and  $J_c(H \downarrow)$  which obey the inequality  $J_c(H \uparrow) < J_c^{st}(B) < J_c(H \downarrow)$ . It was earlier interpreted that the vortex state formed on the decreasing field cycle is a *supercooled* disordered state [14]. In other words, the vortex state formed in decreasing field (from above  $H_p$ ) retains the memory of the vortex correlations from the previous fields. In analogy, we can argue that the vortex state formed on the

increasing field cycle is a *superheated* ordered state. Both of these states are metastable in nature. As argued above, they can be driven into a stable state by oscillating the external field by a small amplitude.

The magnetization hysteresis loop corresponding to  $J_c(H \uparrow)$  and  $J_c(H \downarrow)$  are shown in Fig. 2(b). Note the asymmetry in the hysteresis, usually observed in experiments. For a comparison, we also plot the magnetization hysteresis loop one would obtain within the framework of Bean's critical state model with  $J_c = J_c^{st}$  (applicable in the limit  $B_r \rightarrow 0$ ) which is symmetric in the forward and reverse field cycles, as shown by the dotted line in Fig. 2(b). Details of the magnetization calculation are described in Ref. 20. The minor magnetization curves of the types I and II calculated in the slab geometry, are shown in Fig. 3(a) and Fig. 3(b) respectively. They clearly mimic the behavior seen in experiments. We assumed  $M_{eq}(H) = 0$ , in calculating these magnetization curves. We note that the calculated curves in Fig. 2 and Fig. 3 are not quantitative fits to experimental data, they only serve to illustrate the qualitative features of the observed data.

In Fig. 3(c), we show  $M_{eq}^*(H)$  determined from the calculated minor curves of the type I and type II following Eq. 2 and Eq. 3, respectively. The test of the self-consistency of these procedures lies in reproducing the original form ( $M_{eq} = 0$ ) assumed in the calculation.  $M_{eq}^*(H)$  obtained from these two procedures are not only inconsistent with each other, but, also, do not conform to the original assumption that  $M_{eq} = 0$  [21]. The procedure of Eq. 2 indeed produces a peak like structure in  $M_{eq}^*(H)$  which has been shown earlier from an analysis of experimental data in  $2H - NbSe_2$  following the same recipe [19]. On the other hand, the use of Eq. 3 proposed by Tenya *et al* [18] yields no variation in  $M_{eq}^*$  vs  $H$  across the PE region. Fig. 3(c) illustrates the unreliable and ambiguous nature of these recipes noted above and thus points to the need for a consistent approach in order to overcome their difficulties.



#### IV. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, we will show experimentally that repeated field cycling drives any metastable state into a stable state, which is unique at a given field [20]. We study the minor hysteresis loops traced by repeated field cycling and infer from these measurements the critical current density  $J_c^{st}$  and the equilibrium magnetization  $M_{eq}$  of the stable state.

*DC* magnetization measurements have been carried out using a Quantum Design (QD) Inc. SQUID magnetometer (Model MPMS5) in the peak effect region of a  $2H-NbSe_2$  single crystal ( $T_c \approx 7.25$  K) with the field applied parallel to its  $c$ -axis. The crystal is of approximate dimensions ( $a \times b \times c$ )  $4mm \times 5mm \times 0.43mm$ . As stated earlier, the peak effect in  $J_c$  is manifested as the anomalous enhancement in the magnetization hysteresis (c.f. Fig. 1). The magnetization hysteresis has been studied at different temperatures from 6.7 to 6.95K. Magnetization hysteresis data at 6.95K was measured using a 2 cm full scan length, and the data at the other temperatures was obtained using the half-scan technique [12,22] to avoid artefacts arising due to field inhomogeneity experienced by the sample along the scan length. In the temperature range investigated,  $J_c$  at the peak field  $H_p$  decreases with decreasing temperature (see Table 1).

Fig. 4(a) depicts a part of the hysteresis loop at 6.95K, constituting  $M$  vs  $H$  curves in the increasing (forward) and decreasing (reverse) field cycles measured with a 30 sec wait time at each field. We identify the onset field  $H_{pl}^+$  of the PE on the forward curve, where  $M$  begins to decrease sharply. The field  $H_p$  marks the field at which magnetization hysteresis is maximum. In Fig. 4(a), we show the points A, B, C and D from where the minor hysteresis loops are initiated. A(C) and B(D) are at a field  $H < H_{pl}^+$  ( $H > H_{pl}^+$ ) on the forward and reverse curves, respectively. Minor hysteresis loops starting from both forward and reverse curves are recorded at different fields (spanning the peak region) by repeatedly cycling the field by a small amplitude  $\Delta H$ . The interval  $\Delta H$  is chosen such that it is above the threshold field required to reverse the direction of the shielding currents throughout the sample. From the critical state model, we understand that magnetization

values must always remain confined within the forward and reverse magnetization curves, which constitute the so called magnetization envelope. Further, the  $M - H$  loop in each field cycle must retrace itself.

In Fig. 4(b), we show the minor hysteresis loops (MHLs) measured by repeatedly cycling the field, starting at point A ( $H < H_{pl}^+$ ) on the forward curve. These MHLs in different field cycles retrace each other indicating that the  $J_c$  does not change with field cycling. Therefore, we conclude that the vortex state is in a stable configuration. In contrast, the MHLs shown in Fig. 4(c) (continuous line with data points omitted) starting at B ( $H < H_{pl}^+$ ) on the reverse curve, show shrinkage effects, with each successive field cycle and finally MHL collapses into the minor loop started from point A (open circles) which is replotted in Fig. 4(c). This suggests that the vortex configuration at point B is metastable with a  $J_c > J_c^{st}$ . Repeated field cycling causes the  $J_c$  to fall towards the stable stable value as reflected in the reduction of the width of the MHL with each successive field cycle. It is remarkable that the minor loops starting from both A and B merge into precisely the same loop within the experimental accuracy. This clearly reaffirms the basic assumption of the model that there exists a unique stable state with critical current density  $J_c^{st}$ , independent of the initial vortex state from which it evolves.

