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

Interaction of Vortex Matter with defects in superconducting films

Wilson A. Ortiz

Physics Department, Univ. Federal de São Carlos

wortiz@df.ufscar.br

Grupo de Supercondutividade e Magnetismo
Departamento de Física

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Vortices in Superconductors

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The first part of this plenary talk is devoted to a brief review on superconductivity and to vortices in superconductors: occurrence, dynamics, implications for applications.

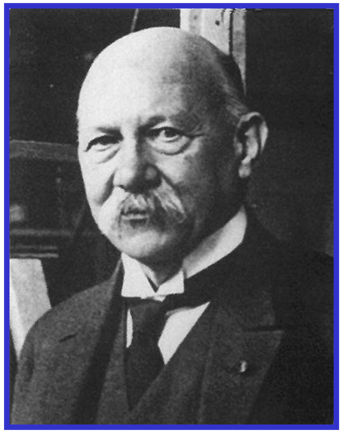
Next, we'll spend some time to review the technique employed in our lab to detect and record spacial flux distribution using Magneto-optical Imaging (MOI).

In the remaining of the talk we'll see some of our recent work on vortex dynamics, including flux avalanches in superconductors.

I. Superconductivity

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.

A bit of history



1913 Nobel Prize in Physics

Front Back

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

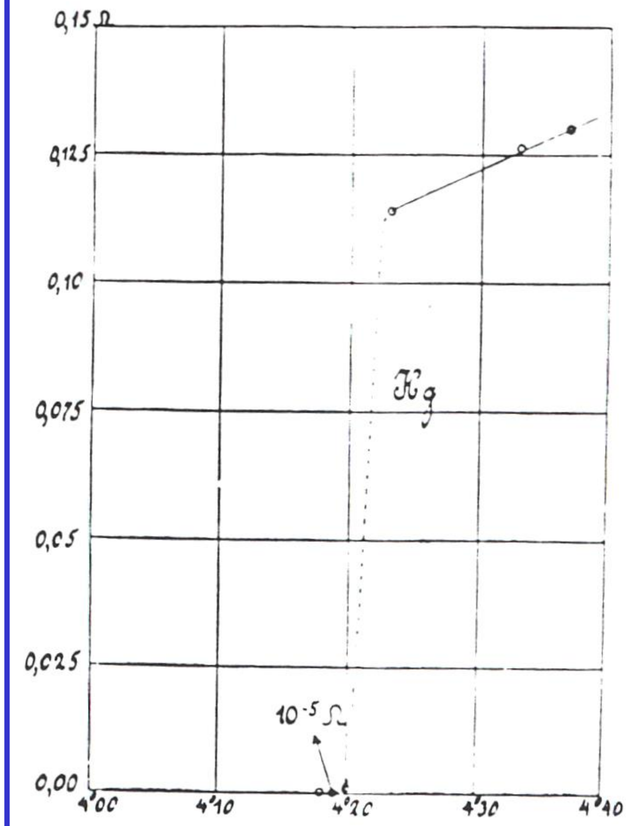
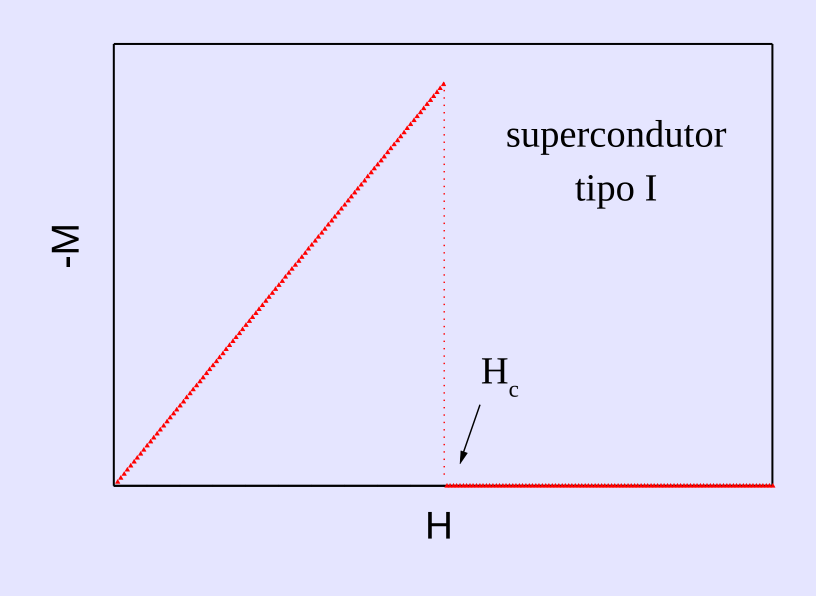


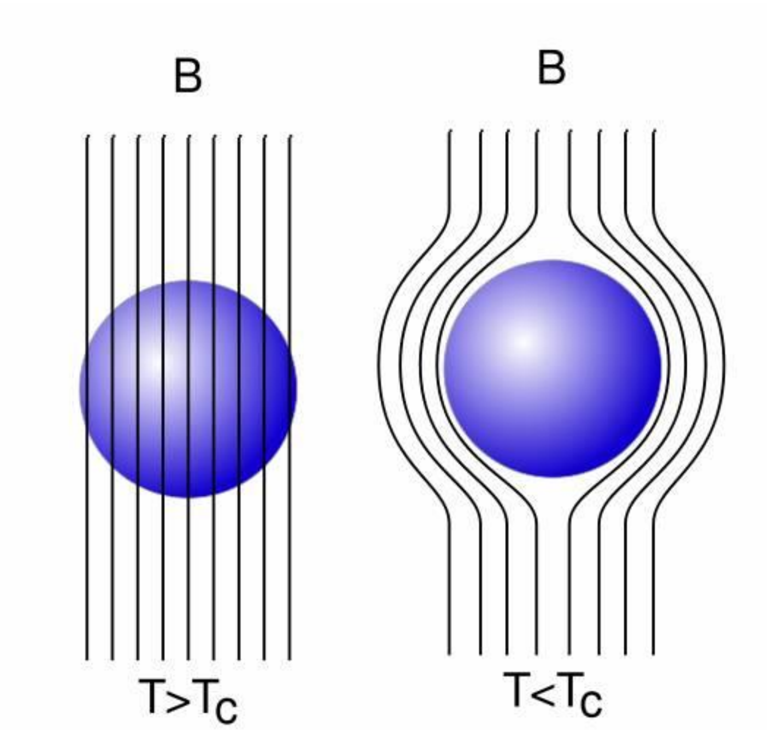
Figure **2.14** Resistivity-versus-temperature plot obtained by Kamerlingh Onnes when he discovered superconductivity in Leiden in 1911.

A bit of history...

Walther Meissner

Robert Ochsenfeld

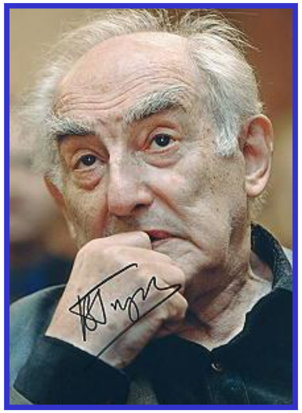


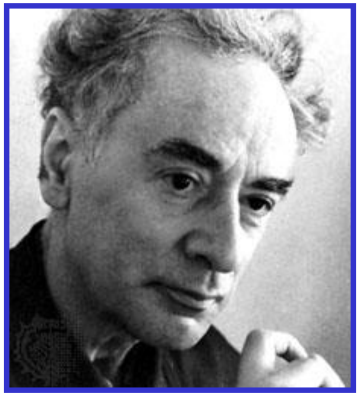


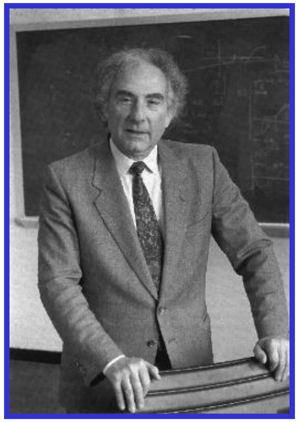
1933 - Meissner effect: perfect diamagnetism

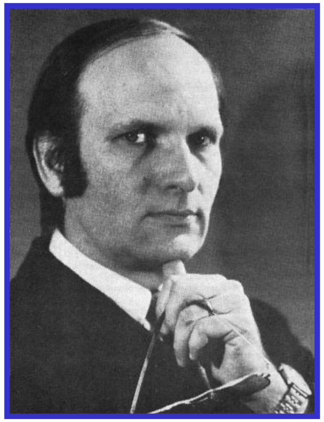
$B = \mu_o(H+M) = 0 \rightarrow M = -H$

A bit of history...









1972

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

1950 – Phenomenological Theory proposed by Ginzburg and Landau

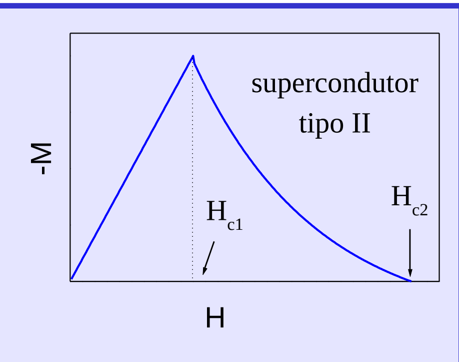
1957 – Microscopic Theory by Bardeen, Cooper and Schrieffer (BCS)

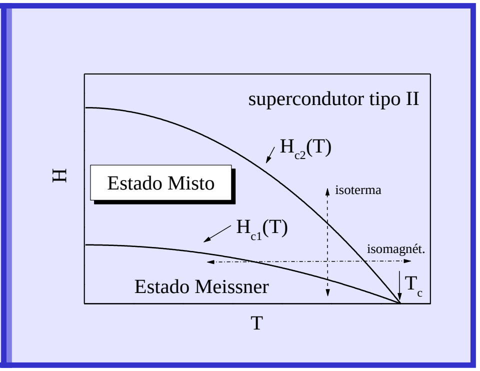
Cooper pairs (bosons) - Phys.Rev.104 (1956)

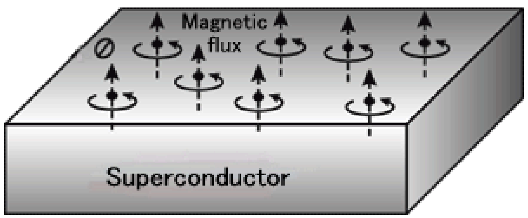
Boson condensate - Phys.Rev.108 (1957); Nobel Prize (1972)

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

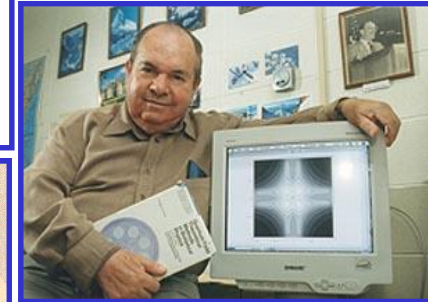
A bit of history...

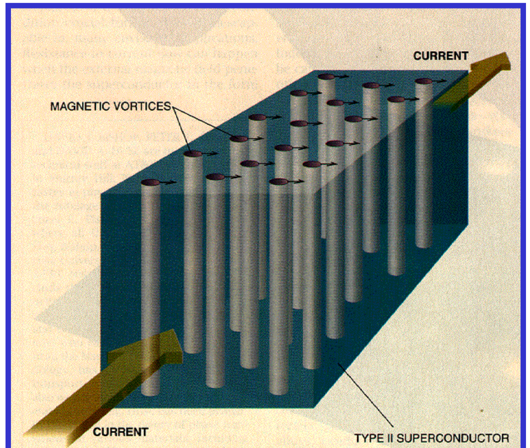






2003





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.

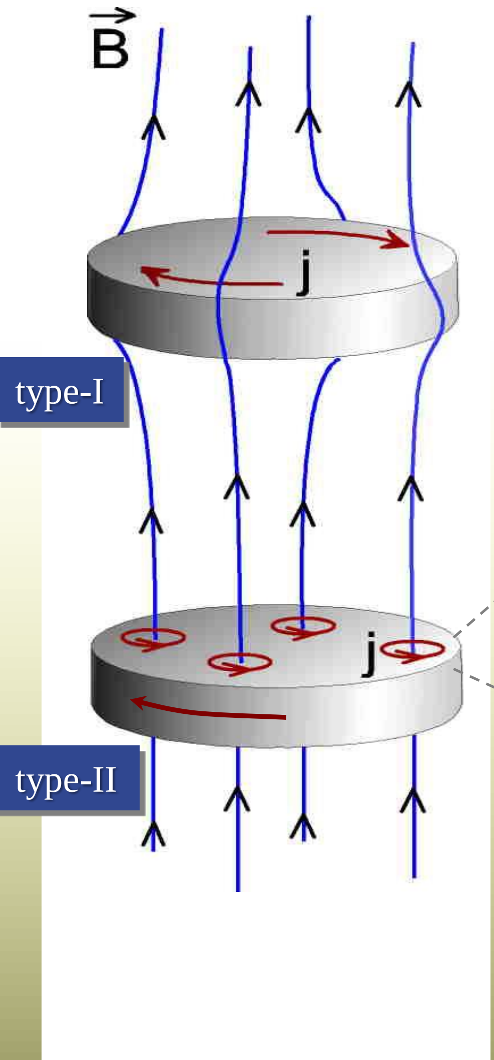
1957 – Abrikosov predicted the existence of another type of SC (type II)

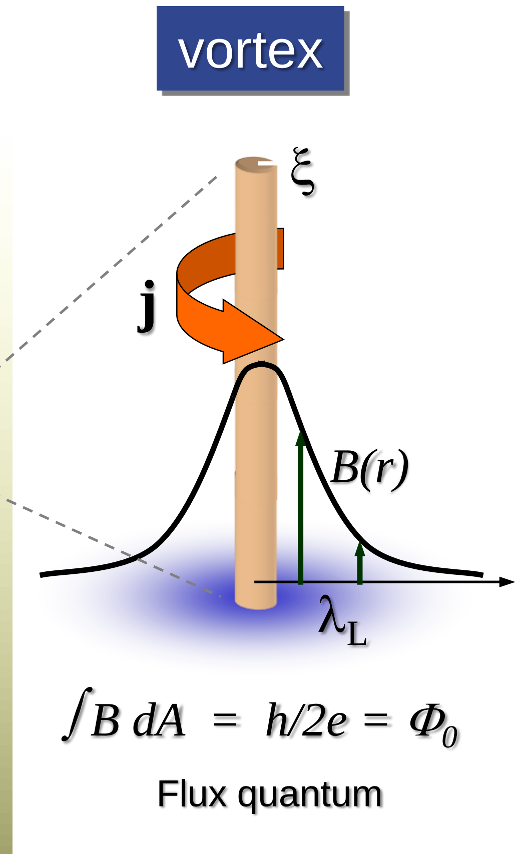
Surface energy can be negative in certain cases ($\kappa = \lambda/\xi > 0.707$)

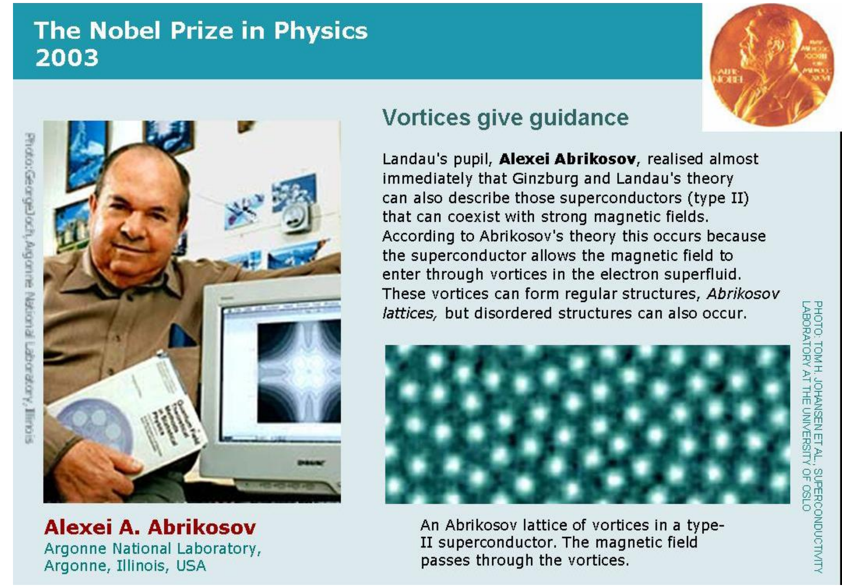
➔ creation of N/SC interfaces becomes energetically favorable

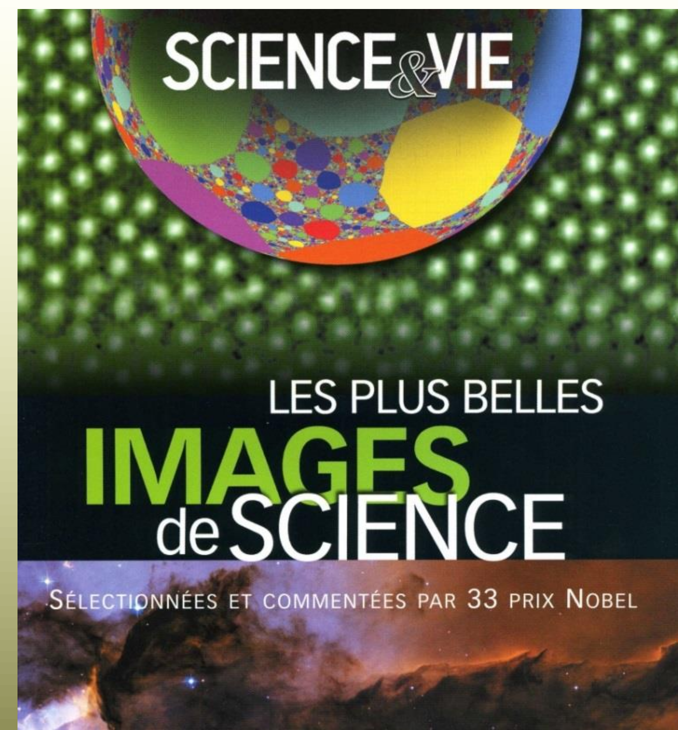
<u>Fluxoides or Vortices</u>: normal regions in the form of "tubes", penetrated by one quantum flux each, $\phi_o \sim 2\times10^{-15}$ SI, surrounded by superconducting screening currents.

Vortex matter

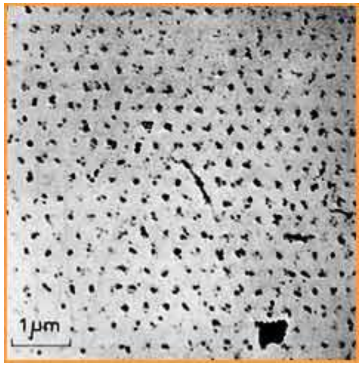








Gallery

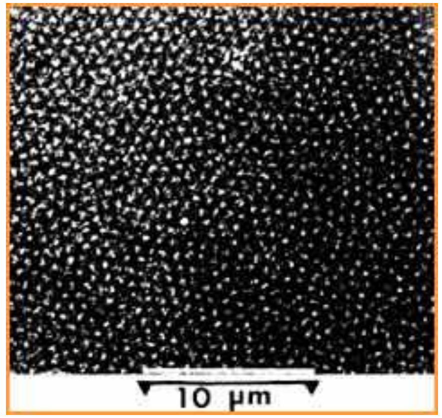


First Image

Bitter Decoration 1967

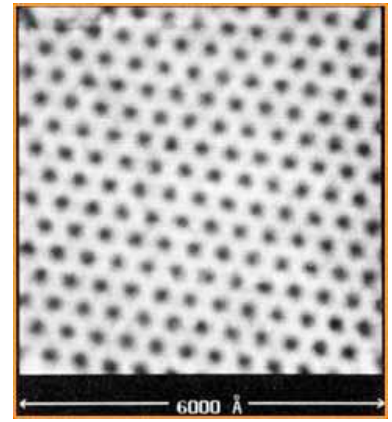
Pb-4at%In rod, 1.1K, 195G

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

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YBaCuO film, 1000G

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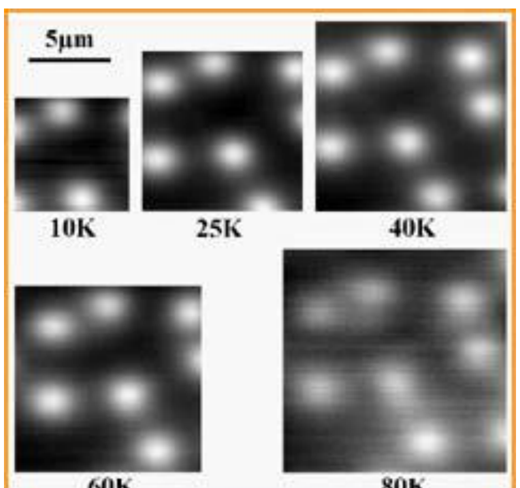
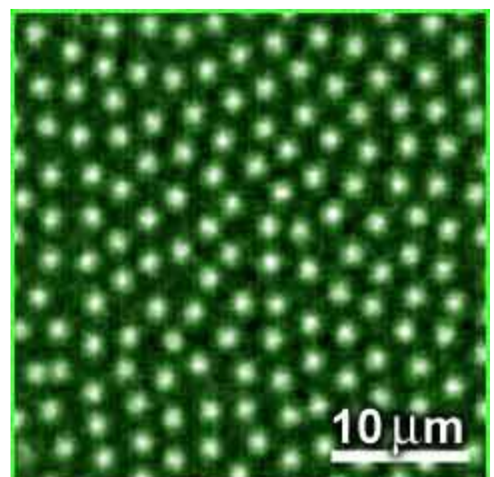




Magneto-Optical Imaging
NbSe2 crystal, 4.3K, 3G

P.E. Goa et al.
University of Oslo

Superconductivity - Basic Concepts

Superconductivity is a Macroscopic Quantum State featuring two distinguishing properties:

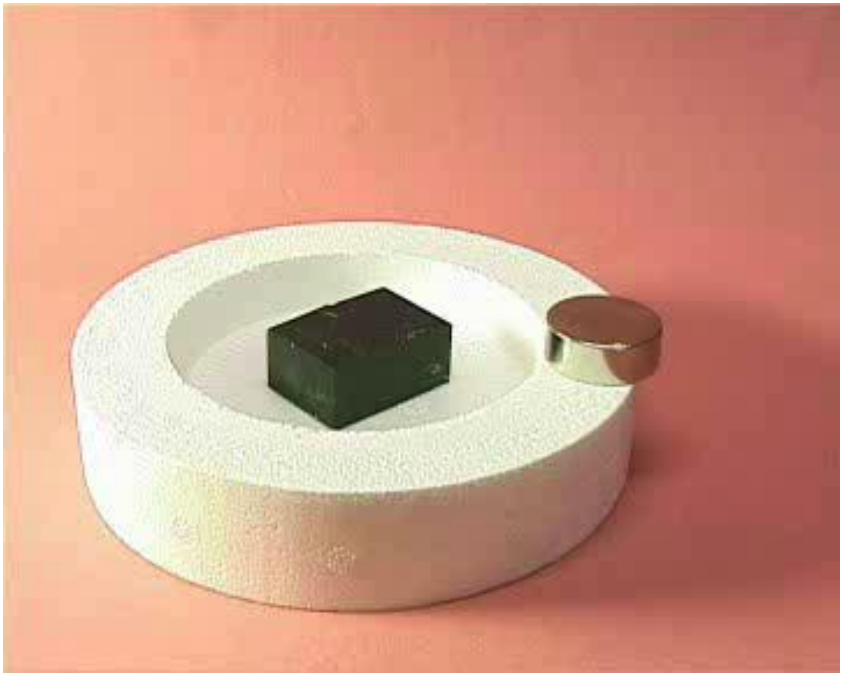
. Supercurrents
  (dissipationless transport)

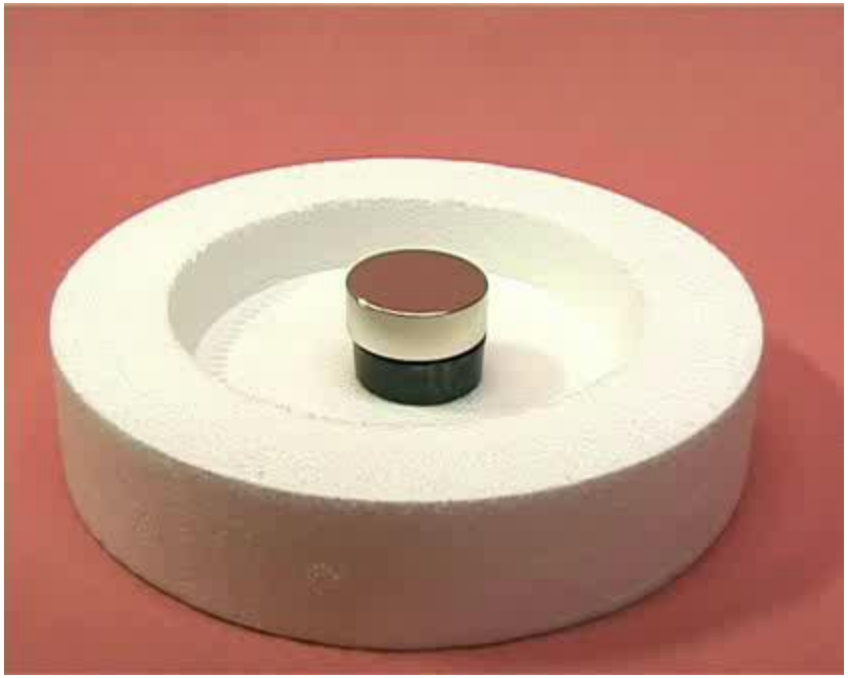
. Screening of magnetic fields
  (Meissner effect)

Screening of magnetic fields - Meissner effect

Zero field cooling (ZFC)

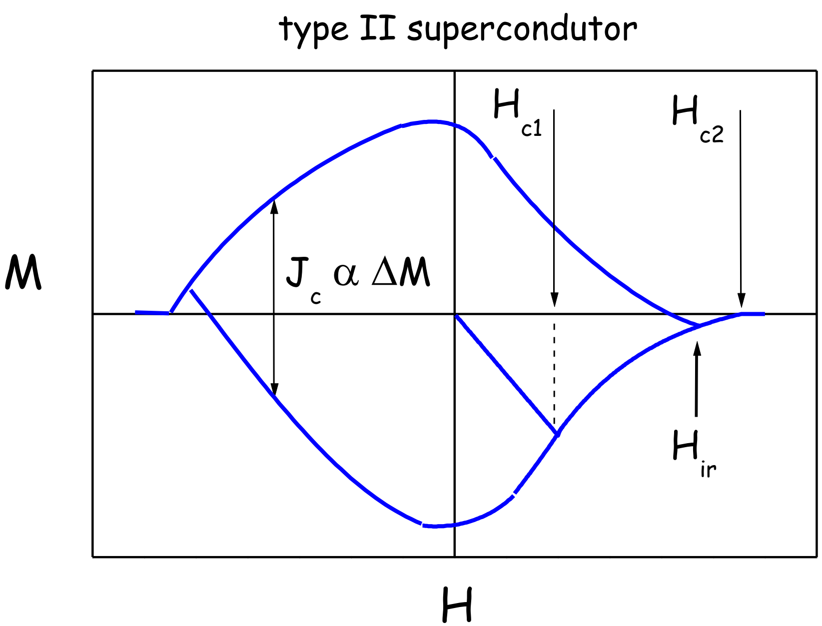
Field-cooling (FC)

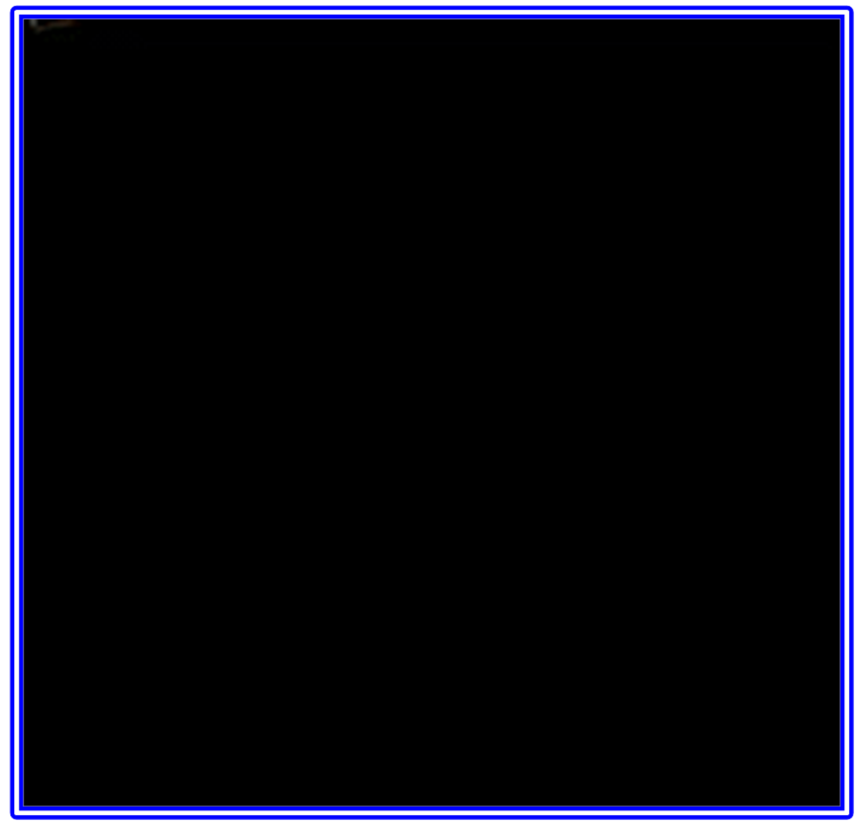




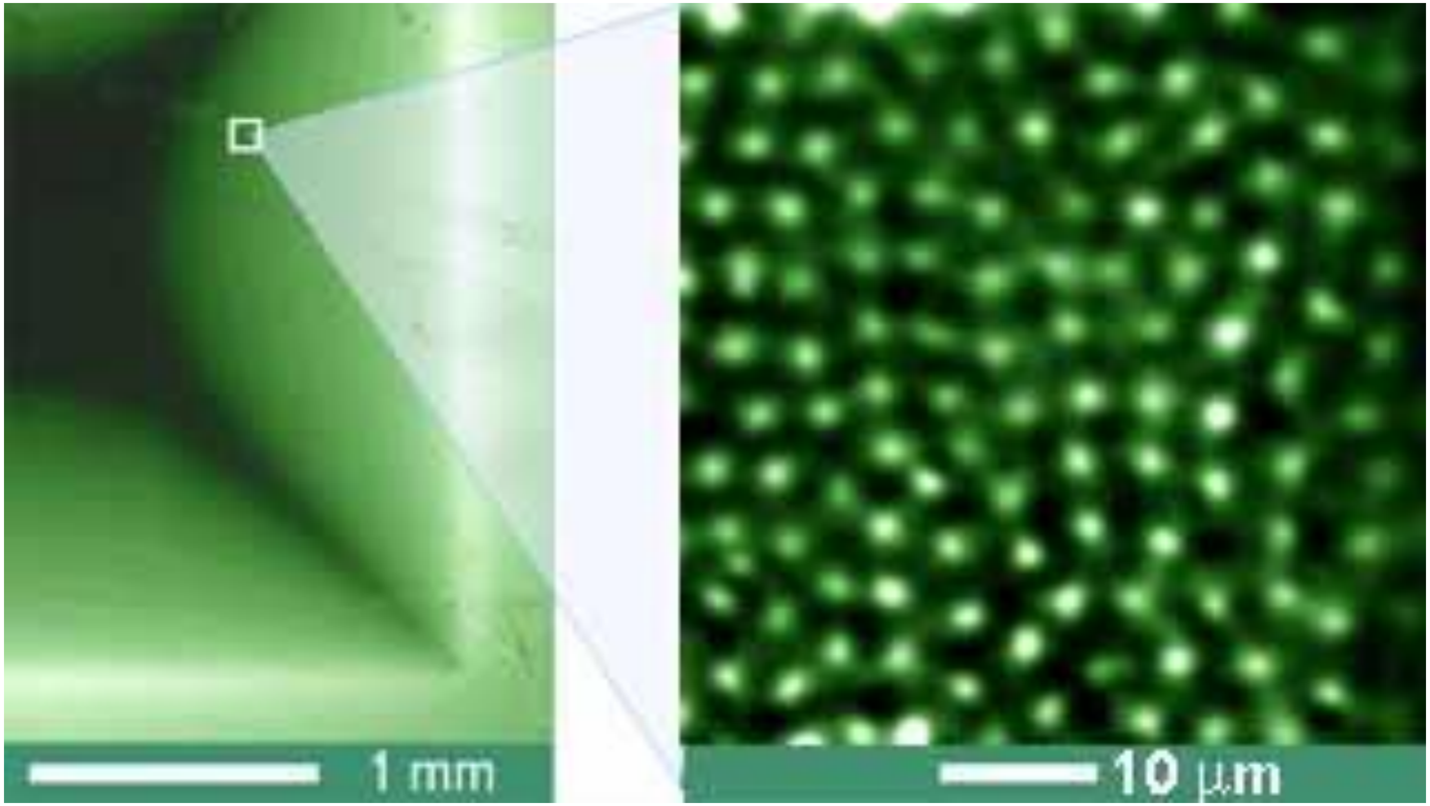
http://www.fys.uio.no/super/

Penetration Profile: Critical State





Flux distribution apparently continuous...
in reality, quantized flux: vortices



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

Vortices are present in almost all applications of superconductors;

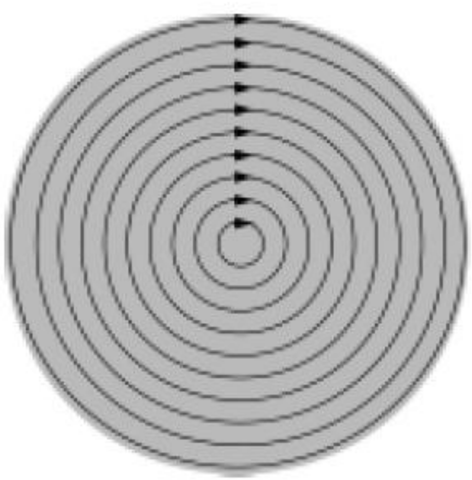
Vortices have a dynamics of their own;

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

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.

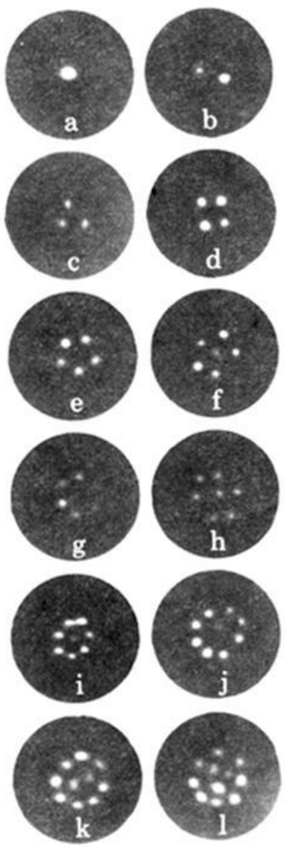
Since the work of London[1] it has become an accepted notion that superfluidity is a manifestation of quantum mechanics on a macroscopic scale. Pursuing this idea in a quite literal way, Onsager and Feynman[2] tried to deduce the qualitative features of a single macroscopic wave function, $\psi(r)$, 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

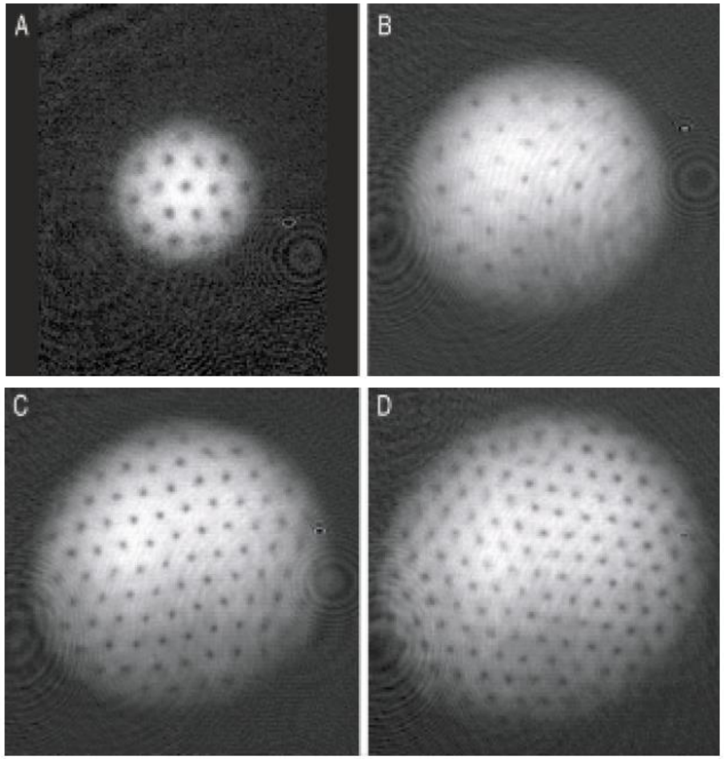


Figure 20. Observation of vortex lattices in rotating Bose-Einstein condensates. The examples shown contain (A) 16 (B) 32 (C) 80 and (D) 130 vortices as the speed of rotation was increased. The vortices have "crystallized" in a triangular pattern. The diameter of the cloud in (D) was 1 mm after ballistic 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*

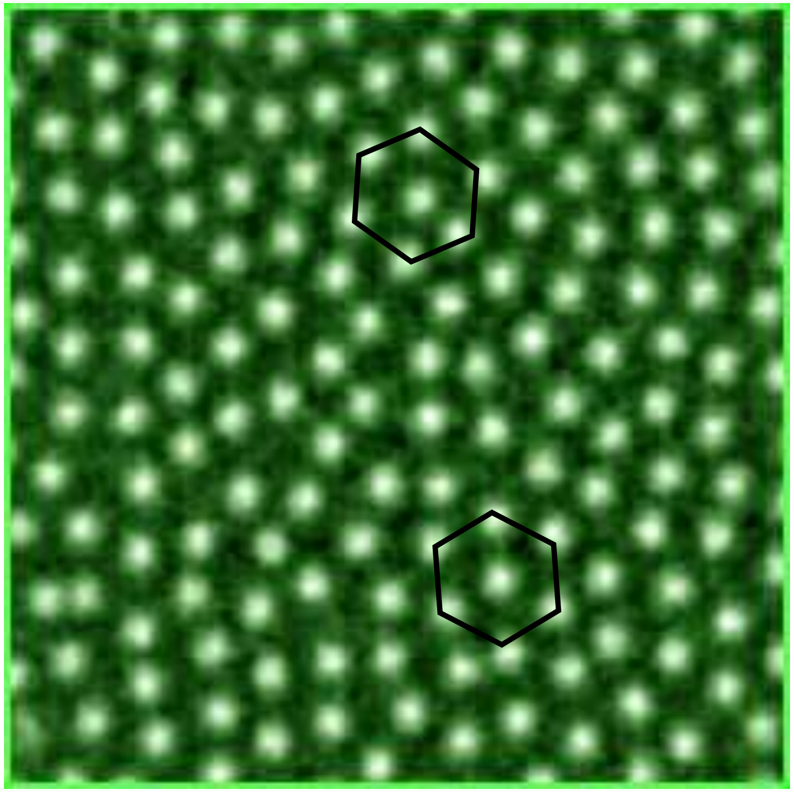
Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA.

Condensate of Na atoms

Vortices in Superconductors

Vortices in Superconductors

Abrikosov lattice

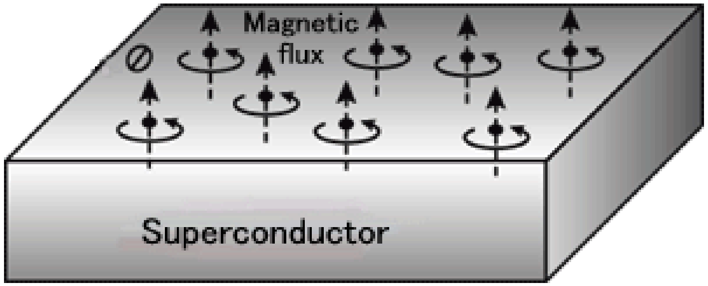


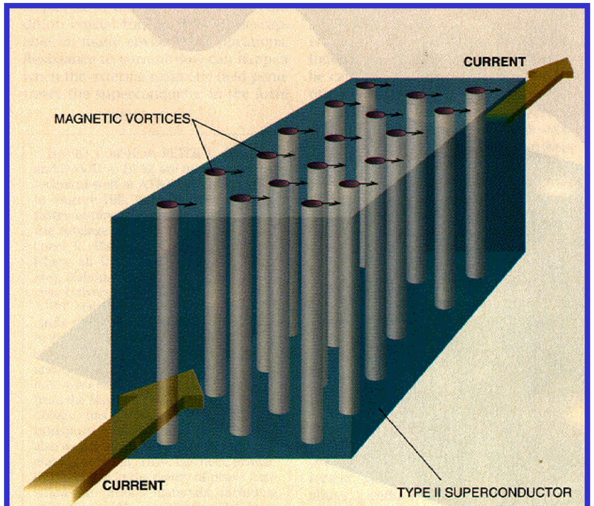
Magneto-optical Imaging

Tom H. Johansen

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

A bit of history...





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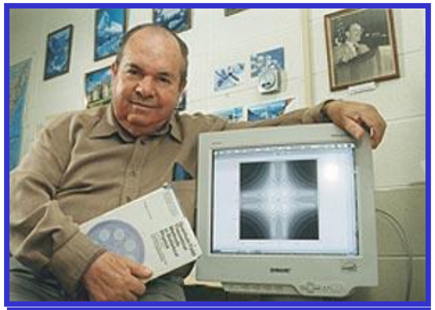


A. Abrikosov
Nobel Prize in Physics in 2003, shared with V. Ginzburg and A. Leggett

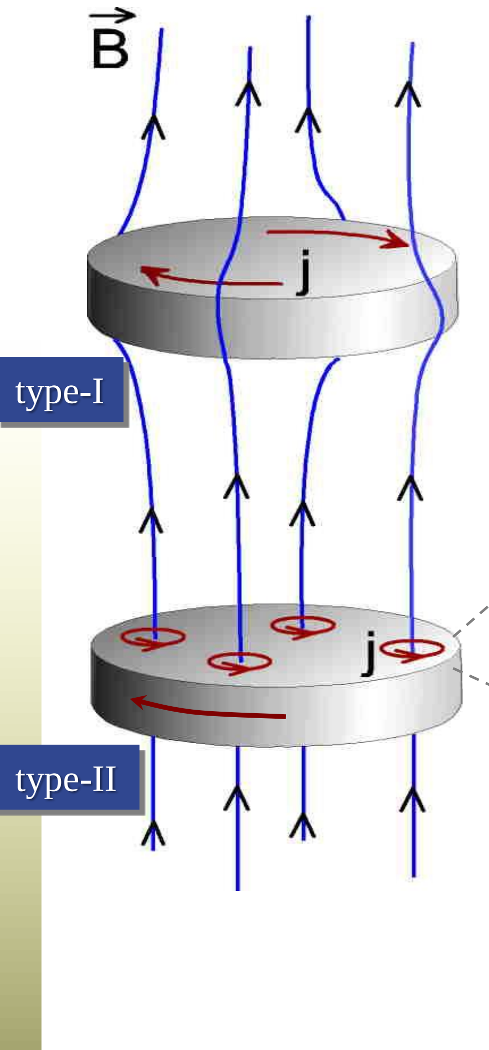
1957 – Abrikosov predicted the existence of type II SCs (flux allowed)

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

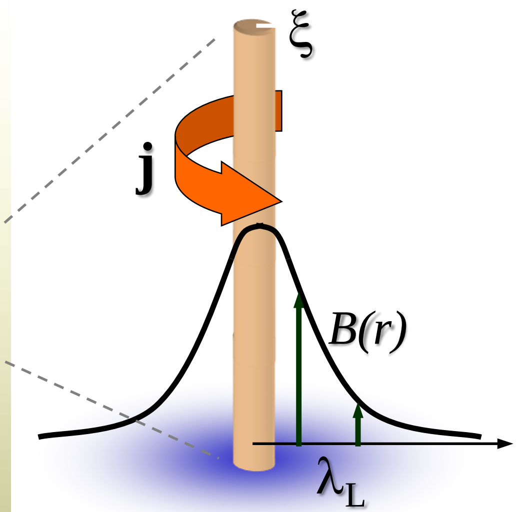
➔ creation of interfaces N/SC become energetically favorable

<u>Fluxoids or Vortices</u>: normal regions in the form of tubes carrying one flux quantum each, $\phi_o \sim 2\times10^{-15}$ SI, surrounded by screening currents

