Escolas de Inverno do IFGW
20 a 31 de Julho de 2015
Instituto de Física "Gleb Wataghin"
UNICAMP, Campinas-SP

Vortices in Superconductors

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Departamento de Física

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Let's get started with this Tutorial on Vortices in Superconductors

1. Superconductivity
2. Vortices in SCs
3. Magneto-optical imaging (MOI)

Superconductivity, a macroscopic quantum phenomenon discovered more than one century ago, is a field including a huge variety of materials, many of which have encountered relevant practical applications.

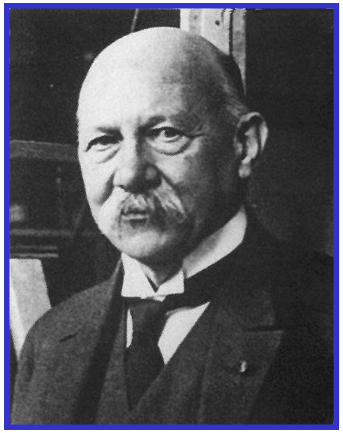
The first part of this Tutorial will be devoted to briefly review the history of Superconductivity, followed by an introductory discussion of the main features of superconducting materials and their uses in real life.

In the second part we'll discuss vortices in superconductors: occurrence, dynamics, implications for applications.

Before finishing we'll devote some time to the MOI technique employed in our lab.

I. Superconductivity

A bit of history



1913 Nobel Prize in Physics

H. Kamerlingh Onnes (Leiden, NL)

1908 – Liquid Helium

1911 – Superconductivity in Hg, T_c ~ 4.2 K

1913 – Superconductivity in Pb, T_c ~ 7.2 K

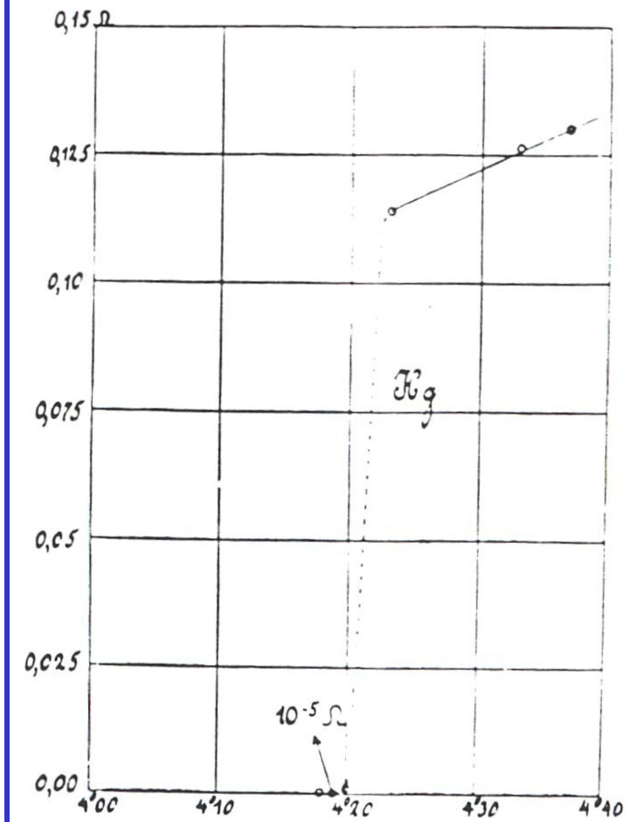
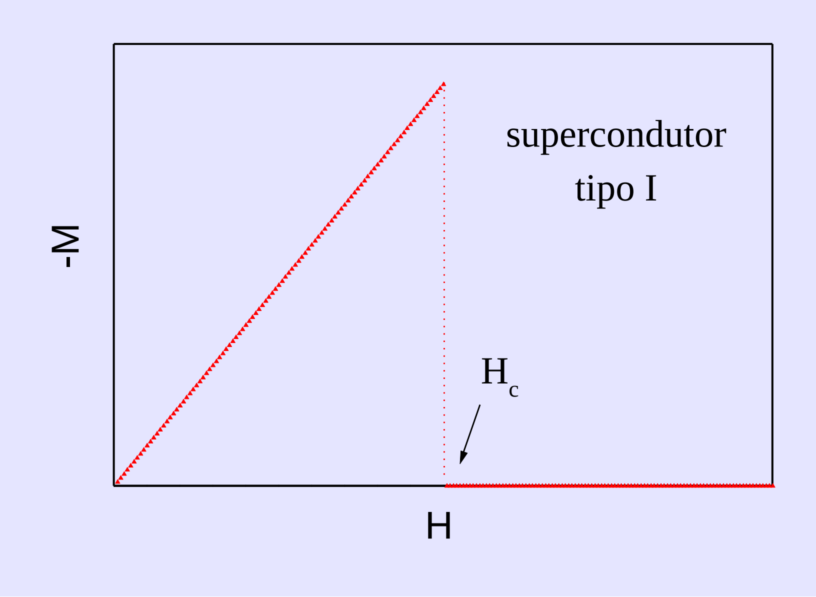


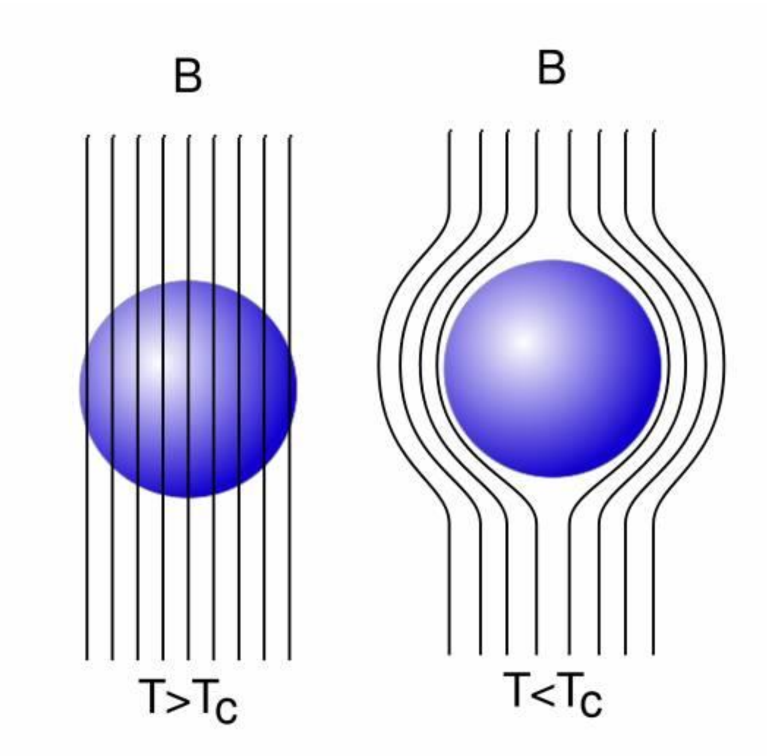
Figure 2.14 Resistivity-versus-temperature plot obtained by Kamerlingh Onnes when he discovered superconductivity in Leiden in 1911.

A bit of history...

Walther Meissner

Robert Ochsenfeld

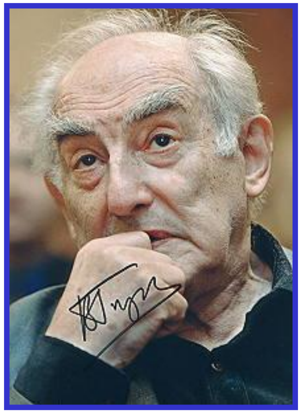
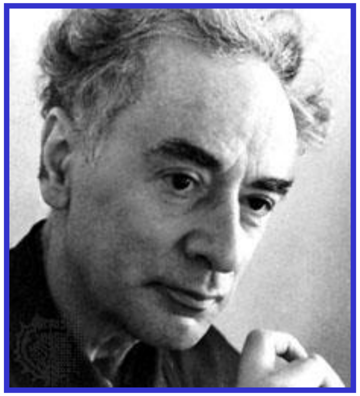


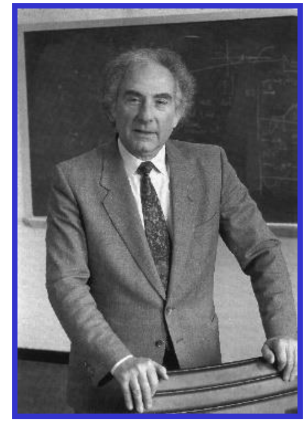
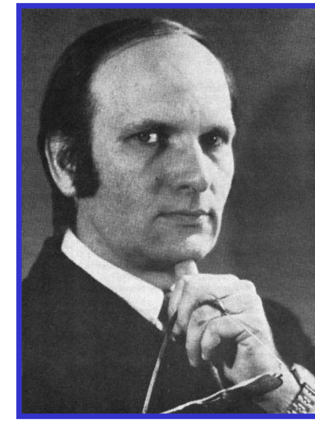


1933 - Meissner effect: perfect diamagnetism

$B = \mu_o(H+M) = 0 \rightarrow M = -H$

A bit of history...


1972

1950's - Fritz e Heinz London (λ); Pippard (ξ)

1950 – Phenomenological Theory proposed by Ginzburg and Landau

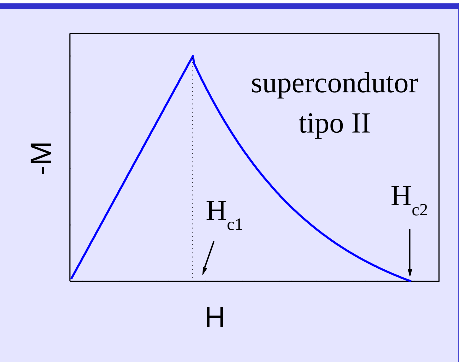
1957 – Microscopic Theory by Bardeen, Cooper and Schrieffer (BCS)

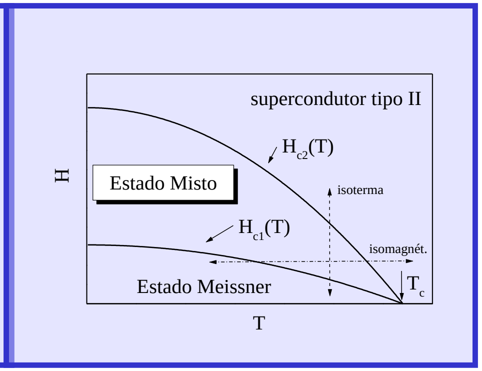
Cooper pairs (bosons) - Phys.Rev.104 (1956)

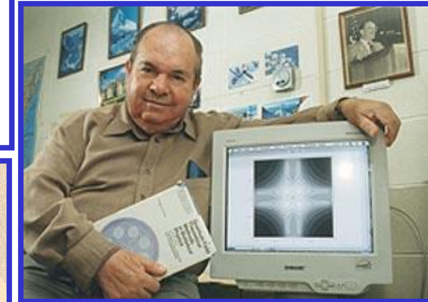
Boson condensate - Phys.Rev.108 (1957); Nobel Prize (1972)

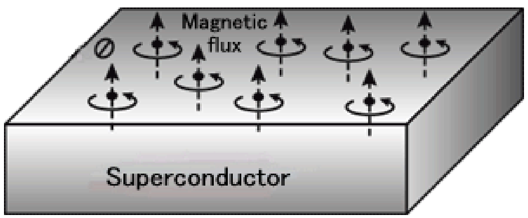
1959 – Gor'kov: GL can be derived from BCS

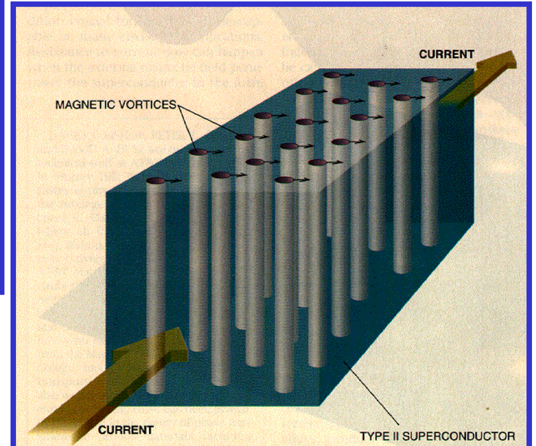
A bit of history...











CURRENT FLOW through a superconductor (*blue rectangular box*) can be disrupted by vortices (*cylinders*). Each vortex consists of a ring of circulating current induced by an external magnetic field (*not shown*). The applied current adds to the circulating current on one side of the vortex but subtracts from the other. The net result is a force that pushes the vortices at right angles to the current flow; the movement dissipates energy and produces resistance.

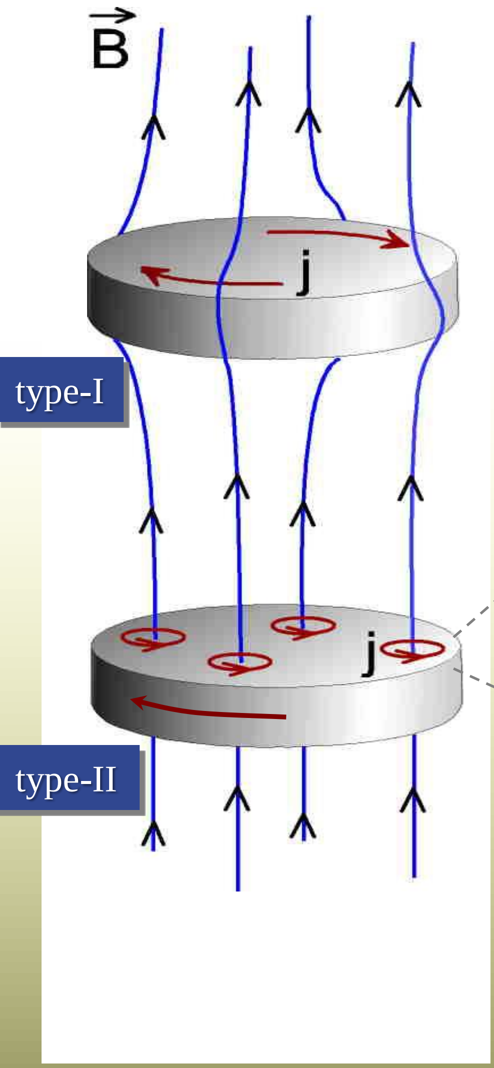
1957 – Abrikosov predicted the existence of another type of SC (type II)

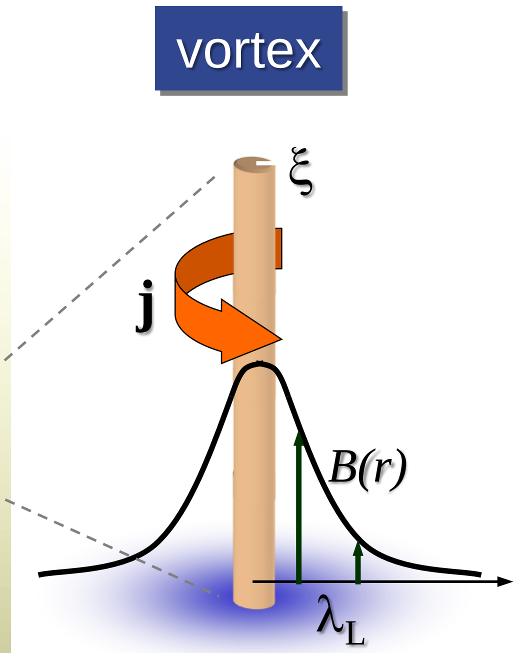
Surface energy can be negative in certain cases ($\kappa = \lambda/\xi > 0.707$)

➔ creation of N/SC interfaces becomes energetically favorable

<u>Fluxoides or Vortices</u>: normal regions in the form of "tubes", penetrated by one quantum flux each, $\phi_o \sim 2x10^{-15}$ SI, surrounded by superconducting screening currents.

Vortex matter





$$\int B\, dA = h/2e = \Phi_0$$

Flux quantum

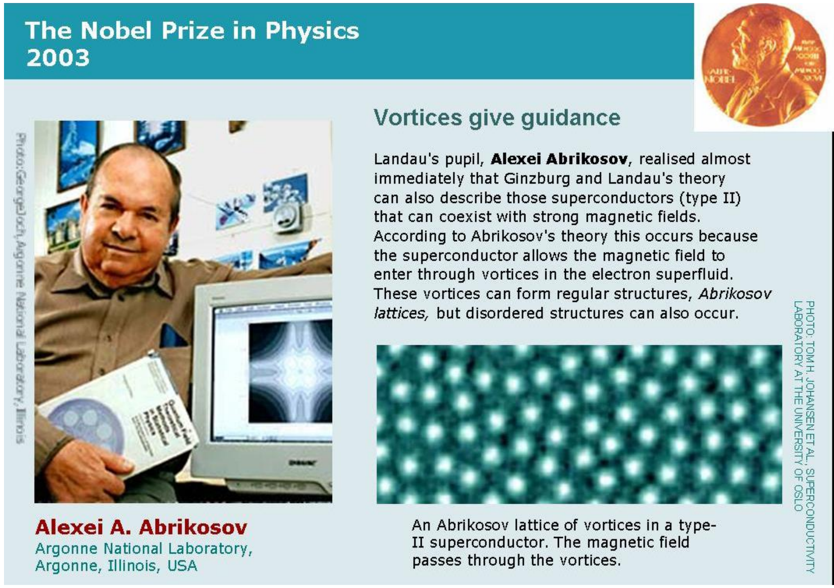

The Nobel Prize in Physics 2003

Photo: George Joch, Argonne National Laboratory, Illinois

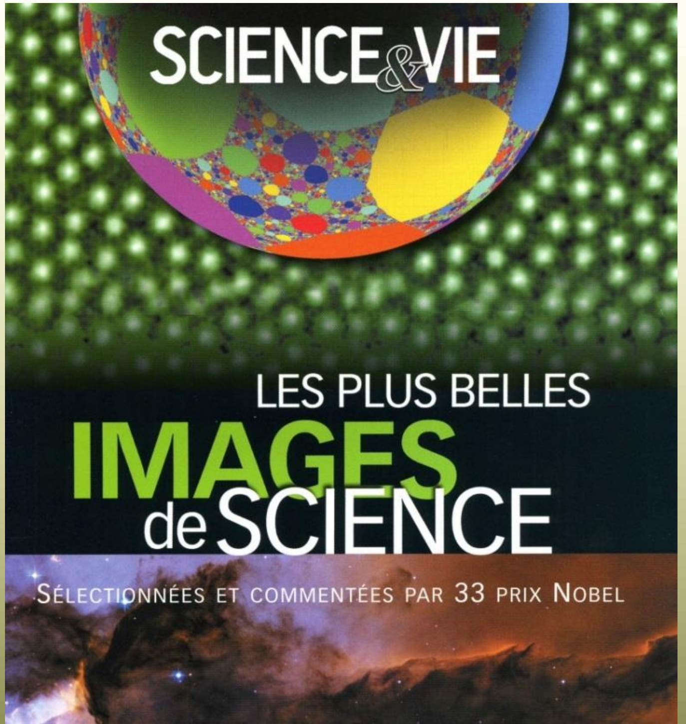
Alexei A. Abrikosov
Argonne National Laboratory, Argonne, Illinois, USA

Vortices give guidance

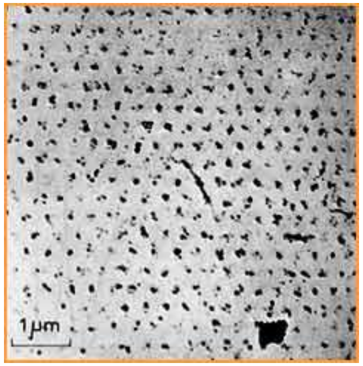
Landau's pupil, **Alexei Abrikosov**, realised almost immediately that Ginzburg and Landau's theory can also describe those superconductors (type II) that can coexist with strong magnetic fields. According to Abrikosov's theory this occurs because the superconductor allows the magnetic field to enter through vortices in the electron superfluid. These vortices can form regular structures, *Abrikosov lattices*, but disordered structures can also occur.

An Abrikosov lattice of vortices in a type-II superconductor. The magnetic field passes through the vortices.

PHOTO: TOM H. JOHANSEN ET AL., SUPERCONDUCTIVITY LABORATORY AT THE UNIVERSITY OF OSLO



A bit of history...

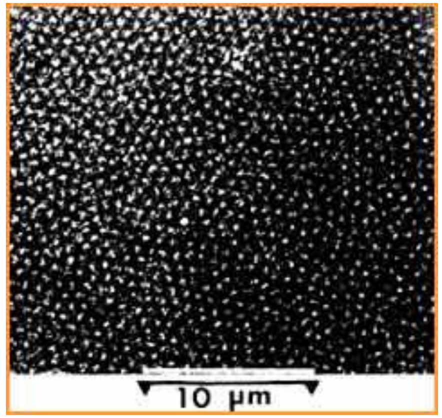


Primeira Imagem

Bitter Decoration 1967

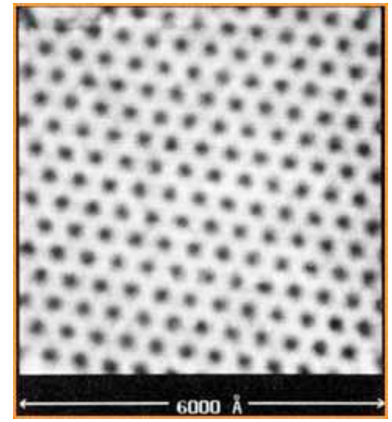
Pb-4at%In rod, 1.1K, 195G

U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart



Bitter Decoration
$YBa_2Cu_3O_7$ *crystal, 4.2K, 52G*

P. L. Gammel et al., Bell Labs

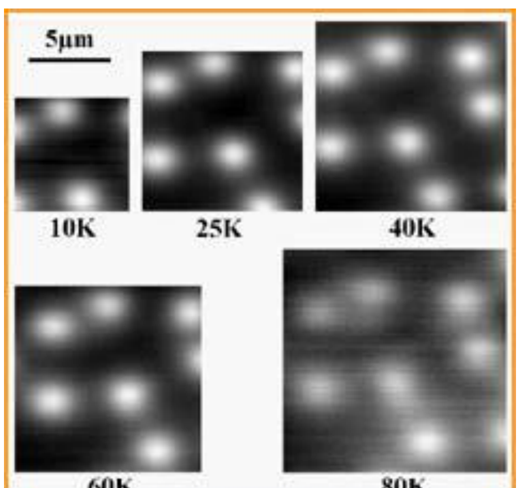


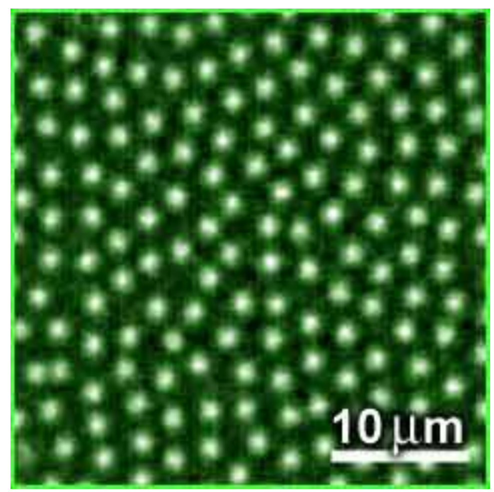
Scanning Tunnel Microscopy
NbSe2, 1T, 1.8K

H. F. Hess et al., Bell Labs

Scanning Hall probes
YBaCuO film, 1000G

A. Oral et al.
University of Bath





Magneto-Optical Imaging
NbSe2 crystal, 4.3K, 3G

P.E. Goa et al.
University of Oslo

A bit of history...

1987

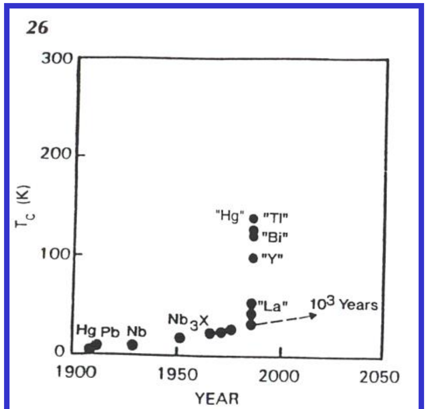


Figure 2.2 Increase in the superconducting transition temperature with time. A linear extrapolation of the data before 1986 predicts that room temperature would be reached in about 1000 years. From left to right $X = Sn$, $Al_{0.75}Ge_{0.25}$, Ga, and Ge for the data points of the *A15* compound Nb_3X (Adapted from Fig. I-1. Poole *et al.*, 1988).

