INTERNATIONAL ATOMIC ENERGY AGENCY
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SMR.959 - 30

MINIWORKSHOP ON STRONG ELECTRON CORRELATIONS
"Disorder and Interaction in Quantum Systems and Their Classical Analogs"

(1 - 19 July 1996)

"Varieties of flux lattice dynamics"

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These are preliminary lecture notes, intended only for distribution to participants.

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NEC

Varieties of flux lattice dynamics

OUTLINE

1. Introduction to the "problem"

2. The System

3. Experimental results

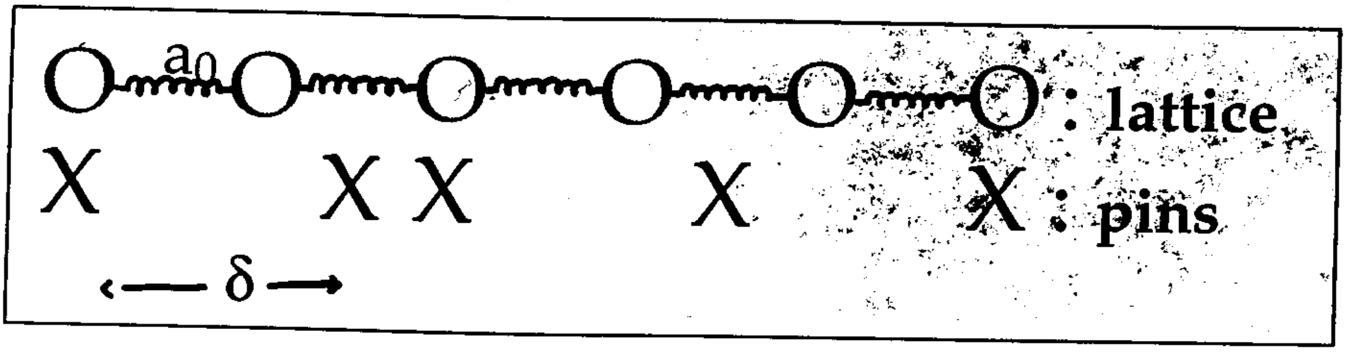
4. "Dynamic phase diagram" : moving phases :elastic, plastic and fluid

5. Length scales, noise and all that

6. Epilogue : statics from dynamics
   flux lattice phase diagram

NEC Research Institute

The generic problem :
Elastic media & quenched disorder



Competition between elasticity and pinning :

$$E_{el} \sim (R)^{d-2};\ E_{pin} \sim (R)^{d/2}$$

Minimize energy →
loss of long range order: correlation length of FLL [Larkin]

$$R_c \sim (K_{el}/V_{pin})^{2/(4-d)}$$

Threshold phenomena in dynamics : F_p

$$F_p \sim (R_c)^{-2}$$

(Soft things get stuck more)

Varying interaction or disorder changes the nature of threshold and dynamics

Interaction dominant :Weak pinning : $R_c \gg a_0, \delta$	
Disorder dominant : Strong pinning : $R_c \sim \delta$	

Question : how does the dynamics vary between the two extremes ?

Examples :

Incommensurate CDW, Wigner solid in 2DEG, Quantum dot array,magnetic bubble array, Domain dynamics in disordered magnets (ferroelectrics?), Colloidal crystals, 2-fluid interface in random porous media, etc.

Ideas :

1. Depinning transition as dynamical critical phenomena (D.Fisher) :

   Scaling laws : e.g., $v \sim (F - F_p)^{\beta}$

   Dynamic correlation length : $\xi_v \sim (F - F_p)^{-\nu}$

Q. Is this description right and/or sufficient ?

2. From HTSC : exotic phases & transitions among them (melting, vortex glass, Bose glass, ...etc.)

Q. Do they occur and how does one find them ?

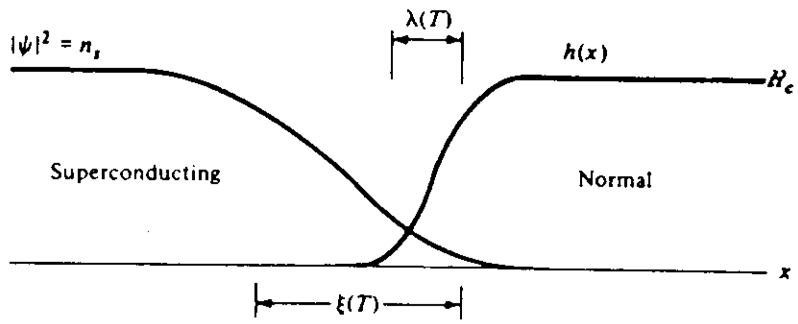
3. ~All studies of phase transitions are made via transport measurements.

Q. How does dynamics relate to thermodynamic phase transitions, in the presence of disorder ?

FLUX-LINE LATTICE

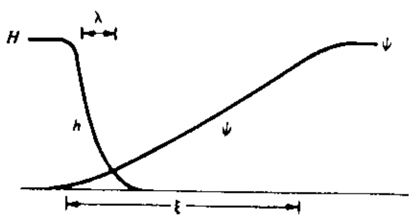
Types of Superconductivity :
relationship between two lengths

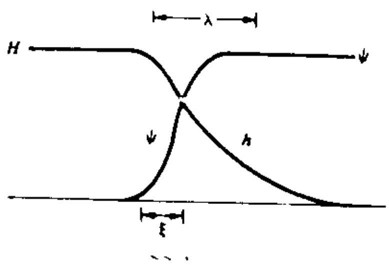
coherence length : ξ : local electronic properties
penetration depth: λ : local magnetic fields



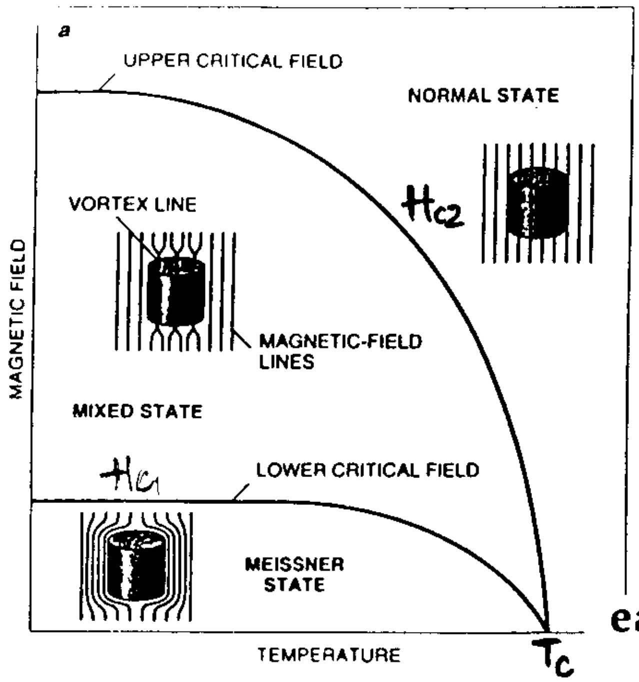
Ginzburg-Landau parameter $\kappa = \lambda/\xi$

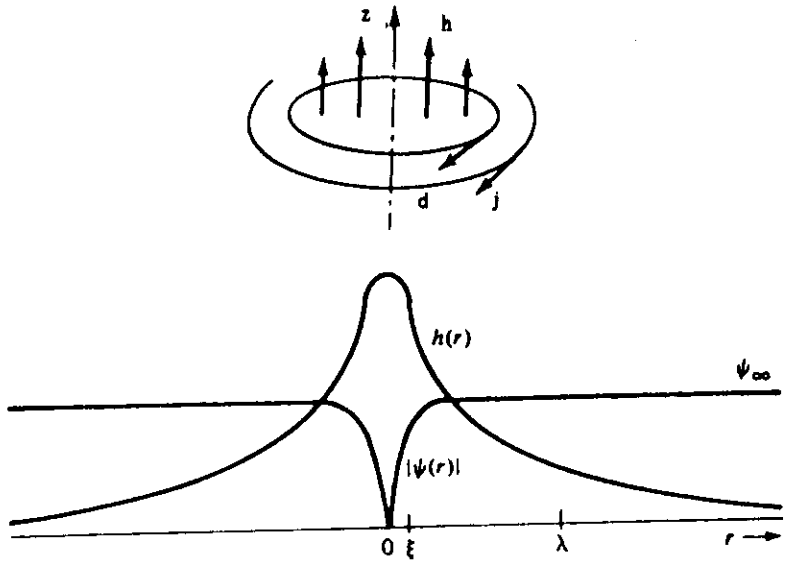
Type I : $\kappa < 1/\sqrt{2}$; **Type II :** $\kappa > 1/\sqrt{2}$





Phase diagram of a type-II superconductor





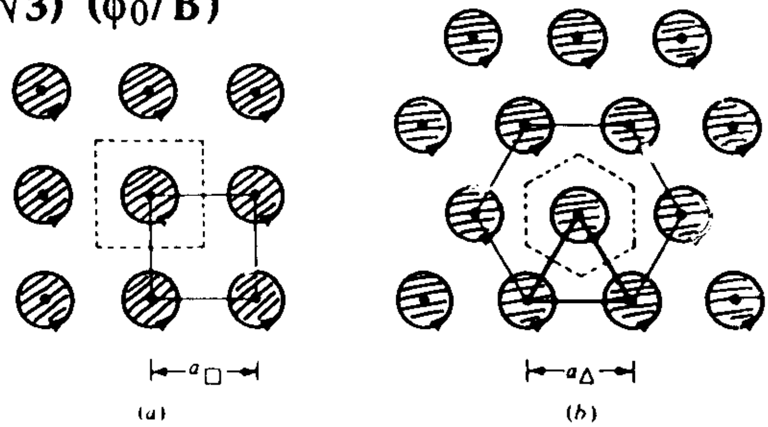
each flux line carries a flux quantum

: $\phi_0 = (ch/2e) = 2 \times 10^{-7}$ gauss.cm^2 .

Repulsion between flux lines
----> flux line lattice (FLL)

increasing H increases density of flux lines :

lattice spacing: $a_0^2 = (2/\sqrt{3})\,(\phi_0/B)$



*** interaction in FLL is tunable by H ***

Elasticity of a flux line lattice

(Maxwell 1892; Friedel, deGennes and Matricon 1963; Labusch 1967 Brandt 1979; Larkin 1979)

- distorting or compressing the lattice costs energy; lattice has finite elasticity

- hexagonal symmetry

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{yz}\\ \sigma_{xx}\\ \sigma_{xy}\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 & 0 & 0\\ C_{12} & C_{11} & 0 & 0 & 0\\ 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0\\ 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{yz}\\ \varepsilon_{xx}\\ \varepsilon_{xy}\end{bmatrix}$$

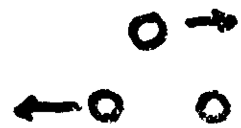
$2C_{66} = C_{11} - C_{12}.$

Three independent elastic moduli are

C_{11} (compression)

C_{44} (tilt)

C_{66} (shear)



$$C_{66} \sim (B_{c2}^2/4\pi)(1 - 1/2\kappa^2)b(1-b)^2(1 - 0.29b)/8\kappa^2,$$

$$C_{11}(k) \sim (B^2/4\pi)(1 - 1/2\kappa^2)(1 + k^2\lambda'^2)^{-1}(1 + k^2\xi'^2)^{-1},$$

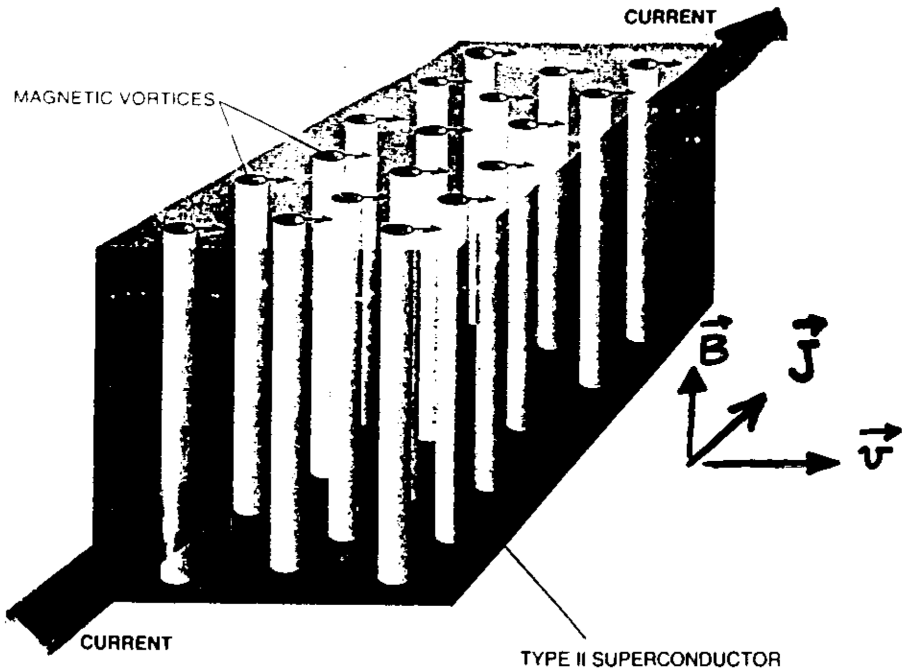
$$C_{44}(k) \sim (B^2/4\pi)[(1 + k^2\lambda'^2)^{-1} + 1/k_{BZ}^2\lambda'^2)^{-1}],$$

$$\text{where } \lambda' = 1/k_h = \lambda/(1-b)^{1/2},\ \xi' = 2\xi/(1-b)^{1/2}.$$

FLL is an extremely soft solid : H =1T, $C_{11} = 8\text{X}10^6$ dynes/cm^2

$C_{66} \sim 5 \times 10^4$

DYNAMICS OF THE FLUX LINE LATTICE



- Lorentz force : $F_L = J \times B$ { current = force)
- If F exceeds threshold force F_P ($= J_c \times B$),
  then FLL moves {Jc <---- critical current}
  Overdamped motion ----> velocity v : $\gamma . v \sim F$
- Electric field $\mathbf{E} \sim \mathbf{v} \times \mathbf{B}$ { voltage = velocity }
  $1\ \mu V/cm.T = 10^2\ \mu m/sec$
- Kim's model (no justification):

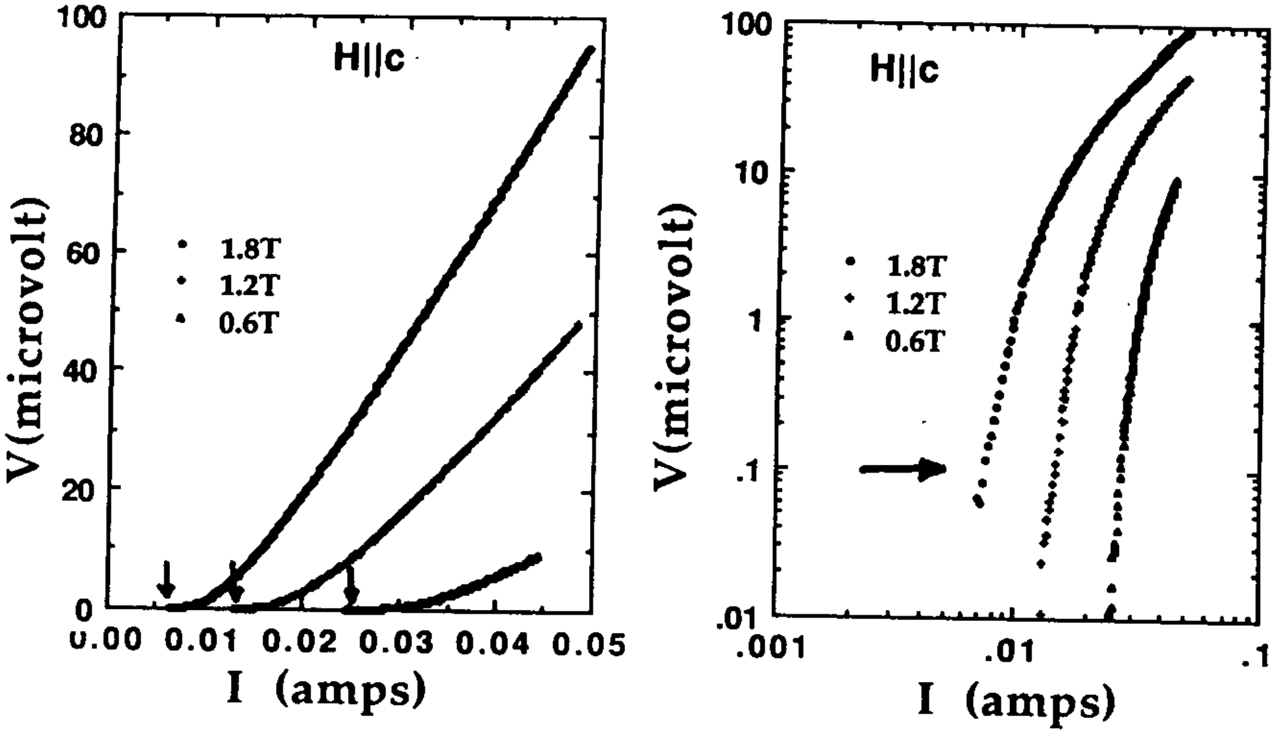
  $\gamma . v = (F_L - F_P)$,
  {γ ~ viscosity/**friction coefficient**}

  Flux flow resistance : $\rho_f = dE/dJ = (\phi_0/\gamma c^2).B$

- **Bardeen-Stephen flux flow model**

dissipation due to normal fraction : $\rho_f = \rho_n . (B/H_{c2})$

I-V curve in log and linear scale



Pinning of FLL

inhomogeneity in order parameter pins FLL

> defects, dislocations, vacancies, second phase , substitutional impurities, ...

summation problem : why is pinning force finite ?

Larkin : FLL is not long-ranged
Threshold force for motion
$F = |J_c \times B|$

exptal signature : voltage criterion (we use ~100nV)

Why $NbSe_2$?