We now focus on the behavior of MHLs which start from a field  $H > H_{pl}^+$ . As shown in Fig. 4(d), the behavior of the minor loops starting at point C is quite different from those started at point A. The increasing field leg of the MHL moves away from the forward magnetization curve in the first field cycle itself and remains outside the magnetization envelope for subsequent field cycles. This clearly suggests that, for  $H > H_{pl}^+$ , the vortex configuration even on the forward magnetization curve is metastable. However, the behavior of the MHLs starting at point D on the reverse magnetization curve is very similar to the behavior of those that start at point B, i.e., the MHL shrinks with each successive field cycle (continuous line in Fig. 4(e)). The data in Fig. 4(d) is replotted in Fig. 4(e) (open circles connected by dotted line), which suggests that the MHLs starting from both C and D collapse into the same final loop (MHL). Firstly, the data in Fig. 4 clearly suggest the

metastable nature of the vortex configuration for fields above  $H_{pl}^+$  both on the forward and the reverse magnetization curves. Further, the eventual MHL obtained on repeated field cycling is independent of the initial vortex configuration. We note that the metastable state on the forward magnetization curve settles into the stable state much faster than that on the reverse curve. This might imply that the vortex configuration on the increasing field cycle is closer to the equilibrium configuration.

The data in Fig. 4 yield the following inequalities for the critical currents in the different field ranges: (i) For  $H < H_{pl}^+$ , the vortex configuration is stable in the increasing field cycle while at the same field value, it is highly metastable in the decreasing field cycle. This can be summarized by the inequality  $J_c(H \uparrow) = J_c^{st}(H) < J_c(H \downarrow)$ ; (ii) For  $H_{pl}^+ < H < H_p$ , the vortex configurations in both increasing and decreasing field cycles are metastable, with the critical currents obeying the inequality,  $J_c(H \uparrow) < J_c^{st}(H) < J_c(H \downarrow)$ ; (iii) For  $H > H_p$ ,  $J_c(H \uparrow) = J_c(H \downarrow) = J_c^{st}(H)$ . These observations are in accordance with the model [20] (cf. Fig. 2(a)). We thus assert that the Eq. 2, proposed by Roy and Chaddah [16] is applicable only for  $H < H_{pl}^+$ . It is unsatisfactory for  $H_{pl}^+ < H < H_p$ , as the vortex lattice on the forward curve is in a *superheated* vortex configuration which is more ordered (but metastable) than the stable configuration. Eq. 3, as proposed by Tenya *et al* [18] is not appropriate in any of the field ranges because the vortex states produced on the reverse curve are *supercooled* vortex configurations [14,23] which are more disordered than the corresponding stable states.

Fig. 5 shows the M-H loop at 6.9K constituting the forward and reverse magnetization curves (dark line with data points omitted) indicating  $H_{pl}^+$  and  $H_p$ . Note the asymmetry (also seen at 6.95K) in the forward and reverse magnetization curves which is the hall mark of the peak effect. We also measured the MHLs by repeatedly cycling the field starting at different points on the forward and reverse curves. The saturated MHLs are again found to be independent of the initial vortex state just as for 6.95K. The locus of magnetization values on the increasing and decreasing field legs of the saturated MHLs measured at different fields are also plotted in Fig. 5 (open circles connected by dotted line). This observed behavior is in excellent qualitative agreement with that expected from the model in Ref. 20 (see

Fig. 2(b)). The locus of saturated magnetization values corresponds to the “table” or the “equilibrium” vortex configuration at different fields.

Having established the existence of a history independent stable state we determine the critical current density  $J_c^{st}$  and the equilibrium magnetization  $M_{eq}$  state at each field from the saturated MHL [24].  $J_c^{st}$  and  $M_{eq}$  are given by,

$$J_c^{st}(H) = [M_{st}(H \downarrow) - M_{st}(H \uparrow)]/2g\mu_0R, \quad (8a)$$

$$M_{eq}(H) = [M_{st}(H \uparrow) + M_{st}(H \downarrow)]/2, \quad (8b)$$

where  $M_{st}(H \uparrow)$  and  $M_{st}(H \downarrow)$  are the magnetization values on the increasing and decreasing field legs of the saturated MHL.  $J_c^{st}$  vs  $H$  and  $M_{eq}$  vs  $H$  data at 6.95K are plotted in Fig. 6(a) and Fig. 6(b), respectively.  $M_{eq}$  exhibits a sharp increase between  $H_{pl}^+$  and  $H_p$  signifying an increase in the equilibrium flux density. This is reminiscent of the characteristic of  $M_{eq}$  across the FLL melting transition observed in cuprate superconductors [25,26]. We argue that the change in  $M_{eq}$  indicates a first order transition in the FLL from an ordered solid to a pinned amorphous state [19] presumably analogous to a Bragg Glass to Vortex Glass/pinned liquid phase transition [27]. The increase in  $M_{eq}$  coincides with the increase in  $J_c^{st}$  near the onset of the peak effect and spans the field range between  $H_{pl}^+$  and  $H_p$ . In Fig. 7(a) and 7(b), we present the  $M_{eq}$  vs  $H$  and  $J_c^{st}$  vs  $H$  data respectively, at 6.9K. We note that the sharp change in  $M_{eq}$  correlates with a sharp increase in  $J_c^{st}$  between  $H_{pl}^+$  and  $H_p$ . We also present the  $\Delta M_{eq}$  values obtained at different temperatures in Table 1.

It is important to understand the nature of the vortex state in the transition region  $H_{pl}^+ < H < H_p$ . One of the well known pictures is the collective pinning scenario [2], where the loss of long range order is expected to permeate uniformly throughout the sample. On the other hand Paltiel *et al* [28] have recently proposed a picture where the disordered phase enters through surface imperfections and coexists near the surface with the ordered phase of the bulk. They argue that the boundary between the disordered region and the ordered region moves into the sample as the temperature (or field) is increased towards  $T_p$  (or  $H_p$ ).

Further possibility is the coexistence of ordered and disordered phases, with an intricate geometrical connectivity of these phases. Irrespective of the particular picture used, our experiments demonstrate a specific and an unambiguous procedure, viz., subjecting the sample to a field cycling, to produce a unique stable state (in a macroscopic sense) across the peak effect region.

We consider this stable state as a pinned equilibrium state, and estimate equilibrium magnetization and the free energy difference or entropy change when the vortex lattice changes from an ordered to an amorphous state. As per the Clausius-Clapeyron relation [26,29], the entropy change per vortex per inter-layer distance  $d$  ( $\simeq 4$  Angstroms) in the  $2H - NbSe_2$  system [19],

$$\Delta s = -(\Delta M_{eq}/H_p)(dH_{pl}^+/dT)(\phi_0 d/k_B),$$

where  $dH_{pl}^+/dT \simeq dH_p/dT \simeq -0.65$  T/K. The value of  $\Delta s$  estimated at different temperatures is tabulated in Table 1. Incidentally these values are comparable to the entropy change reported across the FLL melting transition in high  $T_c$  cuprates.

