Peak effect in 2H-NbSe$_2$

**Fixed T; varying H**

**Fixed H; varying T**

**Peak effect in reduced H**

**I-dependence of peak effect**

* Robust location of resistance minimum in (H,T) space

* Nonlinear; i.e., related to anomalous (H,T)-dependence of pinning
Motion of flux lines: $B$

Lorentz Force: $F_L = J \times B$

Overdamped motion: $v \sim \gamma F$

Electric field: $E = v \times B$, $\parallel J$

Dissipation = Resistance

Intrinsic resistance $R_{ff} = R_n \cdot (H/Hc2)$

Effect of pinning: $V = R_{ff}(1-1_c)$

Expt: Rounded onset
Peak Effect: Different Depinning Process

Variation in \( I-V \)'s
Simulations of a Wigner Crystal
Net voltage: \( V = N_{\text{free}} \cdot <v> \)

For elastic flow: \( N_{\text{free}} \) is independent of \( v \)
\[
\frac{dV}{dl} \sim \frac{1}{(d<v>/dF)} \sim \frac{1}{\mu}; \ \mu = \text{friction coeff.}
\]

For plastic flow: \( N_{\text{free}} \) is \( v \)-dependent

Peaks are caused by jumps in \( I-V \)

i.e., large values of \( dN_{\text{free}}/dl \)

Fingerprint represents a specific sequence of depinning of pieces or “chunks”

Fingerprint of quenched disorder is seen through defects in the \( F \)
as the elasticity is tuned by \( H \).

Coexistence of moving and pinned states

First order like depinning transition
Dynamics of a Disordered Flux Line Lattice

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![Graph showing phase diagram]

FIG. 3. A nonequilibrium phase diagram of the FLL dynamics. $F_p$ is the conventional depinning threshold separating a pinned FLL from a moving elastic FLL. $F_{pl}$ represents the onset of the plastic flow instability in a defective flux lattice. $F_c$ marks a crossover between the plastic flow and a defect-free elastic flow regime as the defects heal at large drives. $b_m$ marks the Lindemann melting field for a disorder-free FLL. For fields above the peak the pinned FLL may be amorphous. See the text for discussions.

Koshelev and Vinokur:

Current induced crystallization:
Shaking temperature $T_{sh} \sim 1/\text{velocity}$

Vortex matter cools as it moves faster

Orders at large velocity

Also, Larkin, Marchetti & Vinokur

PRL
**Peak effect = Amorphization of FLL**

1. $H < H_{pl}$: Stiff lattice depins coherently: elastic flow

2. $H_{pl} < H < H_p$: Soft FLL depins through tears plastic flow,
   "current-induced freezing" at larger forces "dynamical transition" to elastic flow

3. $H > H_p$: entirely incoherent motion: fluid flow
   no transition to coherent motion, force needed for transition diverges around FLL melting
FIG. 3. Drift velocity (a) and differential resistivity $\frac{dv_d}{dF}$ (b) vs driving force for the array with a dense distribution of pinning centers, $N_p/N_e = 133$. The curves obtained by ramping the force up and down are indistinguishable. The error bars represent the value of $v_{\text{rms}}$. Notice that both $v_d$ and $F$ have been divided by $f_p$ to display the data obtained for different values of the pinning force on the same graph.

threshold force is large and clearly nonzero for $N_p/N_e = 133$. While we have not determined the threshold value accurately, we find that the numerical estimate agrees

FIG. 4. Fraction of sixfold coordinated vortices vs driving force. (a) is for $N_p/N_e = 0.5$ and the parameter values of Fig. 2. In this case the curves obtained by ramping the force up and down are virtually indistinguishable and no hysteresis is observed. (b) is for $N_p/N_e = 133$, with the parameter values of Fig. 3 and $f_p = 3$. The lower curves are obtained by ramping up the force from an initial disordered configuration of the flux array. Data for both $N_e = 300$ (circles) and $N_e = 1200$ (triangles) are shown to display the finite-size effect. The upper curve (square) is obtained by ramping down.
FIG. 2 (color). Shown are diffraction patterns from the FLL in three regimes at $T = 4.6$ K. Top: FLL crystal ($H = 1.1$ kOe, $h = 0.47$). Middle: hexatic FLL just below the peak effect ($H = 2.15$, $h = 0.91$). Bottom: ring of scattering from amorphous FLL ($H = 2.25$, $h = 0.96$). The radial width of the peaks determines the positional correlation length ($\sim 1a_0$), the azimutal width of the peaks gives the orientational correlation length, and rocking through the Bragg gives the longitudinal correlation length ($\sim 100a_0$). Nonuniform peak intensities are instrumental artifacts.
Typical behavior of pinning force at fixed T, varying H