Superconducting parameters for $NbSe_2$

T_c=7.1K, $H_{c2,||}$= 4T

Parameter	H $\parallel$ c	H $\perp$ c
κ	9	30
ξ	77Å	23Å
λ	690Å	2300Å
J_c	1-30 A/cm^2	10-200 A/cm^2

Quantity	HTSC	LTSC	$NbSe_2$
$Gi = (kT/H_{c2}^2\, \xi^3)$	10^{-2}	10^{-8}	10^{-4}
$J_c/J_0 = (\xi/R_c)^2$	10^{-2}	10^{-1}	10^{-6}

(1)Among the cleanest single crystals;
e.g., $R_c \sim 400\ a_0$ at H=1T, T=4.2K
Ideal for testing clean system concepts

(2) Dimensionality variation :
H $\parallel$ c : quasi-2D
H $\perp$ c : 3D

Experimental problem in all systems :
disorder not controlled

Strategy : vary interaction by tuning H in a given sample with a given realization of quenched disorder

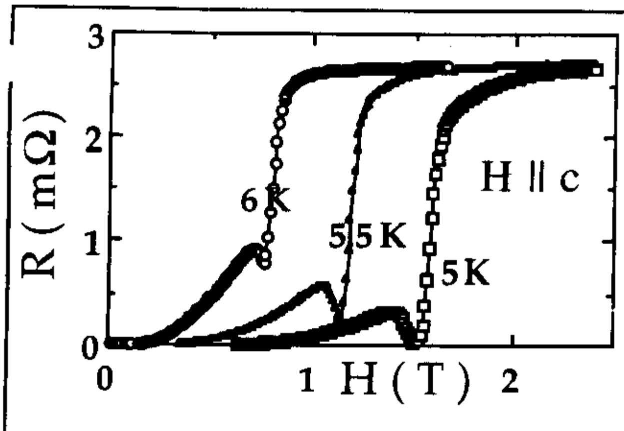
Flux lattice melting : $C_{66} \sim b\,(1-b)^2$
$[b = H/H_{c2}]$
Above melting : flux liquid with no rigidity

Crossover in the dynamics must accompany a thermodynamic melting transition

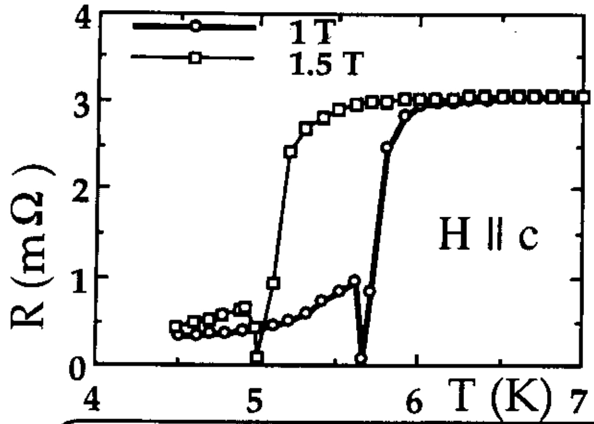
Find a clean weak pinning system and vary H at fixed T or vice-versa and study dynamics

Find : Peak effect !

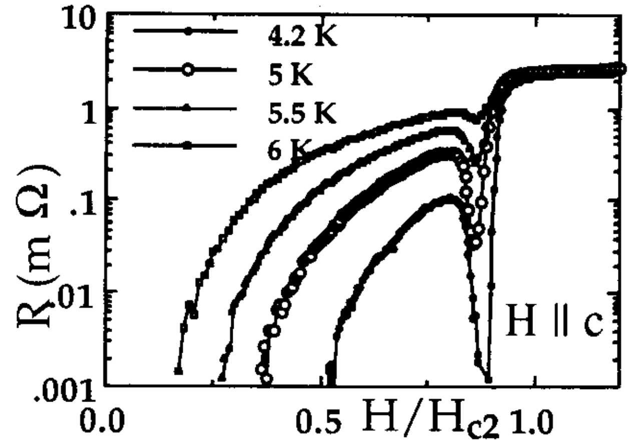
Peak effect in 2H-$NbSe_2$



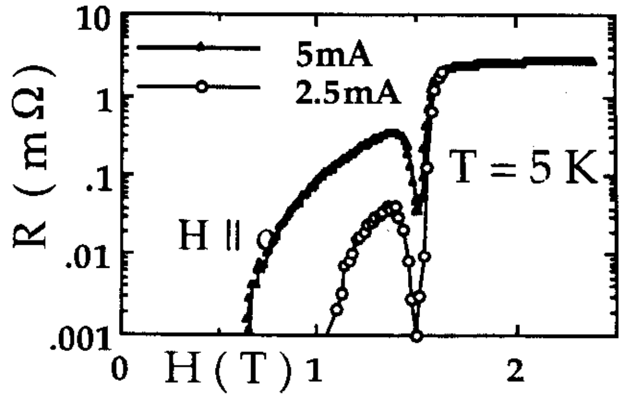
Fixed T; varying H



Fixed H; varying T



Peak effect in reduced H

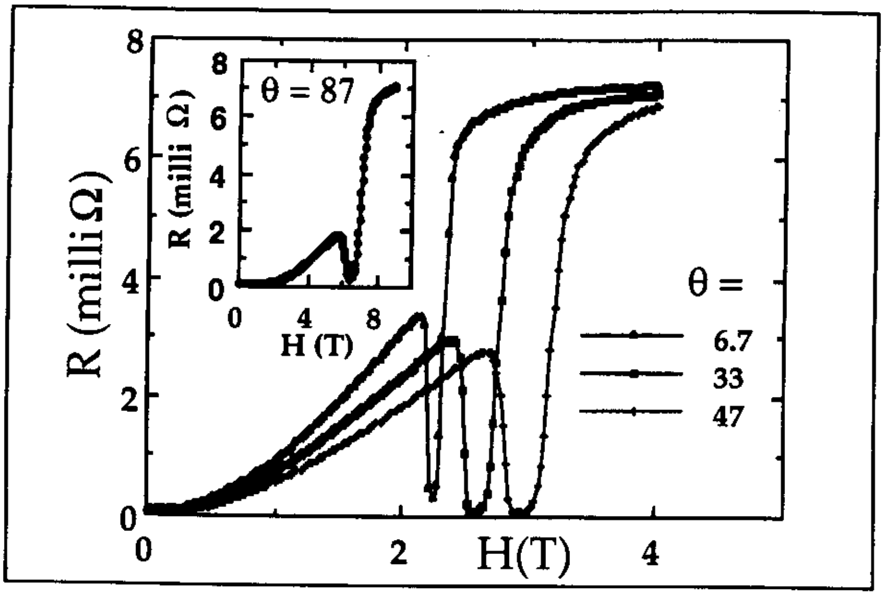


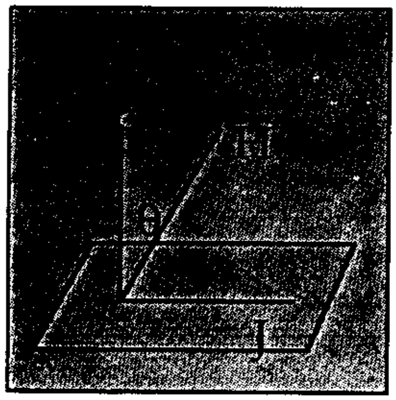
I-dependence of peak effect

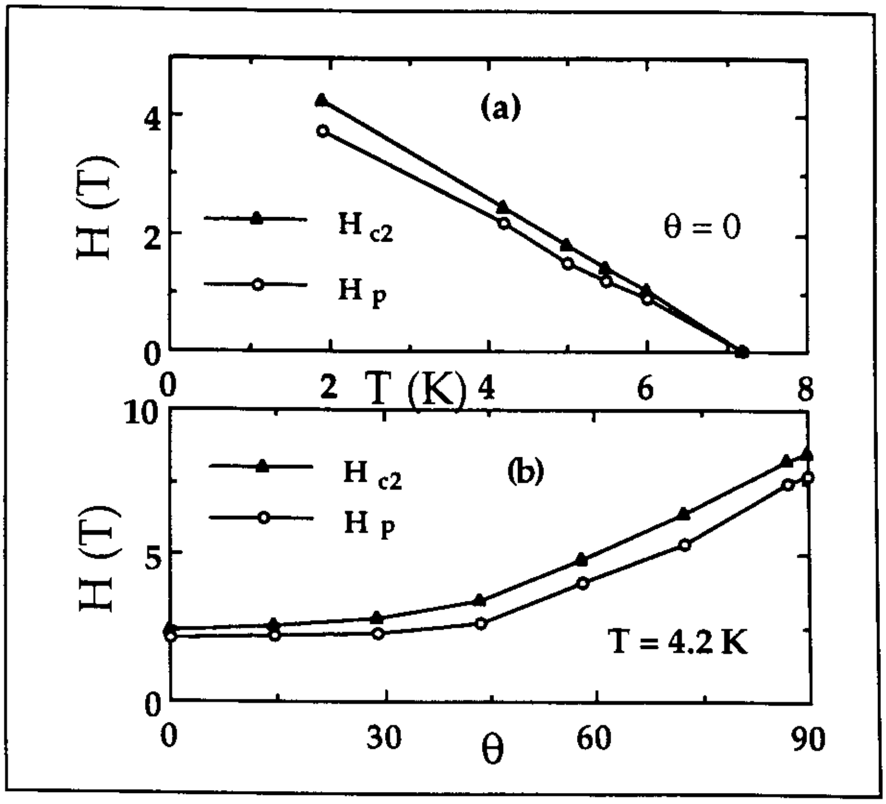
* Robust location of resistance minimum in (H,T) space

* Nonlinear; i.e., related to anomalous (H,T)-dependence of pinning

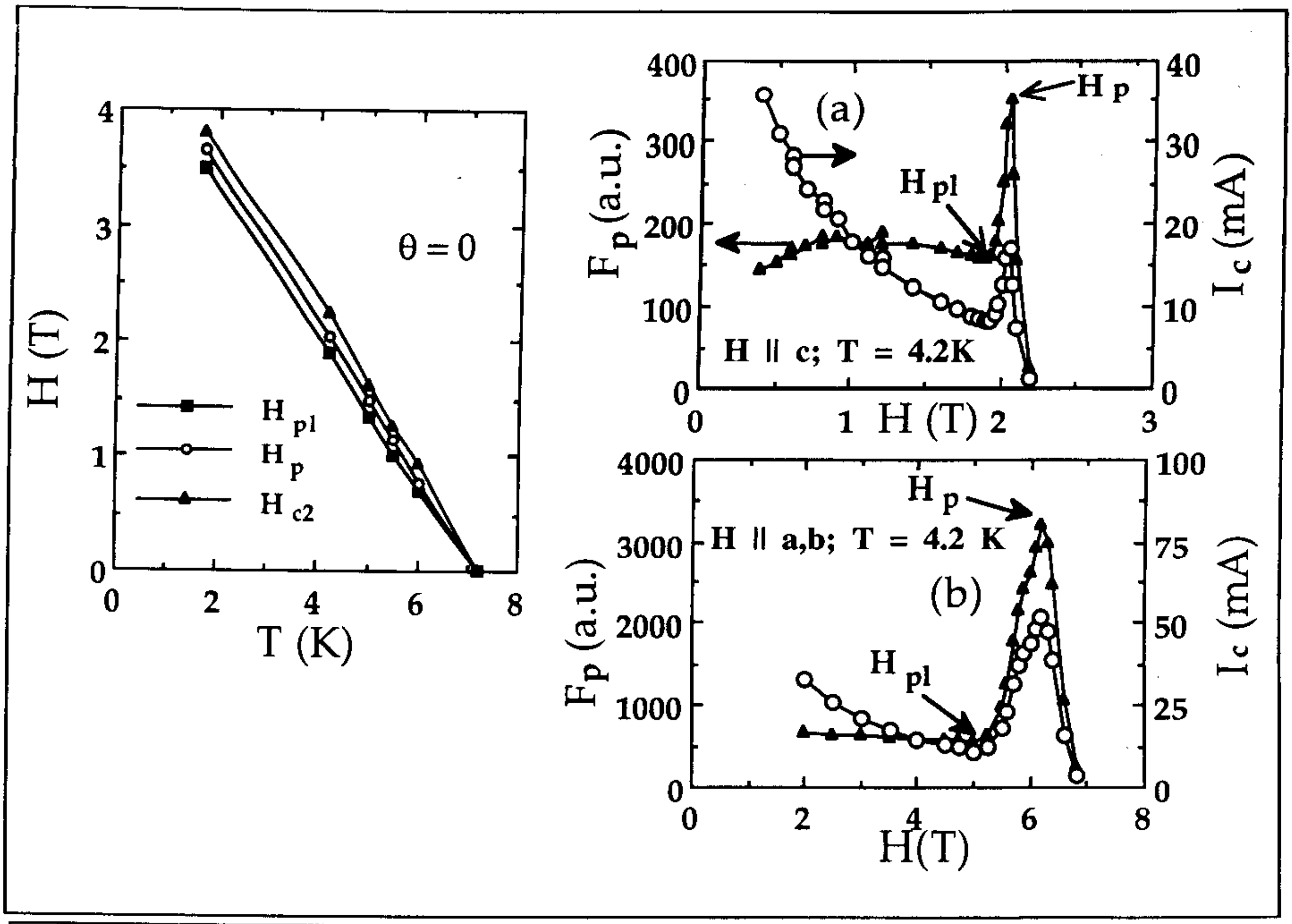
Anisotropy of "Peak Effect"

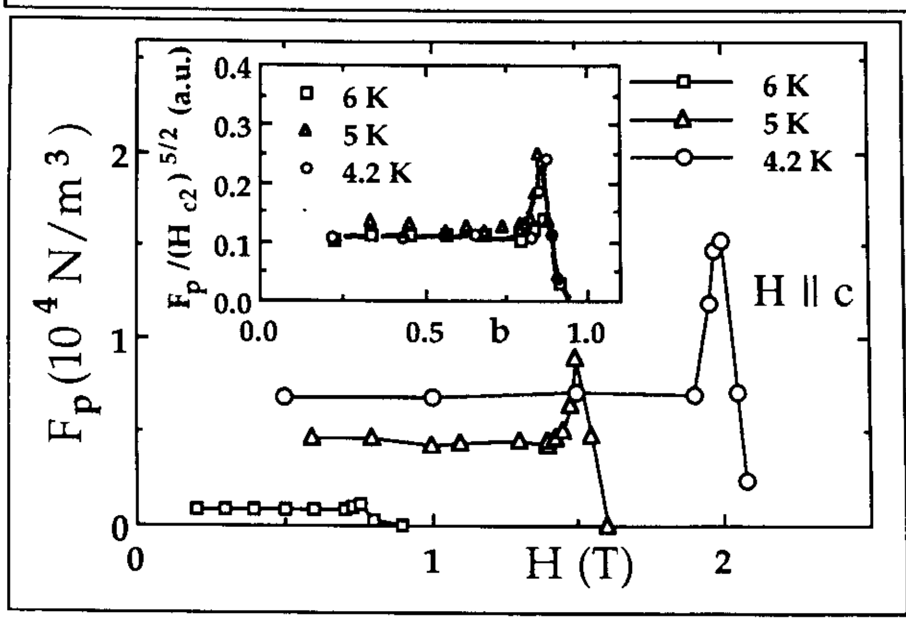






Peak effect [illegible]





n=5/2;
dense point pins
isoelectronic,
substitutional
pins (Ta-atoms?)
(Ullmaier)

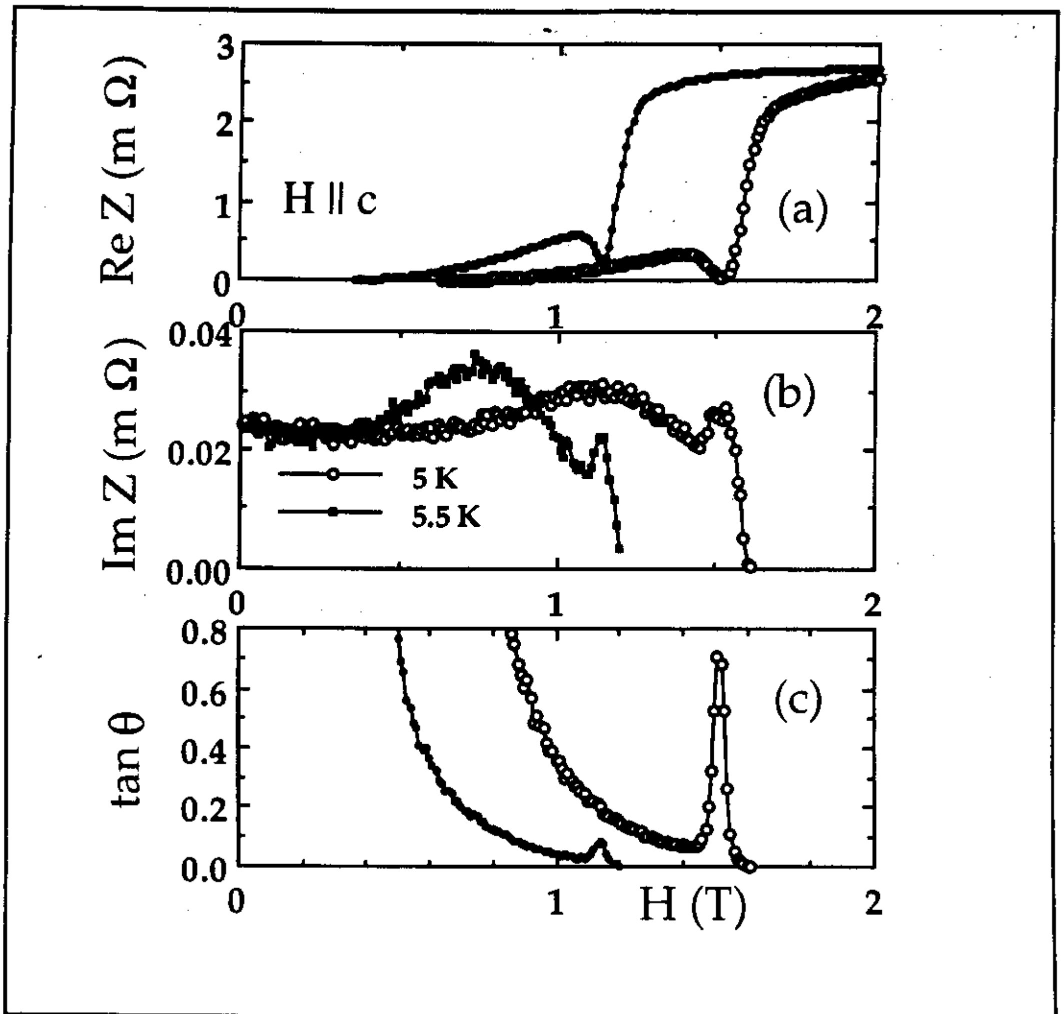
$$F_p(T) = [H_{c2}(T)]^n \cdot f[H/H_{c2}(T)]$$