Vortex matter

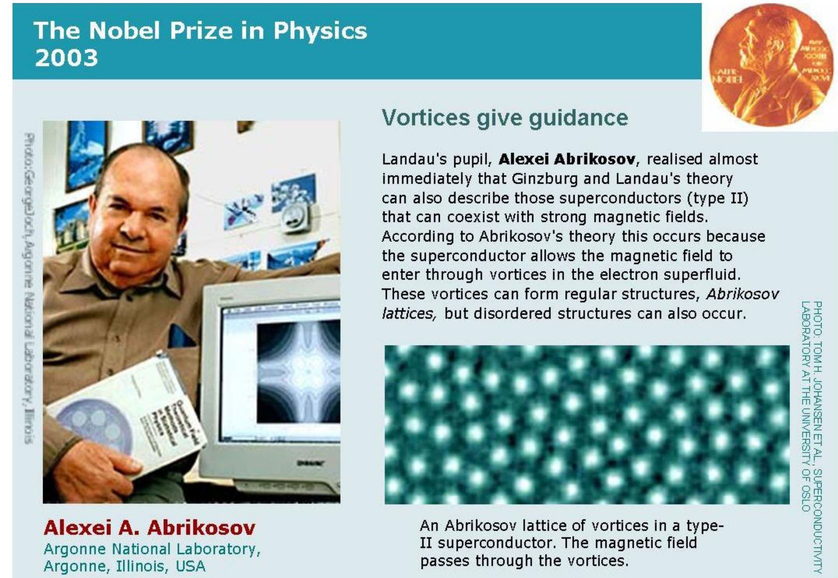


vortex



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

Flux quantum



The Nobel Prize in Physics 2003

Photo: George Joch, Argonne National Laboratory, Illinois

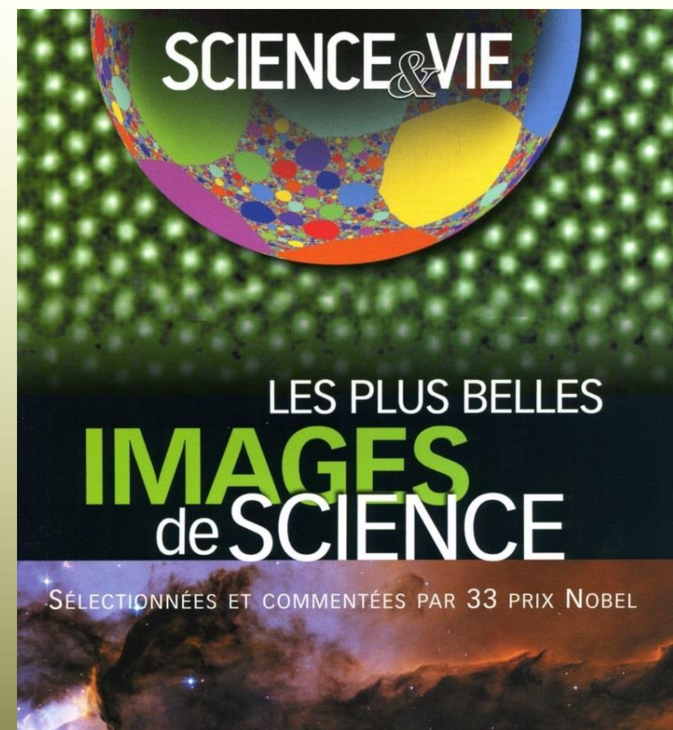
Alexei A. Abrikosov
Argonne National Laboratory, Argonne, Illinois, USA

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



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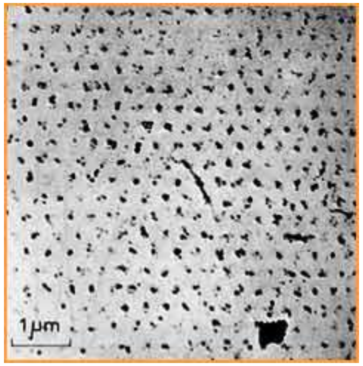
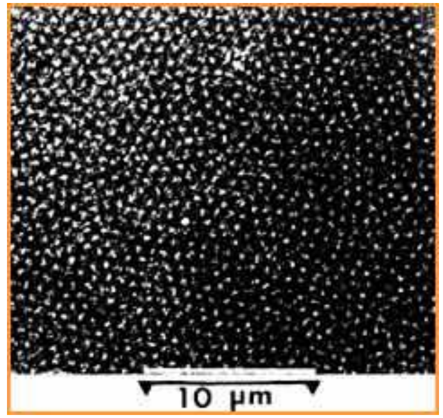


Primeira Imagem

Bitter Decoration 1967

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

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



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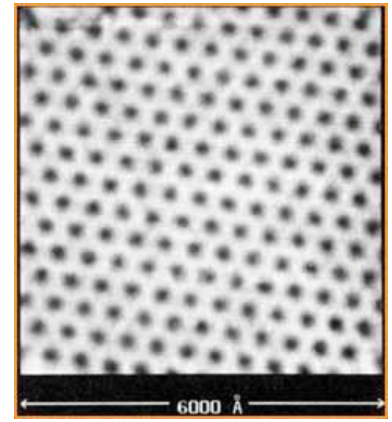
$YBa_2Cu_3O_7$ crystal, 4.2K, 52G

P. L. Gammel et al., Bell Labs



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NbSe2, 1T, 1.8K

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YBaCuO film, 1000G

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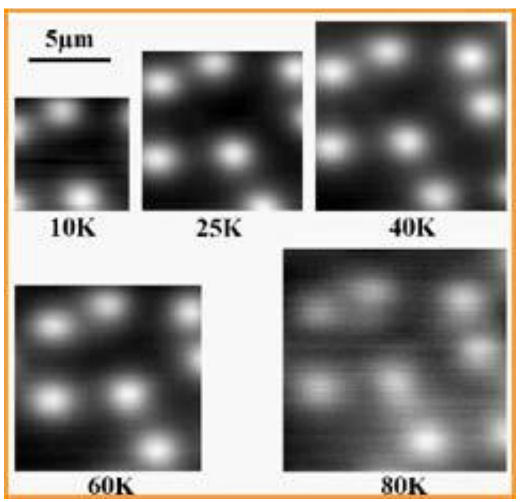
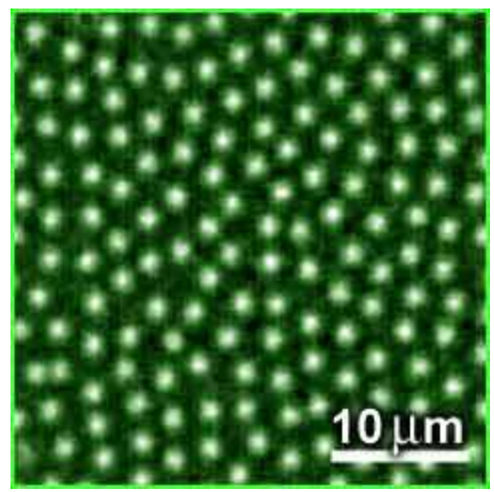


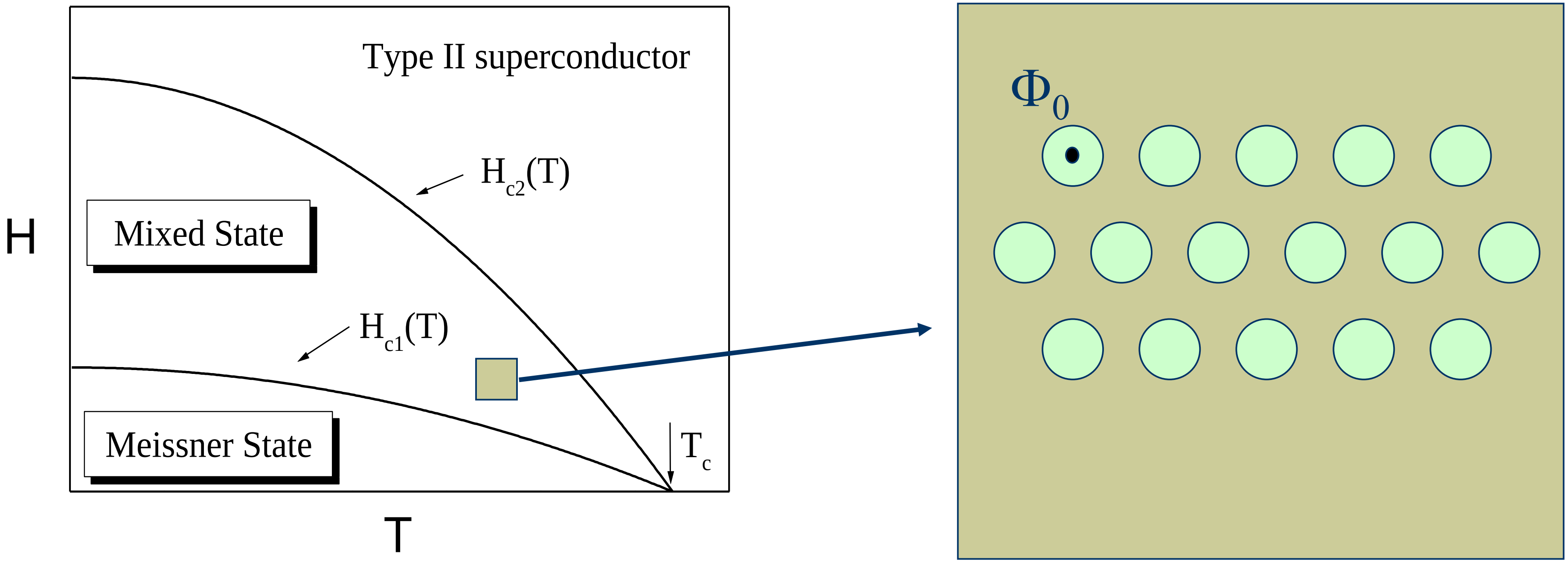


Magneto-Optical Imaging
NbSe2 crystal, 4.3K, 3G

P.E. Goa et al.
University of Oslo

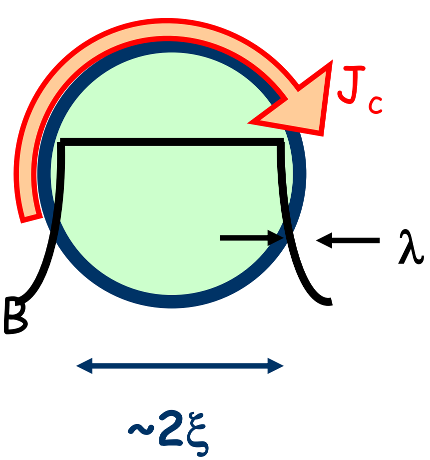
Vortex Dynamics

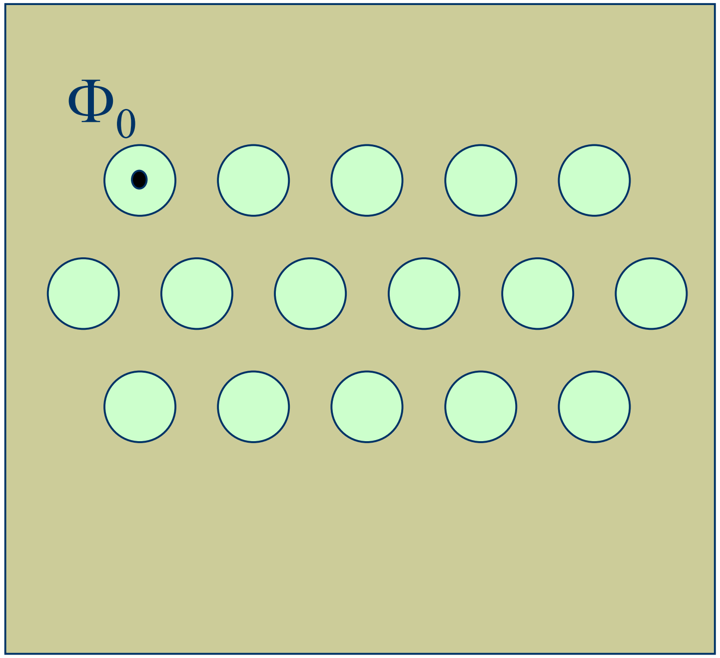
Vortices in the presence of currents: viscous motion ➔ dissipation



Vortices in the presence of currents: viscous motion ➔ dissipation

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

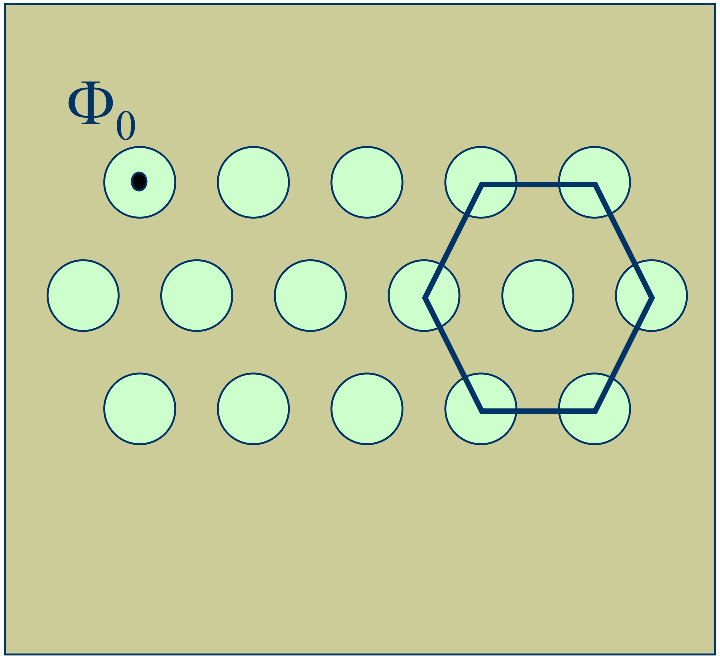




Vortices in the presence of currents: viscous motion ➔ dissipation

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

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



Vortices in the presence of currents: viscous motion ➔ dissipation

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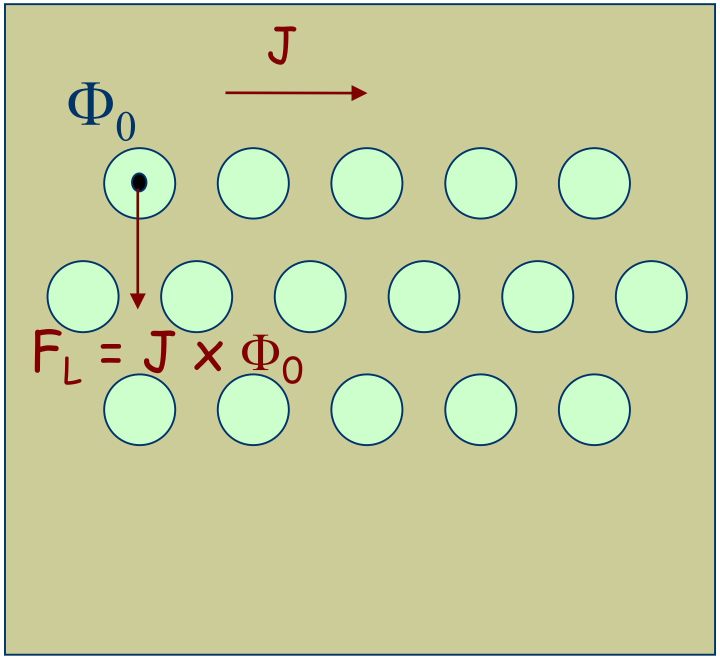
- Collection of vortices: typical elastic, electric, magnetic & thermal properties ➔ Vortex Matter (VM)
- If J is present, VM experiences viscous movement which may lead the sample to its normal state



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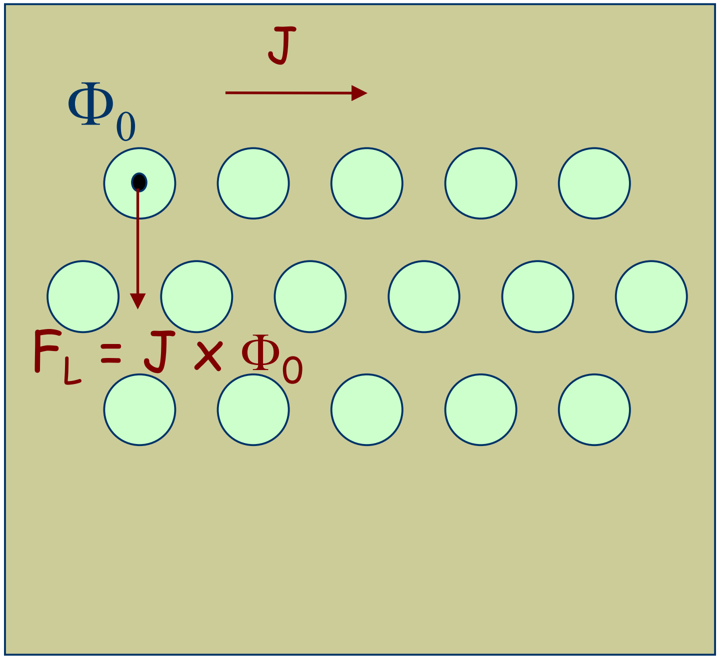
- Collection of vortices: typical elastic, electric, magnetic & thermal properties ➔ Vortex Matter (VM)