An important question that can arise is whether the entropy change can be observed in thermal measurements such as specific heat vs temperature. We recall that the metastability in the vortex state is much greater in temperature scans in a fixed magnetic field [14]. Repeated cycling of the field by a small amplitude may be necessary to produce the "stable" or "equilibrium" state before a thermal measurement is carried out at each temperature.

## V. CONCLUSIONS

In this paper, we have presented a study of the different metastable vortex configurations occurring in the peak effect region of a weakly pinned superconductor  $2H - NbSe_2$  through magnetization measurements. Each metastable vortex configuration is characterized by a critical current density  $J_c$  which is strongly dependent on the magnetic history. It is also shown that any metastable vortex configuration obtained under given field historys can be

driven into a stable configuration by repeated field cycling. This stable configuration has a critical current density  $J_c^{st}$ , uniquely determined by field and temperature as postulated in a recent model [20]. Field cycling appears to act as an effective temperature to drive a metastable state into the stable state, even when thermal energy itself is inadequate to sample the phase space and access the stable state.

The method of recording minor hysteresis loops described here allows us to determine the pinning and equilibrium properties of the stable vortex state satisfactorily. Our equilibrium magnetization data clearly suggest that the transition of the vortex lattice from an ordered state to a disordered state is first order in nature. The smearing of the transition, i.e., the width of the transition region may be a manifestation of the spatially inhomogeneous pinning of the system. The  $J_c^{st}$  data suggests that the loss of quasi-long range order in the vortex lattice also spans the same field window as the magnetization jump. In the collective pinning picture, this amounts to correlation volume of the vortex phase decreasing in this regime and the FLL becoming completely disordered above  $H_p$  or  $T_p$ . The precise coincidence of the  $J_c$  anomaly with the equilibrium magnetization anomaly further illustrates the self consistency of the procedure developed here. It would be interesting to compare the nature of this disorder-driven transition in systems with different types of pinning, e.g. high density of point pins versus low density of extended pins to further understand the nature of this presumably disorder induced phase transformation.

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TABLES

TABLE I. Superconducting parameters in  $2H - NbSe_2$

T(K)	$H_p$ (mT)	$\mu_0 \Delta M_{eq}(\mu T)/4\pi$	$J_c(H_p)$ (A/m <sup>2</sup> )	$\Delta s(k_B)$
6.95	105	3.8±0.4	$54 \times 10^4$	13.6±1.4
6.90	136	5.0±0.4	$36 \times 10^4$	13.8±1.1
6.85	170	1.3±0.4	$26 \times 10^4$	2.9±0.9
6.80	202	1.9±0.4	$17 \times 10^4$	3.5±0.7

## FIGURE CAPTIONS

Fig.1. : Typical magnetization hysteresis loop observed in the peak effect region of a superconducting  $2H - NbSe_2$ . In the panel (a), the minor curve obtained by decreasing the field from the point A, corresponding to a field  $(H + \delta)$  on the forward magnetization curve is shown to saturate at the point B, which corresponds to the field  $(H - \delta)$ . Magnetization values at A and B are  $M(H + \delta, \uparrow)$  and  $M_{ML}(H - \delta, \downarrow)$  respectively (see text). In the panel (b) the minor curve obtained by increasing the field from the point C, corresponding to a field  $(H - \delta)$  on the reverse magnetization curve, saturates at D  $(H + \delta)$  and corresponds to a magnetization value  $M_{ML}(H + \delta, \uparrow)$ .

Fig. 2: (a) Calculated critical current densities  $J_c(H \uparrow)$  and  $J_c(H \downarrow)$  in the increasing and decreasing field cases, respectively. These are compared with the stable critical current density  $J_c^{st}$  (dotted line). In this calculation, we have used  $H_{low} = 0.05T$ ,  $H_p = 0.1T$ ,  $J_{c1} = 10^4 A/m^2$ ,  $J_{c2} = 20J_{c1}$ ,  $H_1 = 0.12T$  and  $H_W = 0.008T$  [20]. (b) Magnetization hysteresis loop corresponding to the  $J_c$  values shown in (a). The hysteresis loop that would be obtained within the framework of critical state model, i.e., in the limit of  $B_r \rightarrow 0$  is also shown in the in this panel as dotted line. The inset shows the functional form of  $B_r$  which is non-zero in the field range  $H_{low} < H < H_p$ .

Fig. 3: Calculated minor curves of type I and type II are shown in panels (a) and (b), respectively. In the panel (c), we show the  $M_{eq}^*$  vs  $H$  obtained using Eq. 2 and Eq. 3, respectively along with the original form,  $M_{eq} = 0$ , assumed in the calculation of the minor curves.

Fig. 4: (a) A part of the magnetization loop (forward and reverse curves) measured at 6.95K on a  $2H - NbSe_2$  single crystal. Also indicated are the characteristic fields,  $H_{pl}^+$  and  $H_p$ . We indicate A and B ( $H < H_{pl}^+$ ) and C and D ( $H_{pl}^+ < H < H_p$ ) starting from which

the minor hysteresis loops are measured. (b) Minor hysteresis loops started from point A (open circles). In different field cycles, they are seen to retrace the same loop. (c) The MHL started from B (continuous line) shrinks with each successive field cycle. The increasing and decreasing field legs of the first and second cycles are numbered. After five field cycles, the hysteresis loop is seen to merge with the loop shown in (b), which is replotted (open circles). (d) Minor hysteresis loops started from point C (open circles). In the first field cycle itself, increasing field leg of the MHL moves away from the forward curve and remains outside the magnetization envelope for the subsequent field cycles. (e) The minor loops starting from D (continuous line) are seen to collapse onto the loop shown in (d), which is replotted.

Fig. 5: Magnetization hysteresis loop of  $2H - NbSe_2$ , recorded using *half scan technique* [22] at 6.9K (continuous line). The open circles are the saturated magnetization values obtained after repeated field cycling.  $H_{pl}^+$  and  $H_p$  are also marked. The locus of the saturated magnetization values is shown as a dotted line.

Fig. 6: (a) Stable critical current density  $J_c^{st}$  in the field range  $80 \text{ mT} < \mu_0 H < 105 \text{ mT}$ . In the inset, we show the  $J_c^{st}$  vs  $H$  in the entire field range. Filled triangles and open circles correspond to the values obtained from the MHLs initiated from the forward and reverse magnetization curves respectively. (b) Equilibrium magnetization  $M_{eq}$  as a function of field at 6.95K. Note that the sharp change in  $M_{eq}$  coincides with the PE onset field  $H_{pl}^+$ .

