BES Report on

Basic Research Needs for Superconductivity:

Structure & Dynamics of Vortex Matter

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Outline

Current challenges
Enabling characteristics of vortex matter
Basic research & innovative approaches to overcome limitations

Grand Challenges of Superconductivity

- Transform the power grid to deliver abundant, reliable, high-quality power for the 21st century
  - first steps within reach (1G & 2G wires)
  - full transformation requires breakthrough basic research

- Achieve a paradigm shift from materials by serendipity to materials by design

- Discover the mechanisms of high-temperature superconductivity

- **Predict and control the electromagnetic behavior of superconductors from their microscopic vortex and pinning behavior**

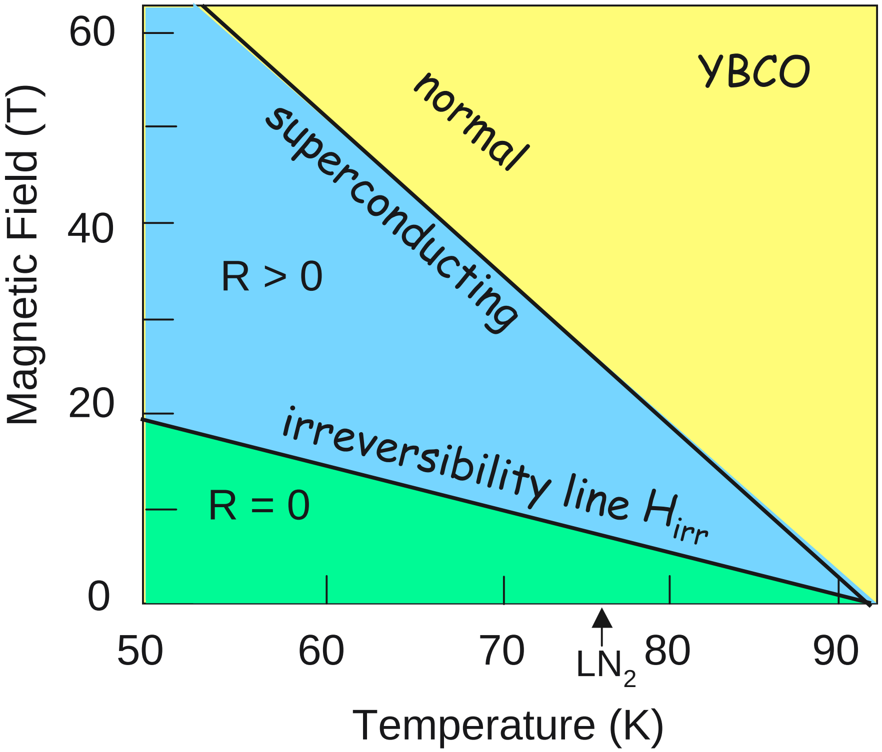
- Multi-scale challenge *and bridges the gap between basic research and applied technology*

BASIC RESEARCH NEEDS FOR
SUPERCONDUCTIVITY

Report of the Basic Energy Sciences
Workshop on Superconductivity,
May 8-11, 2006

Grand Challenges in the Electromagnetic Response of HTS

Enable the operation of HTS at their high temperatures and high magnetic fields

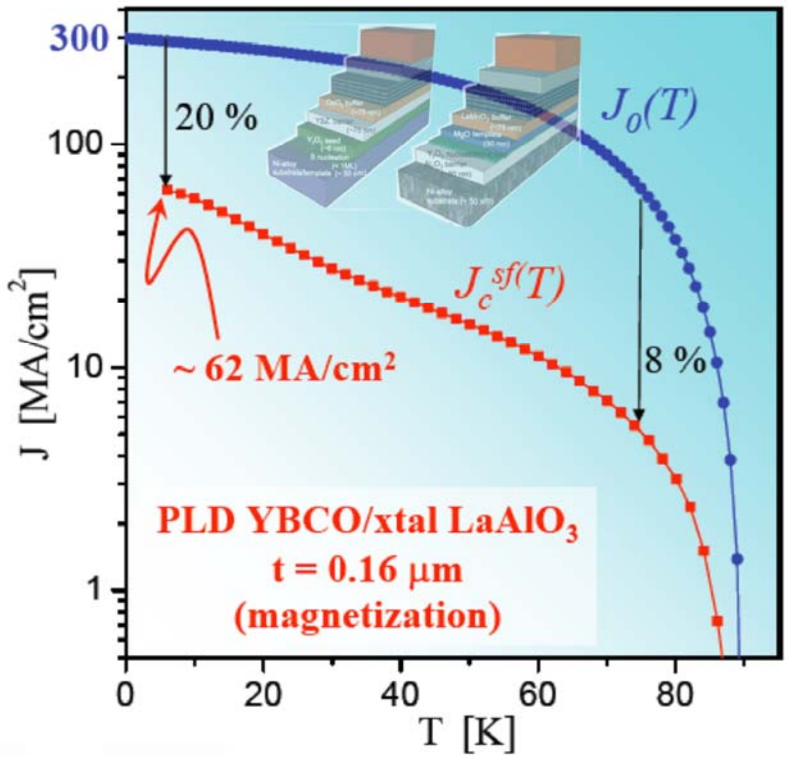


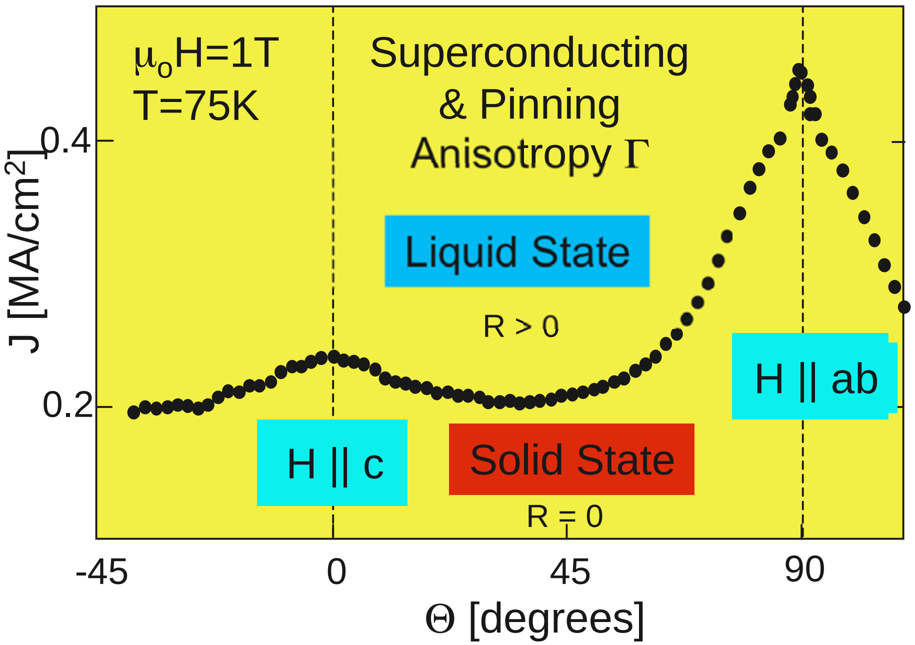
- ***Enhance the critical current to its highest possible value***
- ***Raise the irreversibility line as high as possible***

The performance of the critical current and the irreversibility line are controlled by vortex behavior

Basic Research is needed to understand and control vortex matter in its static and dynamic configurations

Current Status: 2^{nd} Generation HTS Coated Conductors





J.L. MacManus-Driscoll *et al.* , Nature Materials **3**, 439 (2004)

