Dynamic Vortex Phases in Superconductors

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NSF Summer School on Superconductivity
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References

Driven Dynamics

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Spatially Resolved Dynamic Correlation in the Vortex State of High Temperature Superconductors
Daniel López, W. K. Kwok, H. Safar, R. J. Olsson, A. M. Petrean, L. Paulius, and G. W. Crabtree
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G. W. Crabtree, D. Lopez, W. K. Kwok, H. Safar, and L. M. Paulius
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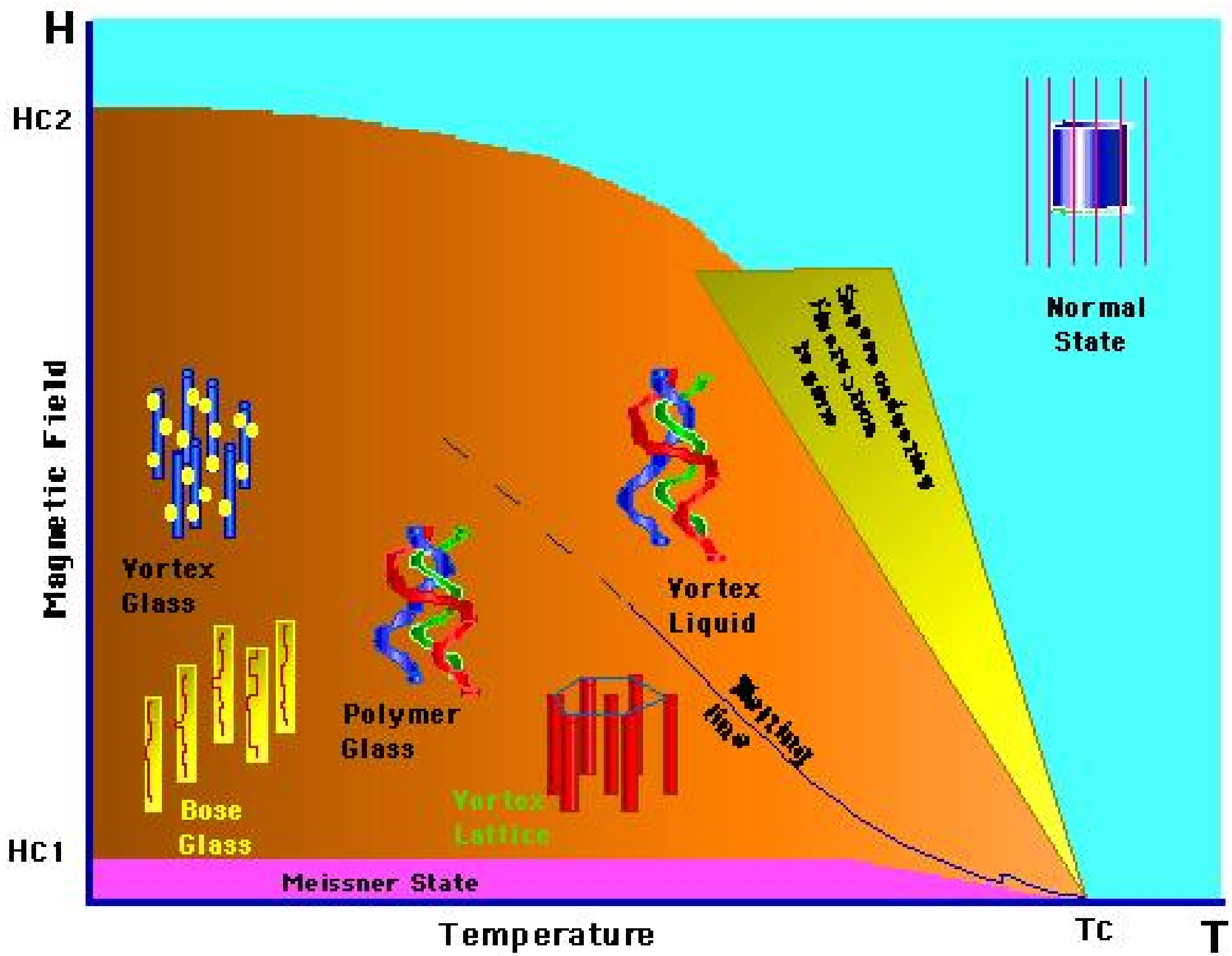
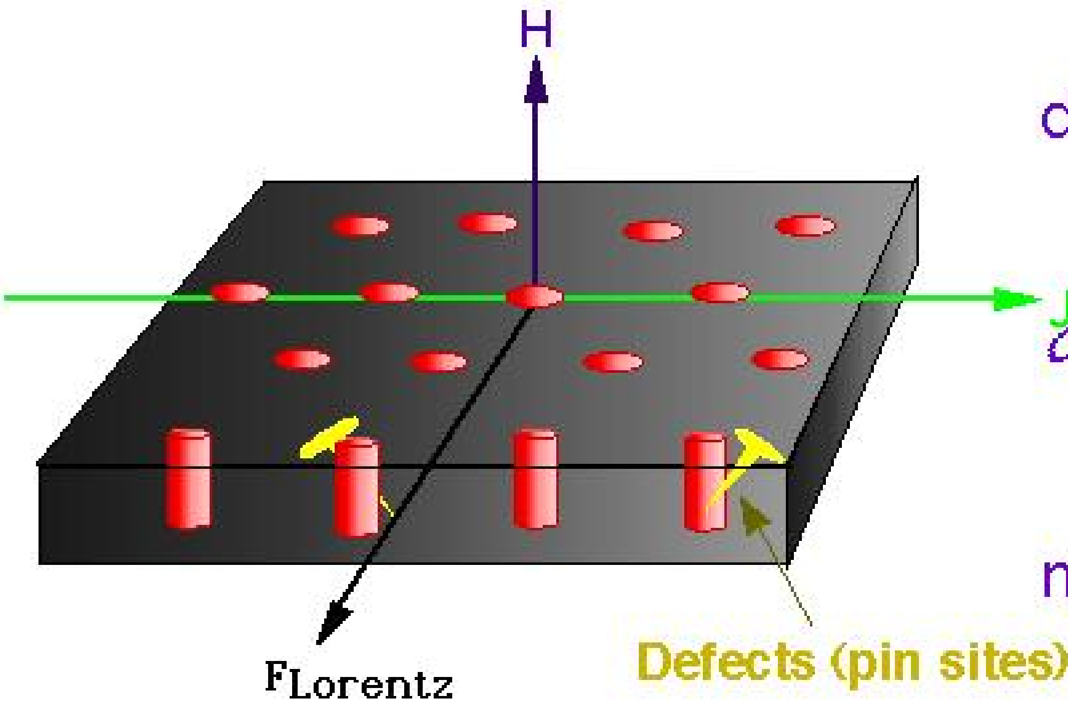
Numerical Simulations of Driven Vortex Systems
G. W. Crabtree, D. O. Gunter, H. G. Kaper, A. E. Koshelev, G. K. Leaf, and V. M. Vinokur
Phys. Rev. B **61**,1446 (2000)

Vortex Matter Equilibrium Phase Diagram



Dynamic Phases



distinct steady states
plastic/elastic

dynamic phase transitions
de-pinning transition

motion → dissipation
no energy conservation
no thermodynamics

basic science: non-linear dynamics

applications: control vortex motion

Dynamic Behavior

dynamic phases

liquid $\rightarrow$ vortex hydrodynamics

solid $\rightarrow$ elastic: same neighbors

plastic: different neighbors

non-linear dynamics

avalanches, chaotic motion, turbulenc

controlled disorder due to pinning defects

depinning at onset of motion

$\rightarrow$ rich dynamic phase diagram

$\rightarrow$ access many dynamic limits

Equilibrium and Dynamic Phases

STATIC VARIABLES

thermal energy (temperature)

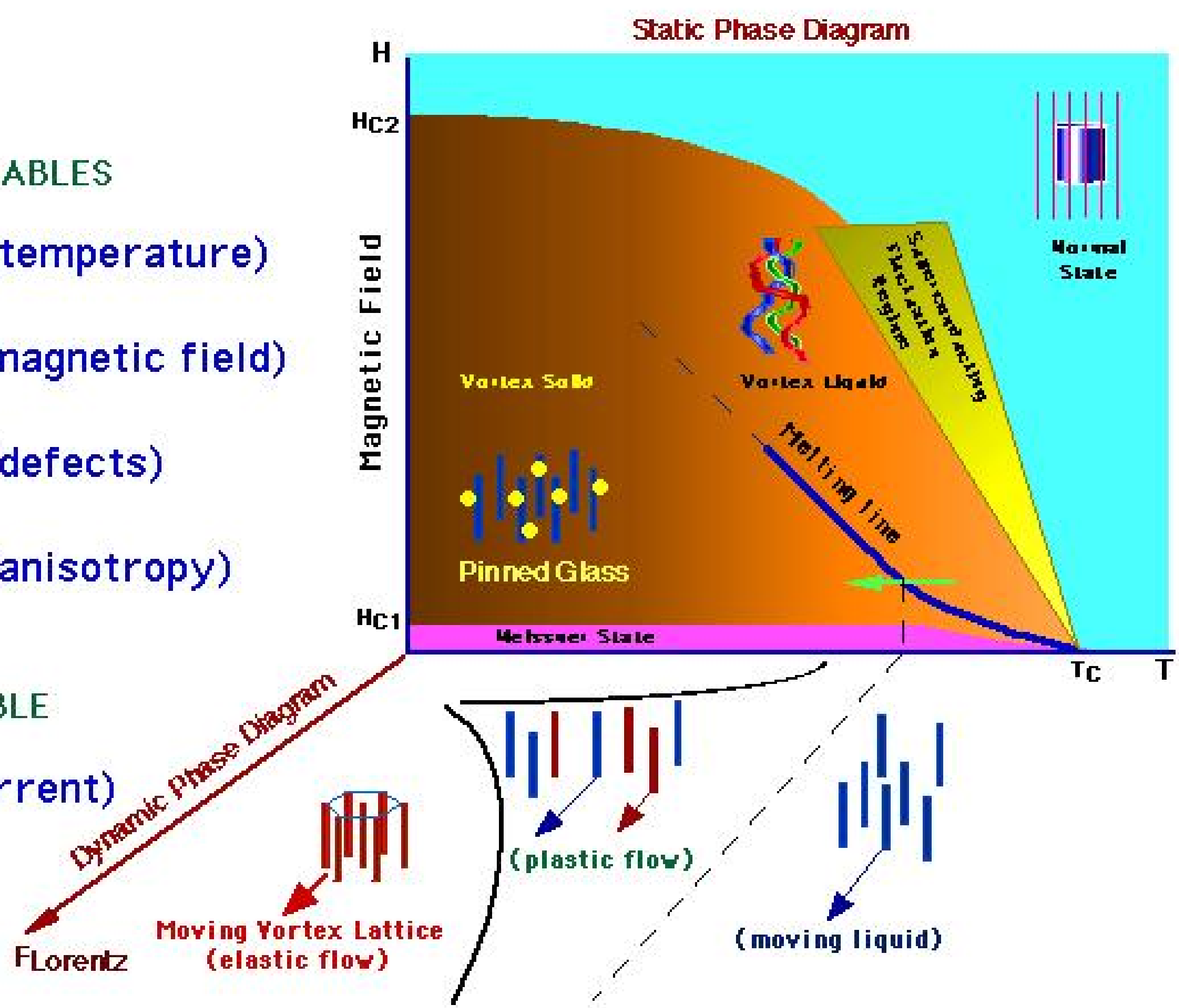
vortex interaction (magnetic field)

pinning energy (defects)

coupling energy (anisotropy)