![Graph showing pinning force vs. magnetic field](image)

- "Peak effect" 
- $T = 4.2K, H \parallel c$
- $H_p$, $H_{pl}$, $H_{irr}$
- $H_{pl}$: onset of plastic flow

**Larkin-Ovchinnikov: Collective Pinning**

- Collective volume: $V_c = R_c^2 L_c$
- Pinning: $W = n_0 \langle \xi^2 \rangle$
- Pinning force density: $F_p = |J_c X B| = (W/V_c)^{1/2}$

**Formula for $F_p$:**

$$F_p = n_0^2 a^4 / [16a^3 \cdot C_{44} \cdot C_{66}^2]$$

- Pinning provides information about correlation of the lattice:
- Softer lattice is pinned better

**Intermediate H:** $C_{66} \sim (H_{c2} - H)^2$; $f^2(H_{c2} - H) \cdot J_c \sim 1/B$; $F_p \sim$ constant

**Higher H:** Nonlocal $C_{44}$ softens; $V_c$ shrinks rapidly

- $F_p$ increases until $R \sim a$ at $H_p$:
- **Amorphous FLL**

**Even higher H:** $V$ constant; $F_p \sim f^2 \sim (H_{c2} - H)$

**Peak Effect**

- Amorphization of FLL
- but what causes it?
Power law scaling in two regimes of dynamics

3-D FLL (H ⊥ c)

\[ V \propto (I - I_c)/I_c \]

T = 4.2 K; H = 4.0 T

below peak

\[ I \]

above peak

\[ H \perp c \]

\[ V = \ \begin{cases} \beta = 1.3 & \text{below peak} \\ \beta = 1.7 & \text{above peak} \end{cases} \]

Quasi-2D FLL (H || c)

\[ \log(V) \propto \log((I - I_c)/I_c) \]

H = 6.6 T

H = 6.4 T

below peak

\[ \beta = 1.3 \]

above peak

\[ \beta = 1.7 \]

Regime Pe elsewhere depinning?
Anomalous frequency dependence in plastic flow

$I = I_{dc} + \delta I \cos \omega t$

regime I
elastisc

50 kG

$\frac{dV}{dI}$ 100Hz
$\frac{dV}{dI}$ 2Hz

Current (amps)

0.001

0.002

0.003

0.004

0.005

0.006

0.007

0.008

0.009

0.1

$I$ (amps)

plastic

56 kG

$\frac{dV}{dI}$ 2Hz
$\frac{dV}{dI}$ 100Hz

regime II

$\frac{dV}{dI}$ (ohms)

0.002

0.004

0.006

0.008

0.1

$I$ (Amps)

0.02

0.04

0.06

0.08

0.1

$\frac{dV}{dI}$ (ohms)

$I$ crossover

H = 57 kG

regime III

fluid

58 kG

$\frac{dV}{dI}$ 2Hz
$\frac{dV}{dI}$ 100Hz

Current (amps)

0.02

0.04

0.06

0.08

0.1

$I$ (amps)

60 kG

$\frac{dV}{dI}$ 100Hz
$\frac{dV}{dI}$ 2Hz
Onset of noise coincides with onset of V

Noise depletes at large current

Restricted to narrow H-regime: $H_{pl} < H < H_p$
1. Rigid Solid: spatially coherent motion
   power law $F-v$ curves [critical phenomena?]
   $L_v \sim$ system size: non-defective motion
   "elastic flow"

2. Soft Solid: incoherent motion at small $F$
   non-power law $F-v$; first order depinning
   $L_v \sim$ large; a few chunks
   "plastic flow"
   but, dynamical transition at large $F$ to "elastic flow"