At 20K, only 20% of the depairing current

At 77K, only 8% of the depairing current

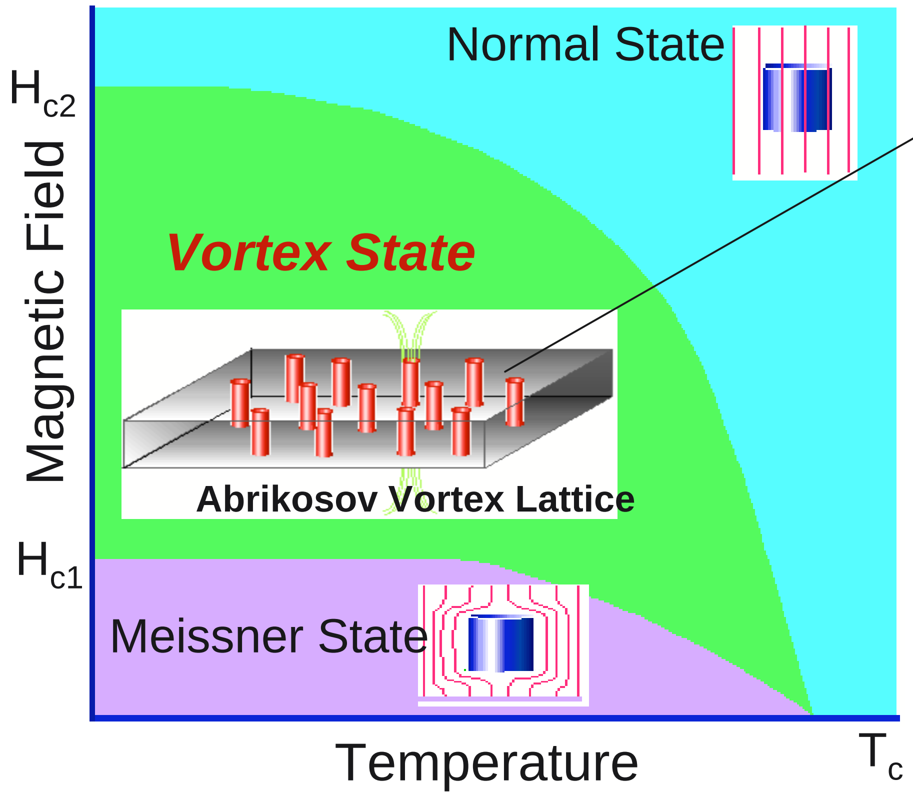
Inadequate high field critical current

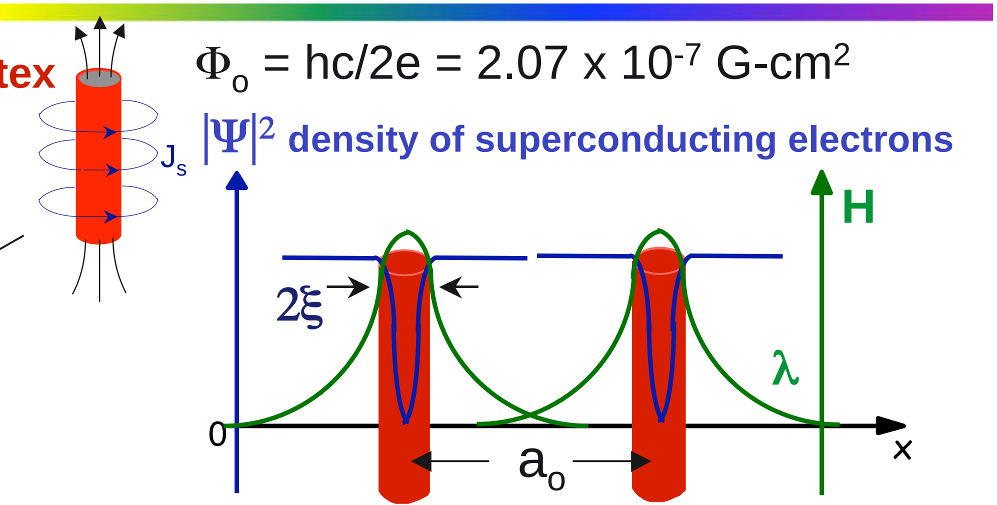
L. Civale and S. Foltyn (LANL)
http://www.energetics.com/meetings/supercon05/html

Large anisotropy leads to strong field orientation dependence of J_c(H)

How do we meet these challenges?

Vortices Determine the Electromagnetic Behavior

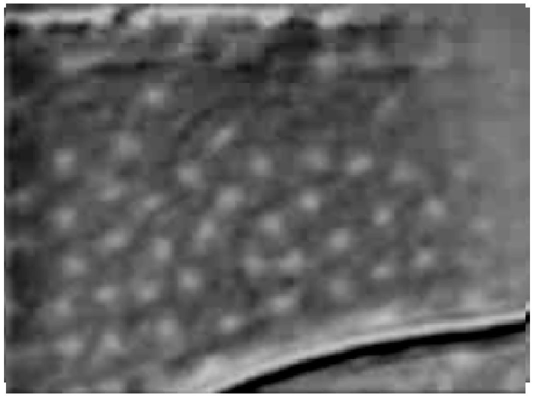




Φ_o = hc/2e = 2.07 x 10^{-7} G-cm^2

$$\xi(T) = \frac{\xi(0)}{\sqrt{1-T/T_c}} \qquad \lambda(T) = \frac{\lambda(0)}{\sqrt{1-T/T_c}} \qquad a_o \sim \sqrt{\Phi_o/B}$$

These seemingly simple nano-scale 'vortices' control all the complex electromagnetic behavior of applied superconductors