DYNAMIC VARIABLE

Lorentz force (current)



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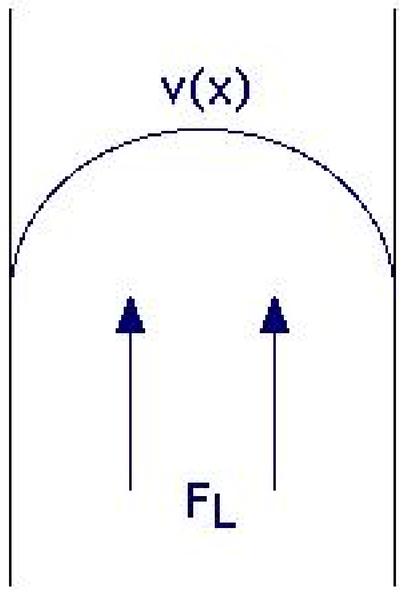
Liquid



continuous velocity profile

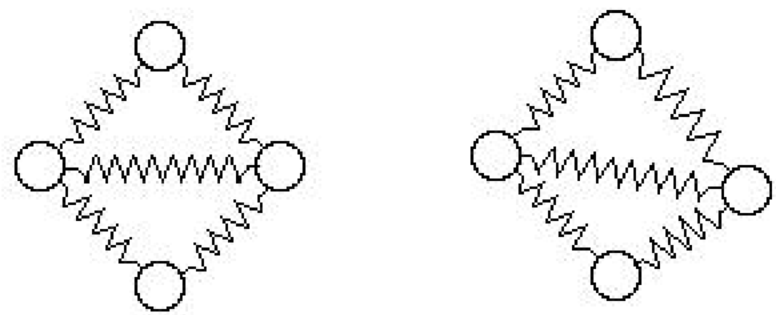
controlled by viscosity/friction

$\rightarrow$ hydrodynamics

Solid

viscosity $\rightarrow$ shear modulus

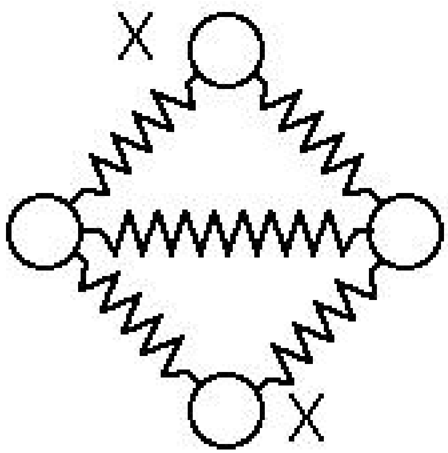
new elastic energy of deformation



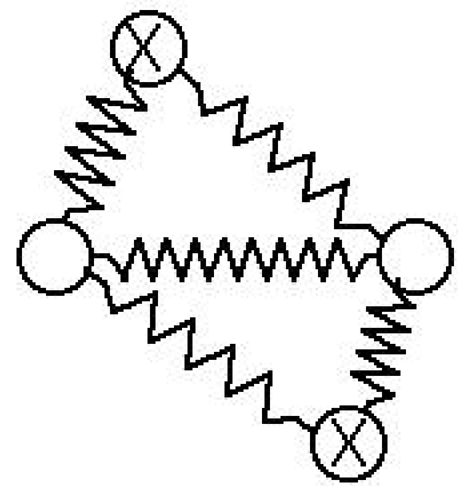
constraint on motion:

don't stretch the springs

Statics
Elastic Coupling and Pinning

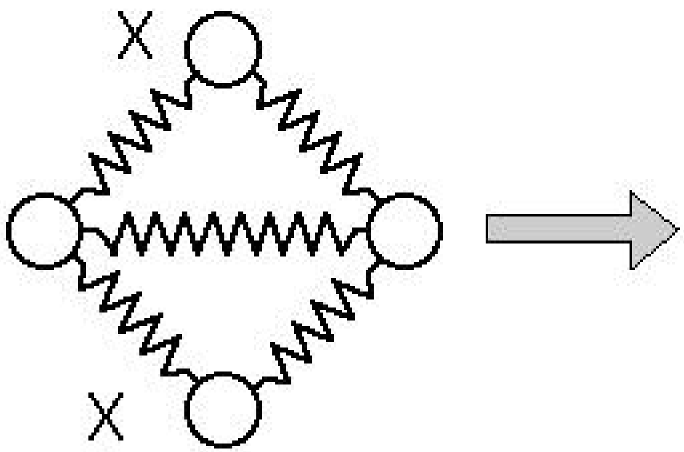


strong shear modulus
→ weak pinning

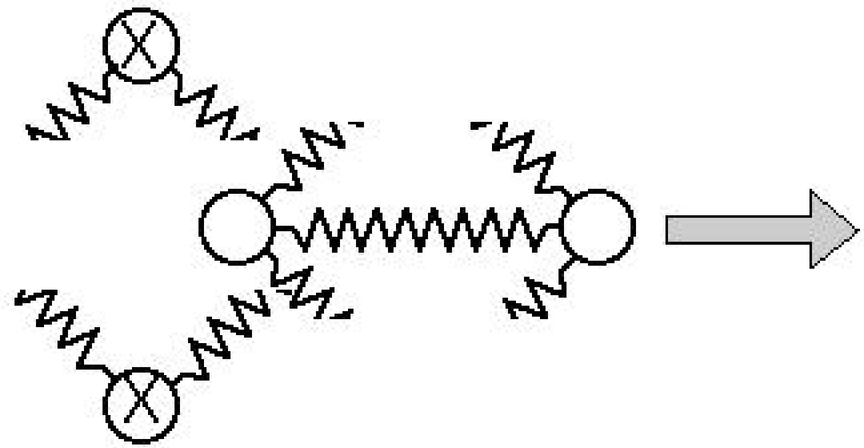


weak shear modulus
→ strong pinning

Dynamics
Elastic Coupling and Motion



strong shear modulus
→ elastic flow

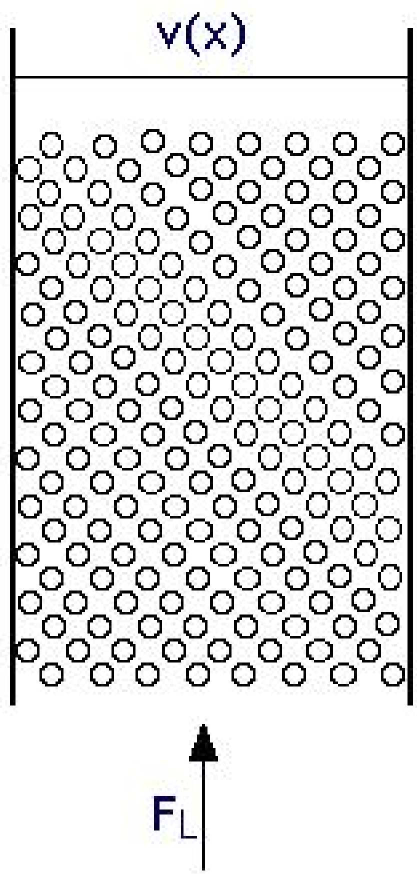


weak shear modulus
→ plastic flow

Dynamic Solid Phases

elastic flow

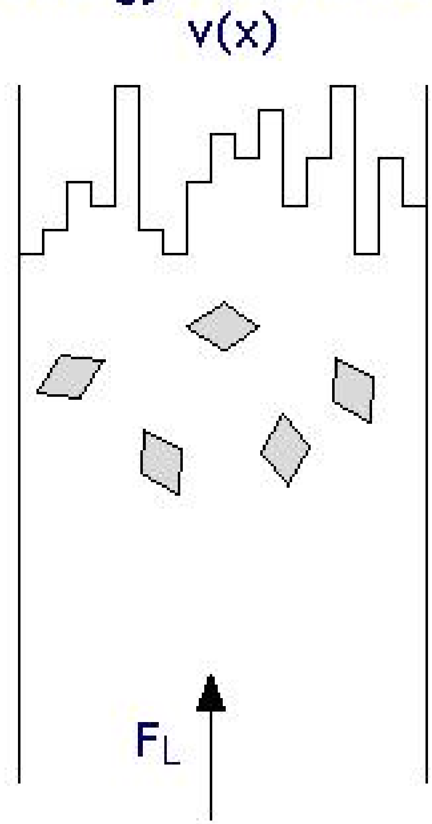
elastic energy minimized globally



motion of a single elastic object

plastic flow

elastic energy minimized locally



motion of several elastic objects

discontinuous velocity profile

Numerical Simulations of Driven Vortex Systems

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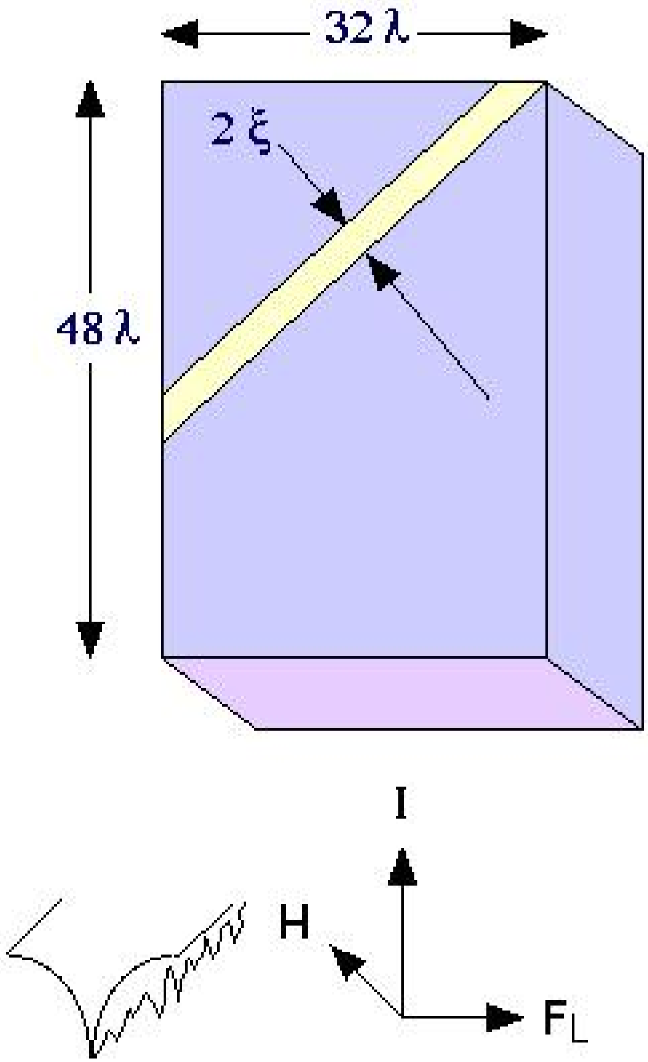
Planar Defect Simulation

twin boundary in YBCO



twin boundary: random pinning
in band of width 2 ξ

no pinning elsewhere

no thermal flucuations
→ vortex solid

$\kappa = \lambda/\xi = 4$

boundary conditions

along I: periodic

along F_L : $\mathbf{J} \cdot \mathbf{n} = 0$

along H: infinite and homogeneous

Ginzburg-Landau Model

- Order parameter, ψ; vector potential, $\mathbf{A}$
- $\mathbf{B} = \nabla \times \mathbf{A}$, $\mathbf{E} = -\dfrac{\partial \mathbf{A}}{\partial t}$, $\nabla \times \mathbf{B} = -\sigma \dfrac{\partial \mathbf{A}}{\partial t} + \mathbf{J}_s$
- Superelectron density, $n_s = |\psi|^2$
- Supercurrent

