Vortex Matter in Magnet – Superconductor Hybrids

Igor Lyuksyutov
Department of Physics
Texas A&M University

In collaboration with:
D. Naugle, W. Wu, Z. Ye, K. Kim, E. Ozmetin, H. Lee

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The Welch Foundation, ***Texas Advanced Research Project***

Overview

- Motivation
- Nanoscale magnetic field sources
- Superconductor with embedded nanorods
- Array of magnetic and superconducting nanowires
- Conclusion

Characteristic Scales

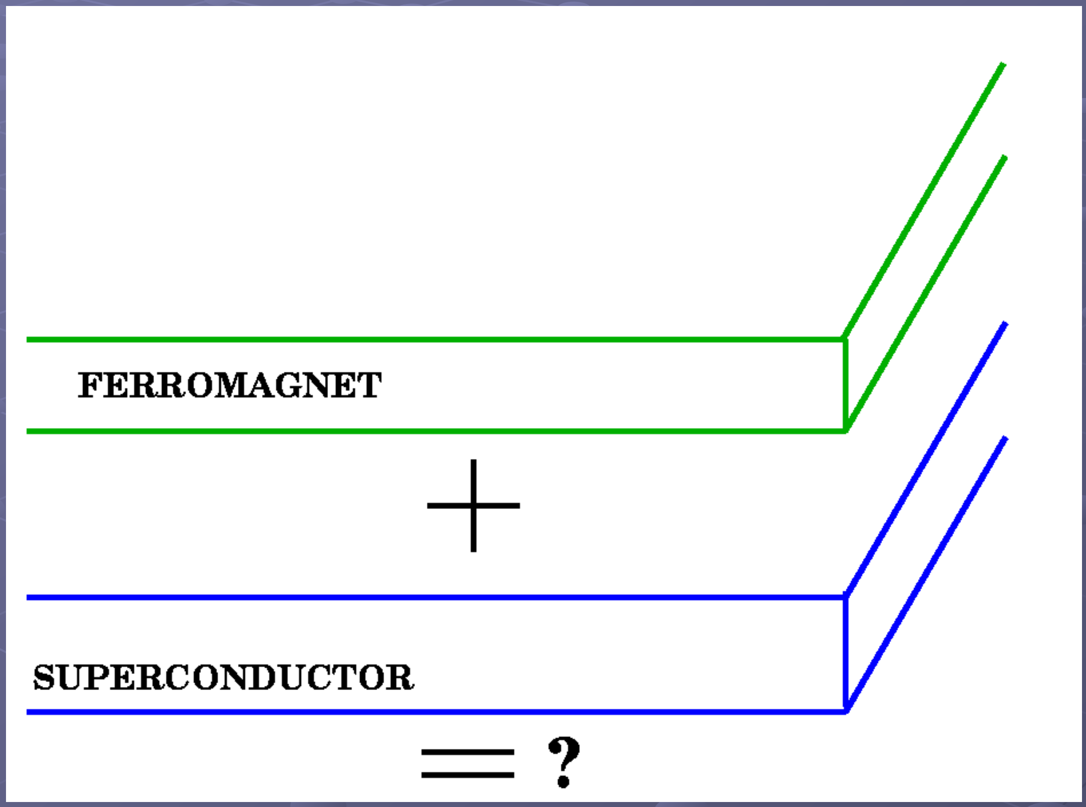
Coherence length ξ

Penetration depth λ

Vortex Energy $$\varepsilon = \varepsilon_0 \ln \frac{R}{\zeta} + \varepsilon_1$$

$$\varepsilon_0 = \frac{\phi_0^2 d}{16\pi^2 \lambda^2} \qquad \phi_0 = \frac{hc}{2e}$$

Superconductor Film on Magnetic Substrate



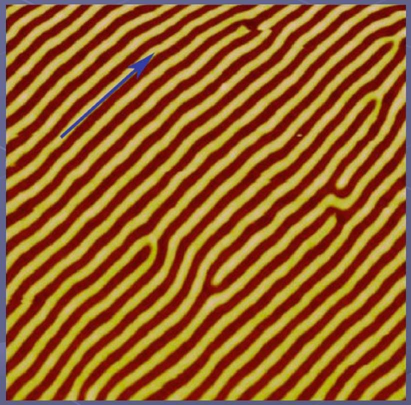
Homogeneous Superconductor in Inhomogeneous Magnetic Field

Magnetic Field from Magnetic Domains and Domain Walls

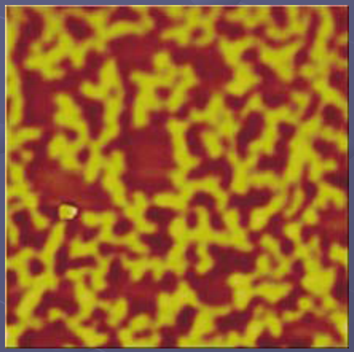
Theory: Bulaevskii et al, (1999), E. Sonin

Experiment:

V. Vlasko-Vlasov et al, Phys. Rev. B **77**, 134518 (2008)

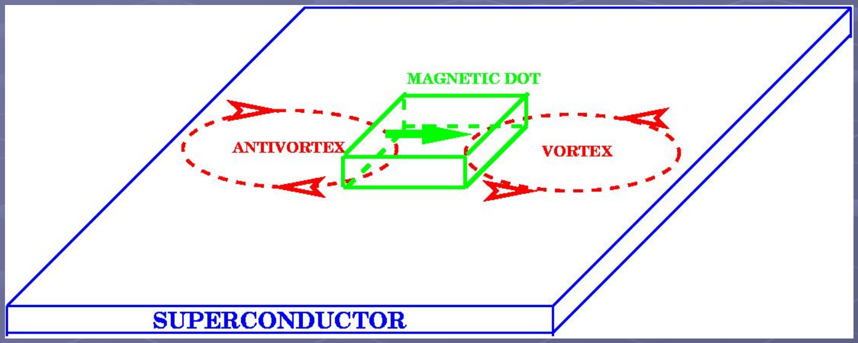


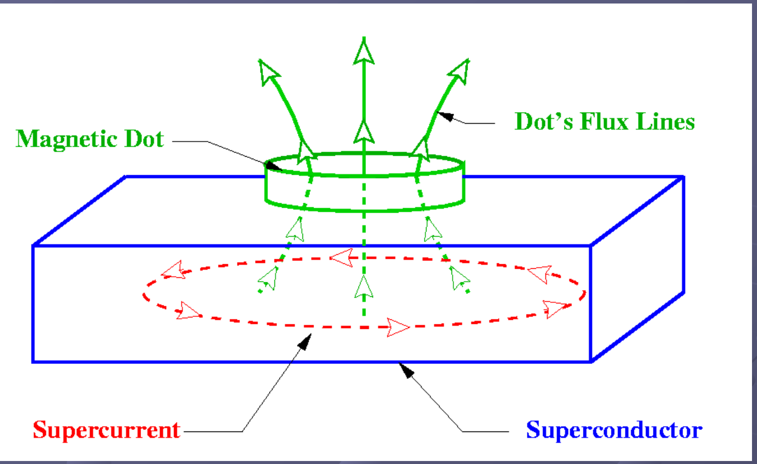
From: W. Gillijns et al, Phys. Rev. B **76**, 060503R (2007)



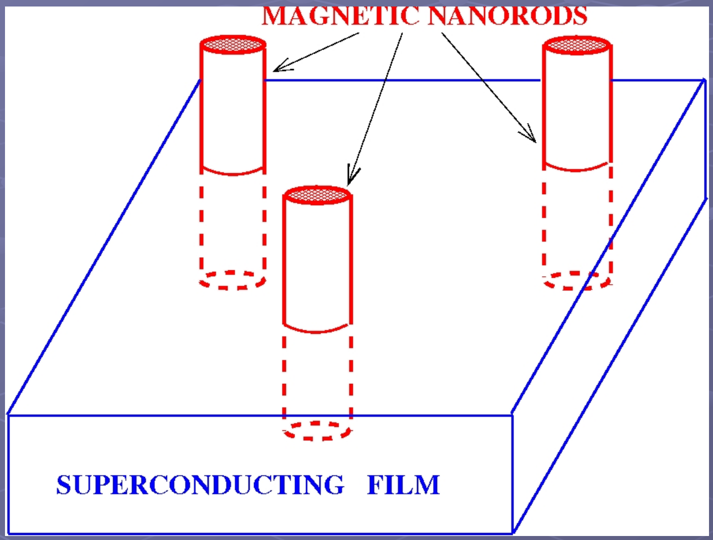
MFM pictures 5X 5micron ^2 at 300 K
The dark /bright color represents domains with positive /negative magnetization

