EXPERIMENTS ON NON-EQUILIBRIUM VORTEX STATES

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2001 BOULDER SCHOOL
ON NONEQUILIBRIUM STATISTICAL MECHANICS

MOTIVATION

❶ APPLICATIONS - power lines, MRI, magnetoencephalography, magnets, microwave relays and switches,levitation, gyroscopes, motors, (http://superconductors.org/Uses.htm)

- without vortices -superconductivity limited to narrow range of H , T
- without pinning - superconductivity useless

❷ BASIC SCIENCE - systems of interacting particles in a random potential (Wigner crystals, CDW, Colloids, Soft metals) - extra knob : particle density • H.

Common phenomenology:

- Dynamic Phase transitions
- Metastabillity
- History effects, memory
- Critical slow down, Jamming
- Cyclic softening

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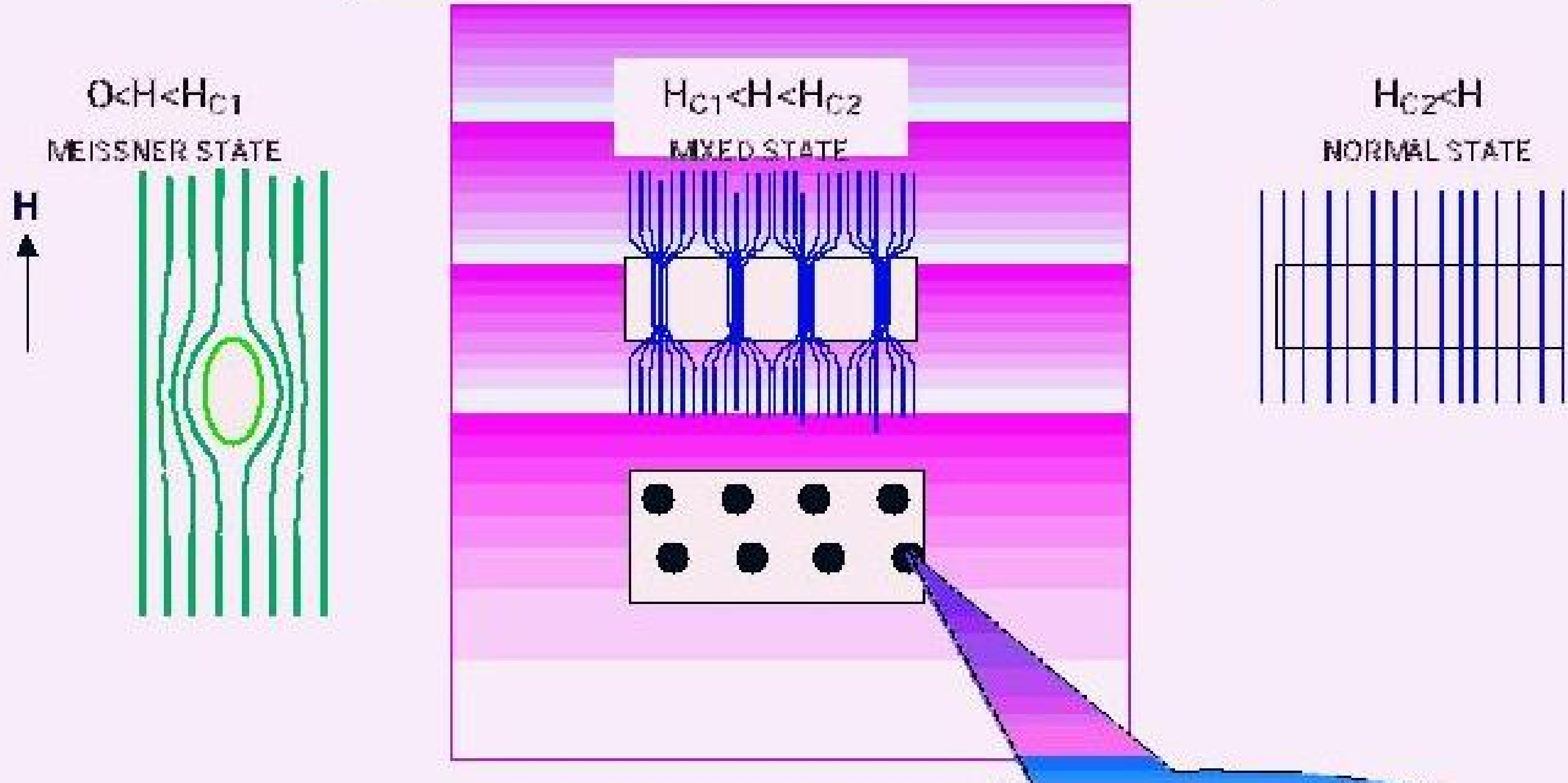
OUTLINE

- SINGLE VORTEX
  - ✓ Vortex dynamics
- EFFECT OF BOUNDARIES
  - ✓ Bean Critical State
  - ✓ Surface barrier
- VORTEX LATTICE
  - ✓ Phase diagram
- EFFECTS OF RANDOM POTENTIAL
  - ✓ Collective Pinning
  - ✓ Peak Effect
  - ✓ Metastable states
- CURRENT DRIVEN ORGANIZATION
  - ✓ Cyclic softening
  - ✓ Jamming
  - ✓ Memory
  - ✓ Metastable to stable transition - a model

DYNAMICS OF SINGLE VORTEX

- The magnetic vortex
- Vortex motion
- Pinning

TYPE II SUPERCONDUCTOR



FILAMENT OF MAGNETIC FLUX
=VORTEX

Φ_0 =hc/2e= 2x10^{-7} G cm^2

REVIEWS

- Blatter et al., Rev. Mod. Phys. **66**, 1125 (1994)
- Tinkham "Superconductivity"

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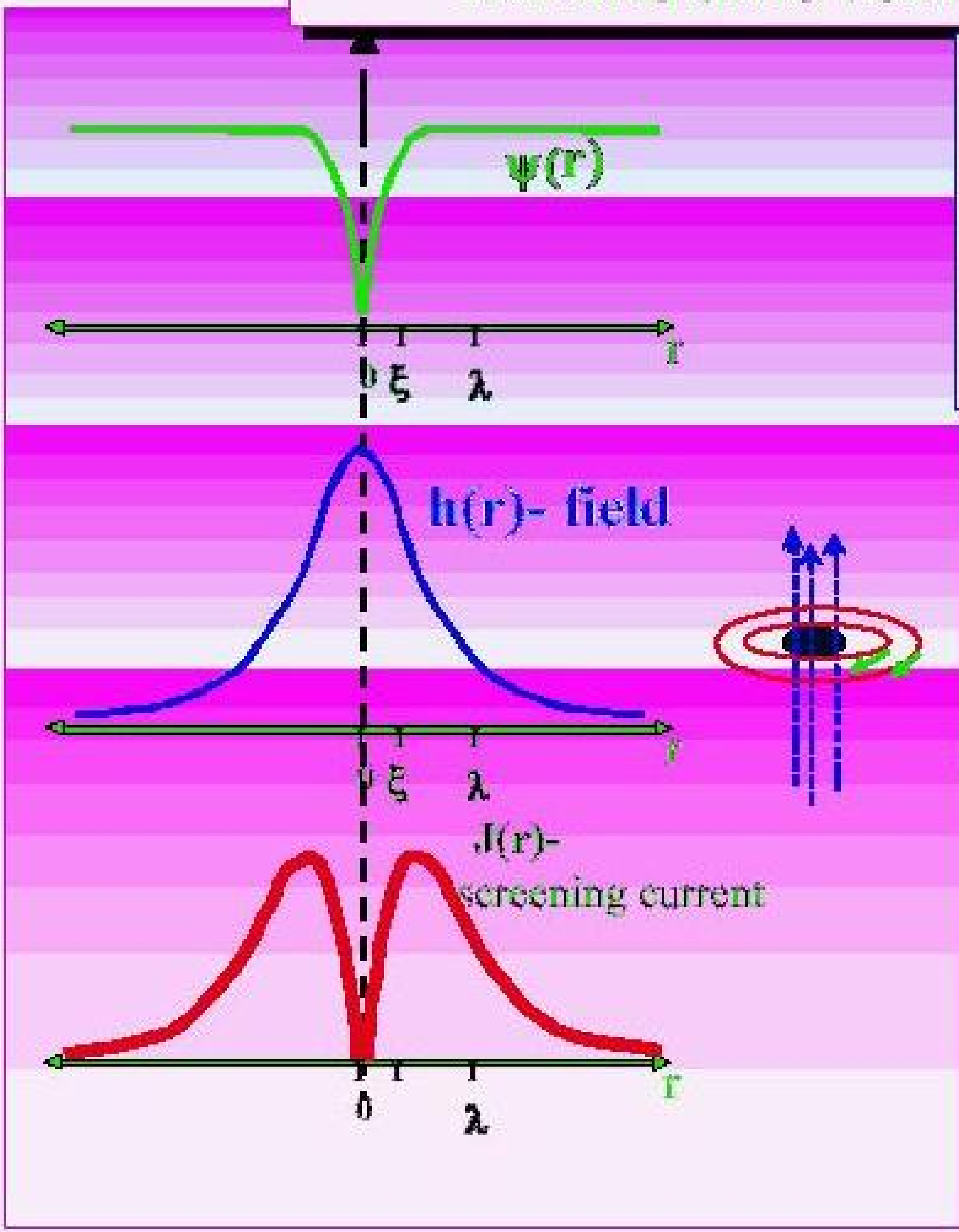
THE MAGNETIC VORTEX



COHERENCE LENGTH

superconducting characteristic length

$$\xi_o^{\;2} = \frac{\hbar^2}{m_e \alpha}$$

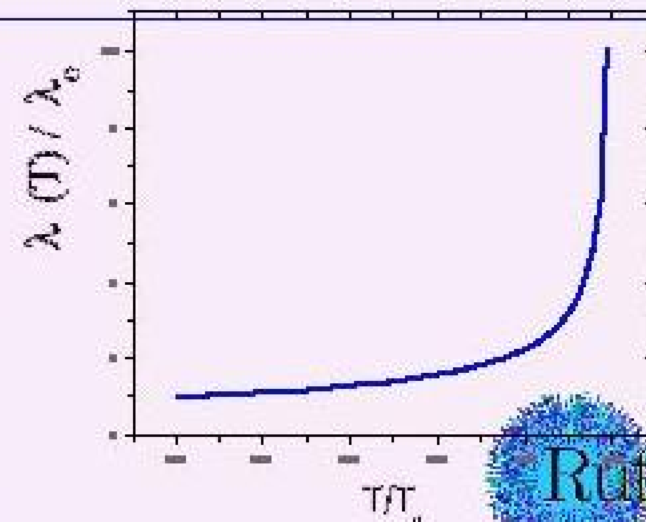
$$\xi(T) = \xi_o / (1 - T/T_c)^{1/2}$$

LONDON PENETRATION DEPTH-

magnetic field characteristic length

$$\lambda_o^{\;2} = \frac{m_e c^2}{4\pi\, n_s e^2}$$

$$\lambda(T) = \lambda_o / (1 - T/T_c)^{1/2}$$



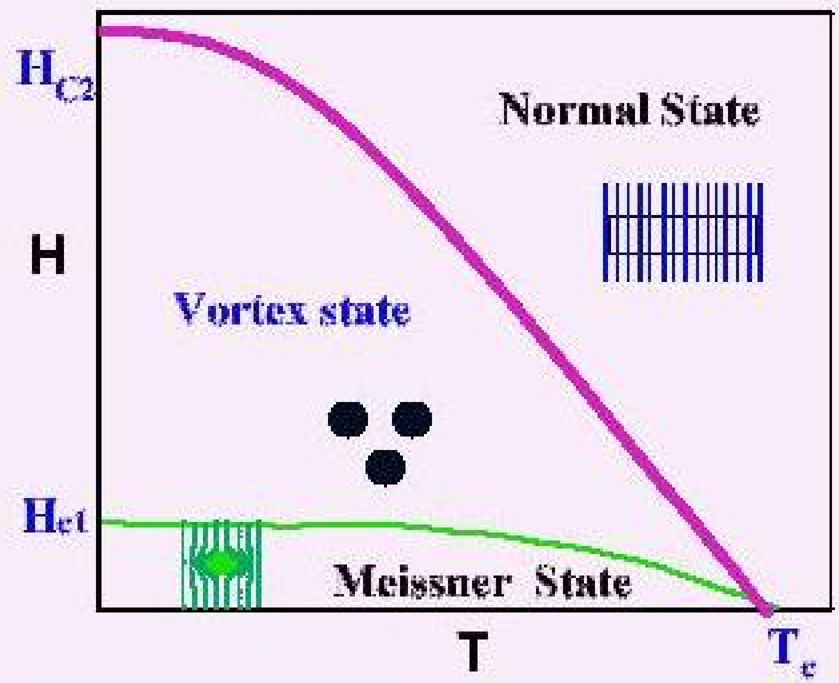
CRITICAL FIELD

Upper critical field $$H_{c2} = \frac{\phi_o}{2\pi\xi^2}$$

Lower critical field $$H_{c1} = \frac{\phi_o}{4\pi\lambda^2} ln\kappa$$

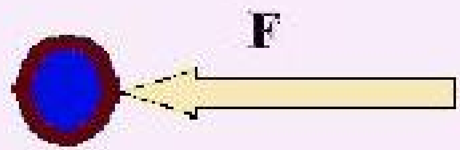
$\kappa = \lambda / \xi$ – *Ginzburg parameter*

Type II superconductor κ>1.4



EQUATION OF MOTION- VORTEX MASS

$$F = m\,\dot{v} + \eta\, v$$



Response time:

$$\tau = \frac{m}{\eta} \approx 10^{-15}\,\text{sec}$$

Vortex mass per unit length ~$m_e k_f$

- De Gennes & Matricon 64
- H. Suhl 65
- J.M. Duan 94

Instantaneous response $\mapsto$ no inertia $\mapsto$ **m~ 0**

$$\boxed{F = \eta\, v}$$

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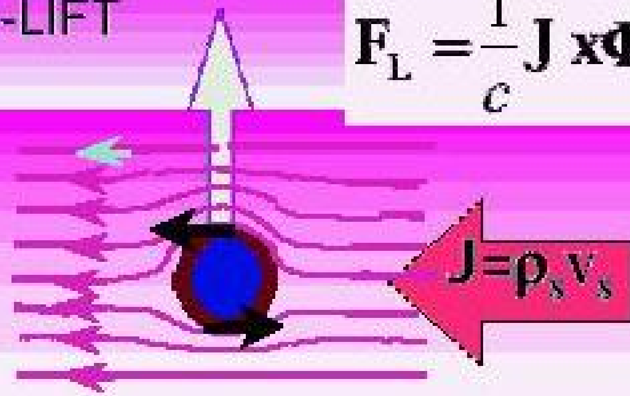
VORTEX +CURRENT - STEADY STATE

Stationary Vortex

Lorentz Force -LIFT

$$\mathbf{F}_L = \frac{1}{c}\mathbf{J}\ \mathbf{x}\boldsymbol{\Phi}_0 =_s \frac{\rho_s}{c}\mathbf{v}_s\mathbf{x}\boldsymbol{\Phi}_0$$



current density

Moving Vortex $\mathbf{v}_v$ - steady state-no dissipation

Galilean invariance

$$\mathbf{F} = \frac{\rho_s}{c}(\mathbf{v}_s - \mathbf{v}_v)\times\boldsymbol{\Phi}_0 = 0$$

$\Rightarrow \mathbf{v}_v = \mathbf{v}_s$ Vortex is dragged with current - superfluid

ADD DISSIPATION

$$\mathbf{F} = \frac{\rho_s}{c}(\mathbf{v}_s - \alpha_l \mathbf{v}_v) \times \Phi_0 = \eta \mathbf{v}_v$$

$\therefore$

$$\mathbf{F}_L = \eta \mathbf{v}_v + \alpha_l \mathbf{v}_v \times \hat{z}$$

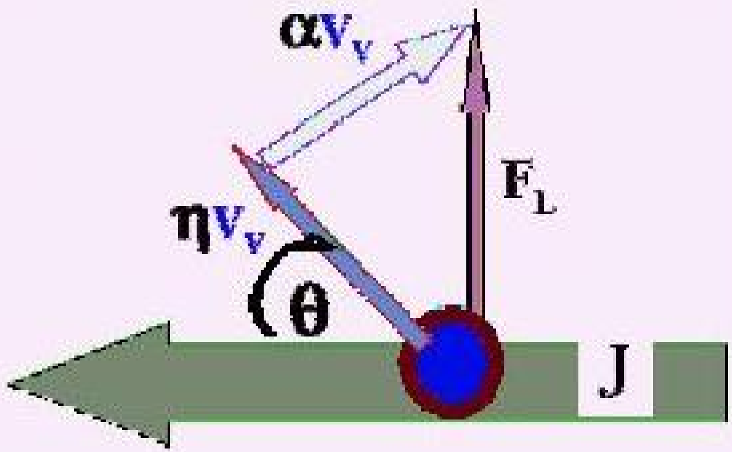
Friction Force

$$\eta = \Phi_o \rho_s \frac{\omega_o \tau}{1 + \omega_o^2 \tau^2}$$

Hall Force

$$\alpha_l = \eta \omega_o \tau$$

Hall angle : $\theta = tan^{-1} \frac{\eta}{\alpha}$



τ – scattering relaxation time
ω_o –level separation of q-particles in core

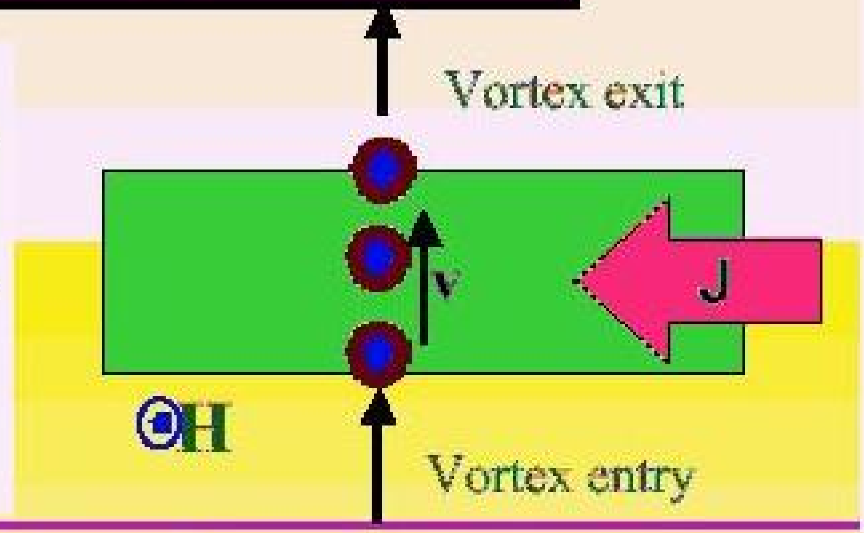
1. Kopnin & Kravtsov 1976
2. Kopnin &Salomaa 1991
3. Caroli, de Gennes, Matricon 1964

Vortex Motion and Dissipation

For most superconductors

$$\omega_0 \tau \ll 1 \mapsto \alpha_f \ll \eta \mapsto \quad F = \eta v = \frac{1}{c} J \times \Phi_0$$

- vortex velocity ⊥ to the current
- no Hall voltage



Faraday → Moving vortices = electric field

$$E = \frac{1}{c} n_m v \times \Phi_0 = \frac{n_m}{n} \frac{\Phi_0 B}{c^2 \eta} J$$

Density of moving vortices

Resistivity ρ

Free Flux Flow regime- all vortices moving

$$\rho \cong \rho_n \frac{H}{H_{c2}}$$

Bardeen Stephen - 1965

Moving vortex creates dissipation

- Superconductivity is destroyed

PINNING

- **If vortices are PINNED - Superconductivity restored**

Pinning center=
hole, impurity, etc.