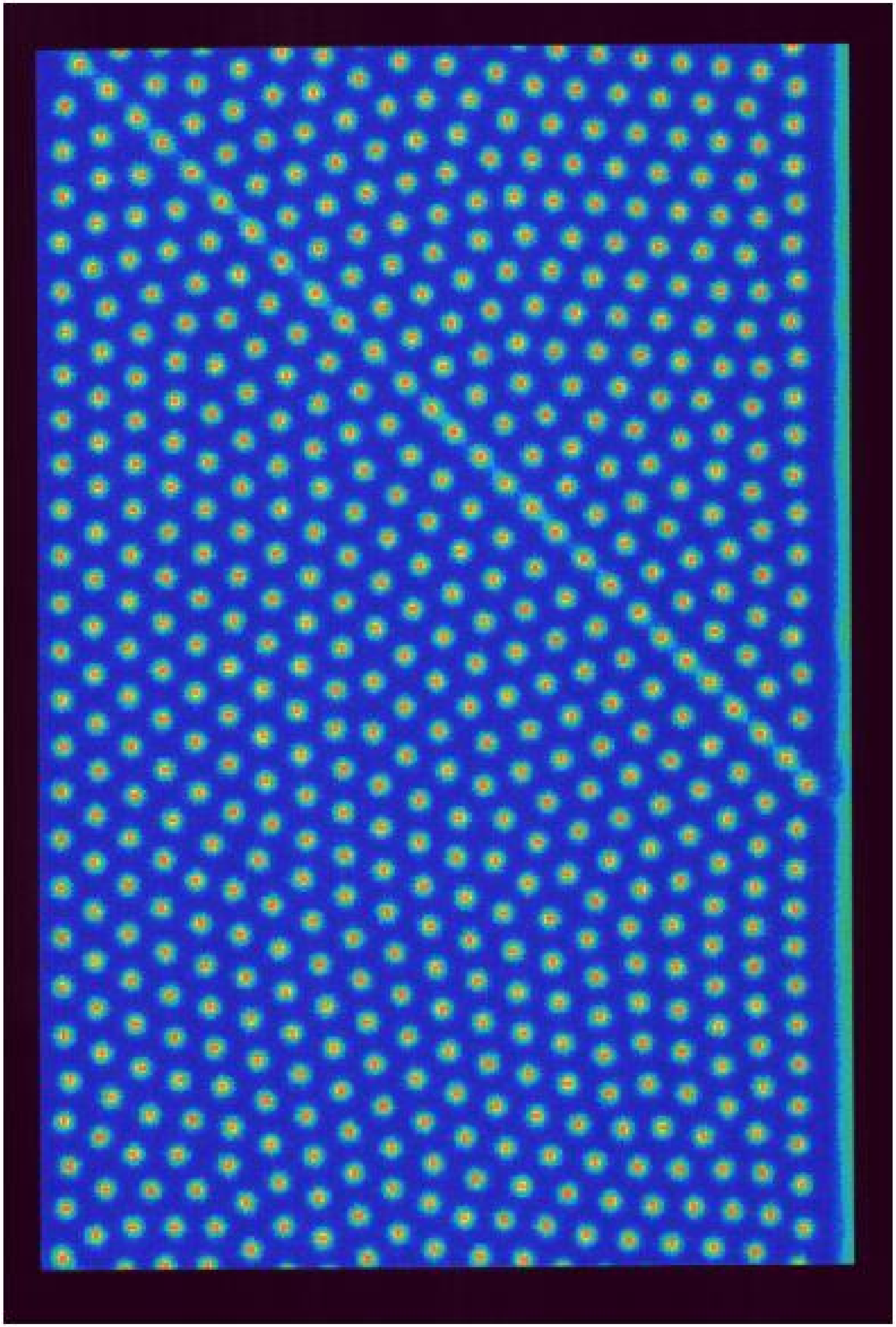
$$\mathbf{J}_s = \frac{1}{2i\kappa}\left(\psi^* \nabla \psi - \psi \nabla \psi^*\right) - |\psi|^2 \mathbf{A}$$

- Free energy density, GL approximation

$$\mathcal{L}[\psi, \mathbf{A}] = -|\psi|^2 + \frac{1}{2}|\psi|^4 + \left|\left(\frac{1}{i\kappa}\nabla - \mathbf{A}\right)\psi\right|^2 + |\nabla \times \mathbf{A}|^2$$

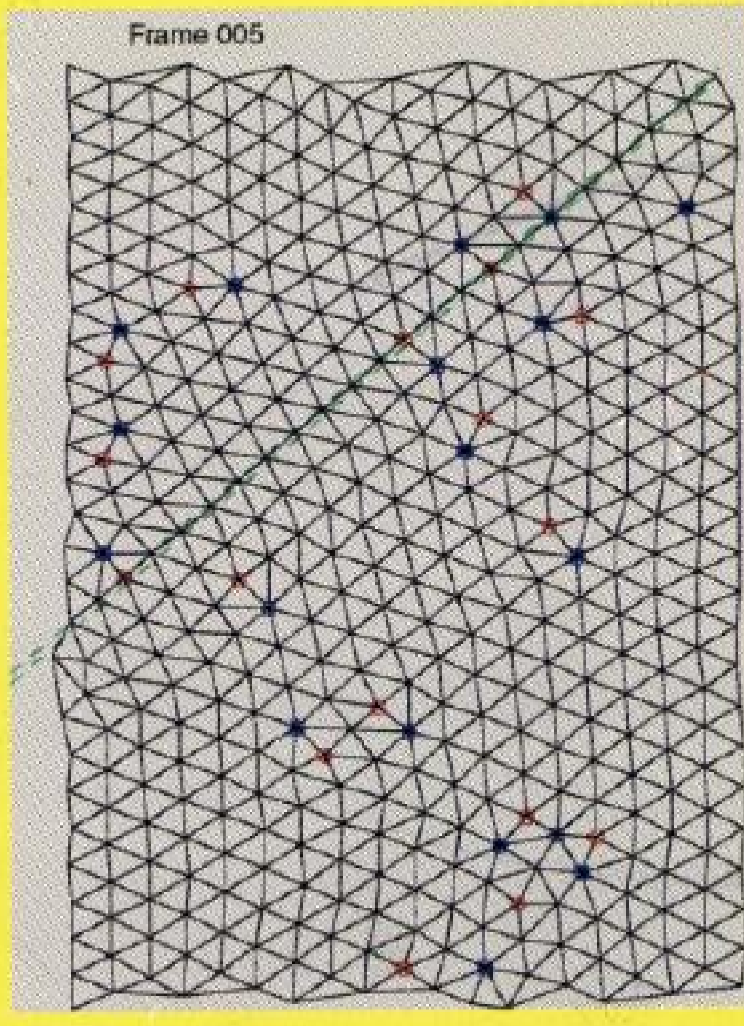
- Time-dependent GL model

$$\frac{\partial \psi}{\partial t} = -\frac{\delta \mathcal{L}}{\delta \psi^*}, \quad \sigma \frac{\partial \mathbf{A}}{\partial t} = -\frac{1}{2}\frac{\delta \mathcal{L}}{\delta \mathbf{A}}$$