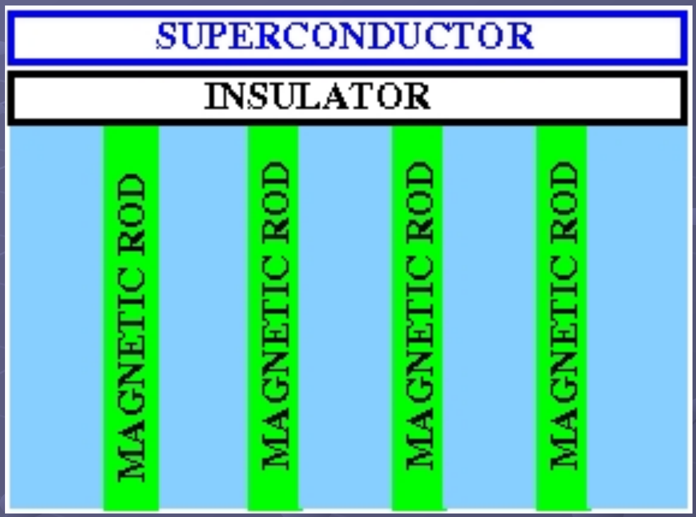
Magnetic dots

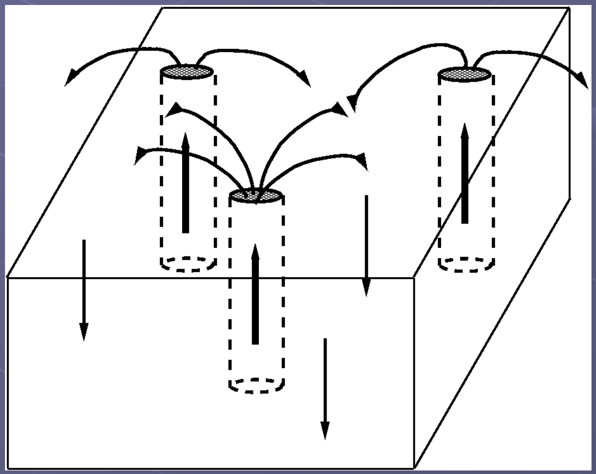




Magnetic rods

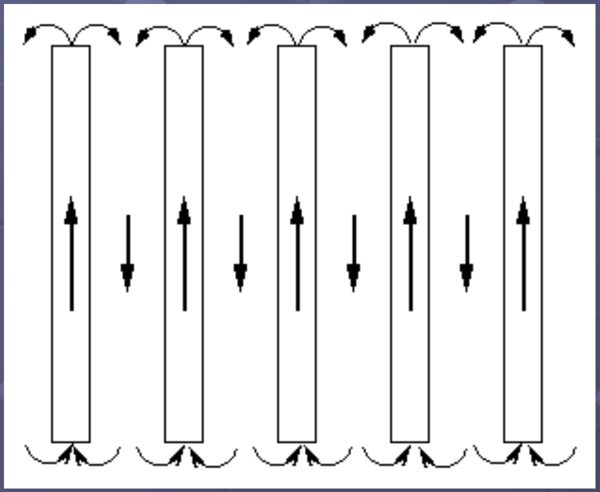






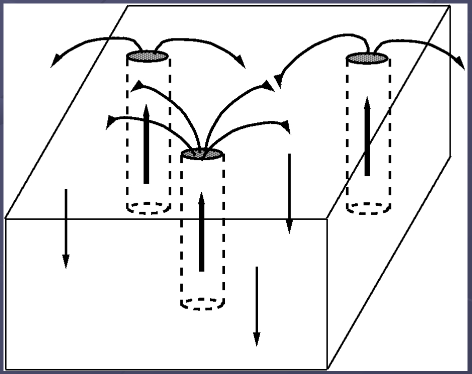
Nanoscale Magnetic Fields via Hybrids: Arrays of Magnetic Nanorods

- Magnetic field inside array

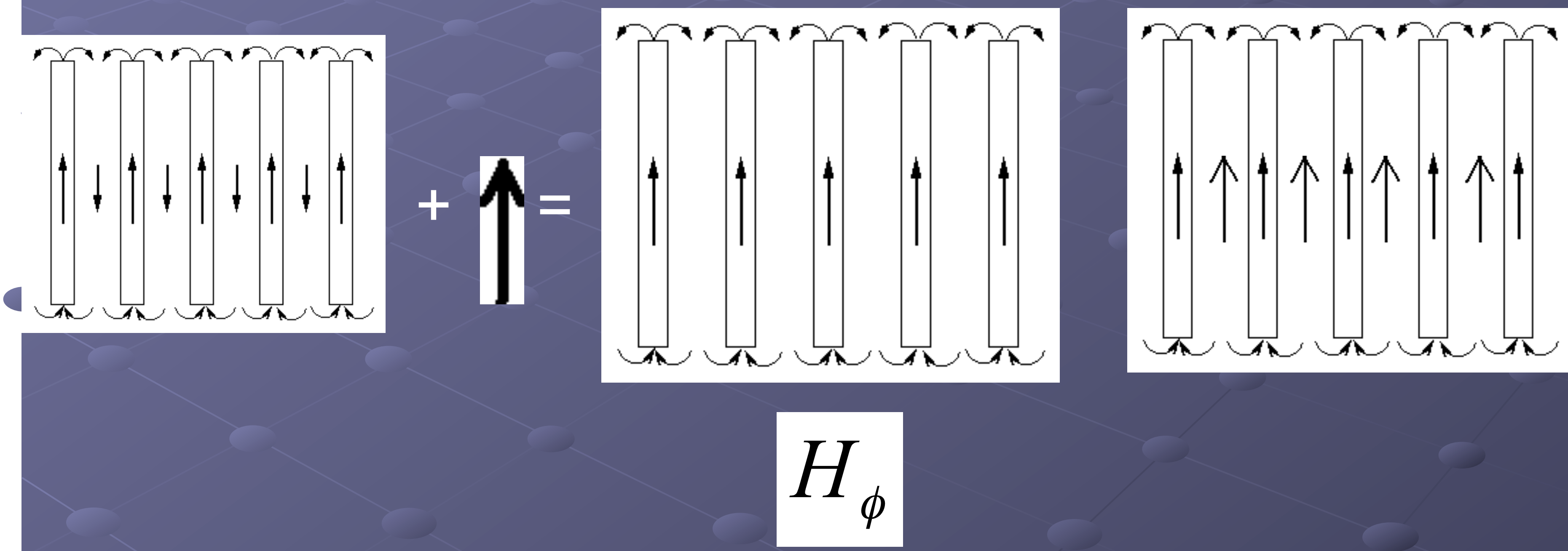


- Template: $-4\pi M(\pi R^2 / A)$

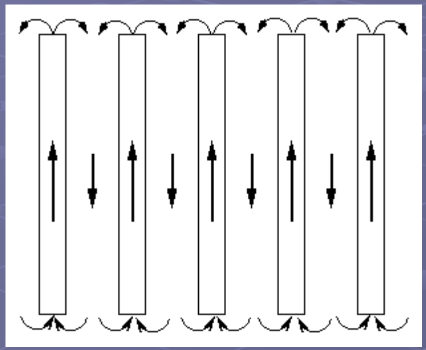
- Nanowire: $\vec{B} = 4\pi\vec{M} + \vec{H} = 4\pi\vec{M}(1 - (\pi R^2/A))$

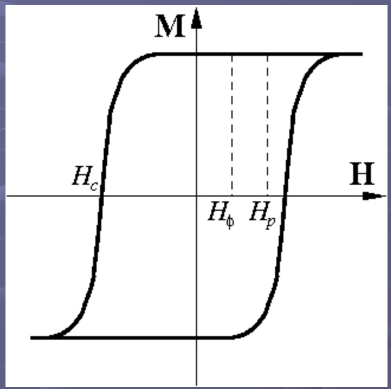


Nanoscale Magnetic Fields via Hybrids: Arrays of Magnetic Nanorods in External Field



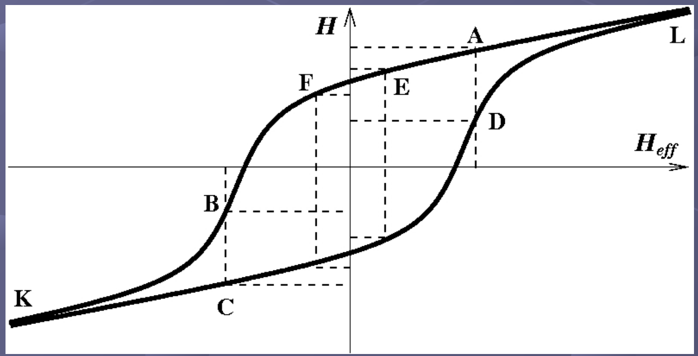
Phase Diagram

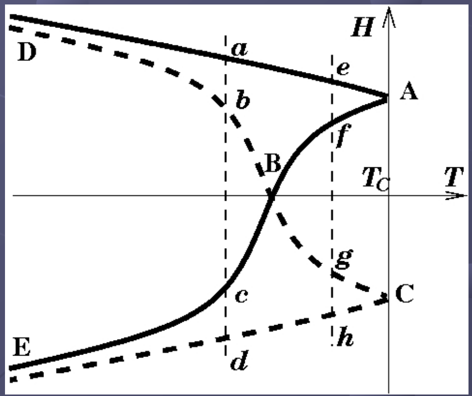




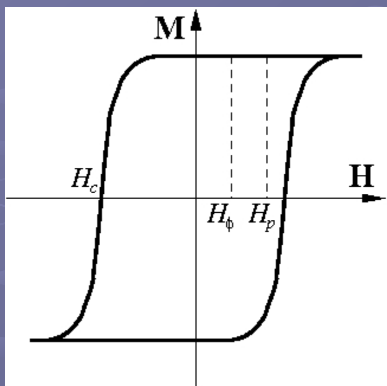
$H_{eff} = H - H_{return}(H_{eff})$

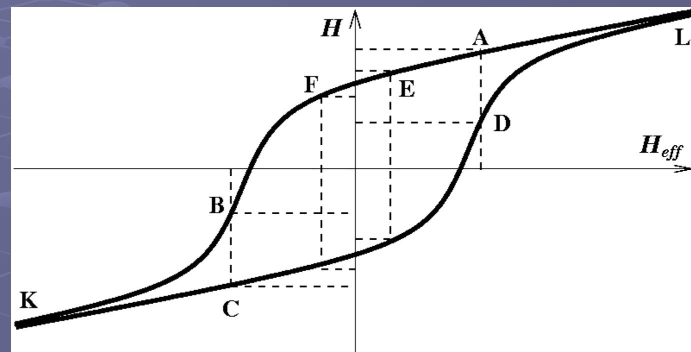
$H_{return}(H_{eff}) = 4\pi(A_{rod}/A_{cell})\,M(H_{eff})$