Pinning Force per unit length

$F_{\rho} < H_c^2 \xi^2$

- Critical current density

$F_L = F_p \quad \mapsto \quad J_c$

- $J < J_c$ - **Pinned - no dissipation**
- $J > J_c$ - **unpinned** ⟹ Moving vortices ↦ voltage drop

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✷ EFFECTS OF BOUNDARIES

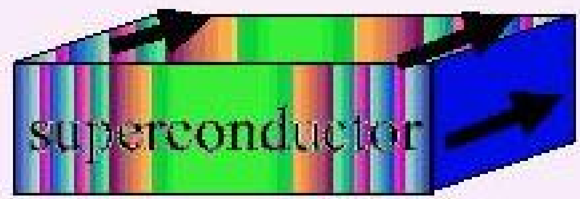
- Type I - no vortices
- Type II with Vortices
  - Bean Critical State
  - Surface Barrier

TRANSPORT CURRENT DISTRIBUTION

Metal

Uniform

Type I Superconductor
NO VORTICES



Edge current

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TRANSPORT CURRENT DISTRIBUTION WITH VORTICES

. Bean Model

- Bean (62) and London (63) -The critical state

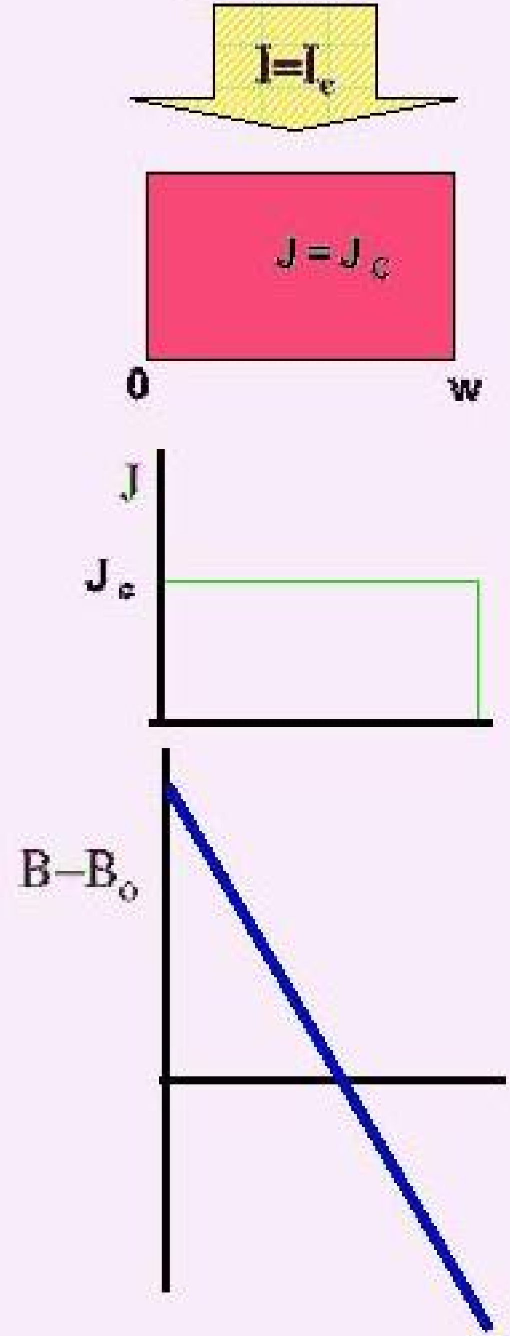
➡ Static balance between the magnetic driving force JxB and the pinning force F_P

$$|(Bx(\nabla xH))| = BJ_c (B)$$

➡ In this state the bulk current density is either $+J_c$, $-J_c$ or zero.

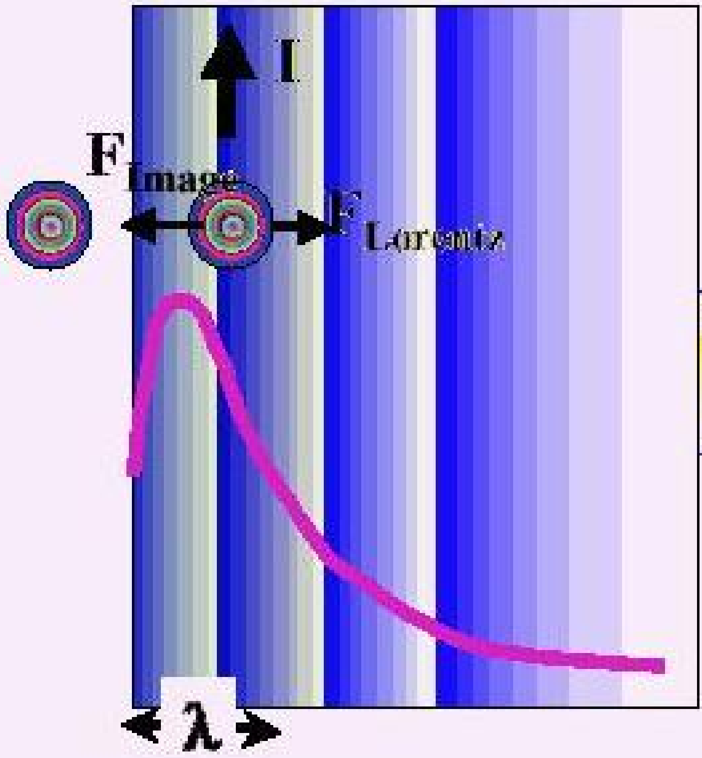
➡-Solutions define the macroscopic current patterns.

$I=I_c$ UNIFORM



THE SURFACE BARRIER

Vortex attraction to image in edge
→ Bean-Livingston barrier (PRB -64)



- $I<I_s$ Vortex entry and exit inhibited
  - NO Vortex motion

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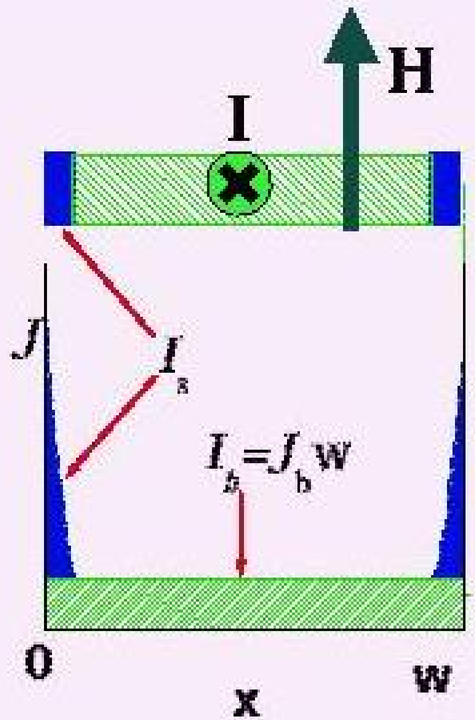
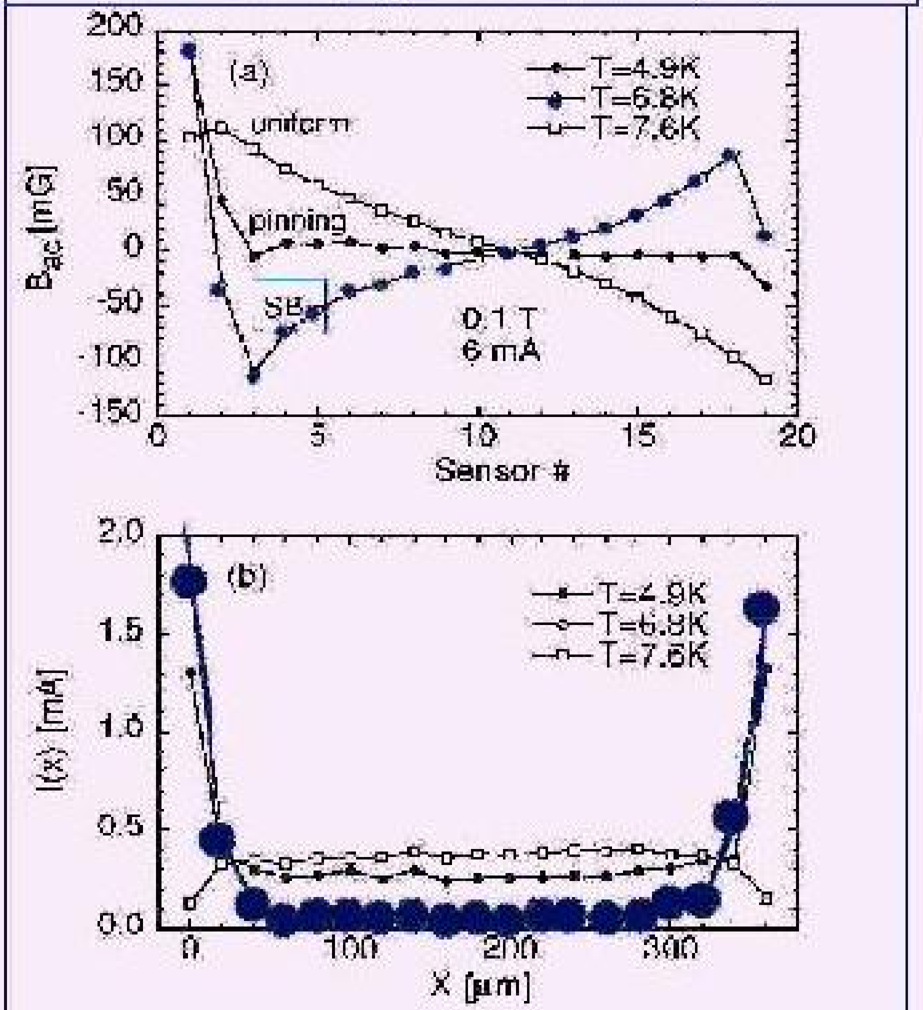
Vortex motion and Current distribution

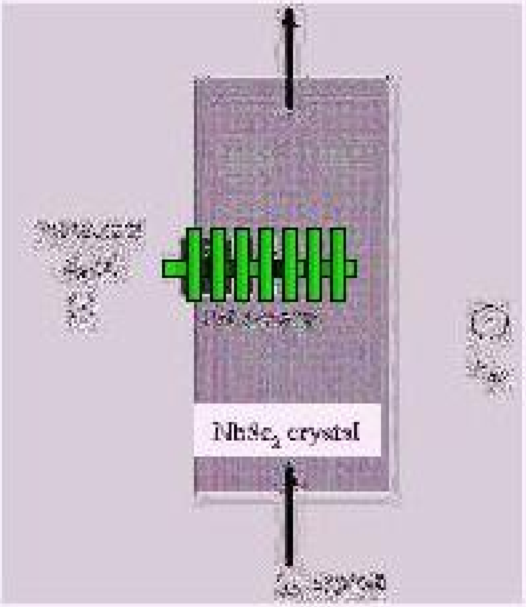
- Vortex flow $I = I_s + I_B$



Local Magnetization Measurements

Y. Paltiel et al., Phys. Rev. B **58**, R14763 (1998)





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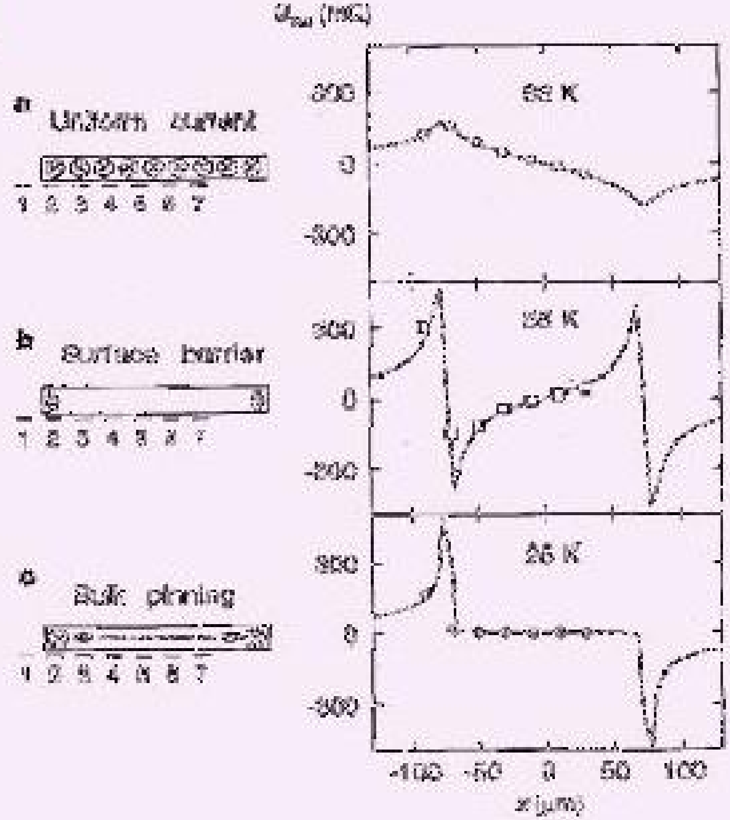
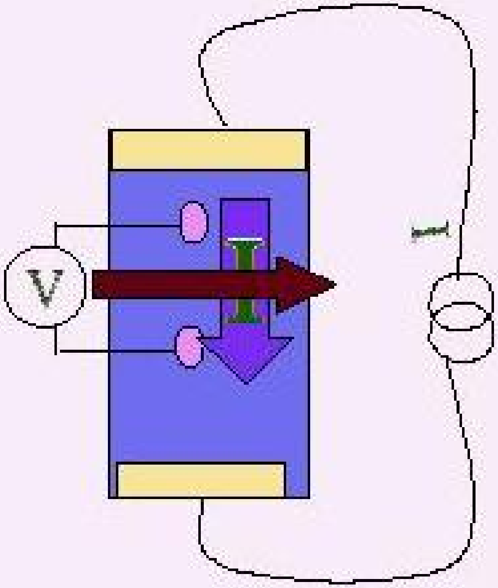
Local Magnetization Measurements

- D. T. Fuchs et al., Nature 391, 373 (1998) - BiSrCaCuO
- D. T. Fuchs et al., Phys. Rev. Lett. 81, 3944 (1998)
- Y. Paltiel et al., Phys. Rev. B 58, R14763 (1998) – 2H-$NbSe_2$

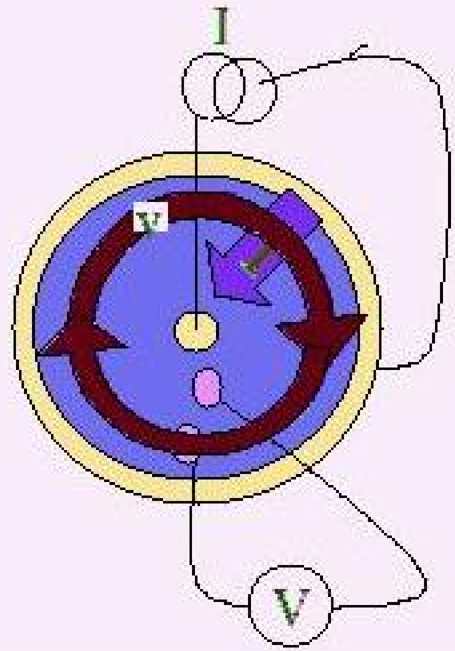


EFFECT OF SAMPLE GEOMETRY

Slab



Corbino Geometry



- VORTICES ENTER AND EXIT AT EDGES, THROUGH SURFACE BARRIER
- NEW VORTICES ARE DISORDERED
- "OLD VORTICES" MOTIONALLY ORDERED
- COEXISTENCE