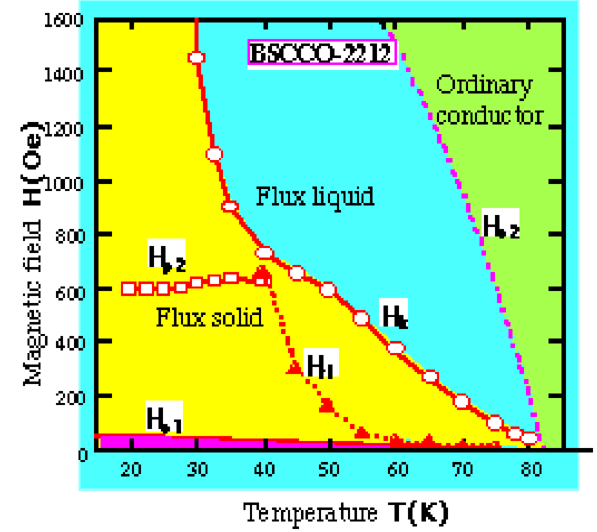


Fig. 27. Magnetism phase diagram showing domains of different flux states.

1986 – Age of the "High Temperature Superconductors" – HTS (type II)

17/04/86 - Bednorz & Muller – $Ba_xLa_{5-x}Cu_5O_y$ – T_c ~ 30 - 35 K

1987 – Chu, Zhao - $YBa_2Cu_3O_{7-\delta}$ (YBCO, YBaCuO, Y-123) – T_c ~ 92 K

1988 – $Bi_2Ba_2CaCu_2O_y$ – T_c ~ 110 K

1993 – $Tl_2Ba_2Ca_2Cu_3O_{10-x}$ – T_c ~ 132 K, $HgBa_2Ca_nCu_{n+1}O_{2n+4}$ – T_c > 130 K,

Great hopes for applications partially frustrated: ceramic materials are diffict to mold and, moreover, critical currents are limited by weak-links.

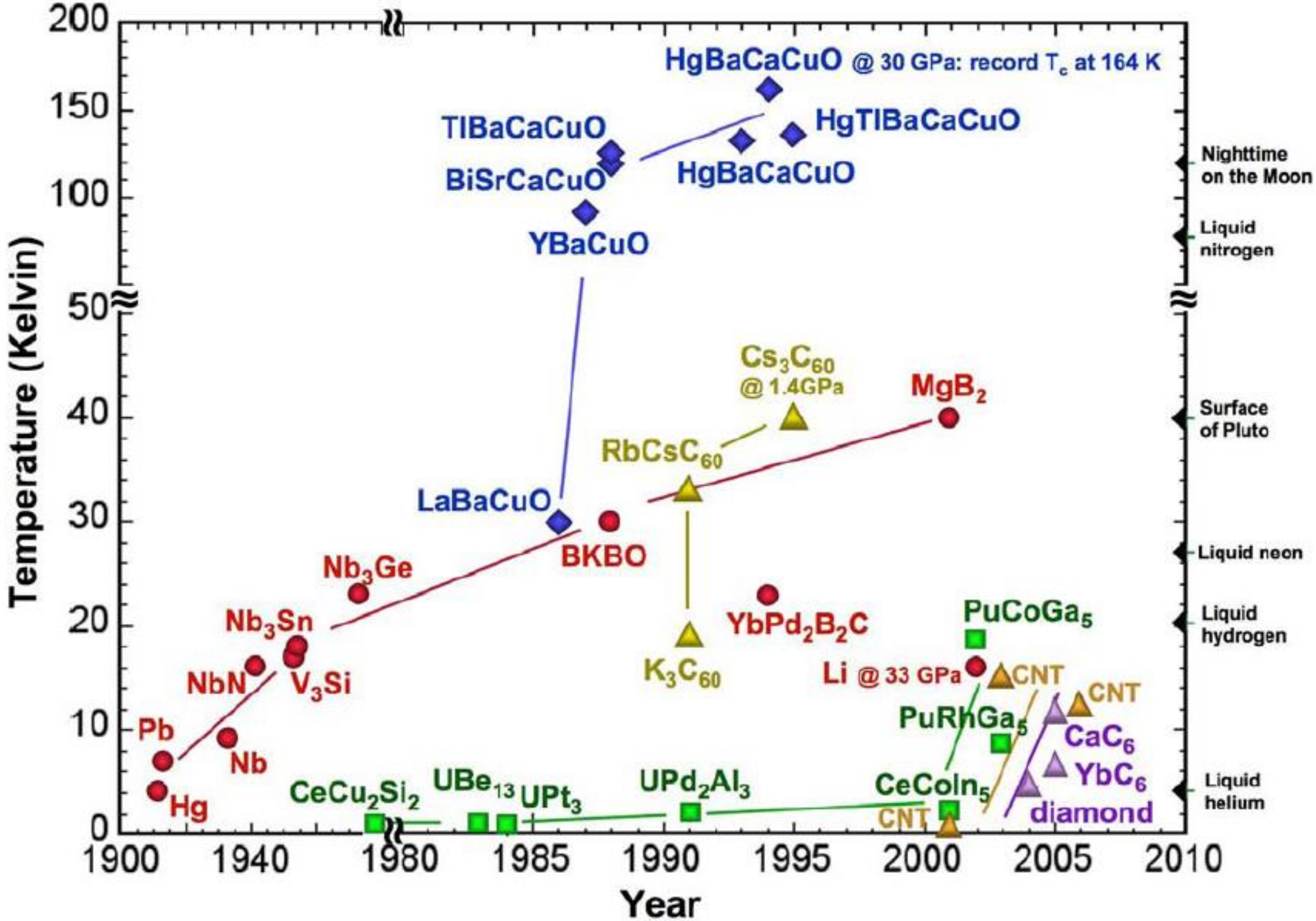


Figure 24 The observed superconducting transition temperature (T_c) of a variety of classes of superconductors is plotted as a function of time. Recent discoveries have increased the highest-observed T_c in a number of materials to unprecedented levels, such as in heavy fermion ($PuCoGa_5$), carbon nanotubes (CNTs), and graphite intercalated compounds (CaC_6).

Wide list of aplications:

Energy - production, storage & distribution;

Sensing magnetic fields;

Production of strong magnetic fields for:

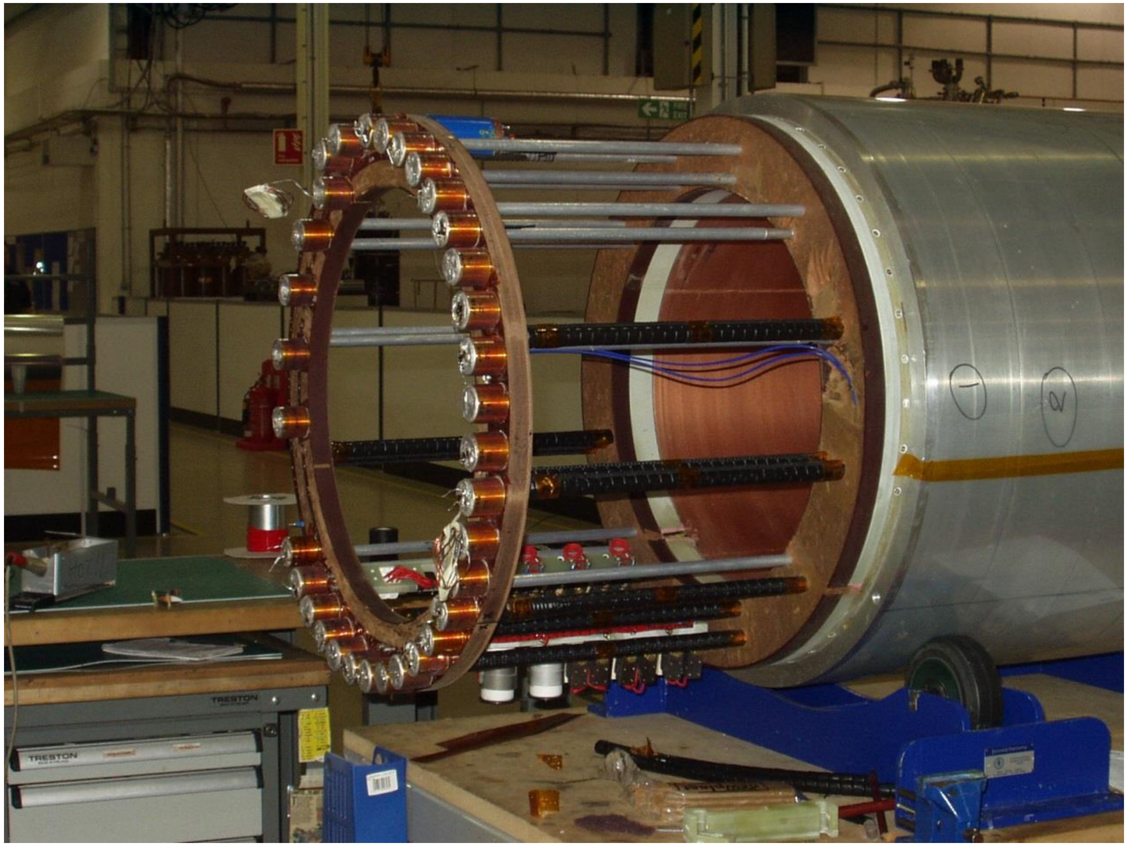
- Nuclear Magnetic Ressonance (research)
- NMR Imaging (medical use)
- Deflection, focusing and detection of charged particle beams (particle acelerators)
- Plasma confinment (fusion reactors)
- Levitation (transport of load and people)

Some applications

Current Limiters (transmission lines)

QUbits (quantum computing)

Wires for solenoids – generation of high magnetic fields (labs; NMRs)



Some applications

SQUIDs – flux detectors (labs; magnetographies: encephalo-, cardio-)

Some applications

Magnetic levitation:

Bearings for large rotors (fly wheels)

Maglev prototype (Japanese, Nb-Ti)

Test vehicle (Chinese, HTS)

HTS SC cables - Second Generation

American
Superconduct

Voltage regulating systems of Eolic Generators

Superconductivity - Basic Concepts

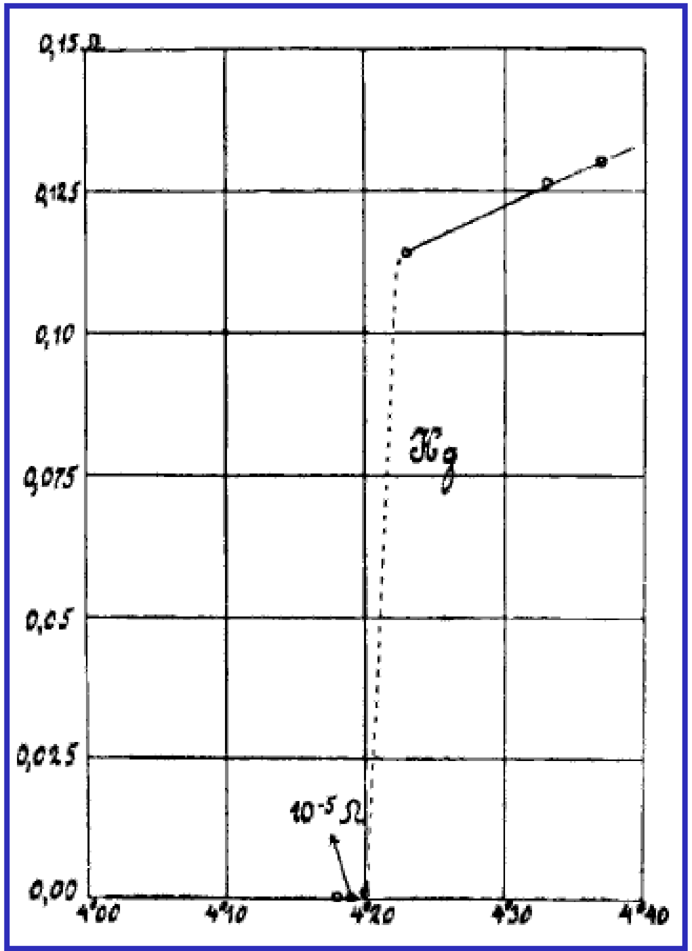
Superconductivity is a Macroscopic Quantum State featuring two distinguishing properties:

. Supercurrents
  (dissipationless transport)

. Screening of magnetic fields
  (Meissner effect)

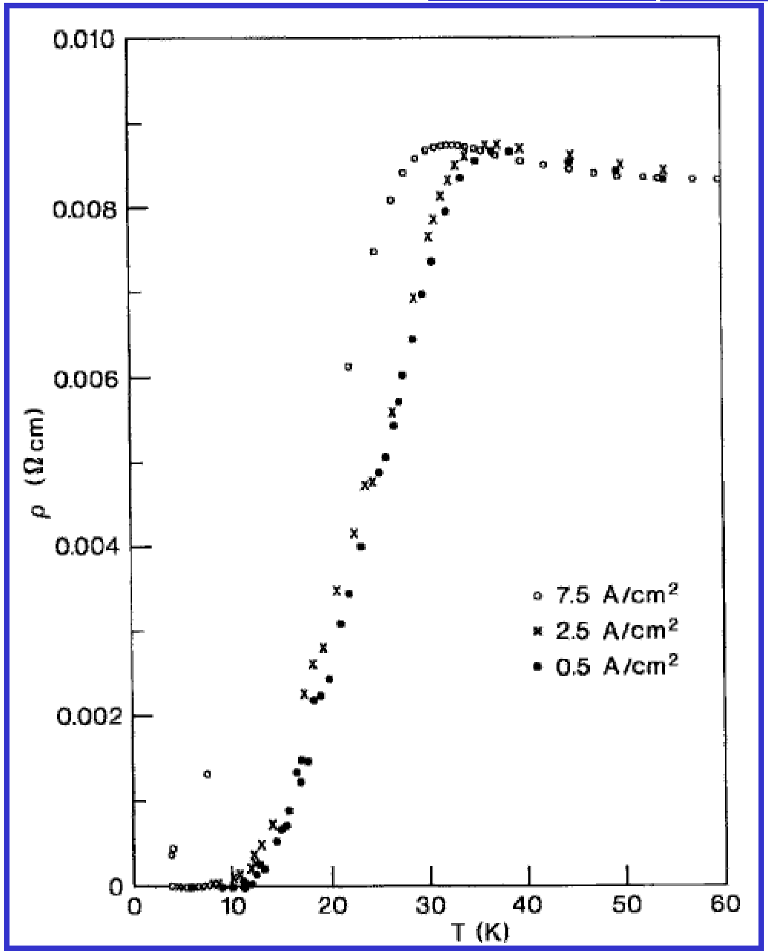
Zero-voltage supercurren

Two classics: H. K. Onnes and Bednorz & Mu



H. Kamerlingh Onnes

Hg - 1911



Bednorz & Müller

$La_{2-x}Ba_xCuO_4$ - 1986

At any given temperature (T) and applied magntic field (H), a superconducting sample is able to carry a maximum supercurrent density, J_c, the Critical Current:

$$J_c = J_c\,(H,T)$$

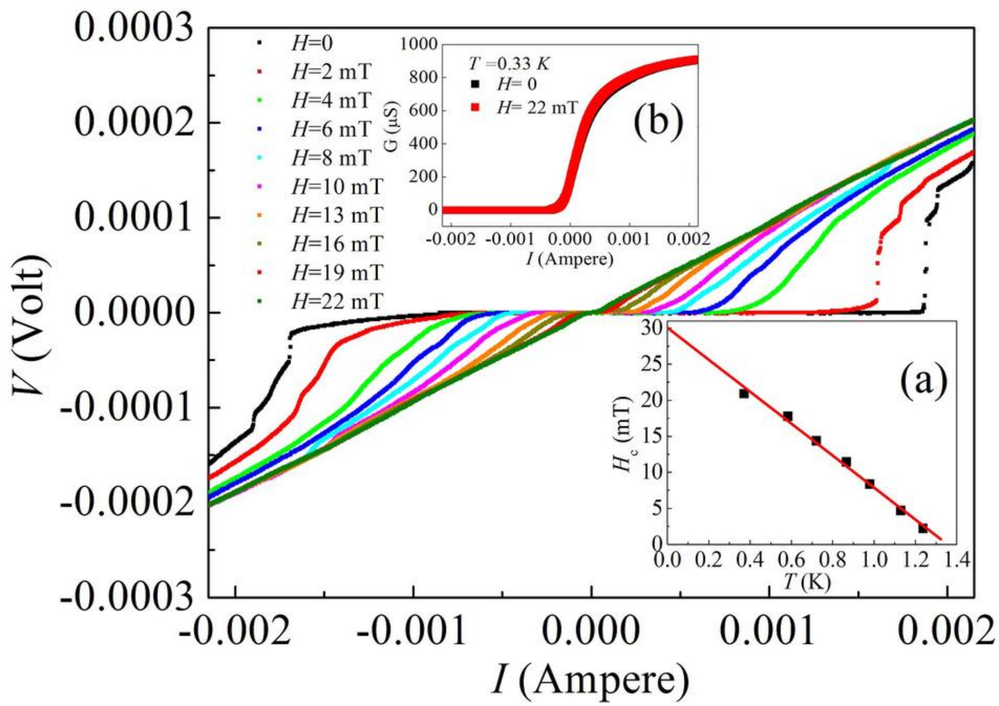


Figure 6: Four-terminal current-voltage characteristics of the Al film *V(I)* at various magnetic fields *H*.

Scientific Reports **3**, Article number:2274 doi:10.1038/srep02274

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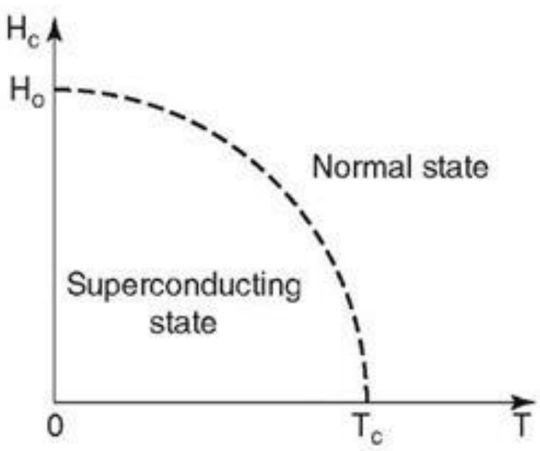
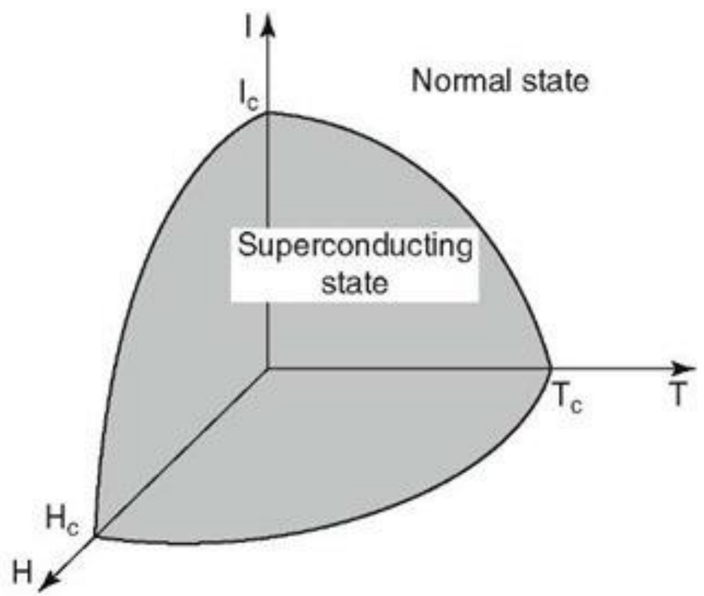


(a)



(b)

Superconductivity - Basic Concepts

Superconductivity is a Macroscopic Quantum State featuring two distinguishing properties:

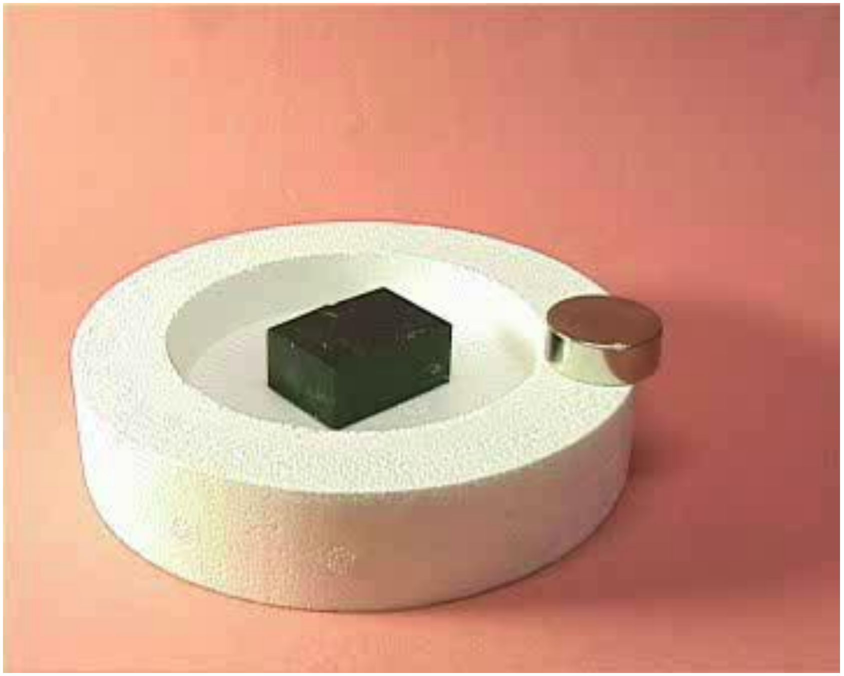
. Supercurrents
  (dissipationless transport)

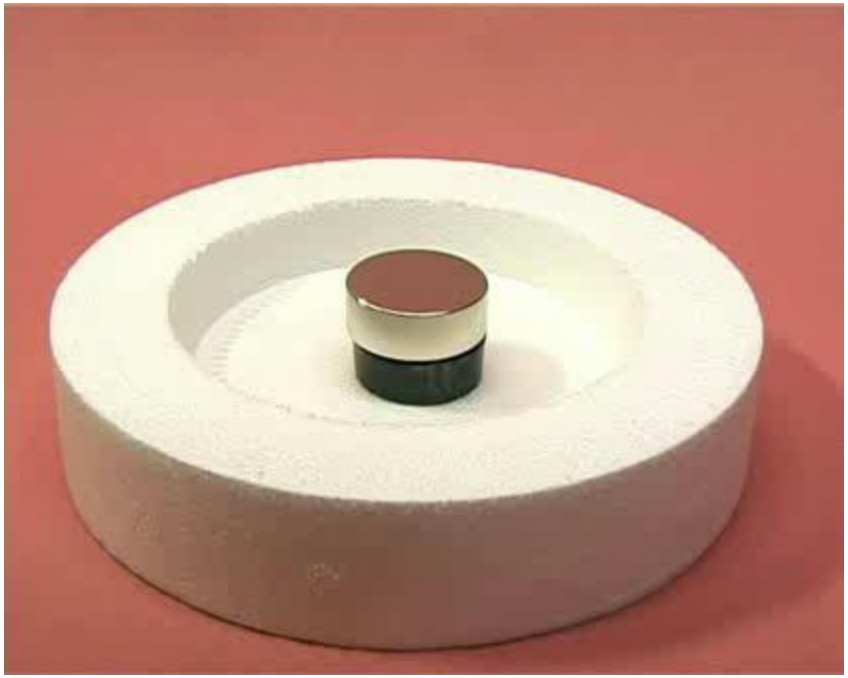
. Screening of magnetic fields
  (Meissner effect)

Screening of magnetic fields - Meissner effect

Zero field cooling (ZFC)