- 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

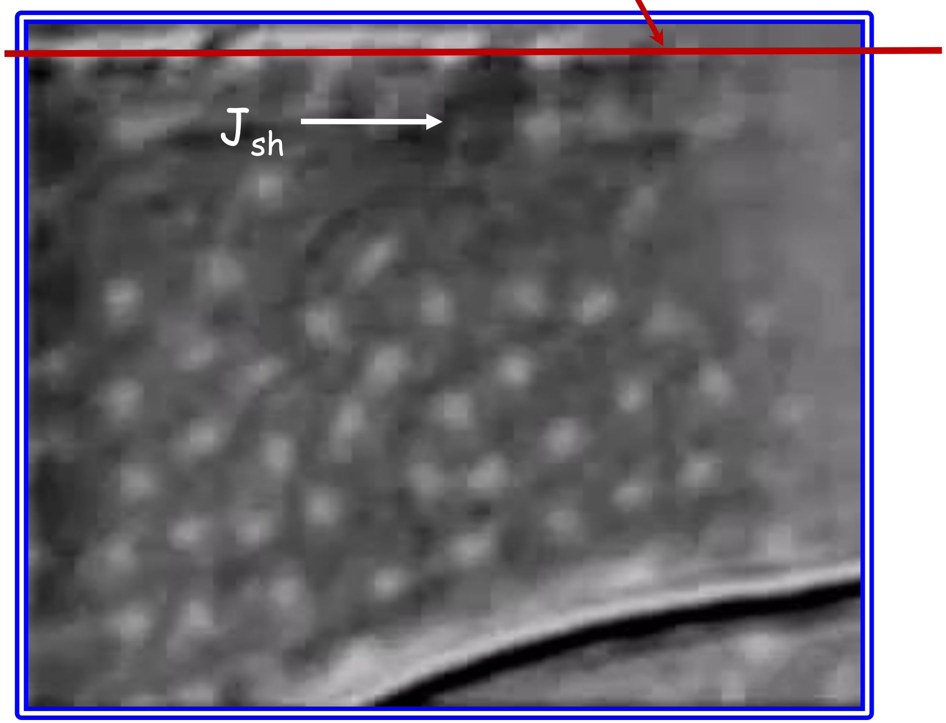
- PCs are crucial to enable Jc > 0

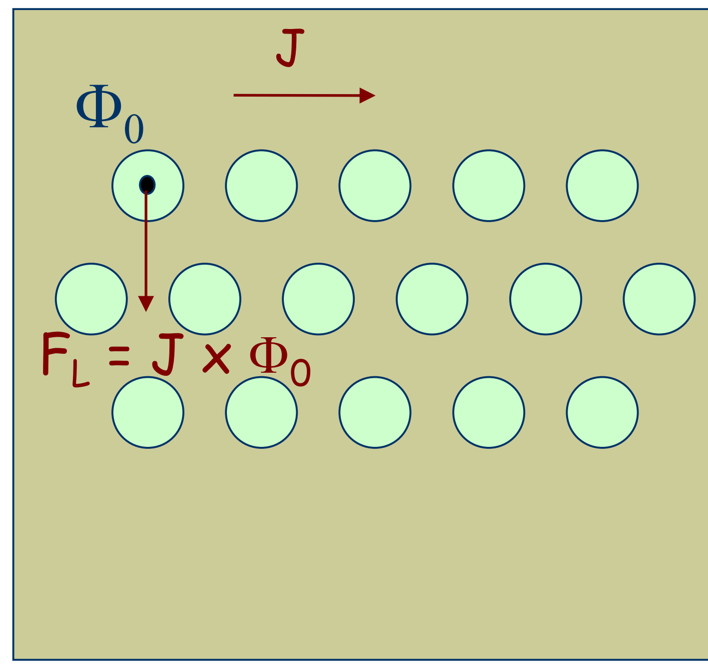


Alexei Abrikosov acting as a “pinning center” for his admirers
Leuven, july 2006

- Vortex entry

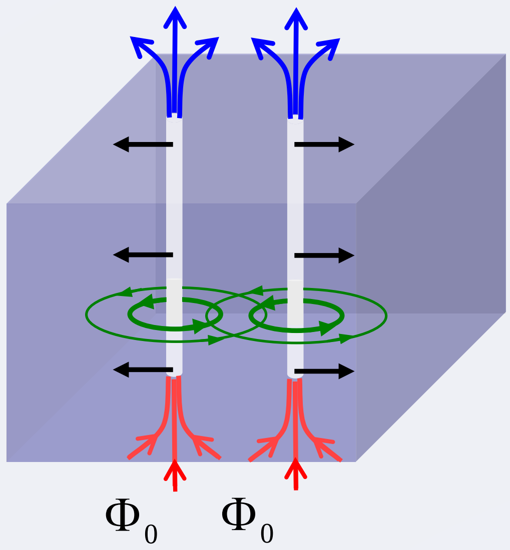
sample border



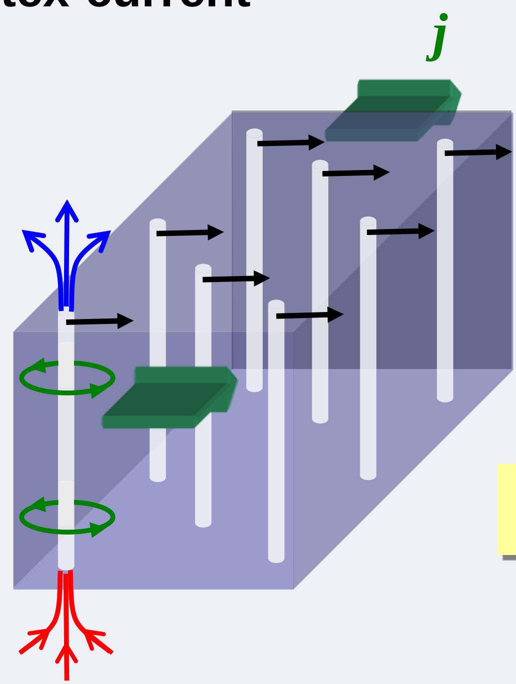


Interactions

vortex-vortex



vortex-current

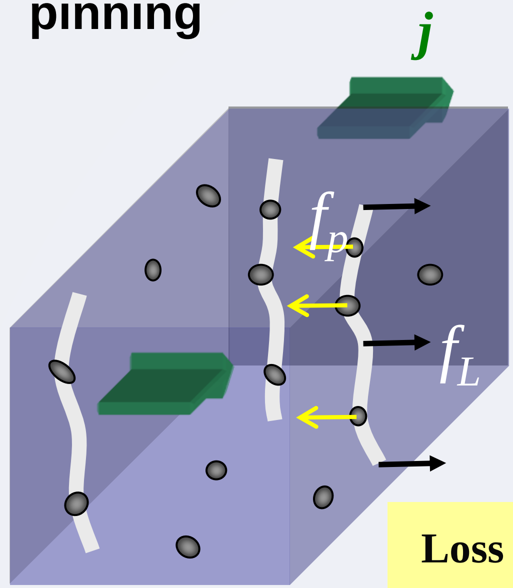


$$\vec{f_L} = \vec{j} \times \vec{\Phi_0}$$

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

Loss = jE

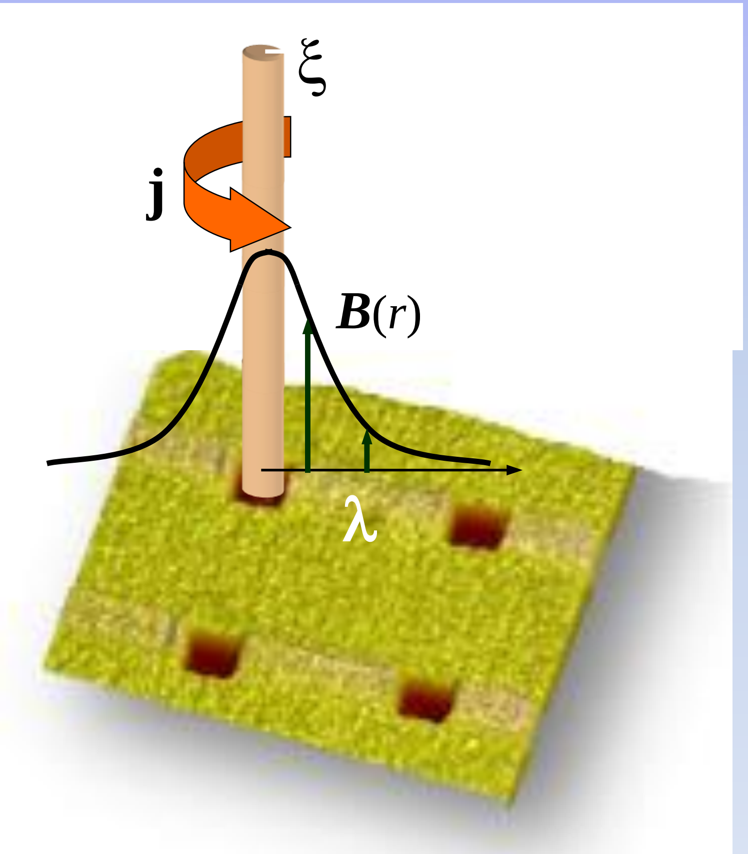
pinning



+ $k_B T$

Loss = 0

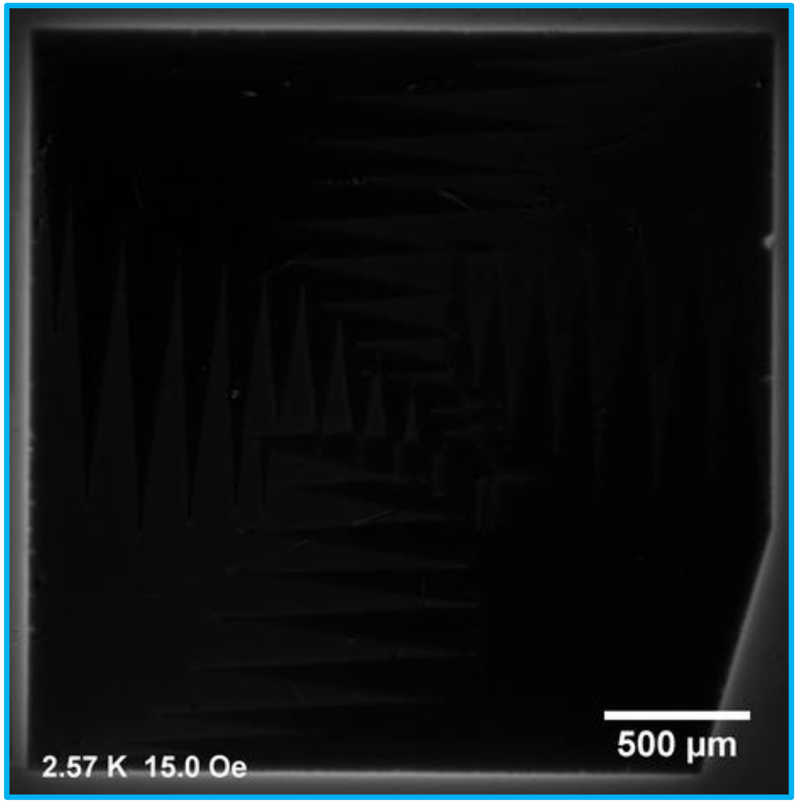
defects: pinning centers



Vortex Avalanches

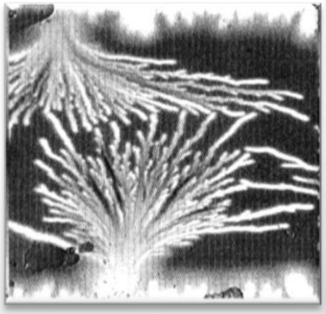
Facts

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

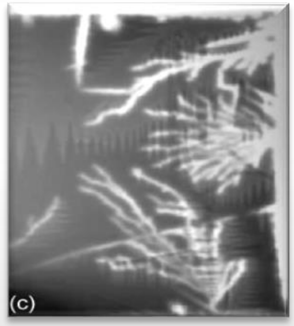


Nb film

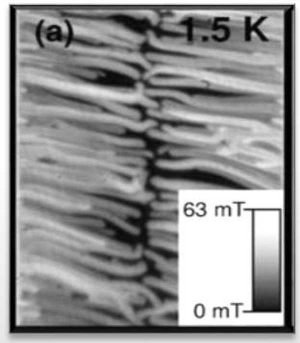
Magneto optical images of avalanches in superconducting thin films



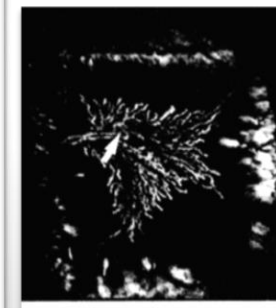
Nb
5.97 K, 135 Oe
Remanent state
Durán *et al.* 1995



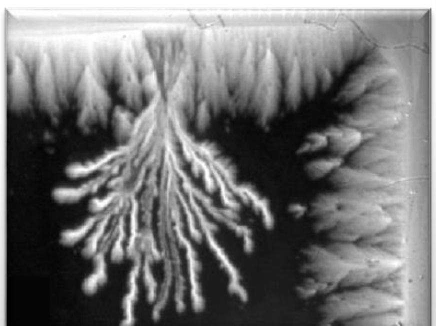
Nb_3Sn
3.5 K, 263 Oe
Rudnev *et al.*
2003



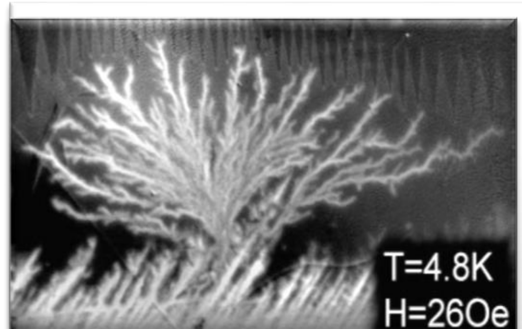
Nb
5.97 K, 135 Oe
Welling *et al.*
2004



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

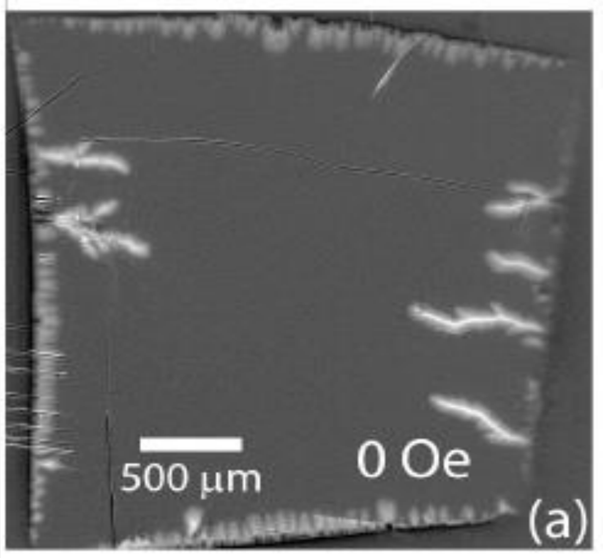


MgB_2
10 K, 170 Oe
Johansen *et al.* 2004



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

Some images captured @ GSM/São Carlos

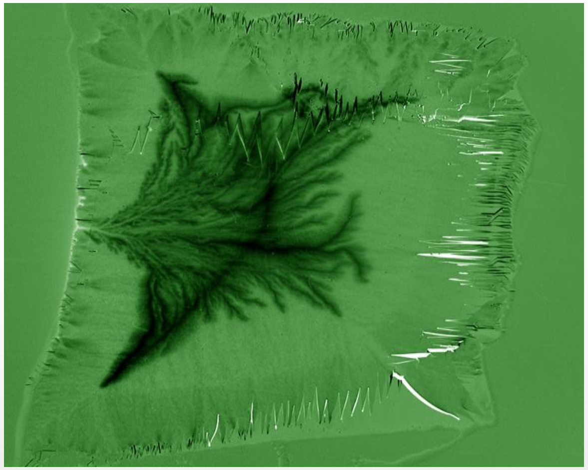


Nb (Plain)

Remanent state

3 K, after 4 Oe

GSM, 2011

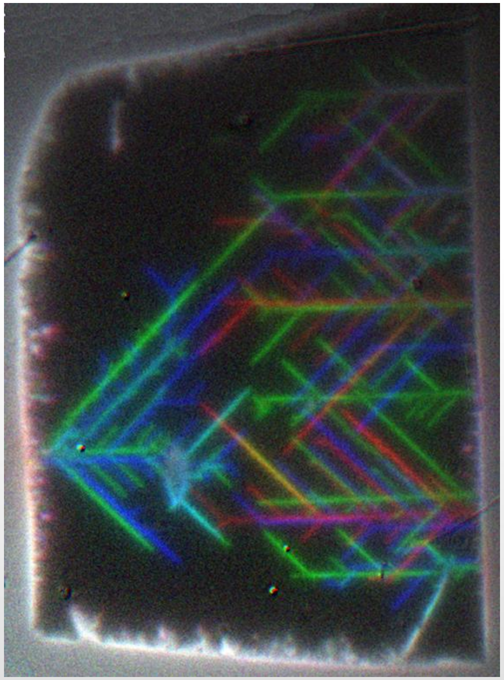


a-MoSi (Plain)

3 K

ZFC → 60 Oe → 10 Oe

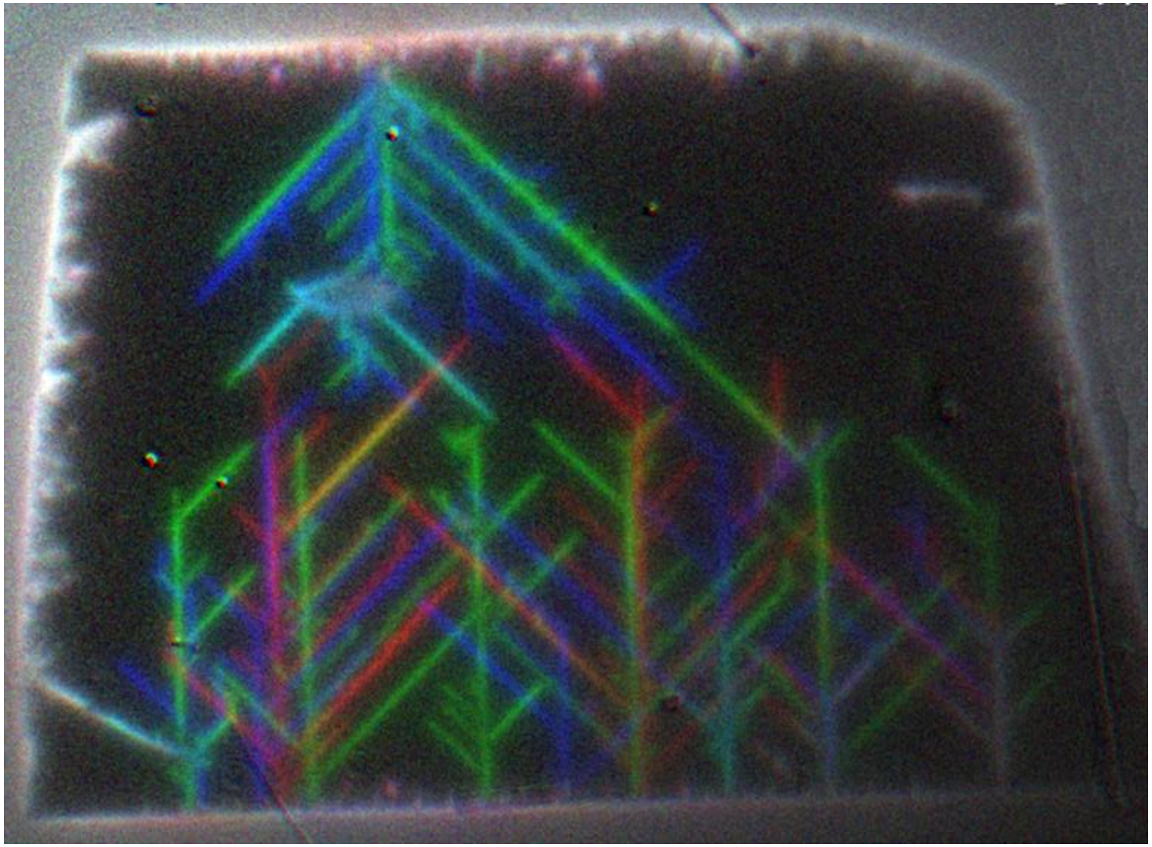
GSM, 2011



a-MoGe (AD04)

4.5 K, 1 Oe

GSM, 2011



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

GSM, 2011

Thermomagnetic Instabilities

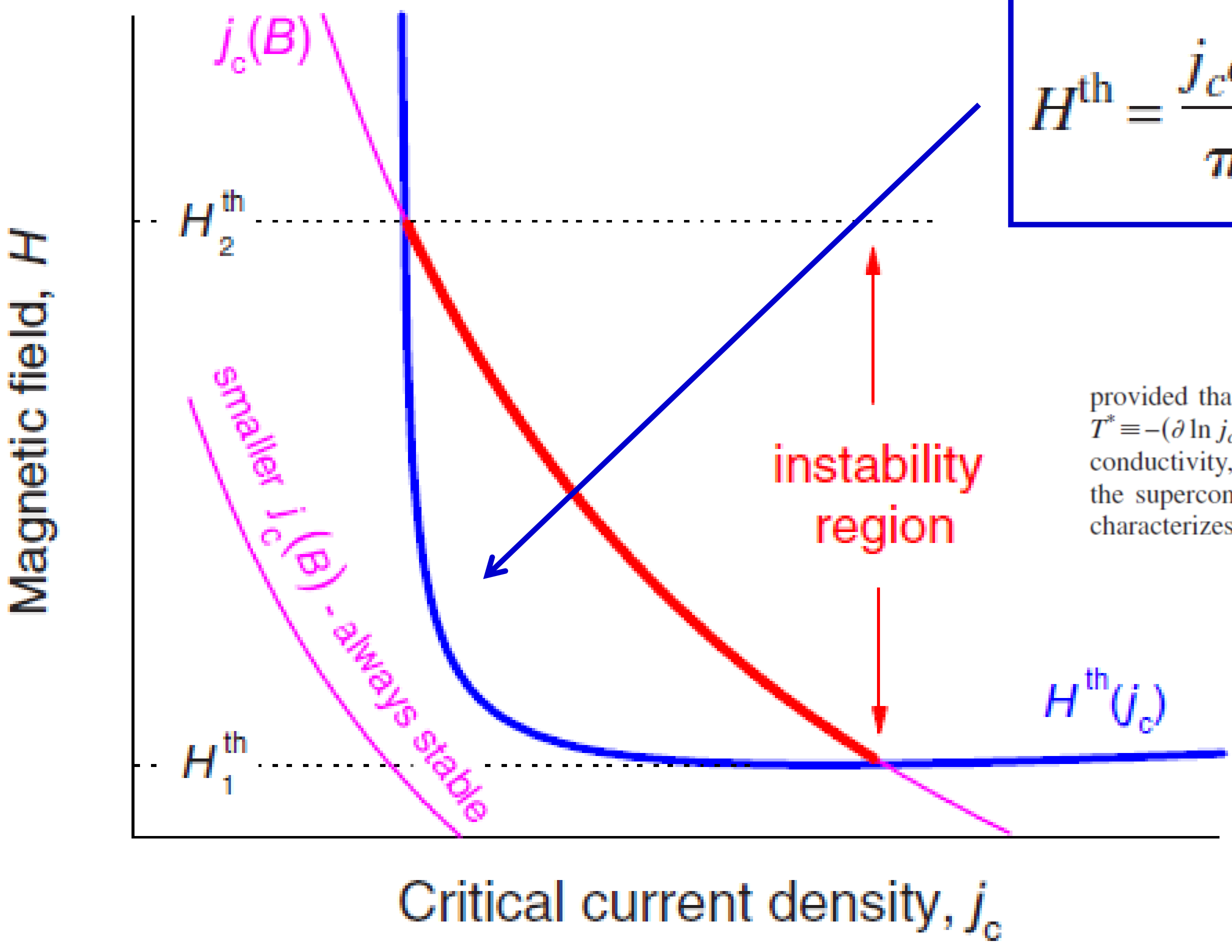
Thermal diffusion > Magnetic diffusion

Magnetic field penetrates smoothly

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

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

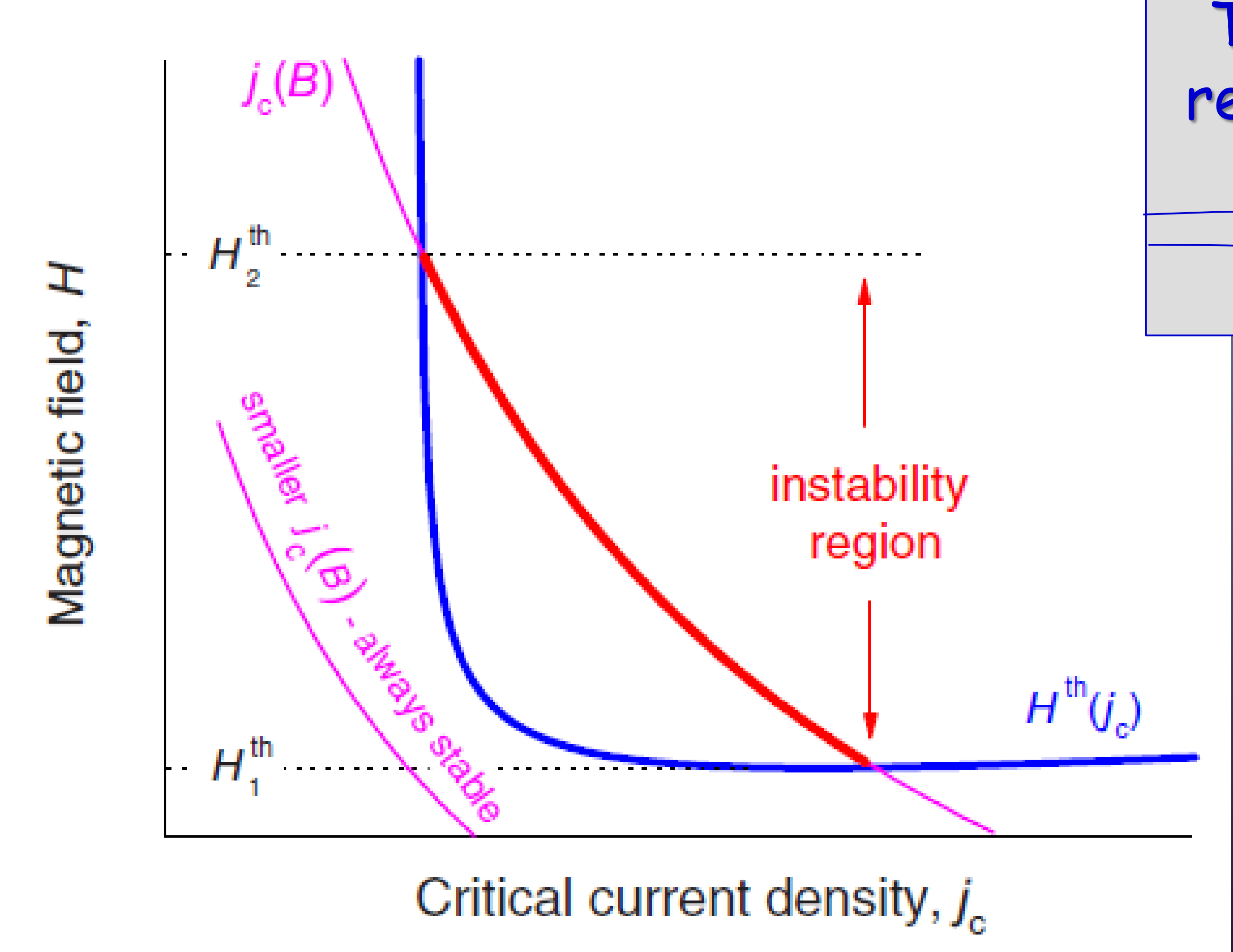
V. V. Yurchenko, D. V. Shantsev, and T. H. Johansen