- CIRCULAR MOTION
- NO CROSSING OF EDGES
- NO DISORDERED PHASE

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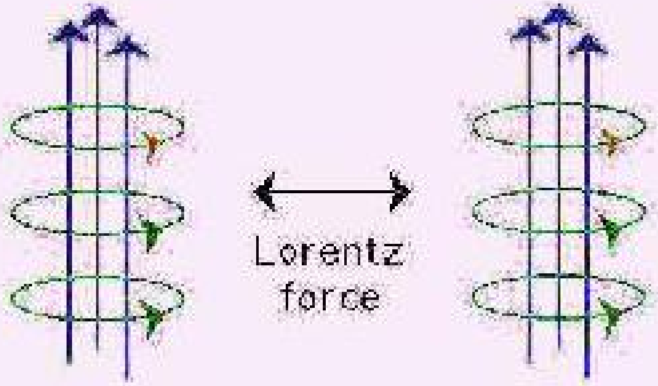
✷ THE PHASE DIAGRAM

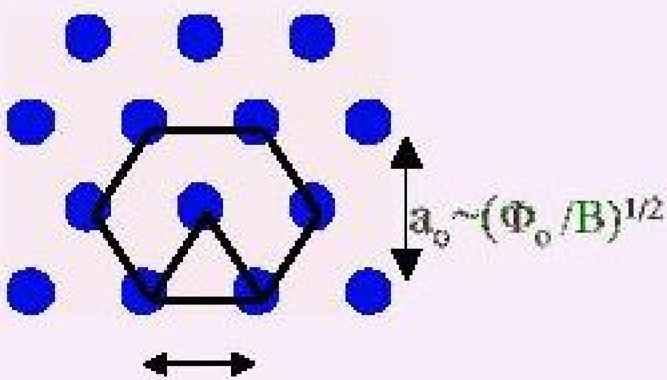
- Vortex interactions
- Physical Parameters
- $NbSe_2$

VORTEX-VORTEX INTERACTIONS



analogy: solenoid

repulsive interaction ⇒ Abrikosov lattice

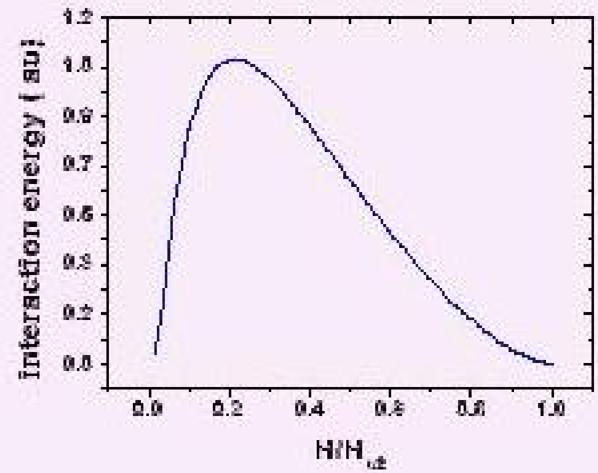


-Interaction Energy per unit volume

SHEAR MODULUS

$$c_{66} a_0^2 = \left(\frac{\Phi_0}{4\pi\lambda} \right)^2 \qquad H >> H_{c1}$$

$$\approx \left(\frac{\Phi_0}{4\pi\lambda} \right)^2 \left(\frac{a_0}{\lambda} \right)^{3/2} e^{-a_0/\lambda} \qquad H \cong H_{c1}$$



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VORTEX PHASE DIAGRAM

- Interactions (H) $\mapsto$ crystal

$$\frac{c_{66}a^2}{H_c^2} = \left(\frac{\xi_0}{\lambda}\right)^2$$

- liquid $\mapsto$ vortex glass
- Crystal $\mapsto$ Bragg glass

[Giamarchi and LeDoussal 96]

- Fluctuations

thermal (T) $\mapsto$ liquid

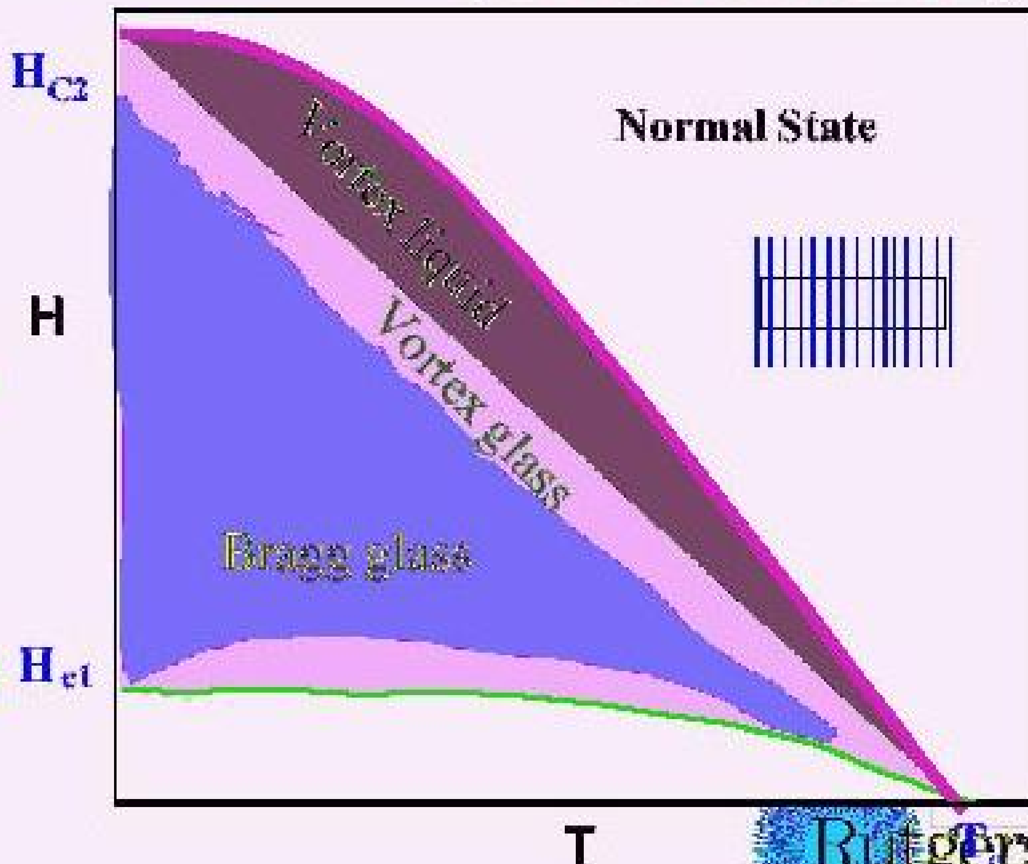
$$Gi = \frac{k_B T_c}{\varepsilon H_c^2 \xi^3}$$

Random potential (pinning) $\mapsto$ glass

$$\frac{J_p}{J_0} = \left(\frac{\xi}{R_c}\right)^2$$

Coupling (anisotropy) $\mapsto$ 3D -line

$$\varepsilon = \frac{\xi_c}{\xi_{ab}}$$



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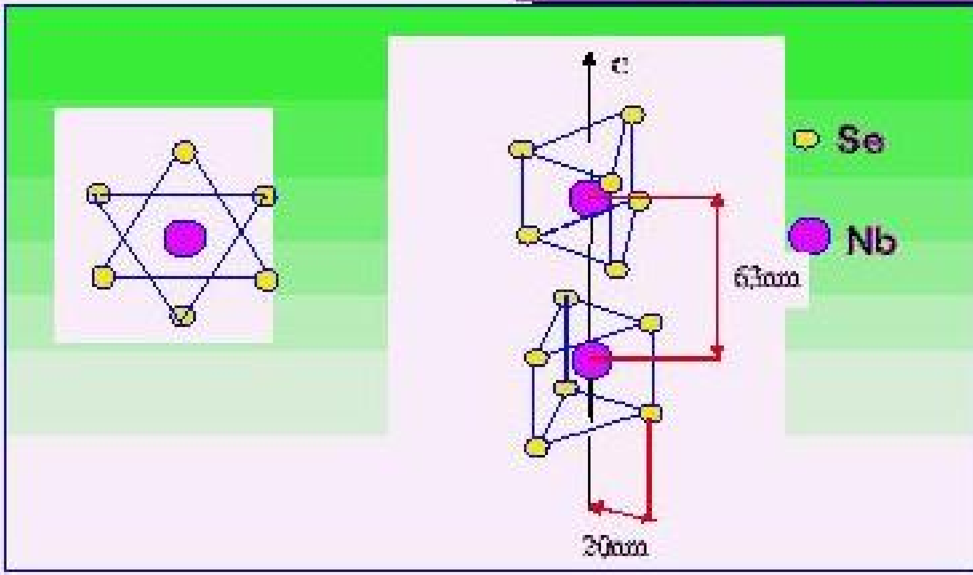
Physical Parameters of Type II Superconductors

	$NbSe_2$	$(K,B)BiO_3$	YBCO	BiSCCO
T_{c0} [K]	7	30	90	80
$\varepsilon = \frac{\xi_c}{\xi_{ab}} = \sqrt{\frac{m^*_{ab}}{m^*_c}}$	0.3	1	0.1-0.125	<0.02
ξ(A)	77	40-50	20	<10
λ(A)	1000	2500	1400	1800
H_{c20} [T]	5	30	150	>500
$Gi = (k_B T_c / \varepsilon H_c^2 V_{coh})^2$	10^{-4}	10^{-5}-10^{-4}	10^{-2}	10^{-1}
$T_c - T_m \sim T_c(\kappa^2 T_c/\varepsilon H_c^2)^{3/2}$	10^{-2}-10^{-1}	10^{-1}-1	1-10	10-50
j_c/j_0	10^{-6}	10^{-2}-10^{-1}	10^{-3}-10^{-2}	10^{-3}-10^{-2}

PROPERTIES of $NbSe_2$



- ANISOTROPIC LAYERED MATERIAL
- LARGE SINGLE CRYSTALS (1x1x0.05mm)
- $\rho_{\parallel} \sim 3\mu\Omega$ cm

		$H \parallel c$	$H \perp c$
COHERENCE LENGTH	ξ	~7.7nm	~2.3nm
LONDON PENETRATION DEPTH	λ	~100nm	~230nm
CRITICAL FIELD	$H_{c2}(T=0)$	~5 T	~22T

RELATIVE STRENGTH OF FLUCTUATIONS

		NbSe	HTC	LTC
THERMAL	$Gi=(k_B T_c/H_c^2 \varepsilon\xi^3)^2/2$	10^{-4}	10^{-2}	10^{-8}
QUANTUM	$Qu=(e^2/h)(\rho_n/\varepsilon\xi)$	10^{-3}	10^{-1}	10^{-3}
ORDER PARAMETER	J_c/J_o	10^{-6} ☺	10^{-2} ☹	10^{-1} ☹

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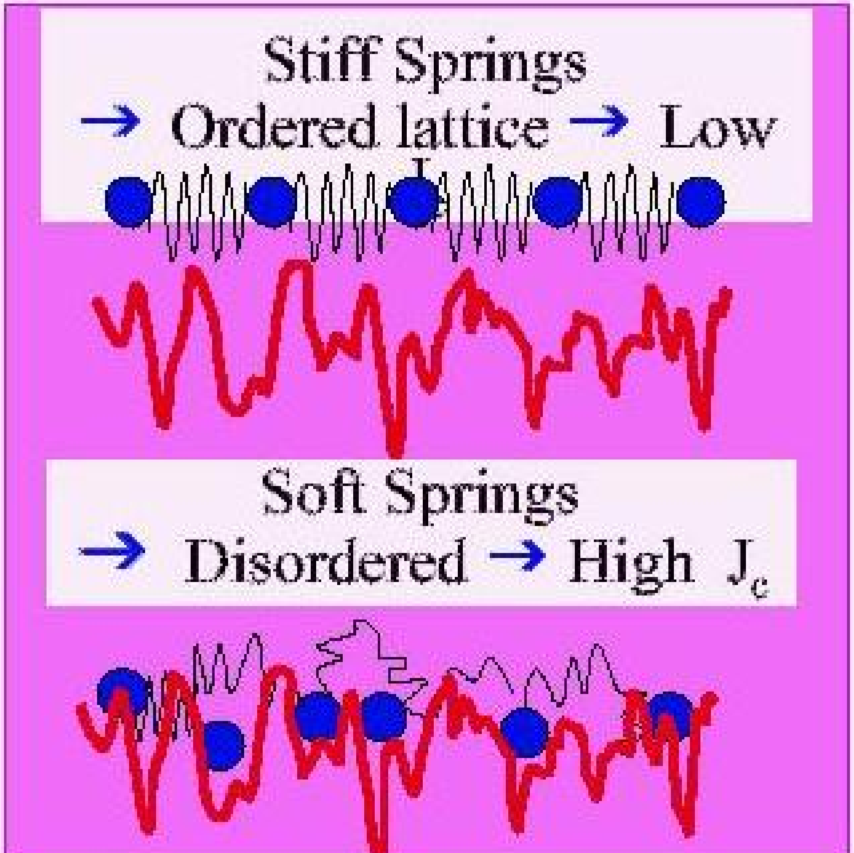
✷ EFFECTS OF RANDOM POTENTIAL

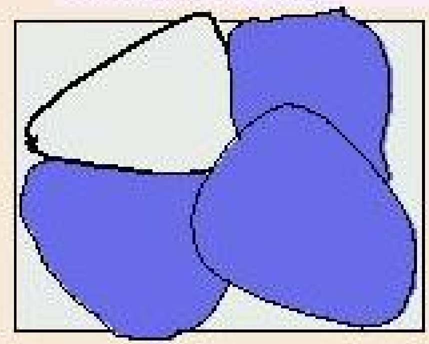
- Collective Pinning
- Peak Effect
- Metastable states

COLLECTIVE PINNING



Elastic Manifold in Random Potential

A. I. Larkin and Y. Ovchinikov - 79
U. Yaron et al - 94



Size of coherent domain

$R_c \sim \xi(J_0/J_c)^{1/2}$

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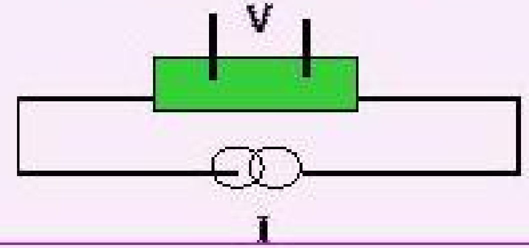
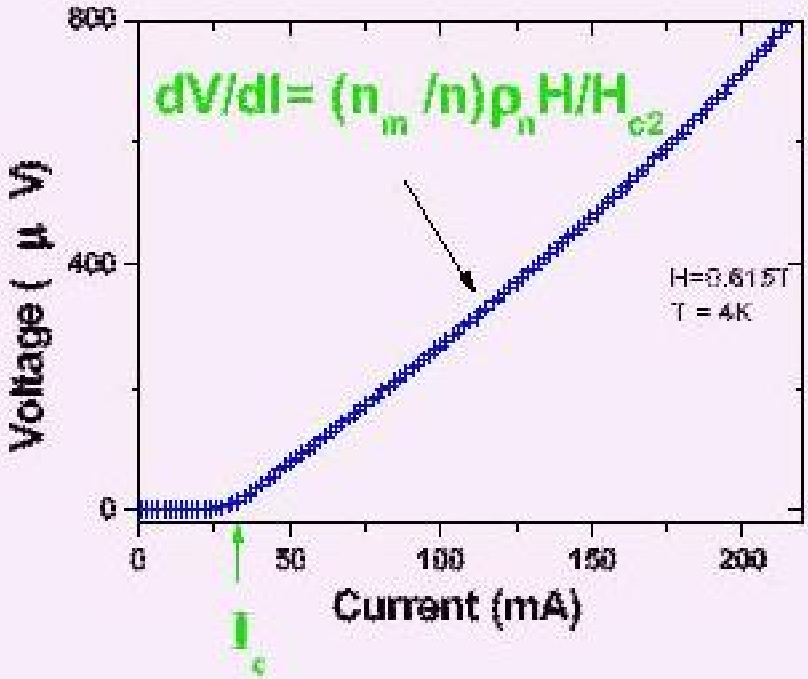
Transport Measurements