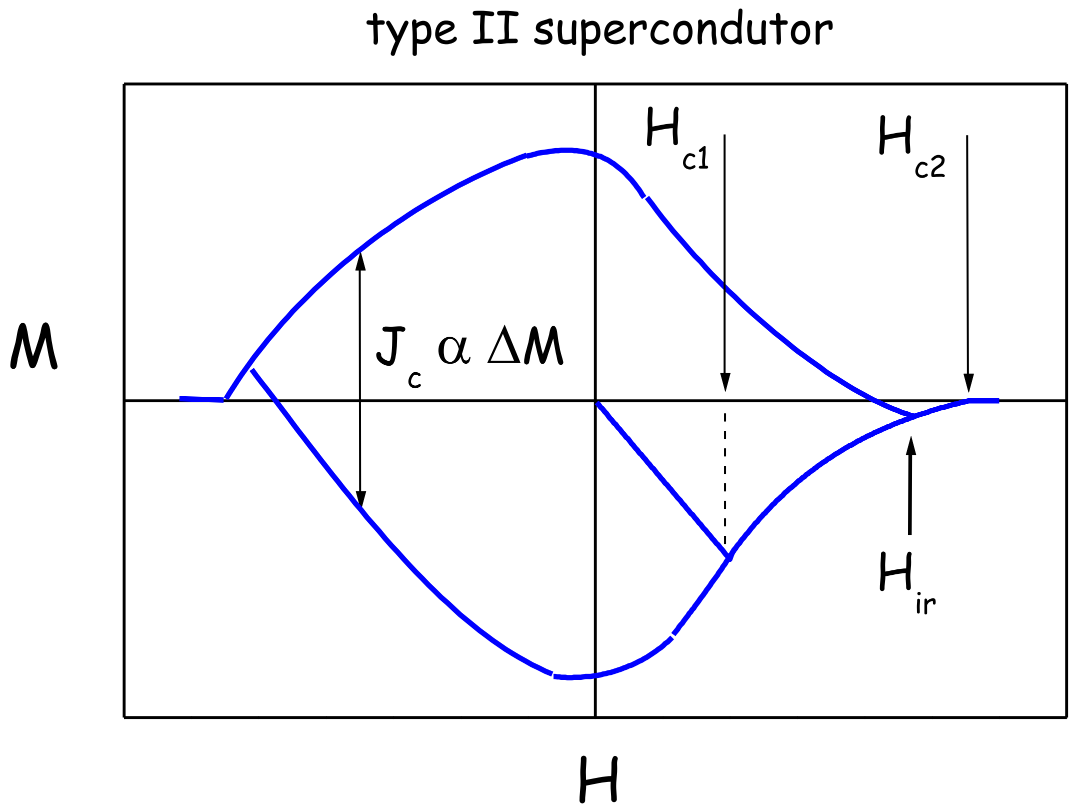
Field-cooling (FC)





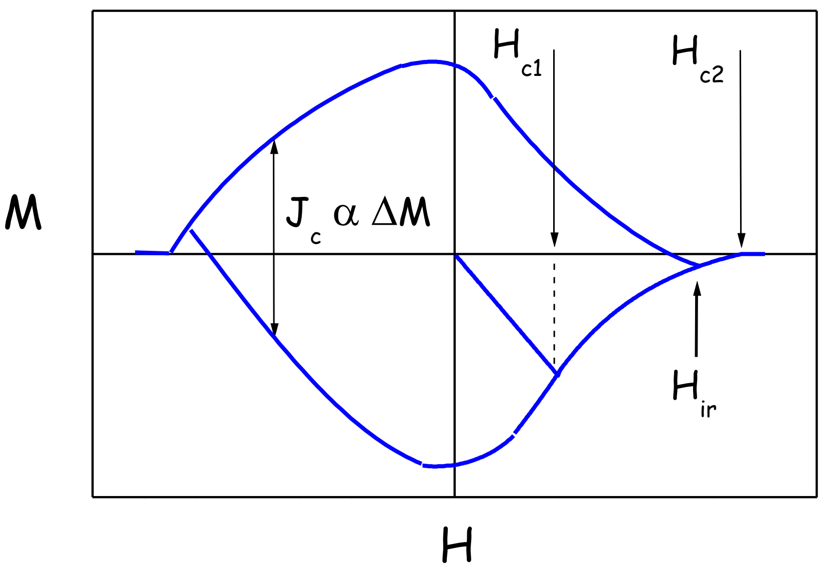
http://www.fys.uio.no/super/

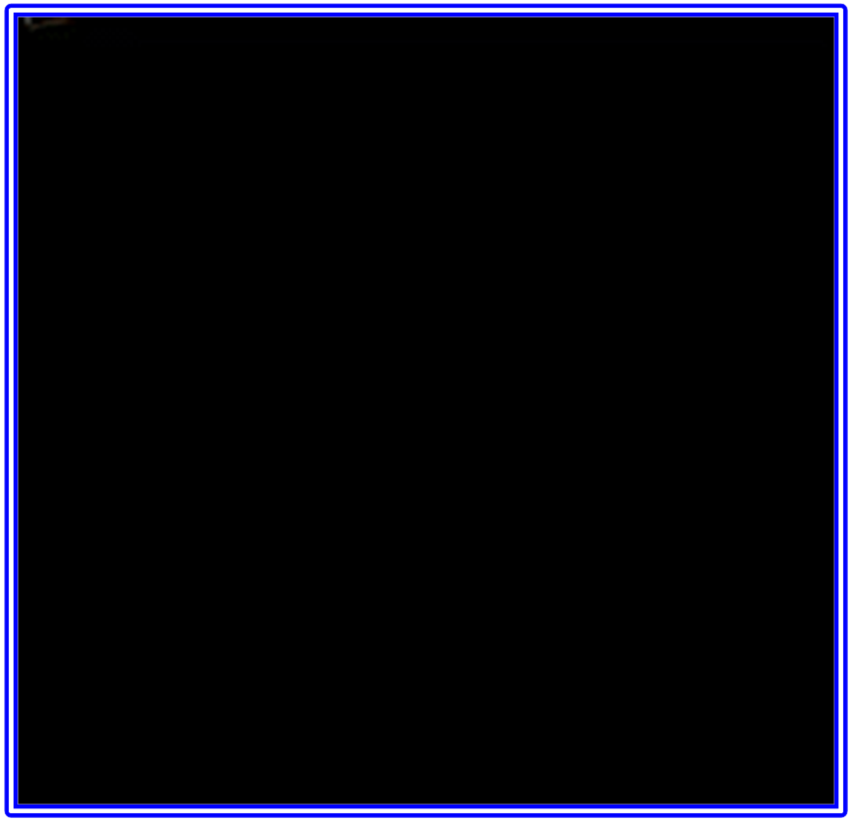
Magnetic Field Screening



Penetration Profile: Critical State

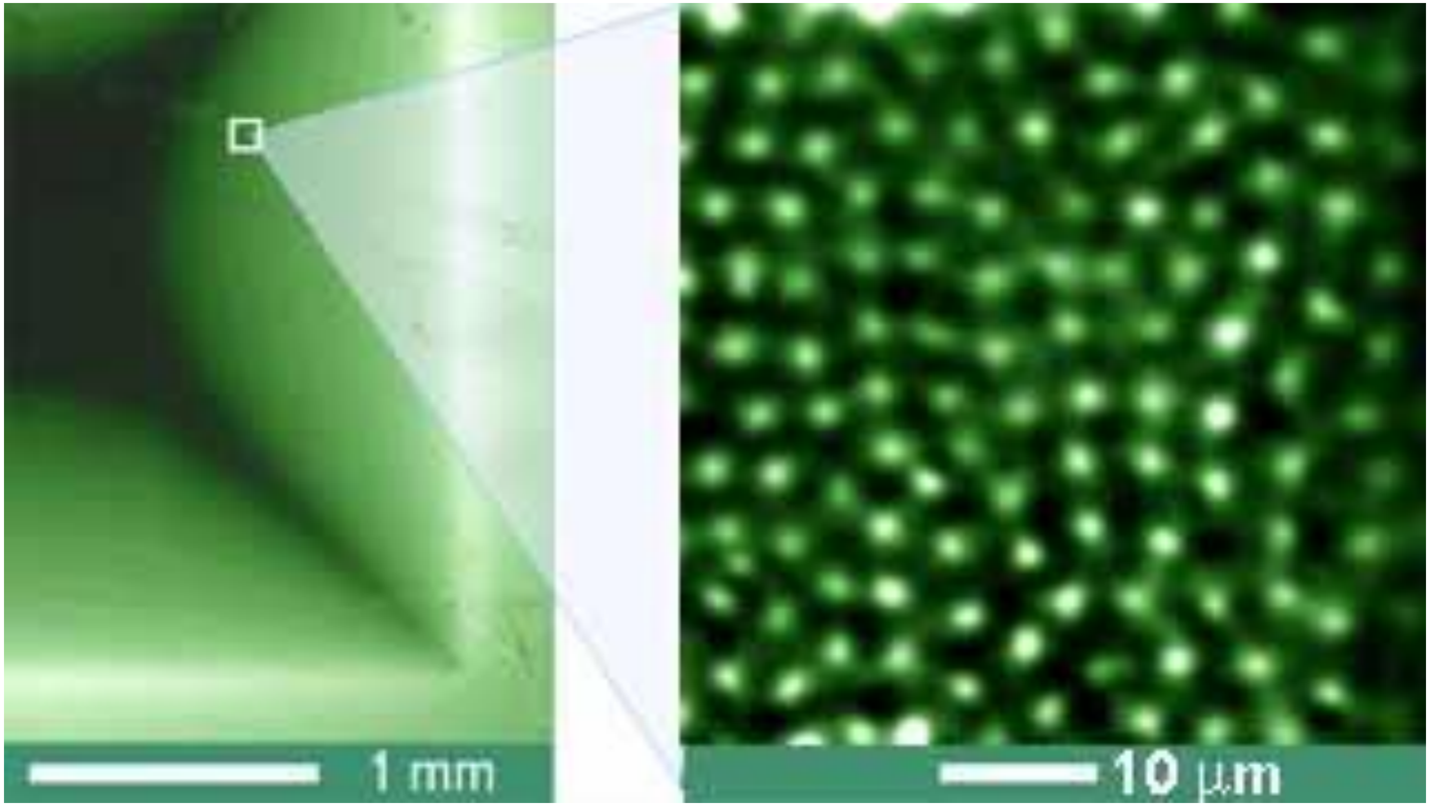
type II supercondutor





Flux distribution apparently continuous...

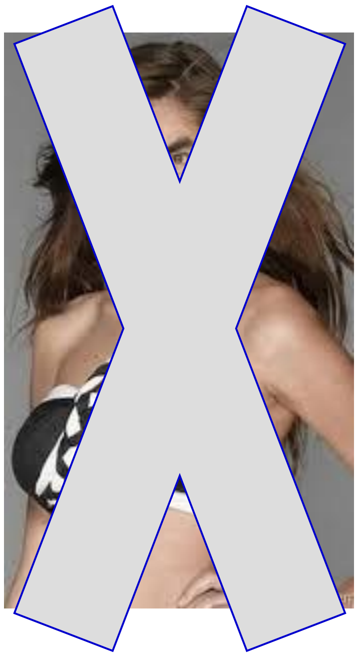
in reality, quantized flux: vortices

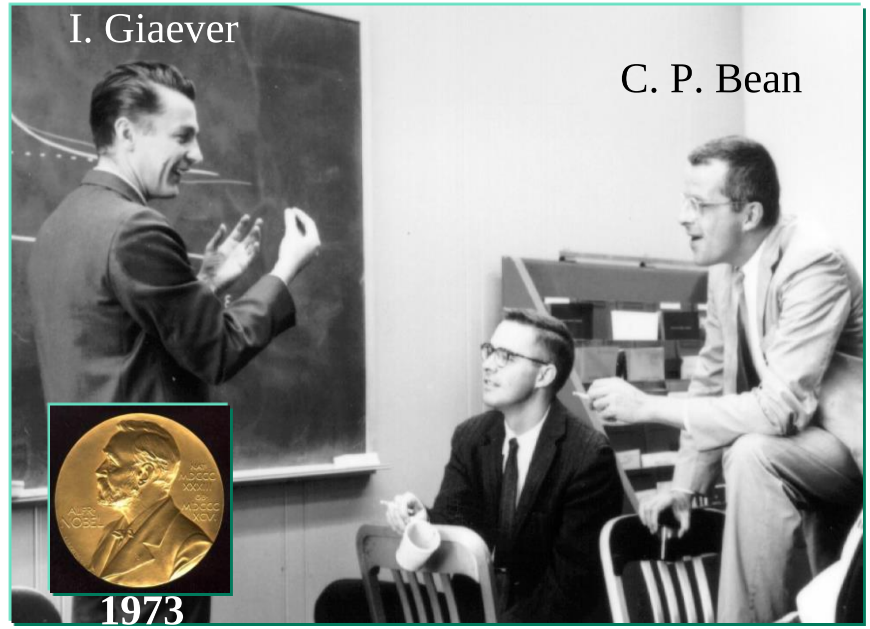


http://www.fys.uio.no/super/

Although quantized, flux is usually (conveniently) treated as "continuous"

Bean Model



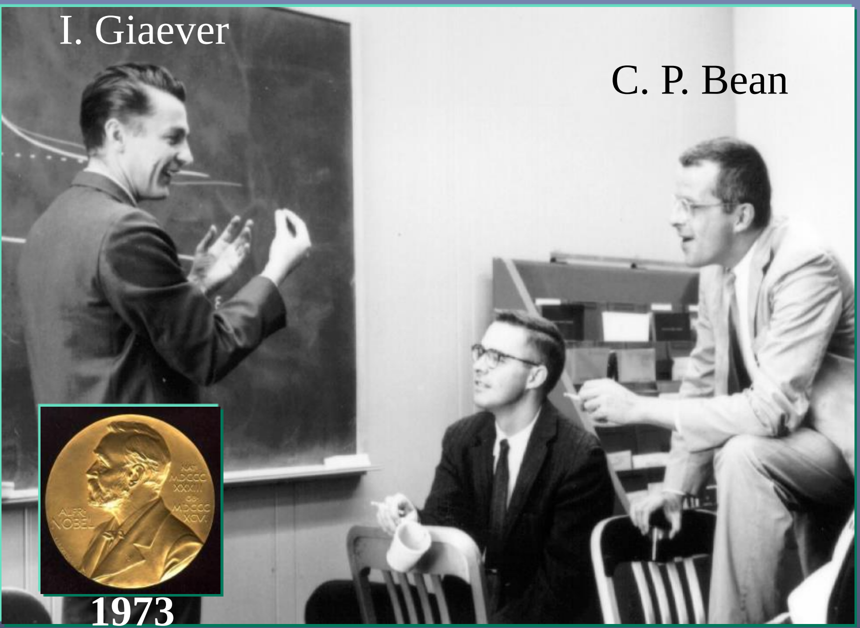


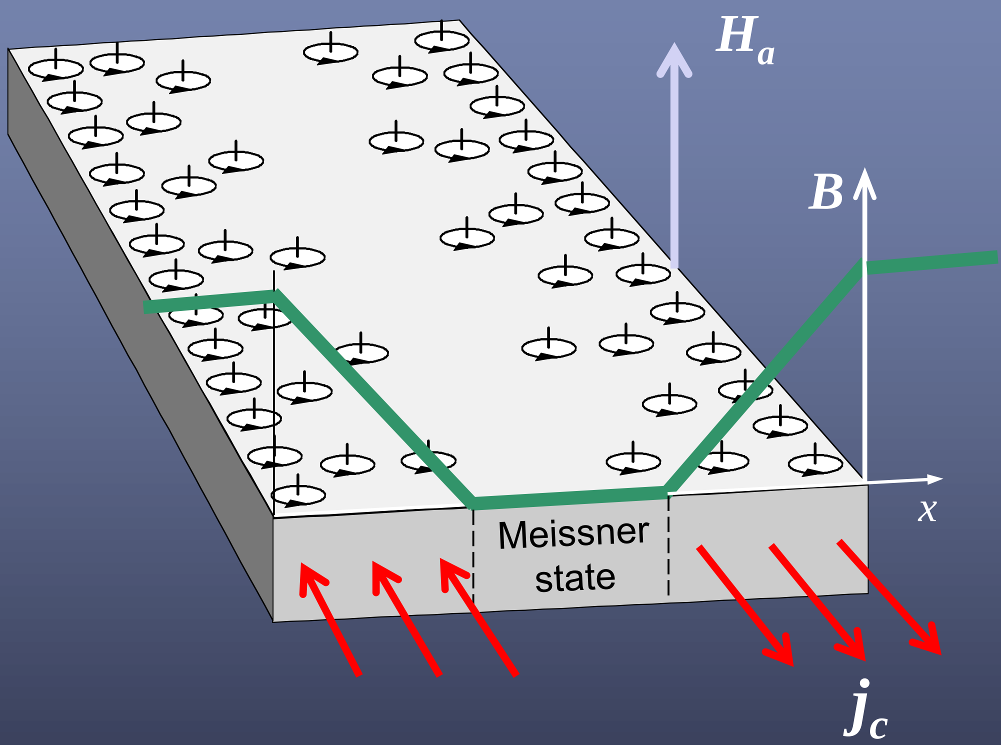
Magnetization of Hard Superconductors
C.P. Bean, Phys. Rev. Lett. **8**, 250 (1962)

citations: 2785

> The basic premise of this theory[10,11] is that there exists a limiting macroscopic superconducting current density $J_c(H)$ that a hard superconductor can carry; and further, that any electromotive force, however small, will induce this full current to flow

The critical state > 50 years !





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C.P. Bean, Phys. Rev. Lett. **8**, 250 (1962)

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critical current density ⇔ critical slope in *B*

The basic premise of this theory[10,11] is that there exists a limiting macroscopic superconducting current density $J_c(H)$ that a hard superconductor can carry; and further, that any electromotive force, however small, will induce this full current to flow

Ampere's law: $\mu_0 \boldsymbol{j} = \nabla \times \boldsymbol{B}$

Critical State: $\mathbf{J} = \mathbf{J_c}$

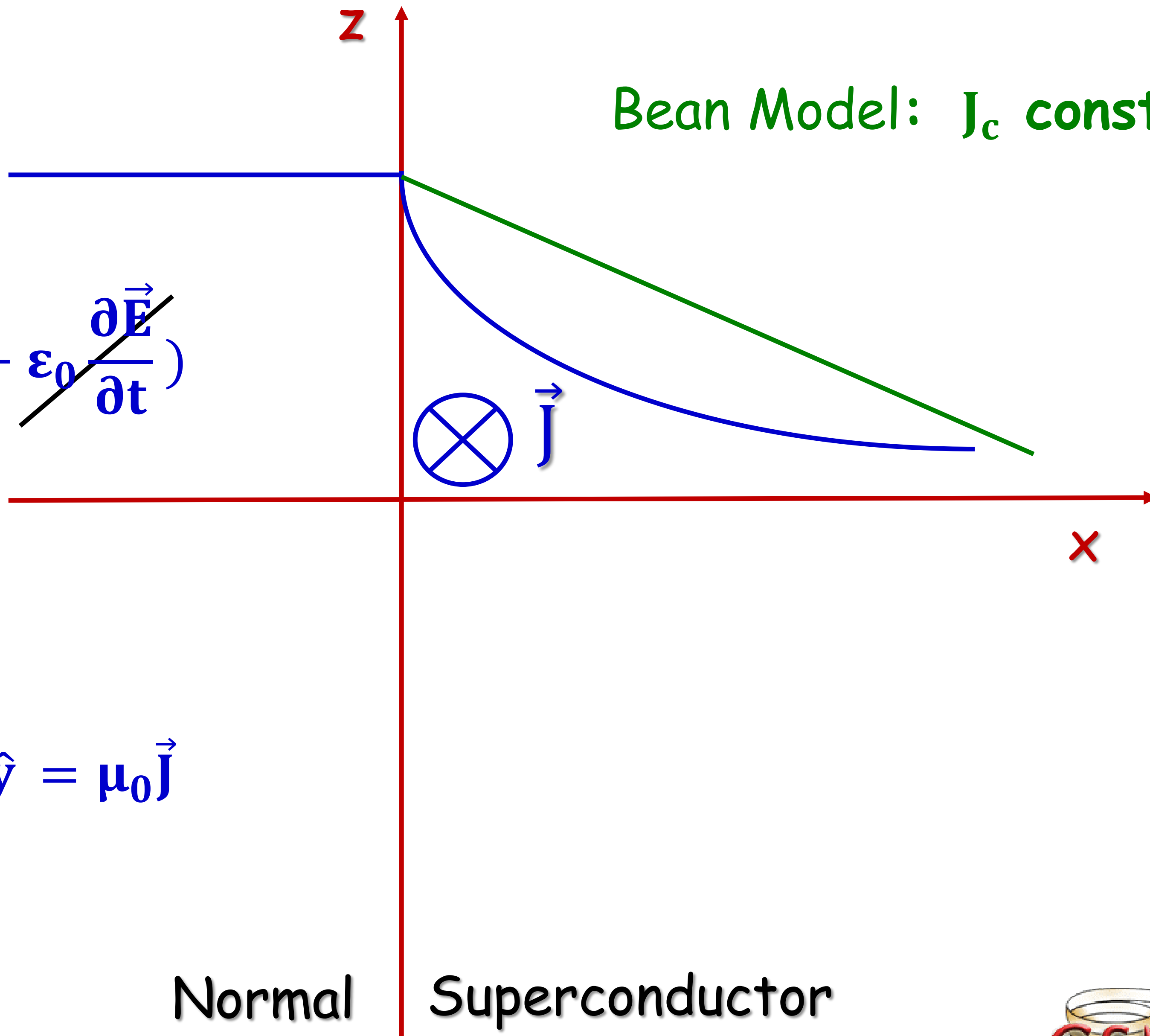
Bean Model: $\mathbf{J_c}$ **const.**

<u>Faraday:</u>

$$\nabla \times \vec{B} = \mu_0 \left(\vec{J} + \cancel{\varepsilon_0 \frac{\partial \vec{E}}{\partial t}}\right)$$

$$\vec{B} = B_z(x)\hat{z}$$

$$\nabla \times \vec{B} = -\frac{\partial B_z}{\partial x}\hat{y} = \mu_0 \vec{J}$$



Vortices are present in almost all applications of superconductors;

Vortices have a dynamics of their own;

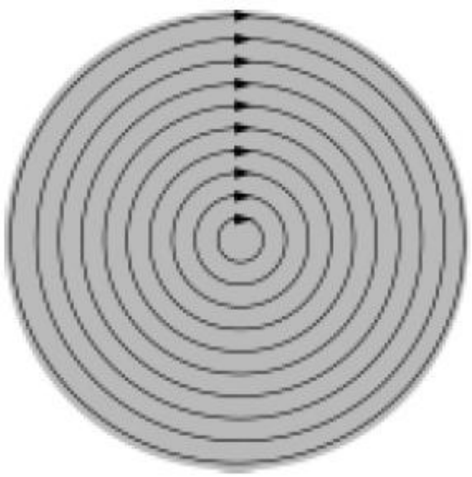
This dynamics determines the superconducting properties which are relevant for applications.

II. Vortices

Vortices in Nature

Vortices in Nature

Normal fluids:
➔ viscosity
➔ “rigid body” rotation



Superfluids:
➔ no viscosity
➔ vortices

Vortices in Nature

Bose Condensate: superfluid He4

VOLUME 43, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 1979

Observation of Stationary Vortex Arrays in Rotating Superfluid Helium

E. J. Yarmchuk and M. J. V. Gordon[a]
Physics Department, University of California, Berkeley, California 94720

and

R. E. Packard[b]
Physics Department, University of Sussex, Brighton, England

(Received 29 May 1979)

The positions of quantized vortex lines in rotating superfluid helium have been recorded using a photographic technique. The photographs show stationary arrays of vortices. The observed patterns are in good agreement with theoretical predictions.

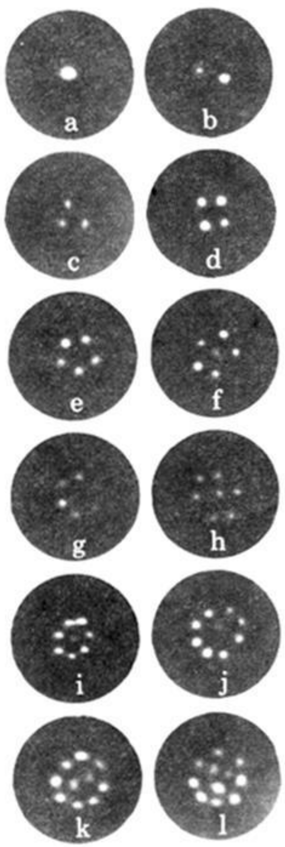
Since the work of London[1] it has become an accepted notion that superfluidity is a manifestation of quantum mechanics on a macroscopic scale. Pursuing this idea in a quite literal way, Onsager and Feynman[2] tried to deduce the qualitative features of a single macroscopic wave function, $\psi(r)$, which would describe the superfluid state. They concluded that the superfluid velocity v_s was proportional to the gradient of the wave function's phase and that the nodes in $\psi(r)$ marked the position of vortex lines with circulation quantized in units of h/m (h is Planck's constant and m the mass of the helium atom).

This paper reports observation of stationary quantized-vortex-line patterns in rotating He II. These patterns display the nodal structure of the stationary states of $\psi(r)$ and provide a vivid demonstration of the long-range coherence of the superfluid state.

phor screen. The light emanating from this phosphor is conveyed (via coherent fiber optics) to room temperature, amplified in a low-light-level television camera, and recorded on a single frame of a movie film. Figure 1 shows a block diagram of the apparatus and the caption describes the essential points.