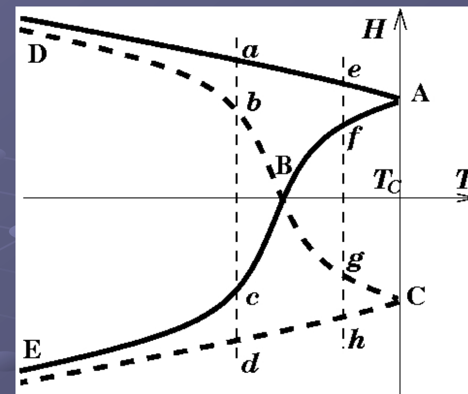


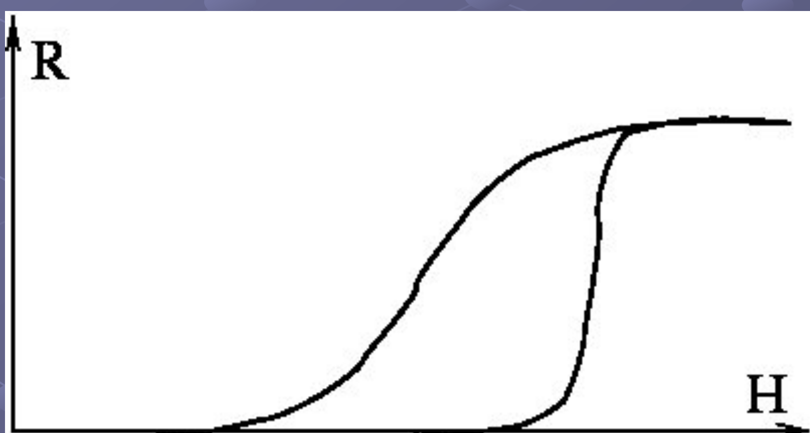


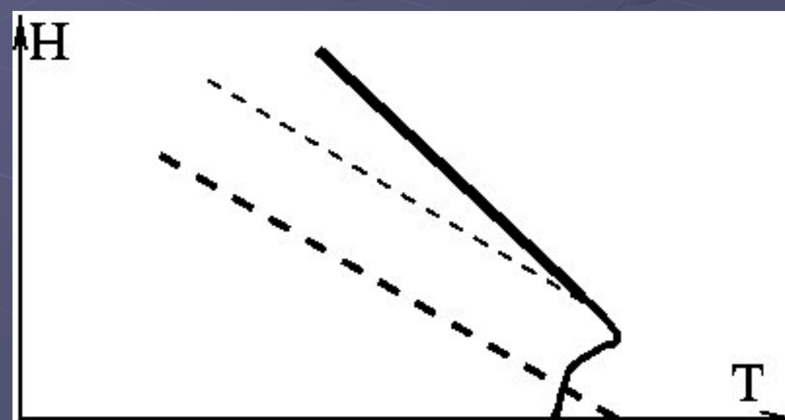
Hysteresis, Resistance and Phase Diagram



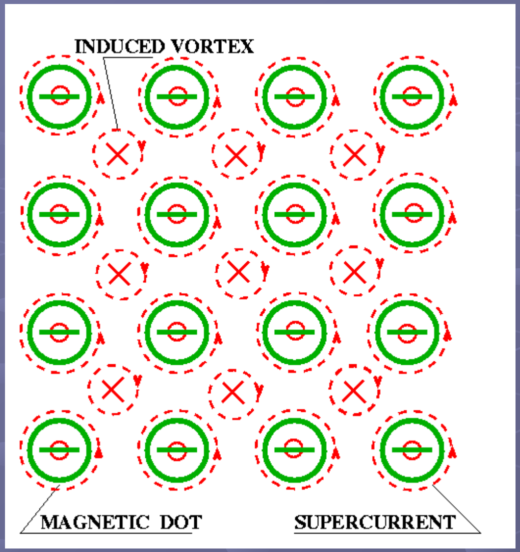




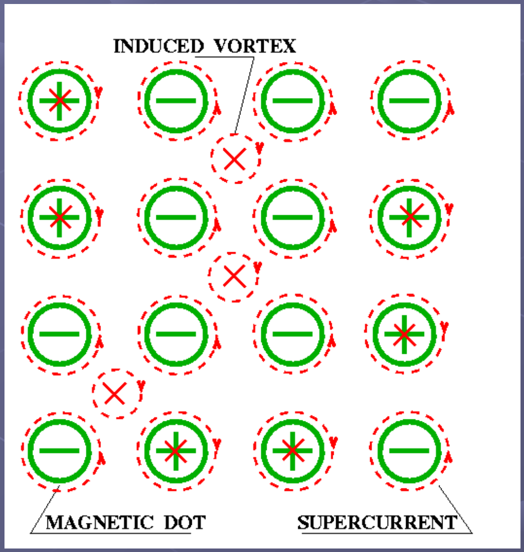




Array of Magnetic Rods with and Without a Magnetic Field



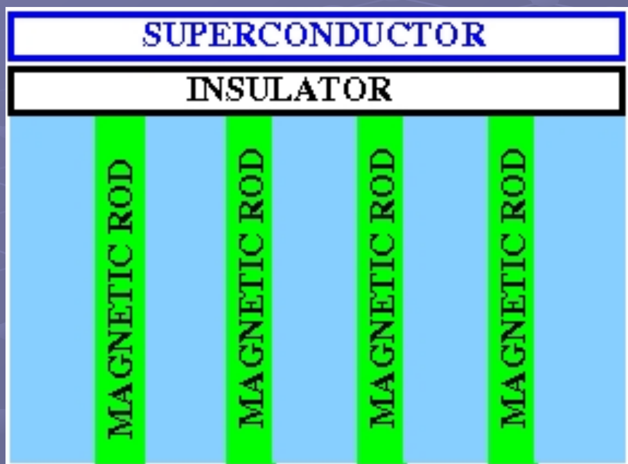
Array of magnetic rods with aligned magnetic moments create vortices bound with dots (o) which induces antivortices (x) in interstitia sites.
Regular lattice of vortices and anti-vortices is strongly pinned.