Fig. 7: (a) Critical current density  $J_c^{st}$  vs  $H$  and (b)  $M_{eq}$  vs  $H$  data obtained at 6.9K. Note that the smeared jump in  $M_{eq}$  vs  $H$ , as marked by the double sided arrow, agrees precisely with a smeared jump in critical current density  $J_c^{st}$  in the peak regime. See text for a discussion.

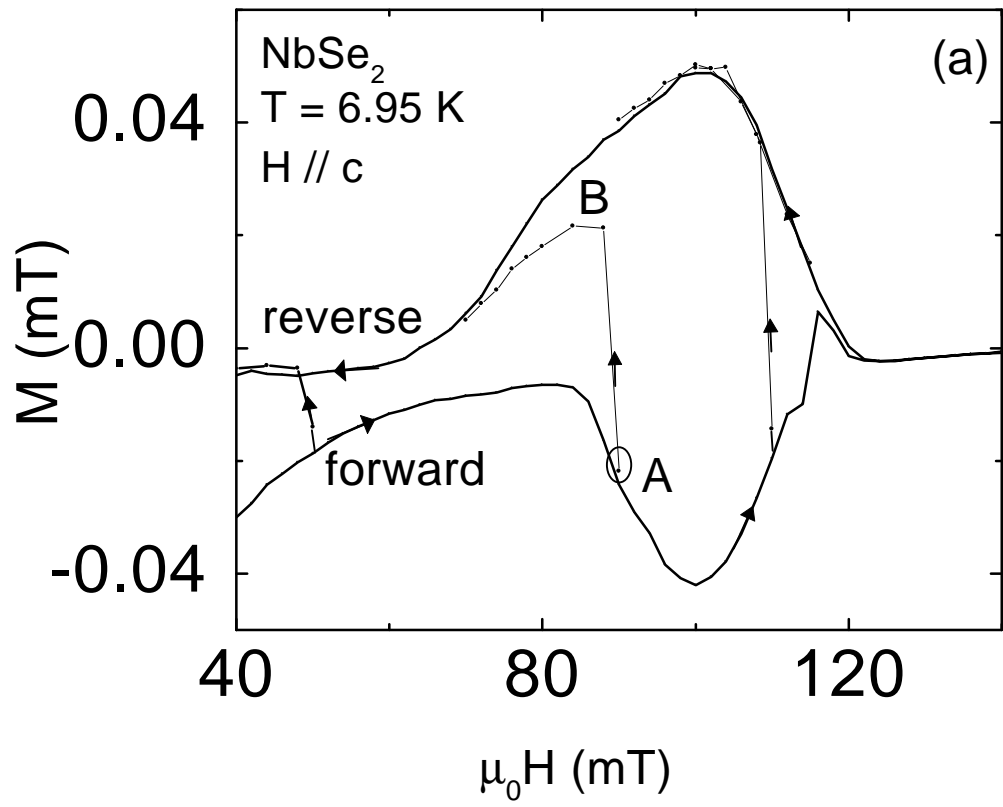


Fig. 1(a) - Ravikumar et al