Since it takes about 10 sec to charge the vortex lines, we can record the vortex pattern about 6 times each minute. In a typical experiment the steady-state features of a pattern are enhanced by making a multiple exposure of many individual movie frames. This method of photographic signal averaging reduces the transient effects of noise due to the image intensifier's dark current. It also obscures random vortex motion caused by mechanical disturbances.

The sample of superfluid fills a cylindrical bucket of 2 mm diam and 25 mm depth. A small



Vortices in Nature

Bose Condensate: cold atoms

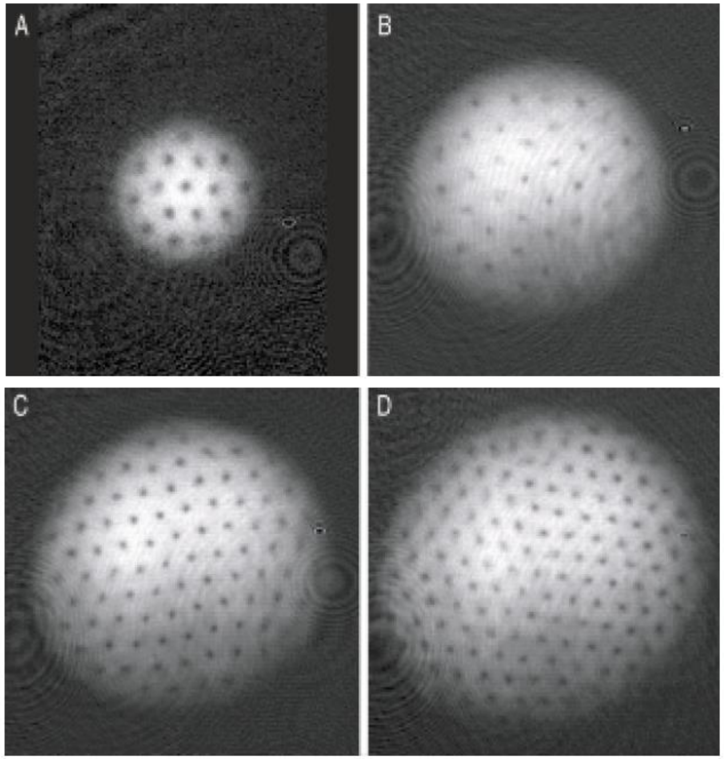


Figure 20. Observation of vortex lattices in rotating Bose-Einstein condensates. The examples shown contain (A) 16 (B) 32 (C) 80 and (D) 130 vortices as the speed of rotation was increased. The vortices have "crystallized" in a triangular pattern. The diameter of the cloud in (D) was 1 mm after ballistic expansion, which represents a magnification of twenty. (Reprinted with permission from ref. [112]. Copyright 2001 American Association for the Advancement of Science.)

WHEN ATOMS BEHAVE AS WAVES: BOSE-EINSTEIN CONDENSATION AND THE ATOM LASER

Nobel Lecture, December 8, 2001

by

WOLFGANG KETTERLE*

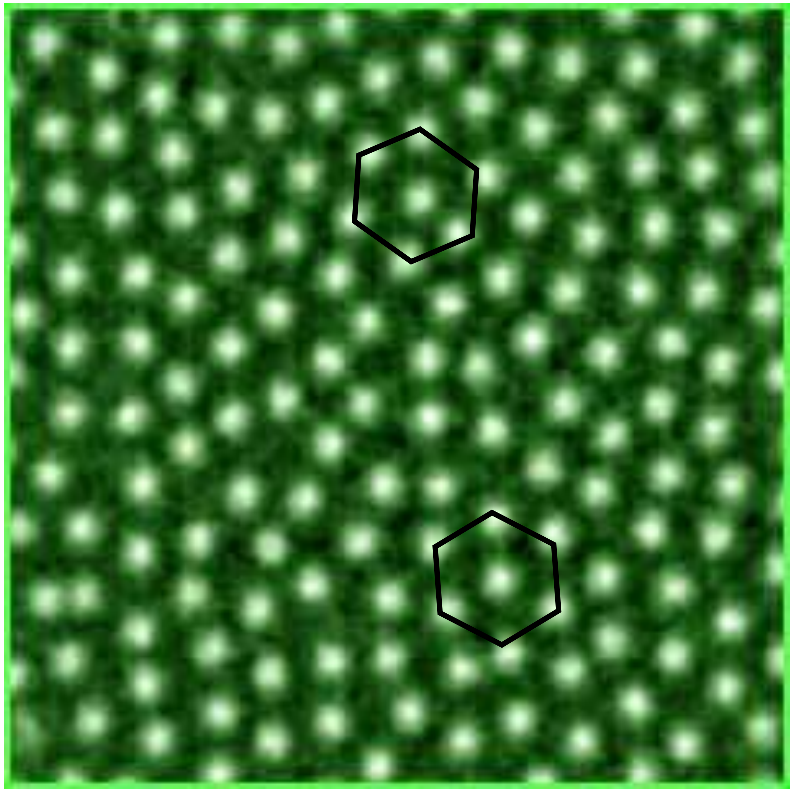
Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA.

Condensate of Na atoms

Vortices in Superconductors

Vortices in Superconductors

Abrikosov lattice

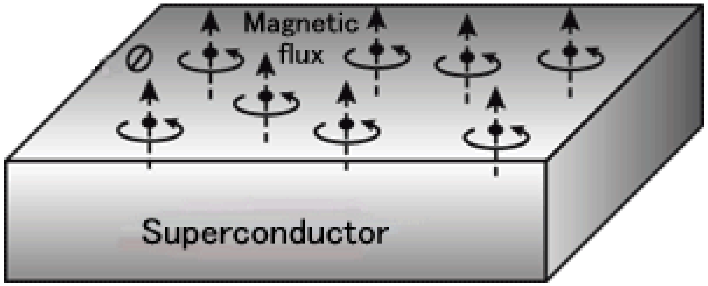


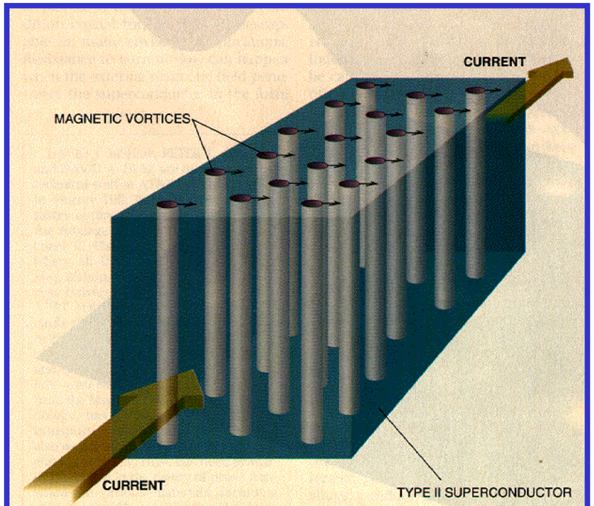
Magneto-optical Imaging

Tom H. Johansen

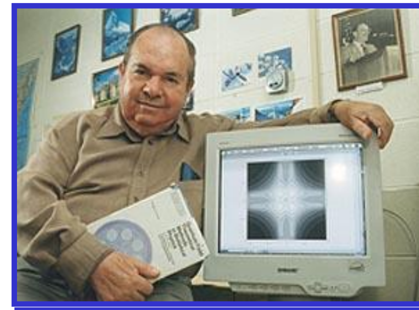
http://www.fys.uio.no/super/

A bit of history...





CURRENT FLOW through a superconductor (*blue rectangular box*) can be disrupted by vortices (*cylinders*). Each vortex consists of a ring of circulating current induced by an external magnetic field (*not shown*). The applied current adds to the circulating current on one side of the vortex but subtracts from the other. The net result is a force that pushes the vortices at right angles to the current flow; the movement dissipates energy and produces resistance.



A. Abrikosov Nobel Prize in Physics in 2003, shared with V. Ginzburg and A. Leggett

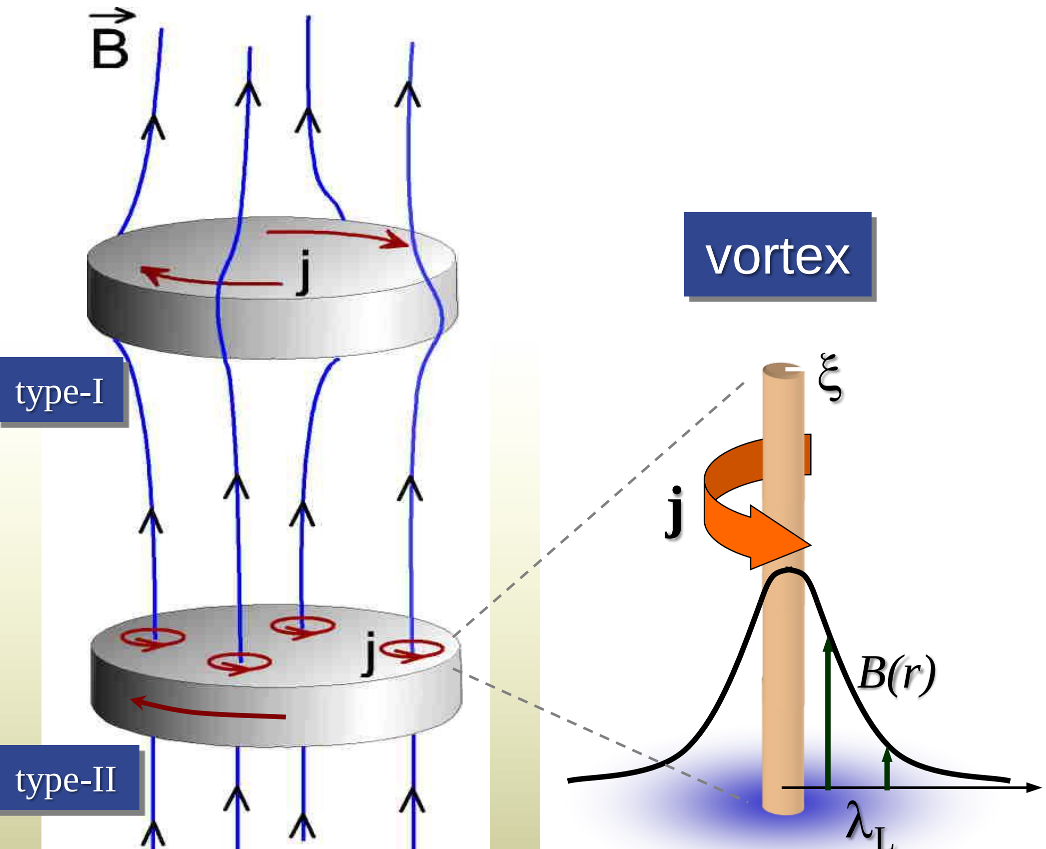
1957 – Abrikosov predicted the existence of type II SCs (flux allowed)

Surface energy can be negative in certain cases ($\kappa = \lambda/\xi > 0.707$)

➔ creation of interfaces N/SC become energetically favorable

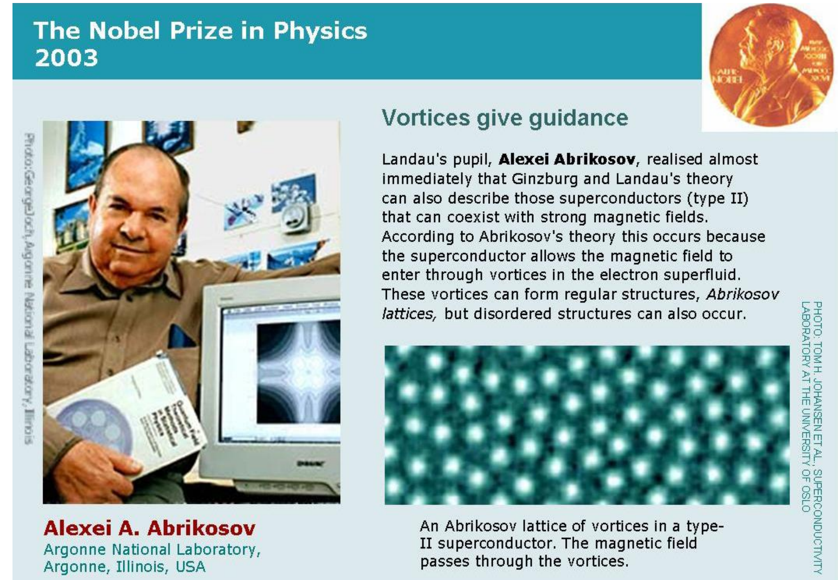
Fluxoids or Vortices: normal regions in the form of tubes carrying one flux quantum each, $\phi_o \sim 2\text{x}10^{-15}$ SI, surrounded by screening currents

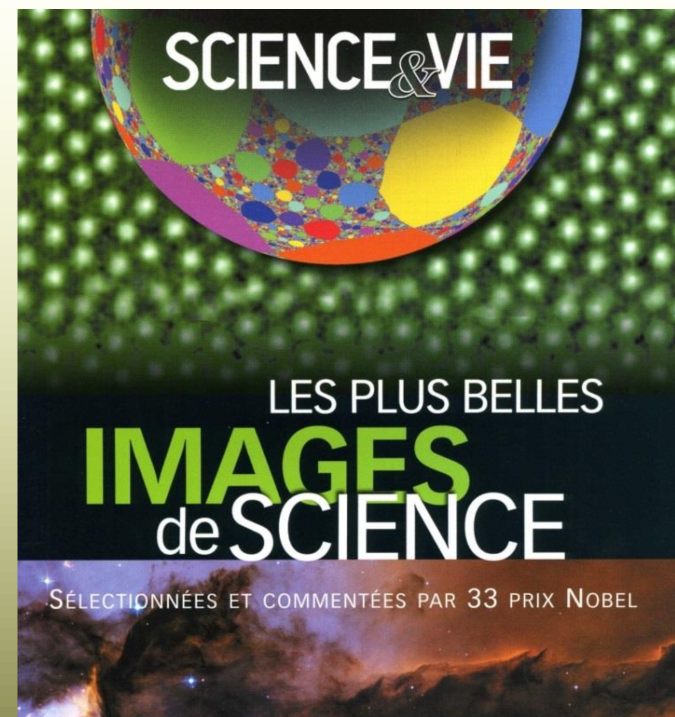
Vortex matter



$$\int B\,dA = h/2e = \Phi_0$$

Flux quantum





Ginzburg-Landau Theory:

$$G_s(\emptyset, \vec{A}) =$$

$$= G_n + \frac{1}{V}\int d^3\vec{r}\,[\frac{1}{2m^*}\vec{p}^*\emptyset^* \cdot \vec{p}\emptyset + \frac{B^2(\vec{r})}{2\mu_0^2} - \mu_0\vec{H}(\vec{r}) \cdot \overrightarrow{M}(\vec{r})$$

$$+ a\emptyset\emptyset^* + \frac{b}{2}\emptyset\emptyset^*\emptyset\emptyset^* + \cdots]$$

where $\vec{p} = i\hbar\vec{\nabla} + e^*\vec{A}$ is the canonical moment and the coefficients are taken as

$$a(T) \sim a_0\left[\frac{T}{T_c} - 1\right]; \quad b(T) \sim b_0; \quad T \sim T_c$$

Superconductivity; Poole, Farach, Creswick and Prozorov

Ginzburg-Landau Theory:

$G_s(\phi,\mathbf{A})$

$\delta_\phi G_s = 0$ e $\delta_A G_s = 0$ ➔ 2 GL equations

Dimensionless GL equations ➔

λ : space scale in equation arrising from $\delta_A G_s = 0$

ξ : space scale in equation arrising from $\delta_\phi G_s = 0$

Energy associated to formation of N/S interface:

– $\sigma_{NS} \propto (\xi - \sqrt{2}\,\lambda)$

– $\kappa = \lambda/\xi$: parâmetro de GL

Ginzburg-Landau Equations:

$$\frac{1}{2m^*}(\hbar^2\nabla^2\phi - 2i\hbar e^*\mathbf{A}\cdot\nabla\phi - e^{*2}\mathbf{A}^2\phi) - a\phi - b|\phi|^2\phi = 0. \quad (6.8)$$

$$\nabla\times(\nabla\times\mathbf{A}) + \frac{i\hbar e^*}{2m^*}(\phi^*\nabla\phi - \phi\nabla\phi^*) + \frac{e^{*2}}{m^*}\mathbf{A}|\phi|^2 = \mathbf{0}. \quad (6.10)$$

From Ampère's Law:

$$\mu_0\mathbf{J} = -\frac{i\hbar e^*}{2m^*}(\phi^*\nabla\phi - \nabla\phi^*\phi) - \frac{e^{*2}}{m^*}\mathbf{A}|\phi|^2. \quad (6.12)$$

Superconductivity; Poole, Farach, Creswick and Prozorov

Vortex Quantization

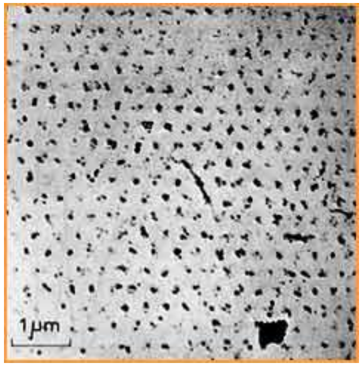
$$\phi(\mathbf{r}) = |\phi(\mathbf{r})|e^{i\Theta} \qquad (6.2)$$

$$\nabla\phi = i\phi\nabla\Theta + e^{i\Theta}\nabla|\phi(\mathbf{r})|, \qquad (6.31)$$

$$\frac{m^*}{e^{*2}}\oint\frac{\mu_0\mathbf{J}}{|\phi|^2}\cdot d\mathbf{1} + \Phi = n\Phi_0. \qquad (6.39)$$

$$\Phi_0 = \frac{h}{e^*}, \qquad (6.36)$$

Gallery

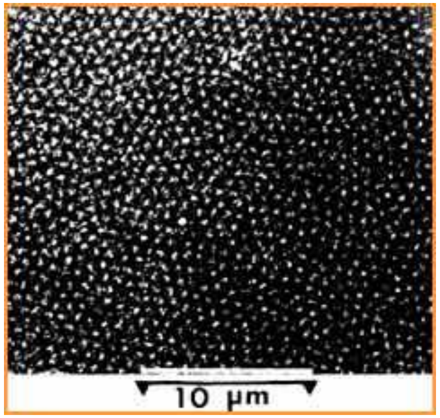


First Image

Bitter Decoration 1967

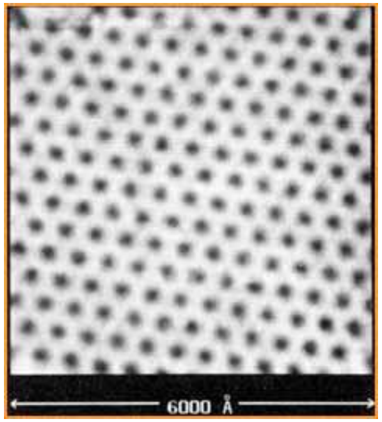
Pb-4at%In rod, 1.1K, 195G

U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart



Bitter Decoration
$YBa_2Cu_3O_7$ crystal, 4.2K, 52G

P. L. Gammel et al., Bell Labs

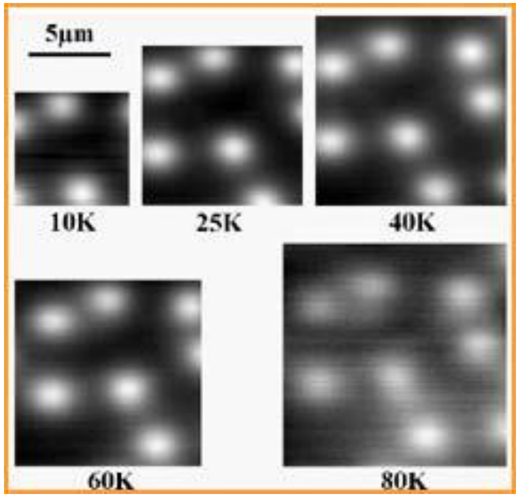


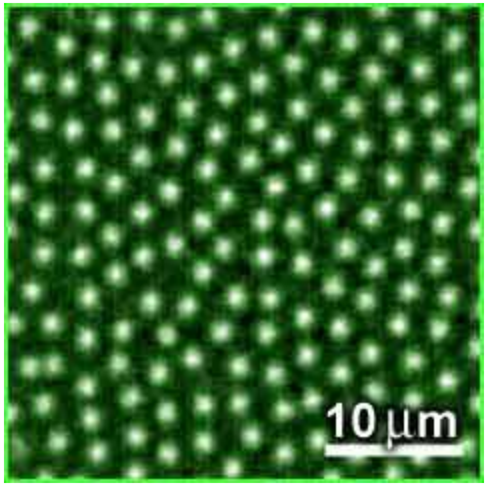
Scanning Tunnel Microscopy
NbSe2, 1T, 1.8K

H. F. Hess et al., Bell Labs

Scanning Hall probes
YBaCuO film, 1000G

A. Oral et al.
University of Bath



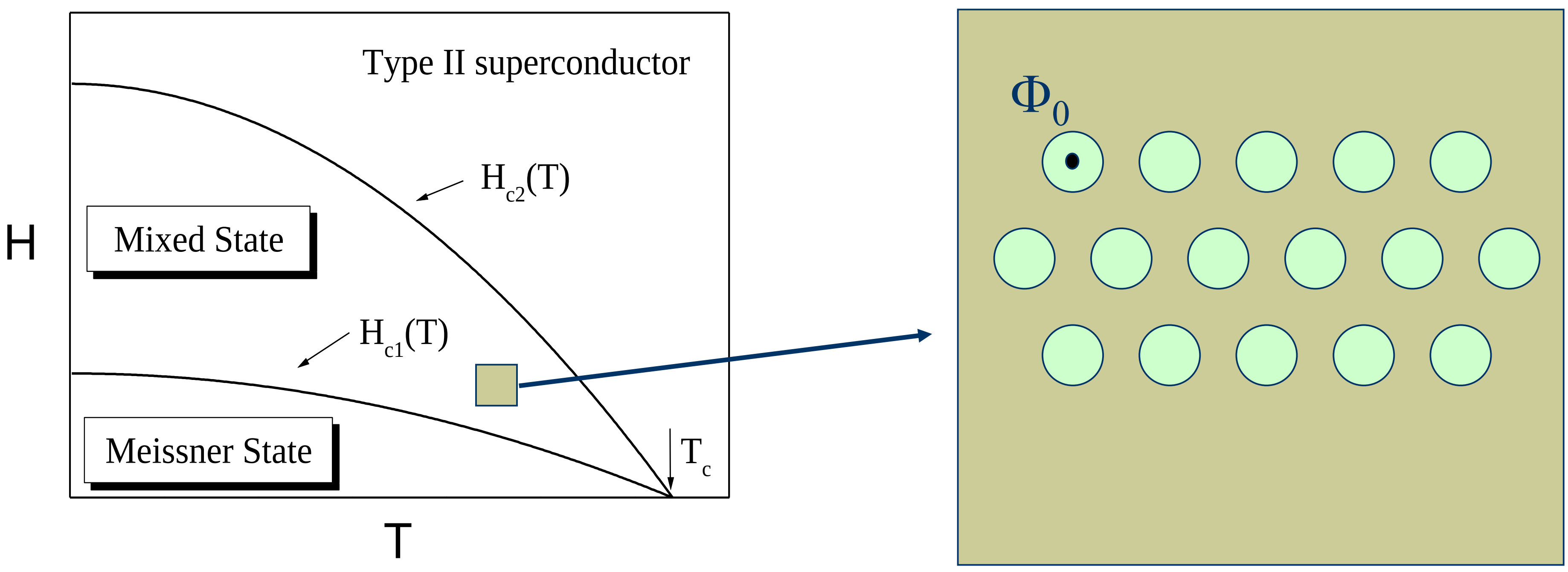


Magneto-Optical Imaging
NbSe2 crystal, 4.3K, 3G

P.E. Goa et al.
University of Oslo

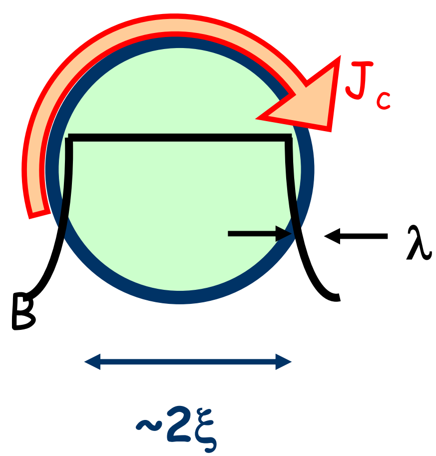
Vortex Dynamics

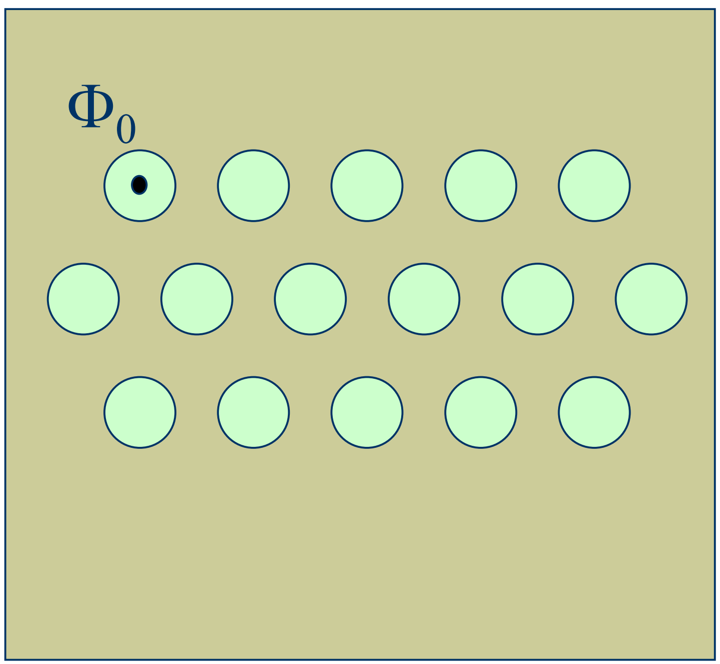
Vortices in the presence of currents: viscous motion ➔ dissipation