3. Liquid: totally incoherent dynamics
   power law $F-v$; a different case - percolation?
   $L_v \sim$ lattice constant, $N$ chunks
   "fluid flow"
   but, thermally melted, hence cannot be coherent
   even at large forces, quenched disorder is always relevant (c.f. puddles)
Current status of moving phase studies

Theory: Nature of moving phase and phase transitions
  Moving crystal (Koshelev and Vinokur)
  Moving Bragg glass (Giamarchi and Ledoussal)
  Moving Smectic (Balents, Radzihovsky and Marchetti)
  Length scales (Balents and MPA Fisher)

Simulations (many):
  confirmation of elastic, plastic and fluid flow
  confirmation of noise in plastic flow
  "chunk" scale and rivers

Experiments on structure of moving phases:
  Bitter decoration:
    Marchevsky et al., PRL 78, 531 (1997).
    Pardo et al., PRL 78, 4633 (1997)
  Electron Holography:
    Tonomura et al., Nature 397, 308 (1999)
  Neutron Diffraction:
    Yaron et al., Nature 376, 753 (1995)

Expanded to other fields: Colloidal systems, CDW's
Possible analogies with granular systems....
quite well-ordered with resolution-limited diffraction peaks. An important theoretical advance was made on the basis of numerical simulations by Koshelev and Vinokur who argued that there could be three distinct regimes of flow. For applied currents below the critical current ($I_c$), these authors found a pinned, moderately disordered solid; at $I_c$, they saw a regime of quite disordered plastic flow, and for currents well above $I_c$, they found a regime where the moving lattice was quite well ordered, perhaps crystalline. This prediction of a plastic flow regime was confirmed by both SANS and magnetic decoration studies of the flowing FLL at $I_c$.

More recently, Giarmarchi and Le Doussal have argued for the existence of a moving-Bragg-glass phase for currents well above $I_c$. This is a phase free from topological defects, with power-law decay of the positional correlations which are anisotropic with respect to the flow direction. Balents, Marchetti, and Radzihovsky have argued instead for a nematic phase. Such a phase is layered in the sense that the vortices flow in channels and are well correlated perpendicularly to their flow, but uncorrelated along it. This is consistent with recent numerical simulations.

In the magnetic decoration technique used here, the FLL is visualized by evaporating 50-A magnetic particles onto the surface of a superconductor held below its transition temperature $T_c$ with a magnetic field applied. The particles follow the field lines of the vortices at the surface of the sample, and land where the vortices are located. Because each pile of magnetic particles has a finite size, the technique is limited to fields below several hundred oersteds. Fortunately, this range of fields covers an interesting region where we can 'tune' the vortex interaction strength relative to the pinning strength, and see a crossover from a nematic structure in the low-field, disorder-dominated limit to a moving Bragg glass in the high-field, interaction-dominated limit.

Our samples were high-quality, single crystals of NbSe$_2$ with typical dimensions of 0.5 x 0.5 x 0.2 mm. They were cleaved just before use to assure a clean surface for the measurement. Samples were cooled down to 4.2 K in a magnetic field applied in the c direction. At low temperatures, the field was removed and the sample was decorated after a certain period of time ($t$).

Figure 1 shows data from a SQUID (superconducting interfer- ence device) measurement of the magnetization of our sample taken as a function of time ($t$) after the 36 Oe field was removed. The flow velocity ($v$) at the edge of the sample was extracted from the magnetization using the relation $v = \frac{\text{m}(t)}{\text{m}(0)} A P(t)$ where $A$ is the area, $P$ the perimeter, and $m(t)$ the magnetization. The average lattice constant plotted was obtained using $a_B(t) = \frac{\Phi_0}{V(t)}$, where $V$ is the sample volume and $\Phi_0$ is the flux quantum. With a one-second decoration time, the plot of the vortex velocity defined two regimes. If the velocity is greater than one vortex lattice constant per second, we find images of vortices in motion. For the regime of vortex velocities less than one lattice constant per second, we obtain quasistatic images of slowly moving vortices. We can work in both regimes. Because of the critical-state profile (independent of velocity regime), we always find a quasistatic, homogeneous structure in the centre of the sample and the critical-state region at the edge. The data shown here is always from the critical-state regime.