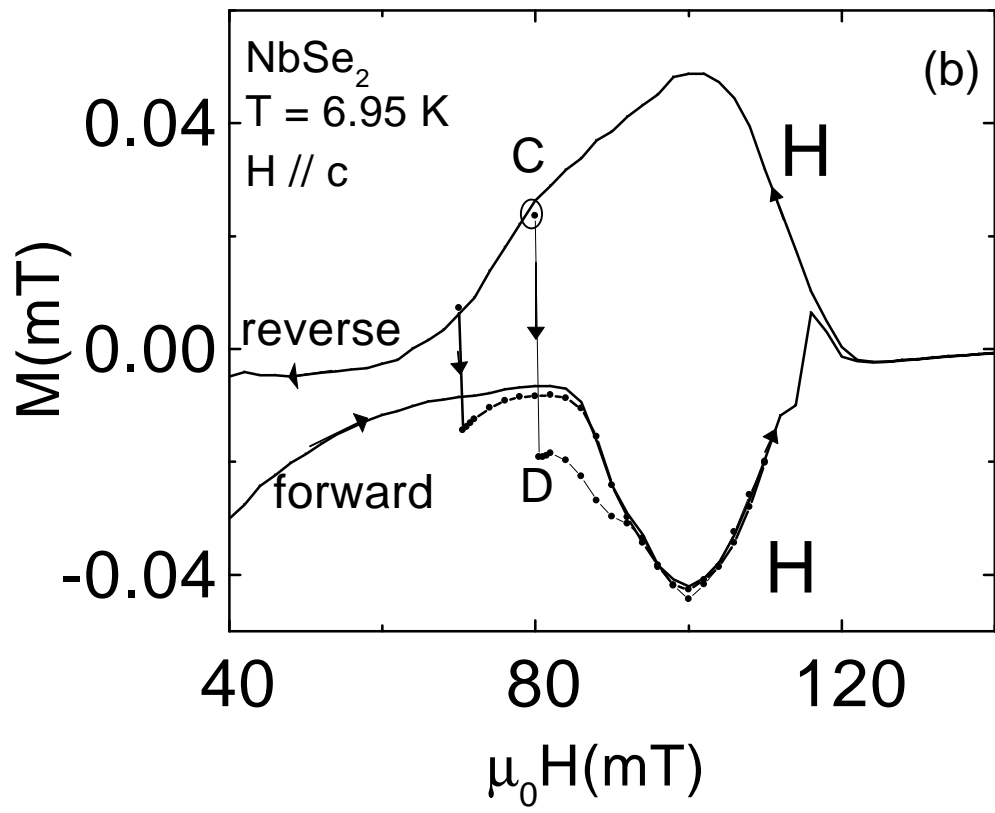


Fig. 1(b) - Ravikumar et al

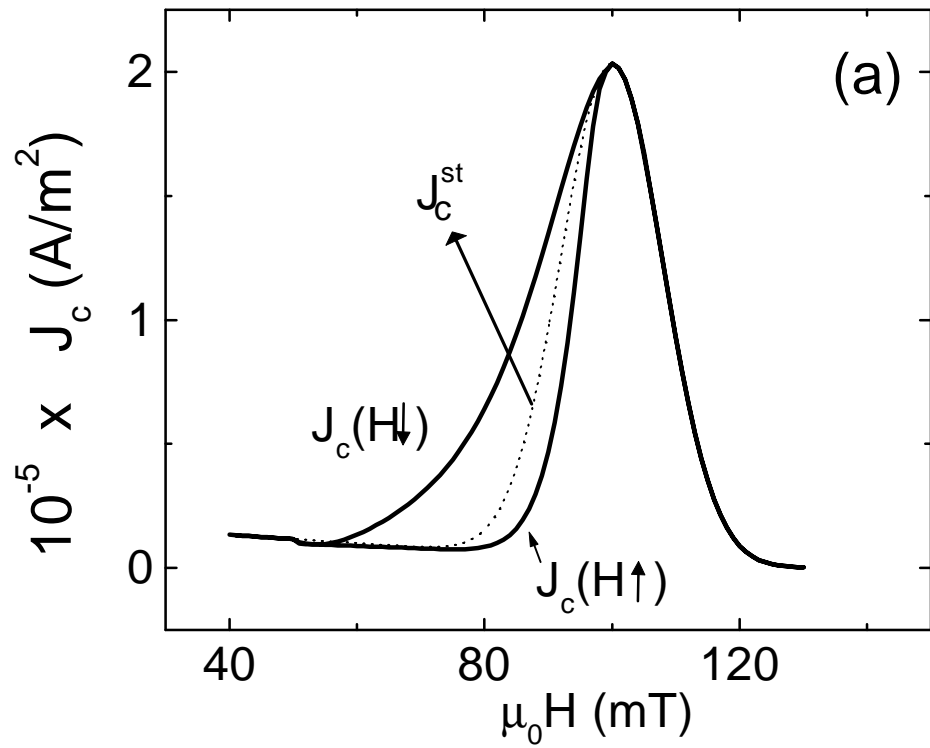


Fig. 2(a) - Ravikumar et al

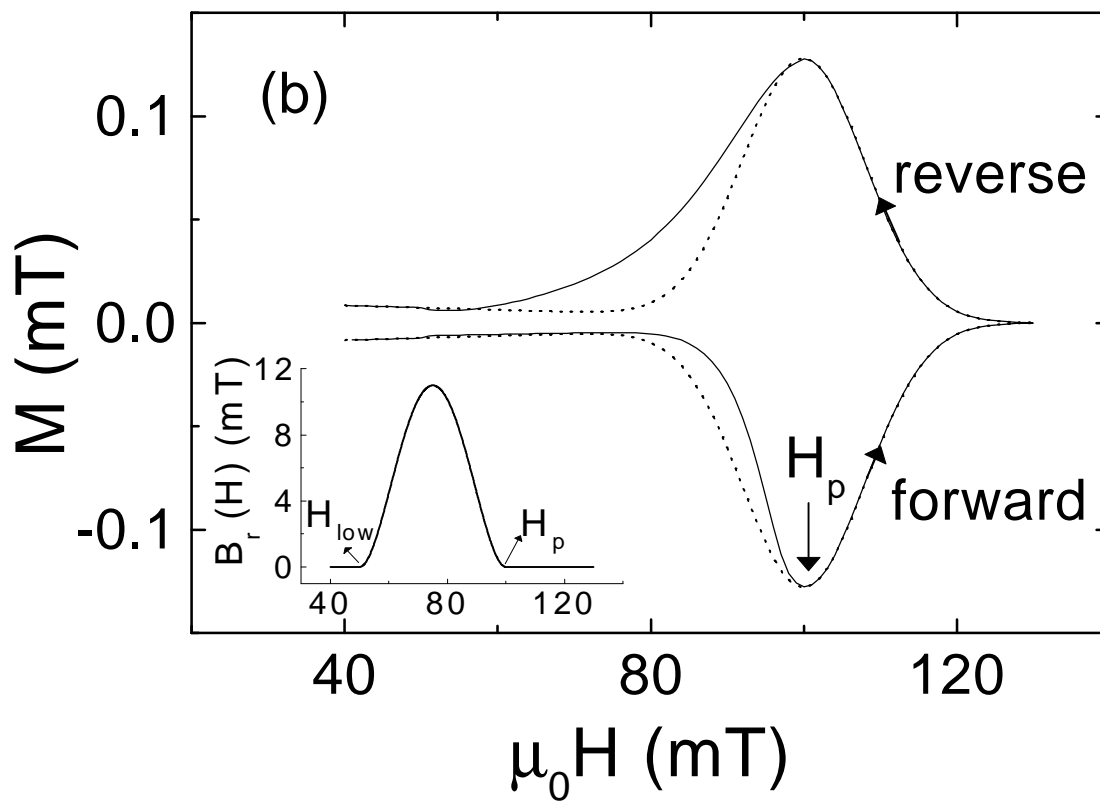


Fig. 2(b) - Ravikumar et al