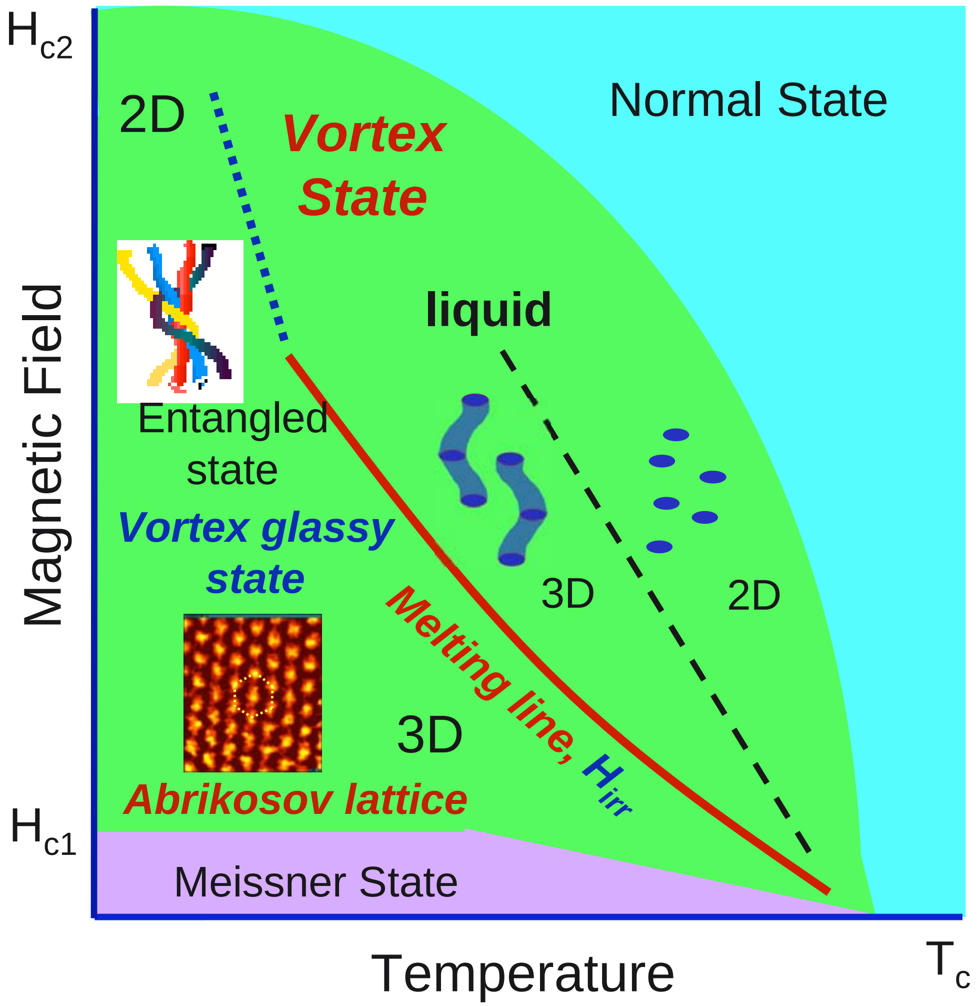


Magneto-Optics NbSe$_2$

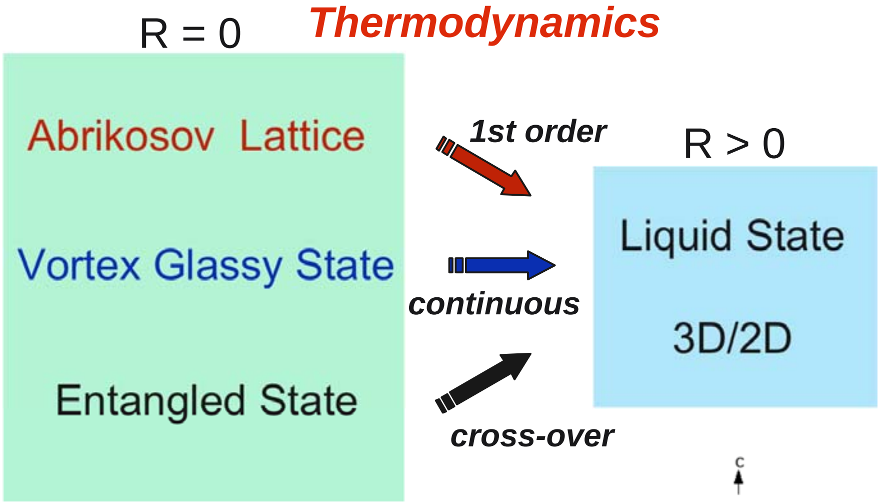
A.A.F Olsen et al., Physica C408-410, 537 (2004)

Rich Thermodynamic Vortex Phases in HTS

Vortex Melting: liquid & solid phases



Thermodynamics


R = 0

Abrikosov Lattice

Vortex Glassy State

Entangled State

1st order

continuous

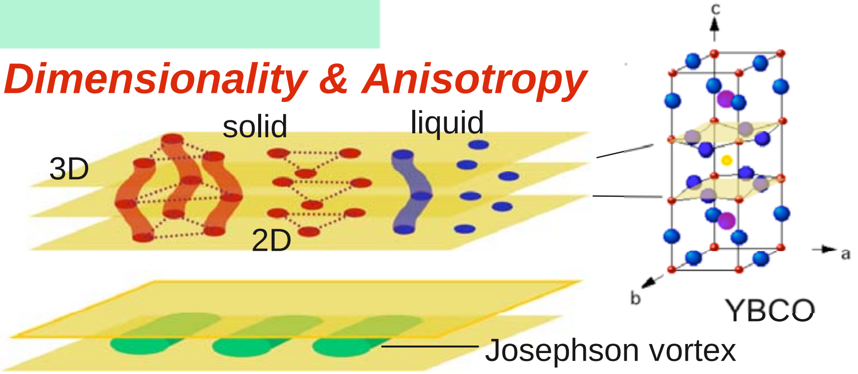
cross-over

R > 0

Liquid State

3D/2D

Dimensionality & Anisotropy

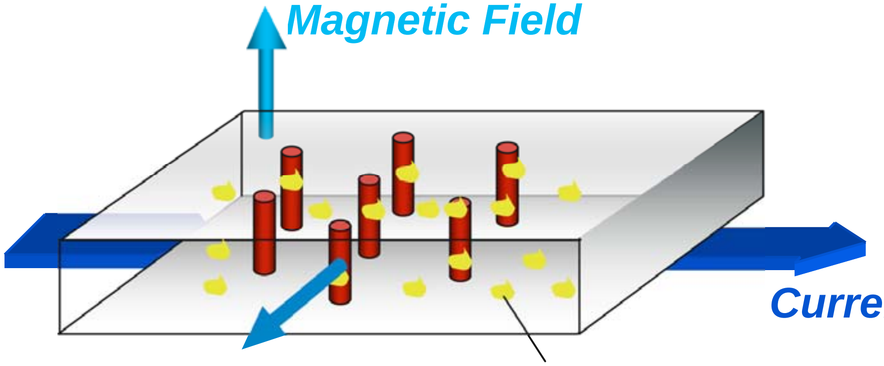


Structures and phase diagram with richness and complexity of ordinary matter

"Vortex Matter"

Understanding Vortex Dynamics to Achieve the Highest J_c

Dissipation driven by field and current



Lorentz Force
$F_L = J \times \Phi_o/c$

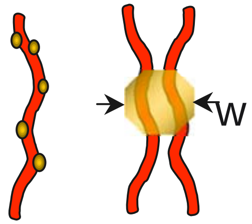
Pin sites
(defects)

Critical current: $\mathbf{F_L = F_{pin}}$

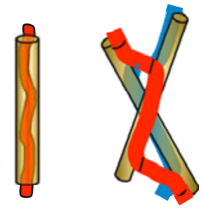
Depairing current: the high possible J_c

$$J_d(T) = \frac{\phi_o}{3^{3/2}\,\pi\mu_o\xi(T)\lambda^2(T)}$$

Types of Defects

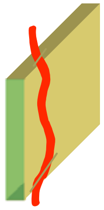


Point defects:
weak-random, large-strong



Columnar & splayed
heavy ion irradiation

Planar defects:
layered structures
twin planes
planar dislocations



Vortex Core
Pinning Energy: $U_{pin} \sim \frac{H_c}{8\pi}\,\pi\,\xi^2 L$

Vortex Dynamics: non-linear micro-scale behavior

Thermal effect	➡	Vortex creep ~ $\exp(-U_p/kT)$
Driving currents	➡	Depinning threshold of J_c
Magnetic fields	➡	Giant flux avalanches

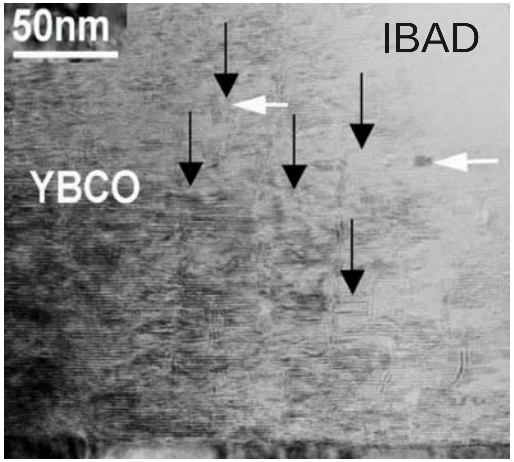
Liquid State Dynamics

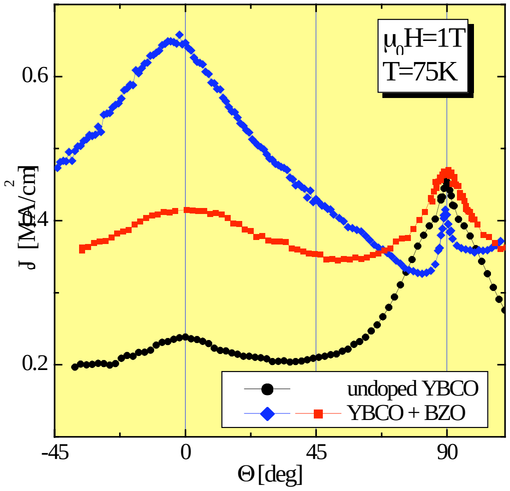
Viscous flow and the absence of critical current