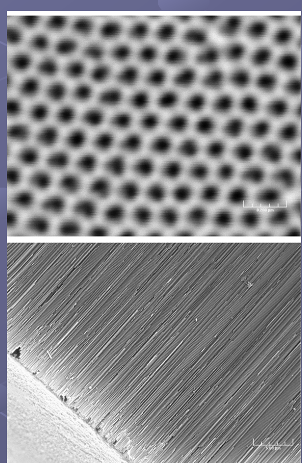


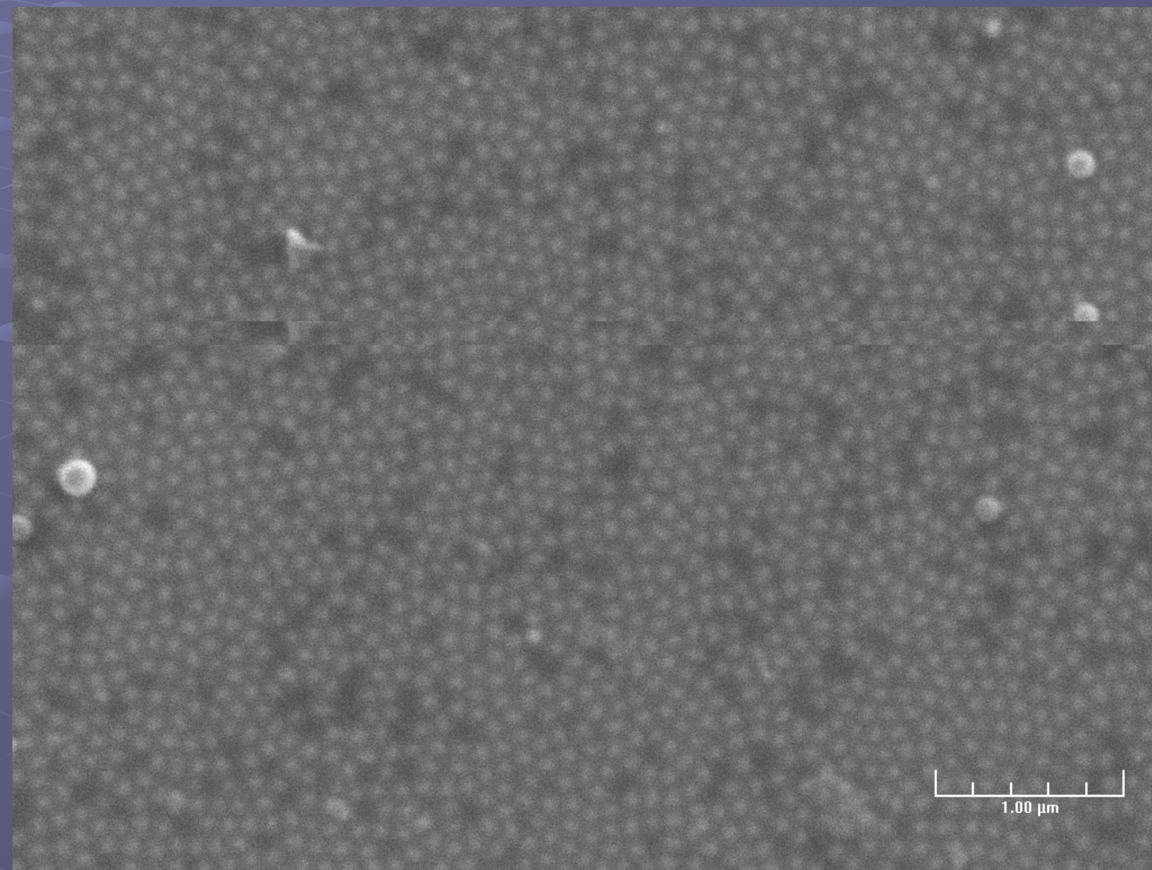
Magnetic rods magnetization direction is random. Induced vortices and antivortices are placed randomly.
Weak pinning of vortices.

Homogeneous Superconductor in Inhomogeneous Magnetic Field

Magnetic Field from Magnetic Nanorods in Alumina Template



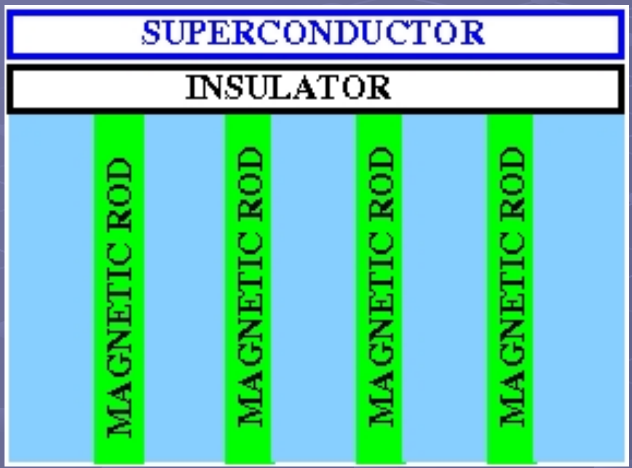


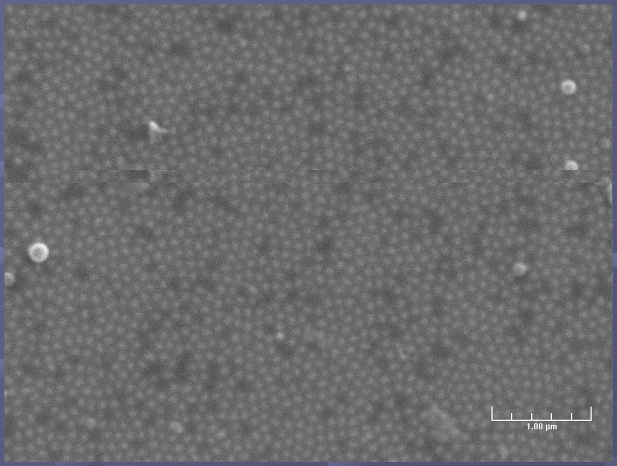


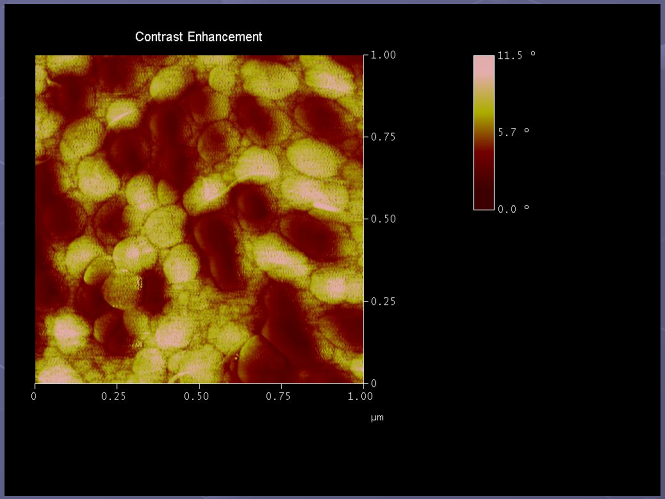
TAMU group (2008)

Homogeneous Superconductor in Inhomogeneous Magnetic Field

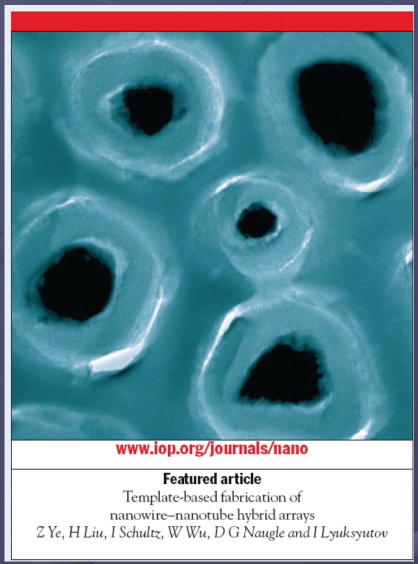
Magnetic Field from Magnetic Nanorods in Alumina Template





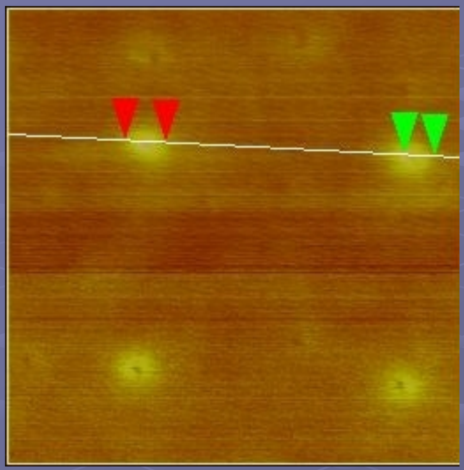


MFM image of the nickel nanowire array with a pitch of 150nm embedded in an alumina matrix the magnetic polarization of the pillars alternately "up" (white) and "down" (black)

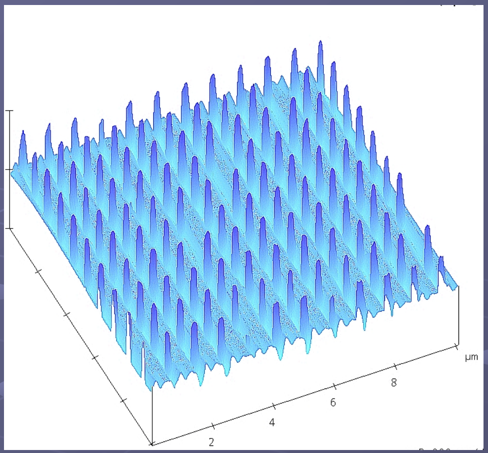


TAMU group (2008)