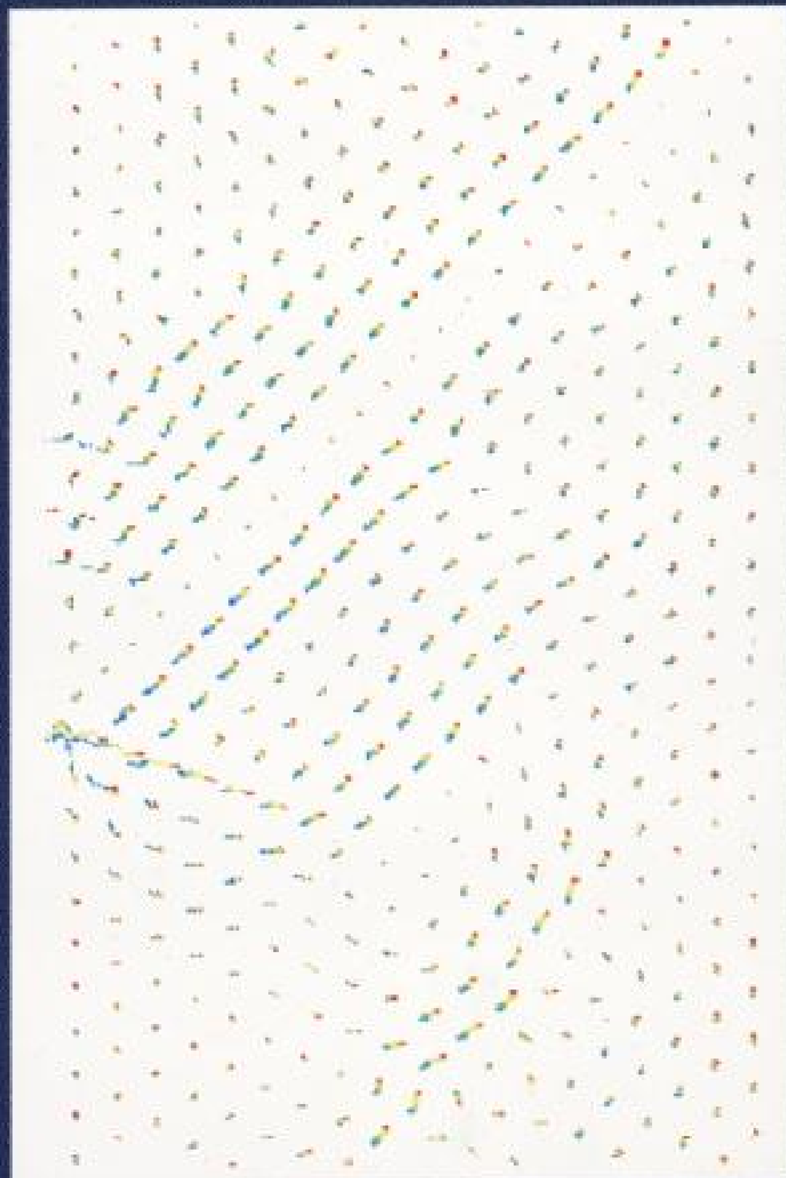


Weak Current – With TB

Dislocation Pattern

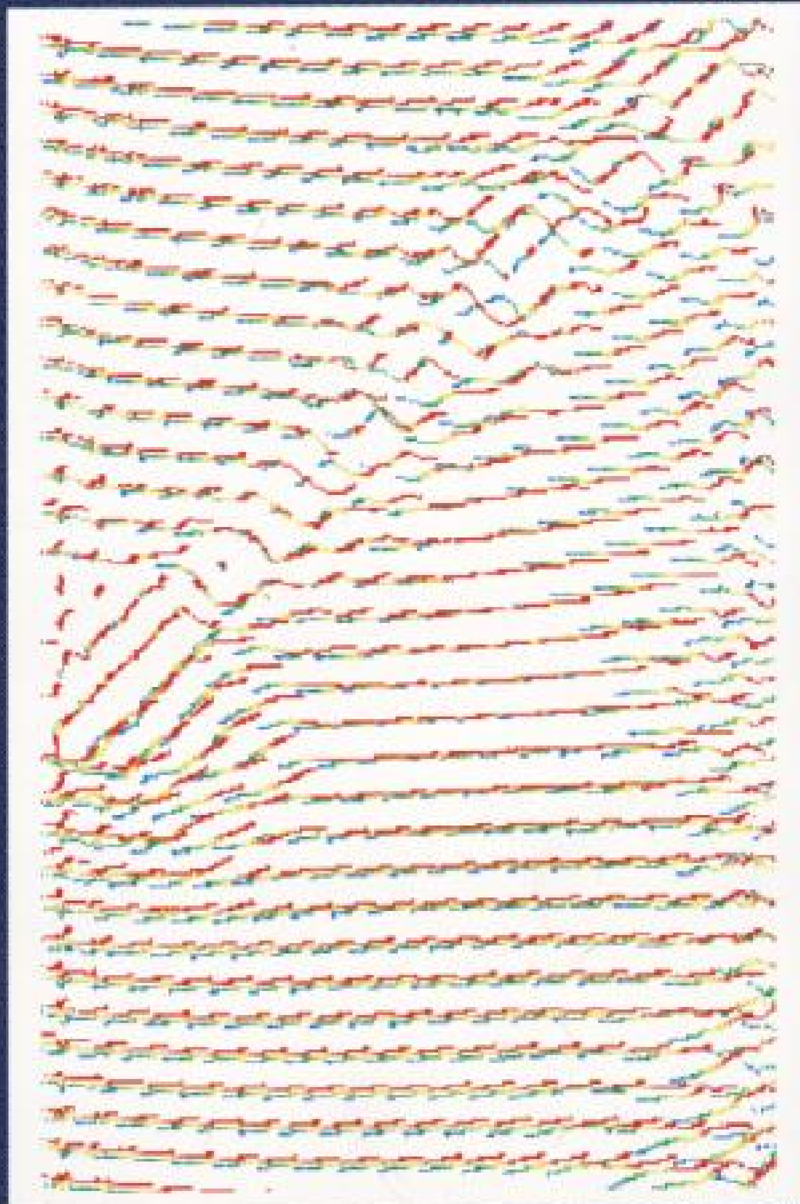


Vortex Trajectories



With TB – Weak Current

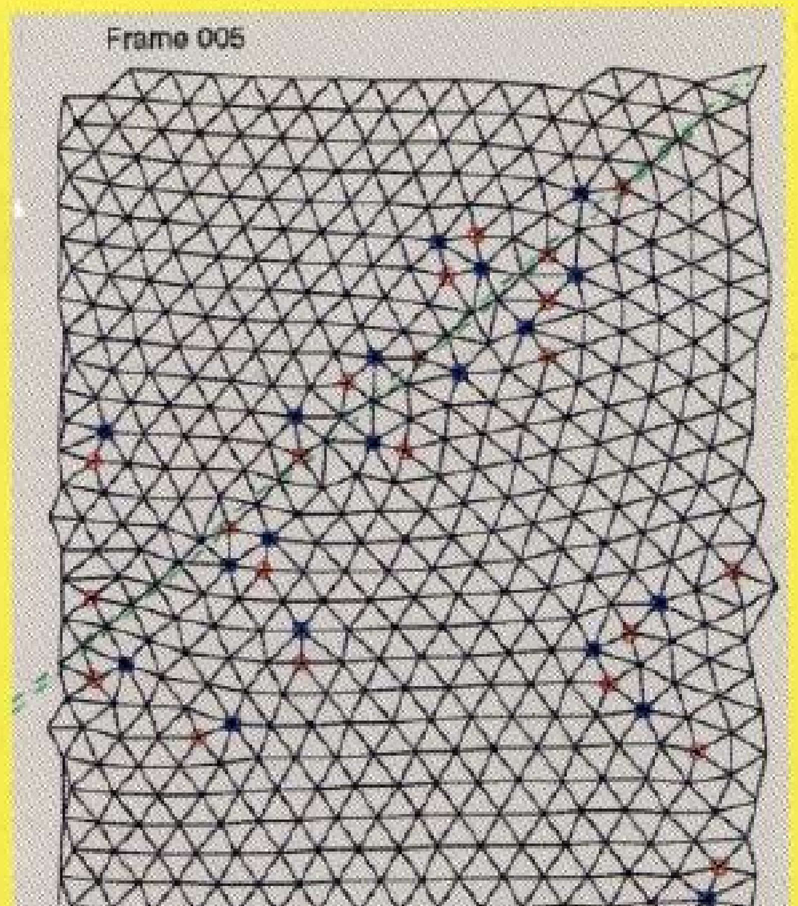
Vortex Trajectories



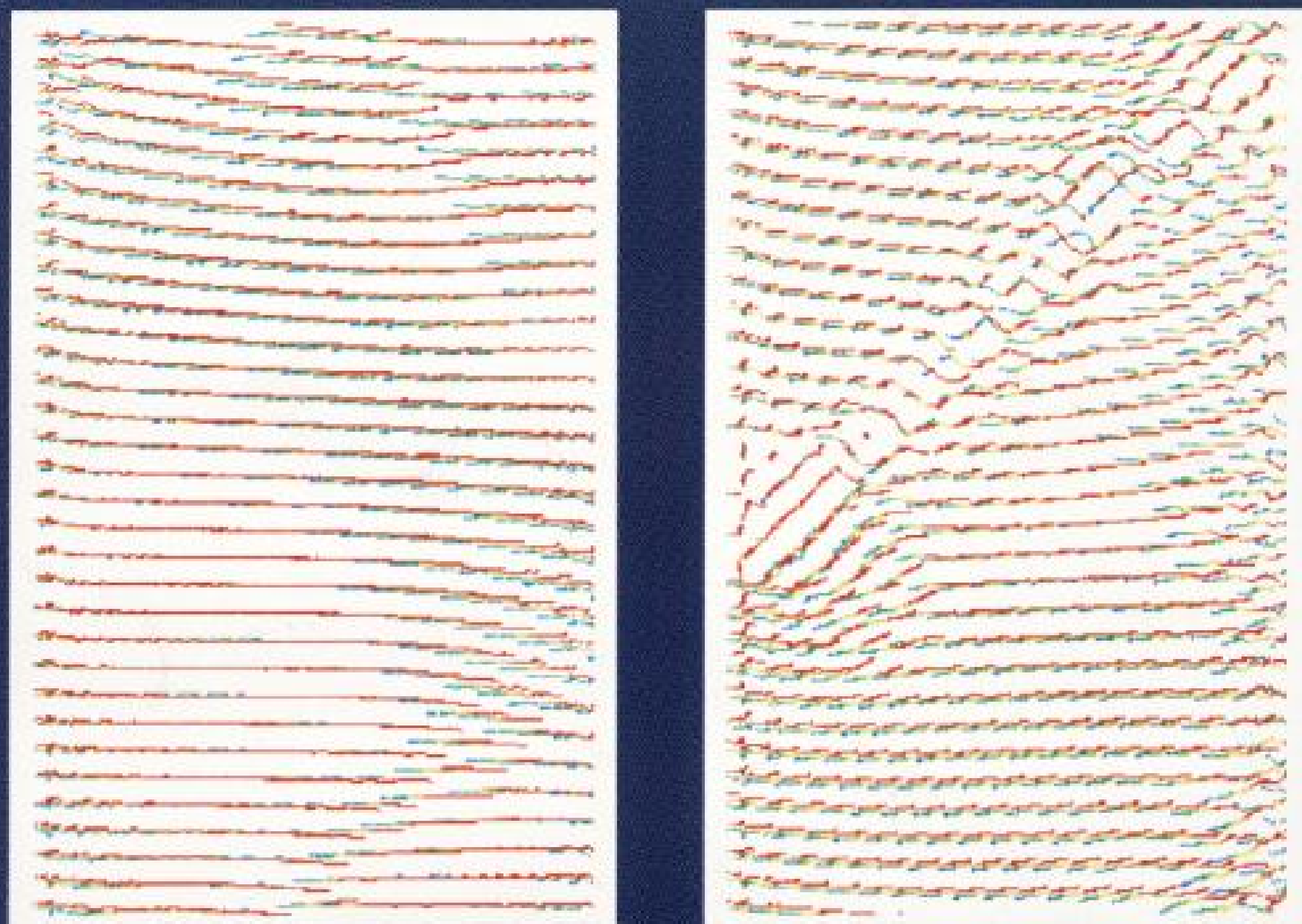
With TB – Intermediate Current

Intermediate Current – With TB

Dislocation Pattern



Vortex Trajectories
Intermediate Current



No TB With TB

(Partial) Vortex Trajectories
Strong Current

No TB

With TB

Types of Vortex Motion

correlated plastic	*uncorrelated plastic*	*elastic*
Lorentz < pinning force	*Lorentz ~ pinning force*	*Lorentz force dominant*
discontinuities in $\|\mathbf{v}\|, \hat{\mathbf{v}}$		**$\mathbf{v}$ continuous**
$a_o < l_{\text{v-corr}} < l_{\text{struct-corr}}$	$l_{\text{v-corr}}$, $l_{\text{struct-corr}} < a_o$	$l_{\text{v-corr}}$, $l_{\text{struct-corr}} \to \infty$
$\hat{\mathbf{v}}$ determined by local structure	**$\hat{\mathbf{v}}$ random**	**$\hat{\mathbf{v}}$ determined by Lorentz force**