Achieve the depairing current in the vortex solid & 'pin' the vortex liquid

Enhancing J_c (T, H, and θ) in Coated Conductors

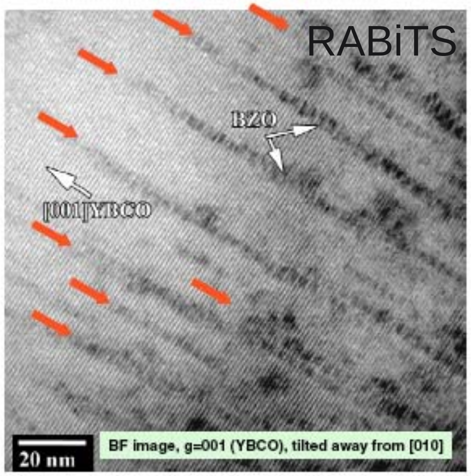
$BaZrO_3$ nano-particles

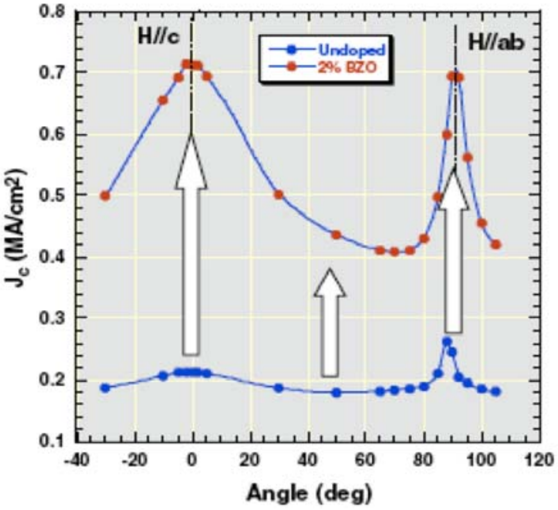




J.L. MacManus-Driscoll *et al.* , Nature Materials **3**, 439 (2004)

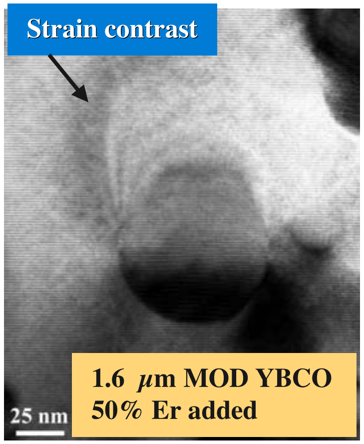
Self-assembled nanodots/rods

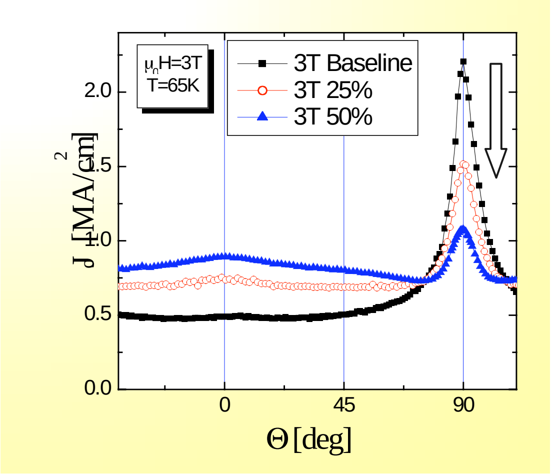




A. Goyal et al., Supercond. Sci. Technol. 18, 1533 (2005)

Rare Earth nano-particles (RE_2O_3)



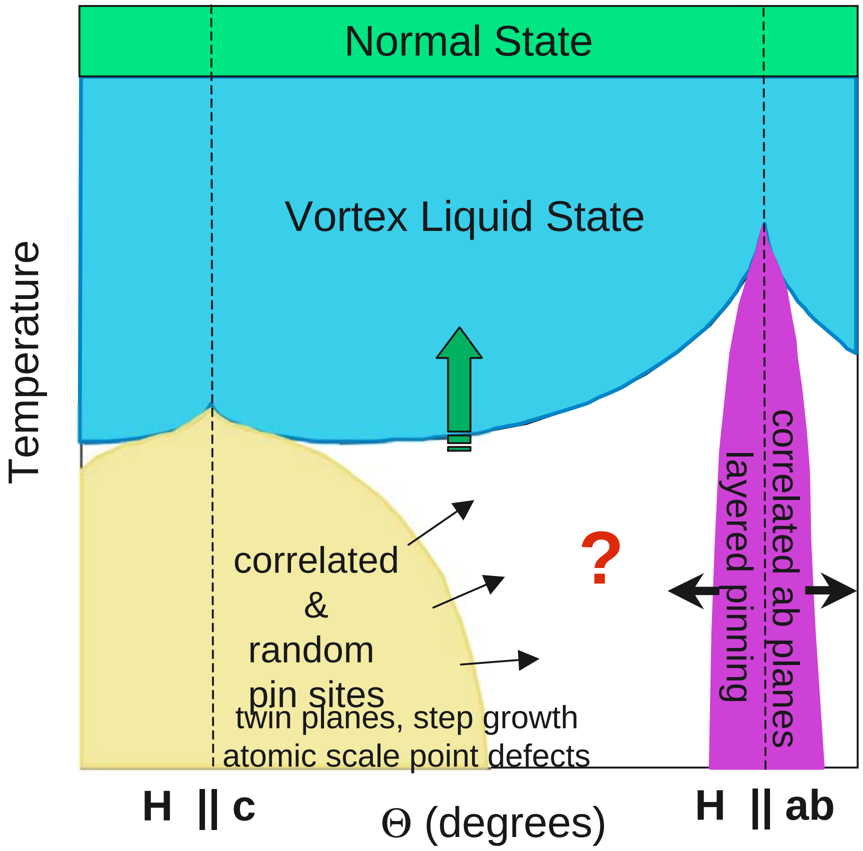


Reduces ab planar intergrowth

T. Holesinger et al.,http://www.energetics.com/meetings/supercon06/html

Challenges Ahead

Increase vortex pinning across the broad spectrum of T, H, θ



Novel Strategies to Increase $J_c(T,H)$

- Nanoscale defect arrays
- Magnetic pinning
- Thermally Driven Vortex Creep

Isotropically enhance the irreversibility line

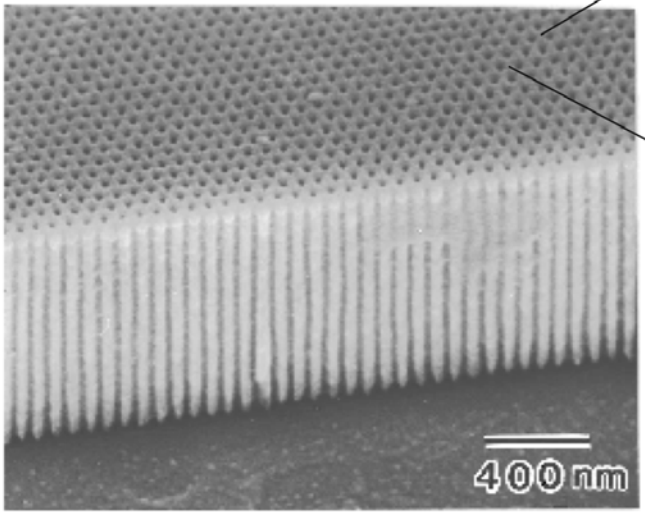
- Meso/Nano shaped defects

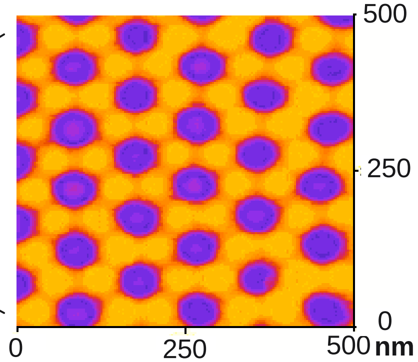
Can we 'pin' or control vortex liquid flow

- Enhance Viscosity to Glassy-like State
- Pinning Schemes / Jamming
- Flow Control via Nano-Patterning