4 Lead Measurement





I_c	↦	degree of order
dV/dI	↦	fraction of moving vortices

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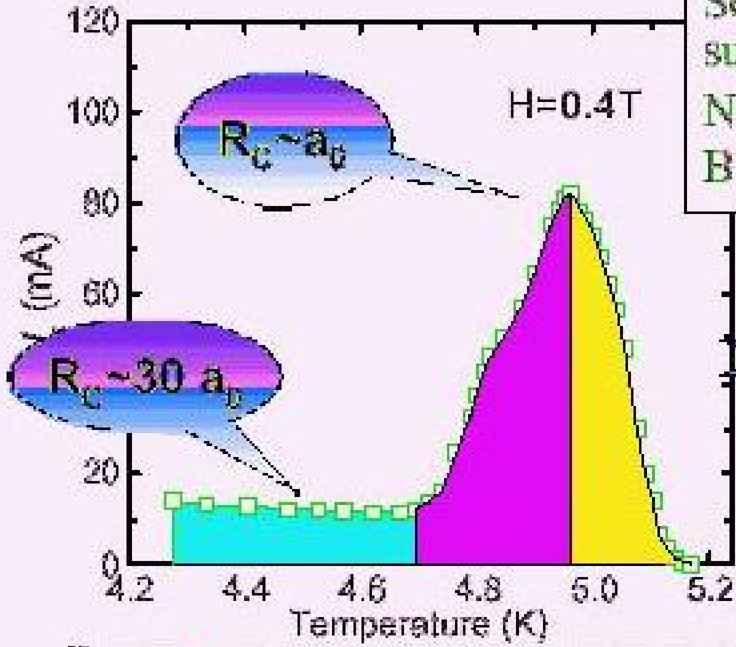
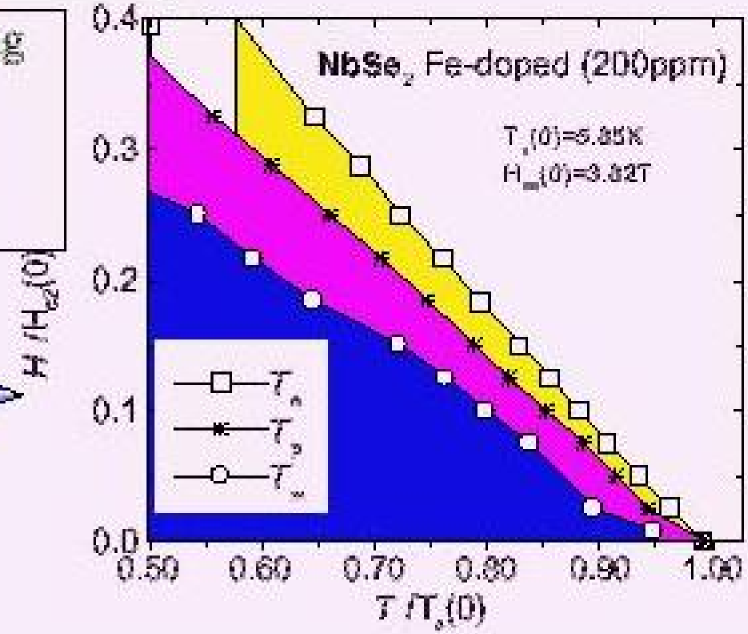
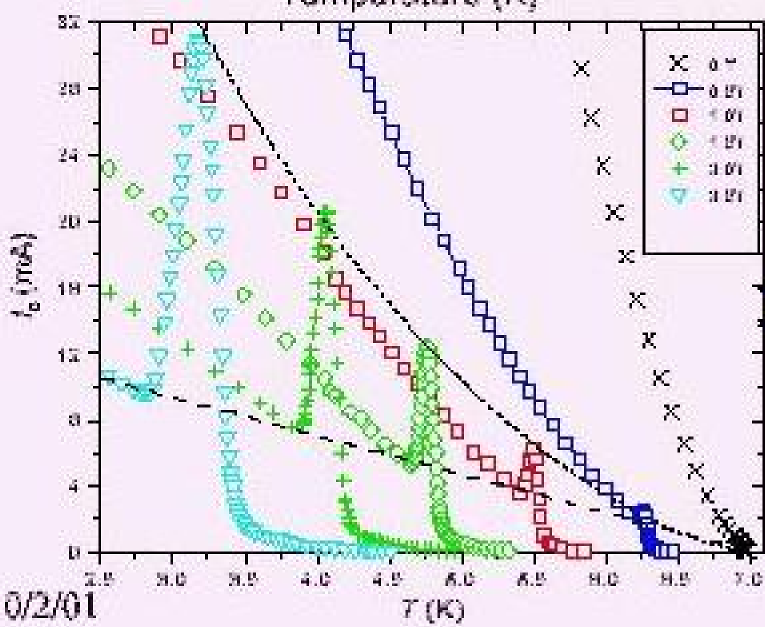
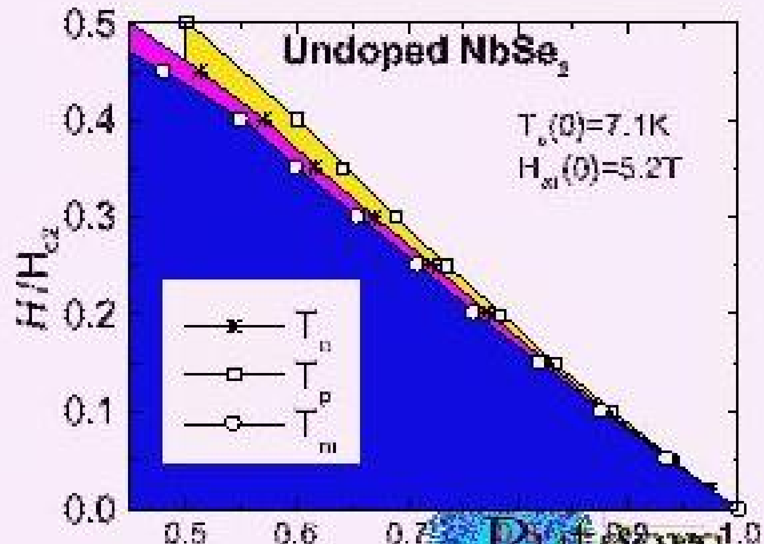
THE PEAK EFFECT

Seen in weak pinning superconductors:
Nb, NbGe, NbSe2, BSCO, YBCO,









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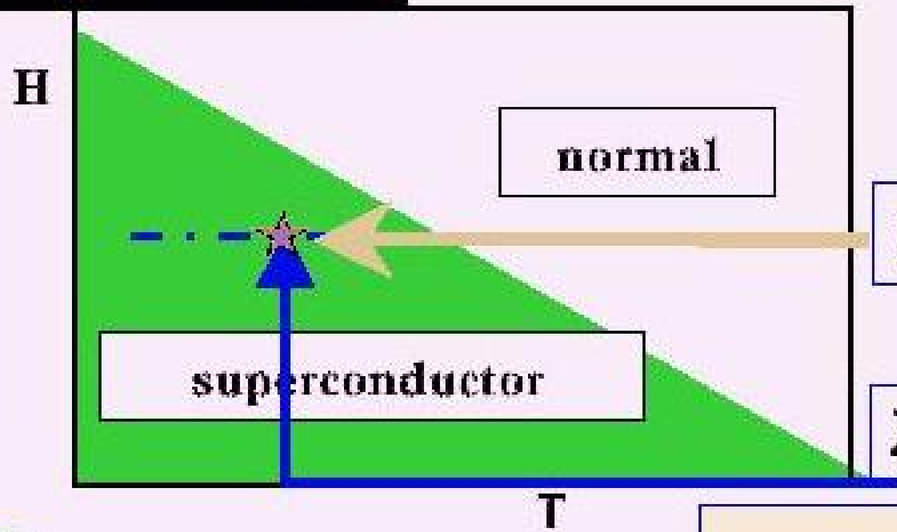
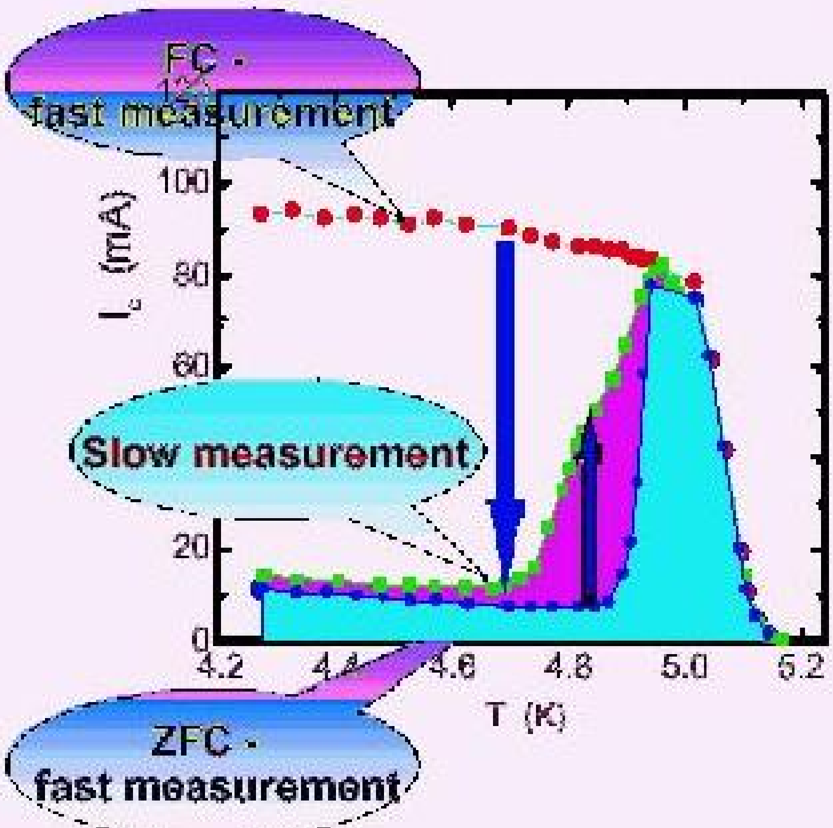
METASTABILITY

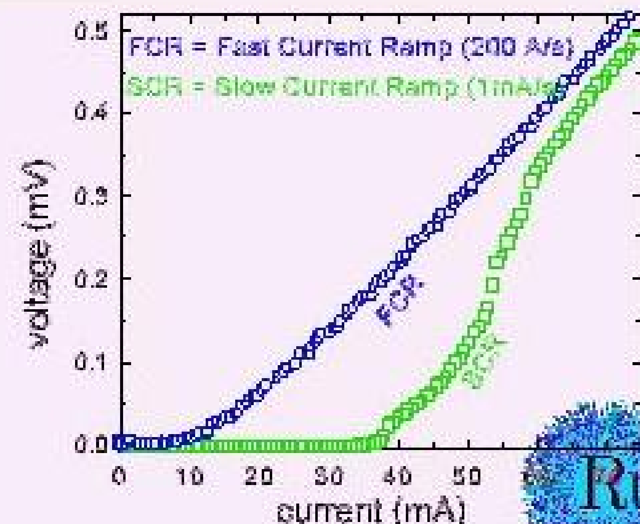


FC- Field Cooling

ZFC- Zero field Cooling

☛ Below the peak I_c depends on method of preparation and measurement speed





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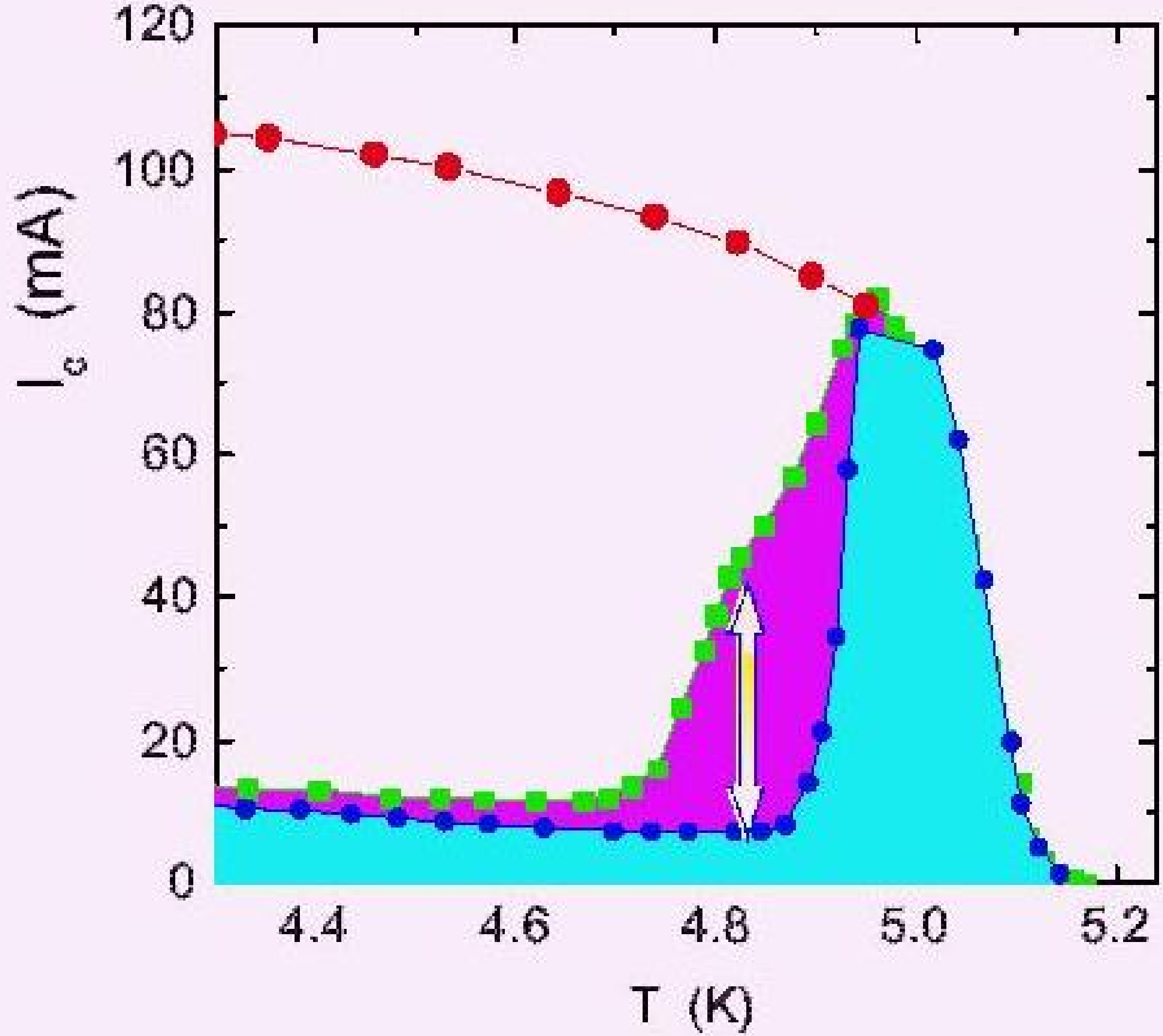
✷ CURRENT DRIVEN ORGANIZATION

- Cyclic softening
- Jamming
- Frequency Memory
- Effect of Boundaries
- Metastable to stable transition

Dynamics of non-equilibrium vortex states
Current Induced Organization



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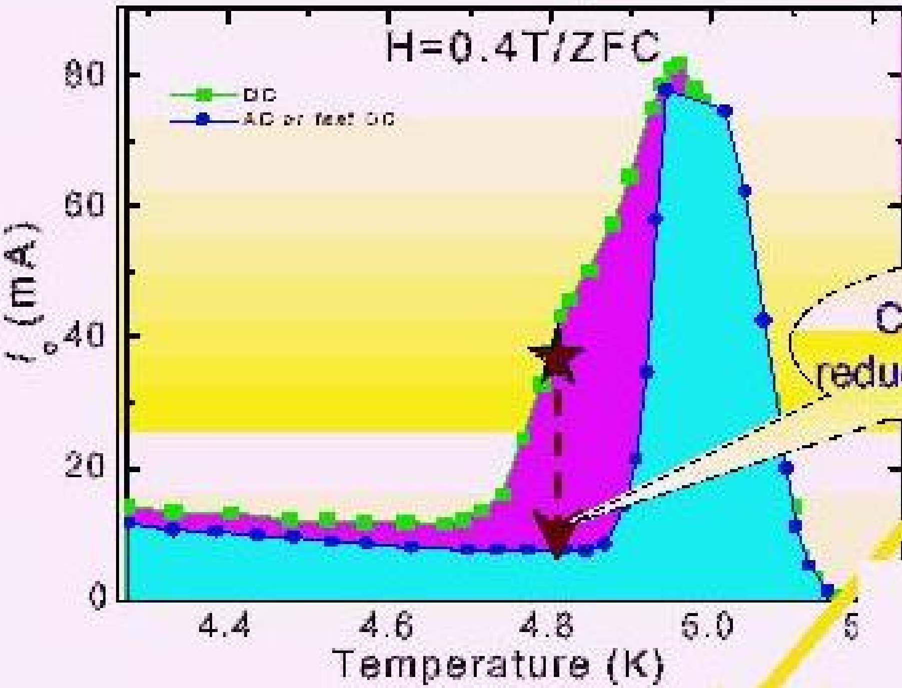
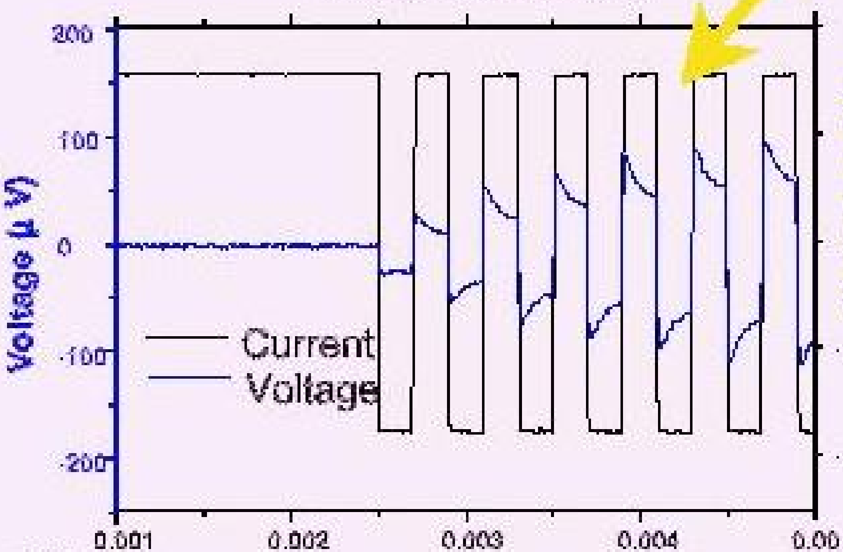
CYCLIC SOFTENING