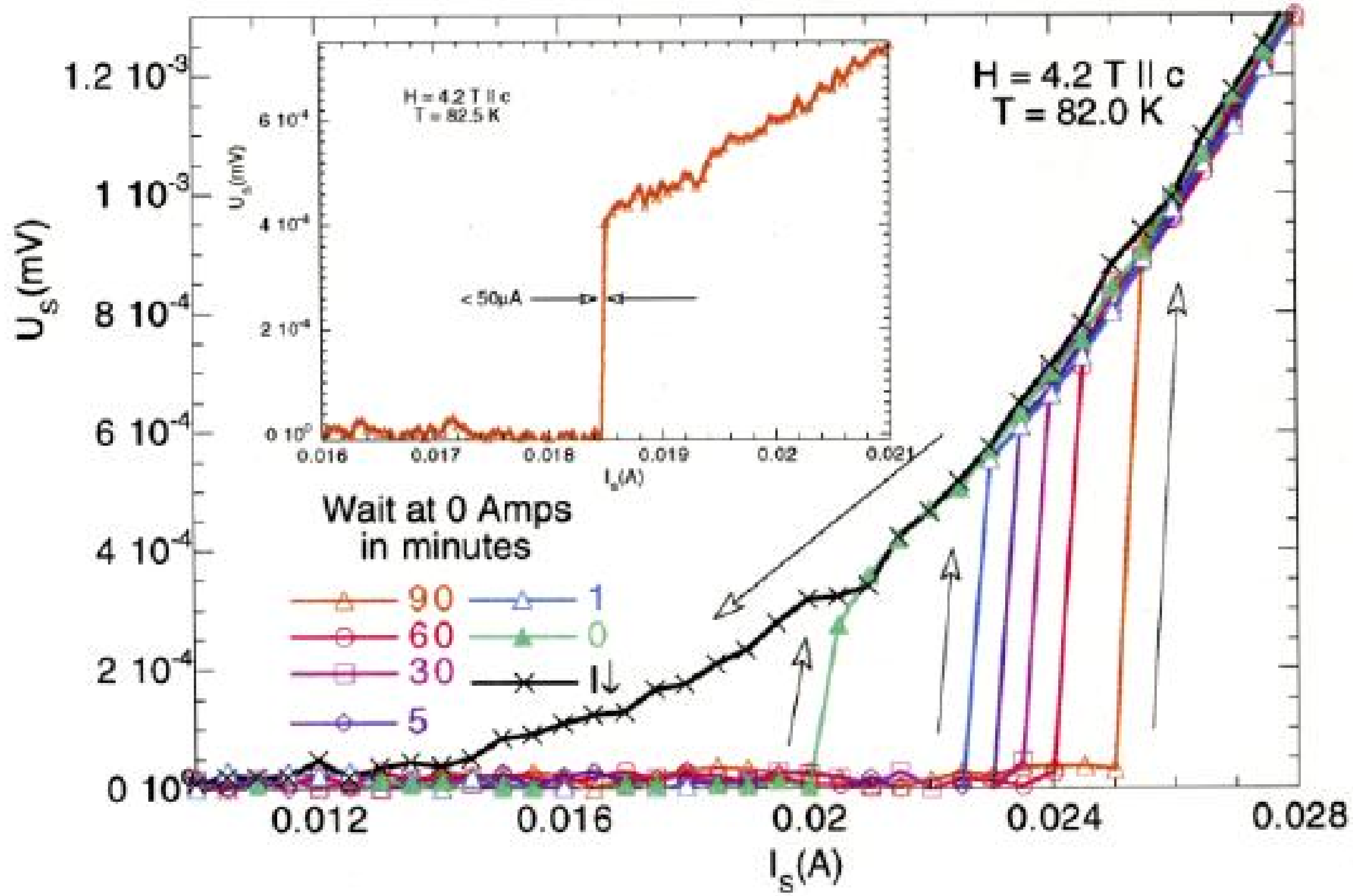
Symmetry in Dynamic Phases

elastic	translational periodicity hexatic orientational order
correlated plastic	hexatic orientational order
uncorrelated plastic	none

dynamic phases defined by symmetry

$\rightarrow$ dynamic phase transitions

"First Order" Dynamic Transitions in the Vortex Solid



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Phys Rev Letters **77**, 2073 (1996)

Dynamic Correlation in Vortex Liquids and Lattices

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outline

driven flow in vortex liquid/solid phases

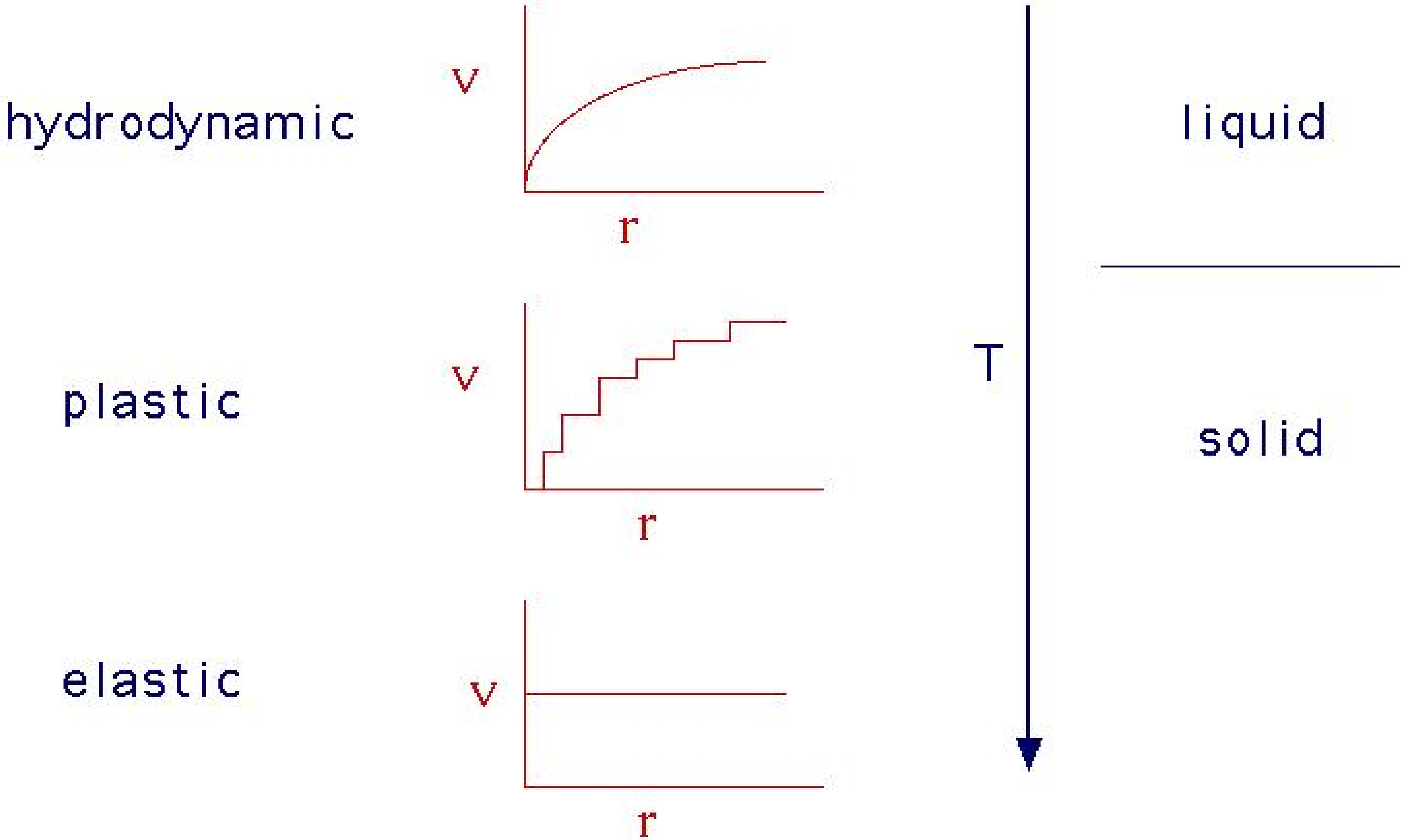
experiment: controlled gradient transport

dynamic correlation in YBCO

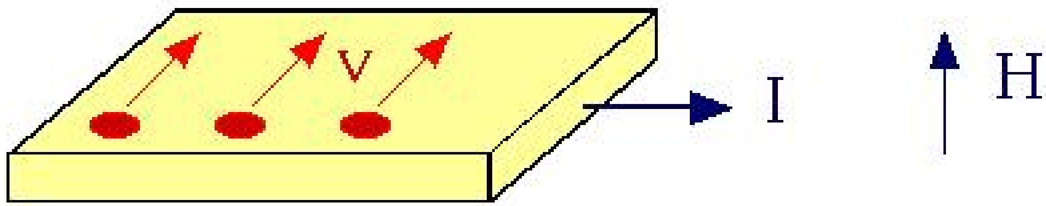
hydrodynamic, elastic, plastic flow

Distinguishing Dynamic States

key feature: velocity profile



Conventional Transport

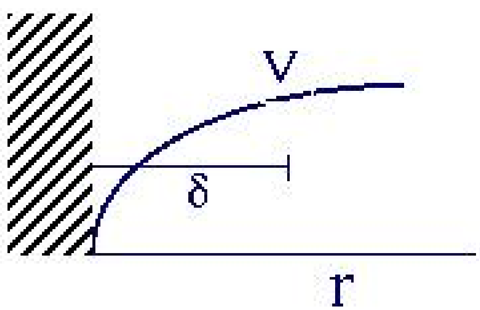


- uniform current density → uniform driving force

  → uniform vortex velocity

  no velocity gradients → cannot distinguish dynamic states

- boundary conditions → velocity profile



resolve v(r) near boundary → δ

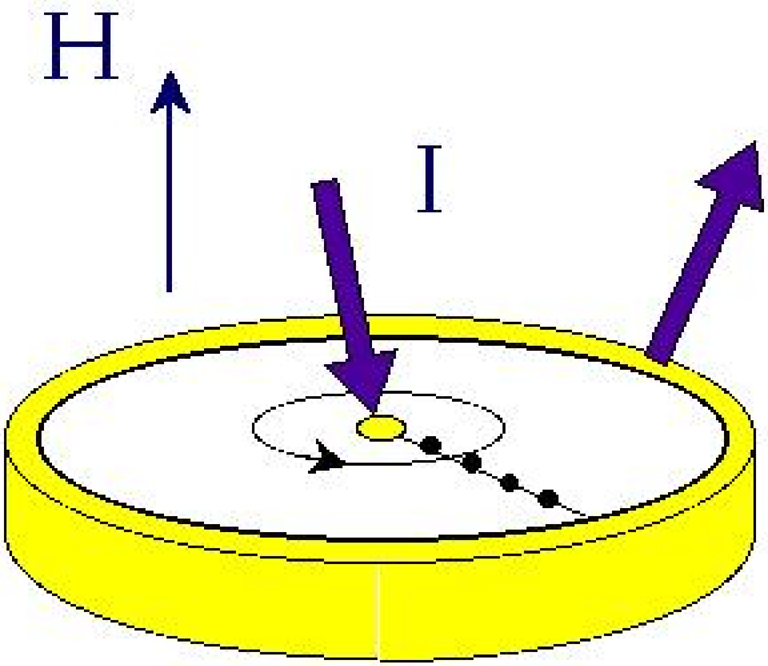
δ diverges at second order glass transition

Marchetti and Nelson PRB (1999)

Controlled Gradient Transport

apply inhomogeneous current

→ measure induced velocity profile



radial current density

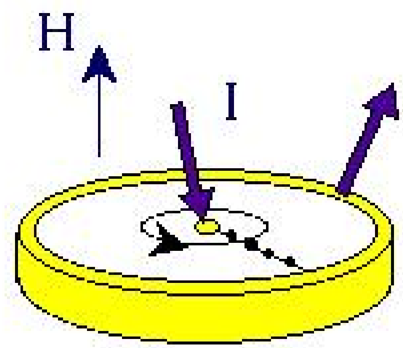
$j(r) = I\,/\,2\pi\, t\, r$

→ Lorentz force gradient

measure voltage along radius

→ sample velocity profile

Velocity Profiles



normal state: Ohm's law

$$E(r) = \rho\, J(r) \sim \rho/r$$

$$V = \int E(r)\, dr \sim \rho \ln r$$

vortex liquid state:

$$\mathbf{E}(r) = \mathbf{B} \times \mathbf{v}/c$$ Faraday/Josephson

$$-\gamma\, \mathbf{v} + \eta\, \nabla^2 \mathbf{v} + \mathbf{F}_L = 0$$ hydrodynamics