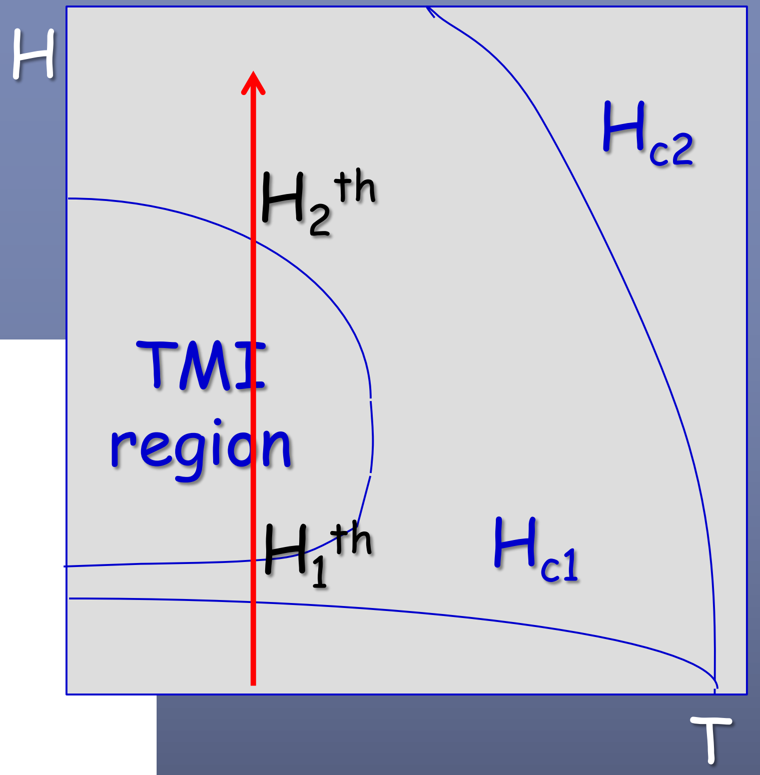
$$\boxed{H^{\mathrm{th}} = \frac{j_c d}{\pi}\,\mathrm{arccosh}\left(\frac{w}{w-\ell^*}\right)}$$

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

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



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



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

Linearized theory predicts

PRL **97,** 077002 (2006)

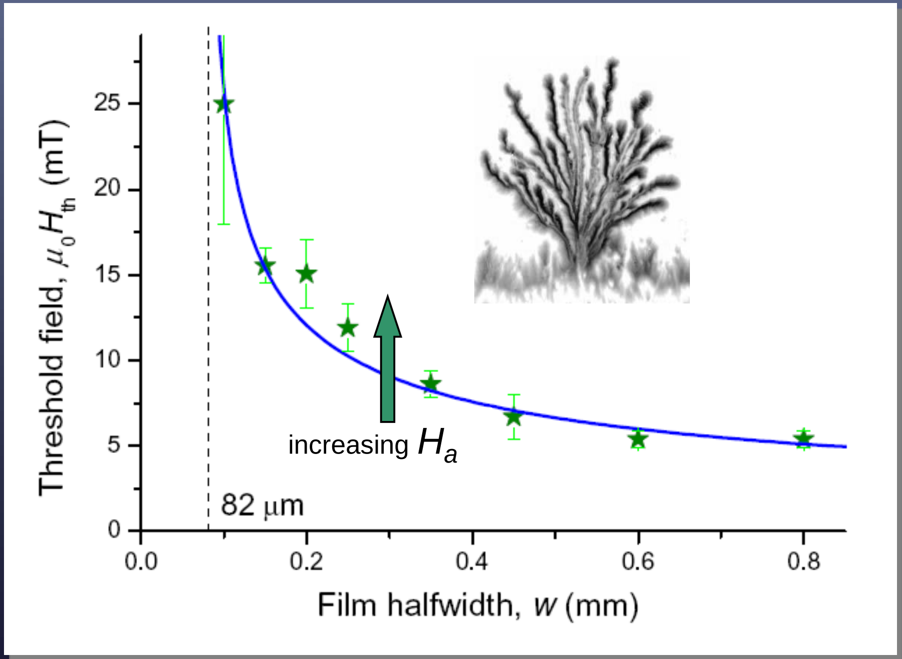
First finger forms at penetration depth:

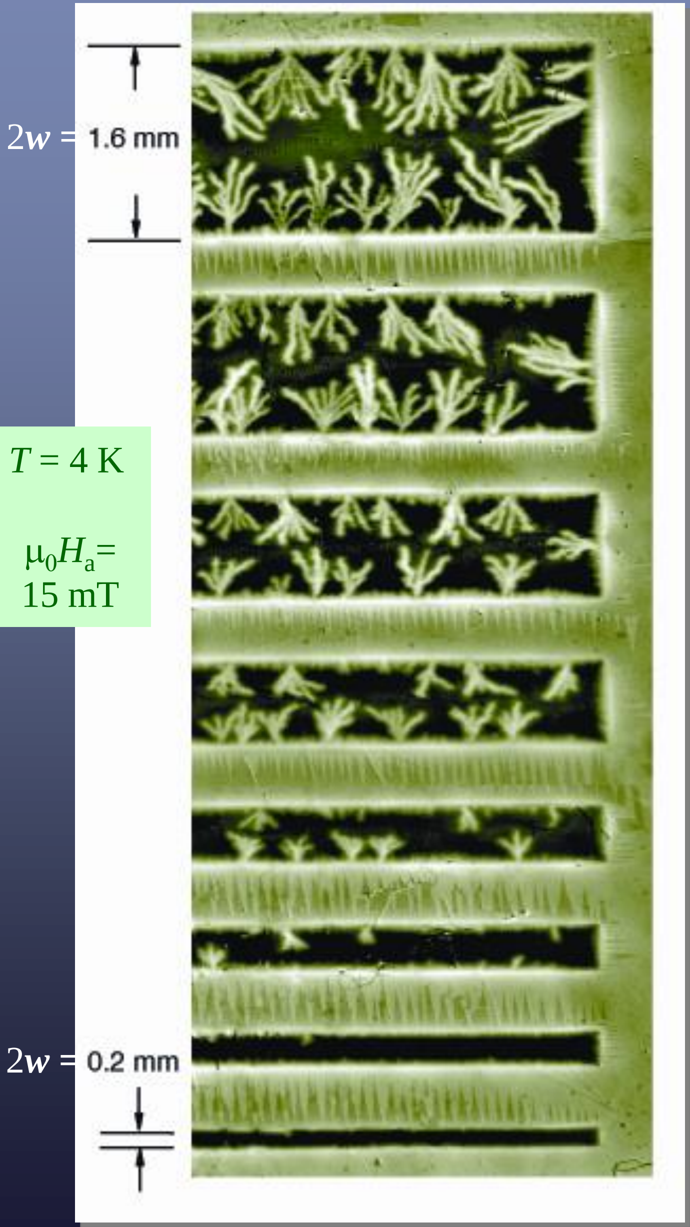
$$l_{\mathrm{th}} = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)^{-1}$$

…provided $2l_{\mathrm{th}} < 2w$

Threshold field:

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

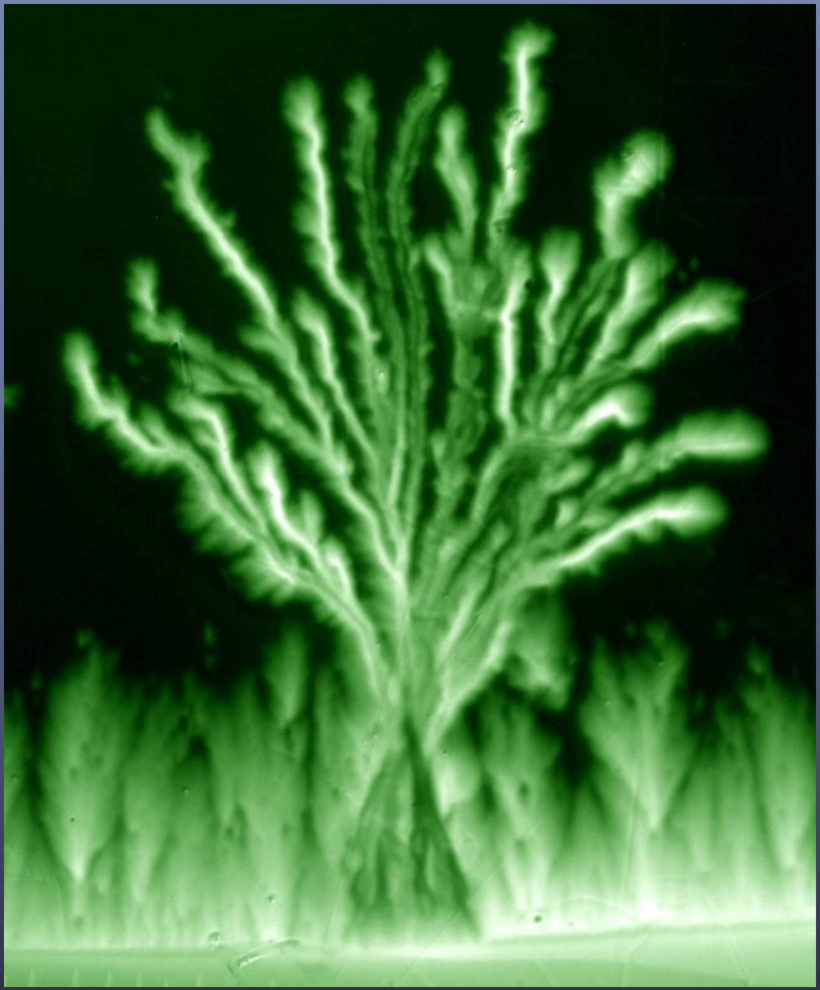




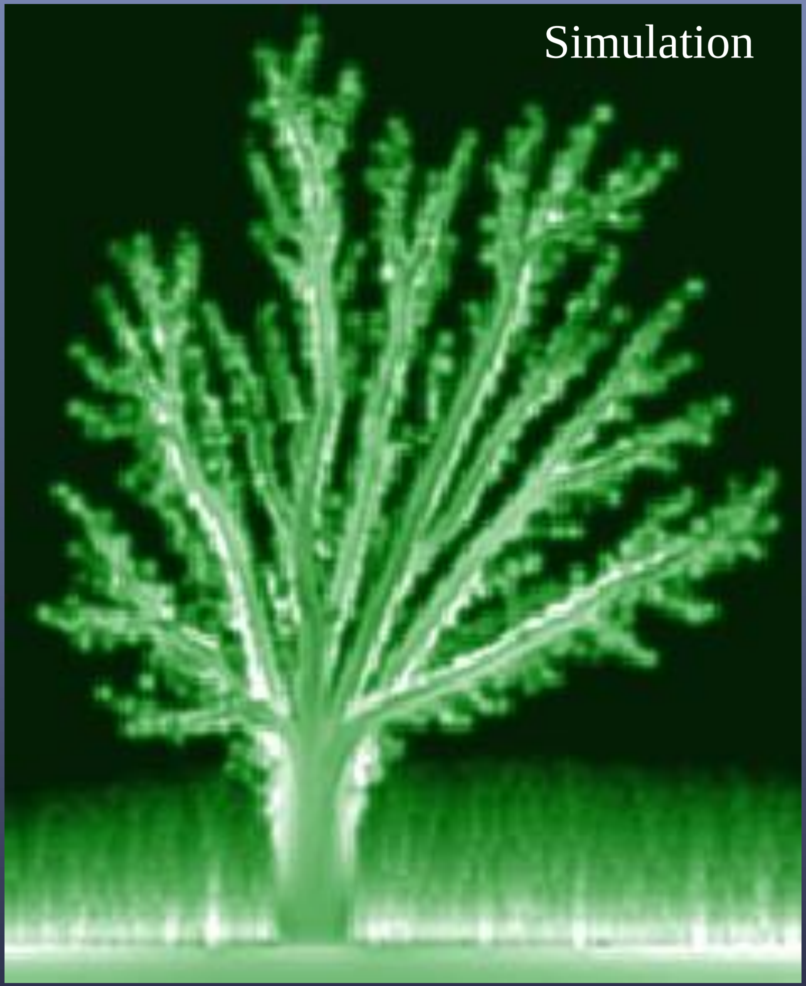
T = 4 K

$\mu_0 H_a$= 15 mT

Numerical solution B_z – distribution



Experiment - MgB_2



Parameters: (MgB_2)

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

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

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

$T_c = 39\ \mathrm{K}$

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

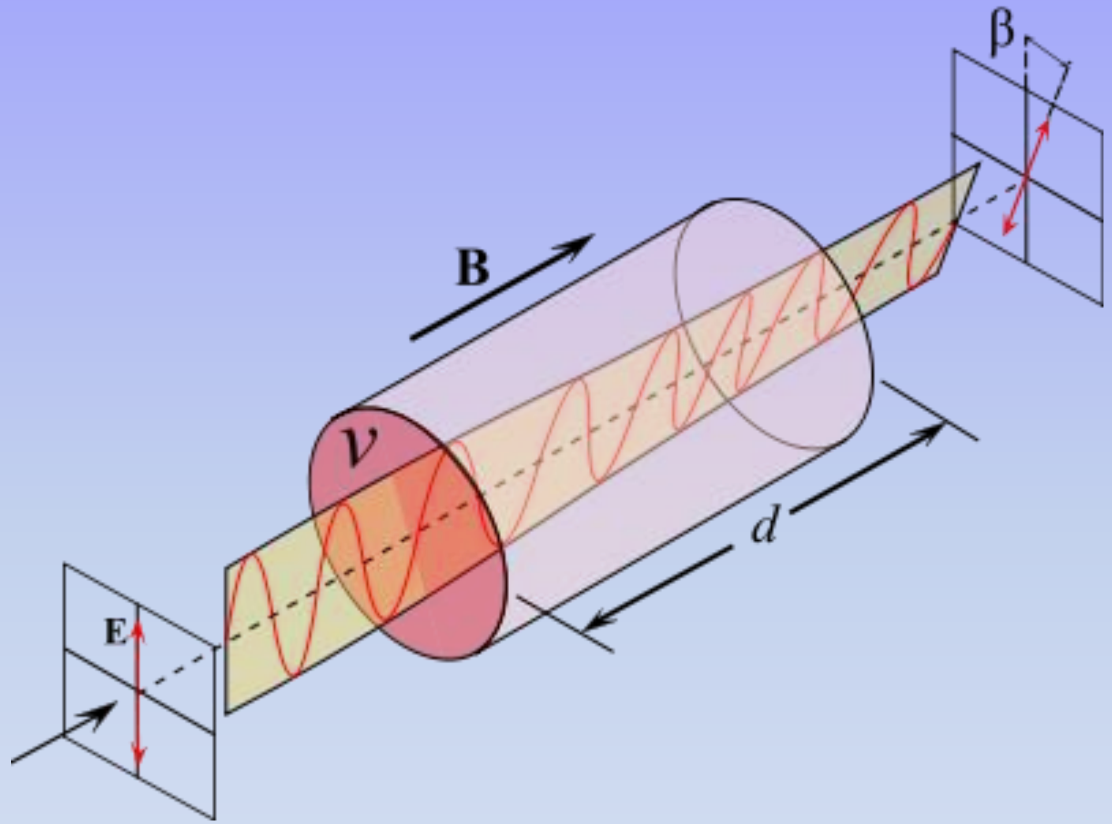
$\dot{H} = 10^{-5} J_{c0}\rho_n/ad$

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

$n = 19$

Magneto-optical Imaging (MOI)

A powerful tool to see magnetism and superconductivity in action

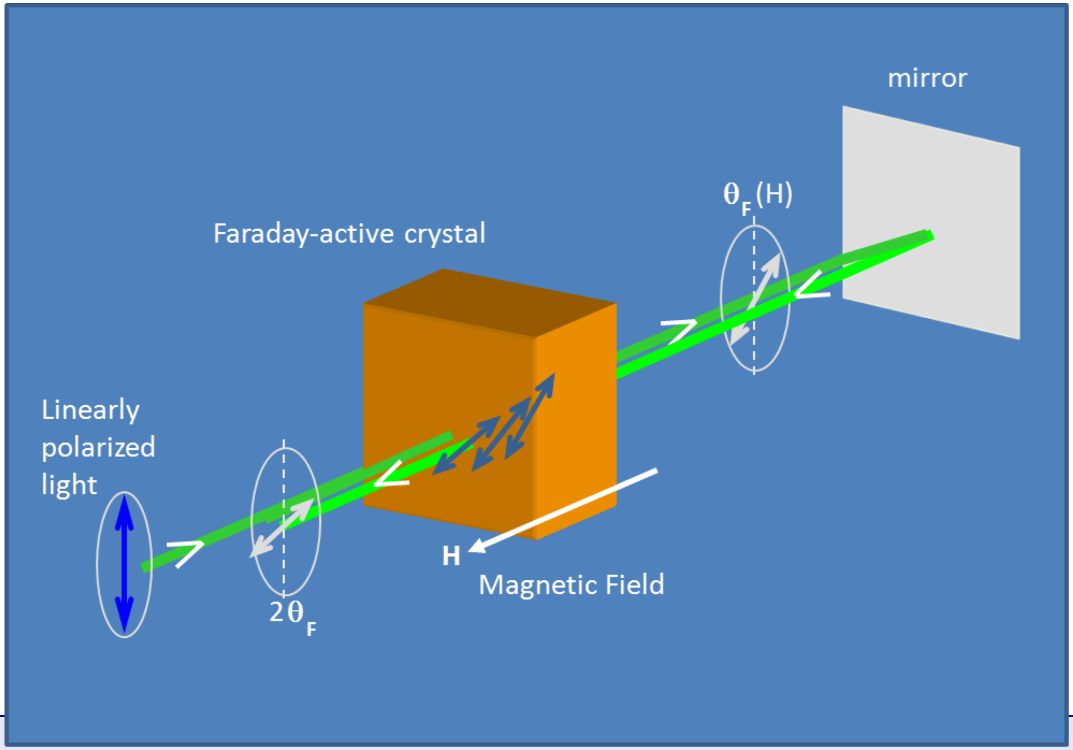


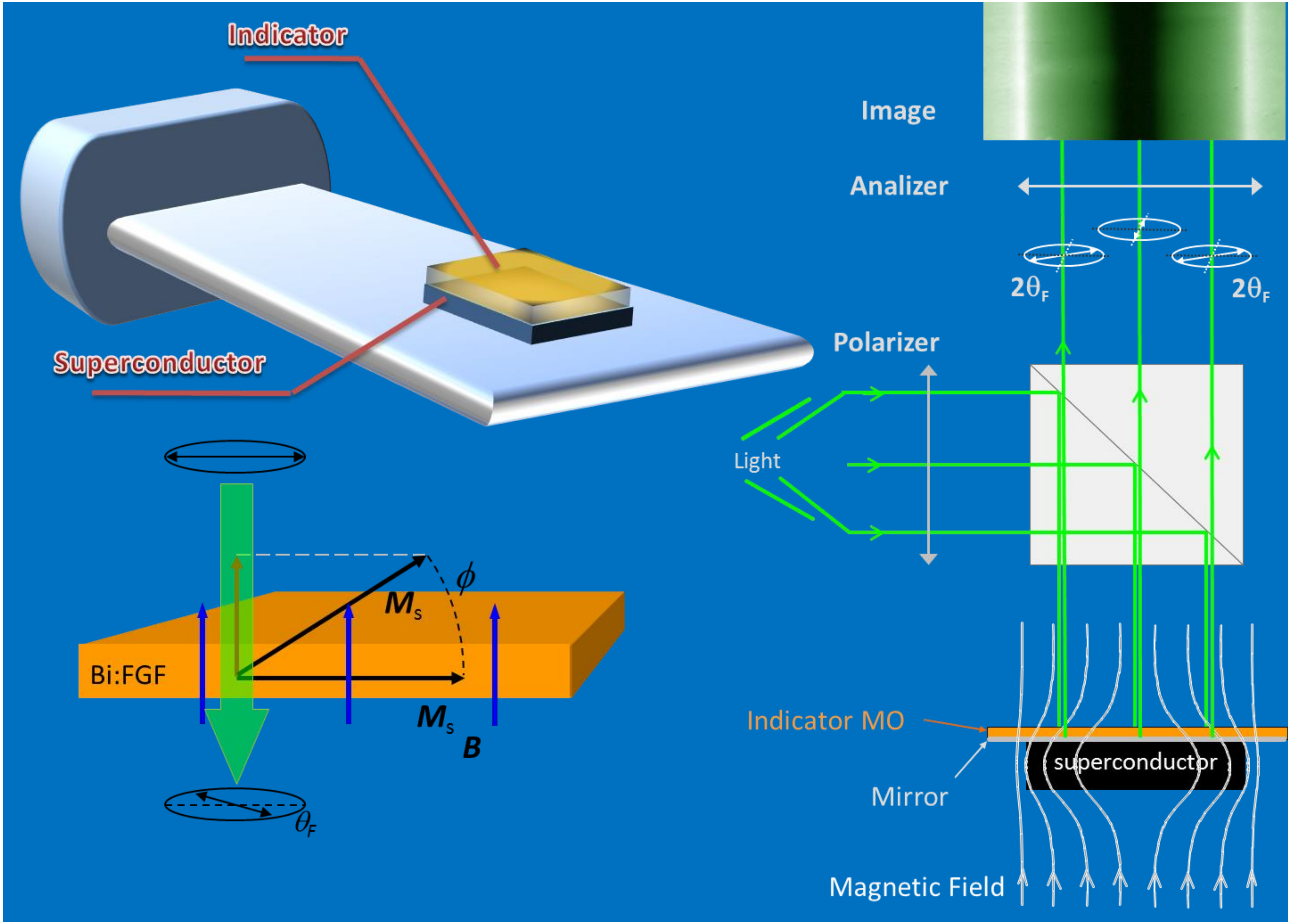
Faraday effect: rotation of the polarization plane

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



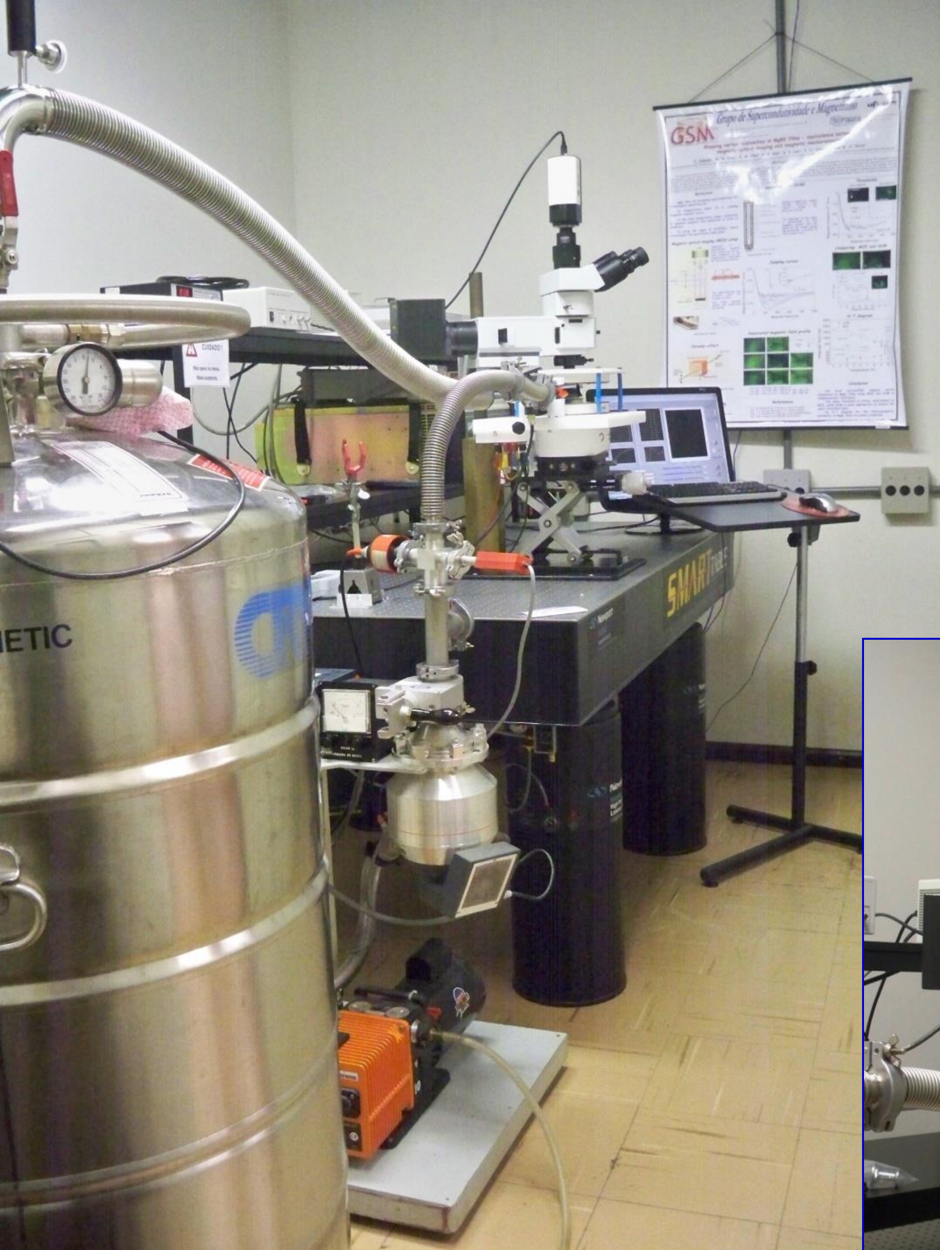

Indicator
Superconductor
Bi:FGF
M_s
M_s
B
ϕ
θ_F
Image
Analizer
$2\theta_F$
$2\theta_F$
Polarizer
Light
Indicator MO
superconductor
Mirror
Magnetic Field