Self-Assembled Nano-Pinning Landscape

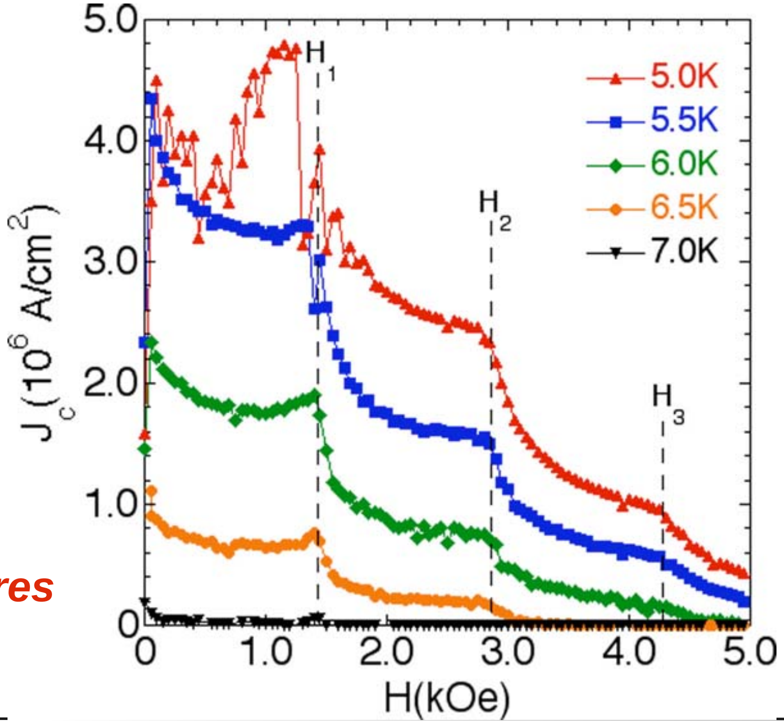
Nb on Anodic Aluminum Oxide Nanoporous Membrane





- $\xi(0)/a \approx 0.1$ $\lambda(0)/a \approx 0.7$

Tailor critical current enhancements to a particular magnetic field



Triangular array of holes: 101 nm period
45 nm diameter

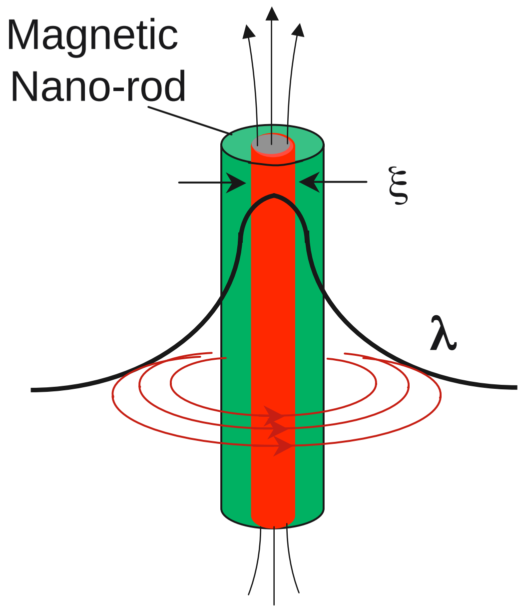
matching field: $H_1 = \dfrac{2\,\Phi_0}{\sqrt{3}\;a^2} = 2255$ Oe

Field matching effect is dominant at all temperatures

U. Welp, Phys. Rev. B. **66**, 212507 (2002).

Augment Core Pinning with Magnetic Pinning

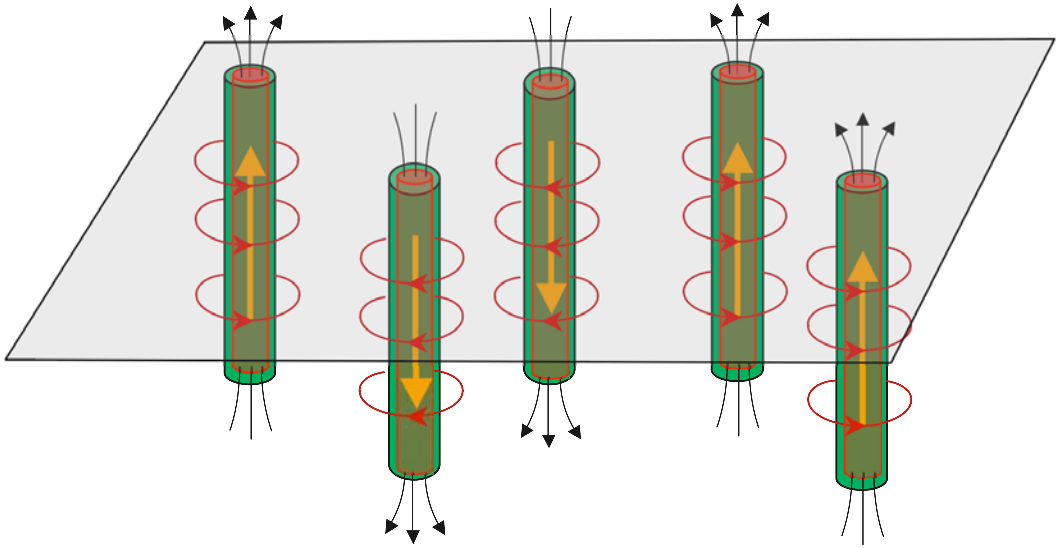
Creation of vortex with nano-magnetic rods



Combine core pinning with magnetic pinning energy

$$U_m = 2\pi \int H(r)\, M_s\, r\mathit{dr}$$

Randomly oriented frozen flux state Glassy pinning landscape



- **Pinning energy proportional to magnetic rod volume > vortex core volume**
- **Temperature independent pinning sites**
- **Shield surrounding from magnetic flux using soft magnets**

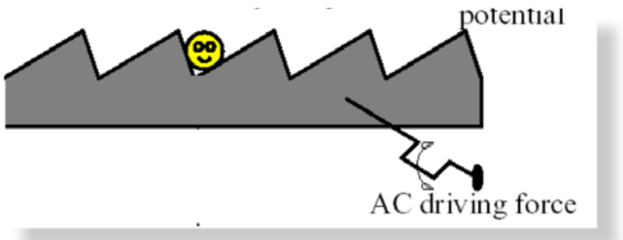
Potential to enhance J_c and H_{c2}

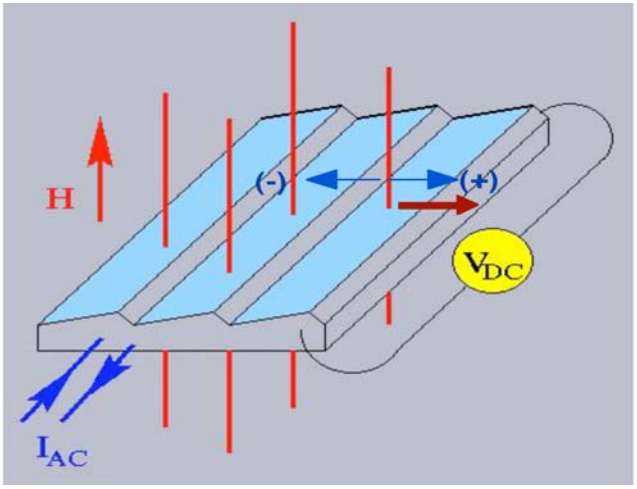
I. F. Lyuksyutov & V. L. Pokrovsky, Advances in Physics,54 (1), 67 (2005)