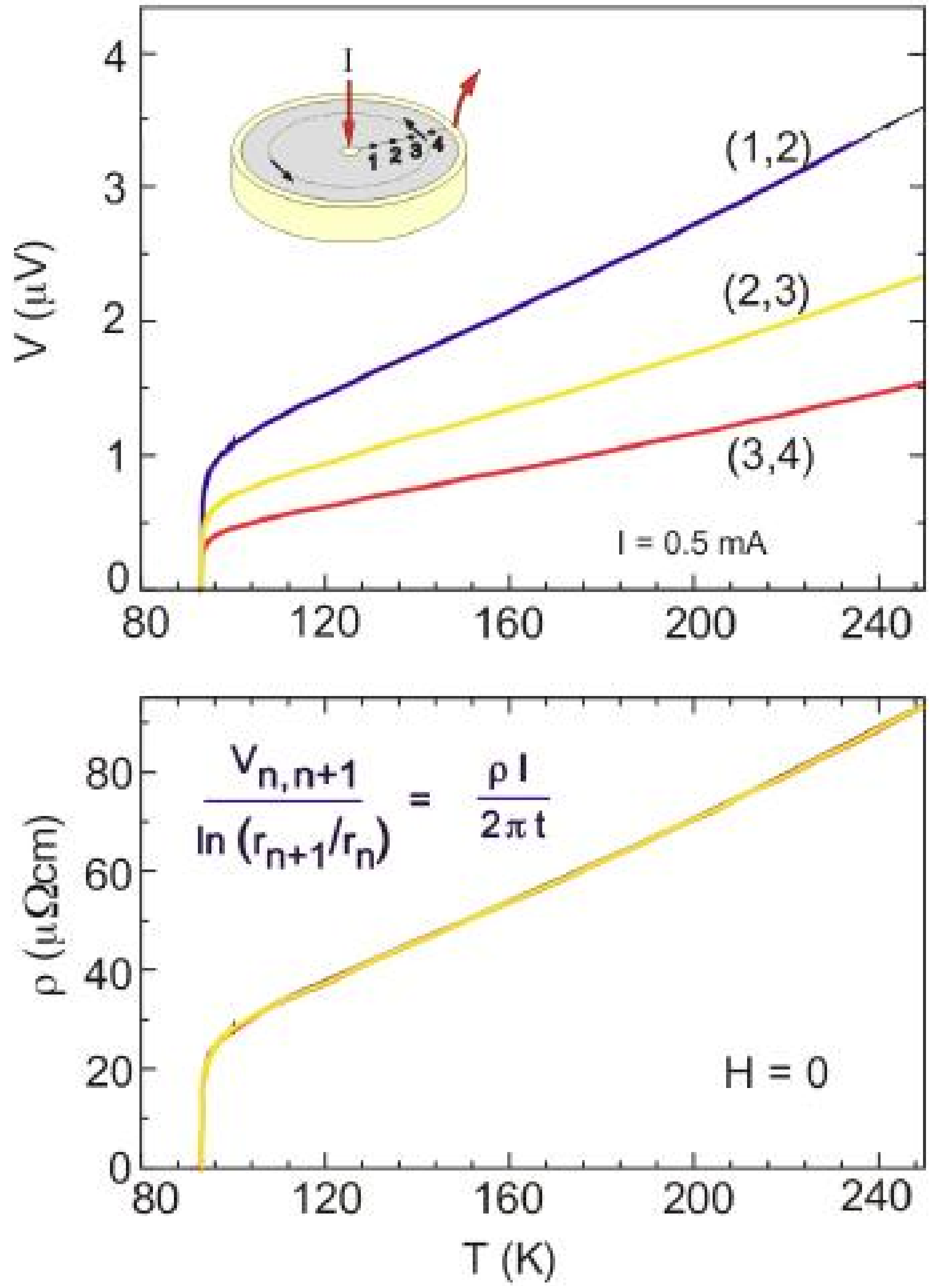
far from boundaries: $F_L \sim 1/r \;\rightarrow\; v \sim 1/r$