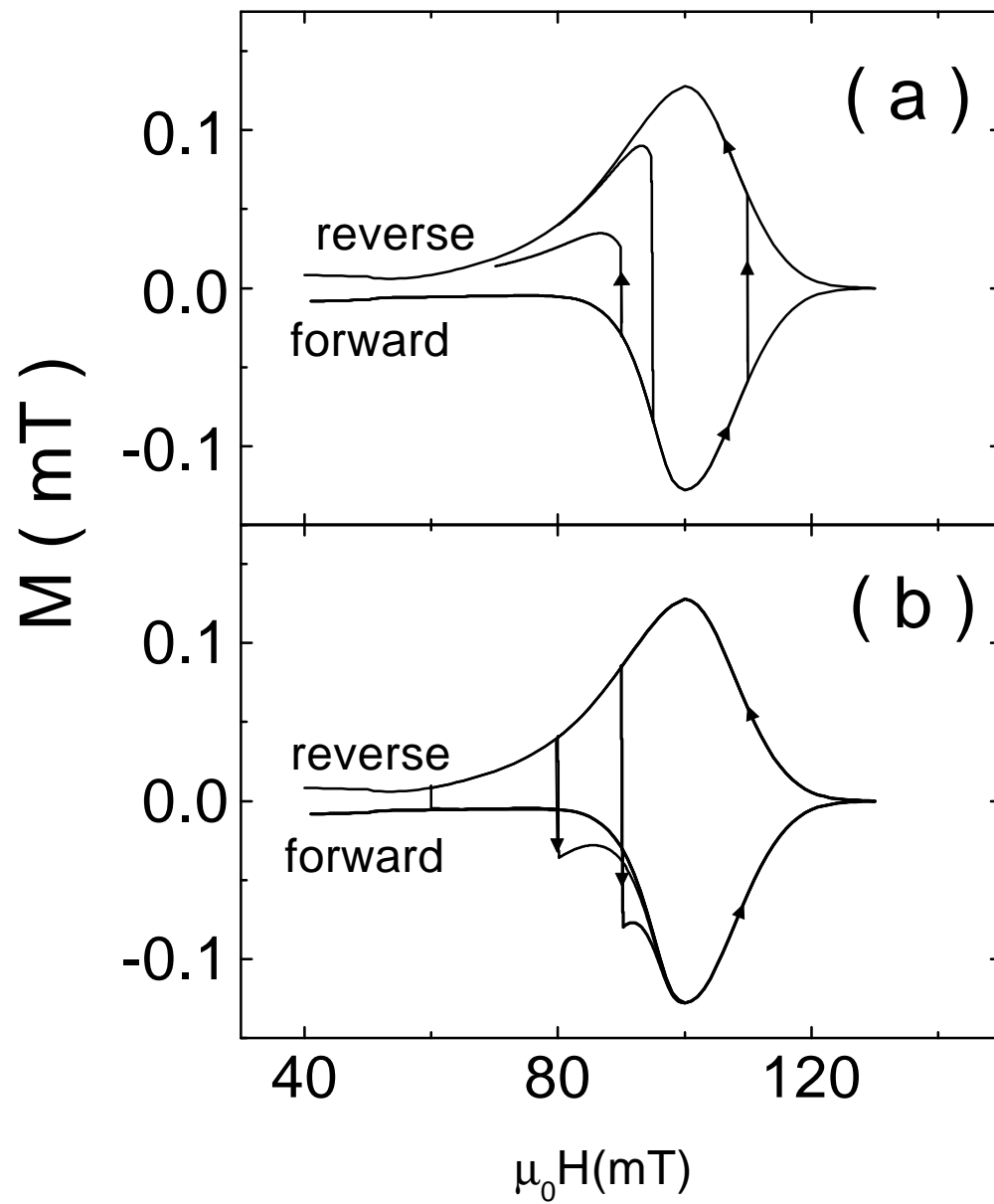


Fig. 3 - Ravikumar et al

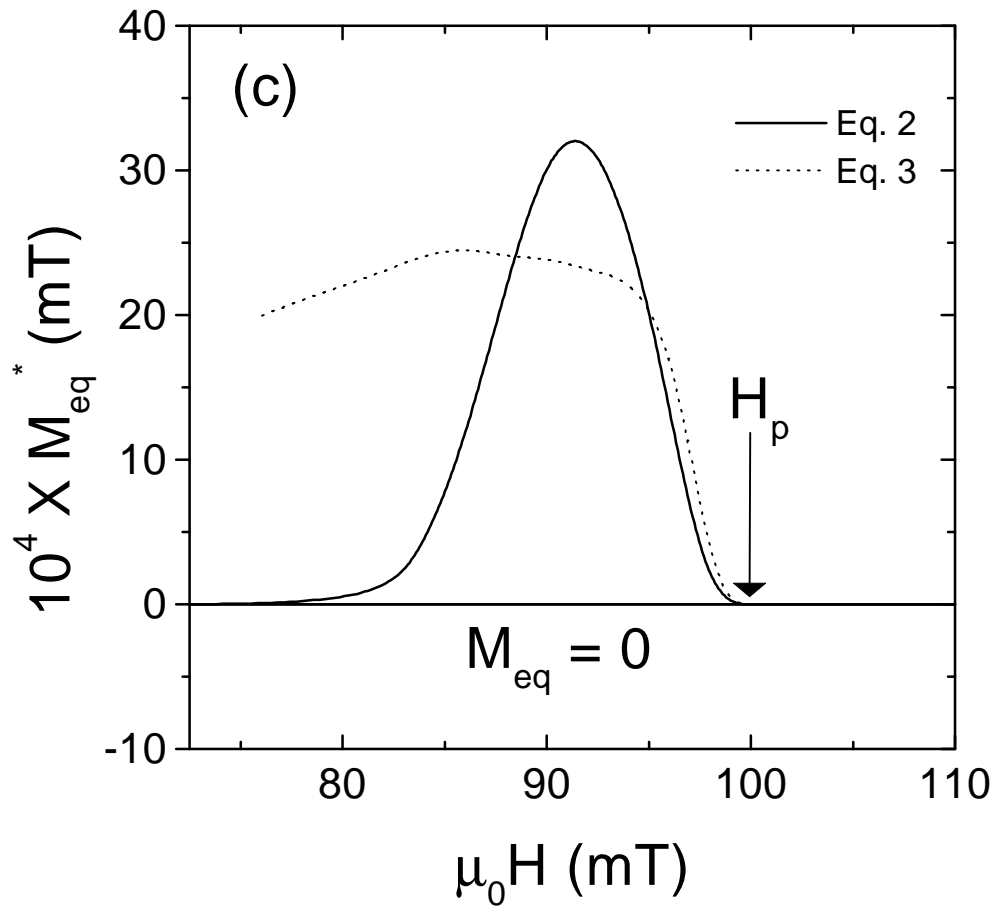


Fig. 3 (c) - Ravikumar et al

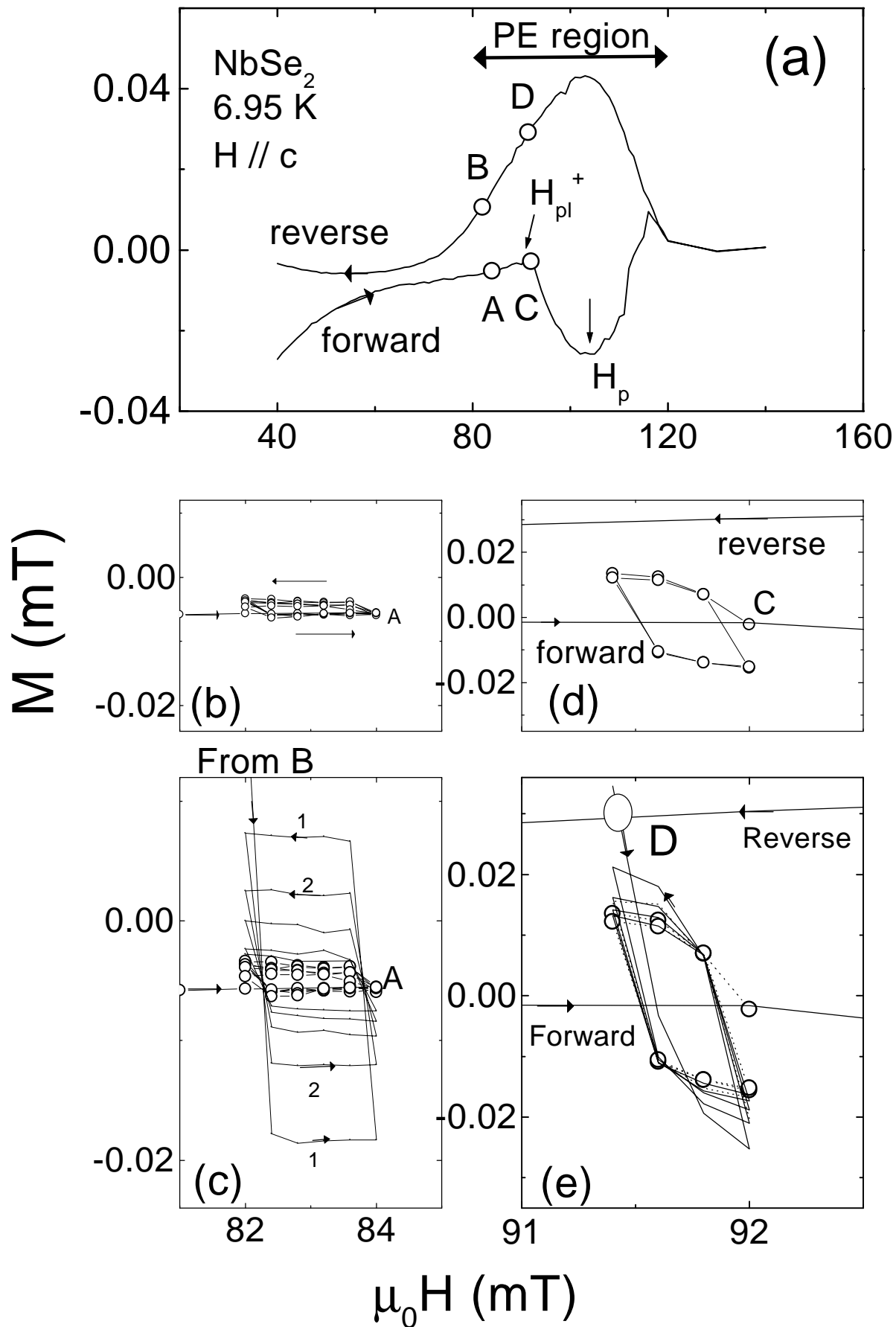


Fig. 4 - Ravikumar et al