Our imaging data are shown in Fig. 2. There are three types of images shown for four different regimes (Fig. 2a–d). The first column shows the real-space images (RS) of the FLL, the second the Fourier-transformed (FT) data and the third a Fourier-filtered (FF) real-space image. In the first column, the flow direction is indicated with an arrow. The row of images in Fig. 2a is low-field/low-velocity data, Fig. 2b is low-field/high-velocity, Fig. 2c is high-field/low-velocity and Fig. 2d is high-field/high-velocity data.

Because the data in row Fig. 2a are in the quasistatic regime, the

![Figure 1](image1.png)

*Figure 1* Average vortex velocity and intervortex spacing $a_B$ as a function of time during flux creep for a sample of NbSe$_2$ at 4.2 K. A field of 36 Oe was originally applied and then removed at $t = 0$. In the moving regime, the vortices move more than the intervortex spacing during an experiment; in the quasistatic regime, the vortices move less than the intervortex spacing during an experiment.

![Figure 2](image2.png)

*Figure 2* Images of the flux line lattice at different fields and flow velocities. Shown are real space (RS; first column) Fourier-transform space (FT; second column) and Fourier-filtered (FF; third column) images. The real-space images were digitized, flux-filtered on a 20 x 20 kernel and Lee filtered with a 5 x 5 kernel. To obtain the Fourier-filtered images, the real and imaginary components of each pixel in the Fourier-transform image were multiplied by a smooth sigmoid function of their magnitude with a threshold of $-1/3$ of the peak magnitude of the FT over the entire image. These data were then inverse-transformed and the absolute value of the inverse transform was used to construct the third column. a. Low-field, low-velocity data (3 Oe, 0.1 µm/s); b, low-field, high-velocity data (3 Oe, 2.8 µm/s); c, high-field, low-velocity data (20 Oe, 0.2 µm/s); d, high-field, high-velocity data (20 Oe, 2.5 µm/s). Notes a and b show a smeared vortex lattice; a and d show a moving Bragg-glass state. The arrows in the first column show the direction of flow.
FIG. 1. Data taken at $T = 1.36$ K, $H = 80$ G, and $f = 96$ MHz on a 1000-$\text{Å}$×3.27-mm×2.54-mm Al film. (a) dc current for several rf current levels, (b) differential dc resistivity, and (c) rf voltage plotted against dc electric field. Values of the rf current and the ratio $n'/n$ are also shown.

FIG. 2. Conductance noise spectra for selected magnetic fields under $133$ A/cm$^2$ at $80$ K. Ticks in the ordinate indicate a noise level of $10^{-18}$ V$^2$/Hz for the data at each magnetic field and solid arrows indicate one decade of the noise power spectral density. Typical BBN and NBN structures are shown in (a) and (b), respectively. The dashed arrows indicate the peak position of the NBN.

FIG. 2. Four traces of $dV/dt$ vs $E$ taken at $86$ K in a 3.3 T field at different rf frequencies $\nu_{\text{rf}}$ (the curves are displaced vertically for clarity). As $\nu_{\text{rf}}$ increases from $50$ to $200$ kHz, the peak positions shift to higher $E$ fields, in agreement with the washboard effect. Vertical bars indicate the predicted positions $E_{\nu_{\text{rf}}}^0$ of the interference peaks with index $p/q$. The inset compares the observed positions of the peaks (open symbols) with the predicted positions $E_{\nu_{\text{rf}}}^0$ assuming the pinned fraction $f = 0$. As $\nu_{\text{rf}}$ increases, the observed peaks shift to higher $E$ fields, in agreement with the washboard effect. Vertical bars indicate the predicted positions $E_{\nu_{\text{rf}}}^0$ of the interference peaks with index $p/q$. The inset compares the observed positions of the peaks (open symbols) with the predicted positions $E_{\nu_{\text{rf}}}^0$ assuming the pinned fraction $f = 0$. As $\nu_{\text{rf}}$ increases, the observed peaks shift to higher $E$ fields.