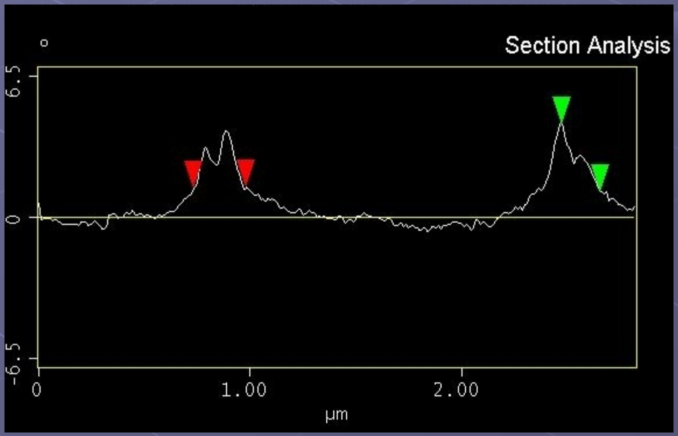
Magnetic Field from Nanorod Array



MFM image of Ni nanorod arrays at 300 K

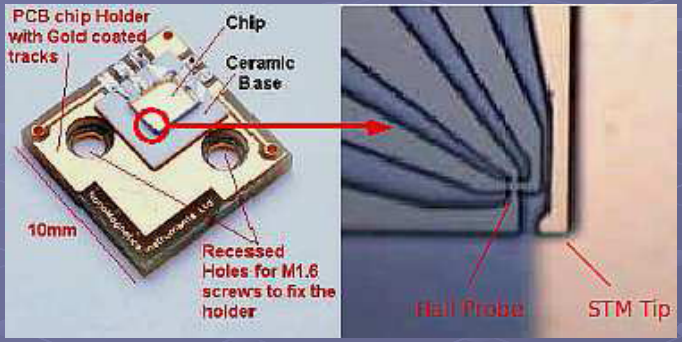


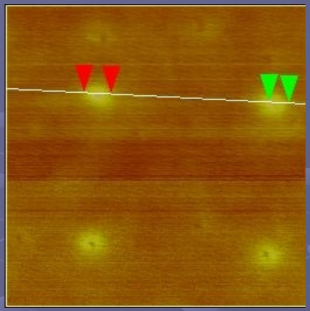
AFM image of Ni nanorod arrays at 300 K



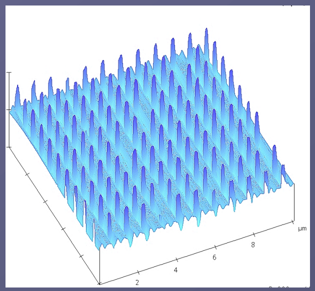
Profile across two nanorods

Magnetic Field from Nanorod Array
Scanning Hall Probe Microscope

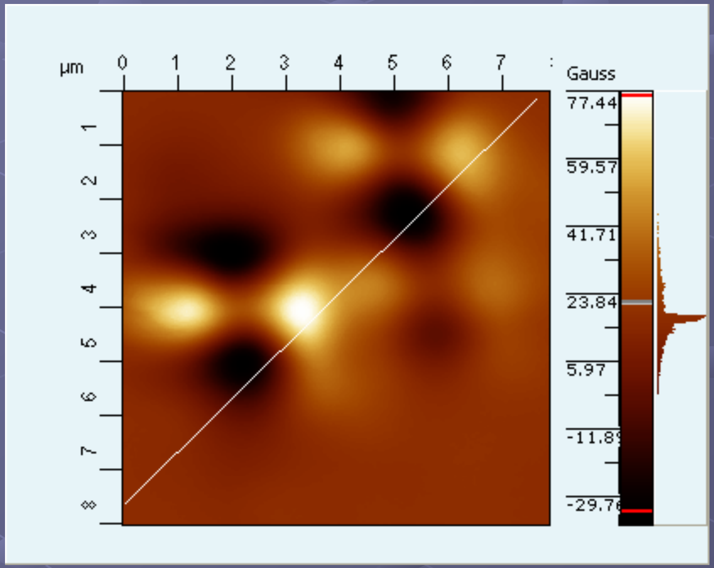




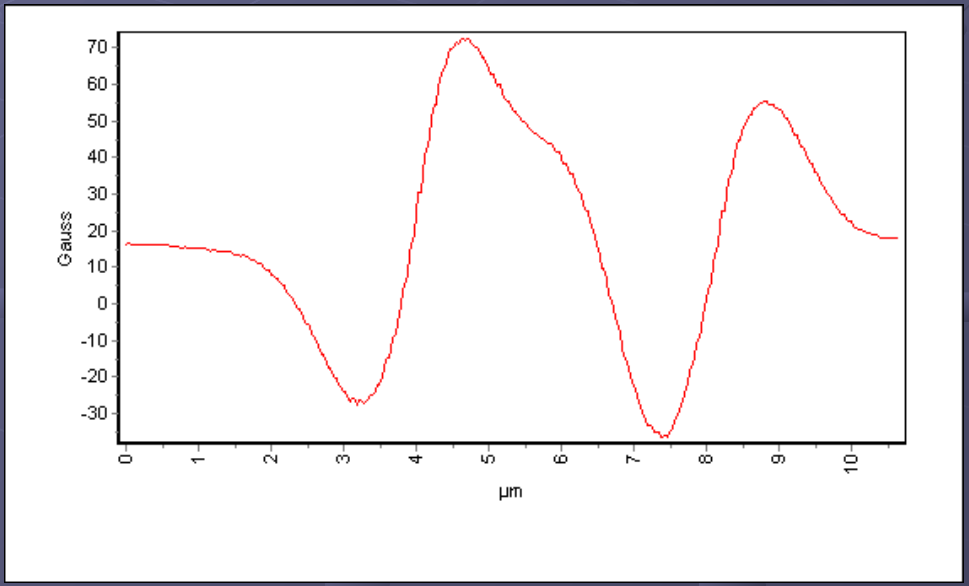
MFM image of Ni nanorod arrays at 300 K



AFM image of Ni nanorod arrays at 300 K



SHPM image of Ni nanorod arrays at 100K



Profile across two nanorods

Magnetic Nanorod and Vortex

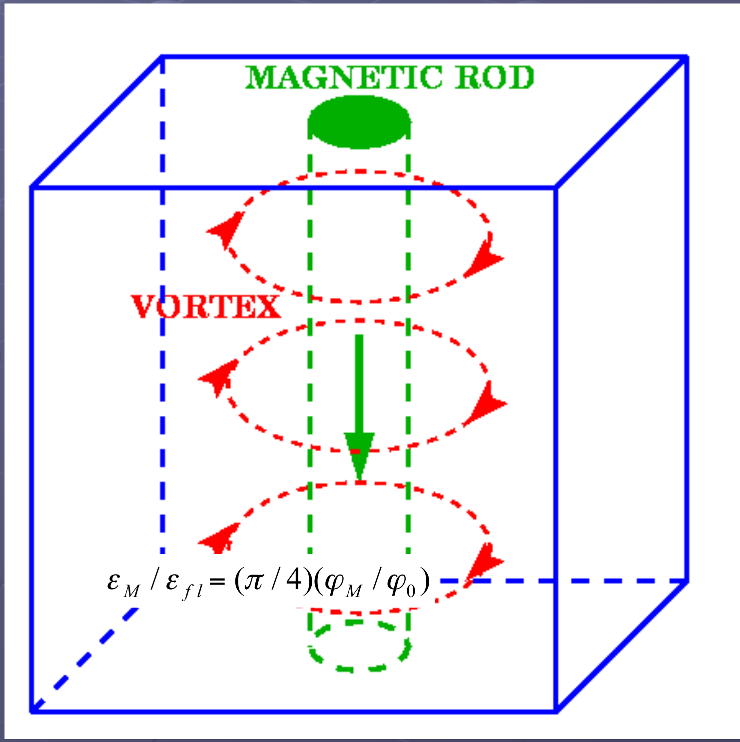
$$\epsilon_{fl} = \frac{\phi_0^2}{16\pi^2\lambda^2} \ln \frac{\lambda}{\xi} = \varepsilon_0 \ln \frac{\lambda}{\xi}$$

$$\epsilon_M = 2\pi \int H(\rho) M \rho d\rho$$

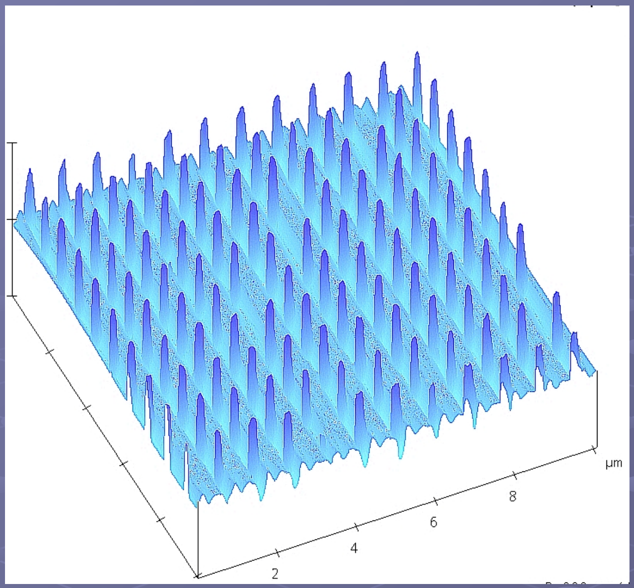
$$H(\rho) = \frac{\phi_0}{2\pi^2\lambda^2} K_0(\frac{\rho}{\lambda})$$