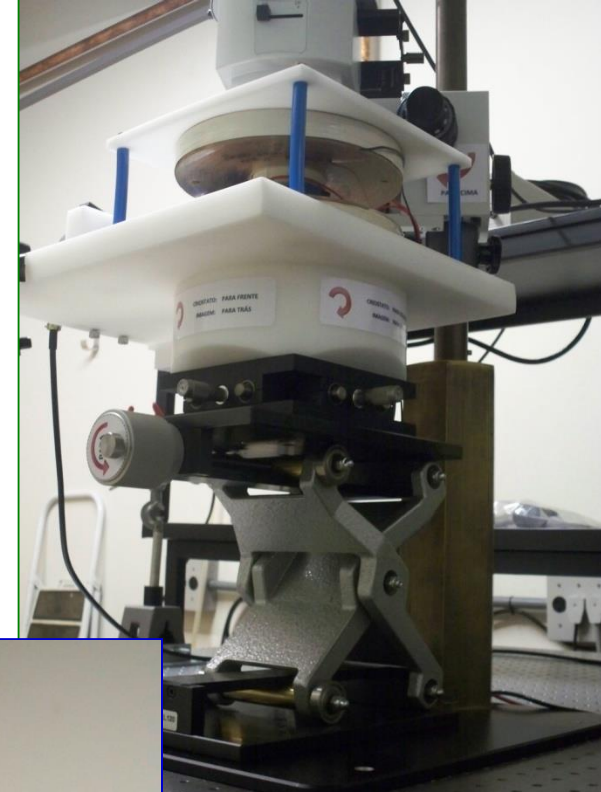
Bismuth-substituted Yttrium-Iron garnet

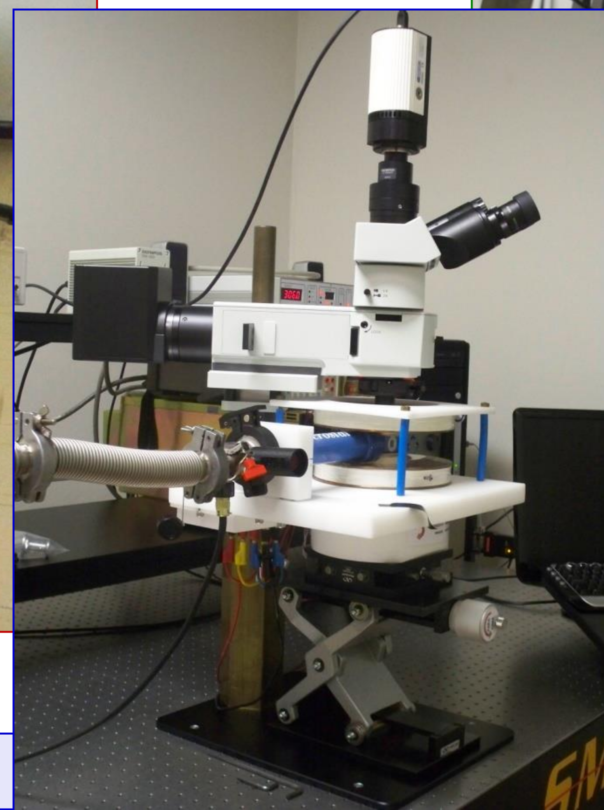
Bi:YIG ($Y_{3-x}Bi_xFe_5O_{12}$)

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

Gadolinium-Galium garnet

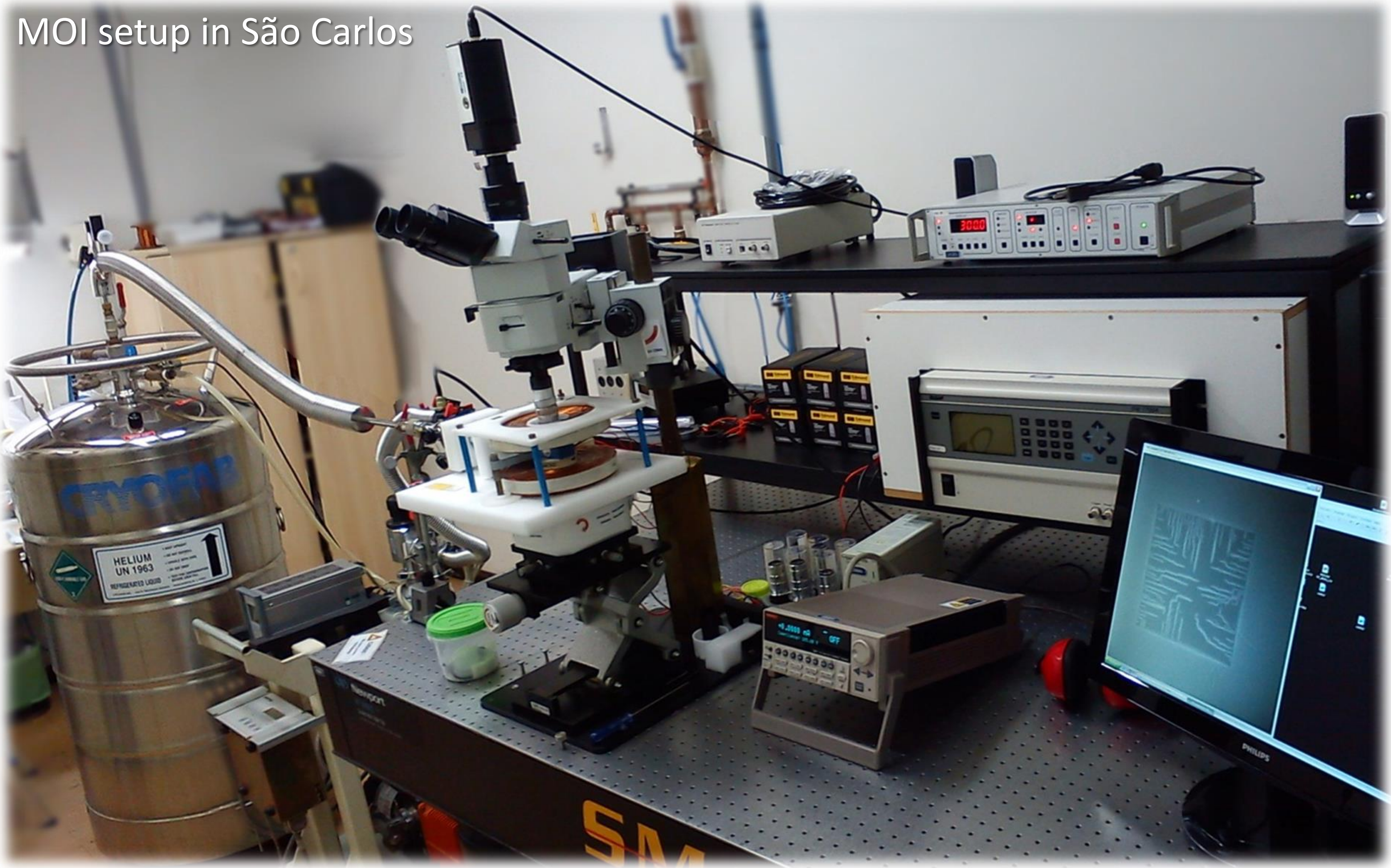






MOI setup
GSM/UFSCar

MOI setup



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)

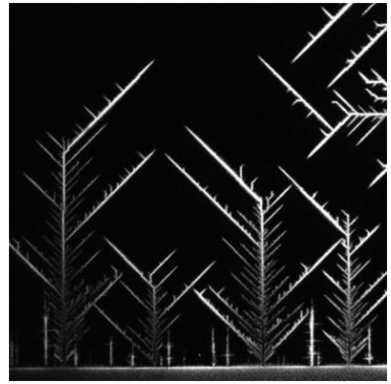
Category: Photomicrography – special lenses, microscopes

Title:
Visualizing Magnetic Fields in Superconductors

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

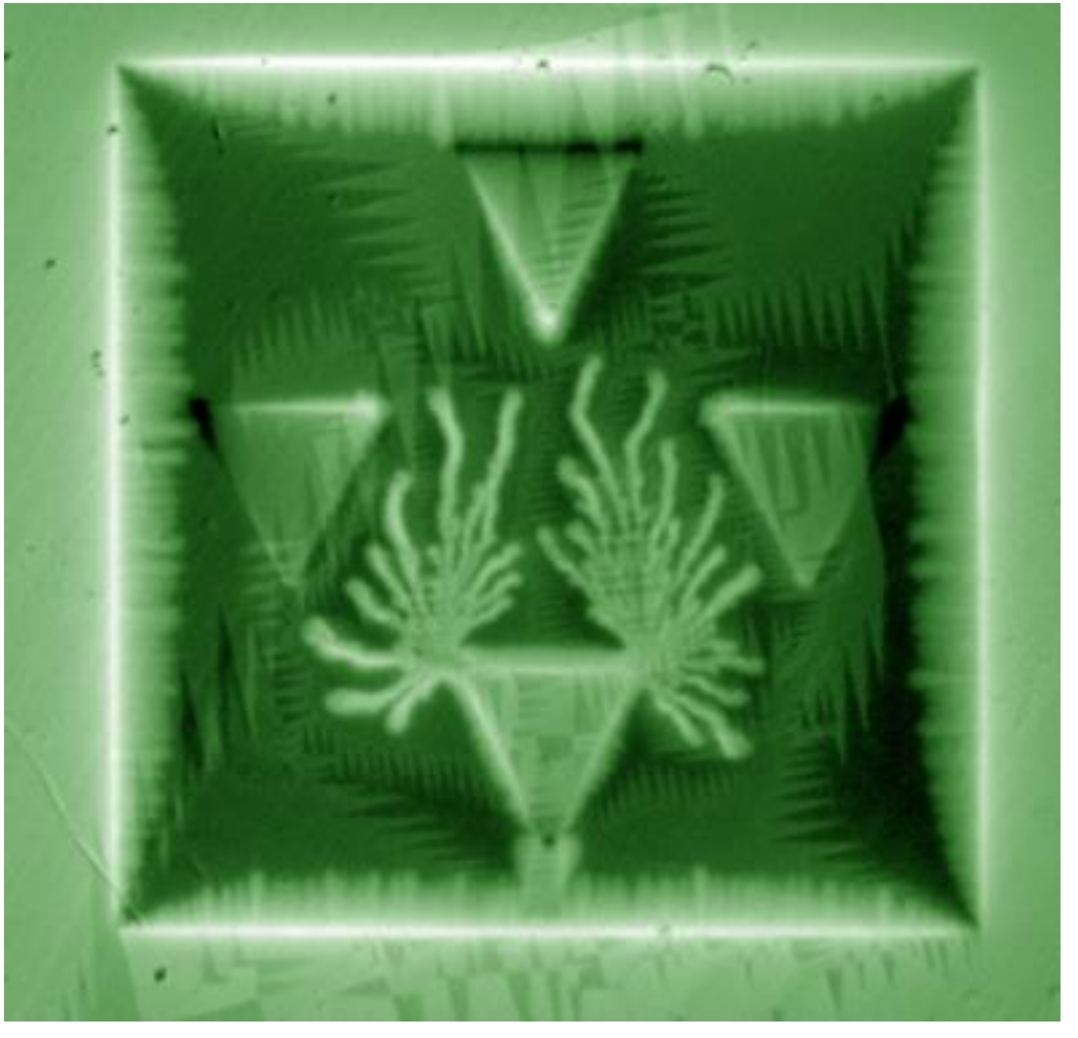
Shows: Magneto-optical image of magnetic flux penetrating into a superconducting film patterned with a square lattice of antidots (nanosized holes not directly visible)

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



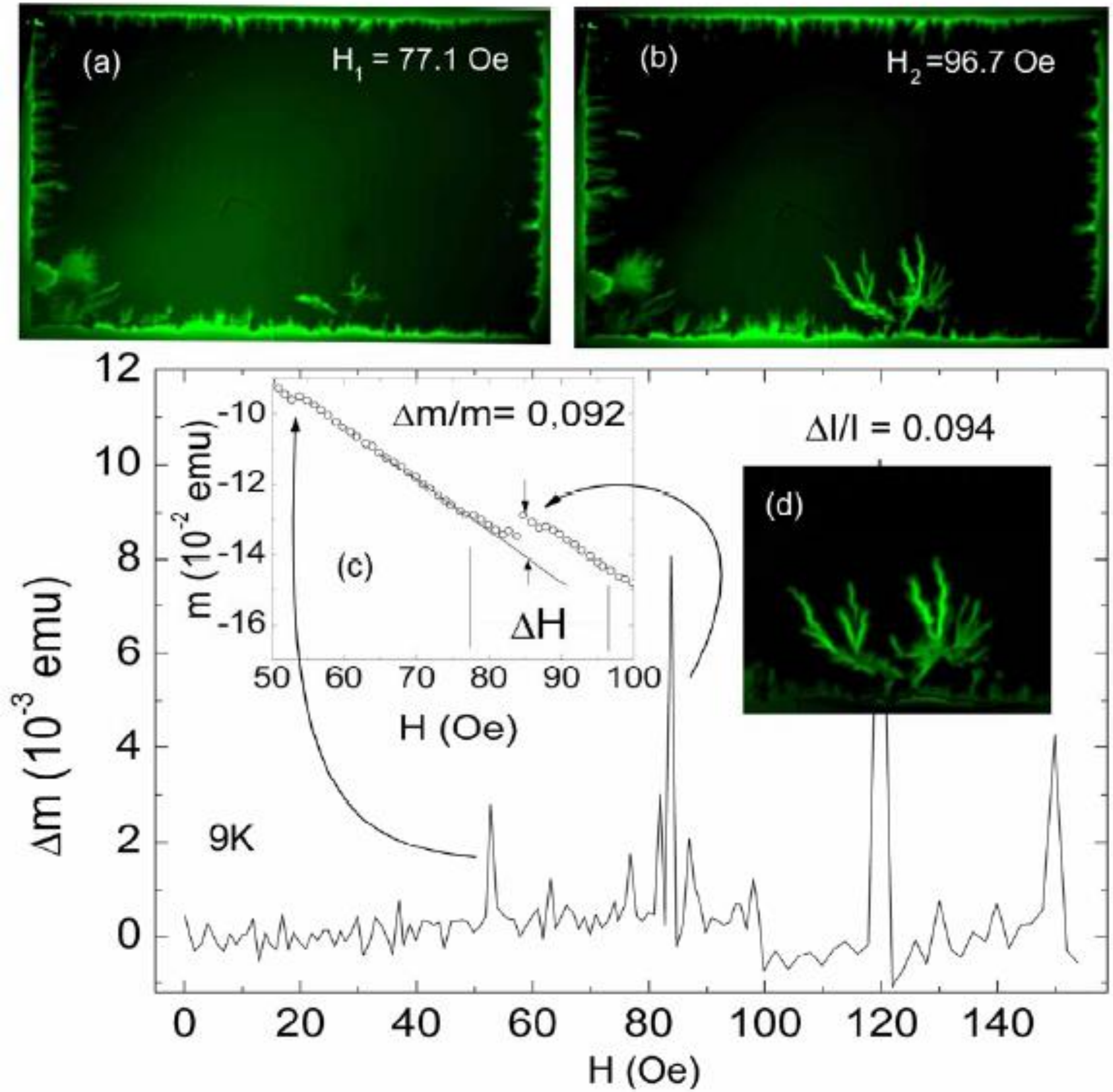
Visualizando o Campo Magnético em Supercondutores
Primeiro Lugar – Categoria Micro

CNPq – 2013 – 3rd place



MgB_2

T = 9 K



(a)
H_1 = 77.1 Oe
(b)
H_2 =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)

22 July 2015

Critical current enhancement and guidance of flux avalanches in microstructured superconducting films

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IFSP, Matão, Brazil

Antonio Marcos H. Andrade
UFRGS, Porto Alegre, Brazil

Alejandro Silhanek
Liège, Belgium

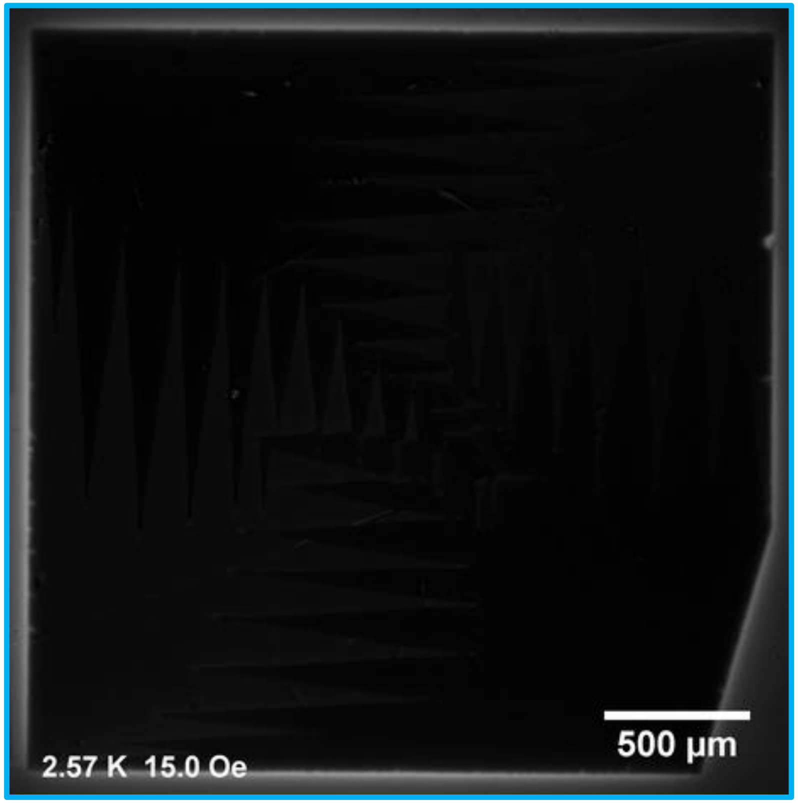
Jørn Inge Vestgården, Tom Henning Johansen
Oslo, Norway

J. Cuppens, M. Timmermans, J. Van de Vondel, V. Moshchalkov
Leuven, Belgium

Carmine Attanassio, Carla Cirillo
Salerno, Italy

Experimetal facts

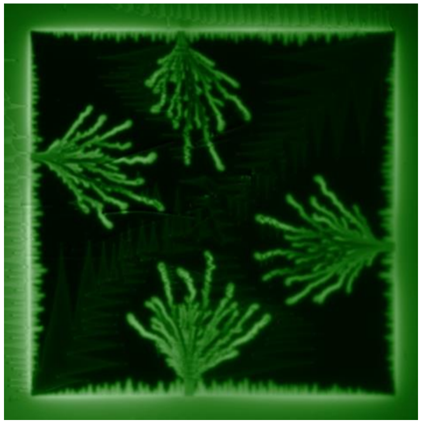
Under certain conditions of temperature and magnetic field, flux avalanches of dendritic form develop into superconducting films, as a consequence of thermomagnetic instabilities (TMI);