Vortices in the presence of currents: viscous motion ➔ dissipation

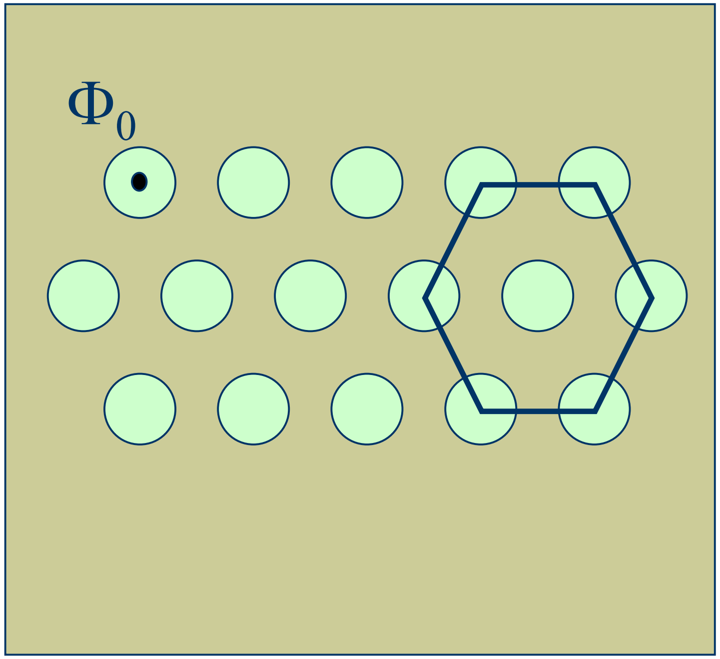
- Vortices (fluxoids) carry quantized flux, $\Phi = n\,\Phi_o$ (usually n = 1)





Vortices in the presence of currents: viscous motion ➔ dissipation

- Vortices (fluxoids) carry quantized flux, $\Phi = n\,\Phi_o$ (usually n = 1)
- Collection of vortices: typical elastic, electric, magnetic & thermal properties ➔ Vortex Matter (VM)



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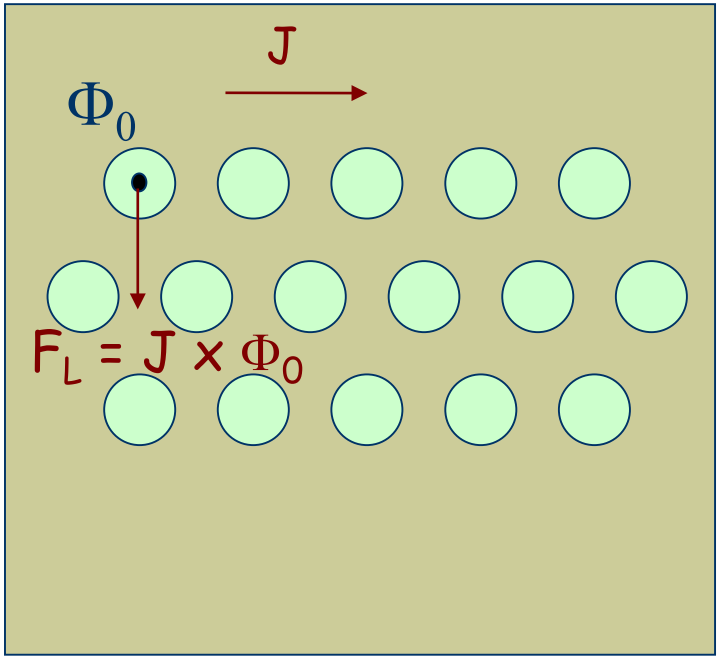
- If J is present, VM experiences viscous movement which may lead the sample to its normal state



Vortices in the presence of currents: viscous motion ➔ dissipation

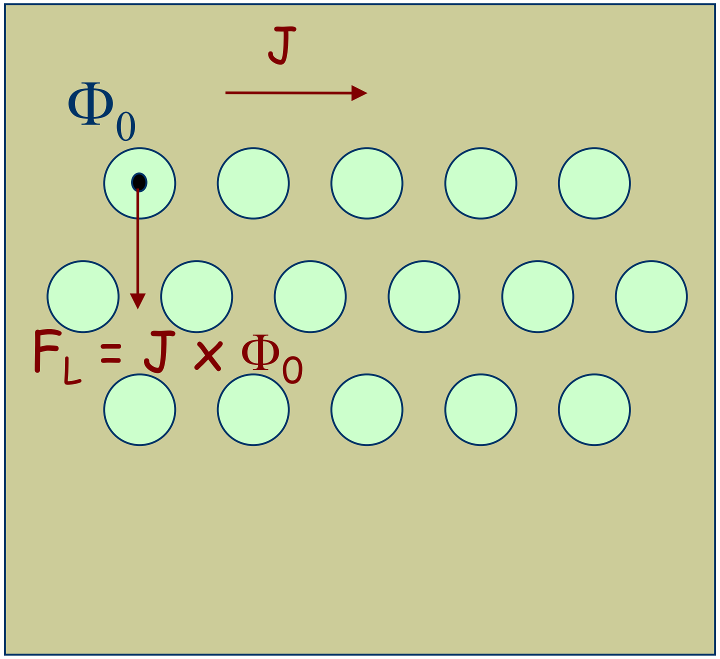
- Vortices (fluxoids) carry quantized flux, $\Phi = n\,\Phi_o$ (usually n = 1)

- Collection of vortices: typical elastic, electric, magnetic & thermal properties ➔ Vortex Matter (VM)

- If J is present, VM experiences viscous movement which may lead the sample to its normal state

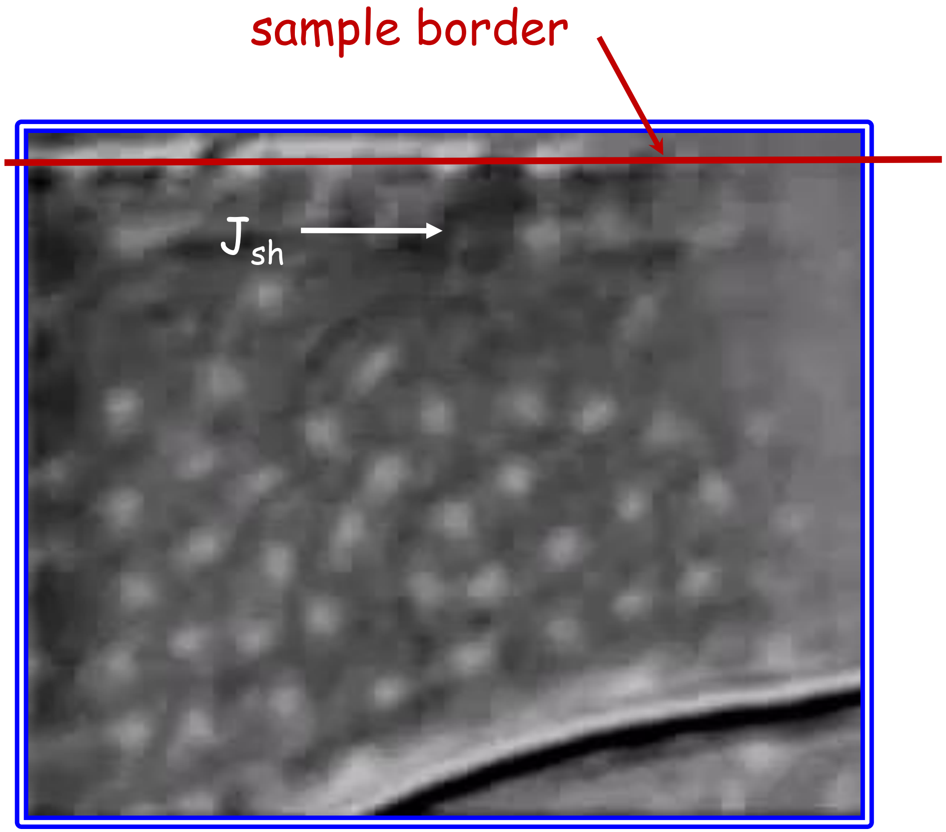
- Pinning centers (PC) can prevent such movement, trapping vortices in potential wells

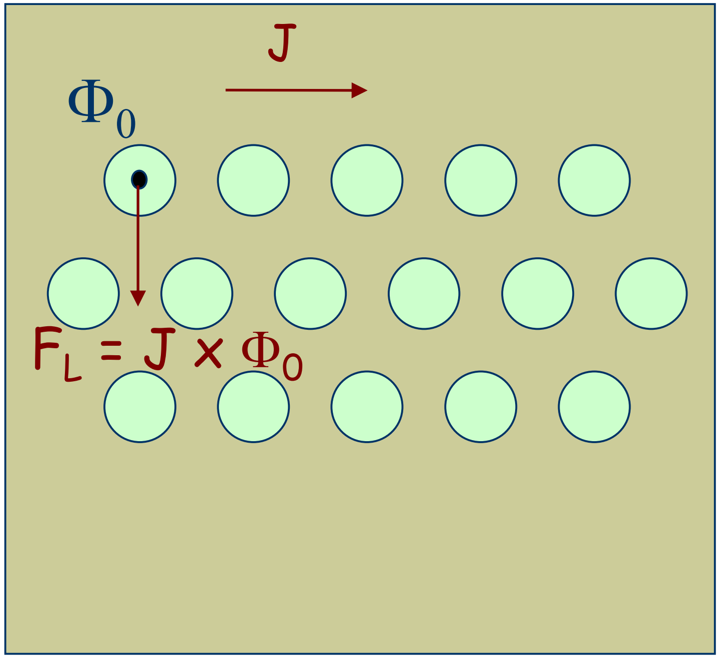
- PCs are crucial to enable Jc > 0



Alexei Abrikosov acting as a “pinning center” for his admirers
Leuven, july 2006

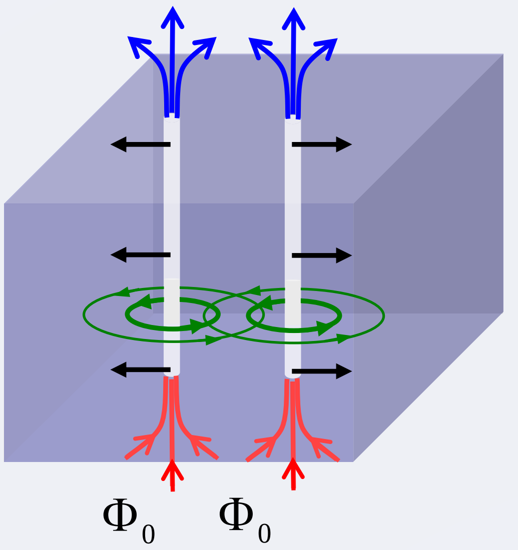
- Vortex entry



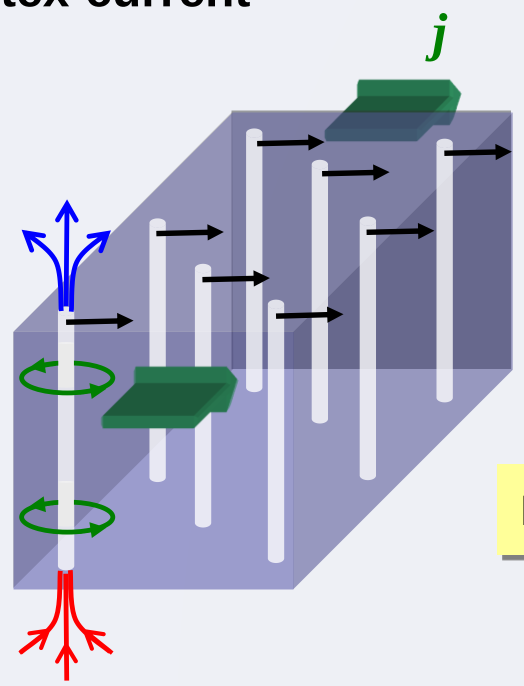


Interactions

vortex-vortex



vortex-current

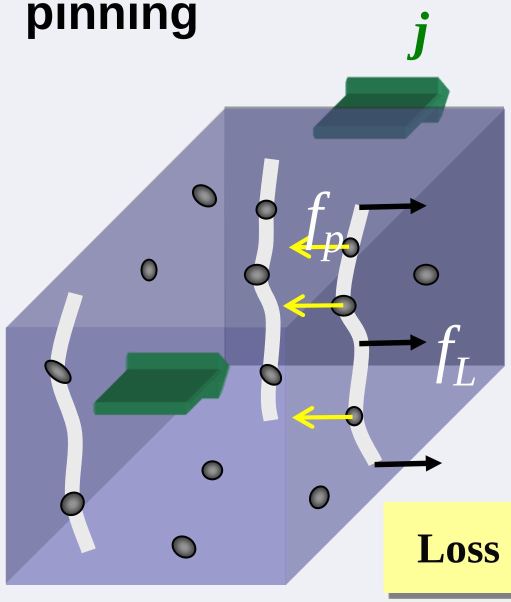


$$\vec{f}_L = \vec{j} \times \vec{\Phi}_0$$

$$E \propto \mathrm{d}B/\mathrm{d}t$$

Loss = jE

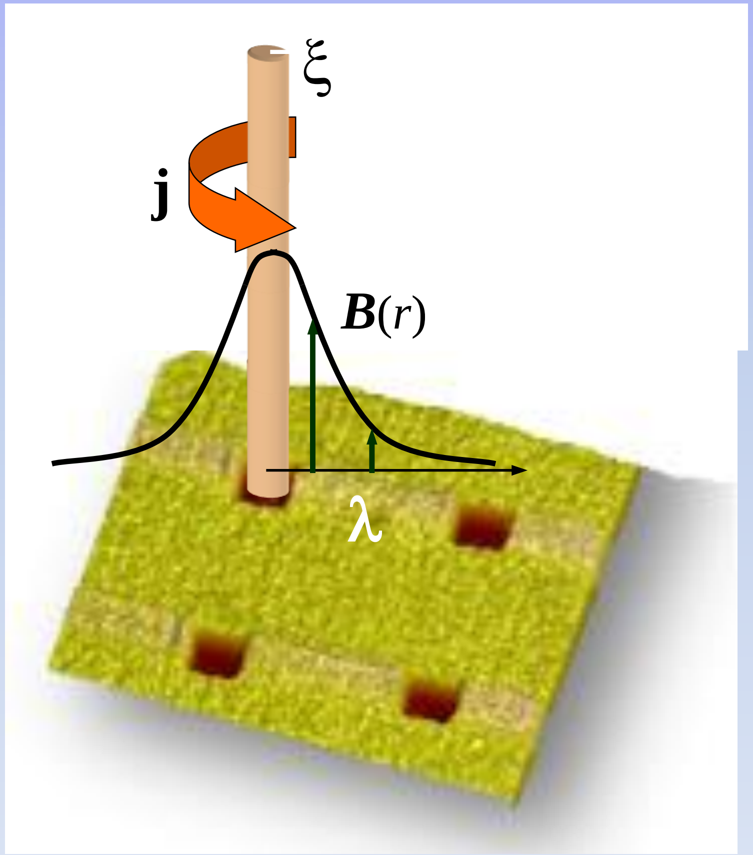
pinning



+ $k_B T$

Loss = 0

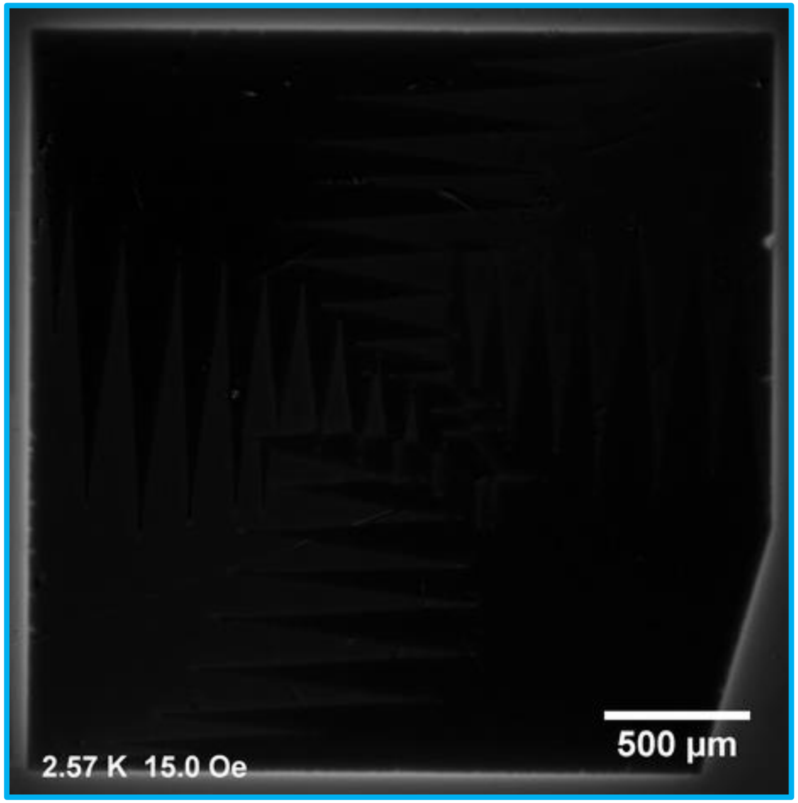
defects: pinning centers



Vortex Avalanches

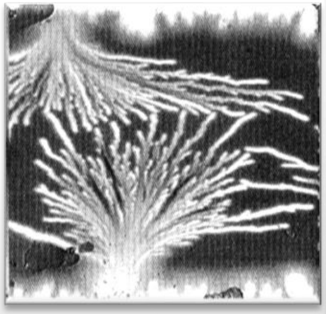
Facts

Under certain conditions of temperature and magnetic field, flux avalanches of dendritic form develop into superconducting films, as a consequence of thermomagnetic instabilities (TMI);

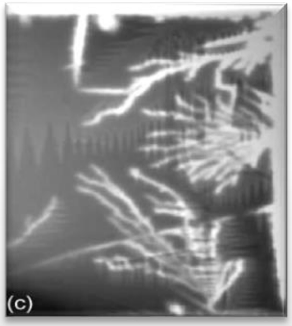


Nb film

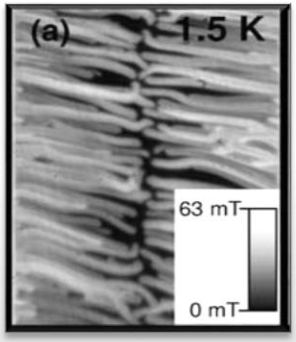
Magneto optical images of avalanches in superconducting thin films



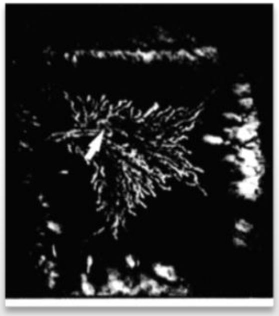
Nb
5.97 K, 135 Oe
Remanent state
Durán *et al.* 1995



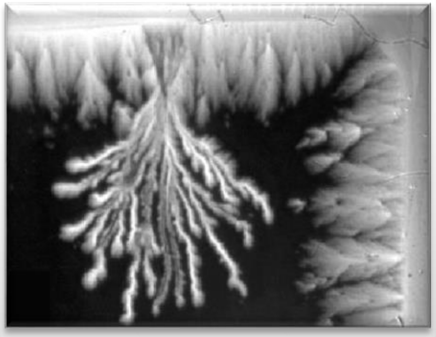
Nb_3Sn
3.5 K, 263 Oe
Rudnev *et al.*
2003



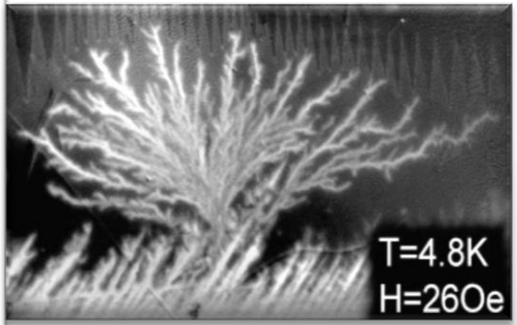
Nb
5.97 K, 135 Oe
Welling *et al.*
2004



YBCO
1.8 K, 600 Oe
After laser pulse
Leiderer *et al.*
2004

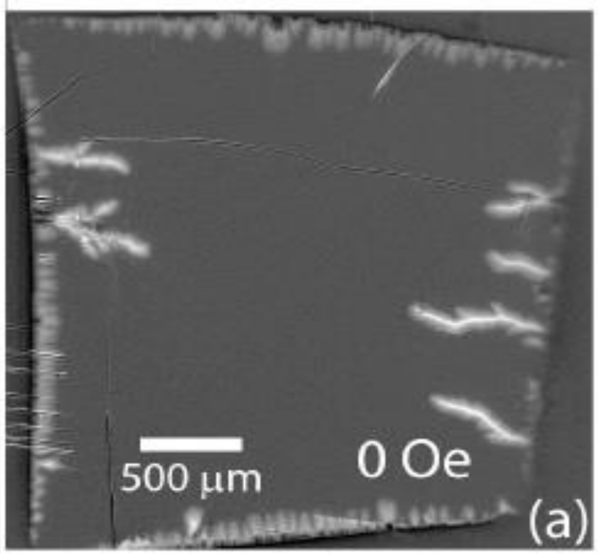


MgB_2
10 K, 170 Oe
Johansen *et al.* 2004



NbN
4.8 K, 26 Oe
Rudnev *et al.* 2005

Some images captured @ GSM/São Carlos

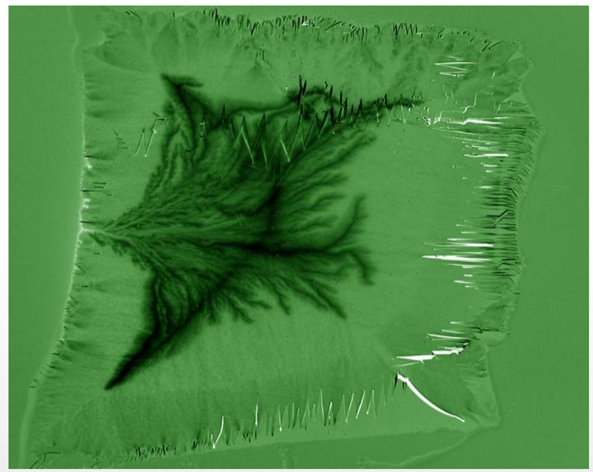


Nb (Plain)

Remanent state

3 K, after 4 Oe

GSM, 2011

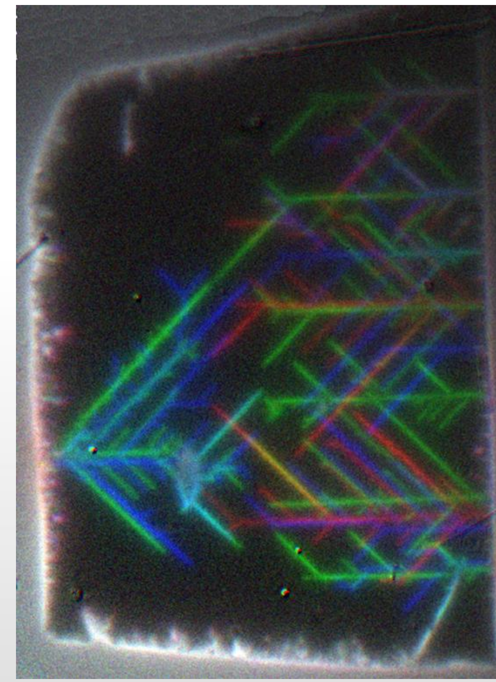


a-MoSi (Plain)