$$\varepsilon_M / \varepsilon_{fl} = (\pi / 4)(\varphi_M / \varphi_0)$$

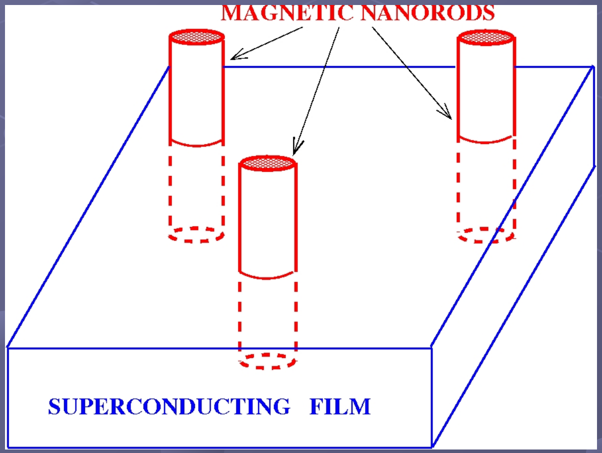
Flux from the rod φ_M

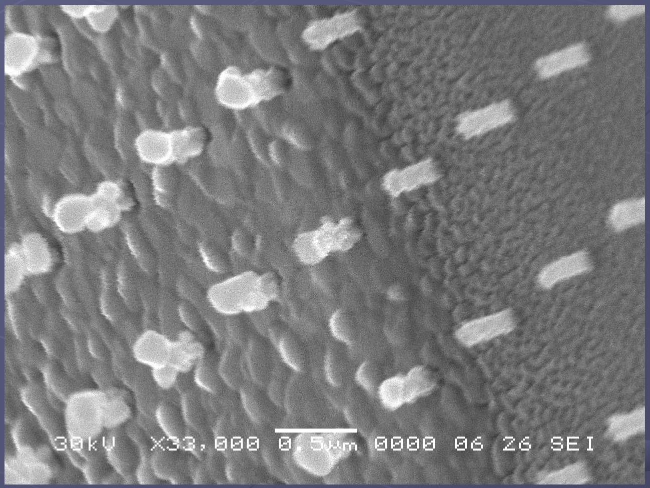


Lyuksyutov, Naugle 1999

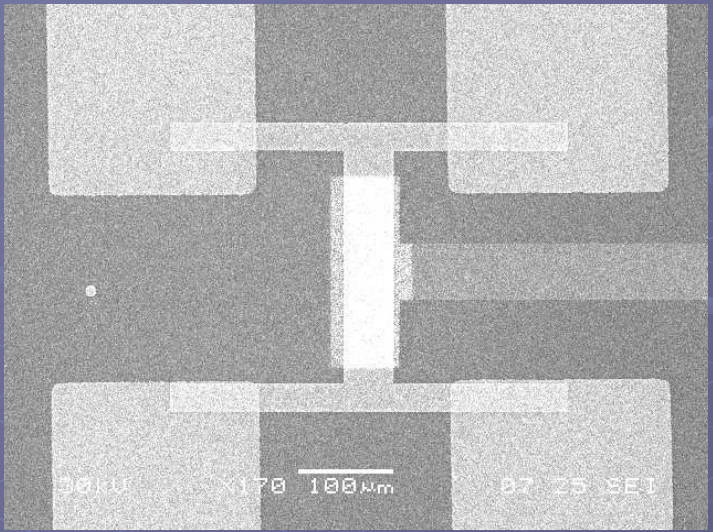


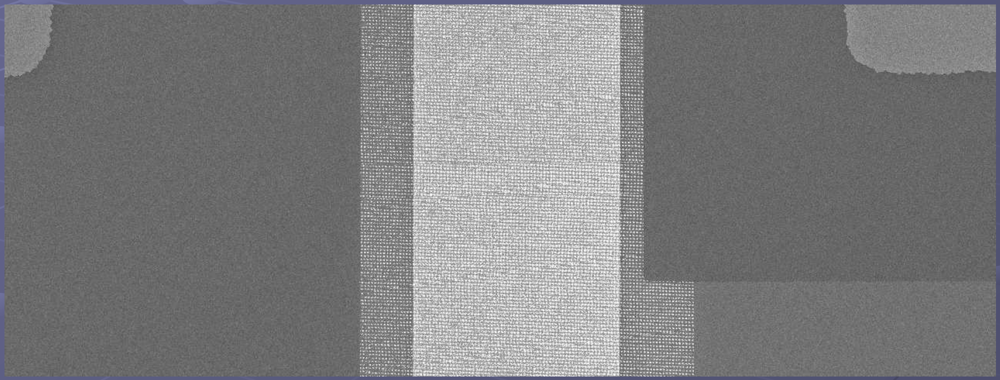
AFM picture of Ni nanocolumn array with period 2 microns, column diameter 50nm and height 350nm;

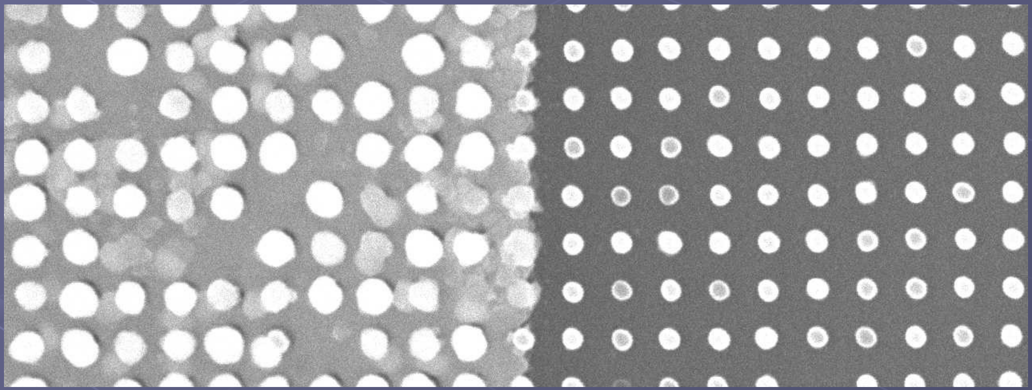




Nickel nanorods embedded into a film of conventional superconductor (left part). Right part shows uncovered substrate (dark) with nickel nanorods (white).


30kV X170 100µm 07 25 SEI

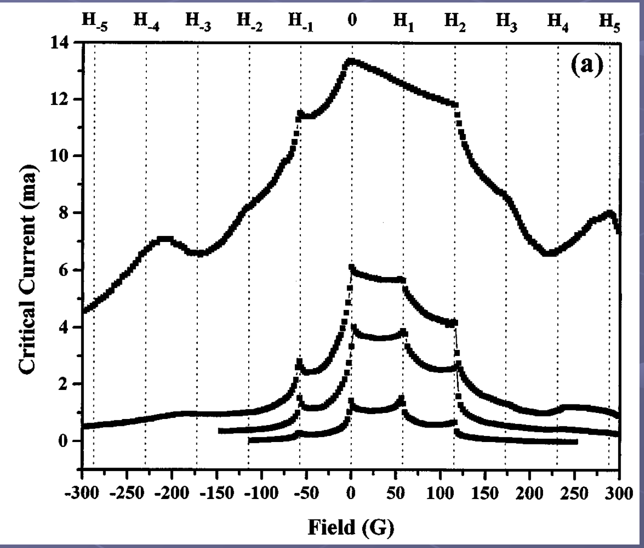


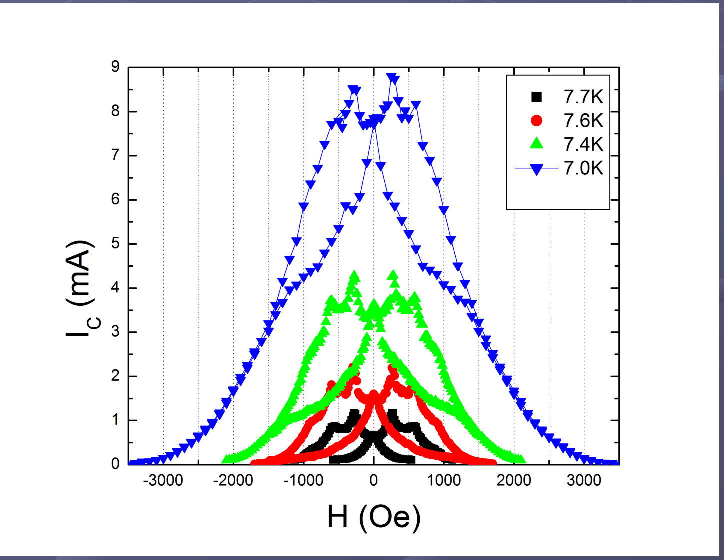


Comparison of Magnetic Dots and Rods

Nickel dots 120 nm diameter by 110 nm height,
niobium film 95 nm thick

Nickel rods 70 nm diameter 350 nm height,
PbBi film 90 nm thick





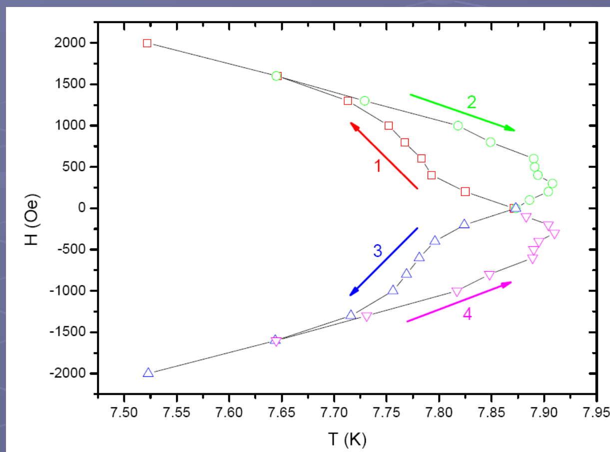
Critical current of Nb film as a function of field for the high density triangular dot array at $T = 8.00$, 8.40, 8.46, and 8.52 K (top to bottom) Tc =8.56 K