T-independent pinning mechanism

AC response in Peak Effect :

$$Z = R + j\omega L$$

$$\tan\theta = \omega L / R$$

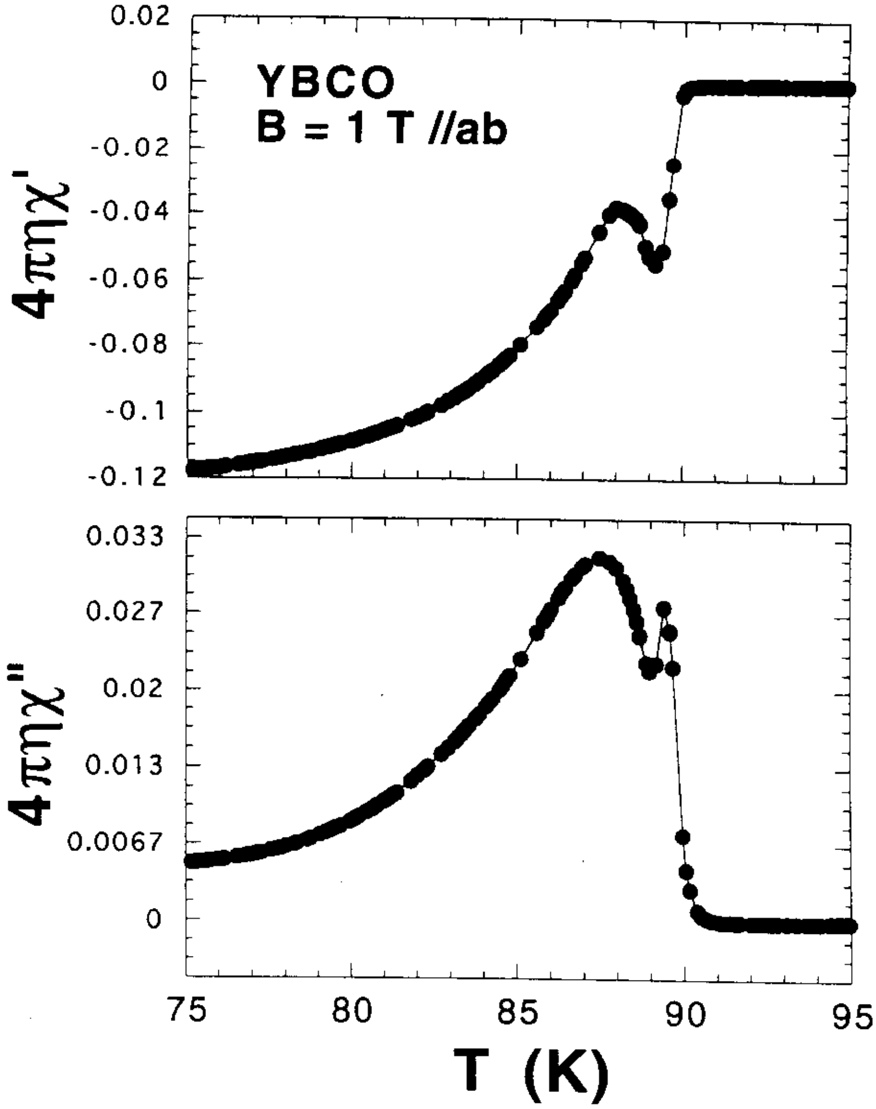


enhanced inductive response

"reentrance to superconductivity"

identical to ac susceptibility studies on peak effect in NbSe2 observed by X.S. Ling et.al (1991)

X.S. Ling, J.I. Budnick, 1992



Explanations of "Peak effect" :

Pippard : soft FLL more strongly pinned; peak is due to a sharper drop in rigidity of FLL than in the pinning interaction.

Larkin-Ovchinnikov : Collective Pinning

Larkin lengths : R_c and L_c;

collective volume : $V_c = R_c^2.L_c$

Pinning : $W = n_p. \langle f^2 \rangle$

Pinning force density : $F_p = |J_c X B| = (W/V_c)$

$$F_p = n_p.f^4/[16a^3.C_{44}.C_{66}^2]$$

1.Intermediate H : $C_{66} \sim (H_{c2}-H)^2$; $f \sim (H_{c2}-H)$

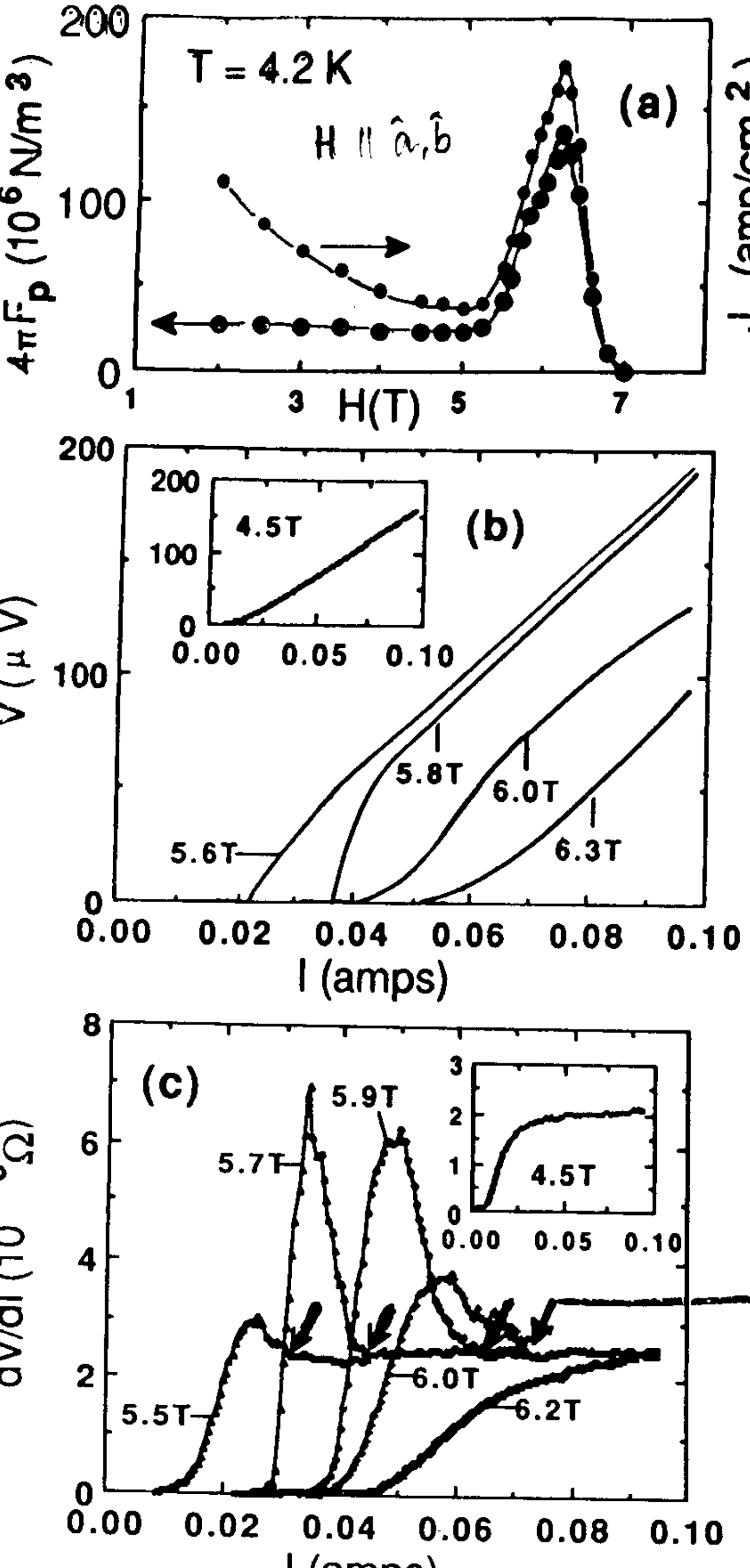
2.Higher H : Nonlocal C_{44} softens; V_c shrinks

F_p increases until $R \sim a_0$ at H; amorphous FLL

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

Quantitative comparison does not work.

Investigate I-V curves as well !



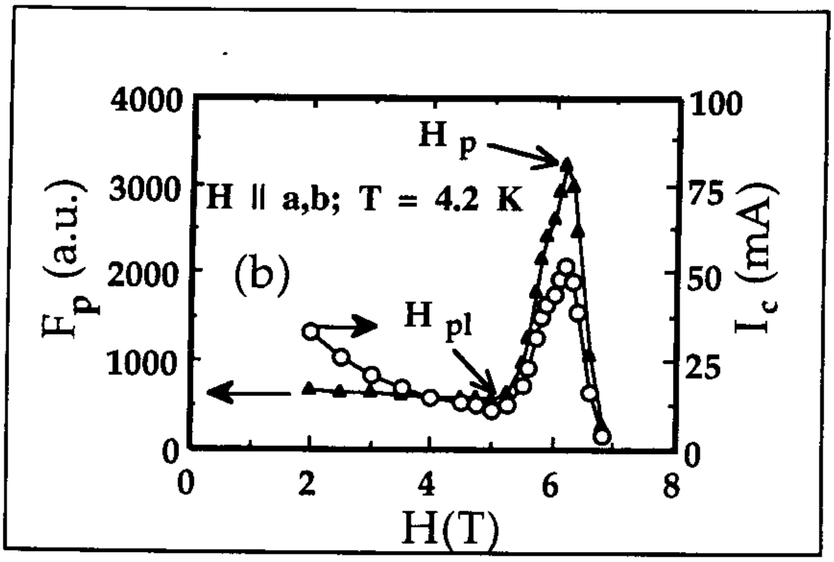
Crossover current I_{cr}

$I > I_{cr}$:

ρ_D ~ Bardeen-Stephen

Evolution of I-V curves in the peak regime

Anomalous I-V curves for H $\perp$ c



Three types of I-V curves

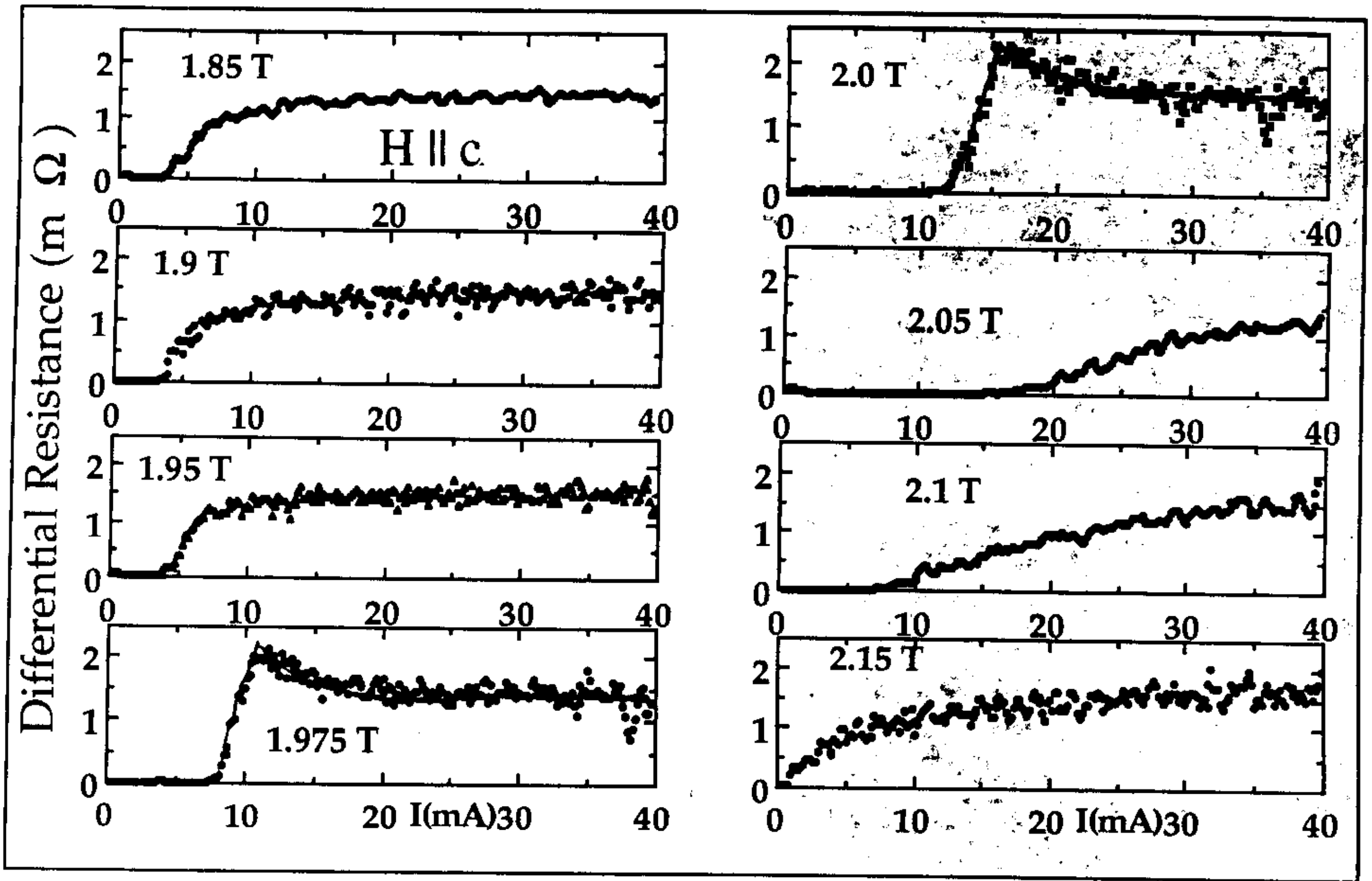
I. $H < H_{pl}$: concave upwards
II. $H_{pl} < H < H_p$: convex upwards
III. $H_p < H$: concave upwards

Regime II is anomalous:
Opposite curvature; noisy, strong thermal instabilities; $dV/dI >$ Bardeen-Stephen R_{ff}

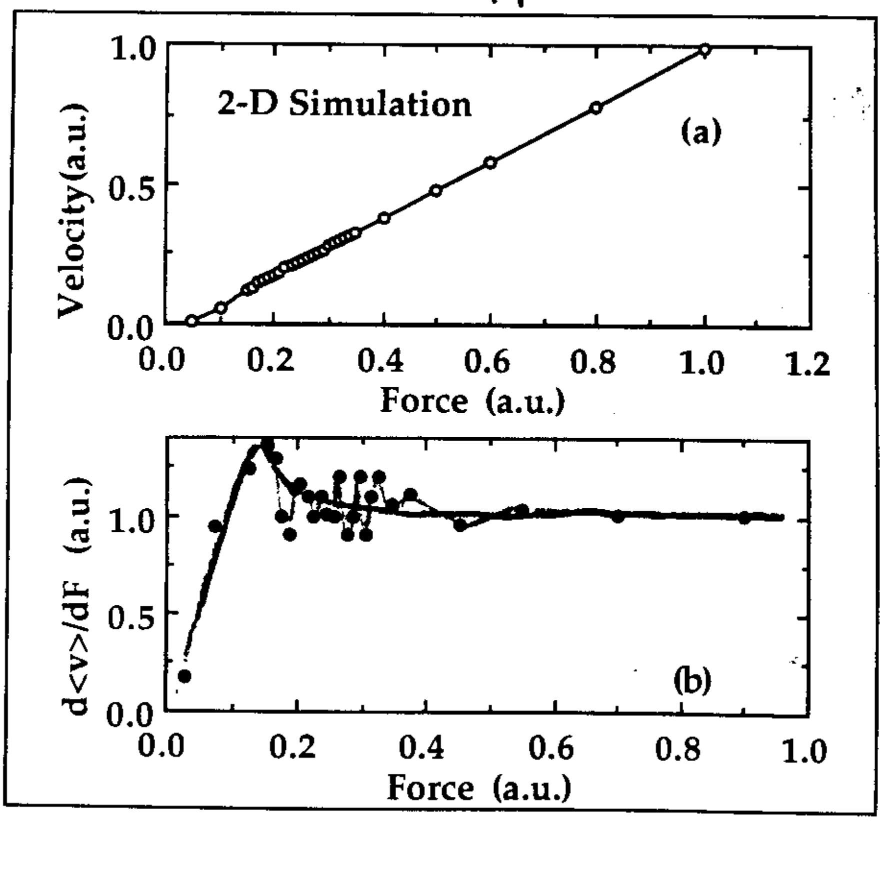
Three regimes of force in regime II

$I < I_c$: pinned FLL
$I_c < I < I_{cr}$: anomalous dynamics
$I_{cr} < I$: recovery of Bardeen-Stephen

Anomalous [dV/dI-vs-I] curves for H || c (quasi-2D)

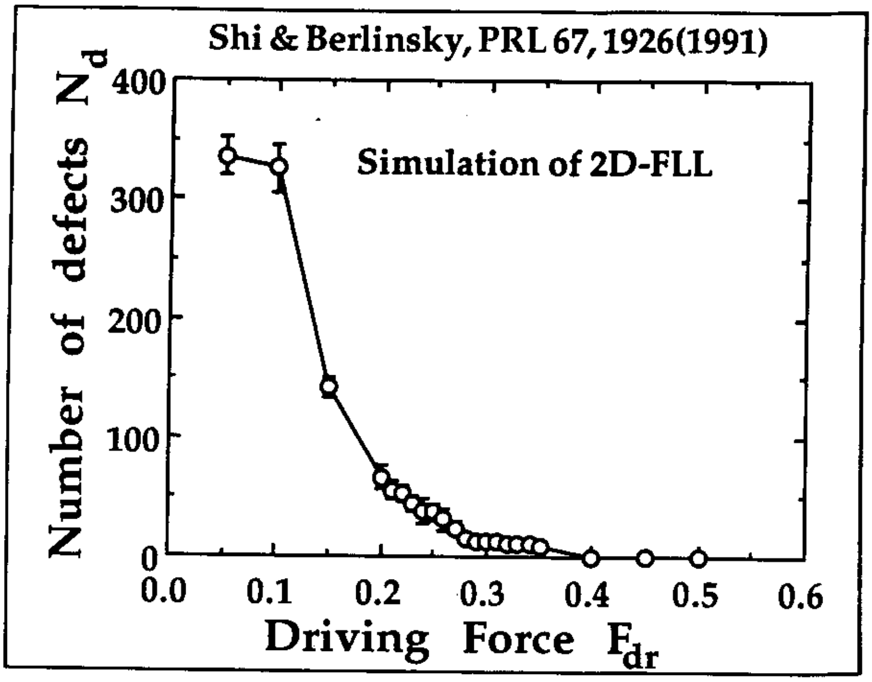


weaker approach to Bardeen-Stephan



Simulation of defective FLL (2-D)
Shi & Berlinsky
(c.f. data for 2T)