Directional Vortex Flow Control with Shaped Pinning Wells

Asymmetric Periodic Potential

RATCHET DRIVE



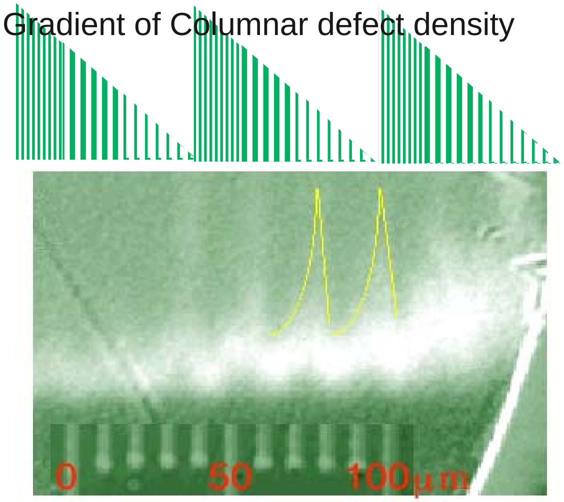


C. S. Lee, et al. Nature 400, 337 (1999)

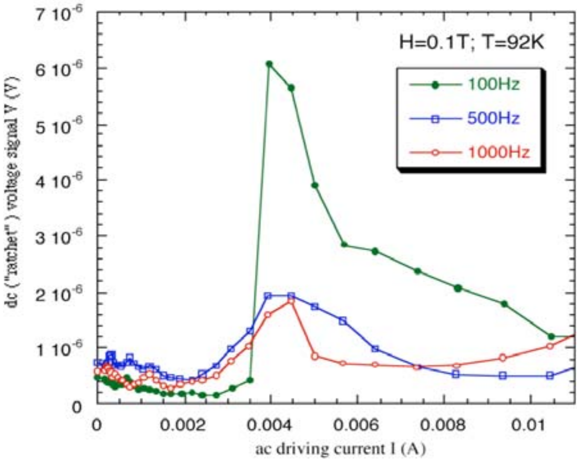
J.E. Villegas, et al. Science 302, 1188 (2003)

Heavy ion lithography

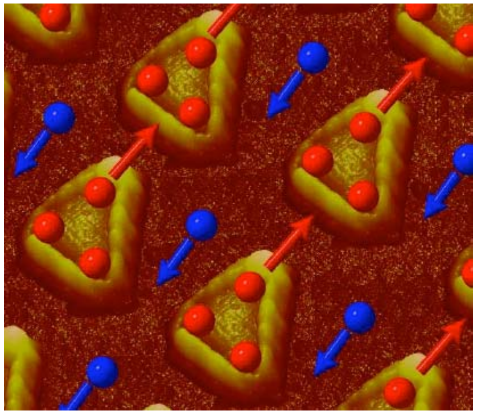
Gradient of Columnar defect density



Ratchet signal in irradiated YBCO

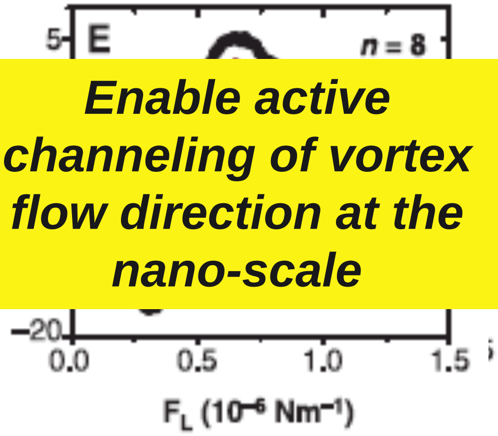


magnetic pinning dots



Ratchet threshold can be set by magnetic field

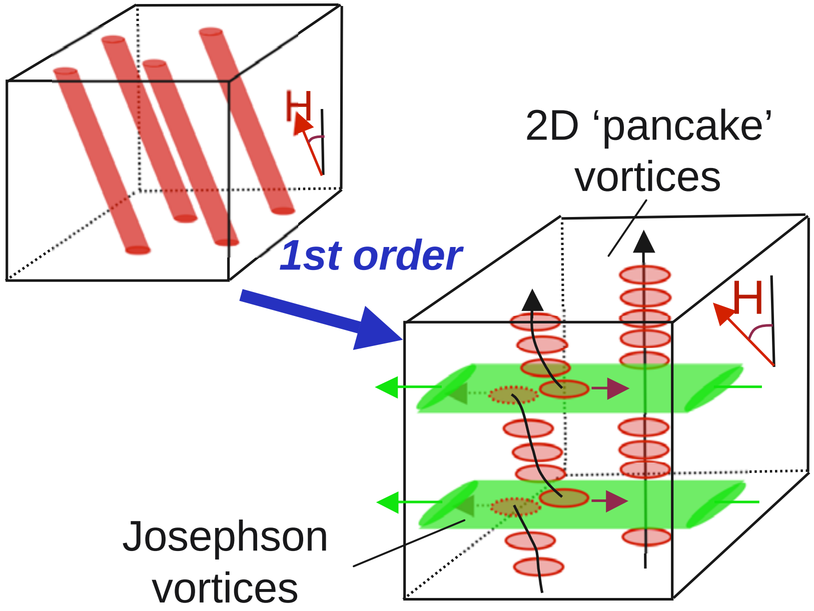
(Vortex Rectifier)



Enable active channeling of vortex flow direction at the nano-scale

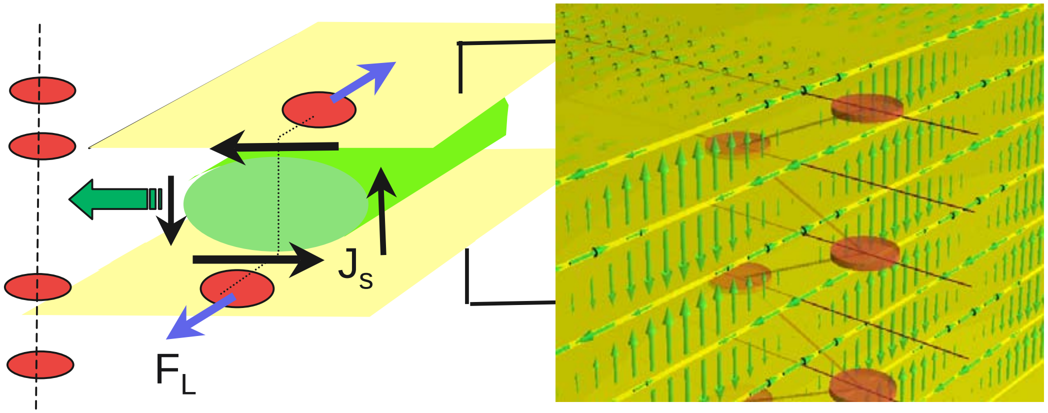
Dynamics of Composite Vortices: controlling viscosity

Composite Vortex States In Highly Anisotropic Superconductors



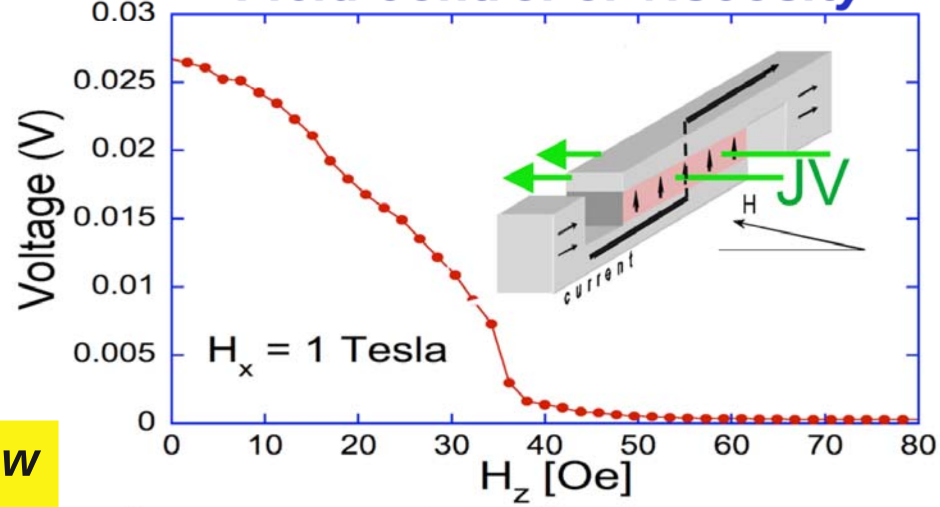
A. Grigorenko et al., Nature 414, 728 (2001)