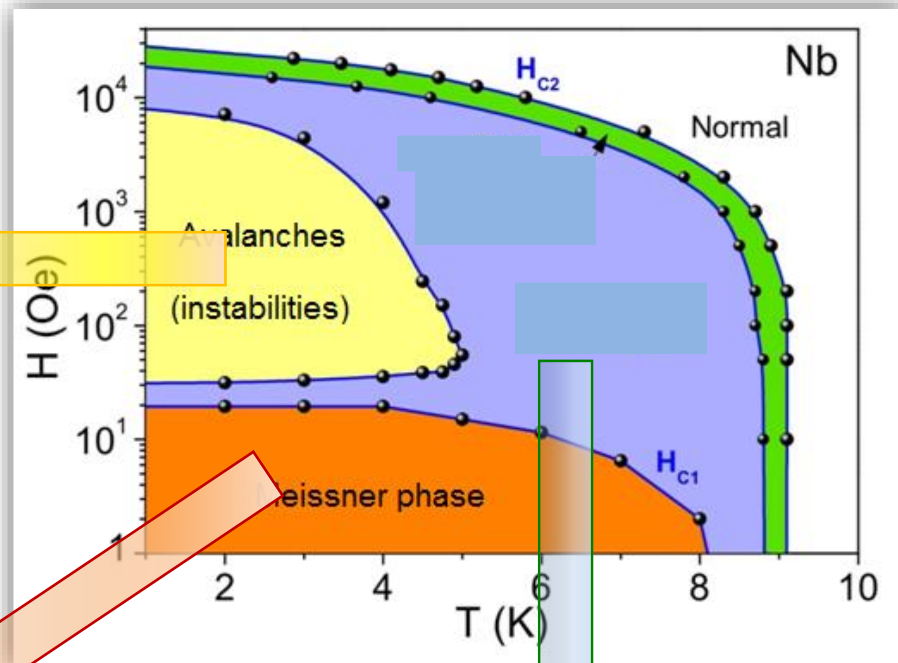


Nb film

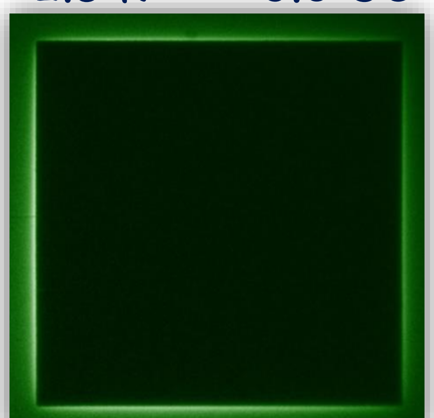
HT-diagram

4.0 K 36.5 Oe

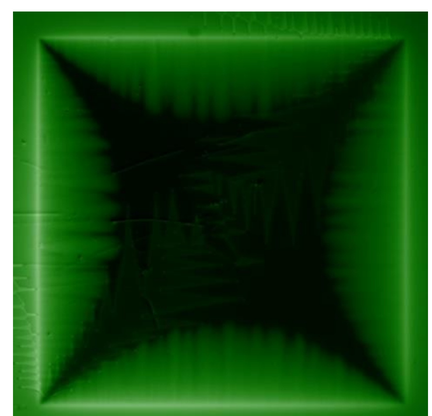




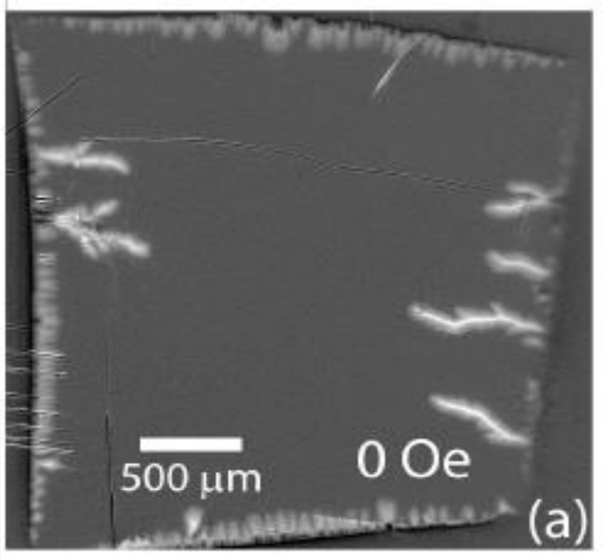
2.5 K 3.0 Oe



6.0 K 48.0 Oe



Lattice of antidots: guidance

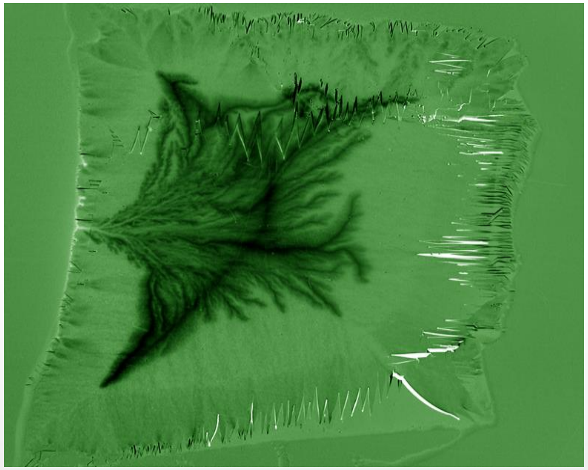


Nb (Plain)

Remanent state

3 K, after 4 Oe

GSM, 2011

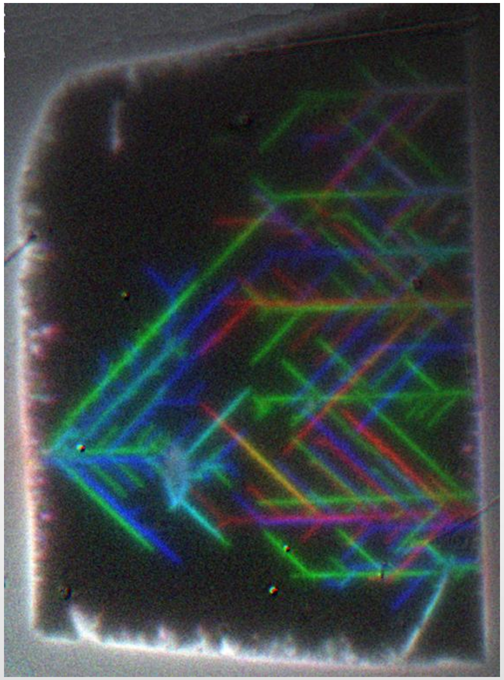


a-MoSi (Plain)

3 K

ZFC → 60 Oe → 10 Oe

GSM, 2011

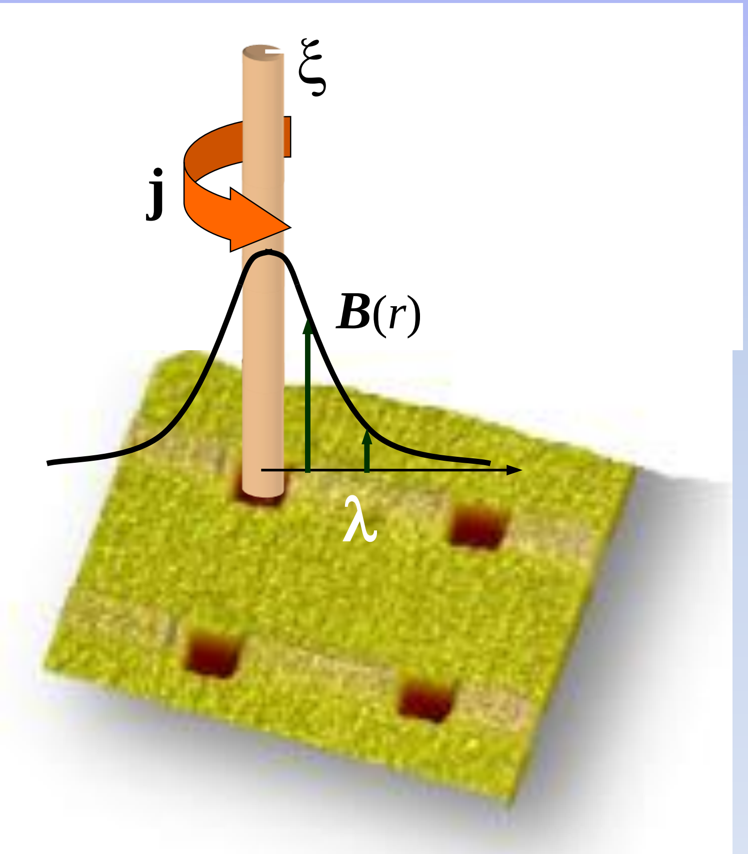


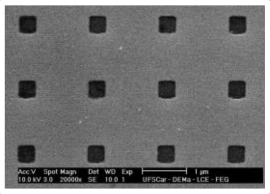
a-MoGe (AD04)

4.5 K, 1 Oe

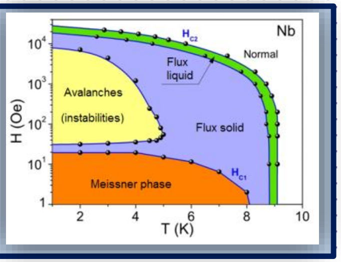
GSM, 2011

Antidots: pinning centers





arrays of antidots



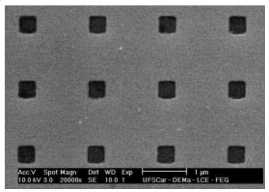
lattice

graded array

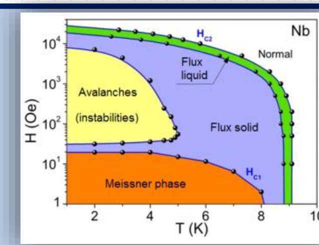
high-T

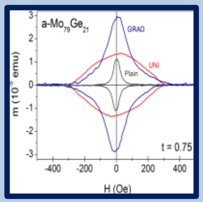
i. Supression of flux avalanches:

magnetic breaking

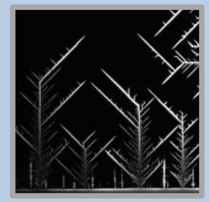


arrays of antidots





Enhancement of J_c



Avalanches

→ lattice

→ graded array

→ suppression

→ guidance

high-T

low-T

i. Supression - Magnetic Breaking

APPLIED PHYSICS LETTERS **96**, 092512 (2010)

Suppression of flux avalanches in superconducting films by electromagnetic braking

F. Colauto,[1] E. Choi,[2] J. Y. Lee,[2] S. I. Lee,[3] E. J. Patiño,[4,5] M. G. Blamire,[5] T. H. Johansen,[6] and W. A. Ortiz[1,a)]

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[3]*National Creative Research Initiative Center for Superconductivity and Department of Physics, Sogang University, Seoul 121-742, Republic of Korea*
[4]*Departamento de Física, Universidad de los Andes, Bogota, DC, Colombia*
[5]*Department of Materials Science, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom*
[6]*Department of Physics, University of Oslo, POB 1048, Blindern, 0316 Oslo, Norway*

(Received 9 February 2010; accepted 10 February 2010; published online 4 March 2010)

Magnetic fields perpendicular to superconducting films often trigger vortex avalanches, which always are very harmful for electronic devices and other applications. Such avalanches can be suppressed by a metal layer placed in contact with the superconductor surface, an effect that up to now has been thought to be a consequence of improved heat conduction. Here we show experimentally that the role of the metal layer is not that of a heat-sink, but rather that of an electromagnetic drag due to eddy currents induced in the metal layer during the abrupt onset of the flux avalanches. The effect is demonstrated for films of MgB_2 and Nb. © *2010 American Institute of Physics*. [doi:10.1063/1.3350681]

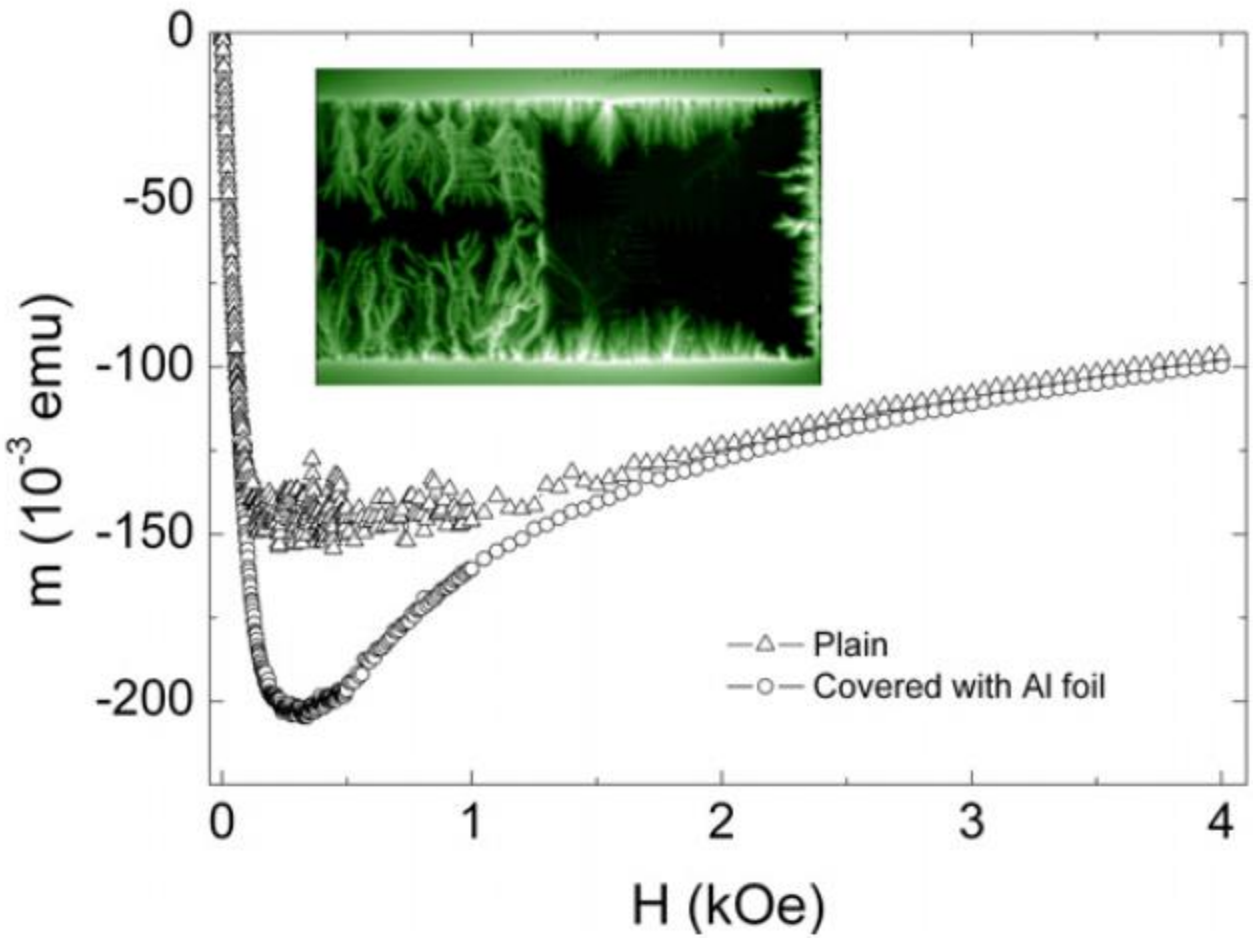


Figure 1. $m(H)$ taken at $T = 4$ K for a plain MgB_2 film (fluctuating) and for the same sample covered with a piece of aluminum foil (smooth). Inset: MOI taken at 4 K and 120 Oe of a similar MgB_2 film half-covered with Al foil.

APPLIED PHYSICS LETTERS **96**, 092512 (2010)

Suppression of flux avalanches in superconducting films by electromagnetic braking

F. Colauto,[1] E. Choi,[2] J. Y. Lee,[2] S. I. Lee,[3] E. J. Patiño,[4,5] M. G. Blamire,[5] T. H. Johansen,[6] and W. A. Ortiz[1,a)]

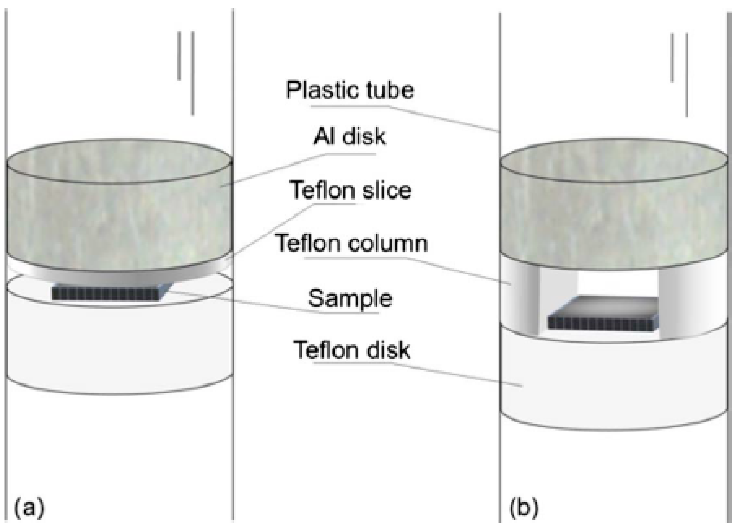


FIG. 1. (Color online) Schematic of the sample mounting with an aluminum disk kept a distance away from the superconducting film sample, which rests on a teflon disk. (a) sheet of teflon is inserted on top of the sample, (b) teflon pillars maintain a gap above the sample.

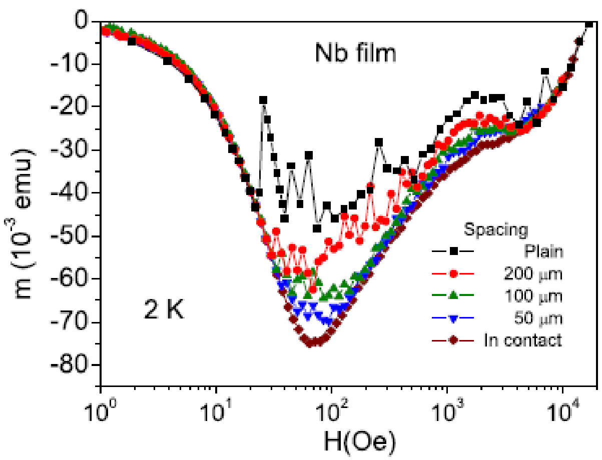
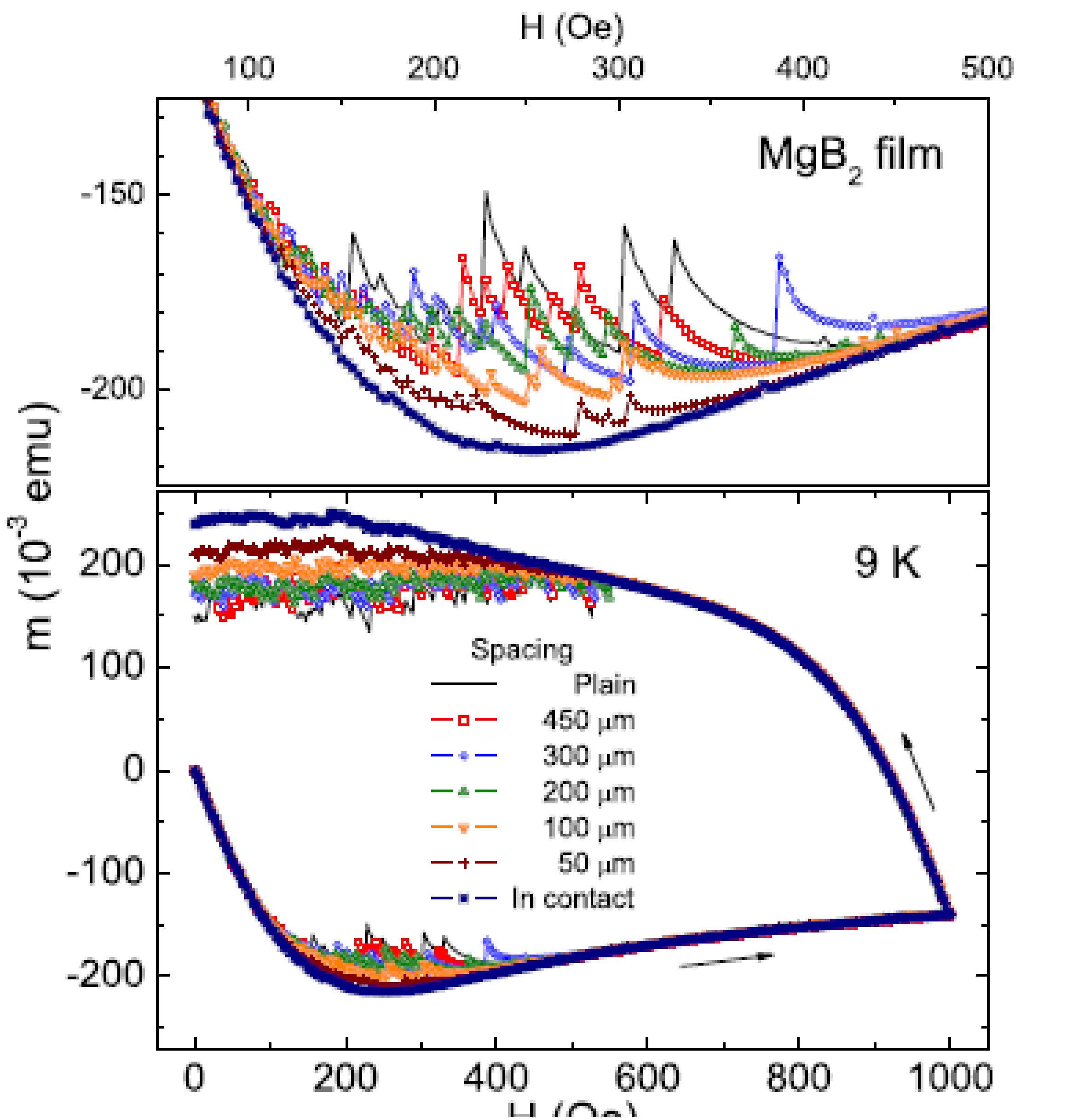
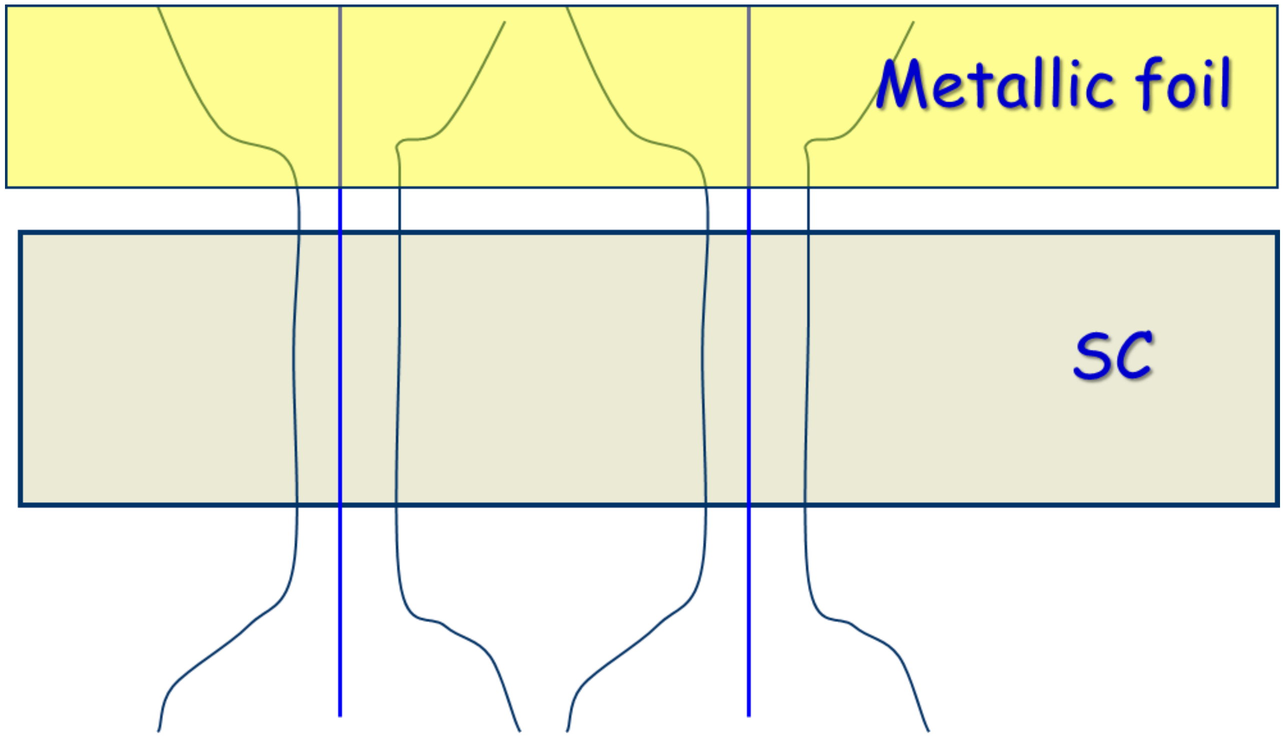