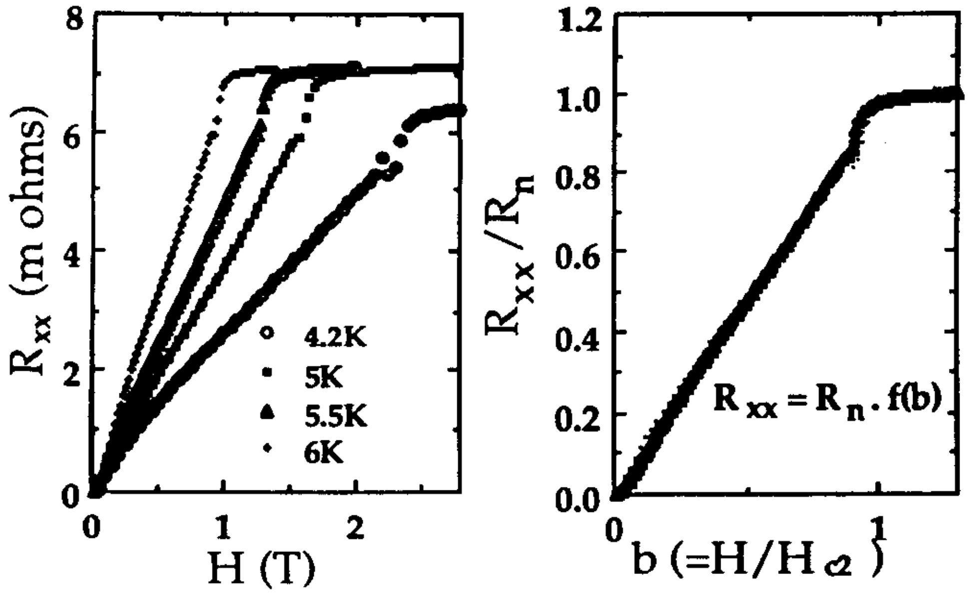
Defective dynamics and plastic flow :



Quasilinear region : free flow;
velocity decreases more at lower forces due to dynamically generated defects
: $\Delta v = [D.n_d(v).a_0^2]R_c/C_{66}$
*Tearing dominates onset of motion
*Many defects at slow motion (filaments)
*Large velocity : pinning less important
- Defects heal : recovery of coherent motion
(Plastic -Elastic crossover)
c.f. Dynamic Melting :Koshelev & Vinokur

Nonequilibrium (Dynamic) phase diagram describes dynamical states and transitions among them

Asymptotic flux flow resistance above crossover-current

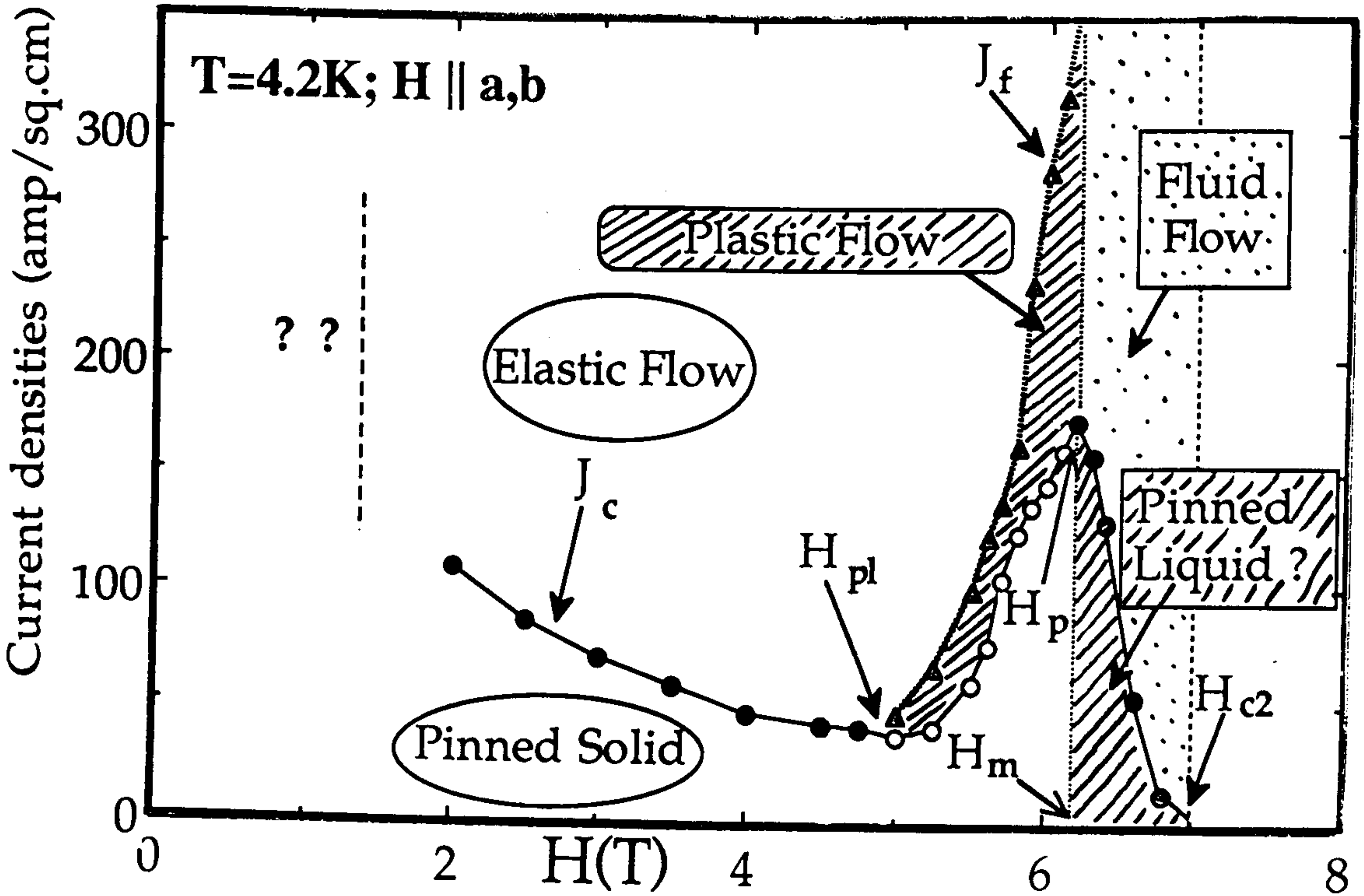


Bardeen-Stephen : $\rho_{xx} = \rho_n . (H / H_{c2})$

$$b(T) = H / H_{c2}(T)$$

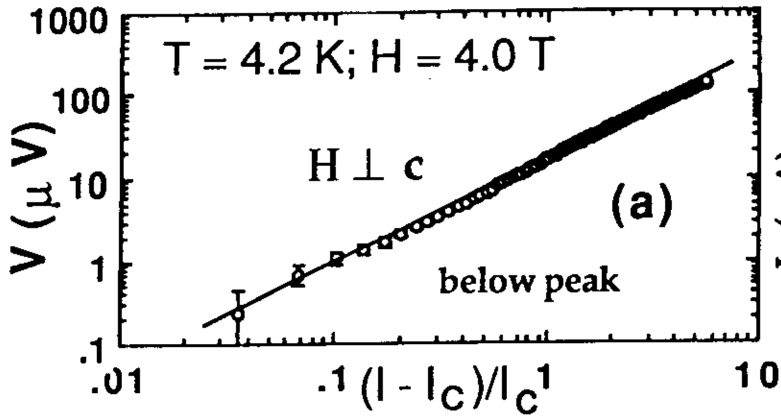
$$\rho_{xx}(T) = \rho_n(T) \; f\left[b(T)\right]$$

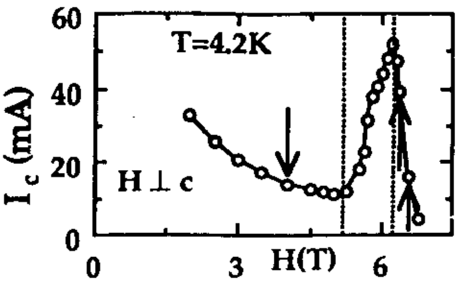
DYNAMICAL PHASE DIAGRAM

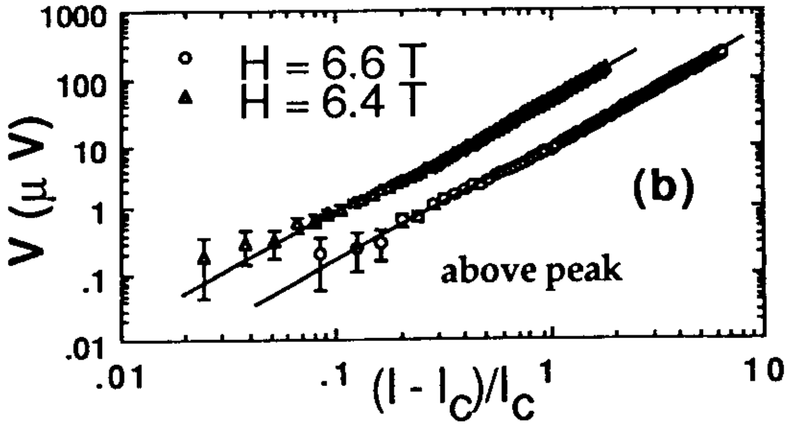


Power law scaling in two regimes of dynamics

3-D FLL ($H \perp c$)





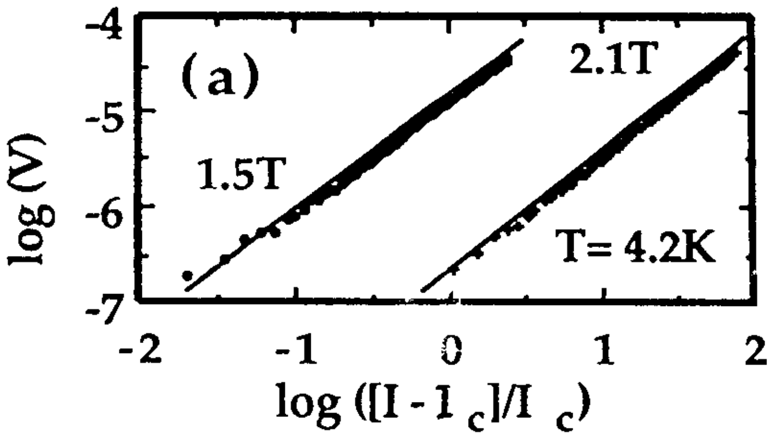


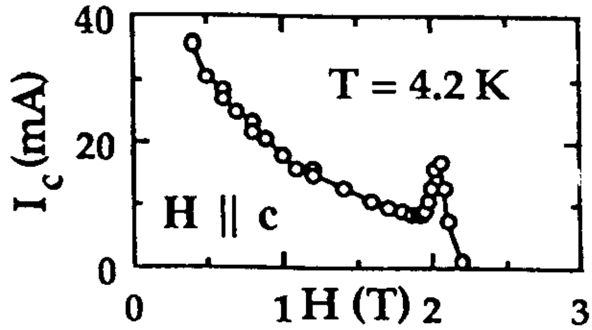
$$V \sim (I - I_c)^{\beta}$$

below peak : $\beta = 1.3$

above peak : $\beta = 1.7$

Quasi-2D FLL ($H \parallel c$)

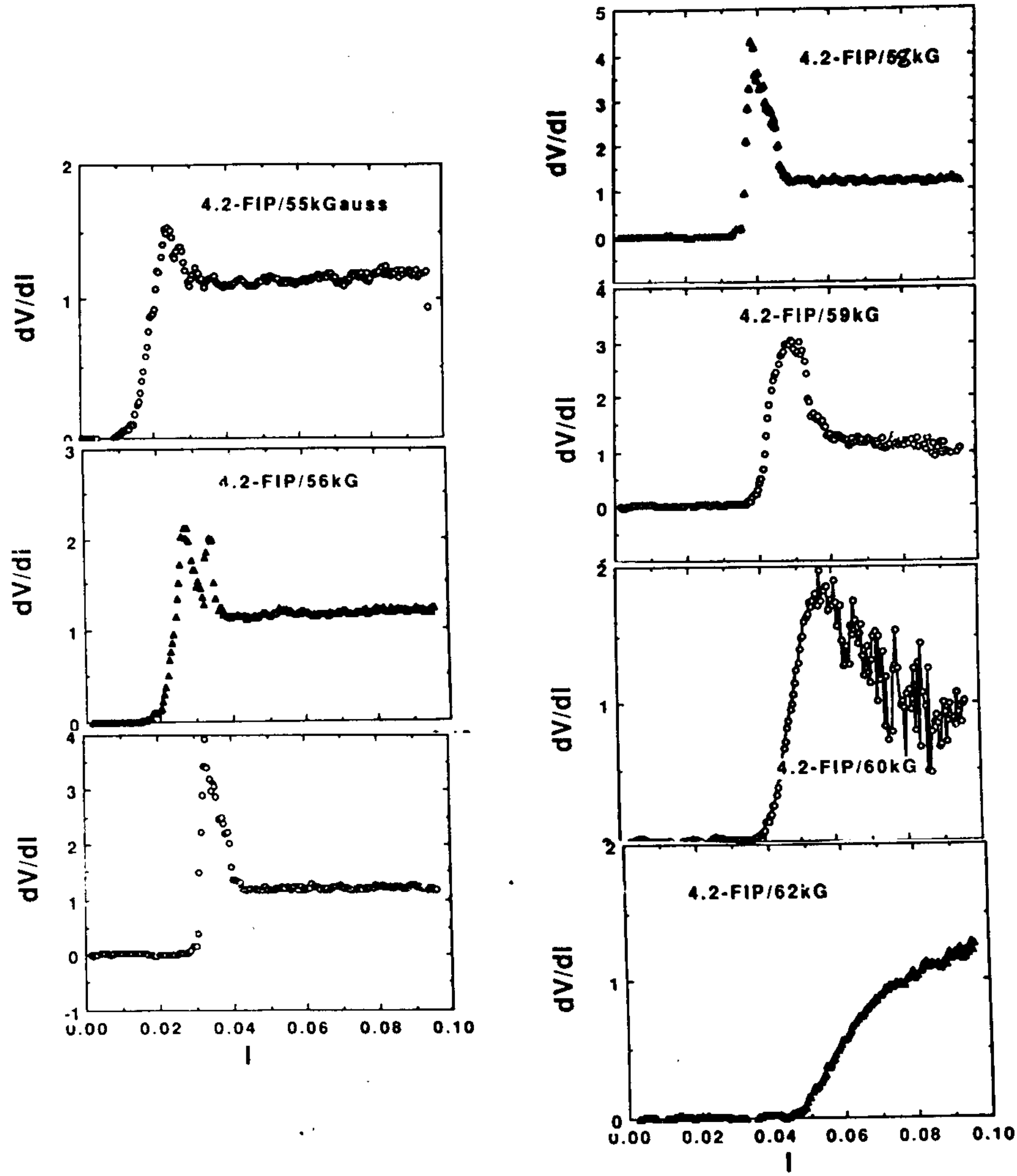




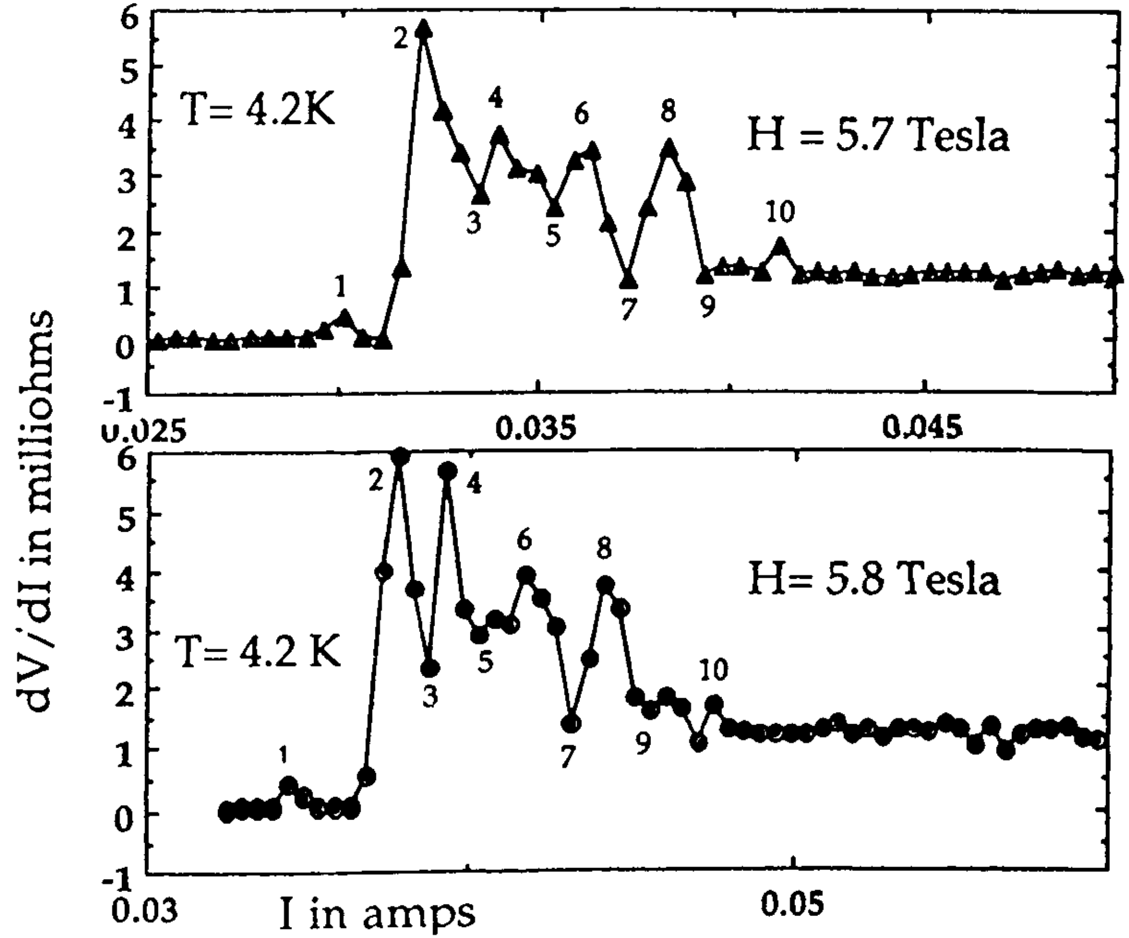
below peak : $\beta = 1.15$
above peak : $\beta = 1.3$