A. Koshelev et al, PRB74, 104509 (2006)



PV interaction with JV

Field control of viscosity

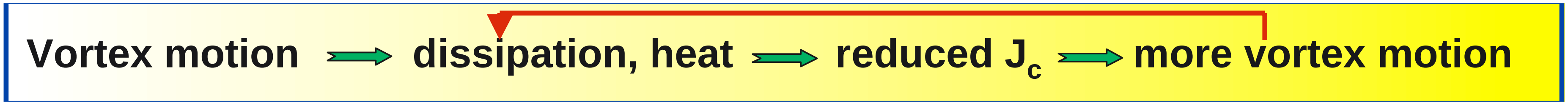


Increase pancake vortices →

Dynamics of Composite Vortices: a new and rich emergent behavior

Vortex Dynamics Under Extreme Conditions

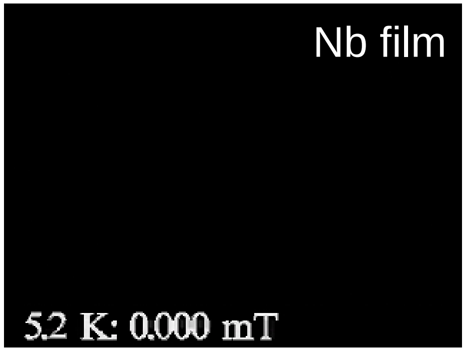
Thermal Runaways & Flux Avalanches



Vortex motion → dissipation, heat → reduced J_c → more vortex motion

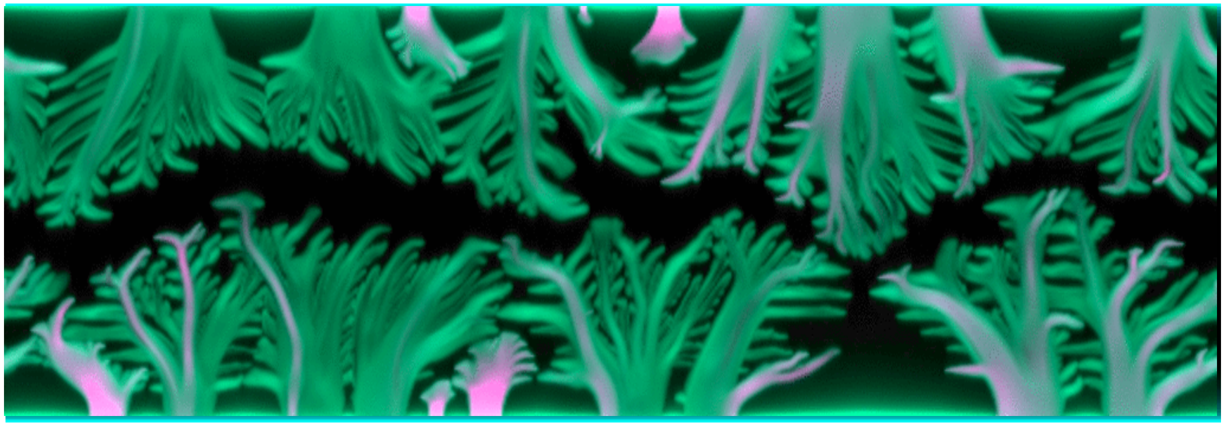
Positive feedback reduces J_c and increases heat formation leading to large flux avalanches and thermal runaways

Magnetic Flux Entry in MgB_2



Flux Avalanches in Nb film
R. J. Wijngaarden, Free University

Simulation of Thermo-Magnetic Avalanches with Random Defects

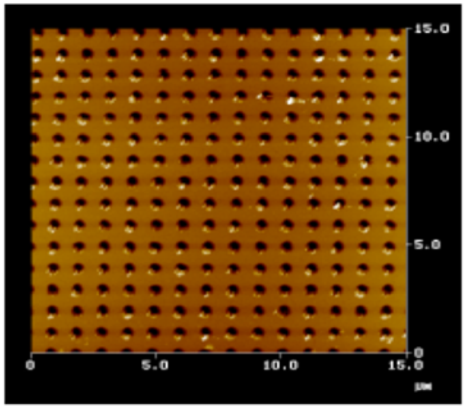


- **I.Aranson, A.Gurevich** et al. PRL 2005

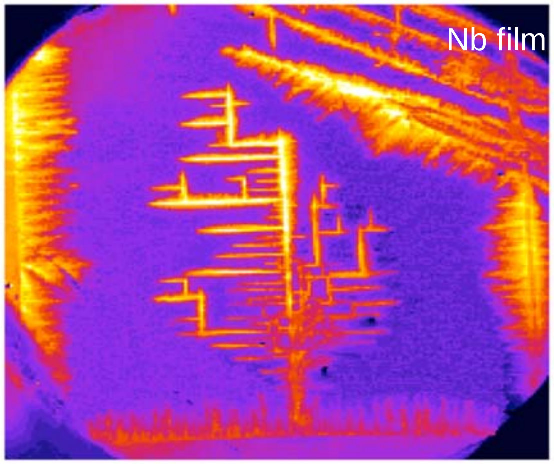
Model macroscopic flux response arising from microscopic vortex behavior through multi-scale simulations

Controlling Bulk Dynamics with Nanoscale-structures

Passive pinning schemes to control thermo-magnetic flux response through nano-patterning



AFM image of 1 x 1 µm^2 hole array in Nb



Corresponding Mag-Opt. Image

Can we combine passive pinning schemes with active vortex channeling strategies to control macroscopic flux behavior

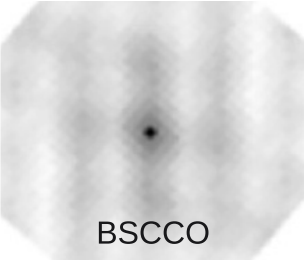
Reducing flux avalanche sizes and redirecting vortex flow from 'hot-spots' may lead to self-healing superconductors

HTS

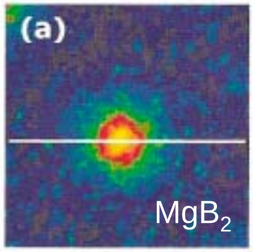
Superconductor → **Vortex Liquid State** → **Normal State**

Conventional Low Tc

From Phenomenological to Microscopic Theory



J. C. Davis



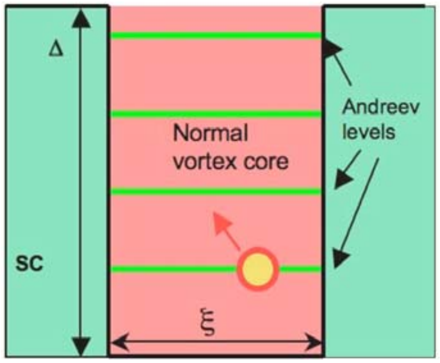
M. Eskildsen

Microscopic Theory of Vortex Pinning:

Structure of vortex core in unconventional superconductors

- New horizons for ATOMIC SCALE pinning schemes

Microscopic Theory of Vortex Dynamics:



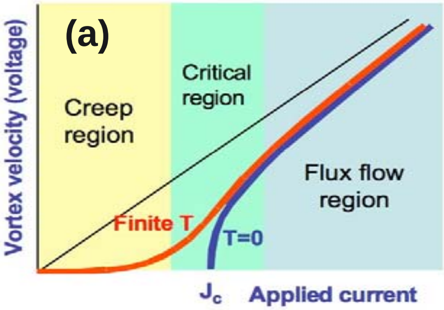
Modification of core levels structure by the host matrix

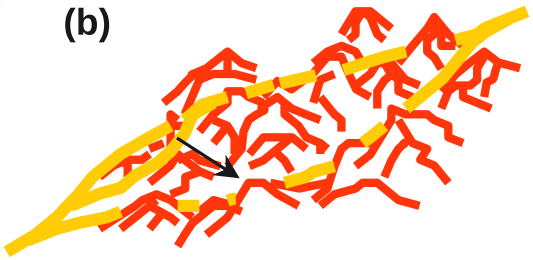
- Shed light on vortex friction vs viscosity

Physics of Nonequilibrium vortex matter:

Response of the glassy states under high driving currents

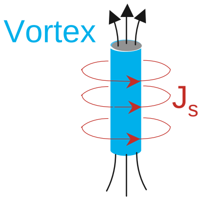
- Key to promote self-healing strategies for HTS