3 K

ZFC → 60 Oe → 10 Oe

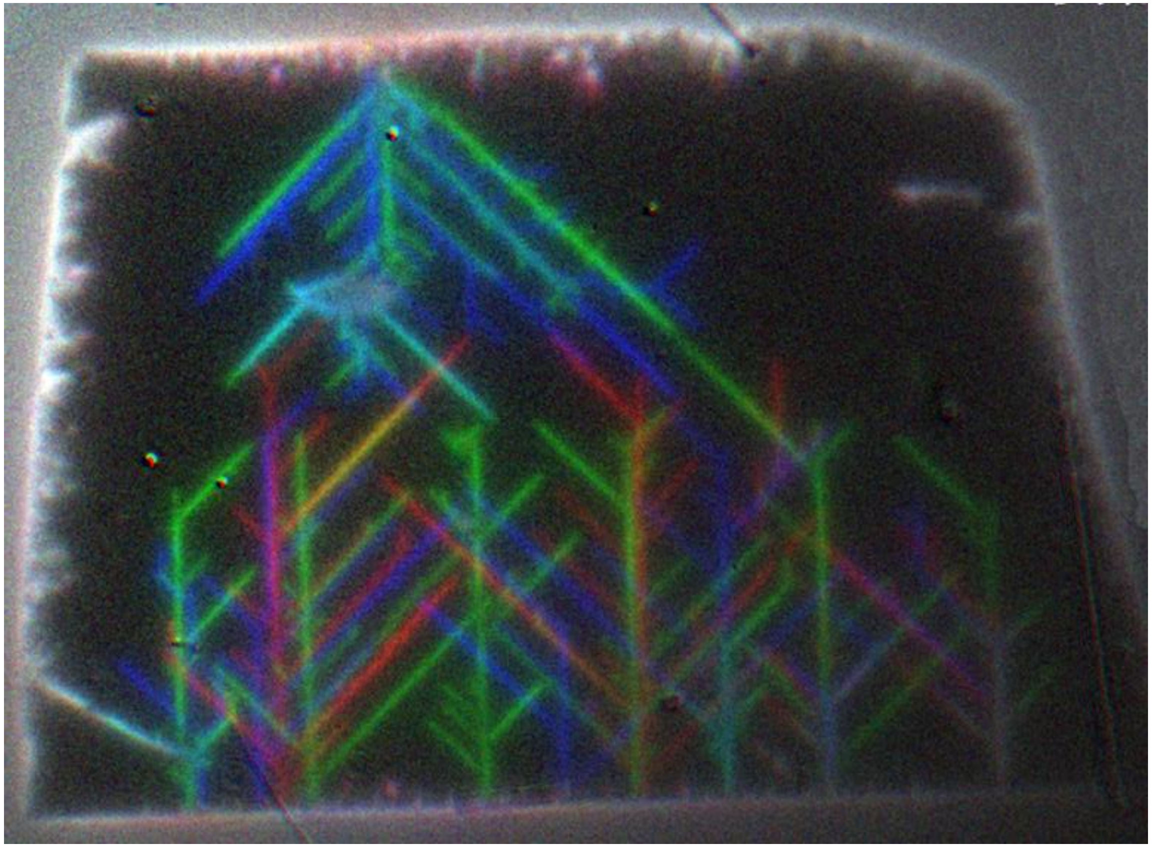
GSM, 2011



a-MoGe (AD04)

4.5 K, 1 Oe

GSM, 2011



a-MoGe (AD04); 4.5 K, 1 Oe

GSM, 2011

Thermomagnetic Instabilities

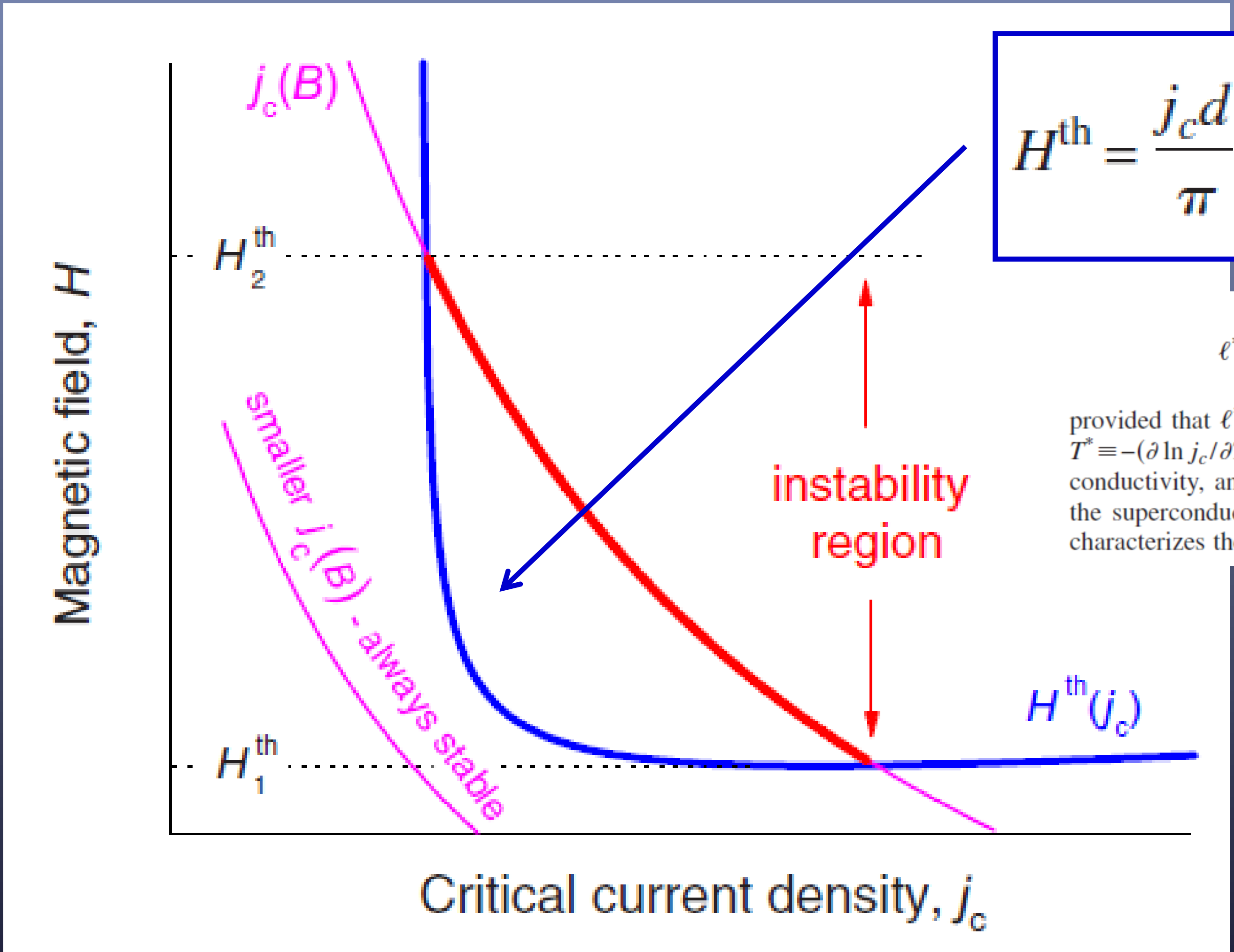
Thermal diffusion > Magnetic diffusion

Magnetic field penetrates smoothly

PHYSICAL REVIEW B **76**, 092504 (2007)

Reentrant stability of superconducting films and the vanishing of dendritic flux instability

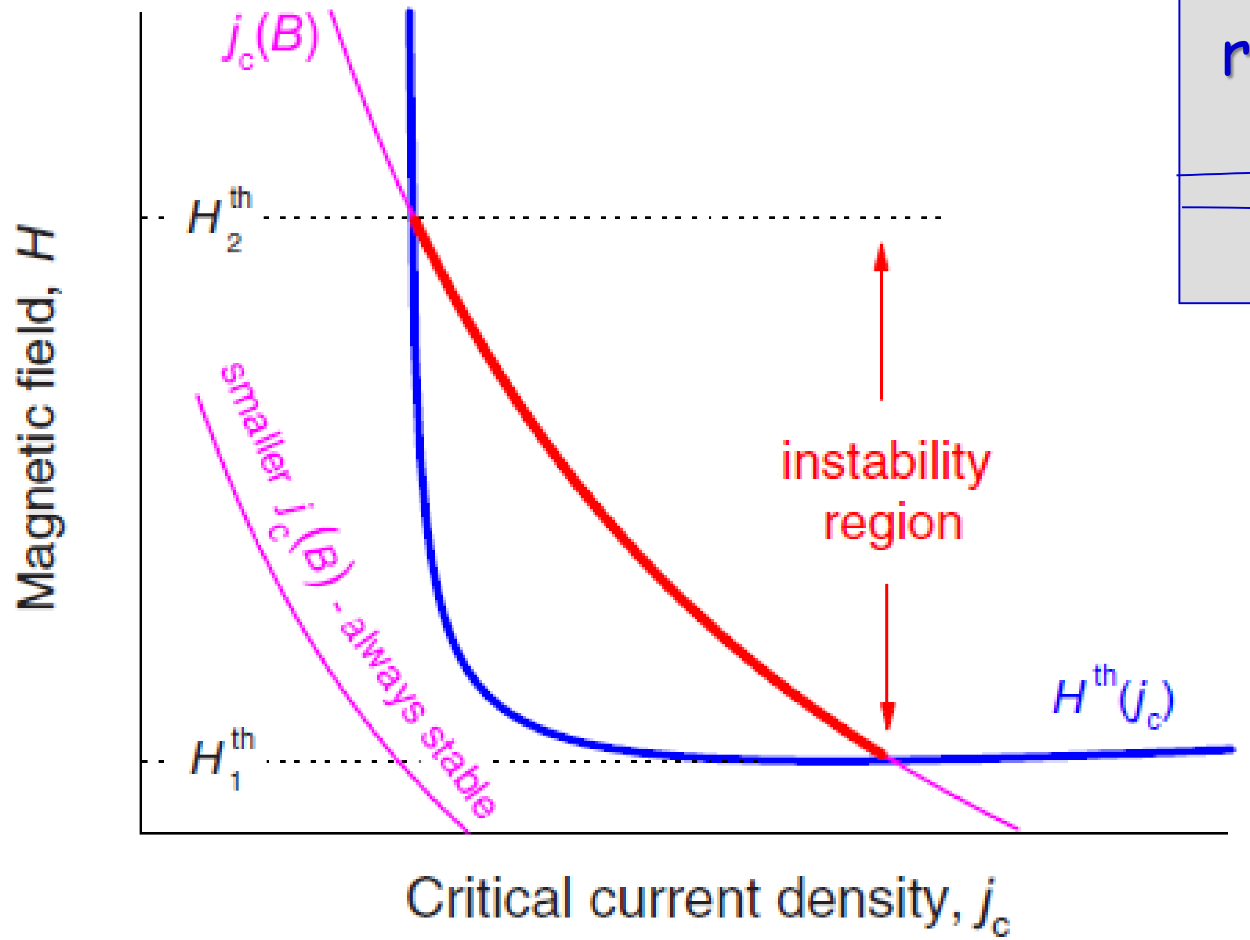
V. V. Yurchenko, D. V. Shantsev, and T. H. Johansen



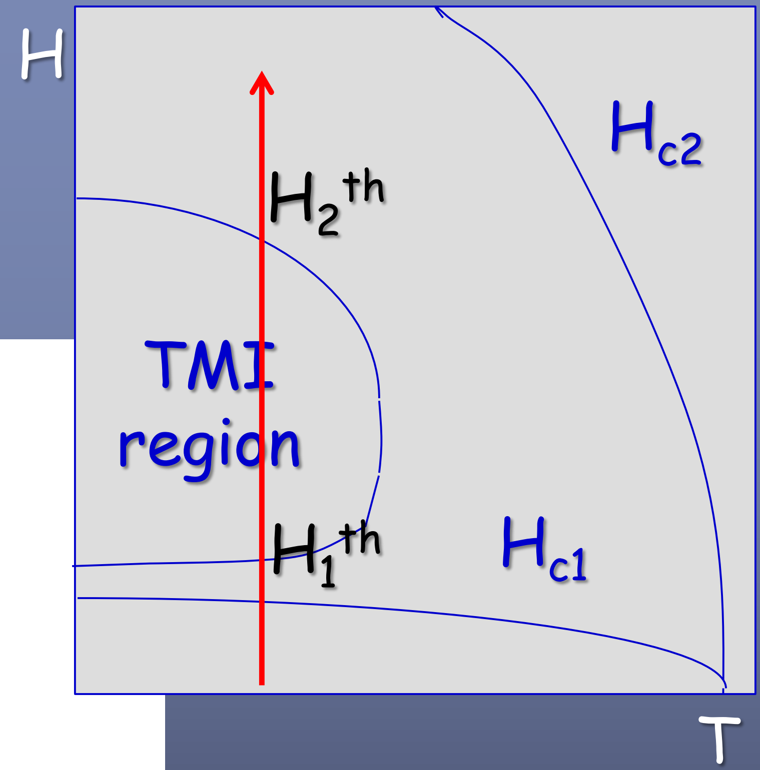
$$H^{th} = \frac{j_c d}{\pi} \operatorname{arccosh}\left(\frac{w}{w - \ell^*} \right)$$

$$\ell^* = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)^{-1}, \qquad (1)$$

provided that $\ell^* < w$. Here, j_c is the critical current density, $T^* \equiv -(\partial \ln j_c / \partial T)^{-1}$, E is the electric field, κ is the thermal conductivity, and h_0 is the coefficient of heat transfer from the superconducting film to the substrate. The parameter n characterizes the nonlinearity of the current-voltage curve of



Magnetic field, H
$j_c(B)$
H_2^{th}
H_1^{th}
smaller $j_c(B)$ - always stable
instability region
$H^{th}(j_c)$
Critical current density, j_c



H
H_{c2}
H_2^{th}
TMI region
H_1^{th}
H_{c1}
T

Granular matter ⇒ avalanches

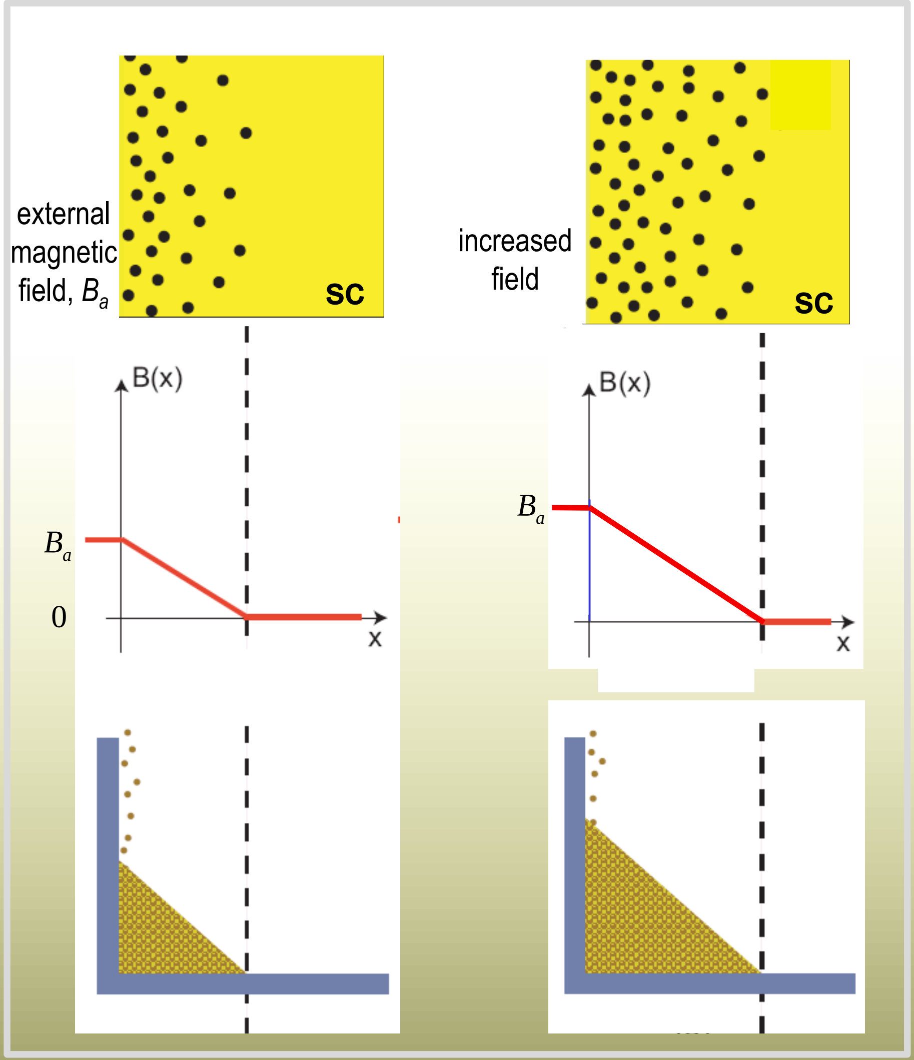
& destroy transport abilities

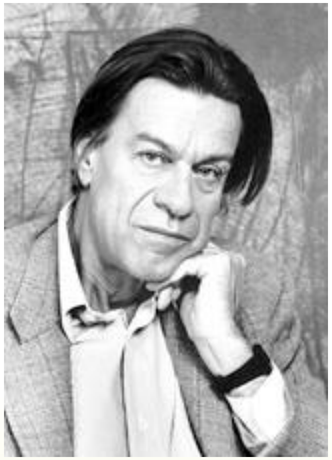
Vortex matter ~ granular medium

vortex penetration

flux density

sand pile





SOFT MATTER

Nobel Lecture, December 9, 1991

by

PIERRE-GILLES DE GENNES

College de France, Paris, France

P. G. DeGennes:

"We can get some physical feeling of this critical state by thinking of a sand hill"

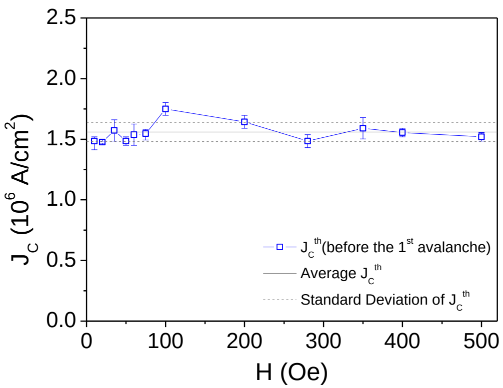
book on Superconductivity (1966)

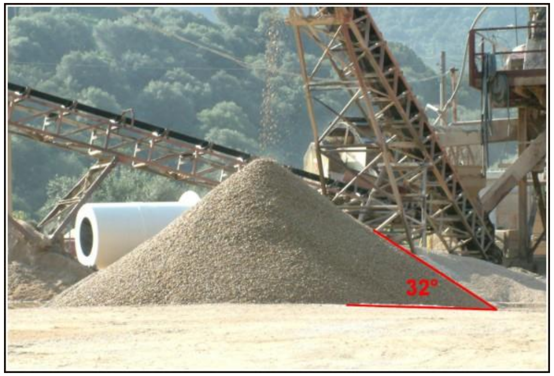
vortex pile ~ sand pile

Expect:

Complex dynamics

Critical Current Threshold





V BEAN MODEL

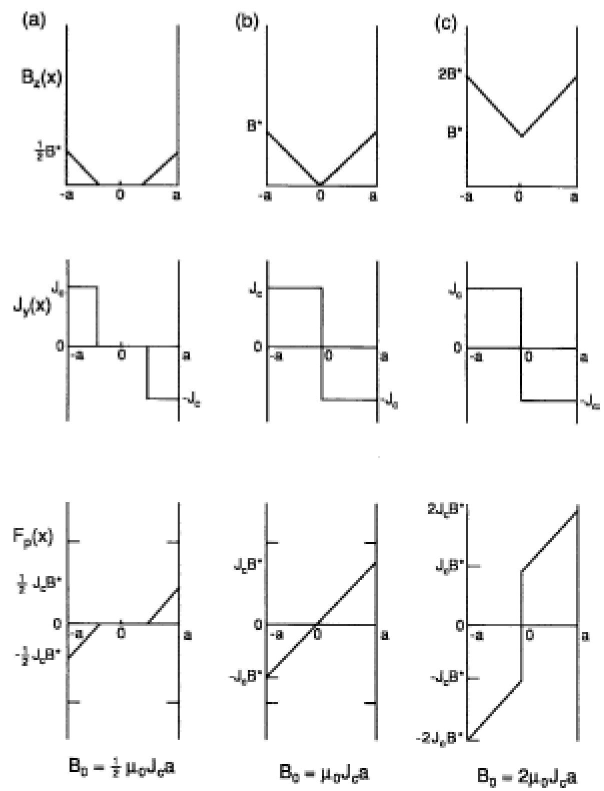
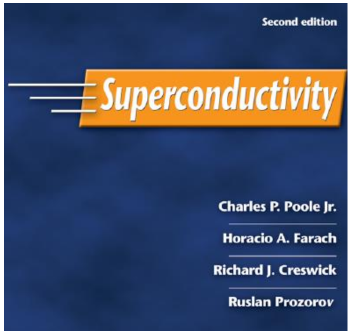


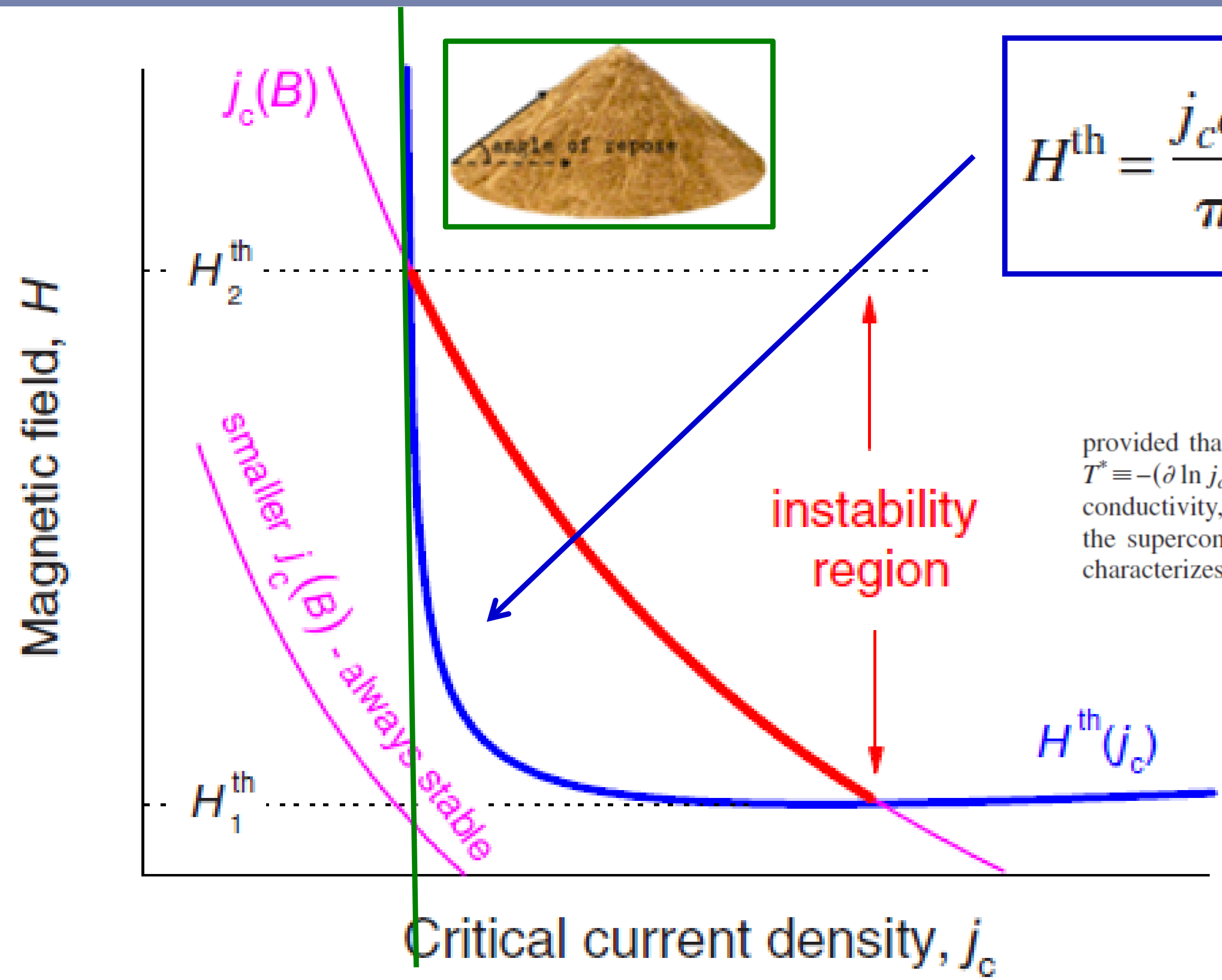
Figure 13.3 Dependence of the internal magnetic field $B_z(x)$, current density $J_y(x)$, and pinning force $F_p(x)$ on the strength of the applied magnetic field B_0 for normalized applied fields given by (a) $B_0/\mu_0 J_c a = \frac{1}{2}$, $B_0/\mu_0 J_c a = 1$, and (c) $B_0/\mu_0 J_c a = 2$. This and subsequent figures are drawn for the Bean model. There is a field free region in the center for case (a), while case (b) represents the boundary between the presence versus the absence of such a region.