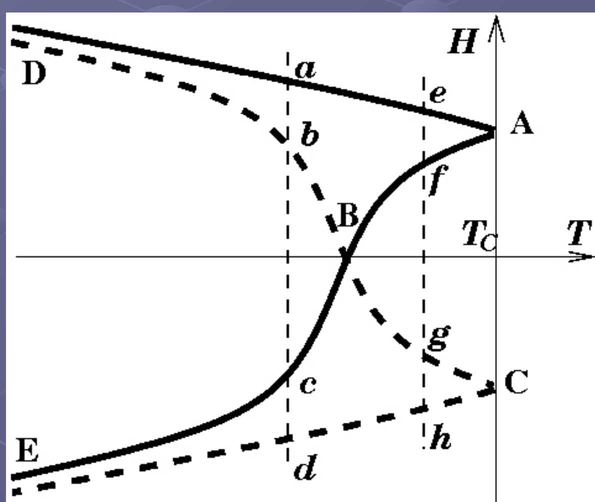
Critical current as a function of field at
T = 7.0K, 7.4K, 7.6K and 7.7K (top to bottom)
Tc = 7.9K for PbBi film with MNC array

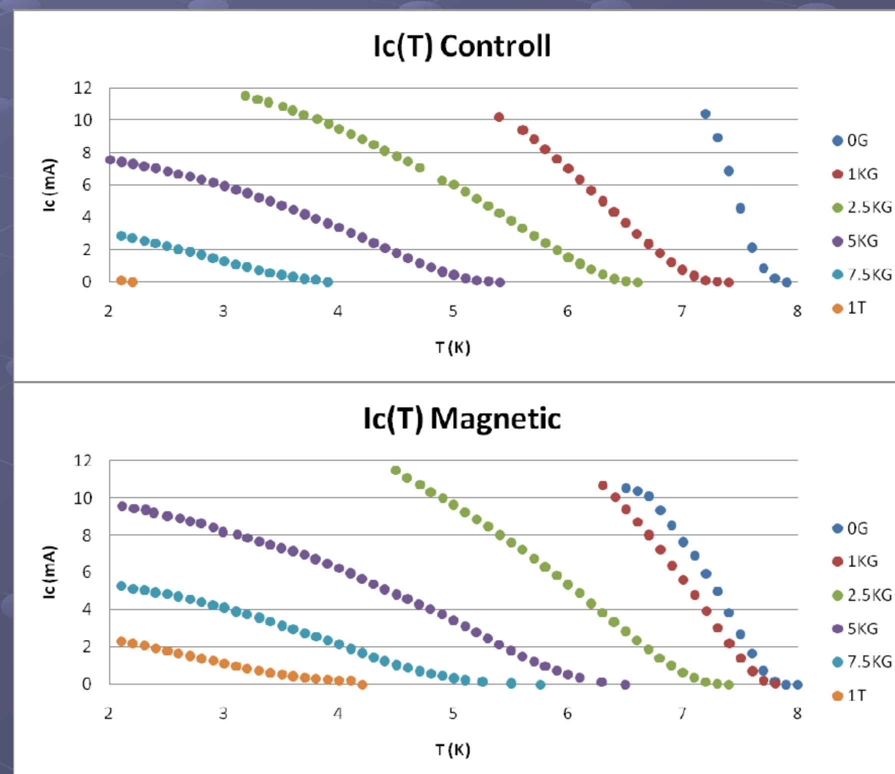
$$H_{Matching} = \frac{\Phi_0}{D^2}$$

$$H_{Matching} = \mathrm{n} \cdot 329\mathrm{Oe}$$

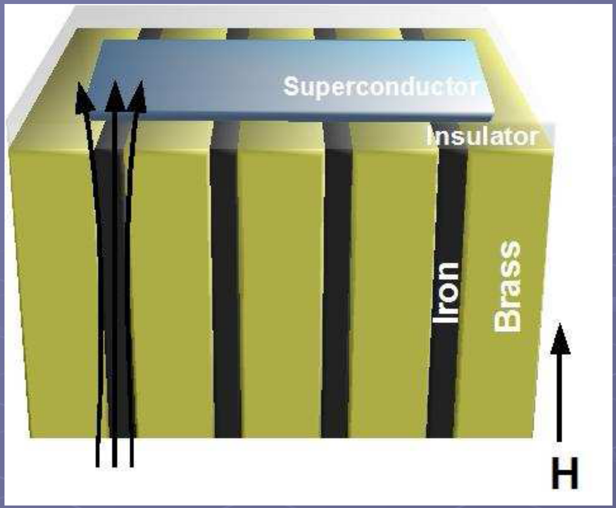
Phase Diagram and Hc2 for Magnetic Nanorods Array

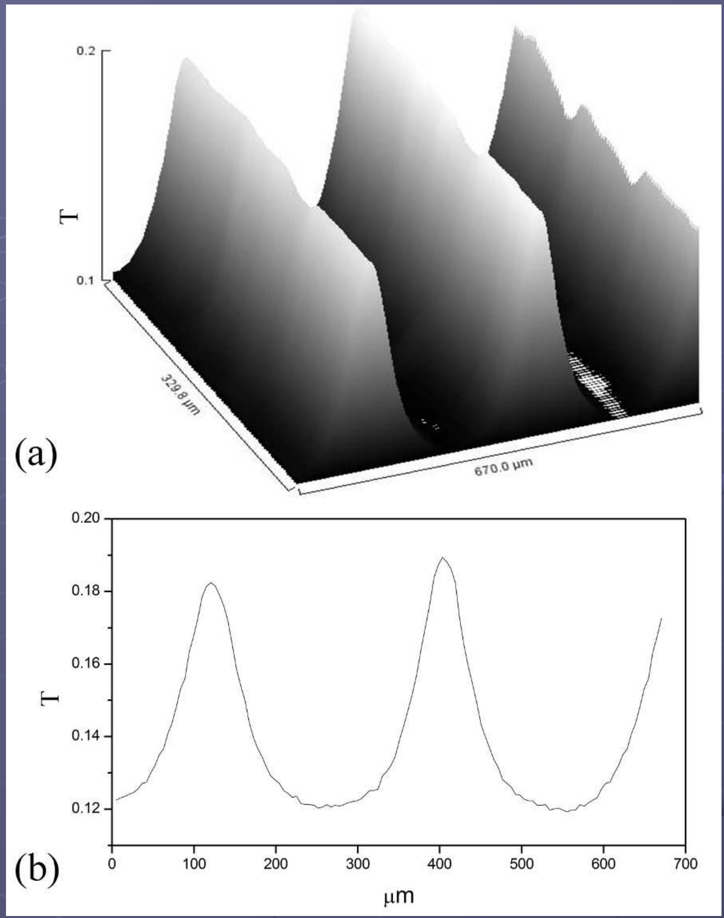


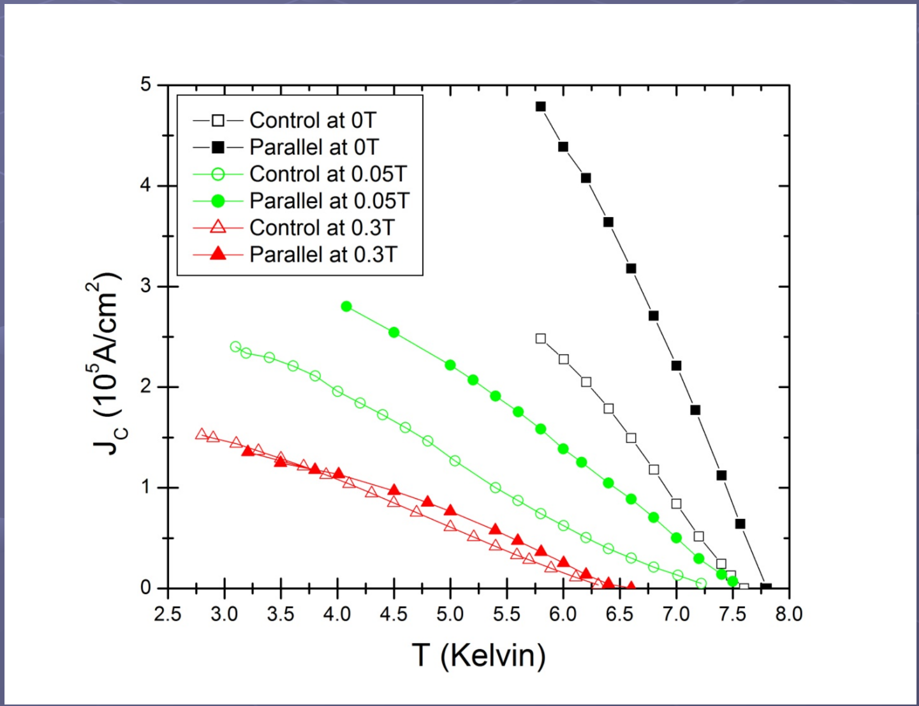




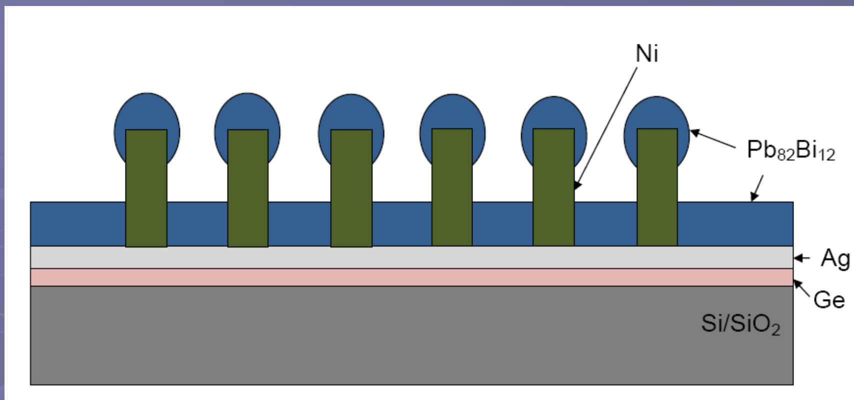
Iron-Brass laminate structure.