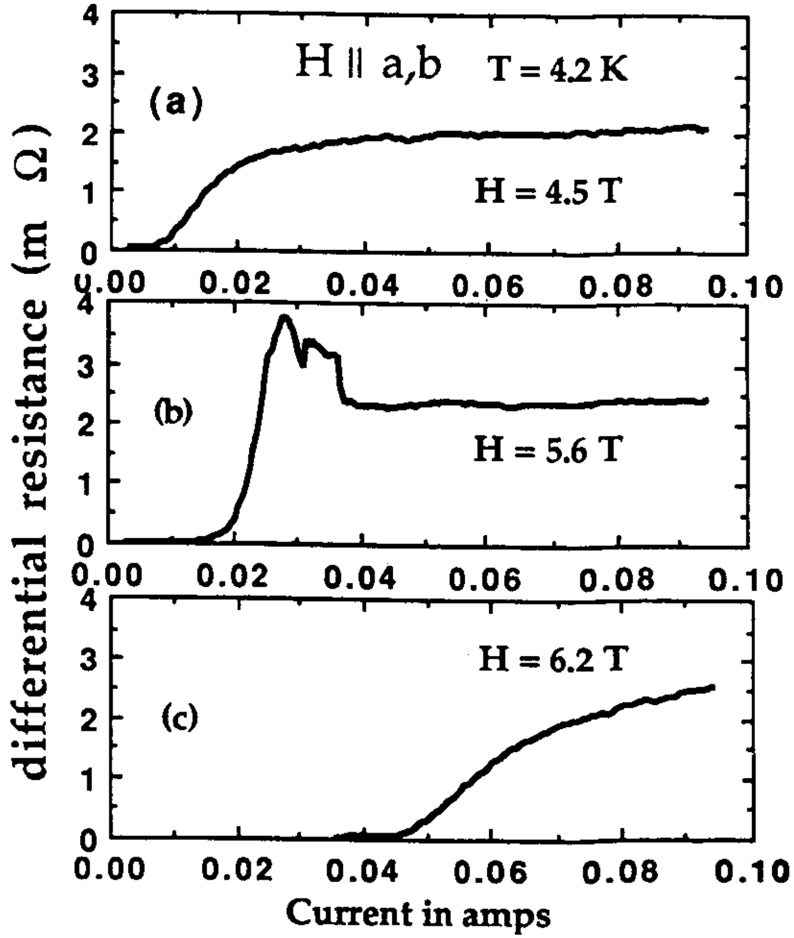
Evolution of I-V curve near the peak

H || a,b



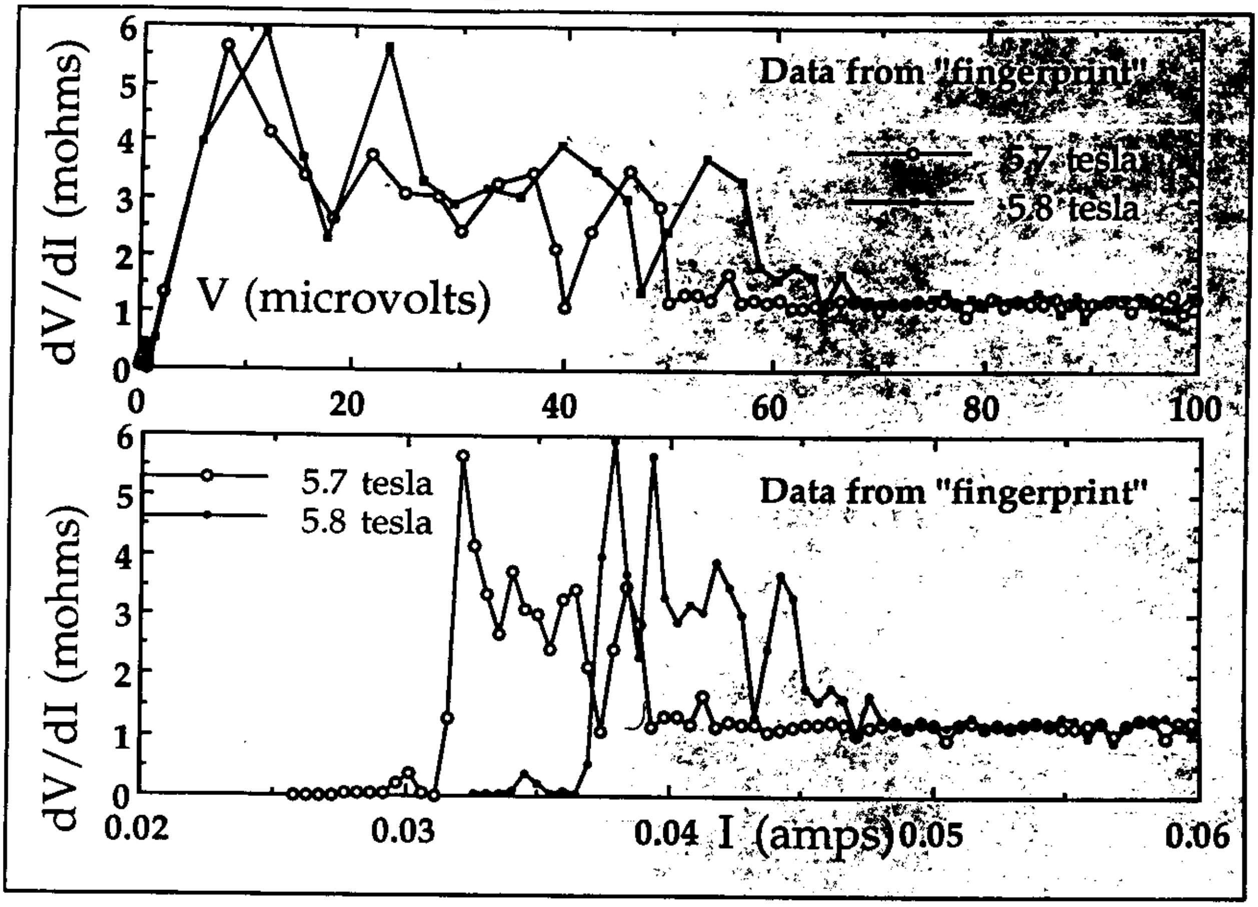
No power law scaling for plastic flow
instead, a fingerprint phenomenon





- Every sample shows unique structure : fingerprint.
- disappears at large I, pinning less important; lattice heals
- A dynamic "transition" to a more correlated FLL at large drive [current-induced freezing ?]

Fingerprint phenomenon (contd.)



Net voltage $V = N_{free} \cdot \langle v \rangle$

For elastic flow : N_{free} is independent of v

$dV/dI \sim 1/(d\langle v\rangle/dF) \sim 1/\mu$; μ = friction coeff.

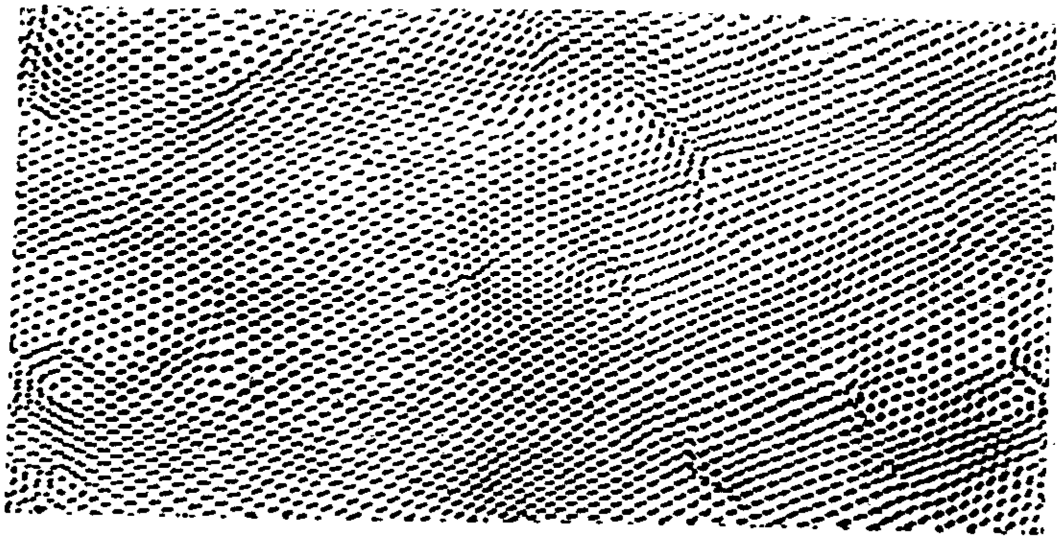
For plastic flow : N_{free} is v-dependent

Peaks are caused by dN_{free}/dI; represent a specific sequence of depinning of "chunks"

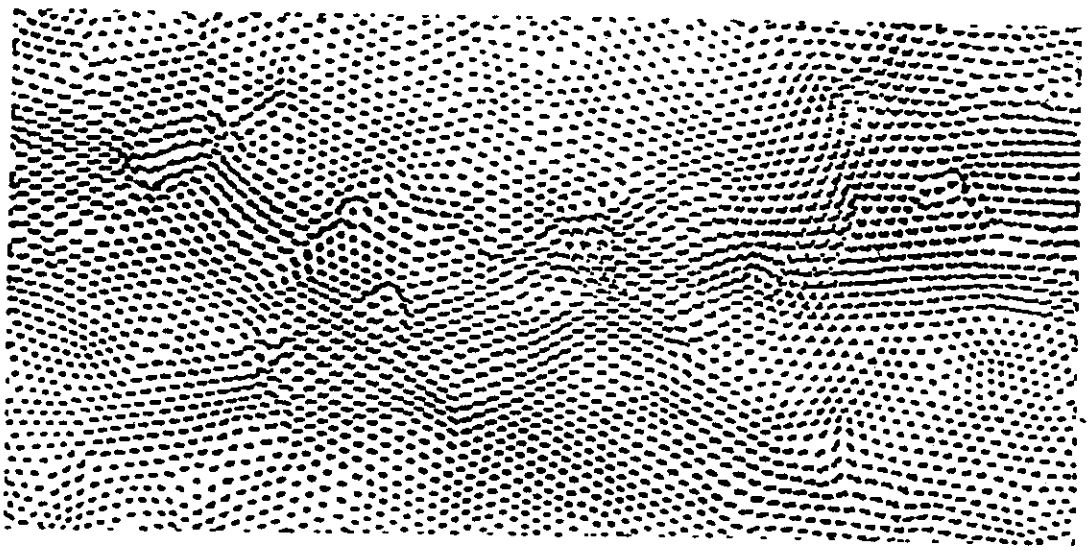
Fingerprint of quenched disorder is seen thru defects in FLL as elasticity is tuned by H.

:*Coexistence of moving and pinned states *

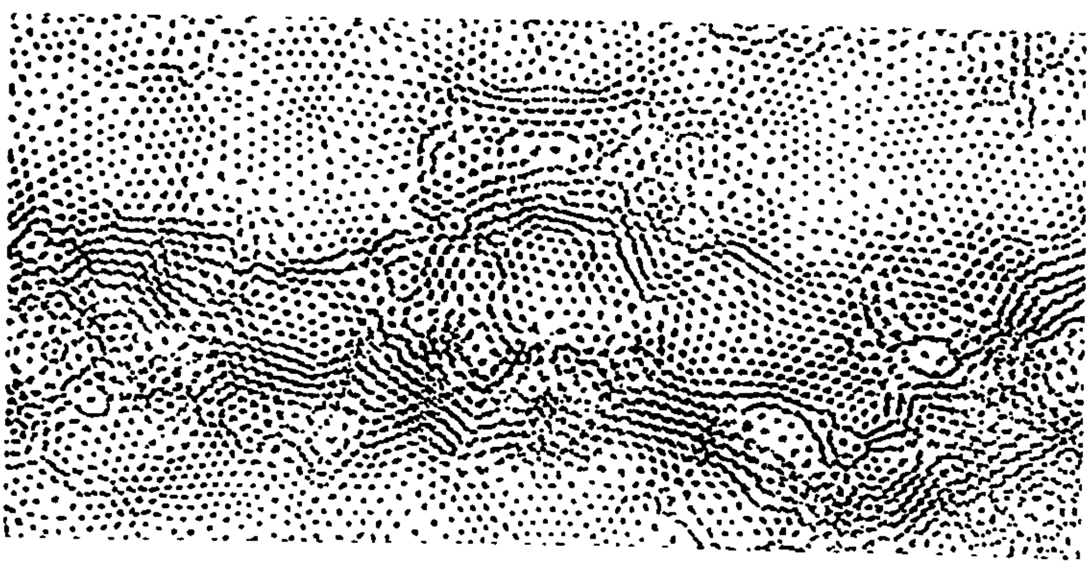
First order depinning transition



(a)



(b)



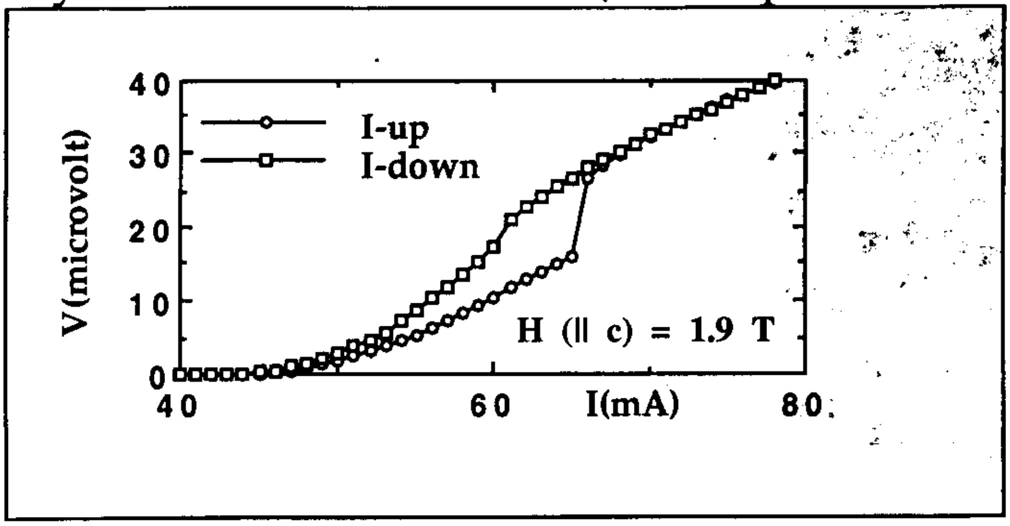
(c)

Cha & Fertig

Simulations of WC's

Consequences of first order depinning

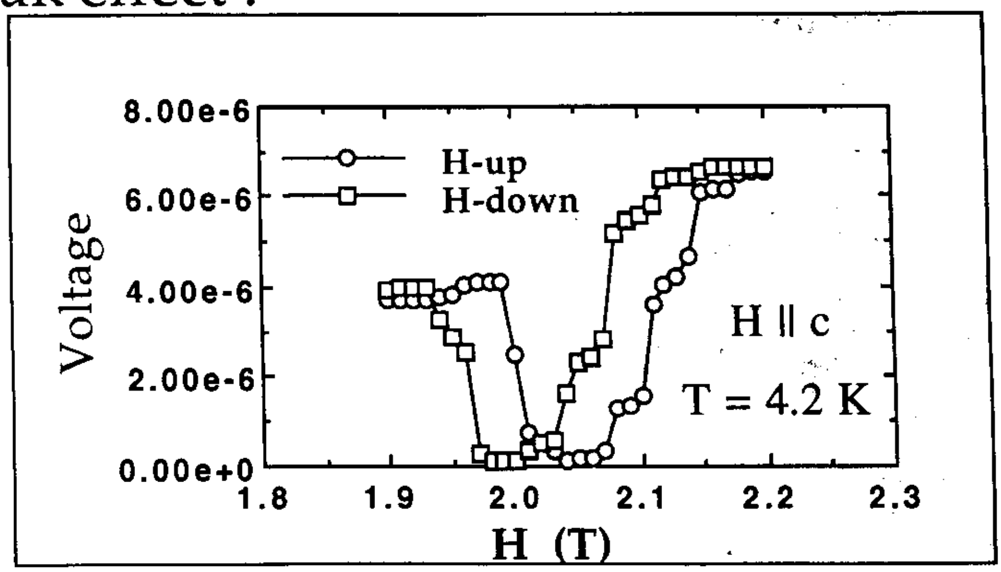
Hysteretic I-V curves (nonequilibrium effect)