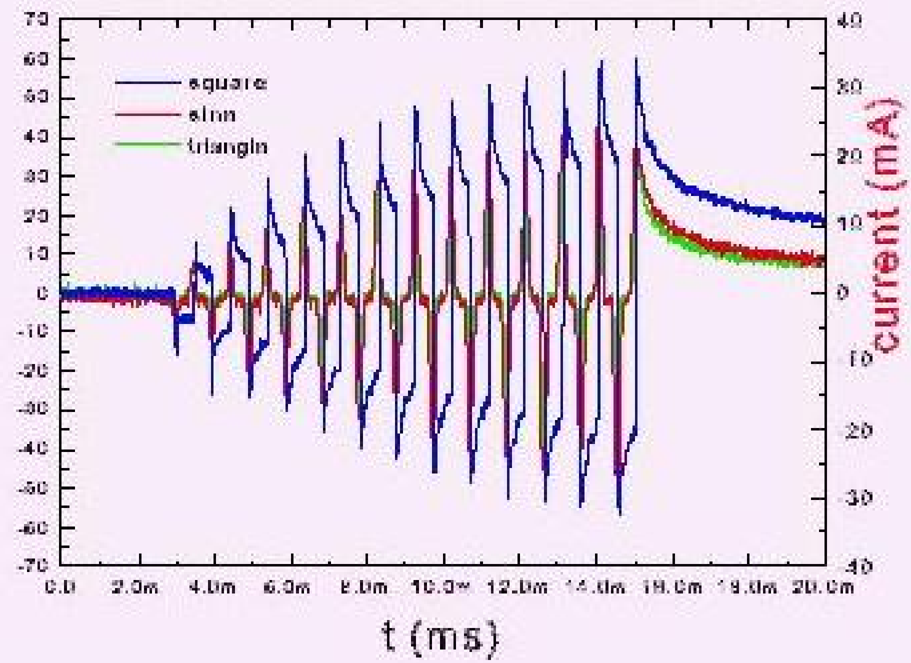
- Henderson, Andrei, Higgins - PRL **81**, 2352 (98)
- Andrei, Xiao, Henderson, Higgins, Shuk, Greenblatt - J. Phys. IV, **Pr10**, 5 (1999)



Critical current reduced by AC drive

"shaking" causes vortices to order.





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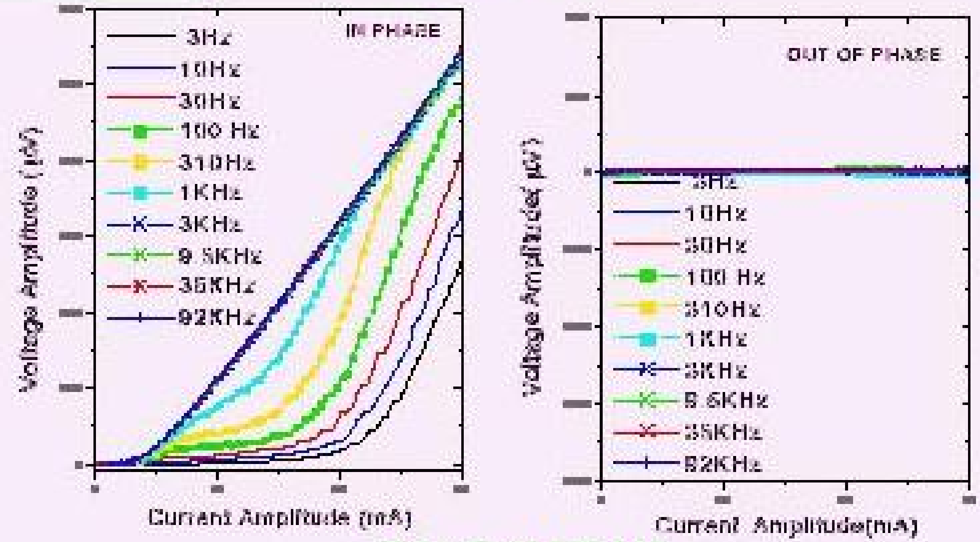
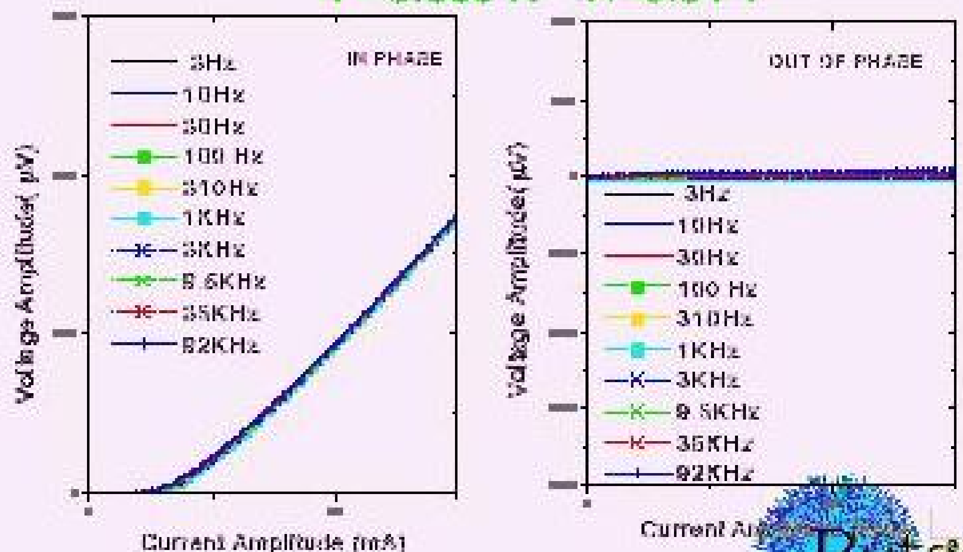
FREQUENCY DEPENDENCE OF I-V CURVES

- Andrei et al J. Phys. IV, **Pr10**, 5 (1999)

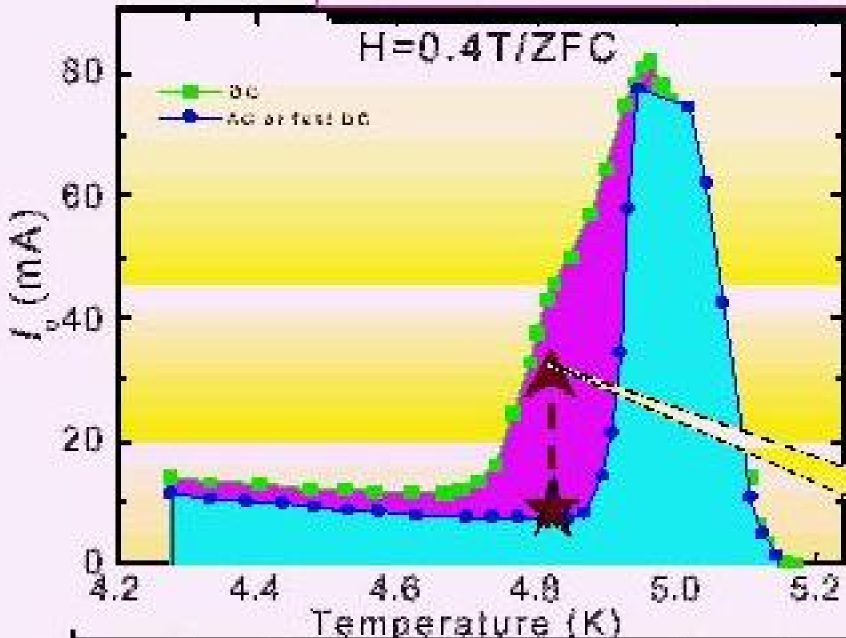
PEAK REGION
T= 4.538 K H=0.51 T



BELOW PEAK
T= 3.996 K H=0.51 T



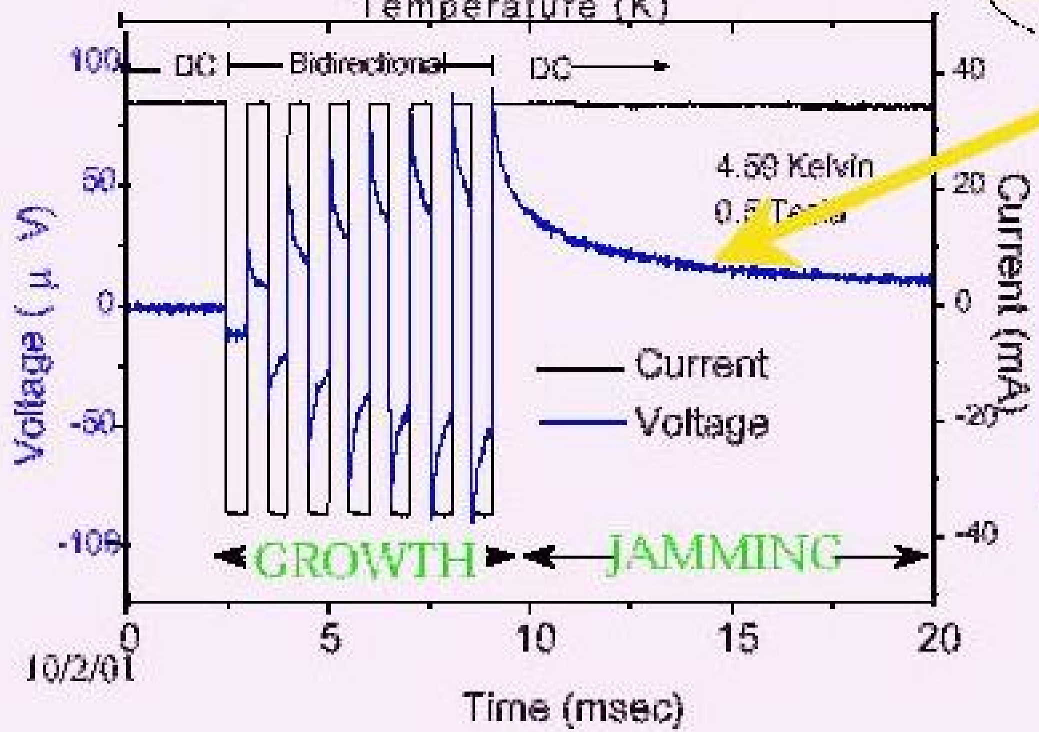
JAMMING- current induced disorder



- Henderson, Andrei, Higgins - PRL **81**, 2352 (98)
- Andrei, Xiao, Henderson, Higgins, Shuk, Greenblatt - J. Phys. IV, **Pr10**, 5 (1999)

DC current → disorder.

I_c INCREASED by DC drive



Jamming in YBCO

- N. Gordeev, et al Nature, 385 324-326 (1997)
- S Kokkaliaris, PAJ deGroot, SN Gordeev, AA Zhukov, R Gagnon and L Taillefer, Phys. Rev. Lett. 82 (1999) 5116

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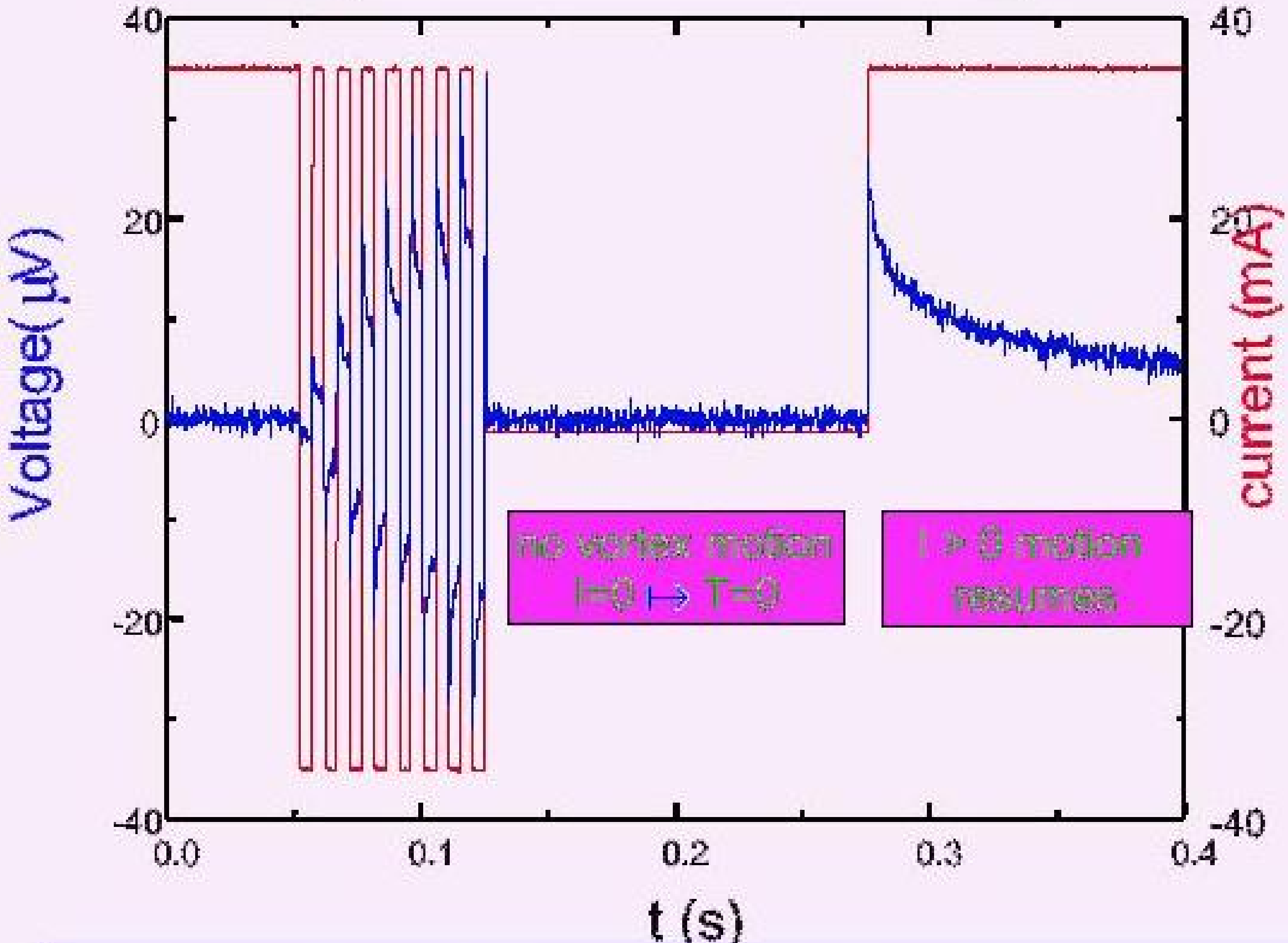
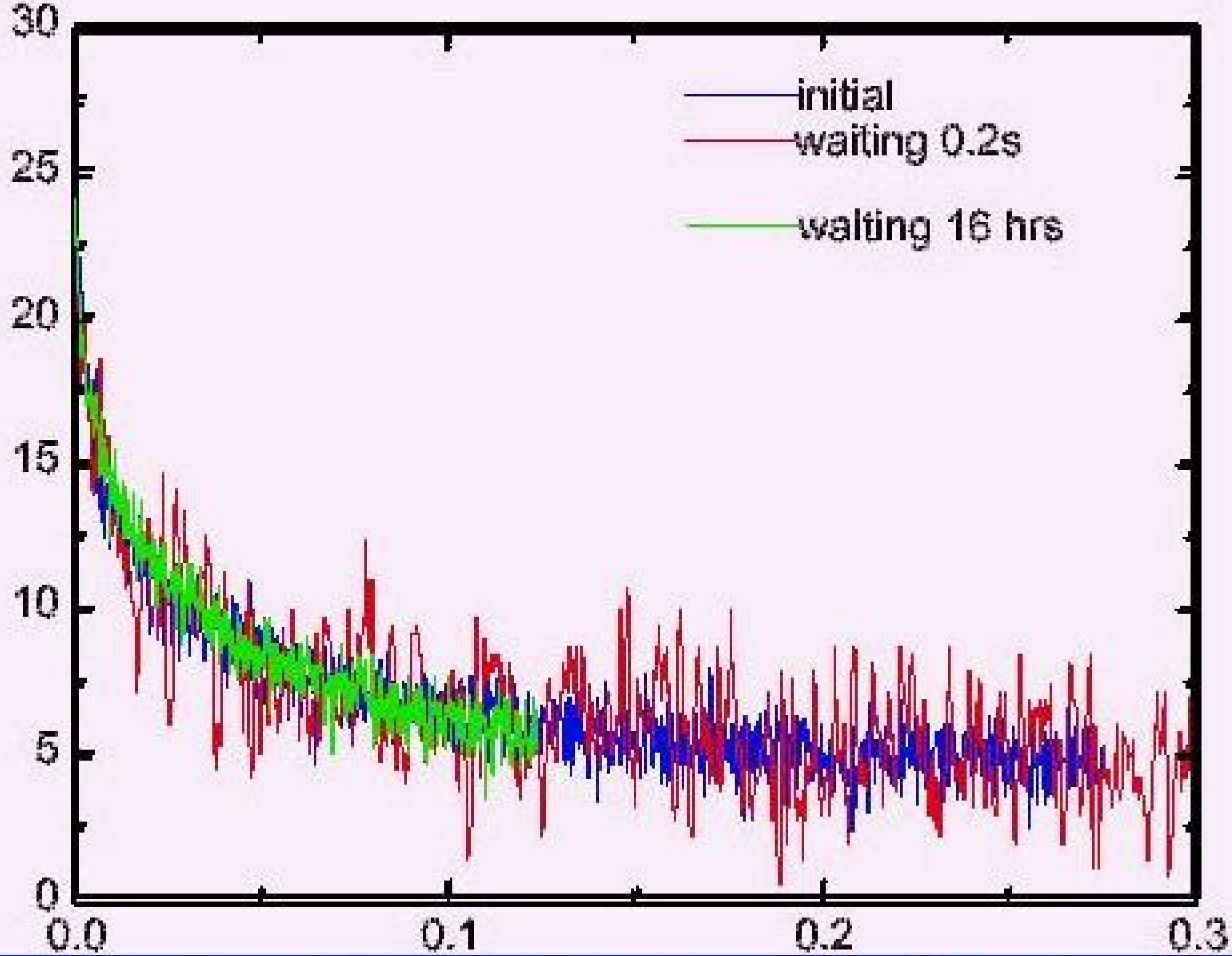
MEMORY



- Current removed → vortex motion arrested
- Current restored → motion resumes where it stopped
- I=0 ~ T=0

HOW LONG DOES IT REMEMBER?