$$\rightarrow \; E \sim B\; v/c \sim 1/r$$

$$V = \int E(r)\, dr \sim \rho_f \ln r$$

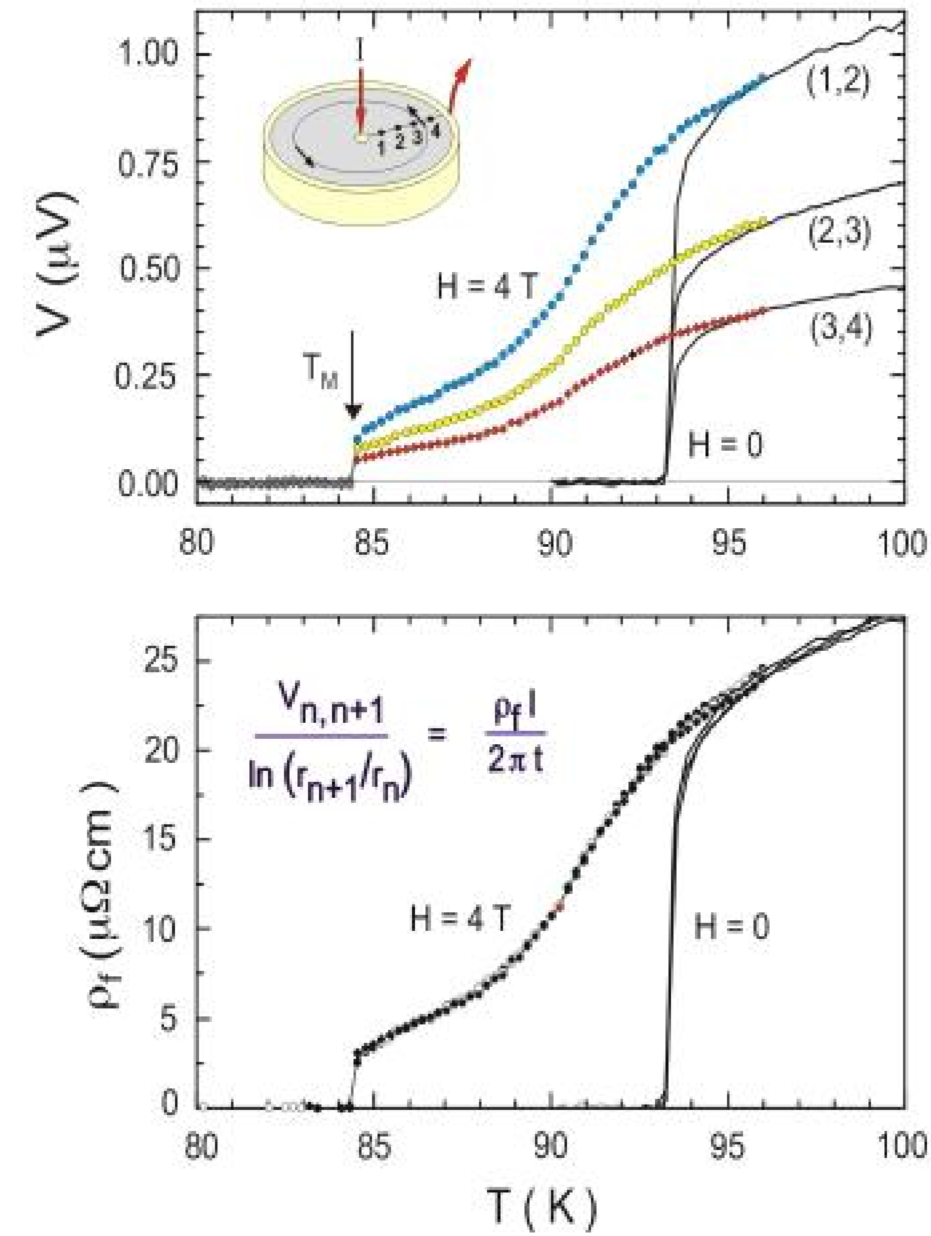
Normal Metal

Ohm's law

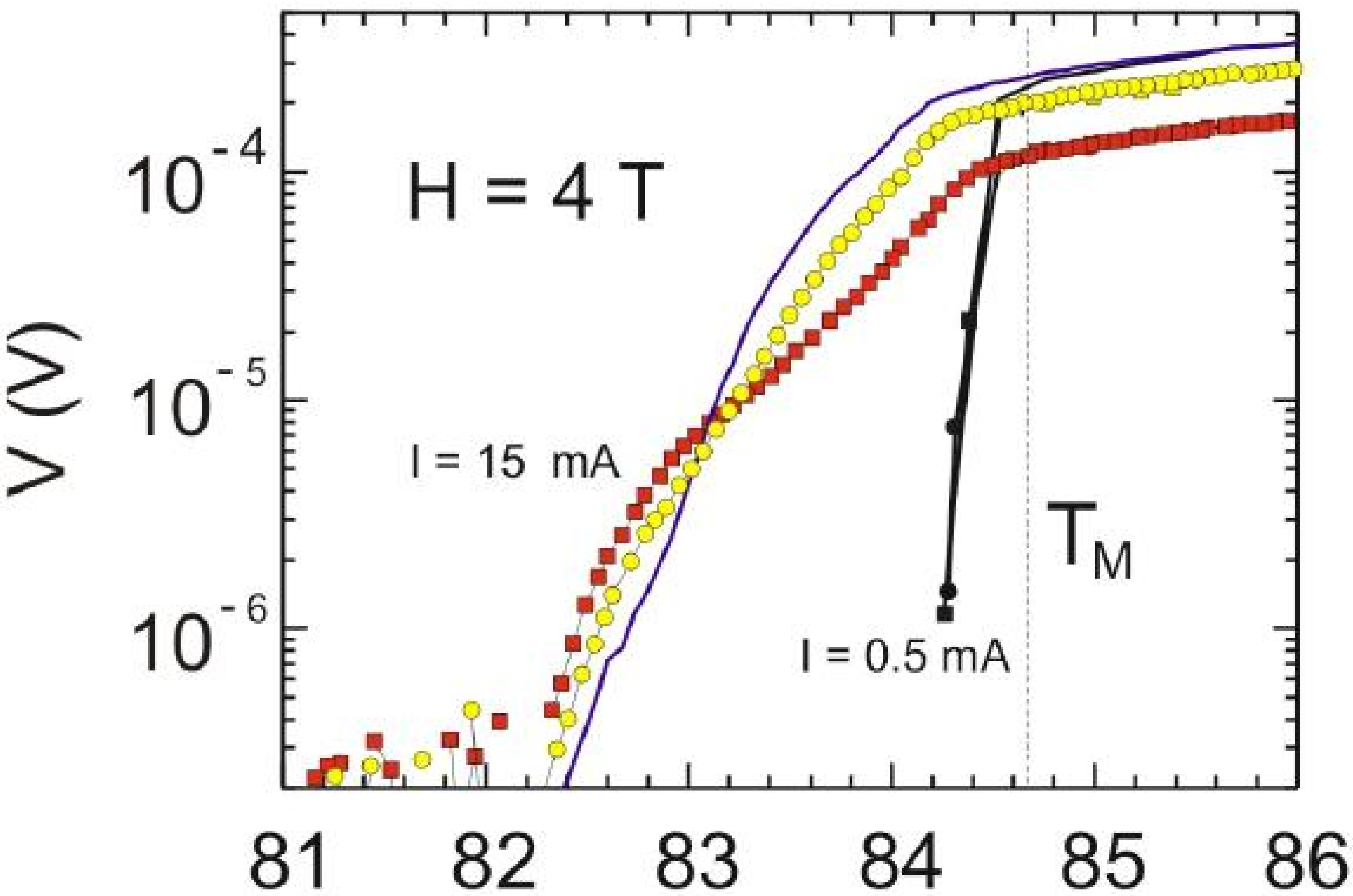


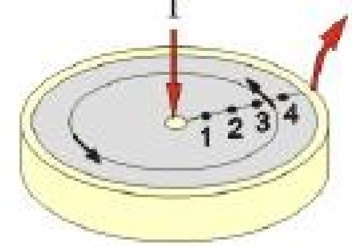
Vortex Liquid

hydrodynamic scaling



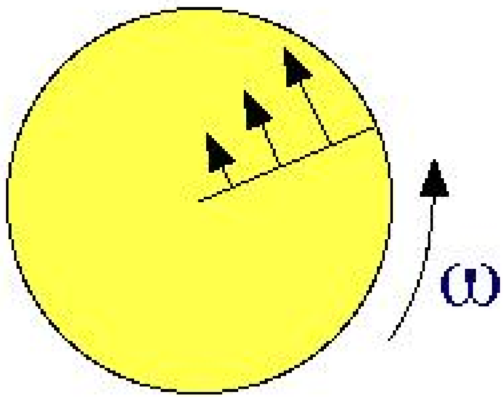
Vortex Lattice





velocity profile reverses

Vortex Lattice Rotation



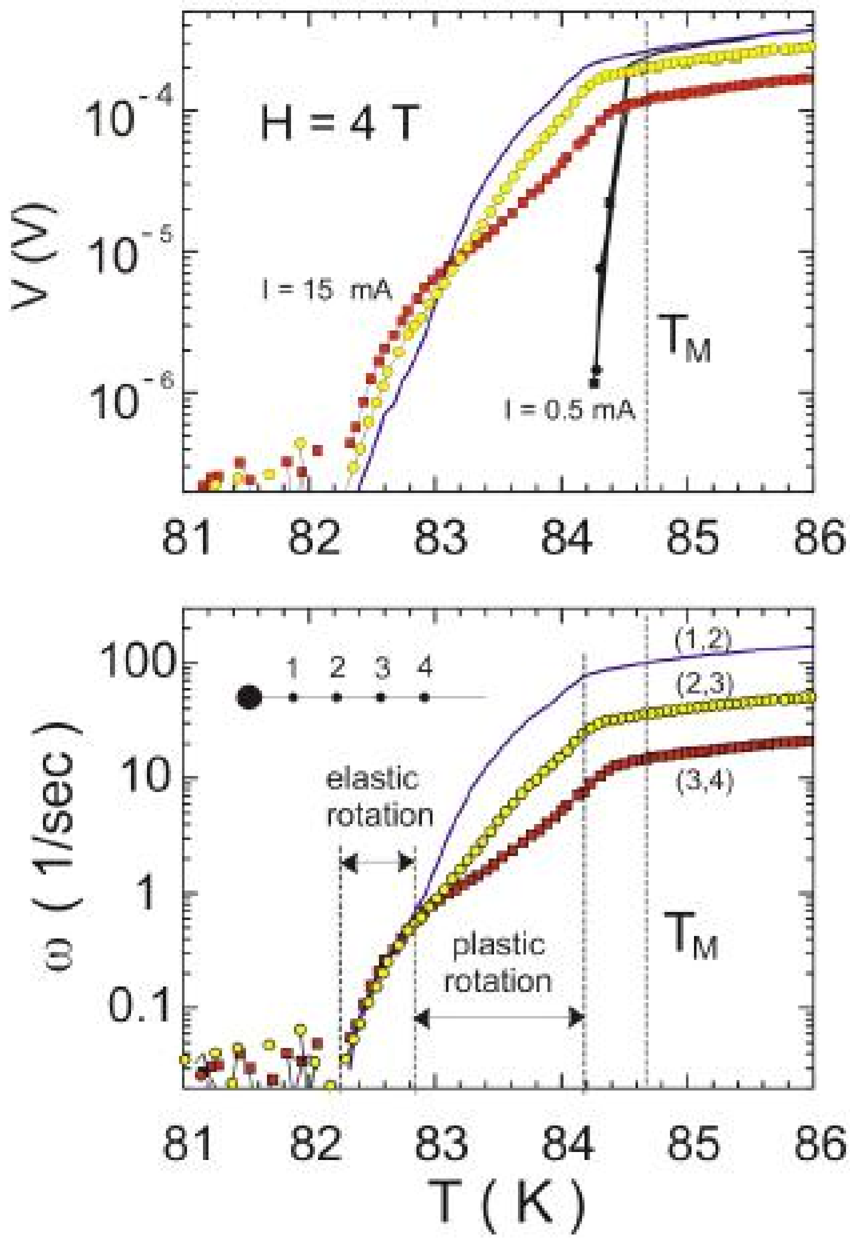
$$v(r) = \omega\, r$$

$$E(r) = B\, v(r)/c \;=\; (\omega B/c)\, r$$

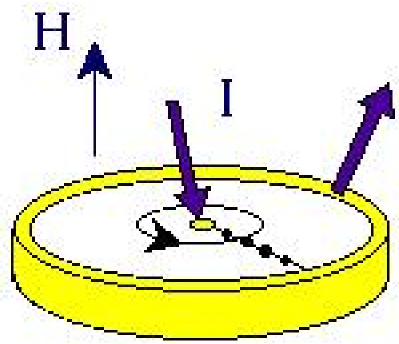
$$V = \int E(r)\, dr \;\sim r^2$$

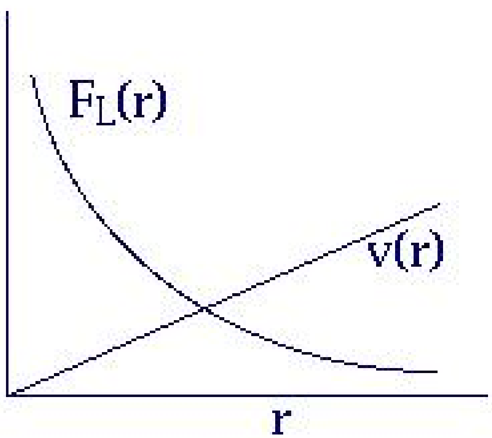
Vortex Lattice

rotational scaling $v = \omega r$

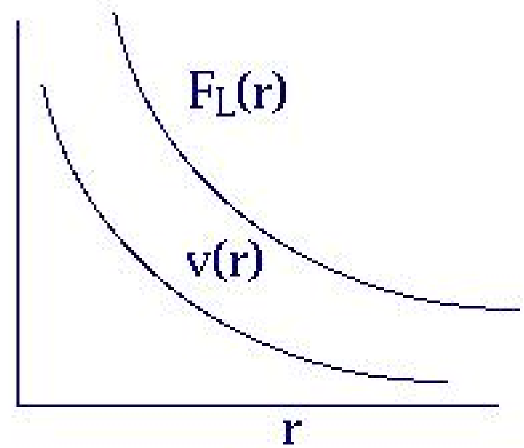


Shear Induced Slip





lattice

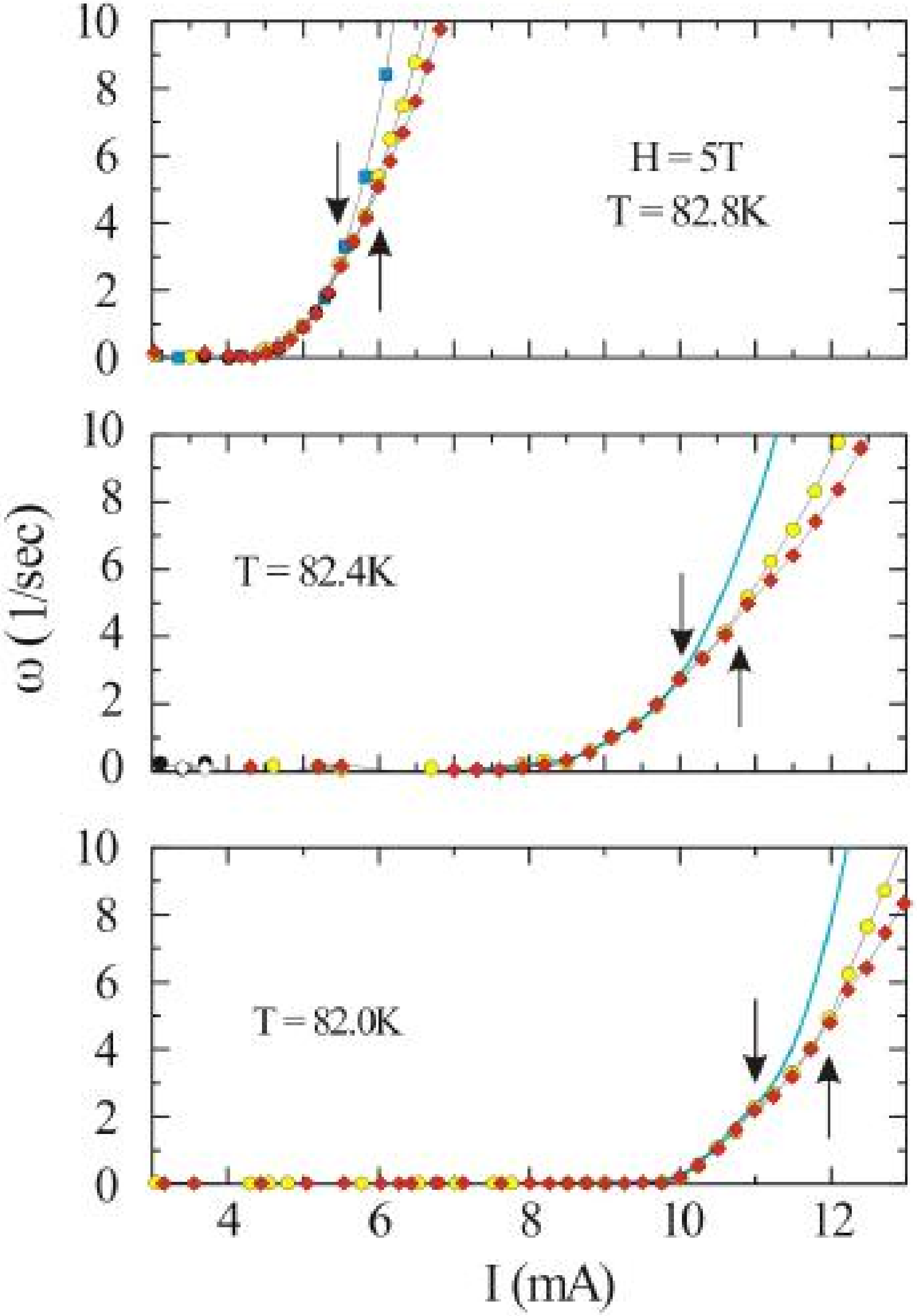


liquid

high drive $\rightarrow$ shear the lattice

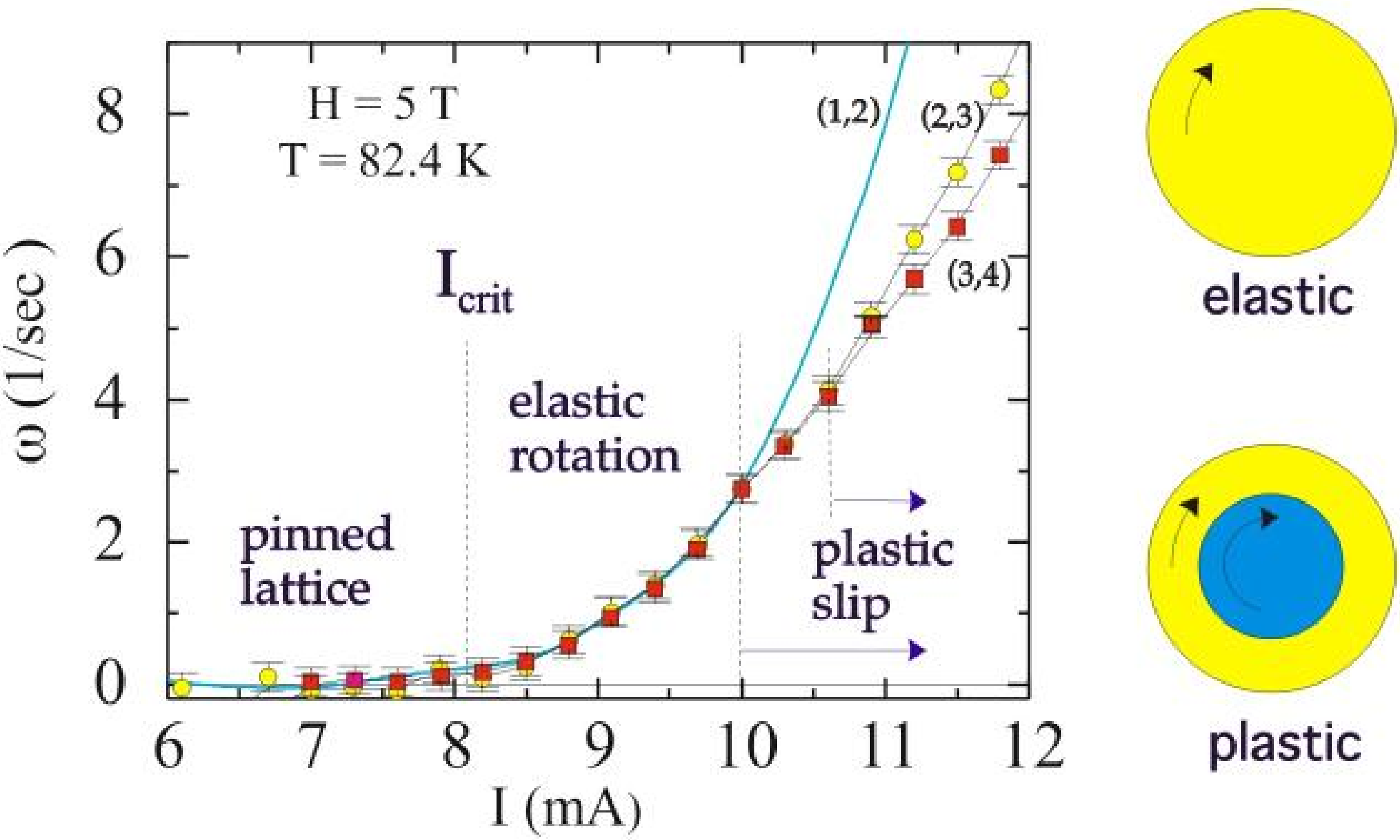
Vortex Lattice

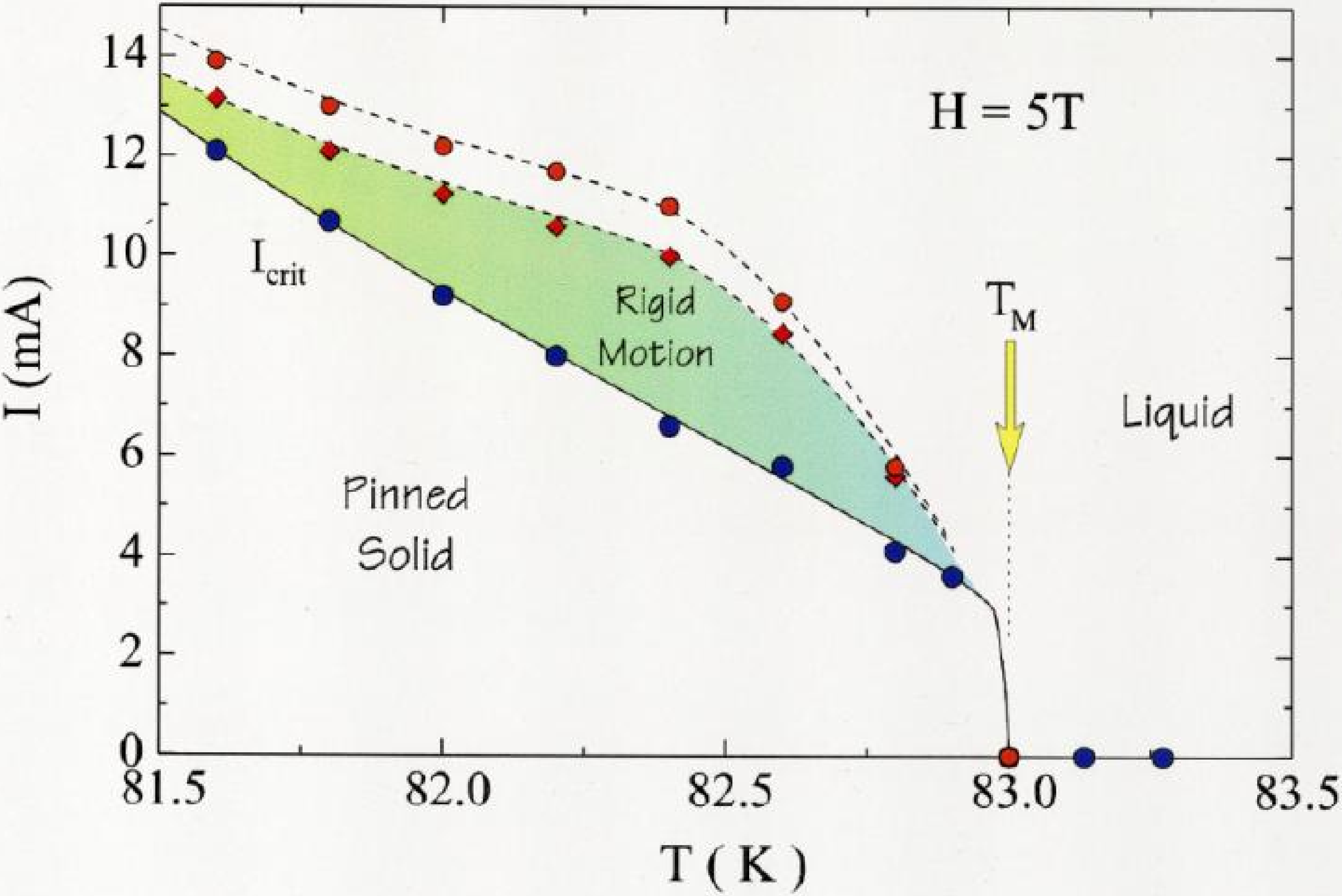
elastic depinning
shear induced plastic slip



Vortex Lattice

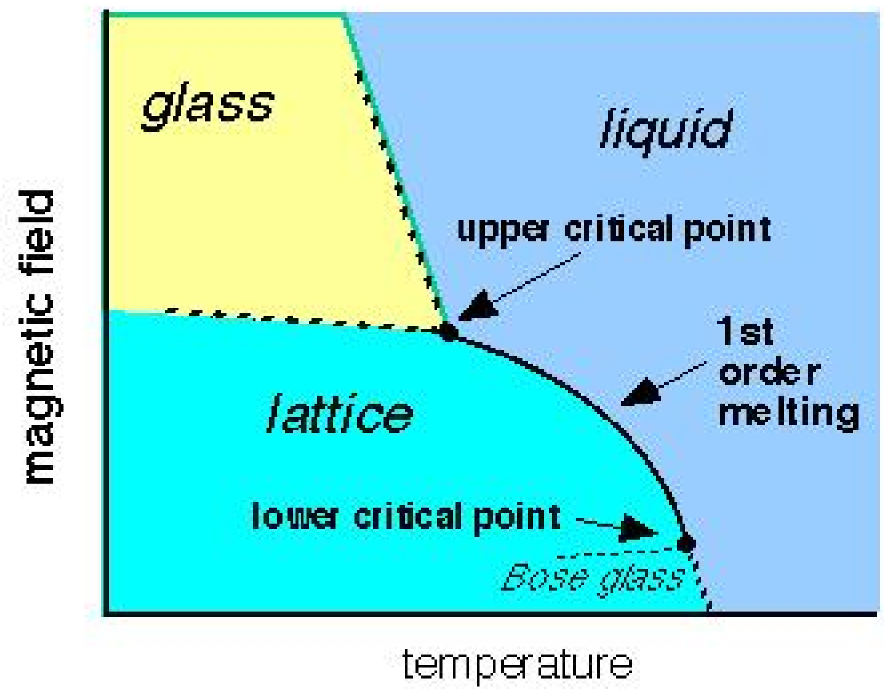
dynamic response





H = 5T
I_{crit}
Rigid Motion
T_M
Liquid
Pinned Solid
I (mA)
T (K)
0
2
4
6
8
10
12
14
81.5
82.0
82.5
83.0
83.5

Dynamics at Equilibrium Phase Transitions



lattice-liquid line: hydrodynamics → elastic rotation

infinite dynamic correlation length in lattice

glass-liquid line: 2^{nd} order equilibrium transition

critical dynamic behavior?

Summary

- rich dynamic phenomena in vortex liquid, lattice, glasses

- controlled gradient transport–

  apply inhomogenous current

  $\rightarrow$ measure induced velocity profile

- observed hydrodynamic, plastic, elastic vortex motion

  elastic depinning

  shear induced plastic slip

- $\rightarrow$ explore dynamics of disordered vortex states

Challenges

experiment: local correlation in driven states

"first order" I-V transitions

nature of depinning transitions

search for drive induced disorder

simulation: define dynamic correlation functions

identify symmetries of driven states

examine role of controlled disorder

theory: conceptual description of phases and transitions without free energy