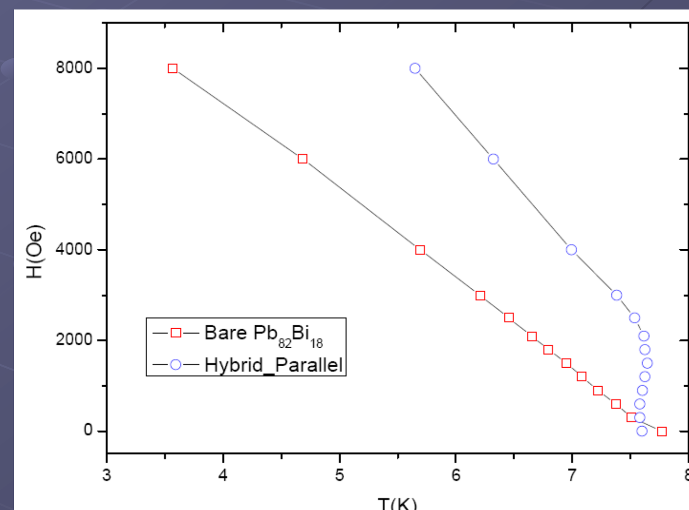
Ni stripes embedded in $Pb_{82}Bi_{12}$ film



Ni stripes: Width ~90nm (from SEM)

Spacing ~250nm (from SEM)

$Pb_{82}Bi_{12}$ 110 nm



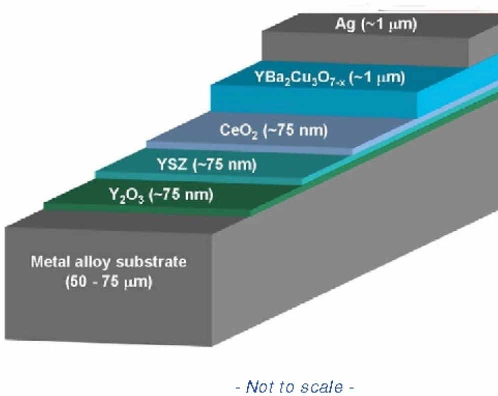
Phase diagram

RABiTS / MOD 2G Strip Architecture

- Substrate: Ni-5a%W alloy
  - Deformation texturing
- Buffer stack: Y_2O_3/YSZ/CeO_2
  - High rate reactive sputtering
- YBCO
  - Metal Organic Deposition of TFA-based precursors
- Ag
  - DC sputtering

Width Evolution

~~1 cm~~ → 4 cm → 10 cm



American Superconductor Corporation

U.S. Department of Energy

2006 Annual Superconductivity Peer Review

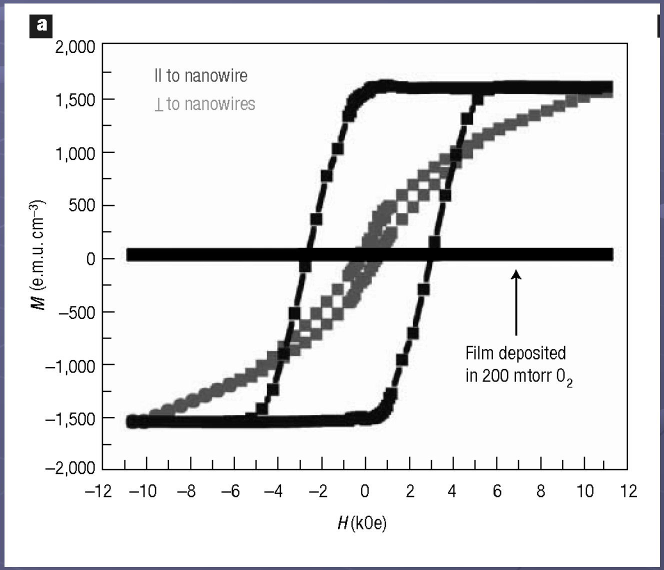
SCALE-UP OF SECOND GENERATION HTS WIRE

Presenters: Steven Fleshler, Alex Malozemoff and Martin Rupich

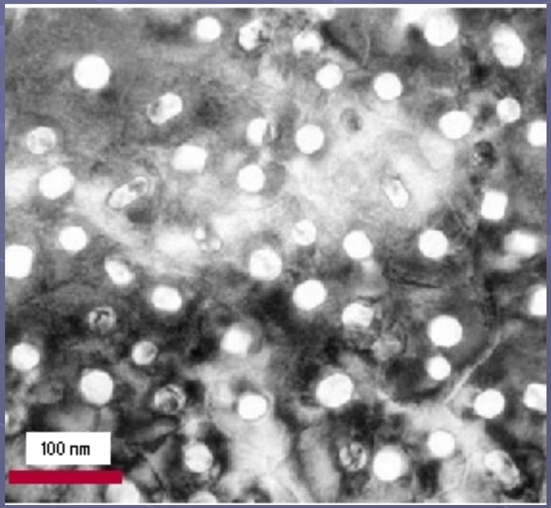
Self-assembled single-crystal ferromagnetic iron nanowires

(α-Fe nanocolumns embedded in a LaSrFeO4 matrix)

Dark-field cross-section image of a film showing
α-Fe nanocolumns embedded in a LaSrFeO4 matrix



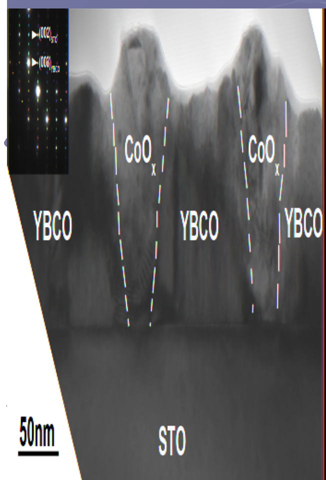
Room-temperature magnetic properties of α-Fe nanocolumns embedded in a LaSrFeO4 matrix. Out-of-plane (wide loop) and in-plane (narrow loop) magnetic hysteresis loops correspond to α-Fe nanocolumns and indicate strong anisotropy

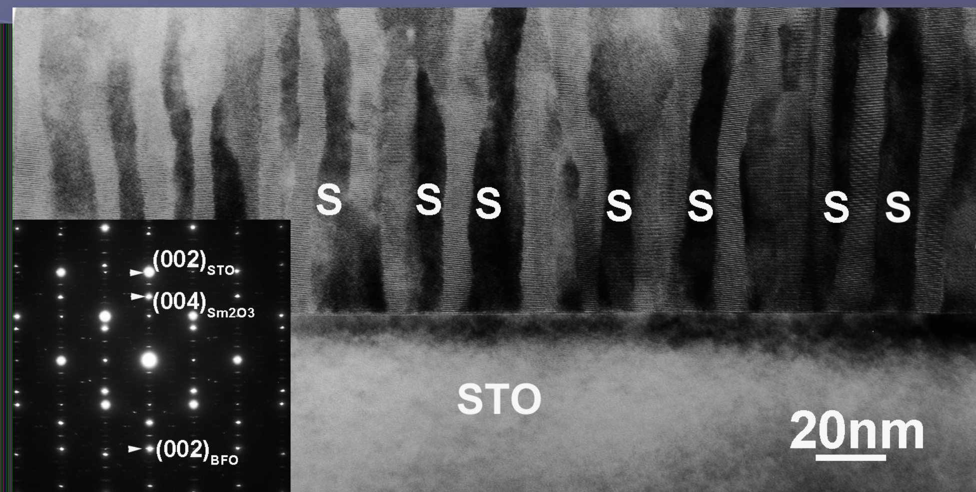


Plan-view TEM image of self-assembled nanostructures in LaSrFeO4 thin films. Film deposited in vacuum at T = 760 °C, showing the decomposition of the perovskite target into a second phase embedded in the matrix

L. Mohaddes-Ardabili et al,
Nature Materials, 3, 533-538 (2004)

Vertically Aligned Nanocomposite (VAN) structure





Cross-section TEM image of YBCO/ CoOx VAN structure (insert is the corresponding selected area diffraction pattern from the view area) produced by Wang at TAMU;

Cross-section TEM image of a BFO/SmO nanocomposite produced by Wang at TAMU showing an ordered pattern of BFO and SmO domains

Conclusions

Interesting physics   with magnetic nanorods

Size is matter

Shape is matter

YBCO films with magnetic nanorods are feasible