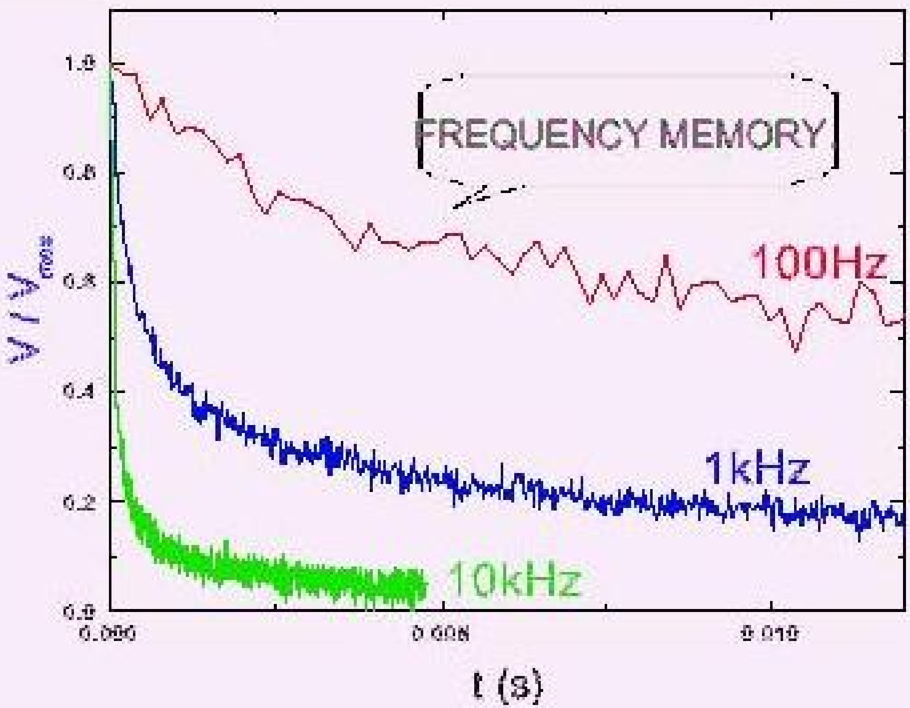


- Experiment repeated by removing the current for various intervals : 0.2ms - 16 hrs.
- In every case the decay was the same as if the drive was not interrupted.
- The memory of the AC drive is encoded in the decay function.

FREQUENCY MEMORY

- Henderson, Andrei, Higgins - PRL **81**, 2352 (98)
- Andrei, Xiao, Henderson, Higgins, Shuk, Greenblatt - J. Phys. IV, **Pr10**, 5 (1999)

- The time scale of jamming depends on the frequency of the drive before it was turned back to dc.

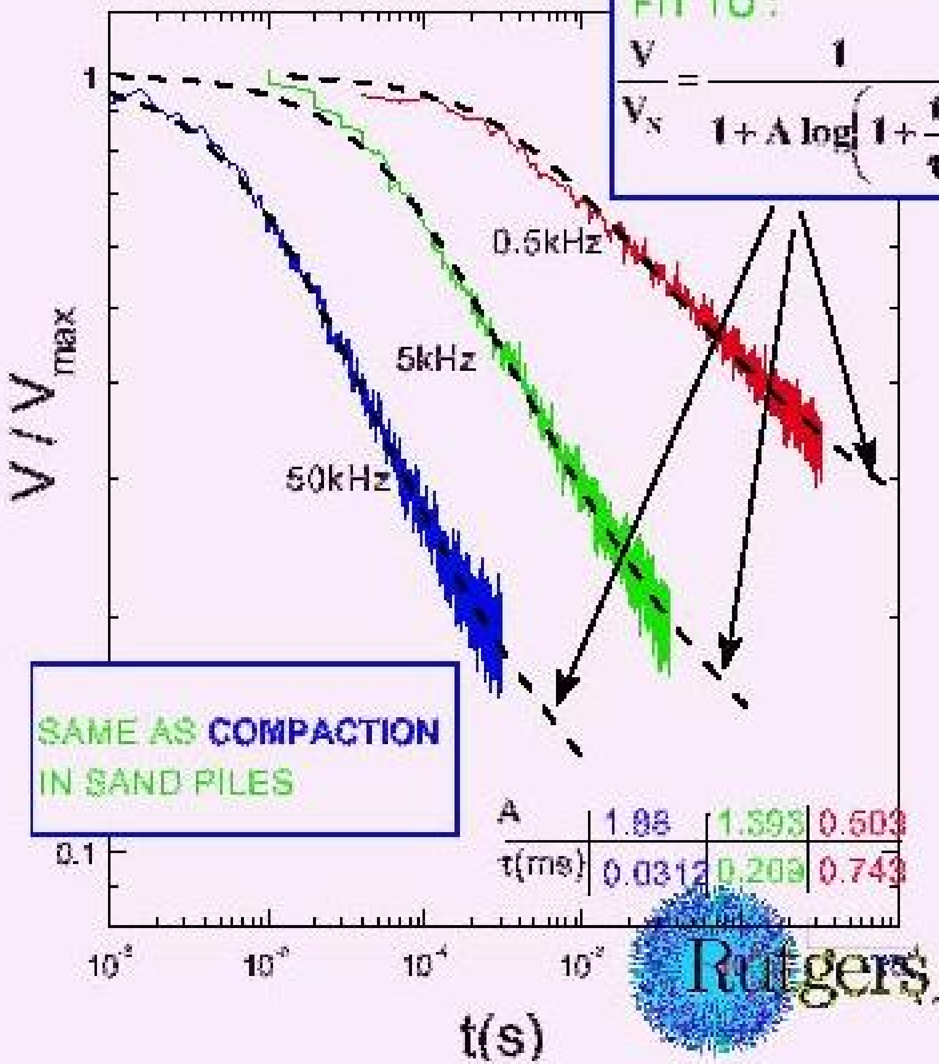


LOGARITHMIC DECAY

- If Switching is stopped BEFORE response reaches saturation The decay is logarithmic in time.

FIT TO :

$$\frac{V}{V_S} = \frac{1}{1 + A\log\left(1 + \frac{t}{\tau}\right)}$$



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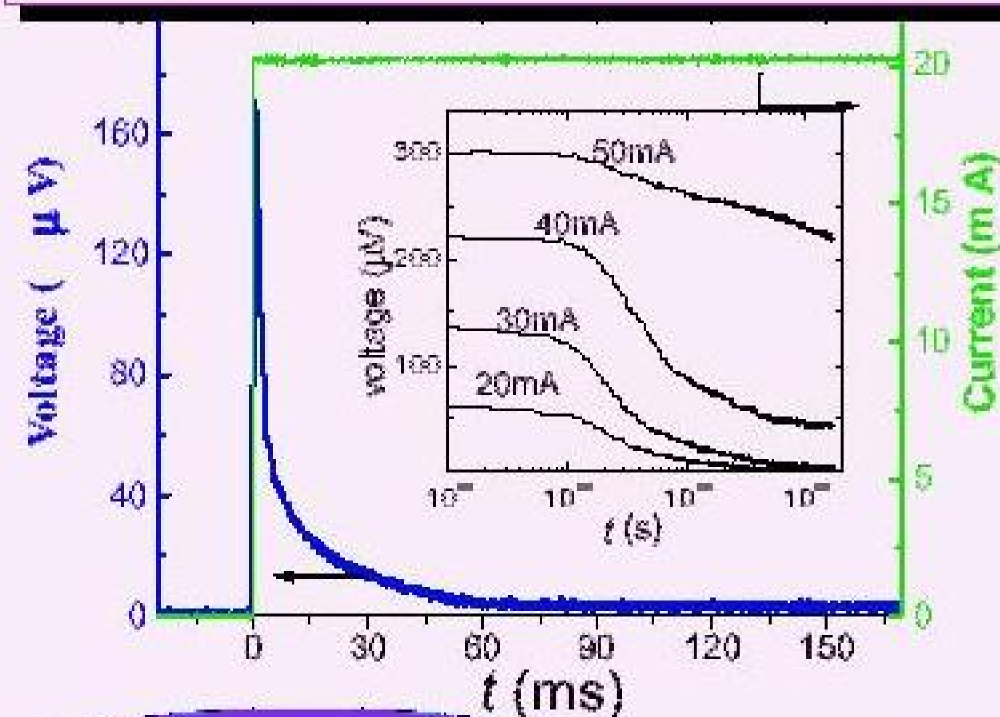
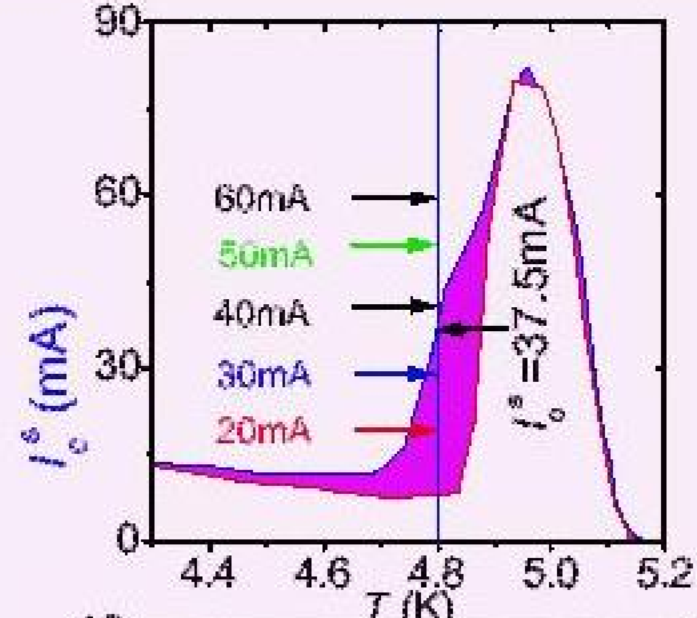
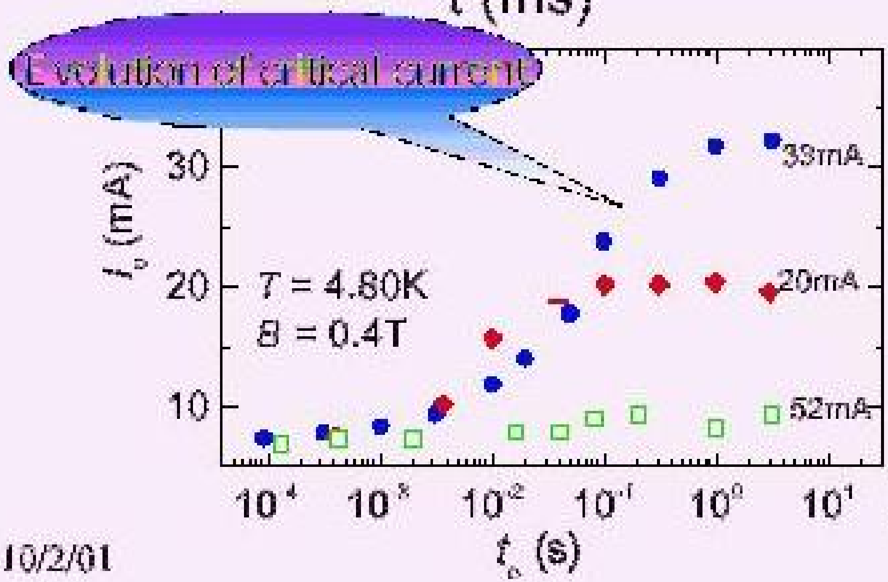
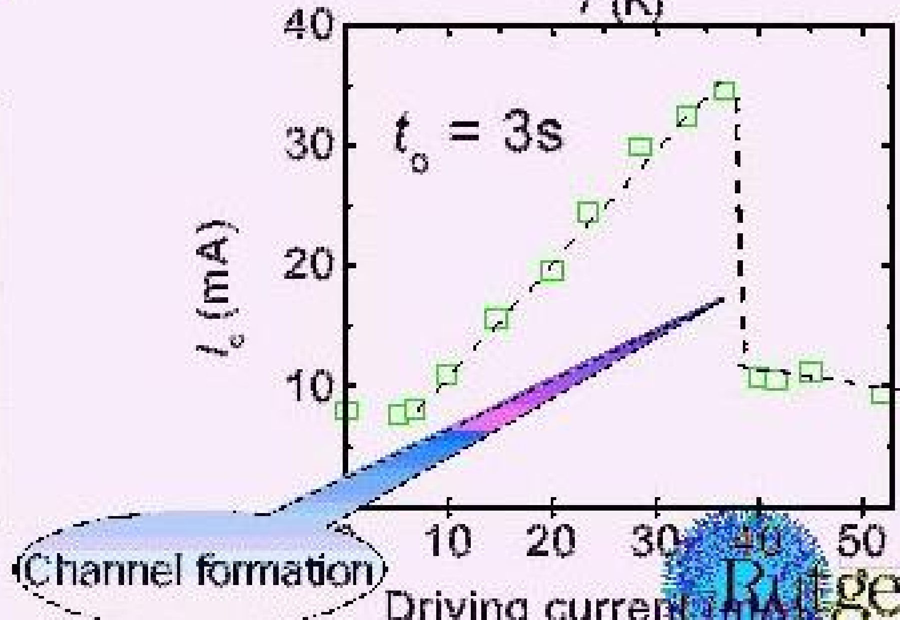
RESPONSE OF ZFC STATE TO CURRENT STEP

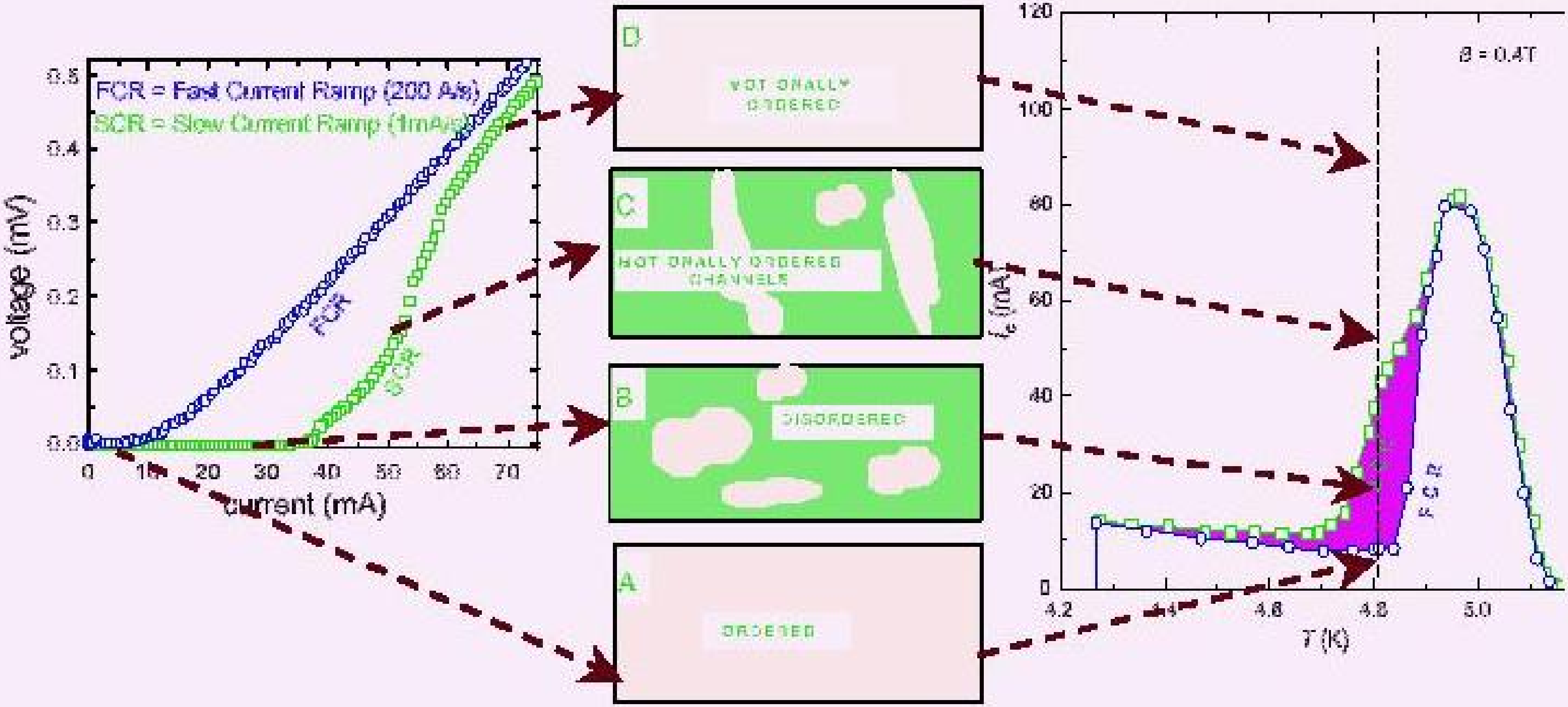
- Z.L. Xiao, E.Y. Andrei and M. Higgins
- Phys. Rev. Lett, 83, 1664, (1999)