PHYSICAL REVIEW B **76**, 092504 (2007)

Reentrant stability of superconducting films and the vanishing of dendritic flux instability

V. V. Yurchenko, D. V. Shantsev, and T. H. Johansen



$$H^{th} = \frac{j_c d}{\pi} \operatorname{arccosh}\left(\frac{w}{w-\ell^*}\right)$$

$$\ell^* = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)^{-1}, \qquad (1)$$

provided that $\ell^* < w$. Here, j_c is the critical current density, $T^* \equiv -(\partial \ln j_c/\partial T)^{-1}$, E is the electric field, κ is the thermal conductivity, and h_0 is the coefficient of heat transfer from the superconducting film to the substrate. The parameter n characterizes the nonlinearity of the current-voltage curve of

Linearized theory predicts

PRL **97,** 077002 (2006)

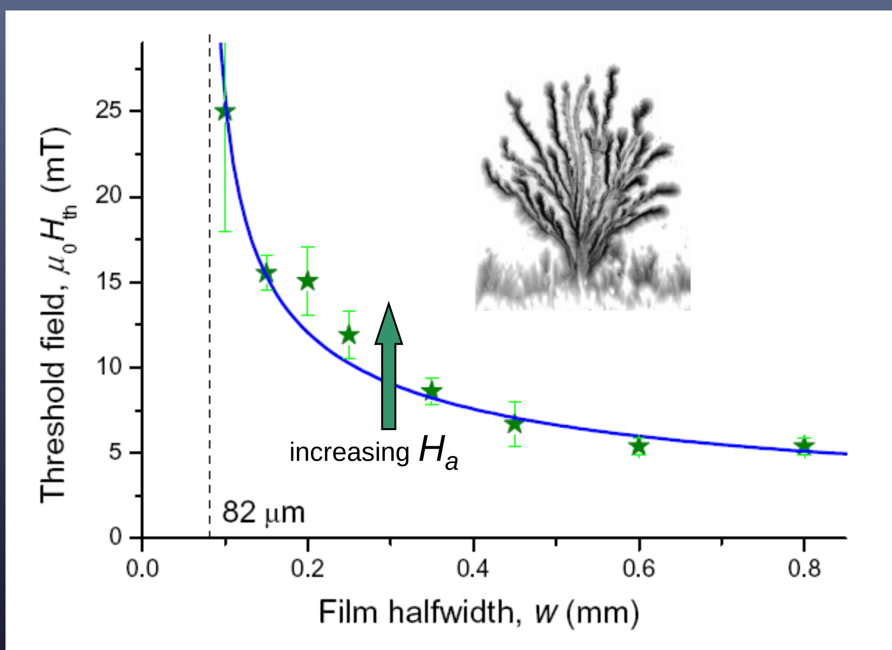
First finger forms at penetration depth:

$$l_{\mathrm{th}} = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)^{-1}$$

…provided $2l_{\mathrm{th}} < 2w$

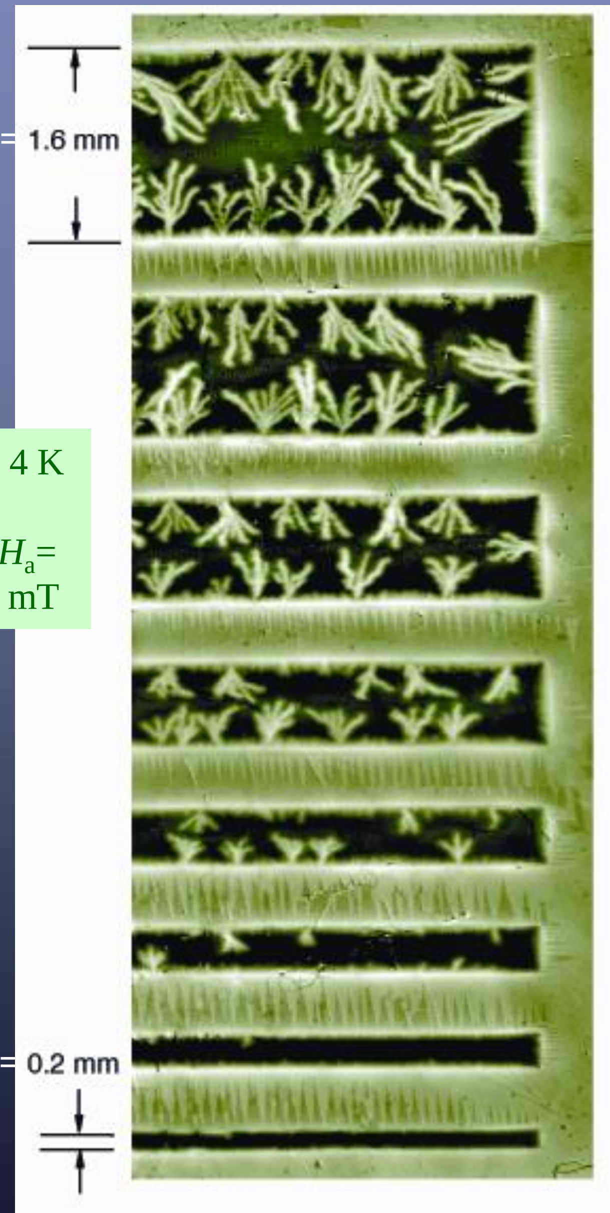
Threshold field:

$$H^{\mathrm{th}} = \frac{j_c d}{\pi}\,\mathrm{arccosh}\left(\frac{w}{w - l_{\mathrm{th}}}\right)$$

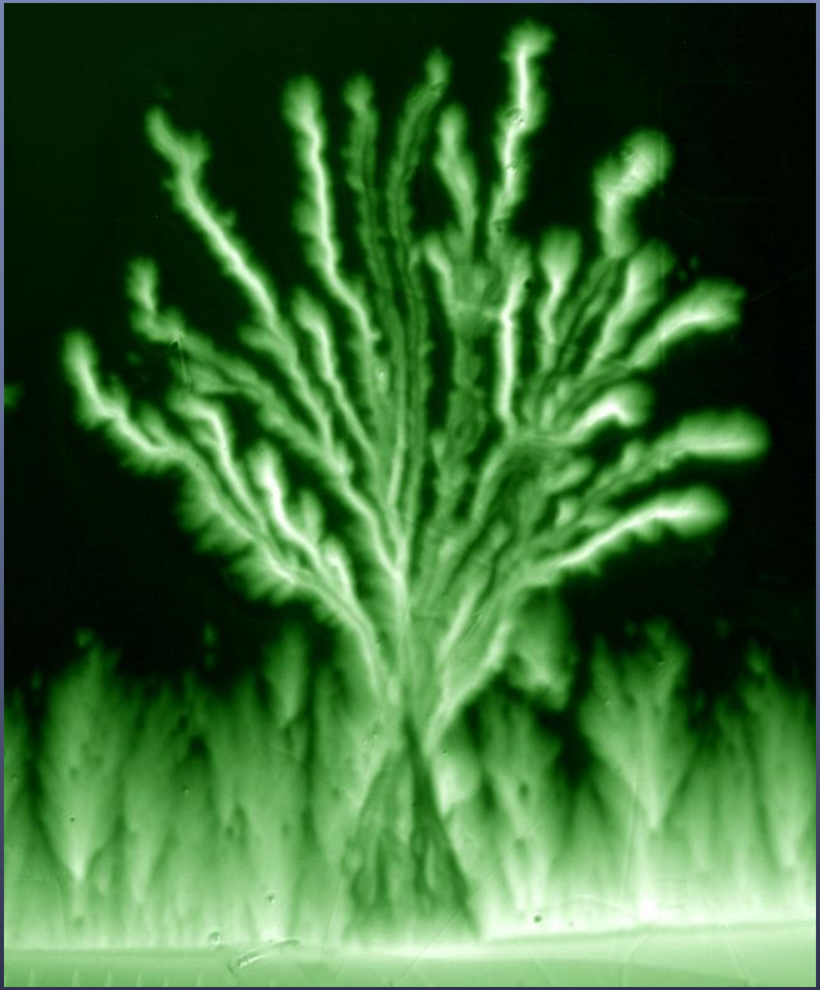


T = 4 K

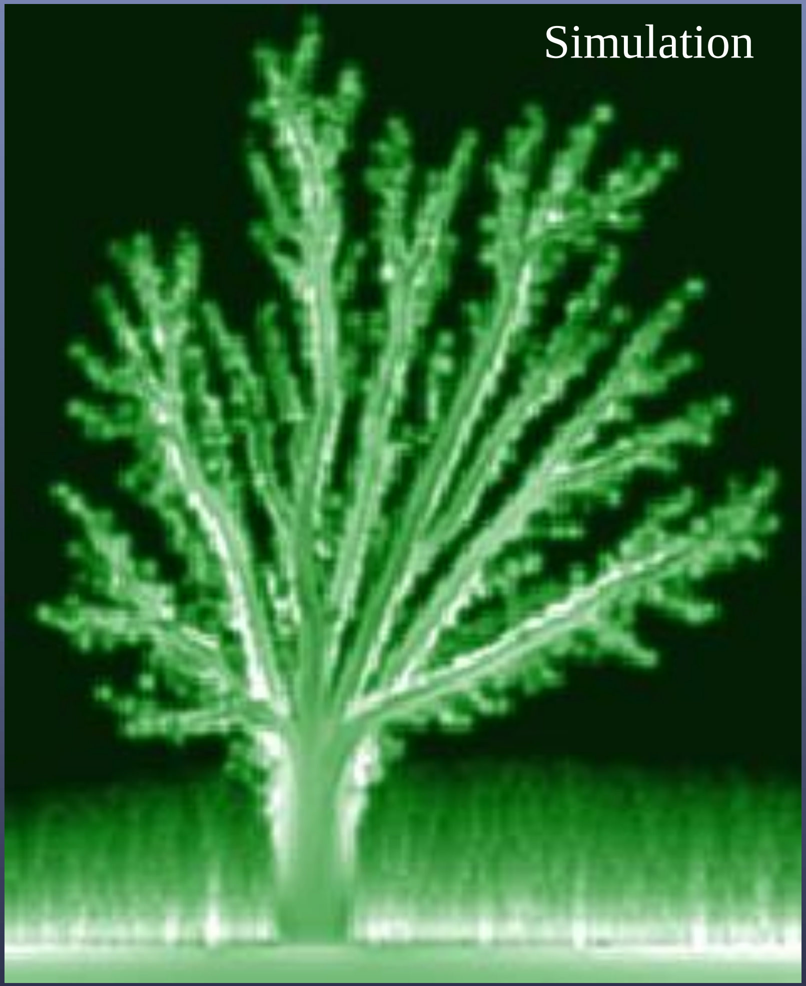
$\mu_0 H_a$= 15 mT



Numerical solution B_z – distribution



Experiment - MgB_2



Parameters: (MgB_2)

$c = 34\ \mathrm{kJ/Km^3} \times (T/T_c)^3$

$\kappa = 172\ \mathrm{W/Km} \times (T/T_c)^3$

$h = 46\ \mathrm{kW/Km^2} \times (T/T_c)^3$

$T_c = 39\ \mathrm{K}$

$\rho_n = 6.8\ \mu\Omega\mathrm{cm}$

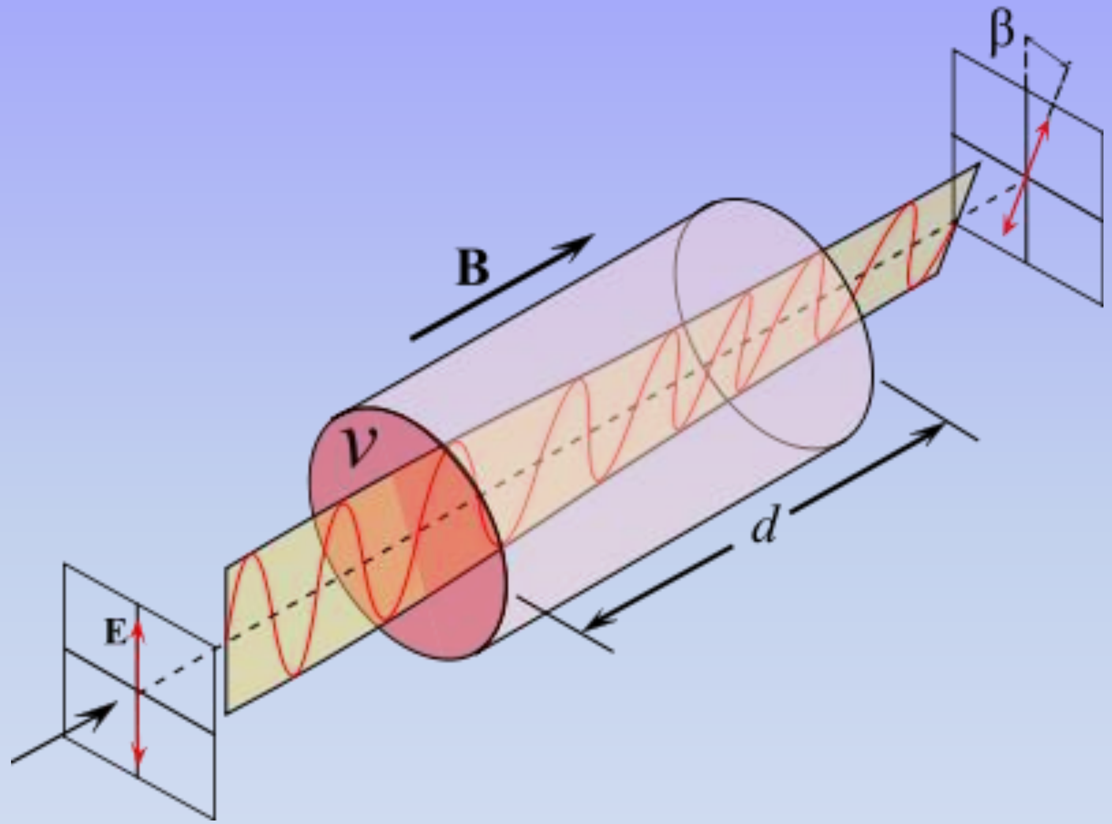
$\dot{H} = 10^{-5} J_{c0}\rho_n/ad$

$J_{c0} = 54\ \mathrm{kA/m}$

$n = 19$

Magneto-optical Imaging (MOI)

A powerful tool to see magnetism and superconductivity in action

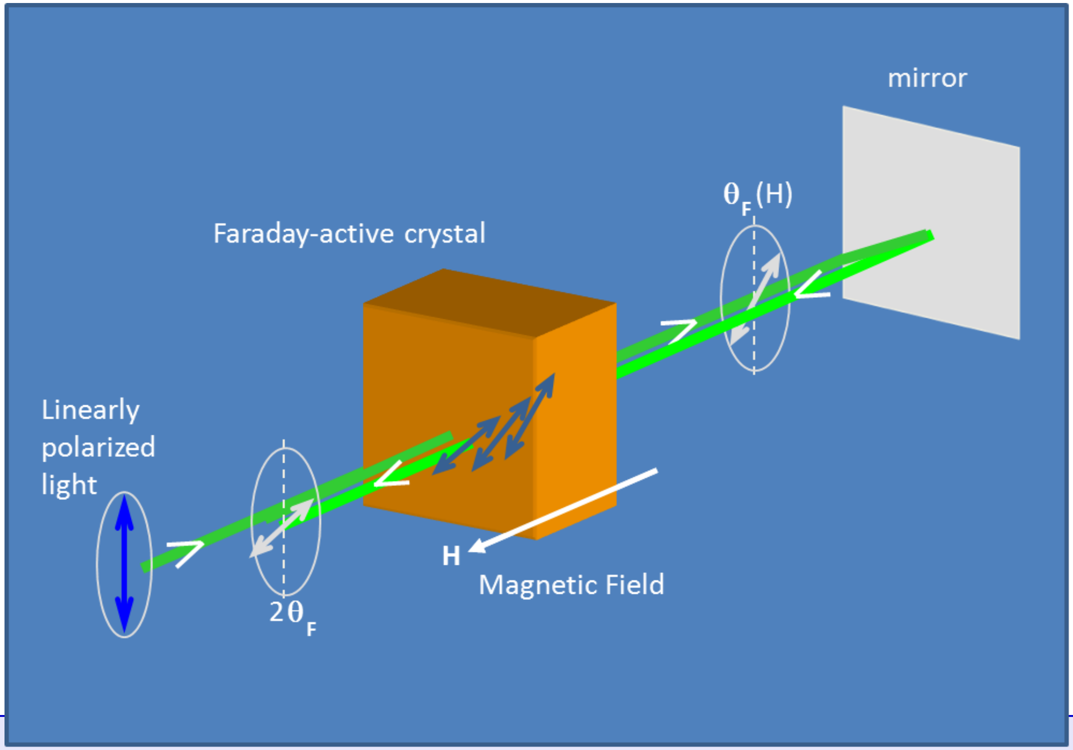


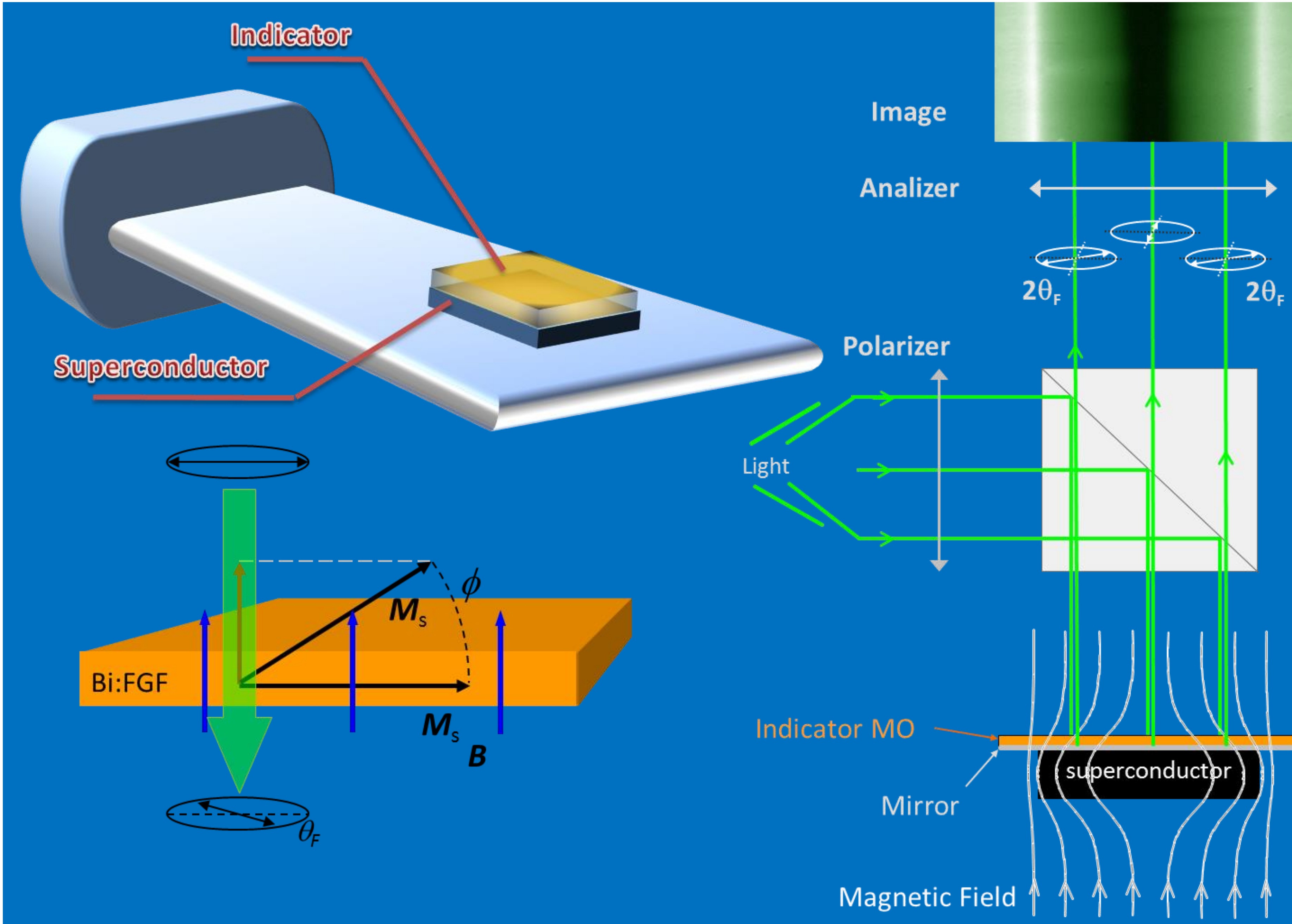
Faraday effect: rotation of the polarization plane

Magneto-optical Imaging

- Faraday rotation of polarized light passing through an indicator (with in-plane magnetization), placed in close contact with the SC sample of interest

➔ space distribution of magnetic flux



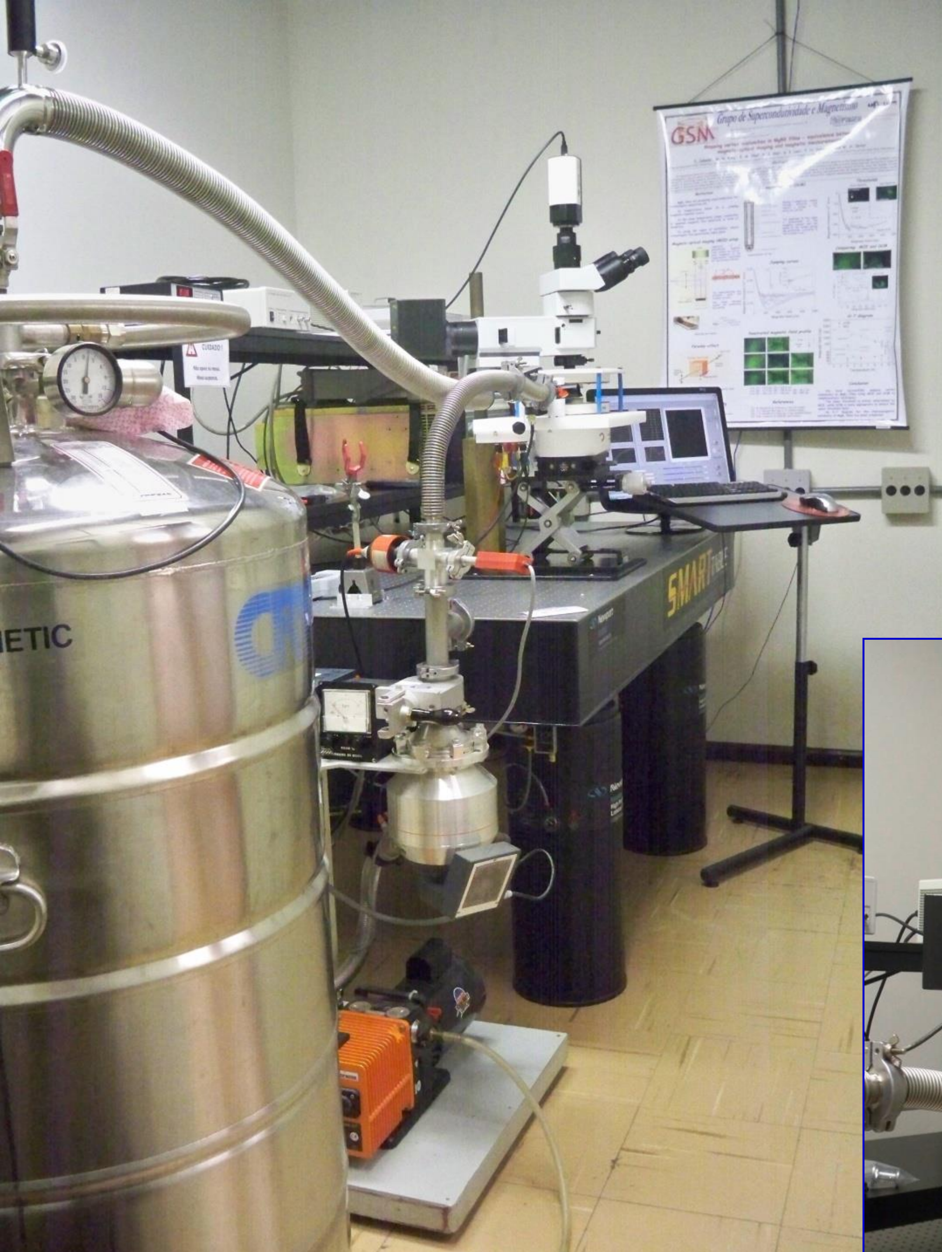

Indicator
Superconductor
Bi:FGF
M_s
ϕ
M_s
B
θ_F
Image
Analizer
$2\theta_F$
$2\theta_F$
Polarizer
Light
Indicator MO
Mirror
superconductor
Magnetic Field