Caution : $I_C \sim I_C\,(H,T)$

Varying H,T can show hysteresis; but is not a thermodynamic effect

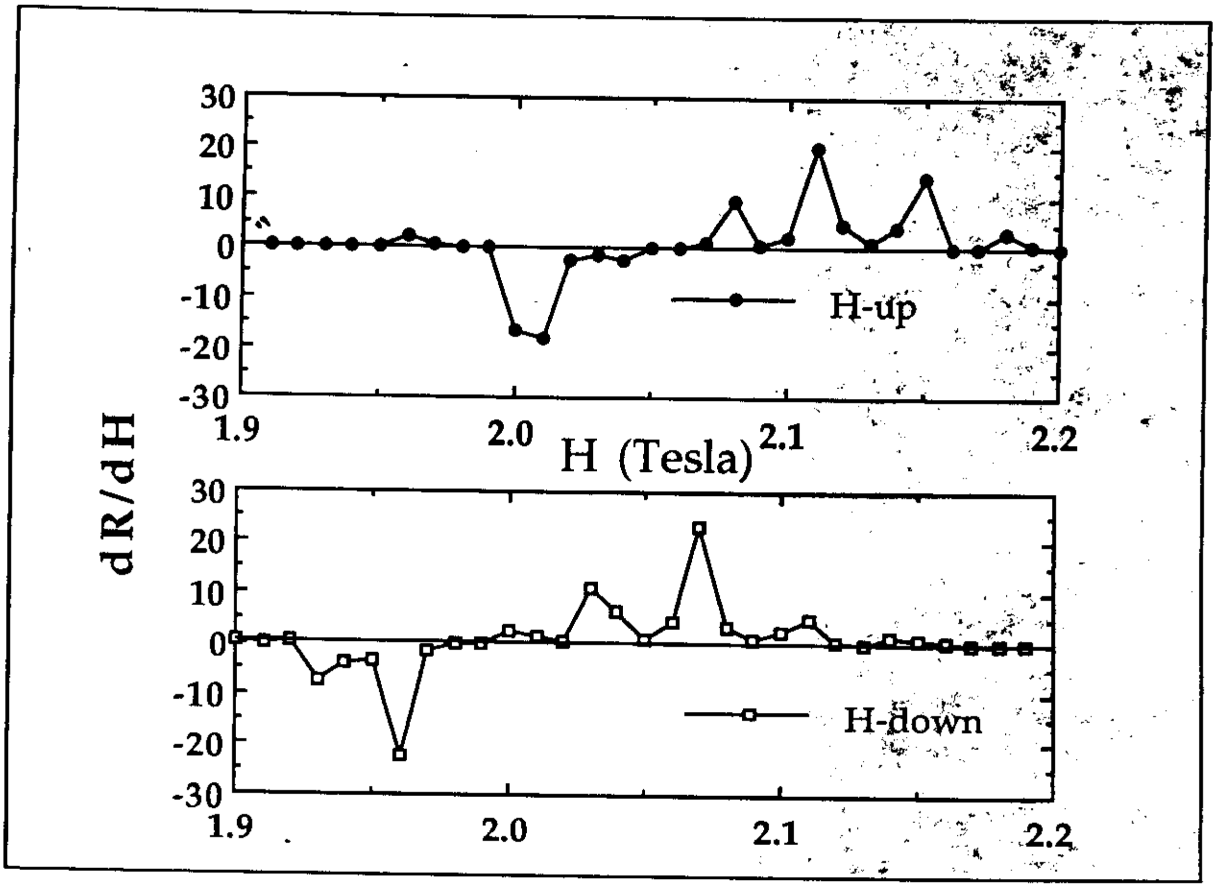
Example : Sign change of Hysteresis due to Peak effect :

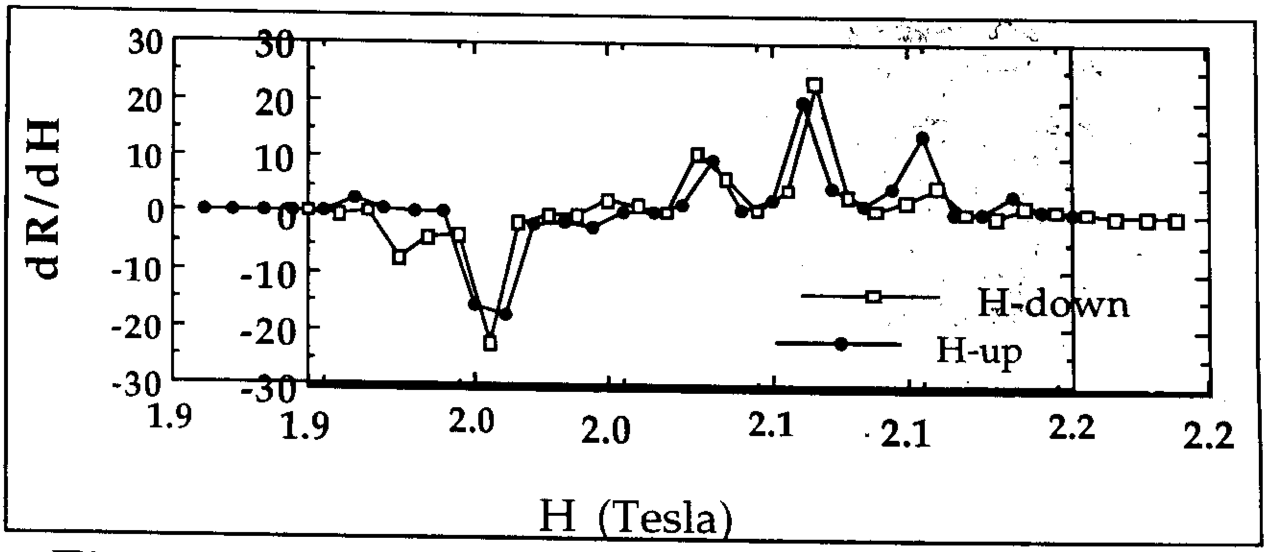


"Fingerprint" survives hysteresis

More mobile state remains more mobile down to lower forces

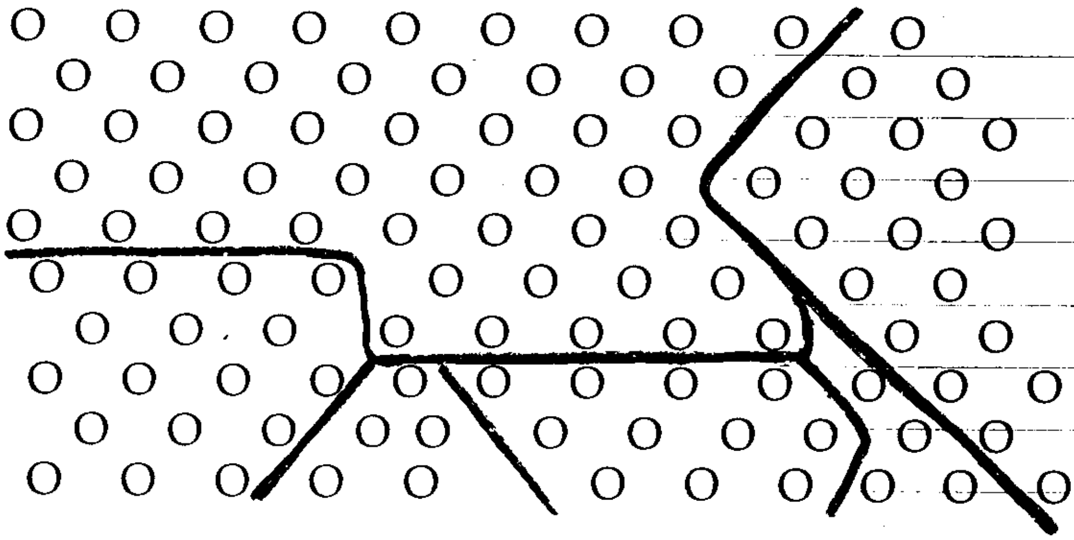
Hysteresis and fingerprint in R-vs-H at fixed T





Fingerprint survives hysteresis
Same sequence of depinning and repinning
but this is not melting !!

Schematic of a defective FLL motion of Chunks ("ladokhod")



Motion of defective lattice ~

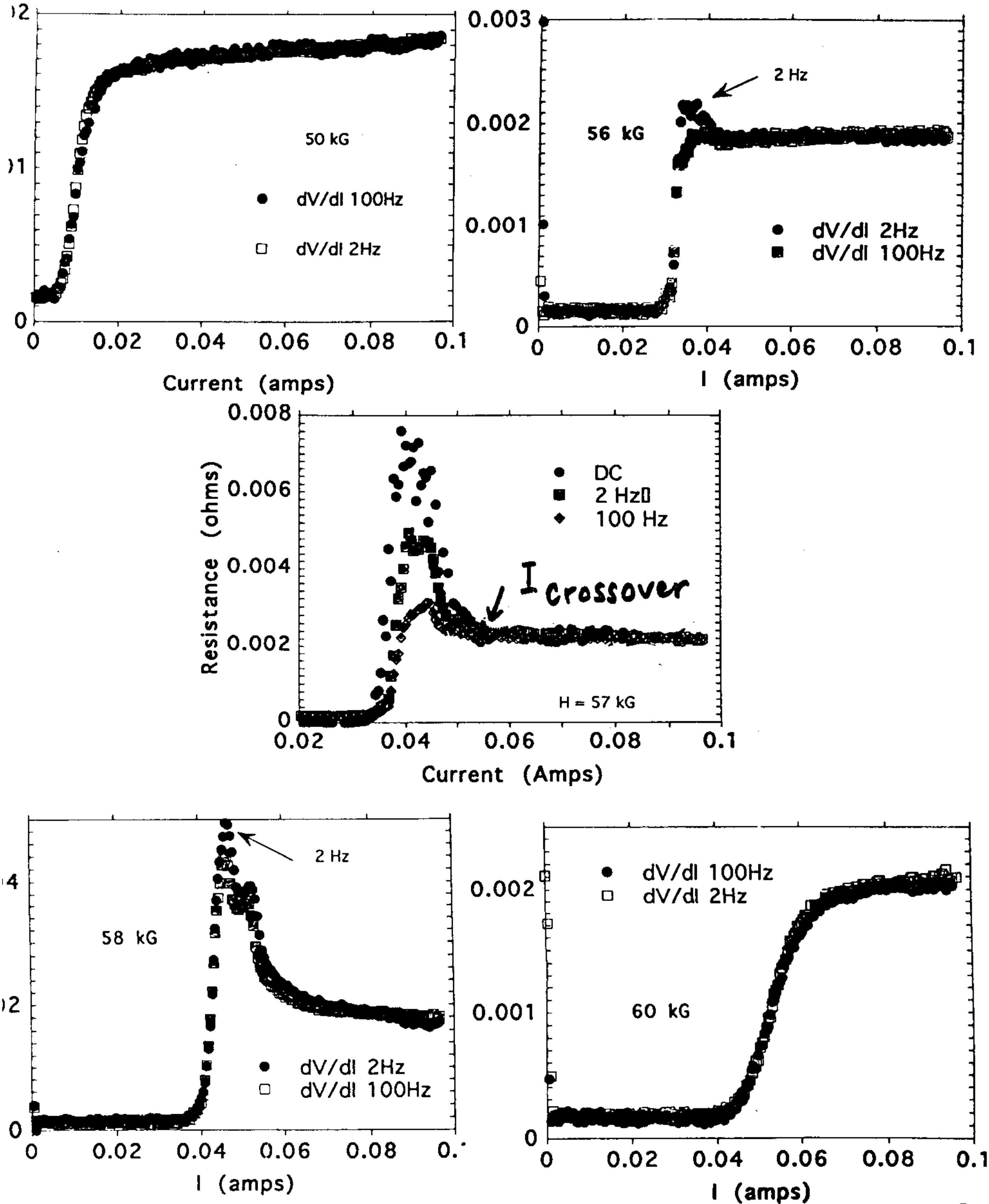
Onset of voltage when a connected path forms across the sample

Trapping of immobile regions - "puddles"

Slow dynamics associated with breakage and healing of moving "chunks"

Noise associated with rearrangement of channels metastability in the moving state

Anomalous frequency dependence in plastic flow



Defective dynamics of elastic media :

CDW : Coppersmith, C & Millis
FLL : Jensen et.al., Shi & Berlinsky, Koshelev, K & Vinokur, Marchetti et.al.,..
Fluid Flow : Narayan & Fisher

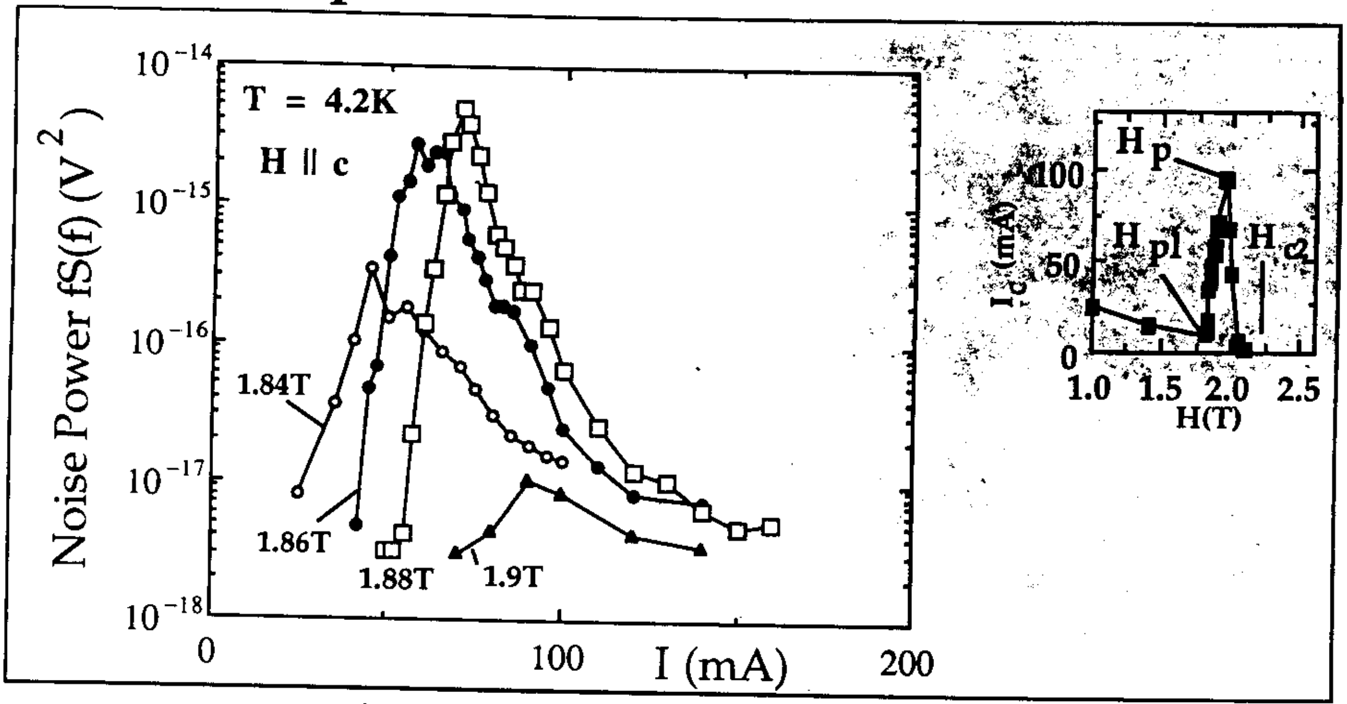
Crossover from interaction-dominated to disorder-dominated dynamics through a regime of motion of chunks (filaments)

New length : transverse "chunk"-size : L_V
time-averaged velocity correlation length $\langle \bar{v}(x)\, \bar{v}(x') \rangle \sim L_V$

distinct from Larkin lengths R_C &L_C and Fisher-length
(instantaneous velocity correlation length) $\xi_V \leftrightarrow \langle v(x,t)\, v(x',t) \rangle$

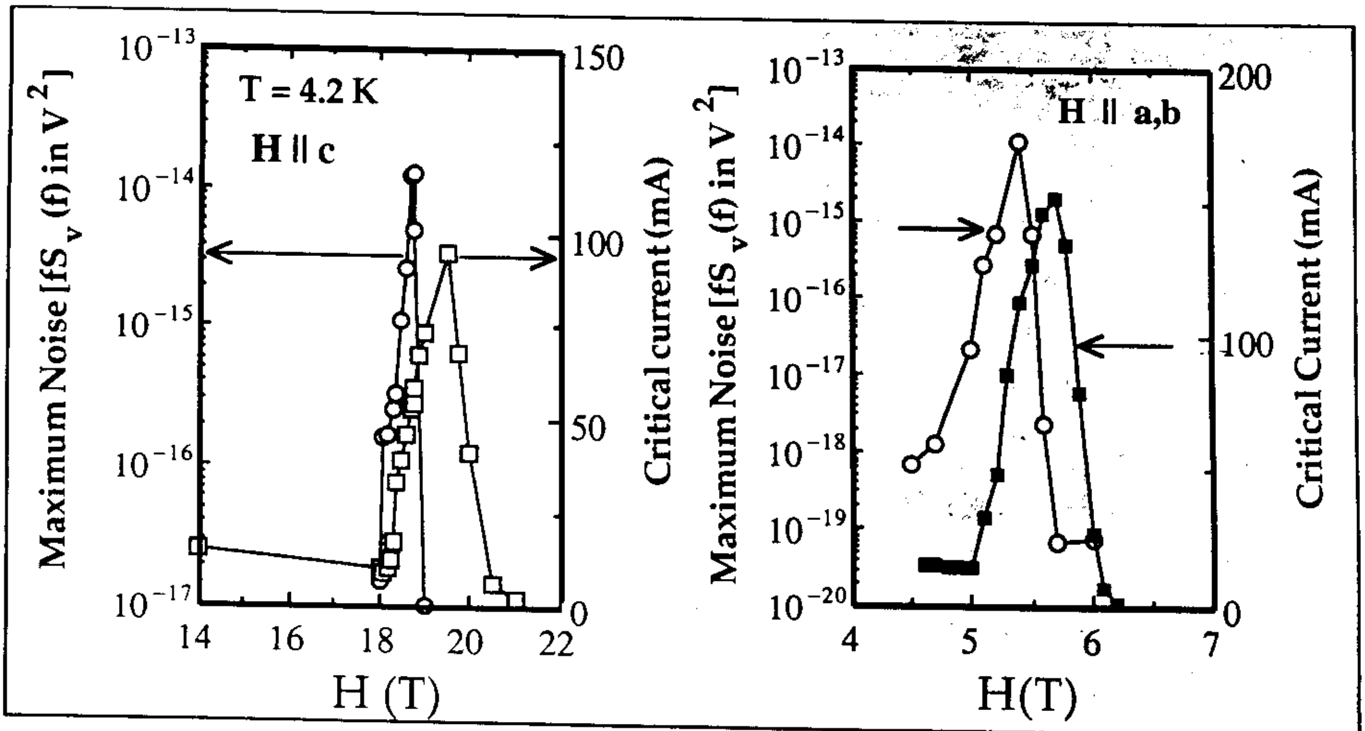
Detection of new length scale through noise