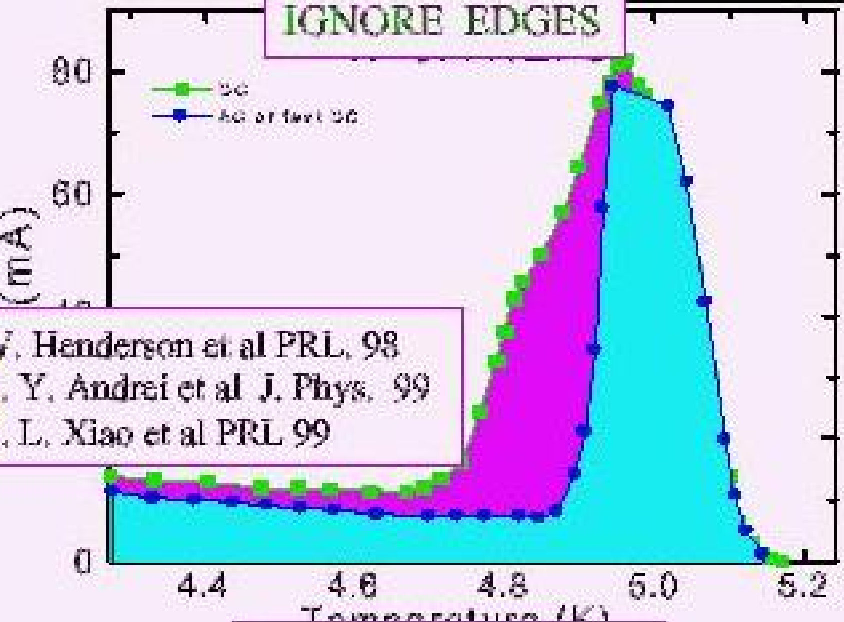





FCR = Fast Current Ramp (200 A/s)
SCR = Slow Current Ramp (1mA/s)
voltage (mV)
current (mA)
FCR
SCR
D
C
B
DISORDERED
A
ORDERED
B = 0.4T
I_c (mA)
T (K)
FCR

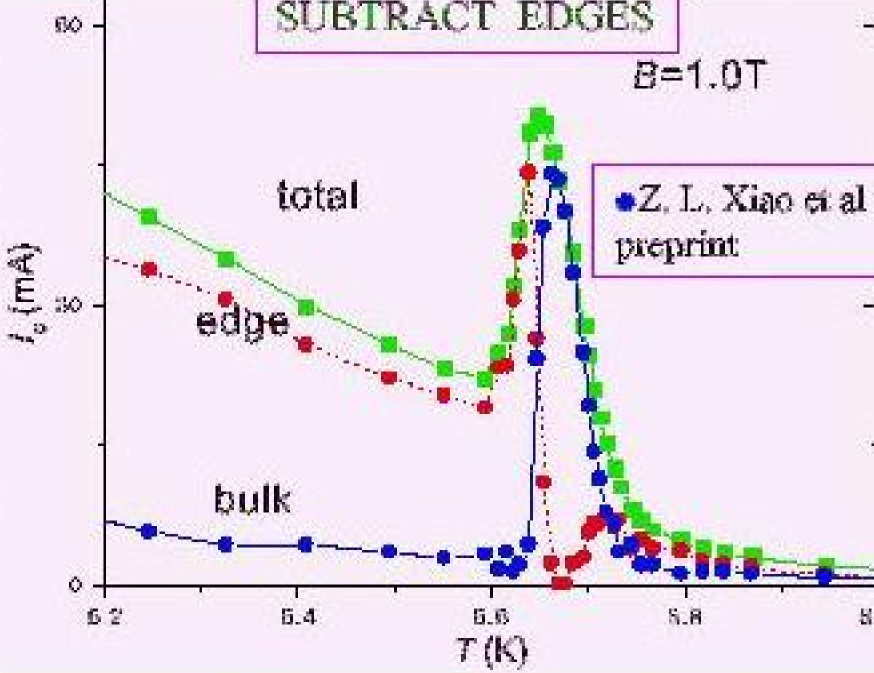
EFFECT OF BOUNDARIES

IGNORE EDGES



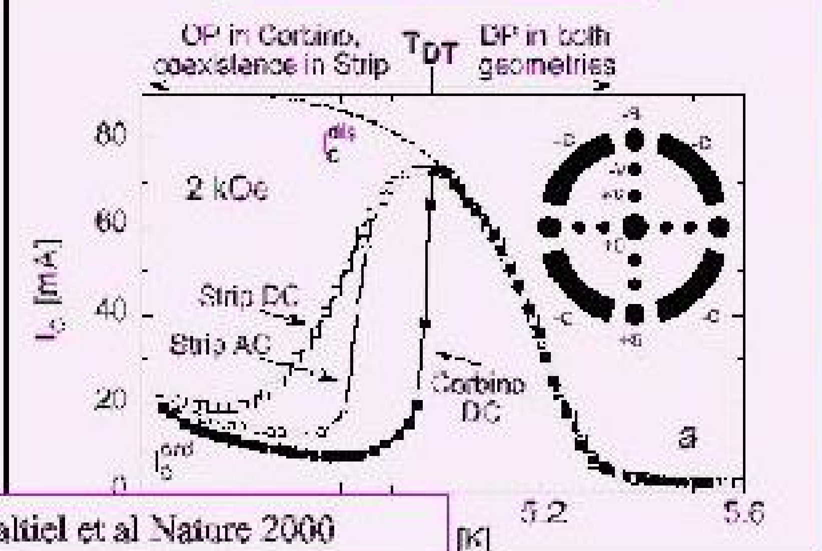
- W. Henderson et al PRL 98
- E. Y. Andrei et al J. Phys. 99
- Z. L. Xiao et al PRL 99

SUBTRACT EDGES



- Z. L. Xiao et al preprint

ELIMINATE EDGES



- Paltiel et al Nature 2000

In the absence of edges

⇓

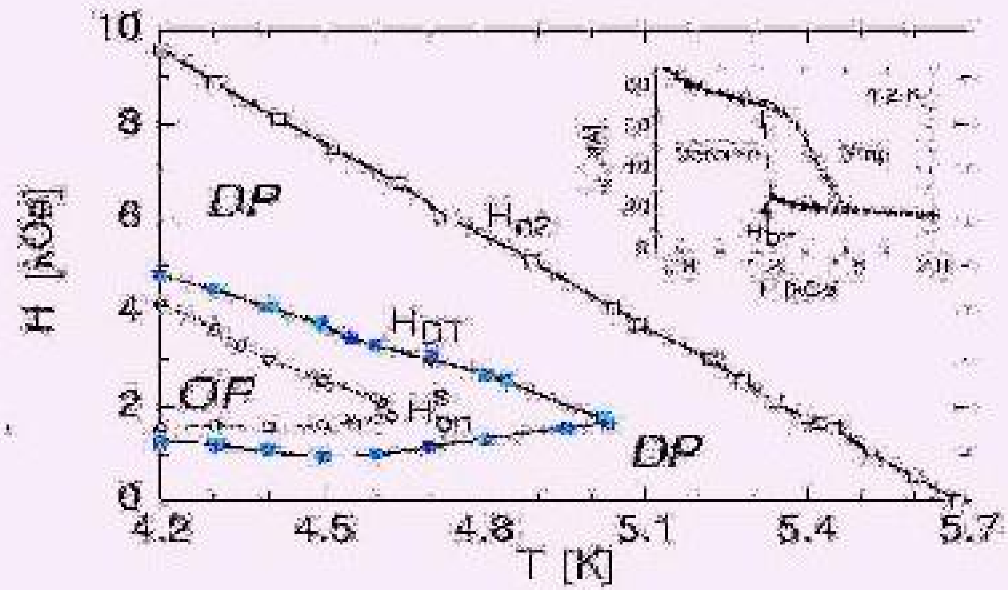
PEAK EFFECT SHARPENS INTO A JUMP

⇓

Consistent with phase transition

(Paltiel et al. PRL 2000)

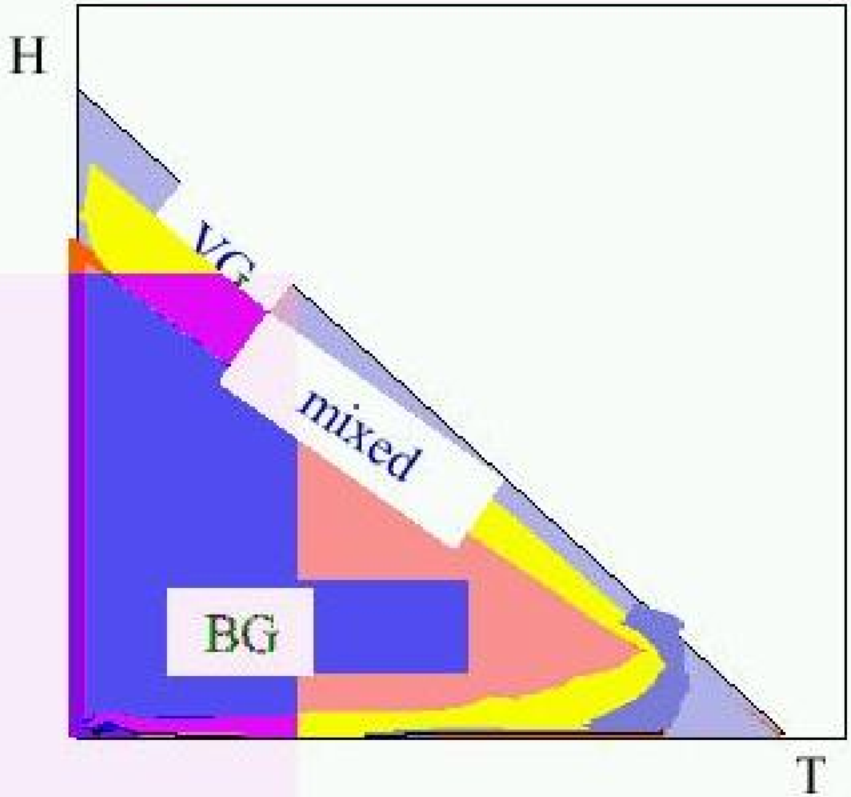
PHASE DIAGRAM



Paltiel et al, PRL 00

DEFECTS+BOUNDARIES = New physics

- Liquid; crystal → Vortex Glass; Bragg Glass
- VG-BG transition → coexistence → Broad Peak effect



Dynamics of Mixed Phase

- Current driven organization
- Tunable critical currents
- Cyclic softening
- Jamming
- Frequency Memory

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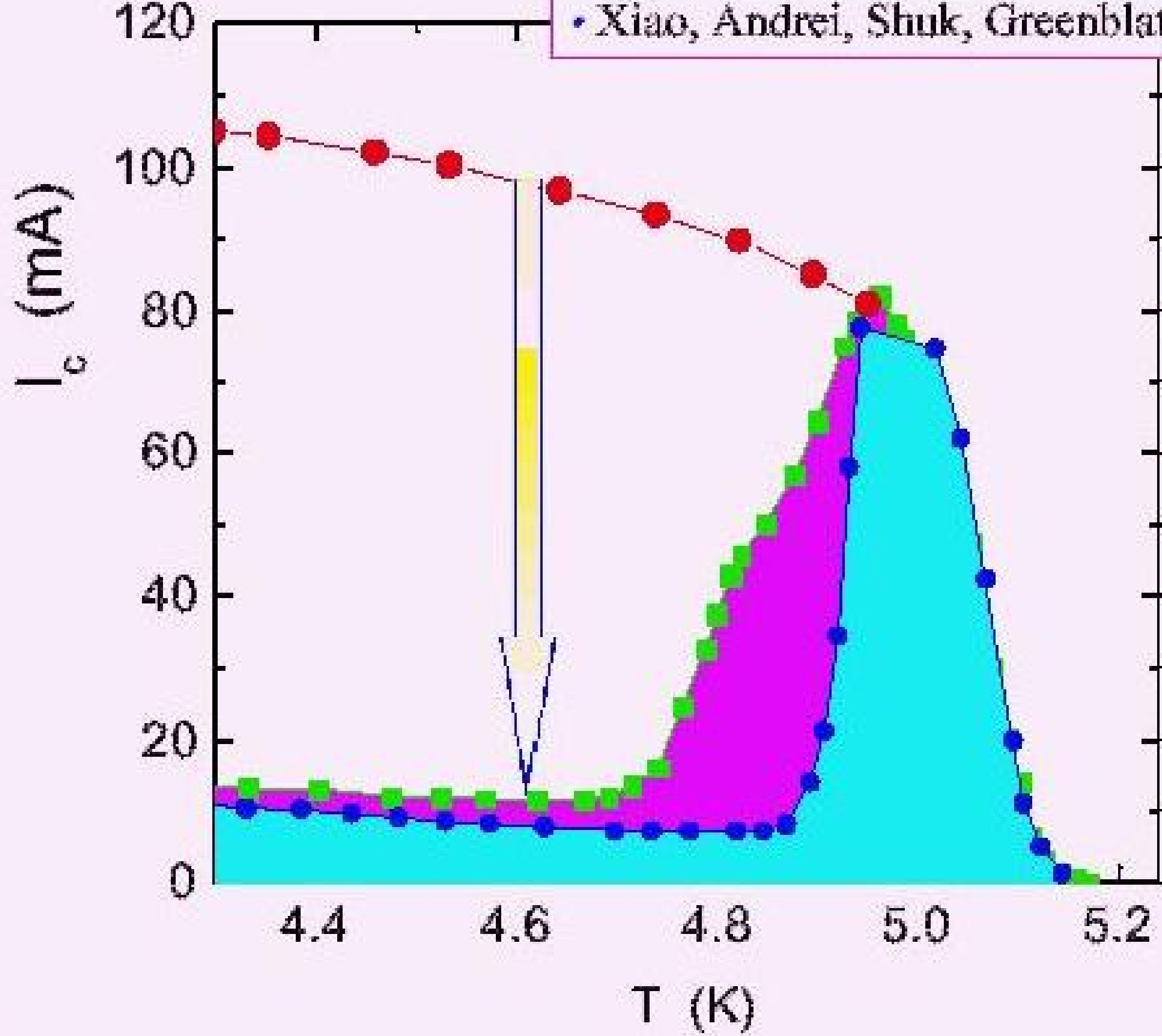
METASTABLE - STABLE TRANSITION
Current Induced Ordering

• Xiao, Andrei, Shuk, Greenblatt - PRL 86, 2431, (2001)