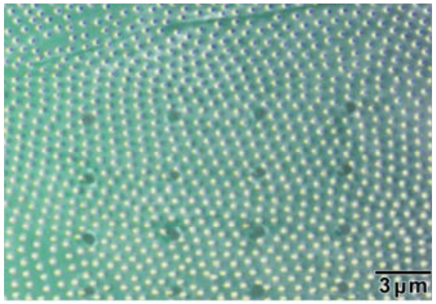




Controlling Vortex Matter is a Multi-scale Challenge

Vortex: nano-sized quantum of magnetic flux

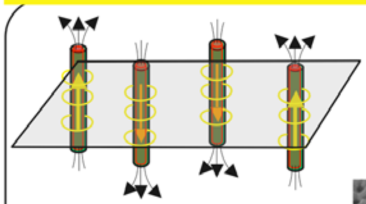




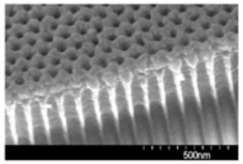
Microscopic Theory

Physics of non-equilibrium vortex matter

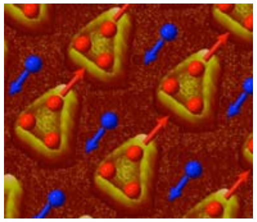
Novel Vortex Control Strategeis



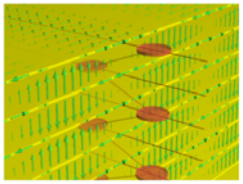
Magnetic pinning arrays



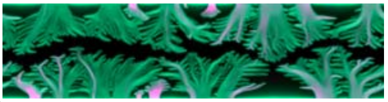
Self-assembled nano-pin sites



Active vortex flow control



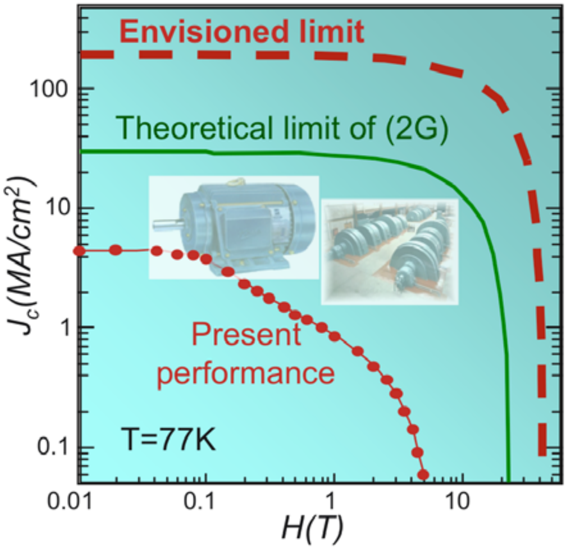
Composite vortex lattices



Simulations

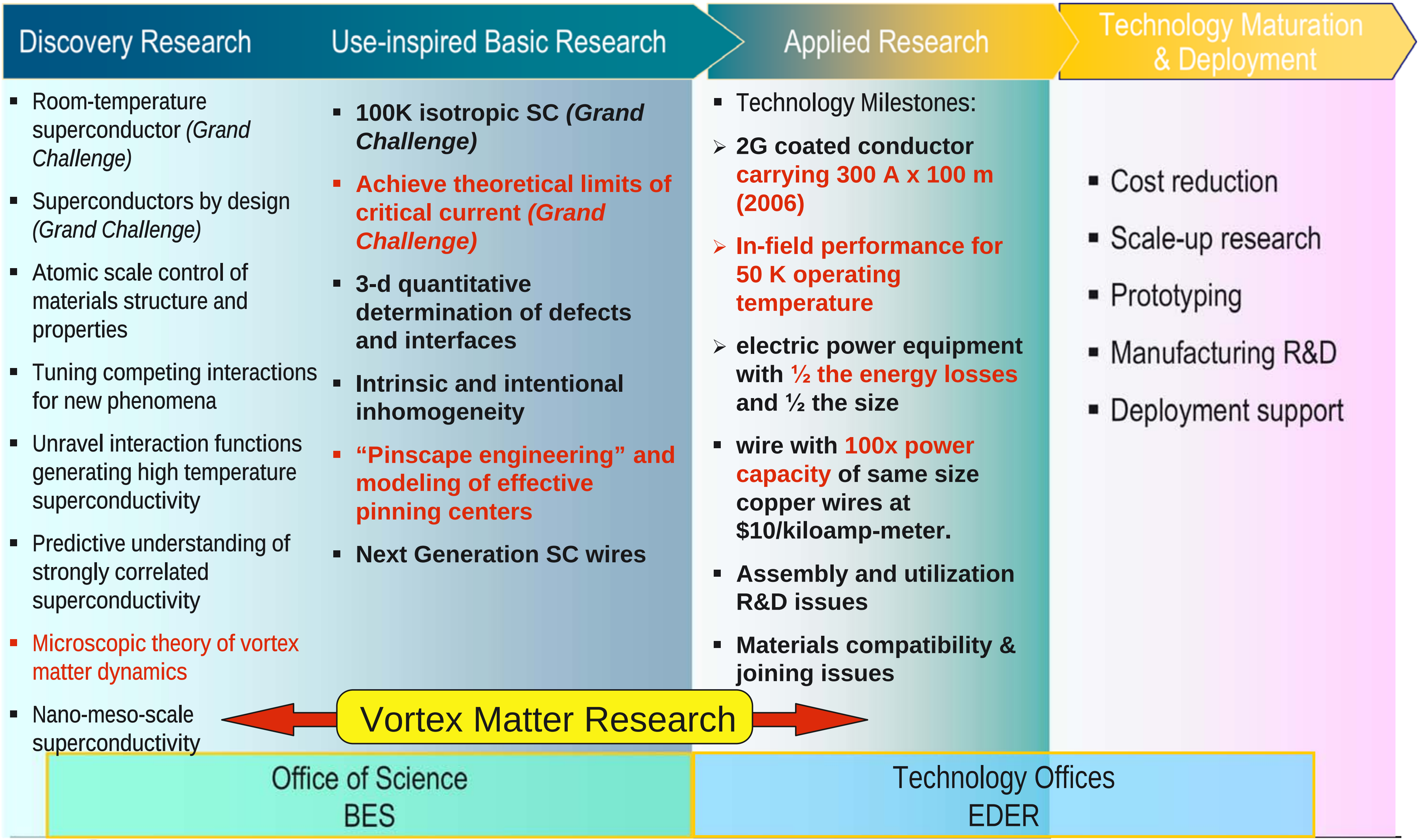
Goals…

Achieve highest J_c & H_{irr}



Learn to control the behavior of vortex matter from nano to bulk behavior

Superconductivity Research Continuum



Discovery Research

- Room-temperature superconductor *(Grand Challenge)*
- Superconductors by design *(Grand Challenge)*
- Atomic scale control of materials structure and properties
- Tuning competing interactions for new phenomena
- Unravel interaction functions generating high temperature superconductivity
- Predictive understanding of strongly correlated superconductivity
- Microscopic theory of vortex matter dynamics
- Nano-meso-scale superconductivity

Use-inspired Basic Research

- **100K isotropic SC *(Grand Challenge)***
- **Achieve theoretical limits of critical current *(Grand Challenge)***
- **3-d quantitative determination of defects and interfaces**
- **Intrinsic and intentional inhomogeneity**
- **"Pinscape engineering" and modeling of effective pinning centers**
- **Next Generation SC wires**

Applied Research

- Technology Milestones:
  - **2G coated conductor carrying 300 A x 100 m (2006)**
  - **In-field performance for 50 K operating temperature**
  - **electric power equipment with ½ the energy losses and ½ the size**
- **wire with 100x power capacity of same size copper wires at $10/kiloamp-meter.**
- **Assembly and utilization R&D issues**
- **Materials compatibility & joining issues**

Technology Maturation & Deployment

- Cost reduction
- Scale-up research
- Prototyping
- Manufacturing R&D
- Deployment support

Vortex Matter Research

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Basic Energy Sciences

BES Report on Basic Research Needs for Superconductivity
http://www.sc.doe.gov/bes/reports/abstracts.html#SC