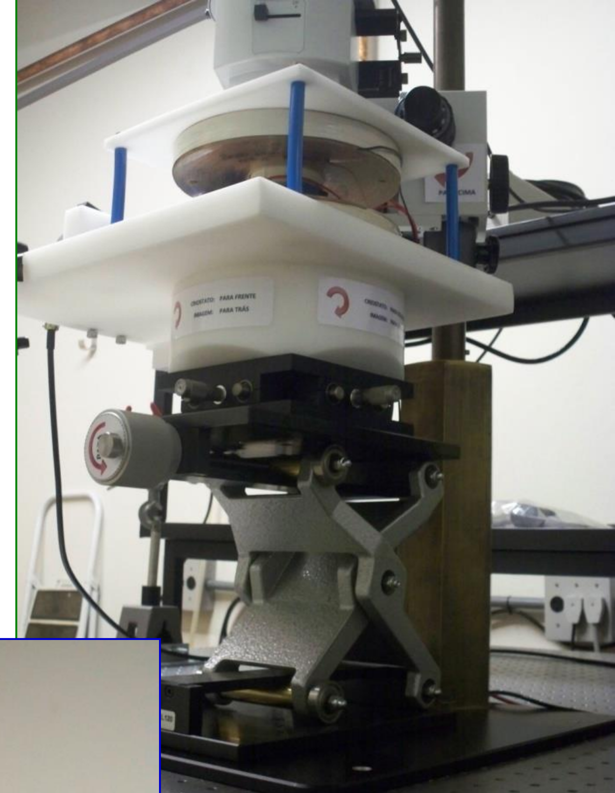
Bismuth-substituted Yttrium-Iron garnet

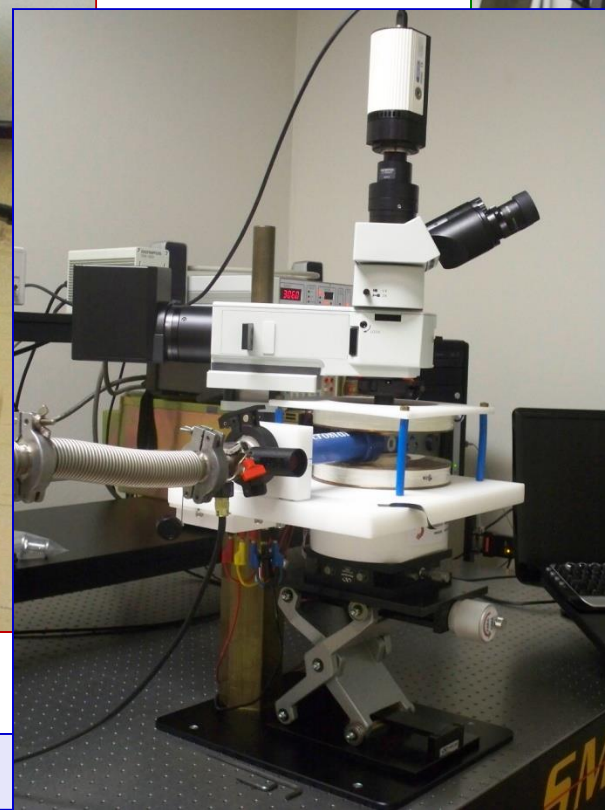
Bi:YIG ($Y_{3-x}Bi_xFe_5O_{12}$)

on (100) substrate of $Gd_3Ga_5O_{12}$ (GGG)

Gadolinium-Galium garnet

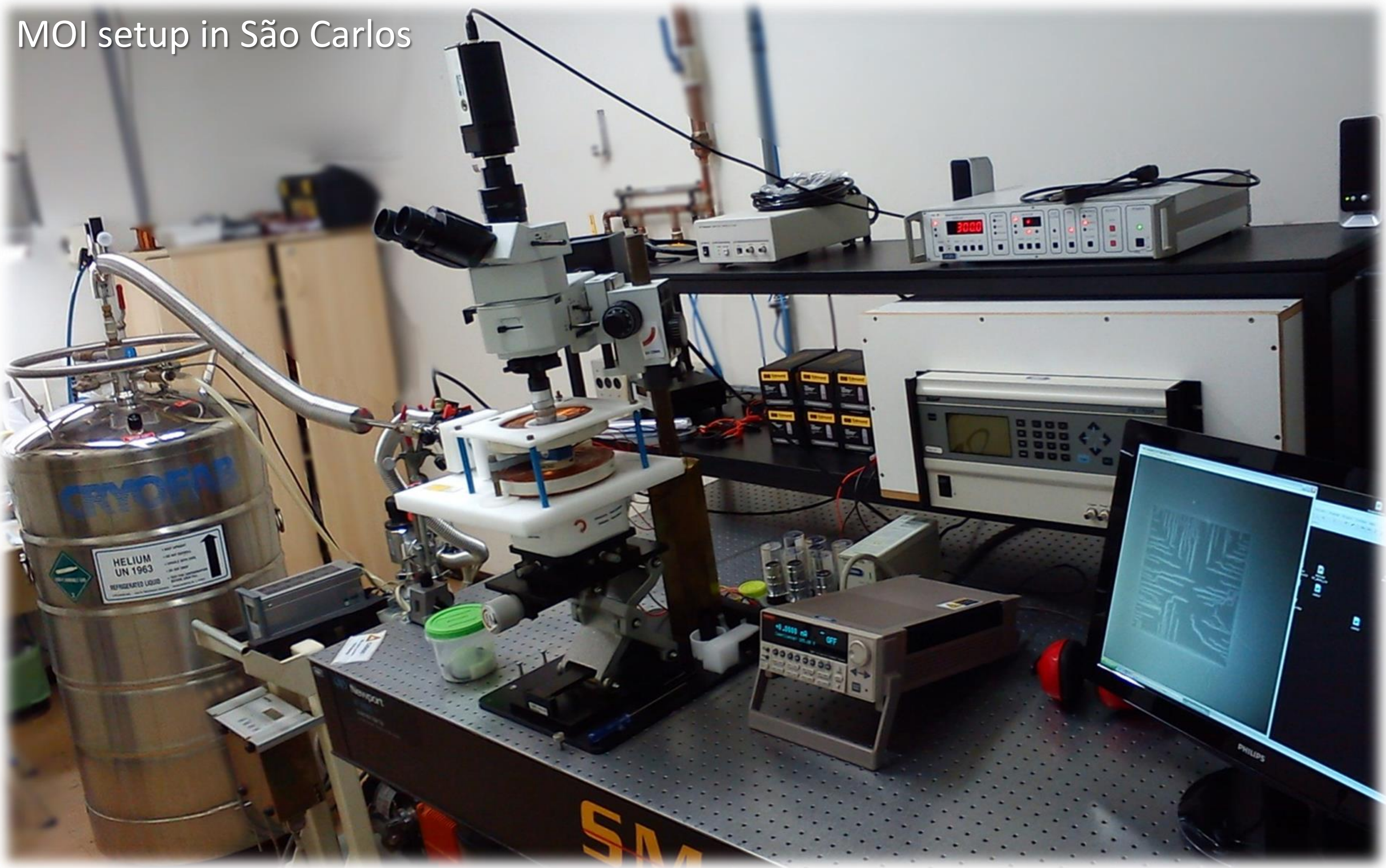






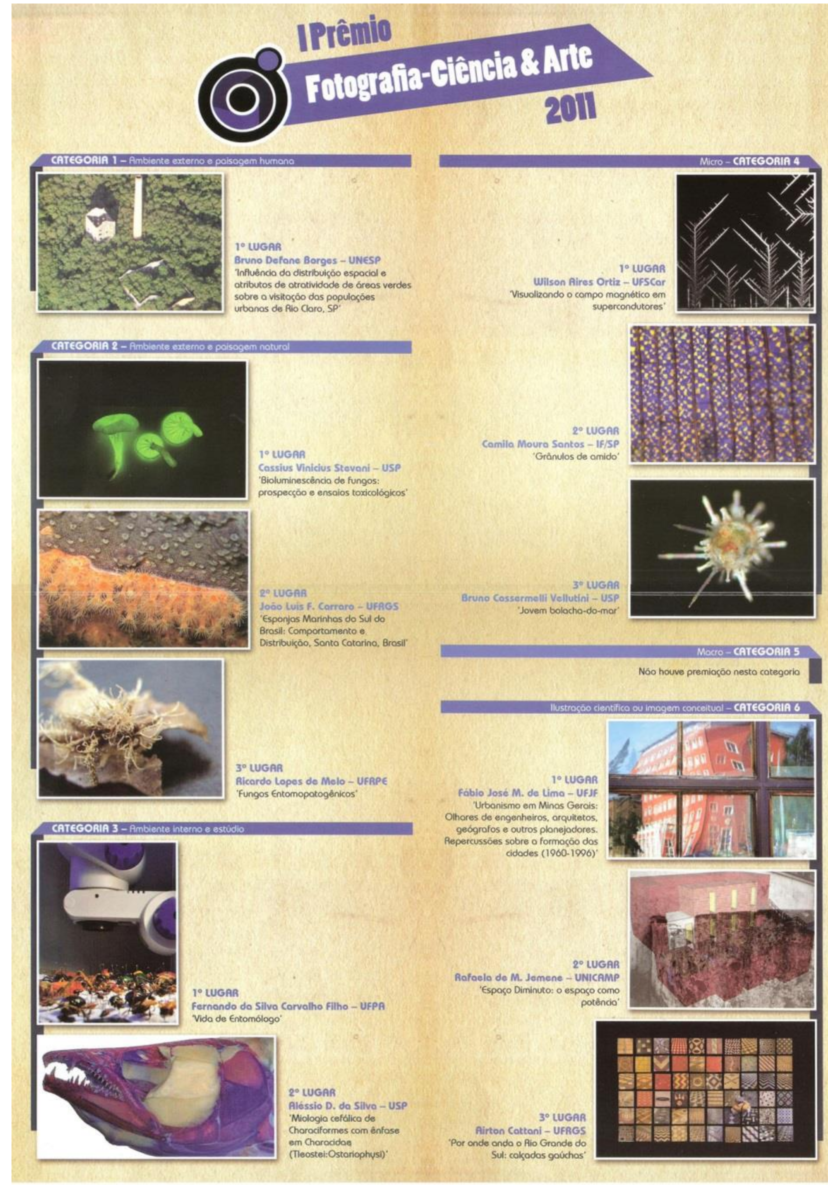
MOI setup GSM/UFSCar

MOI setup


MOI setup in São Carlos
CRYOFAB
HELIUM
UN 1963
REFRIGERATED LIQUID
PHILIPS

Revealing the intrinsic beauty of the problem

Visualizing Magnetic Fields in Superconductors



I Prêmio Fotografia – Ciência & Arte – CNPq 2011

1st Prize: "Photography – Science and Arts"

Brazilian National Research Council (CNPq)

Category: Photomicrography – special lenses, microscopes

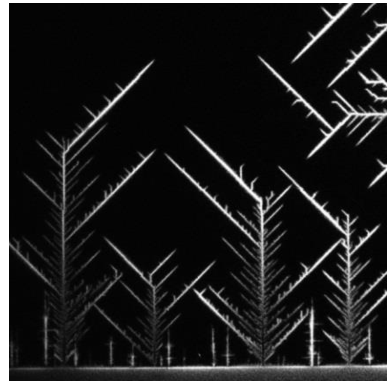
Title:
Visualizing Magnetic Fields in Superconductors

Image recorded by
W. A. Ortiz and coworkers
Univ. Federal de São Carlos, SP, Brazil.

Shows: Magneto-optical image of magnetic flux penetrating into a superconducting film patterned with a square lattice of antidots (nanosized holes not directly visible)

Prize awarded at
the opening ceremony of the
"National Week on Science and Technology",
in Brasília, Oct. 18, 2011.

Intrinsec beauty of the problem



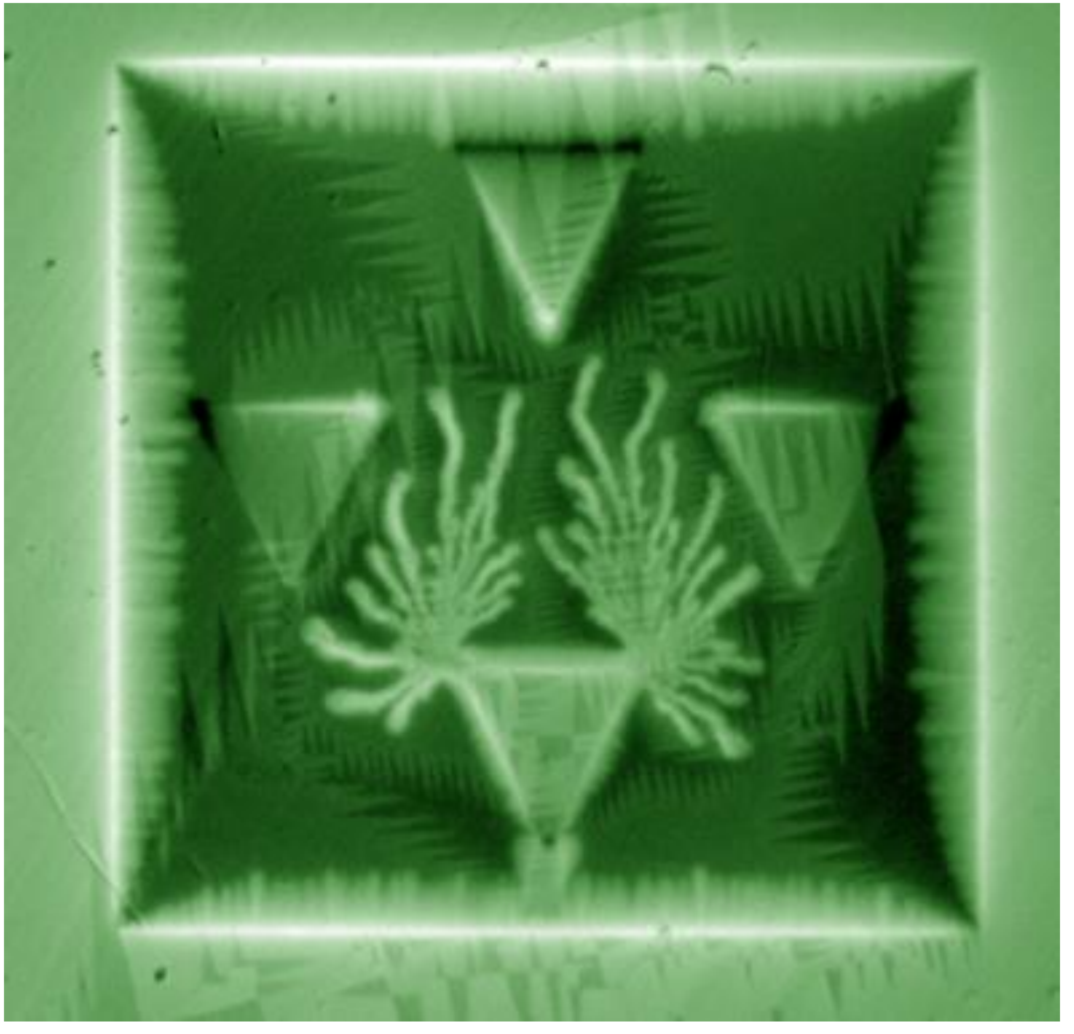
Visualizando o Campo Magnético em Supercondutores

Primeiro Lugar – Categoria Micro

Celebration in Oslo

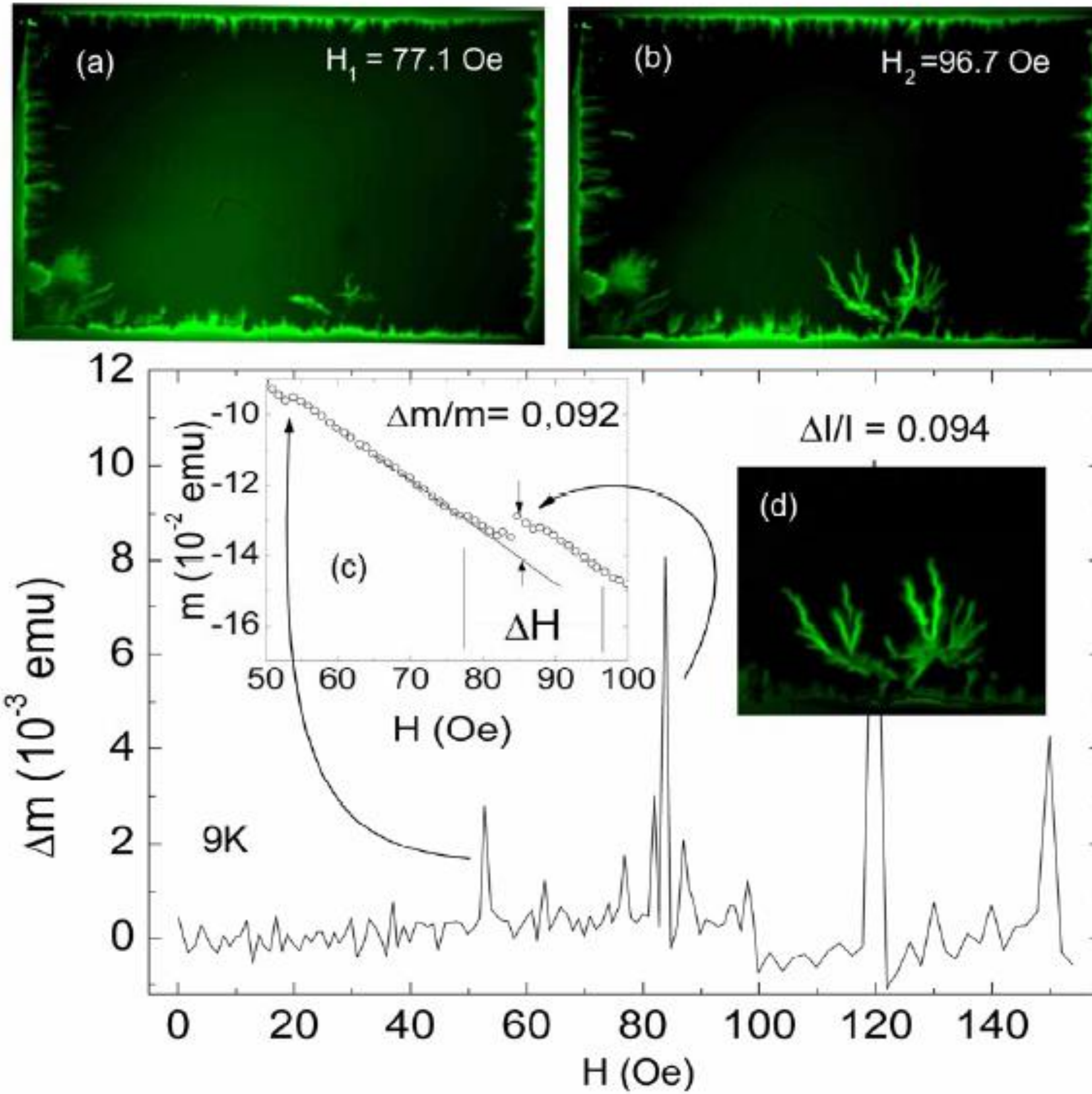
Centre for Advanced Study - Norwegian Academy of Science

CNPq – 2013 – 3rd place

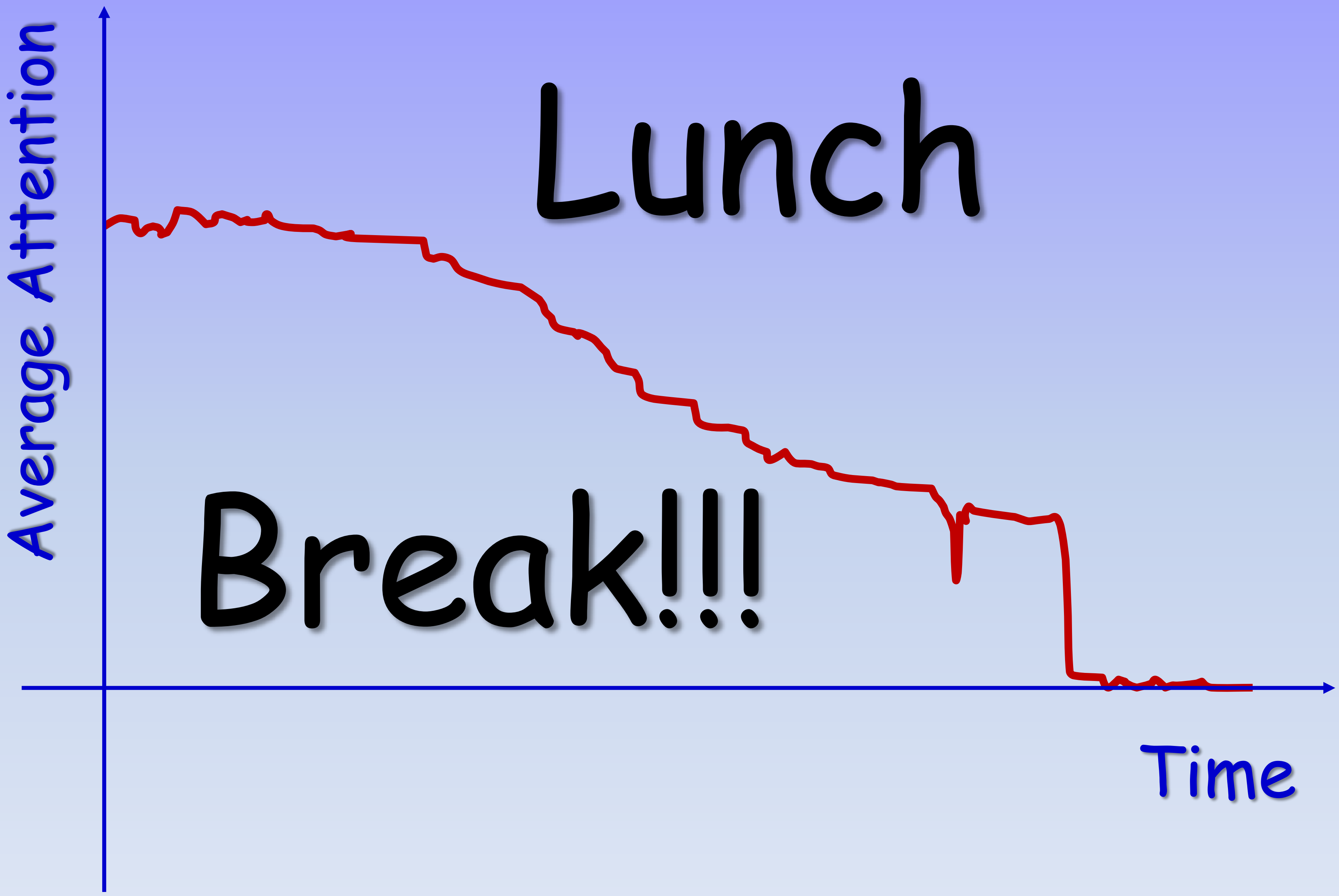


MgB_2

T = 9 K



(a)
H1 = 77.1 Oe
(b)
H2 =96.7 Oe
Δm/m= 0,092
ΔI/I = 0.094
(c)
(d)
ΔH
m (10^-2 emu)
H (Oe)
9K
Δm (10^-3 emu)
H (Oe)


Average Attention
Lunch
Break!!!
Time