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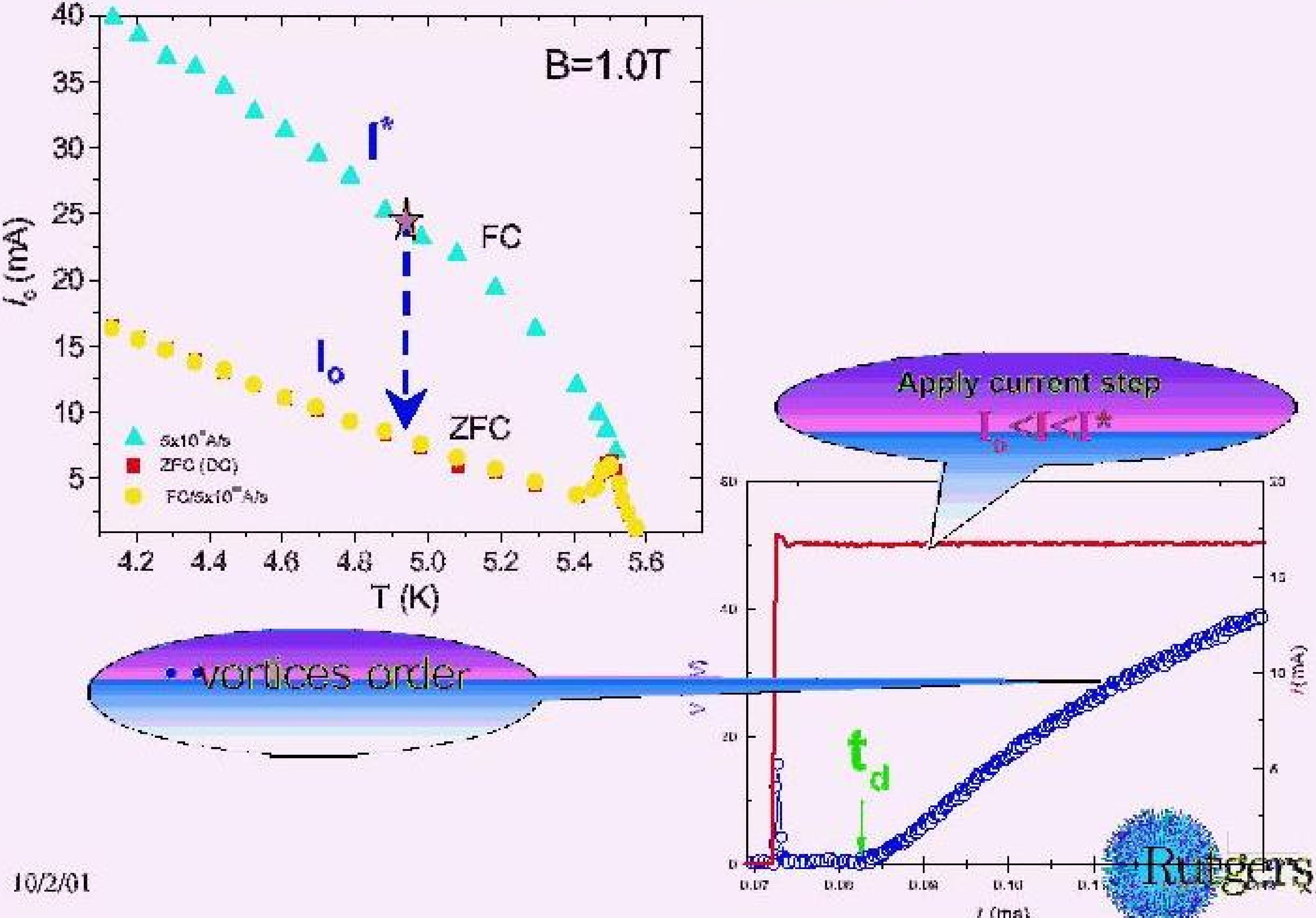
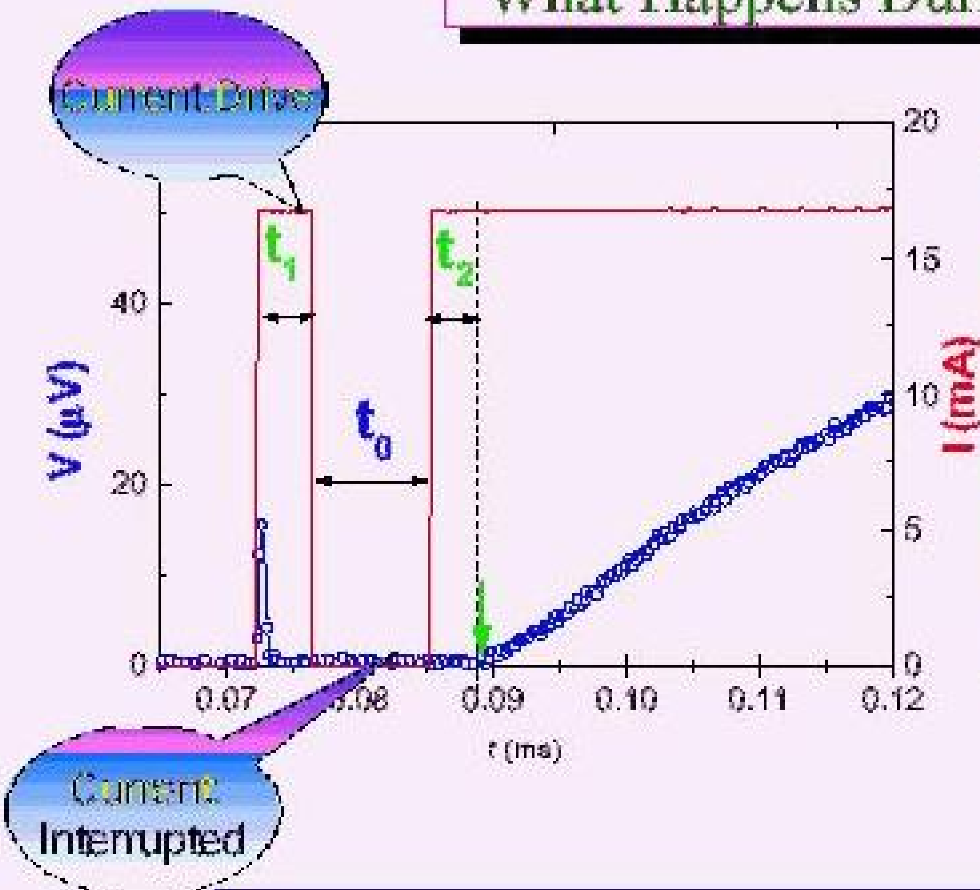
Current Induced Ordering



What Happens During t_d?



- $t_1+t_2 = t_d$ → evolution of vortex state during t_d.
- independent of t_0 → no evolution for I=0
- $t_1+(-t_2) = t_d$ → not reversed by reversing current

- System evolves during t_d
- Evolution stops in the absence of current
- Irreversible process

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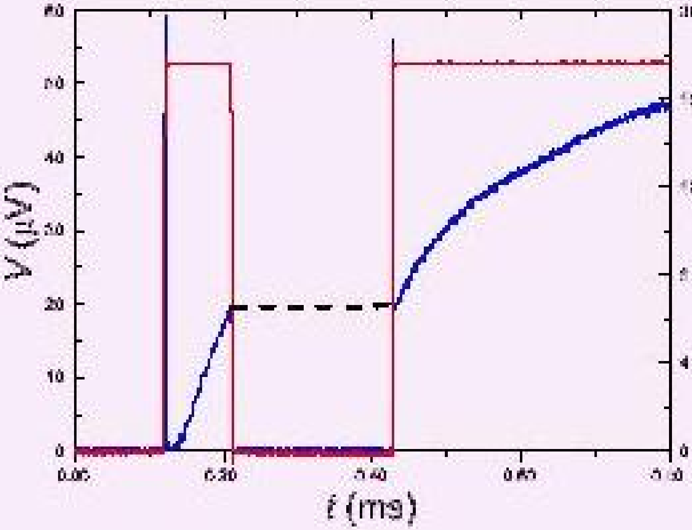
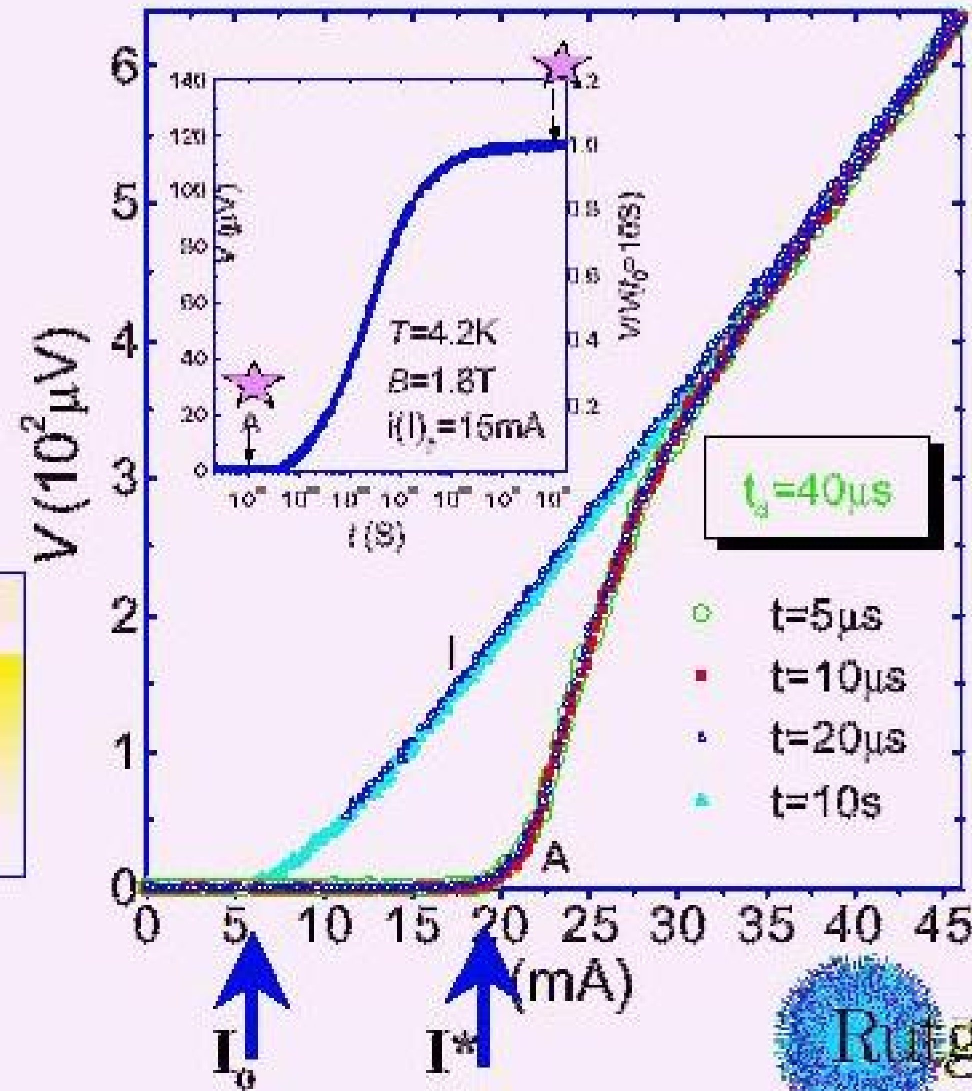
Probing the vortex state during current driven evolution

Current removed → no evolution

Measure fast I-V to determine vortex state





$t<t_d$ → response identical to that of disordered state.

$t>>t_d$ → response identical to that of ordered state

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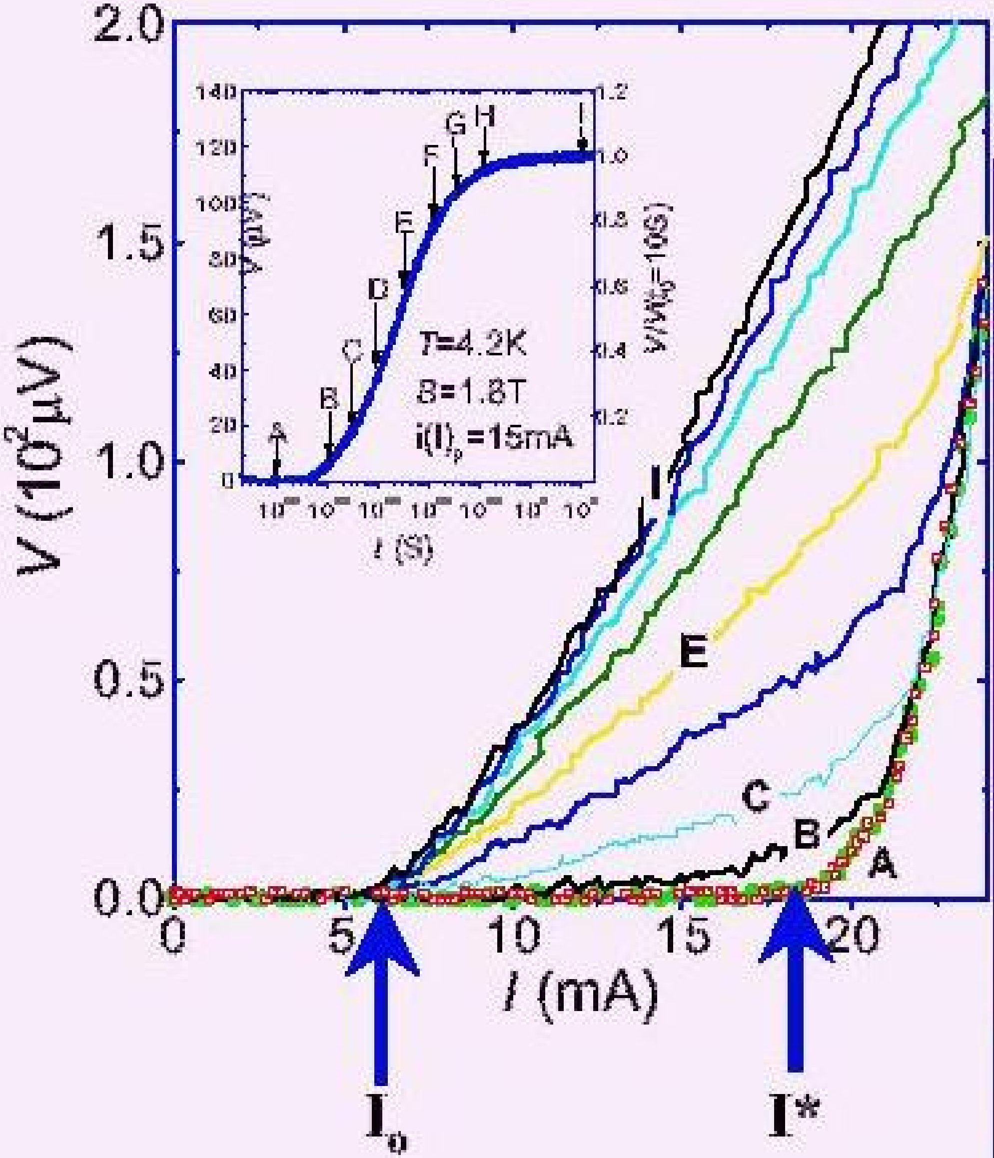
Formation of a channel



A- $t<t_d$=40• s $I_c = I^*$, I-V unchanged → no vortex motion

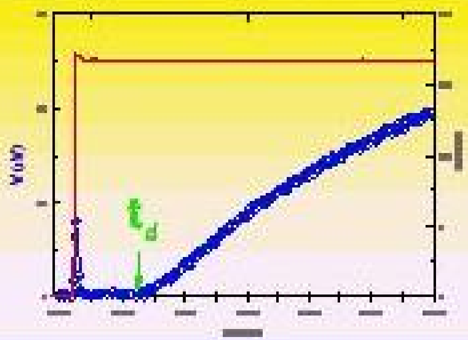
B- t=40• s<t_d<200 $I_o<I_c<I^*$ → channel of mobile vortices.

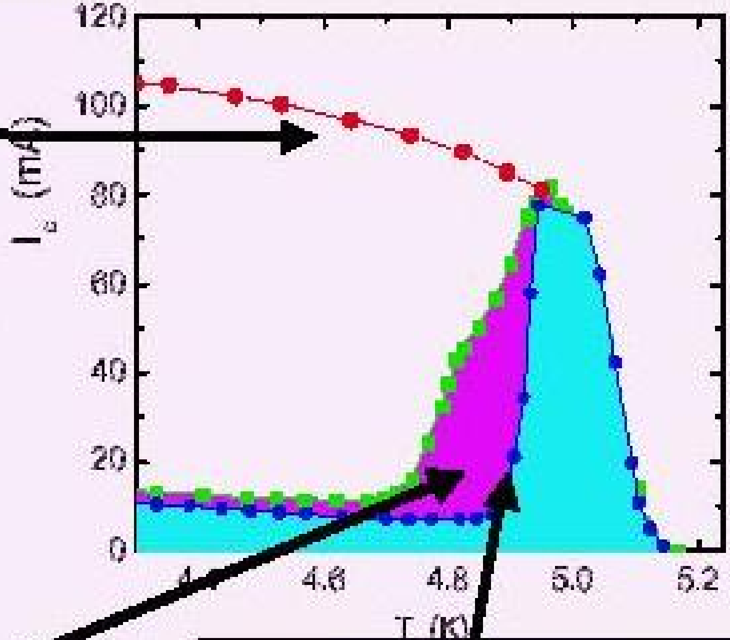
C- t=200• s $I_c = I_0$ channel of ordered vortices.

D-I t>200• s $I_c = I_0$ slope increases → ordered channel expands engulfing whole sample

SUMMARY-
DYNAMICS OF VORTICES +RANDOM POTENTIAL+BOUNDARIES

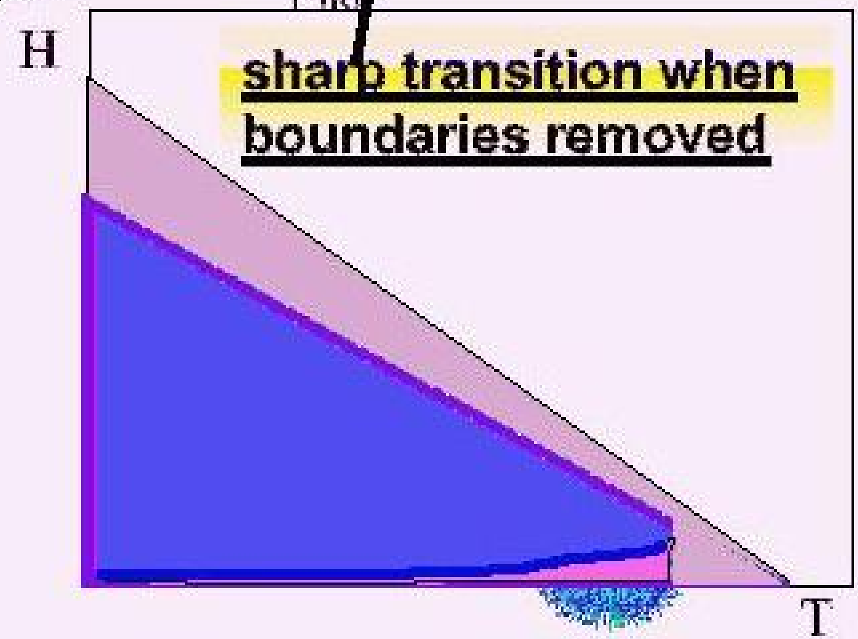
Metastable to stable transition





Dynamics of Mixed State

- Cyclic softening
- Jamming
- Frequency Memory



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