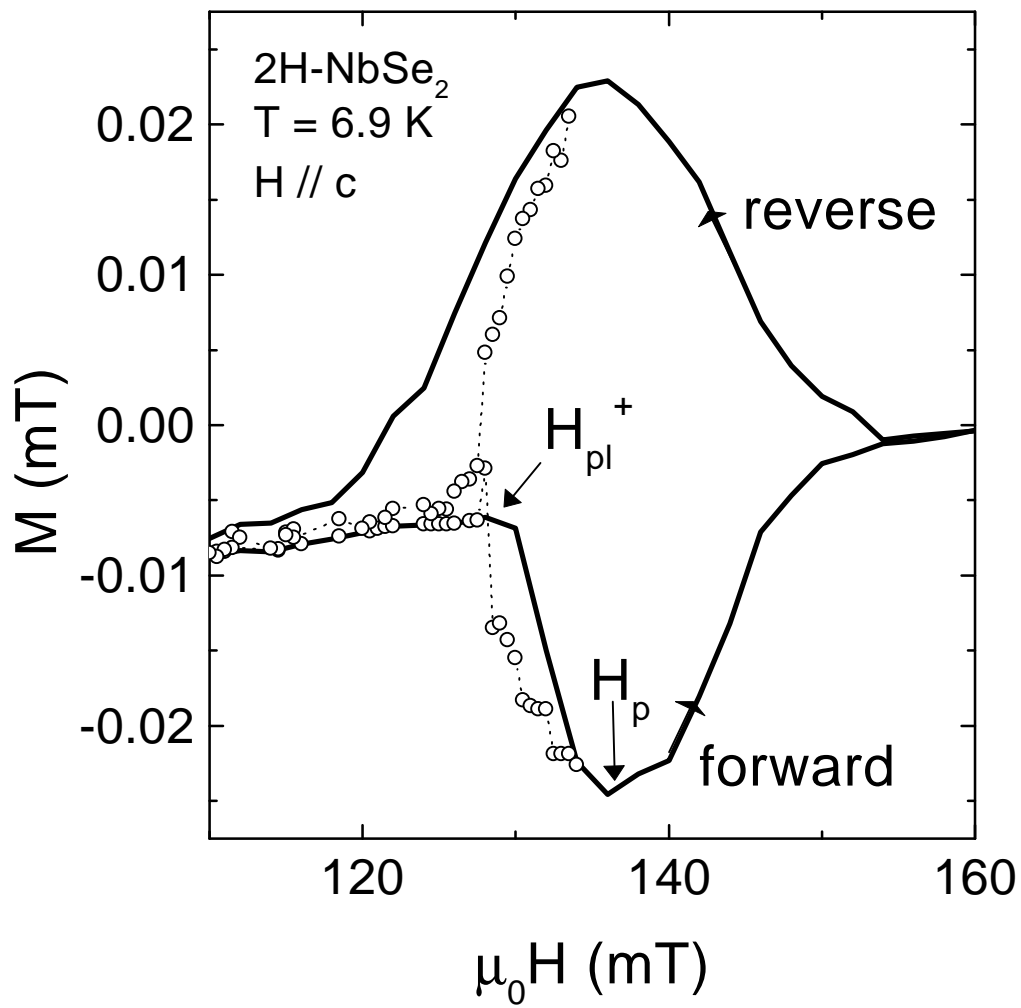


Fig . 5 - Ravikumar et al

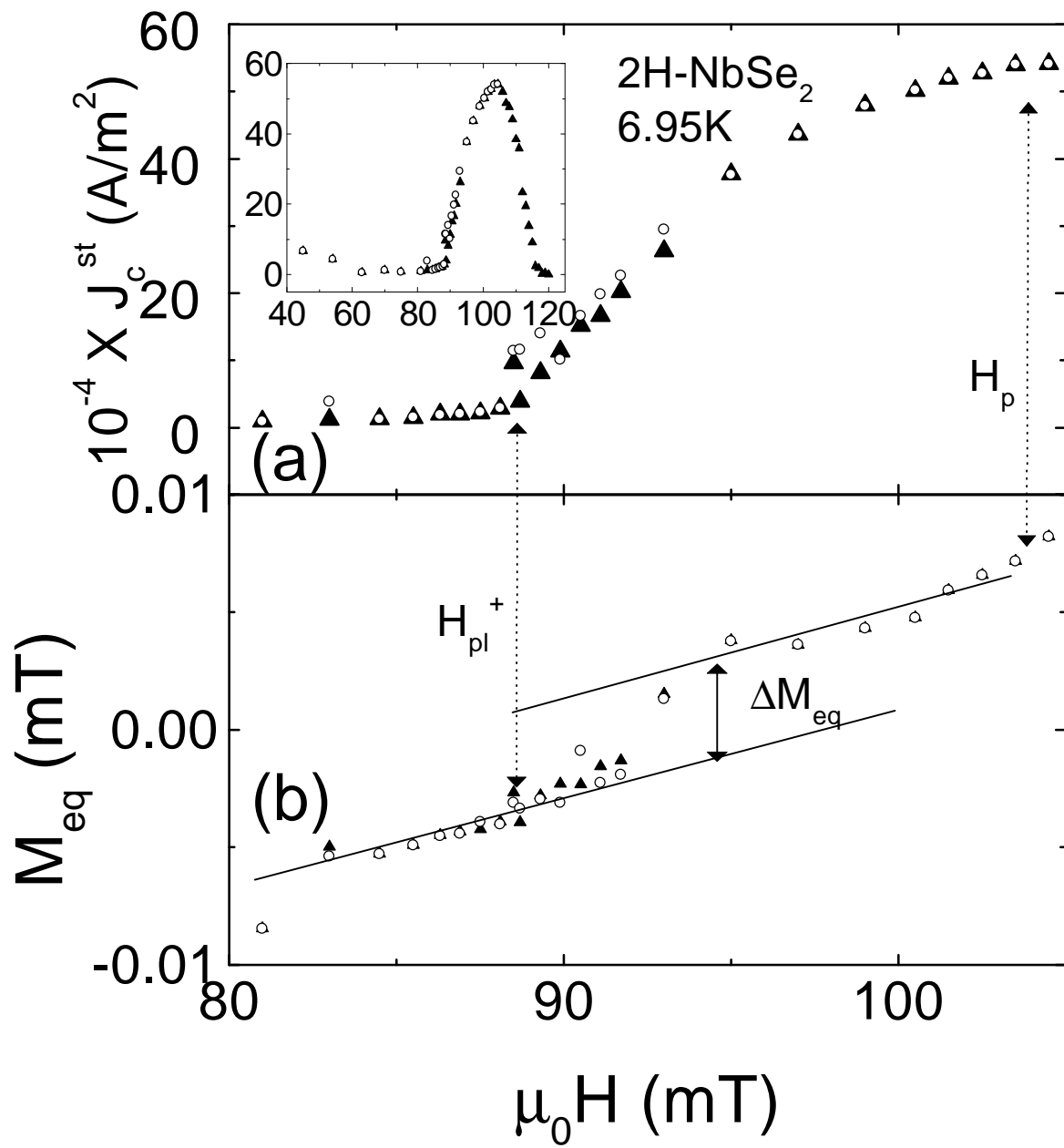


Fig. 6 - Ravikumar et al

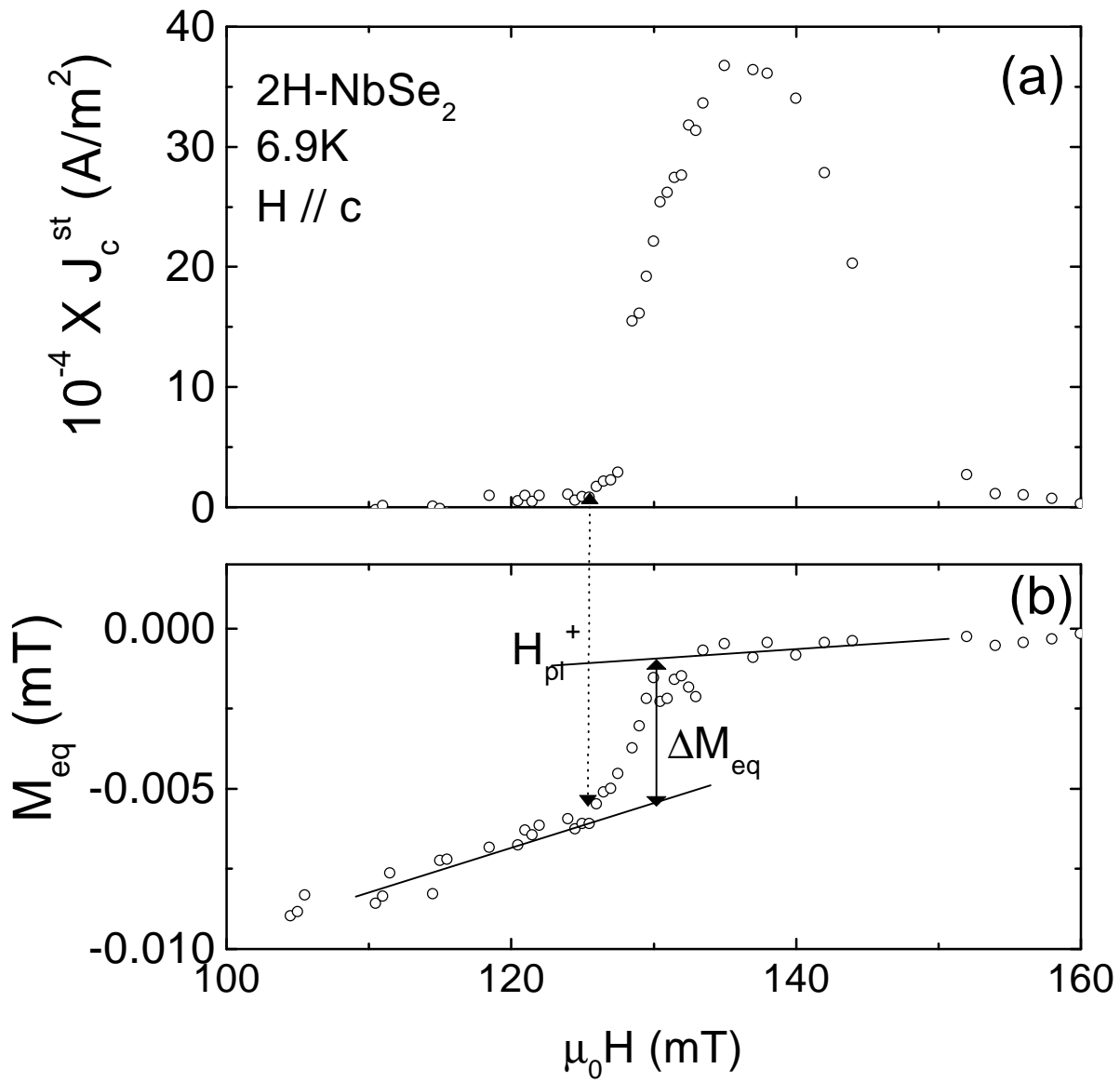


Fig. 7 - Ravikumar et al