Noise in plastic flow



onset of noise coincides with onset of V

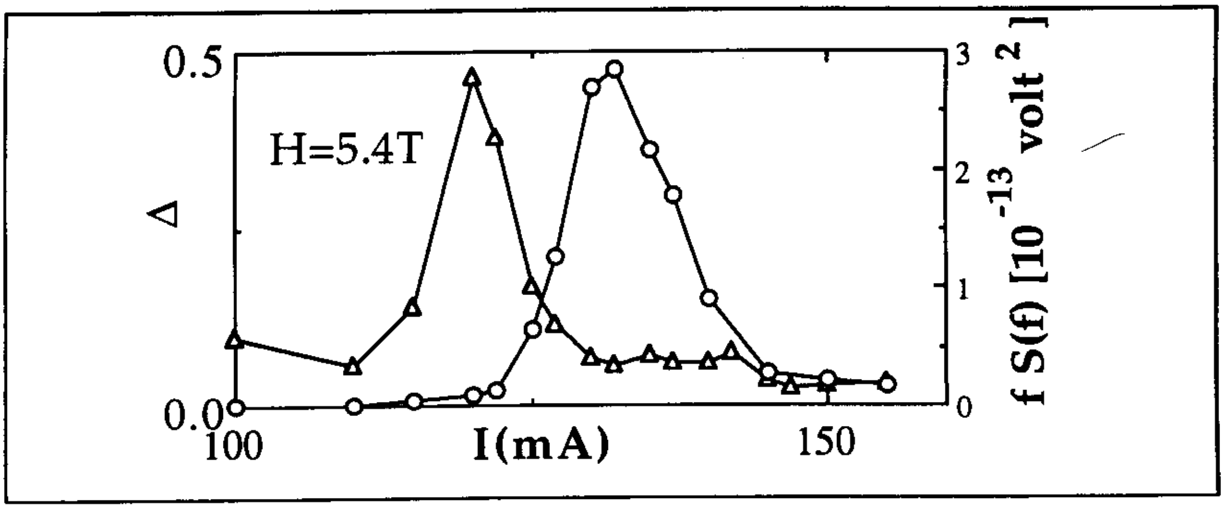
noise depletes at large current



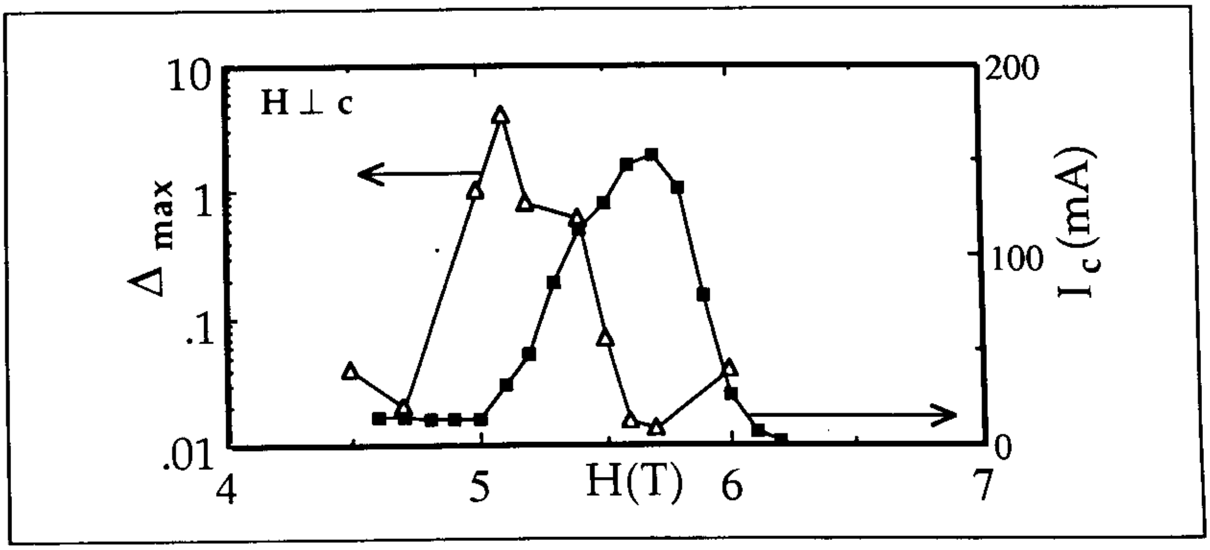
restricted to narrow H-regime :$H_{pl} < H < H_p$

Excess Variance of noise : Δ

Large # of fluctuators : gaussian (small Δ)
Small # of fluctuators : non-gaussian (large Δ)



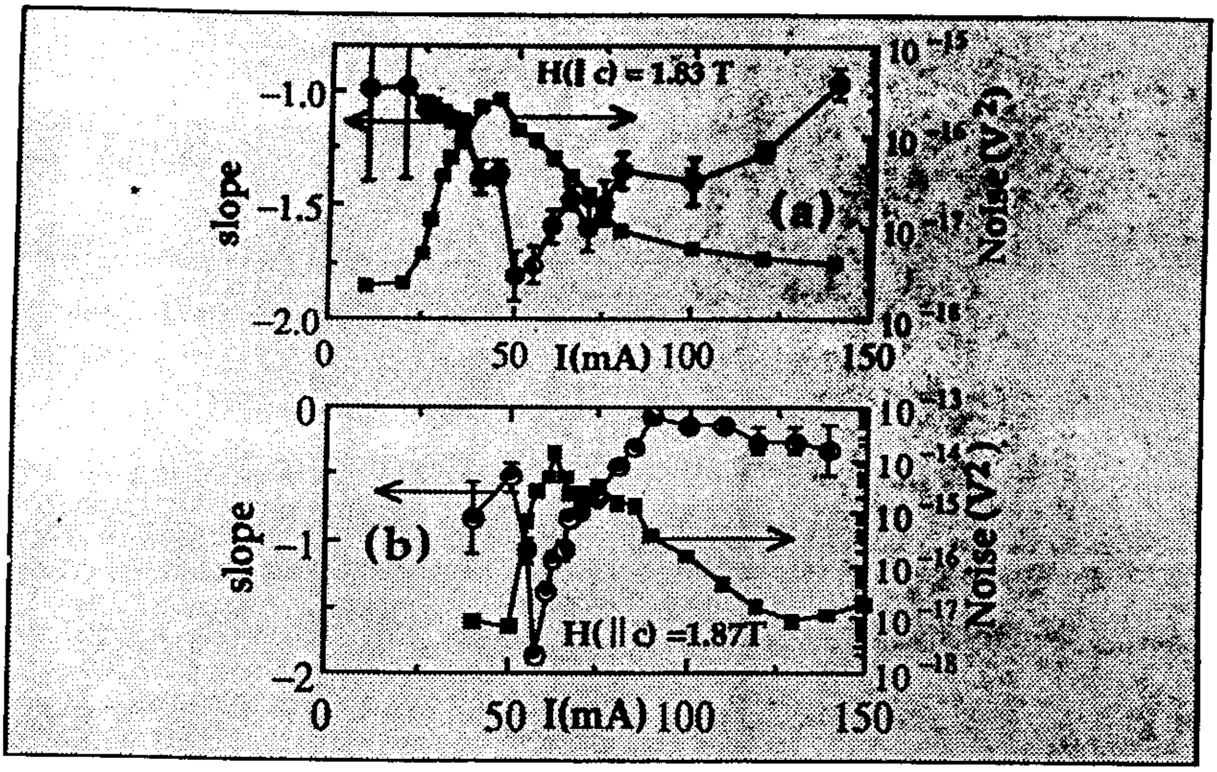
Δ peaks before noise power does



Δ_{max} coincides with H_{pl}
chunks themselves are the fluctuators
direct measure of the dynamic correlation length

Noise spectrum : S (f) ~ $f^{-\alpha}$

α is the slope of a power-law fit



S (ω) ~ $\int \tau g(\tau)d\tau/(1+\omega^2\tau^2)$

if g(τ) ~ 1/τ; then 1/f-noise

slope restricted between 2 and 0

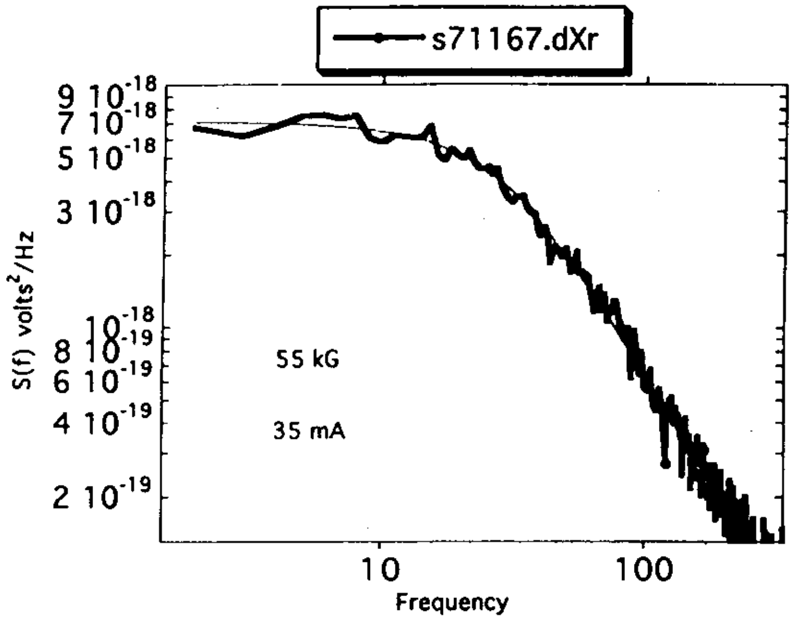
increasing α with I implies most probable τ increasing with I;

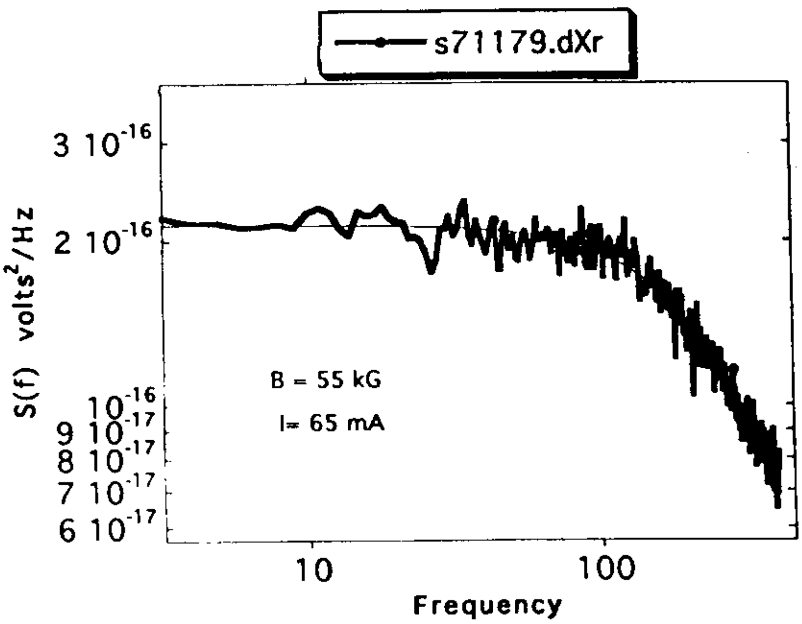
fluid flow is white (uncorrelated) as expected

τ is the rearrangement time of metastable configurations in the moving FLL

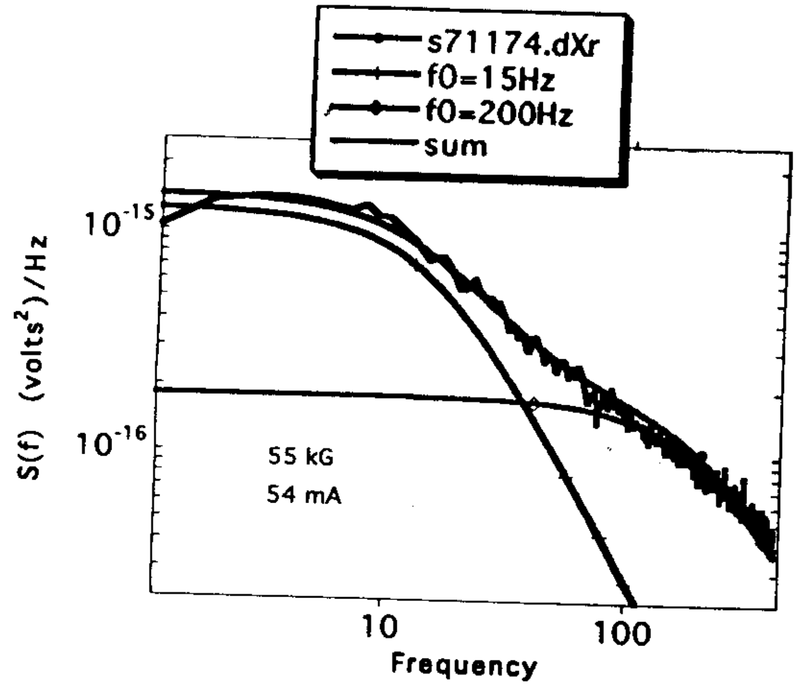
Single Fluctuators

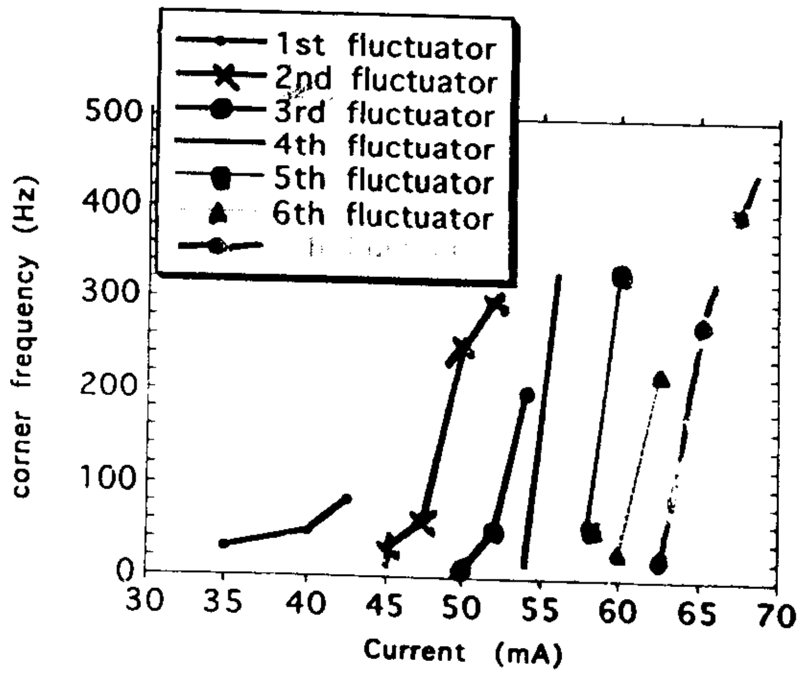
$$S(f) \sim \left[1 + (f/f_0)^2\right]^{-1}$$





Multiple fluctuators





Characteristics of Plastic Flow : $H_{pl} < H < H_p$ and $I_c < I < I_{cr}$

1. absence of power-law scaling for I-V

2. jagged (reproducible) structures in I-V : fingerprint

3. anomalously slow dynamics at small currents
   :slow motion of dislocations in soft FLL
   :normal behavior at higher frequencies

4. extremely noisy :
   metastability in the moving state (not unique)
   coexistence of pinned and moving FLL;
   near degeneracy among different configurations
   noise due to transitions among them

5. hysteresis in voltage (resistance) as either the driving force I or H (T) is cycled, i.e., $[I-I_c(H,T)]$ is cycled;
   purely nonequilibrium effect, <u>not melting</u>

Status of understanding from theory/simulations

1. Plastic flow : ubiquitous ; Jensen et al, Dominguez, Marchetti,Koshelev, Huse, Nori , Fertig (2DEG)
2. Healing at large forces : Dynamic Transition : Koshelev-Vinokur, Balents-M.Fisher
3. Dimensionality effects : Balents-M.Fisher
4. Existence of L_V : divergence at elastic-plastic crossover : Dominguez
5. Phase diagram and divergence of F_{cr} at plastic-liquid crossover : Koshelev -Vinokur
6. Noise in plastic flow : Huse, Dominguez, Marchetti

Dynamics of a Disordered Flux Line Lattice

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(Received 12 October 1992)

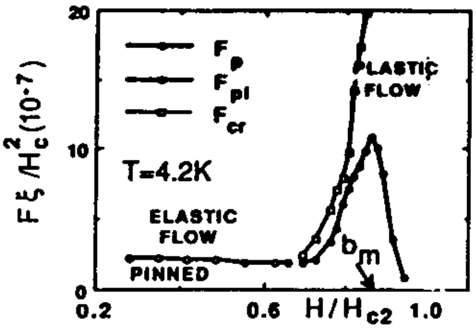

FIG. 3. A nonequilibrium phase diagram of the FLL dynamics. F_p is the conventional depinning threshold separating a pinned FLL from a moving elastic FLL. F_{pl} represents the onset of the plastic flow instability in a defective flux lattice. F_{cr} marks a crossover between the plastic flow and a defect-free 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.

Dynamic Melting of the Vortex Lattice

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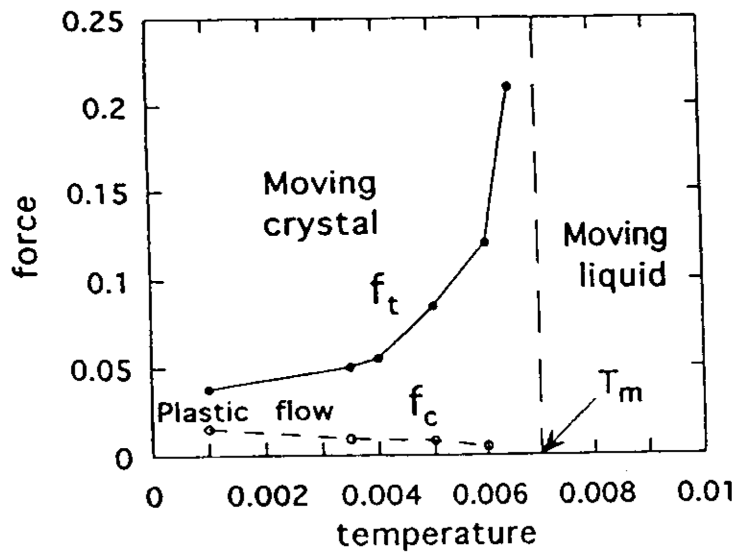
[3]*Institute of Solid State Physics, Chernogolovka, Moscow District, 142432, Russia*
(Received 26 April 1994)



What if the FLL melts ?

- Dense pins : liquid is "individually pinned"
- Flux lines are conserved : have to flow out
- onset of motion : first path connects across (path with smallest value of largest barrier)

resembles percolation, if force can be mapped onto new channels joining...

Expt : $V \sim (I - I_c)^\beta$

percolation : $s \sim (p - p_c)^\mu$

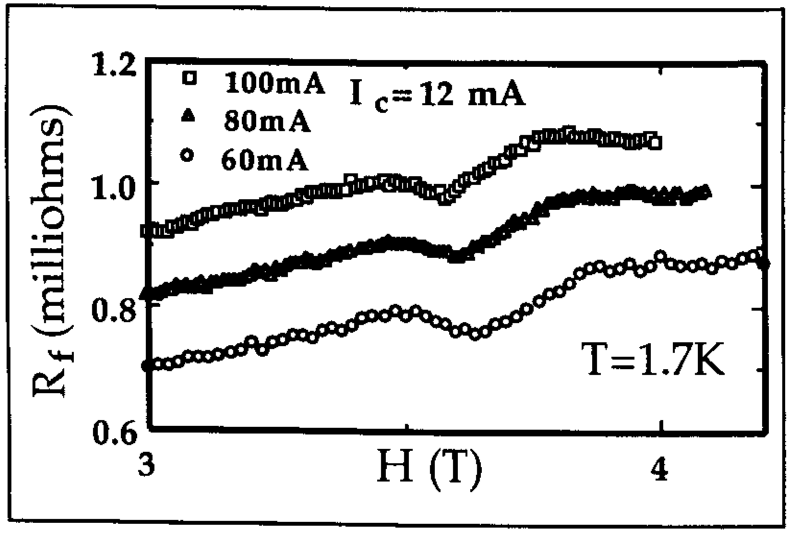
$\beta \sim \mu$ (2D)

2D $\beta = 1.3$

3-D $\beta = 1.7\text{-}1.8$

Disorder-dominated dynamics and fluid flow

Coexistence of static and moving FLL
Puddle effect (c.f. Coppersmith & Millis)



Bardeen-Stephen free flux -flow
$\rho_f = \rho_n(T).f[H/H_{c2}(T)]$; $f(x) \sim x$

Sharp residual anomaly at H_p :
Melting of FLL - puddle formation
reduced mobility due to loss of rigidity and onset of vel. gradient (viscosity) (c.f. Marchetti-Nelson)

Alternative access to "clean" phase transitions (weak pinning cases)
:Drive with large I : $I_c \ll I \ll I_0$;
Study marginal effects of disorder on non-eq. steady state

Models of disorder

Atomic lattice :

typically, many atoms per defect

Flux line lattice :

typically , many defects per flux line

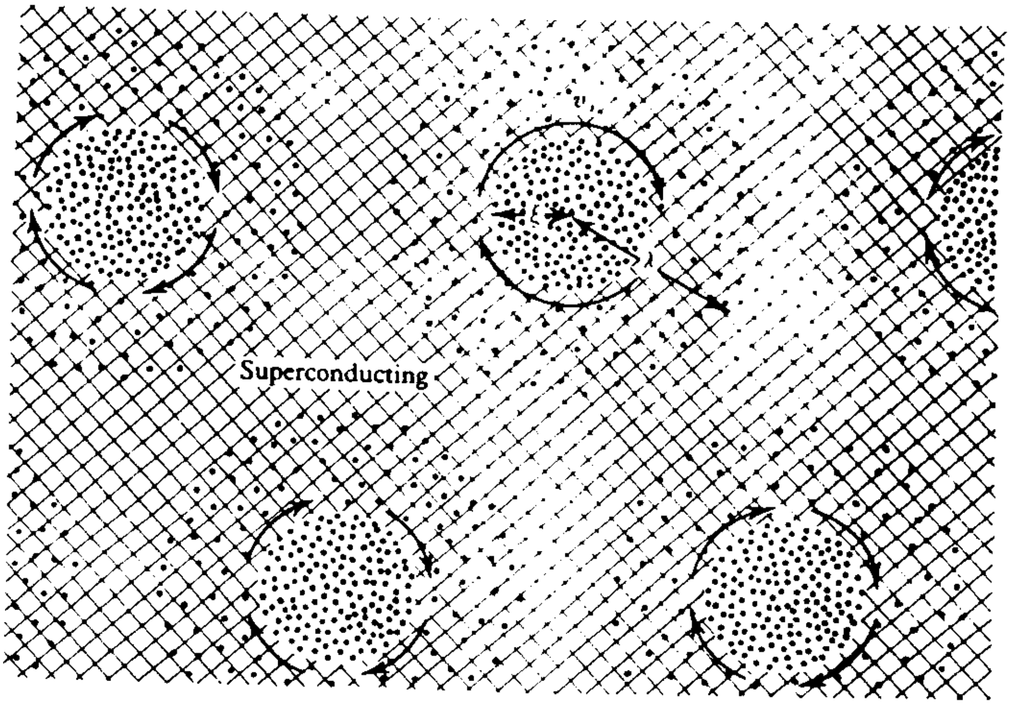


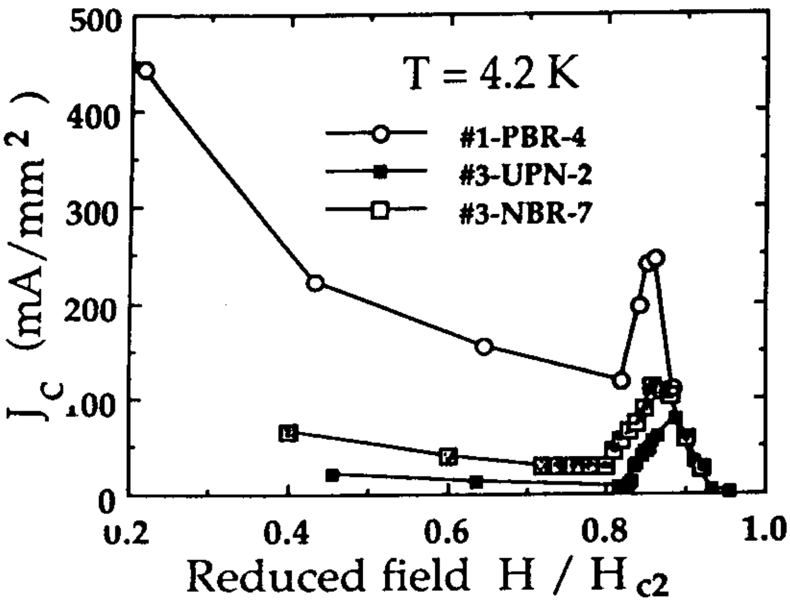
Fig. 213. Array of flux filaments in type II superconductor, showing magnetic field lines concentrated in and around cylindrical cores of normal material. Superfluid vortices flow round the filaments in the penetration regions.

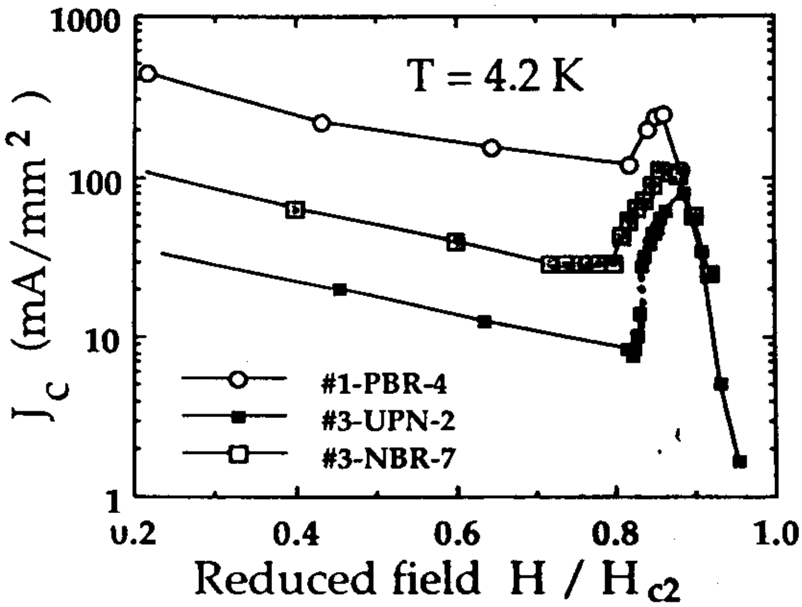
different results for flux liquid if $\rho_{FLL} \gg \rho_{pin}$, or $\rho_{pin} \gg \rho_{FLL}$

$\rho_{FLL} \gg \rho_{pin}$: some lines are not pinned,
R increases (HTSC)

$\rho_{pin} \gg \rho_{FLL}$: lines are individually pinned,
R decreases (Pippard)

Variation of Peak Effect with Disorder





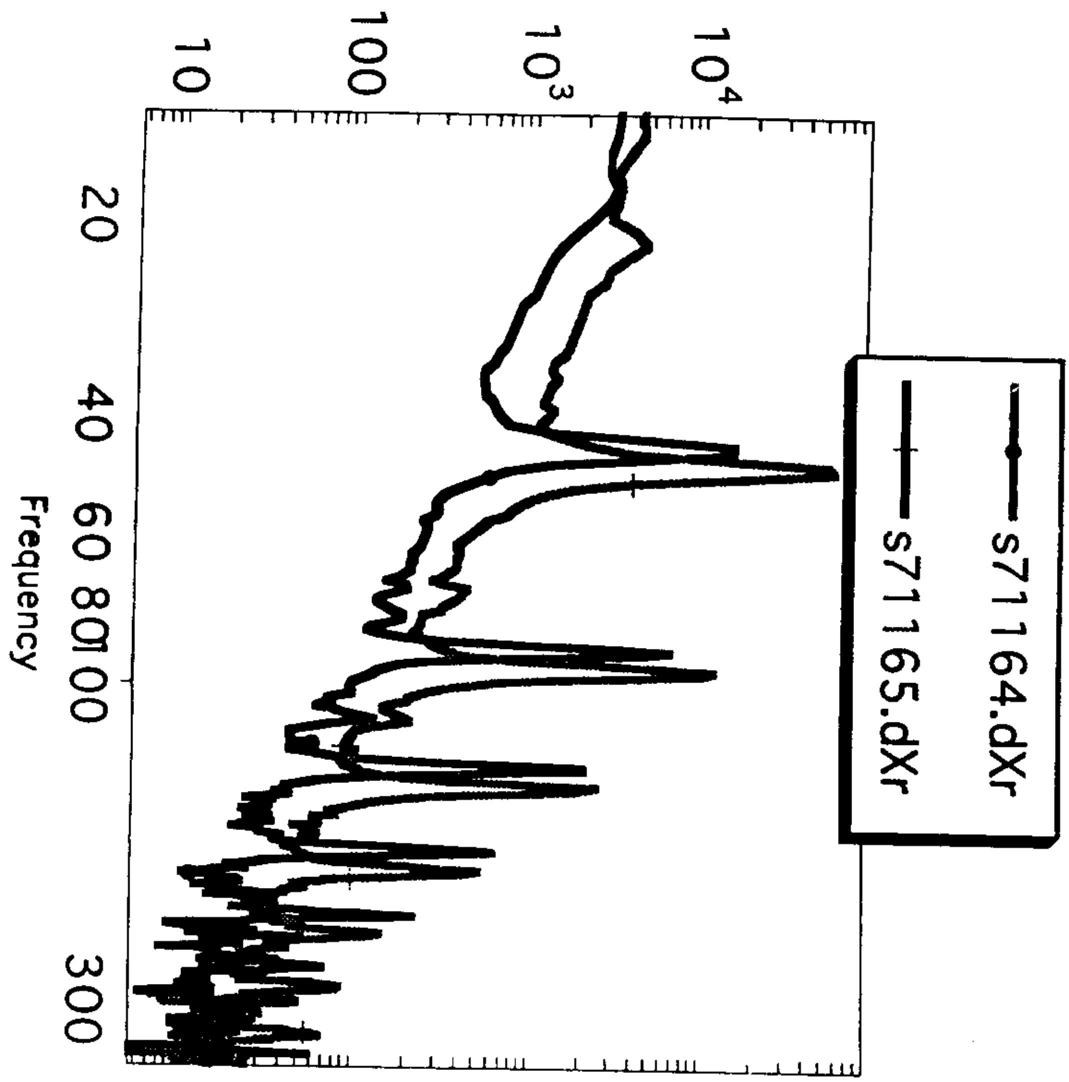
Increasing disorder :

smaller peak-to-valley ratio in J_c

larger disorder-dependence for $H < H_p$

Different regimes of pinning : weak ($H<H_p$)
strong ($H>H_p$)

s71156.dXr



s71164.dXr
s71165.dXr
10
100
10^3
10^4
20
40
60 80100
300
Frequency

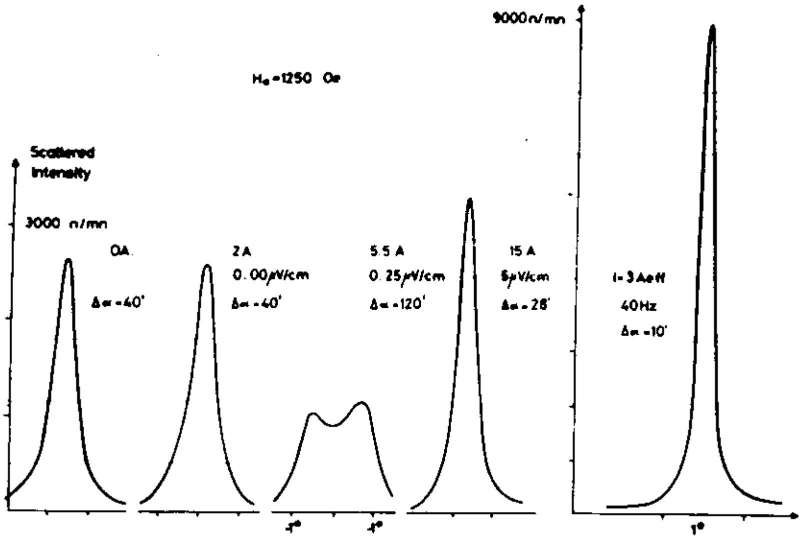


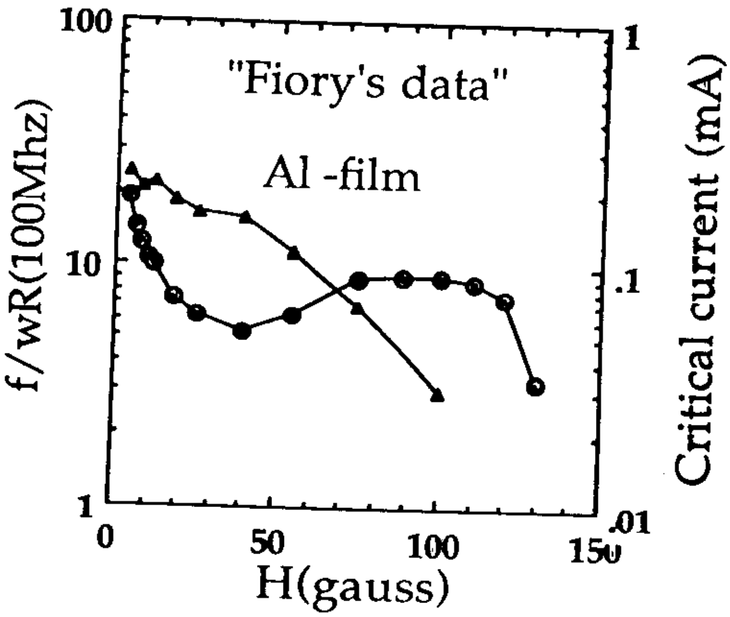
Fig.6.7. Different shapes of the rocking curve for a vortex crystal in monocrystalline Nb with a magnetic field of 1250 Oe. In each case, the integrated scattered intensity, i.e., the area under the rocking curves, remains constant. (a): The first curve is obtained on a vortex crystal generated by increasing the field above H_{c2} and decreasing it to 1250 Oe. The full-width-half-maximum of the rocking curve, $\Delta\alpha$, is a measurement of the mosaicity of this vortex crystal. (b): The second curve is done with an applied direct current of 2A in the zero voltage region of the I-V characteristics (no change in shape). (c): The third curve is for a transport current of 5.5 A (above the critical current = 4.5 A) in the nonlinear region of the I-V characteristics described by the flux creep model (strong broadening of the peak and details of the shape not very reproducible). (d): The fourth curve is for an applied current of 15 A, in the flux-flow region. The width of 28' is the limiting value when the current is increased to 30 A. (e): The last curve is for an applied ac current of 40 Hz and 3 A effective magnitude, the peak value being lower than the dc critical current (rocking curve is very sharp, with $\Delta\alpha$ = 10', representing the highest quality obtained for this sample; note change of scales) (courtesy of P. Thorel)

The magnetization M is defined as

$$M = \frac{1}{4\pi}(B - H_e) \quad , \qquad (6.11)$$

where B is the magnetic flux density averaged over the sample cross section, and H_e the external magnetic field. All methods for determining the magnetization are based on the induction law, relating the voltage V, induced in a coil of N turns, with the rate of change of magnetic flux, $d\varphi/dt$,

$$V = - N\frac{d\varphi}{dt} \quad . \qquad (6.12)$$


"Fiory's data"
Al -film
f/wR(100Mhz)
Critical current (mA)
H(gauss)
100
10
1
0
50
100
150
1
.1
.01

Flow chart for dynamics

rigid solid	soft solid	fluid
	disorder -----> <-----interaction	
elastic deformation stick-slip friction	plastic deformation tearing - wear	viscous drag
single threshold one chunk	multiple threshold several chunks	distribution N chunks
unique sliding state	sample-specific fingerprint of dynamically generated disorder	"rivers"
continuous depinning	first order ≠melting	continuous percolation-like

new length scale : time averaged velocity correlation

Varieties of dynamics : Summary

Rigid Solid :

unique depinning; monotonic approach to BS
power law I-V : $V \sim (I-I_c)^{\beta}$
$\beta = 1.15$ (D=2), 1.3 (D=3) similar to CDW
L_V infinite; coherent dynamics, v-dependent friction

Soft Solid :

multiple depinning; peaks in dV/dI; BS above I_{cr}
Hysteresis in V with cycling of I/H/T
no power law; Fingerprint : breaking up of FLL
slow incoherent dynamics of "chunks" upto I_{cr}
large noise upto I_{cr}; L_V finite

Fluid :

smooth depinning; power law I-V;
$\beta = 1.3$ (2D); 1.8 (3D) $\Rightarrow$ "directed percolation-like"
monotonic approach to BS, but lower value
Puddle effect, i.e., I_{cr} infinite ; viscous drag
$L_V \sim a_0$, the lattice constant

Conclusions

A. Three types of dynamics of a moving FLL in the presence of pinning disorder "Dynamic Phase Diagram"

(1) Elastic (coherent) - rigid lattice
(2) Plastic (chunks) - soft lattice
(3) Fluid (incoherent) - flux liquid

B. Plastic Flow :
Fingerprint phenomenon,Noise, metastability etc.

C. New length scale for a description of dynamics and its divergences :

D. Theoretical Pre-/Post-edictions and consistency checks with simulations

E. Phase diagram of FLL : reentrant melting