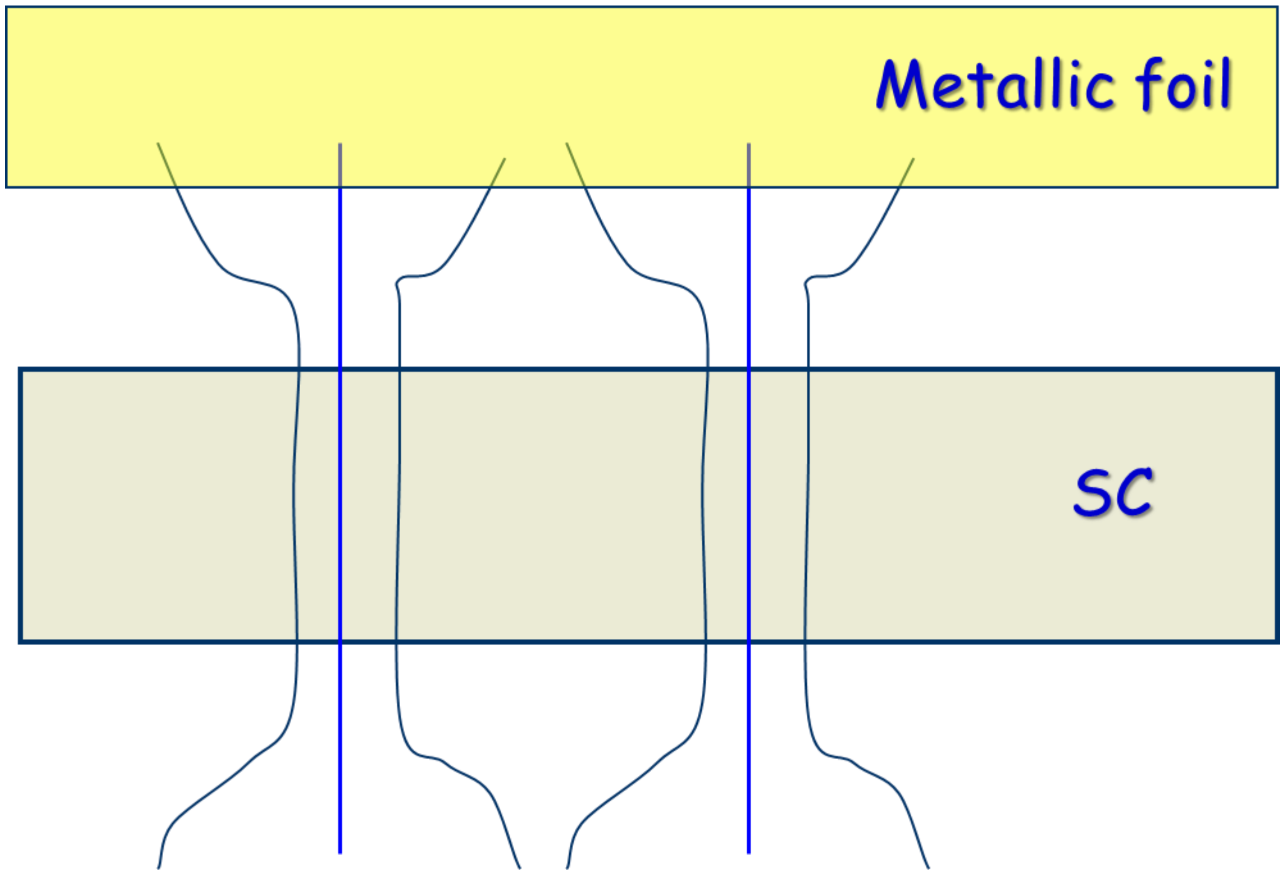
FIG. 3. (Color online) m-H curves for ascending field with the Nb sample and aluminum disk separated by different distances, showing increased suppression of jump activity the smaller their separation becomes.

iting the superconductor depending on the direction of the

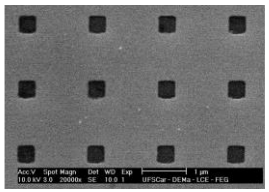


Colauto *et al.* Appl. Phys. Lett. **96**, 092512 (2010)

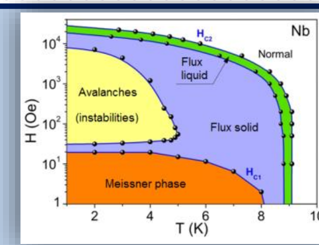

Metallic foil
SC

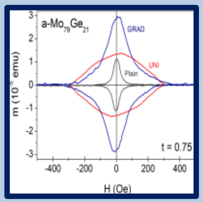

Metallic foil
SC

ii. lattice of antidots: guided avalanches

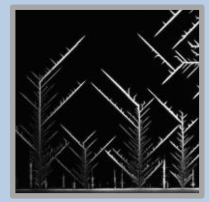


arrays of antidots





Enhancement of J_c



Avalanches

→ lattice

→ graded array

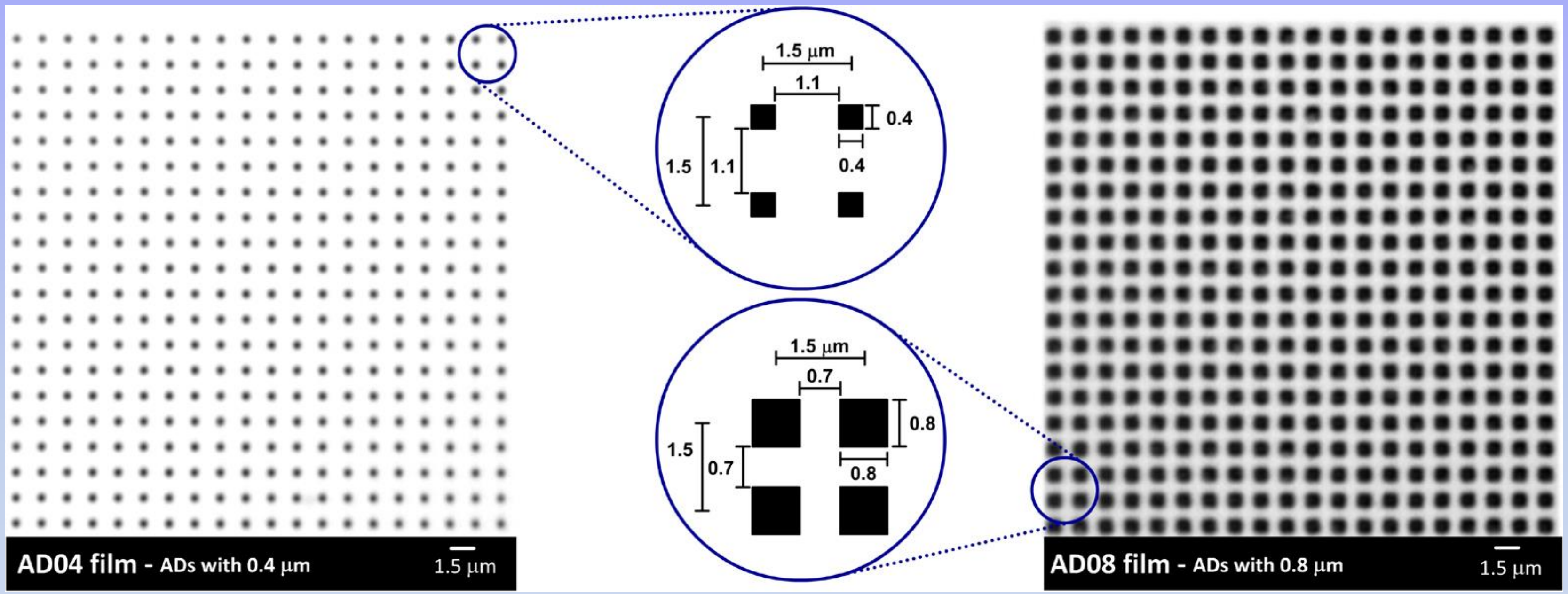
→ suppression

→ guidance

high-T

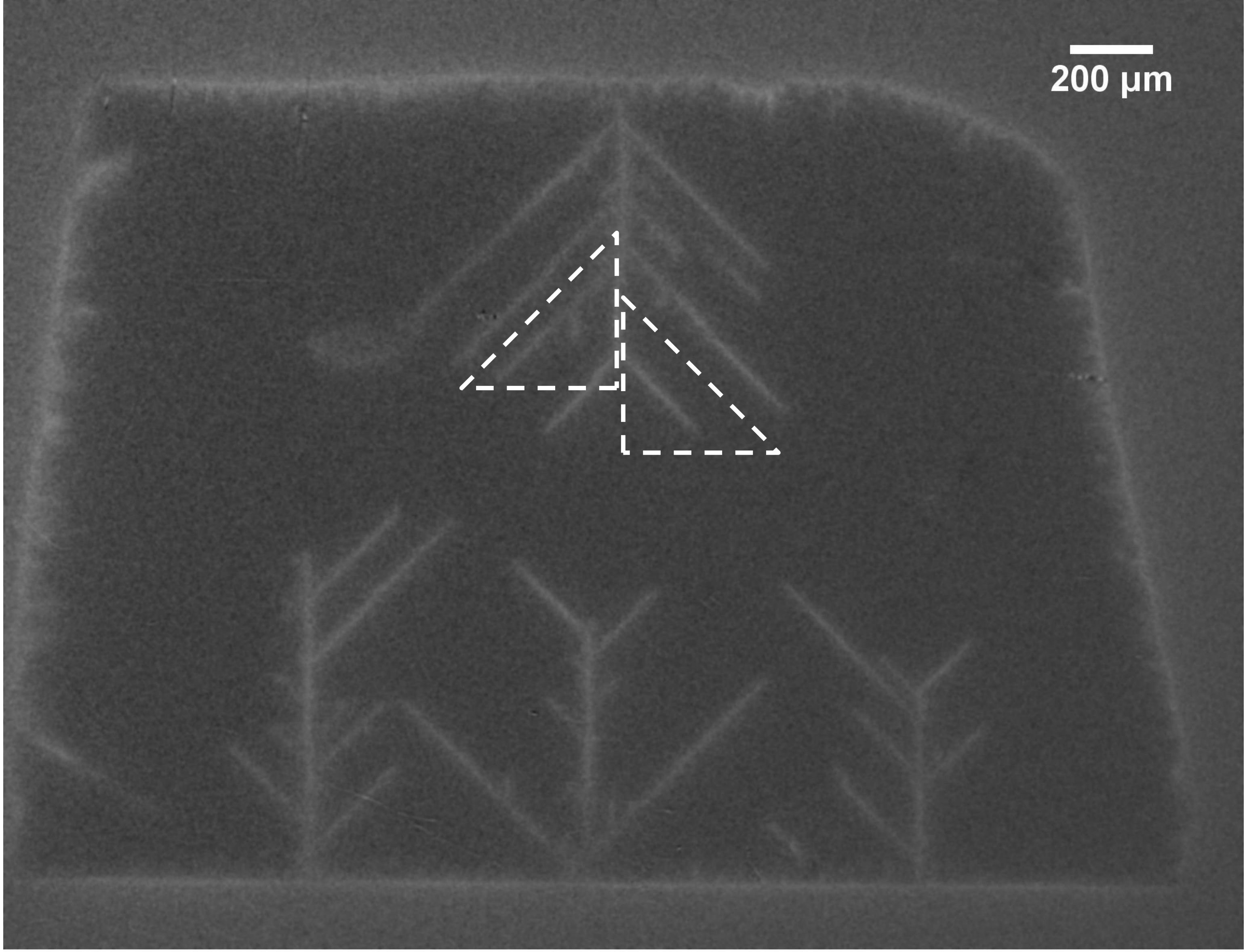
low-T

ii. lattice of antidots: guided avalanches



a-MoGe – AD04

w = 1.5 μm
d = 0.4 μm
t = 25 nm



a-MoGe

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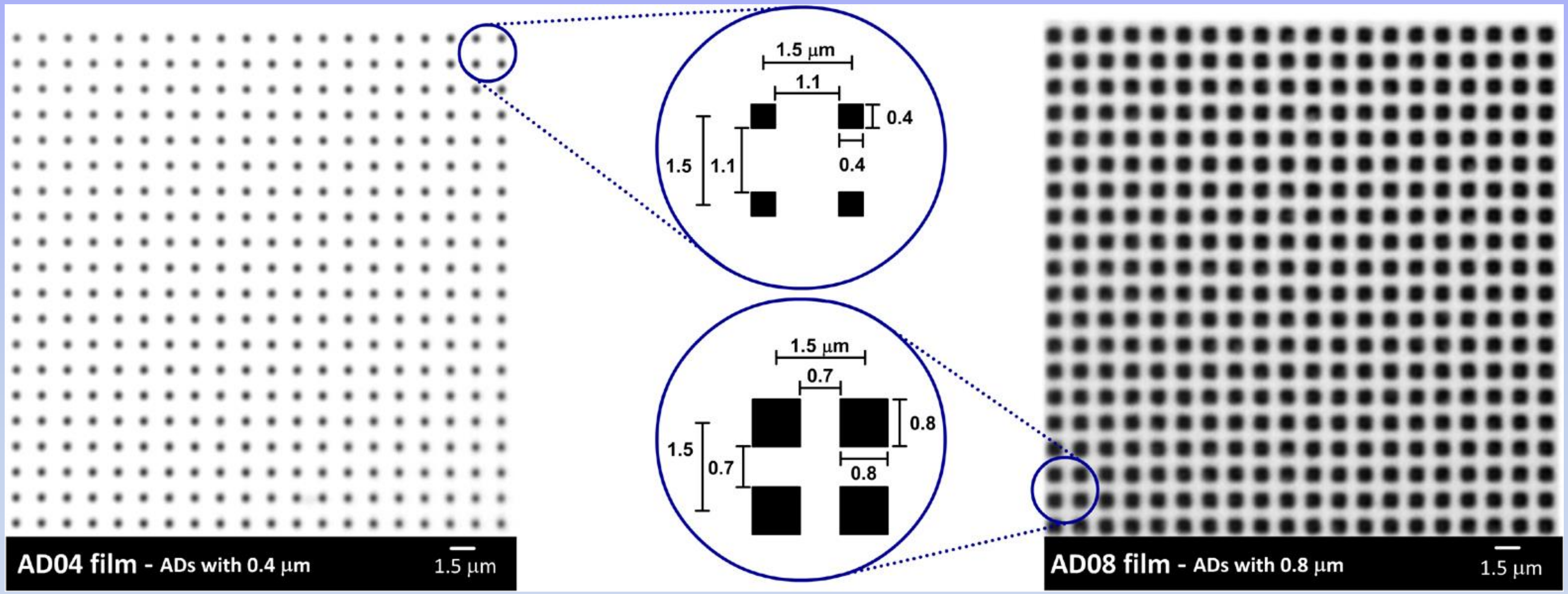
Universidade Federal de São Carlos - Brazil

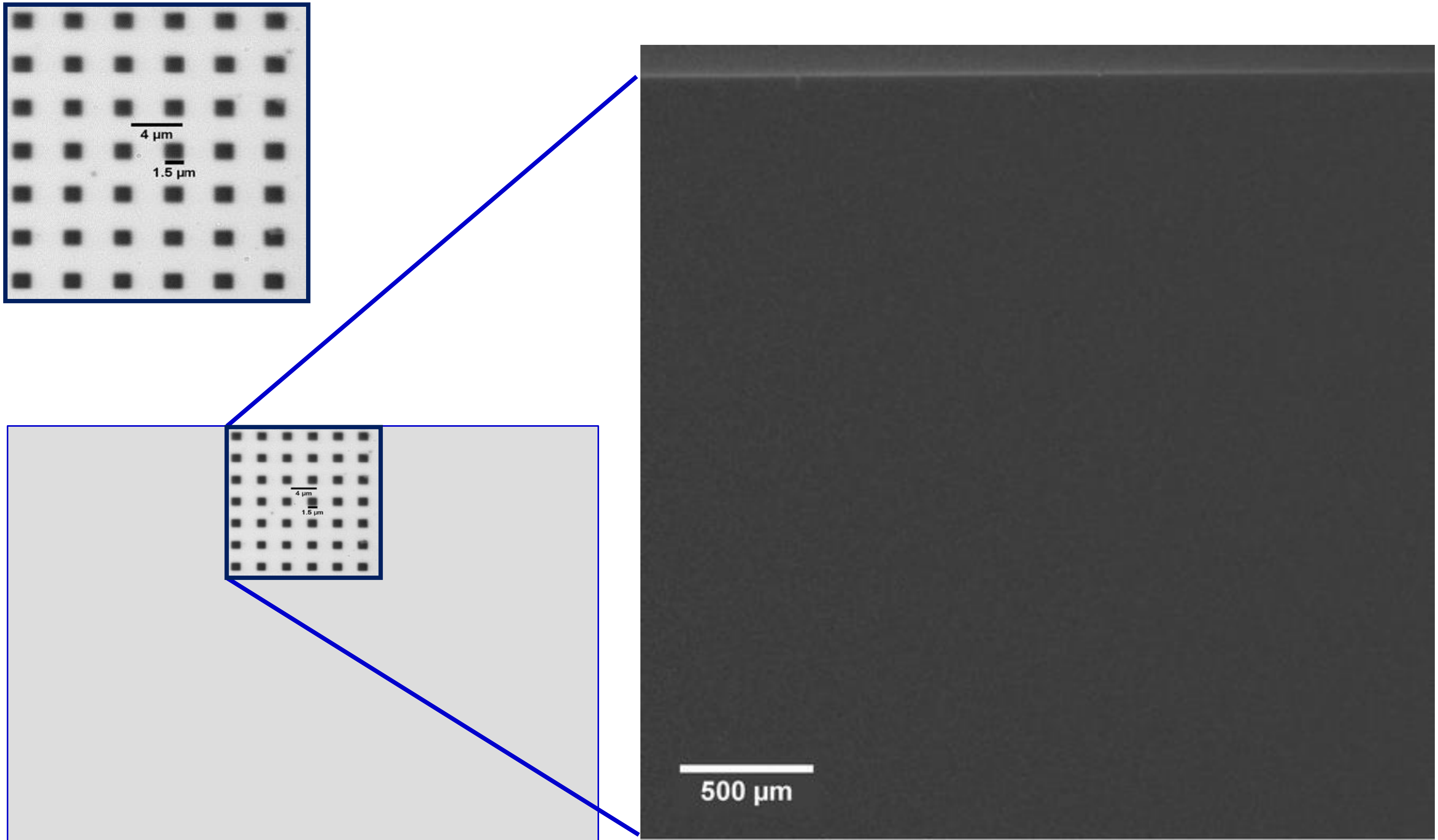
Mo3Ge film | thickness: 25 nm
SQ AD: 0.4 um | SQ Ltt: 1.5 um |

3.000 K 1.0 Oe

ii. lattice of antidots: guided avalanches



Nb
w = 4.0 μm
d = 1.5 μm
t = 45 nm

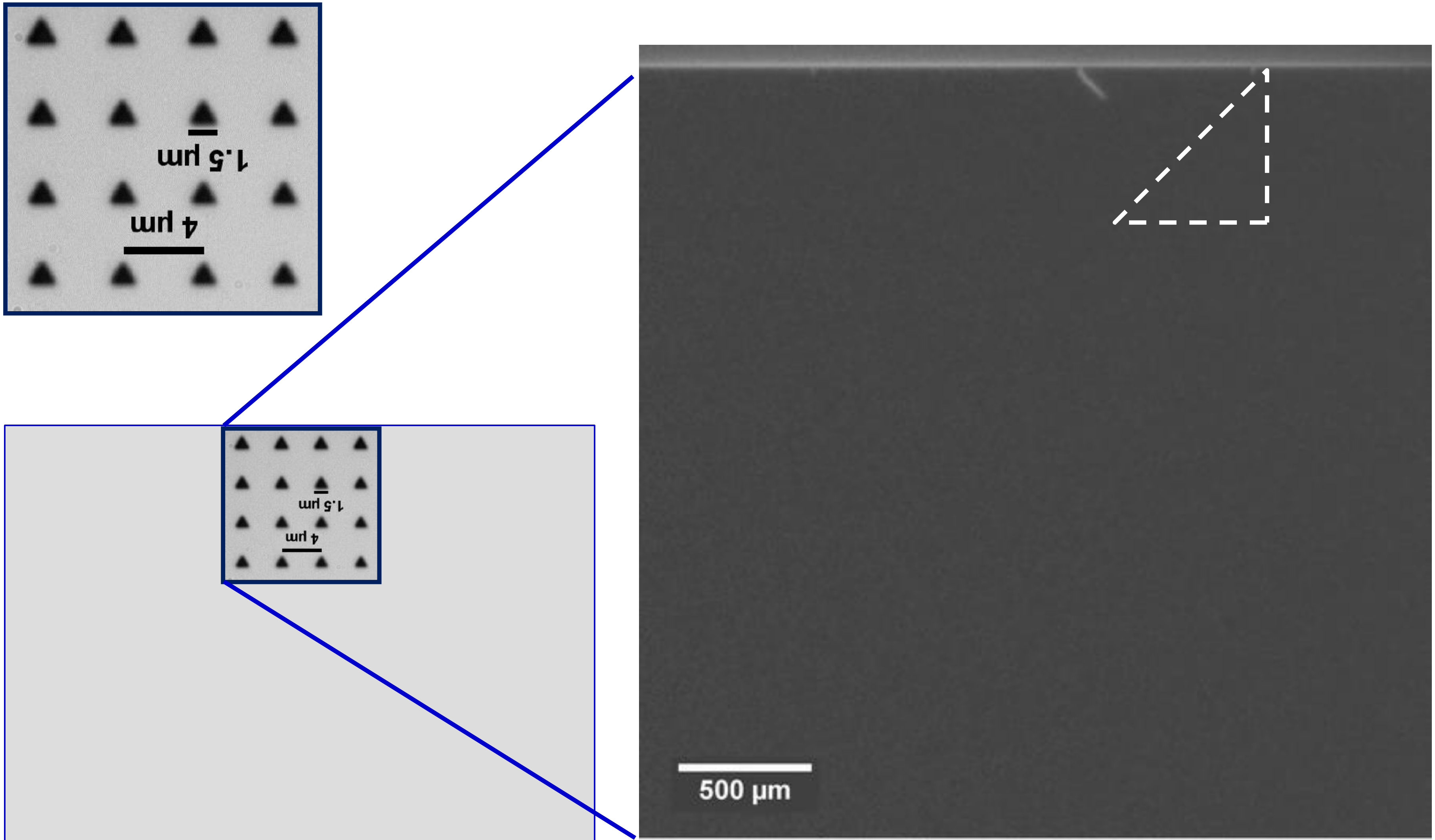


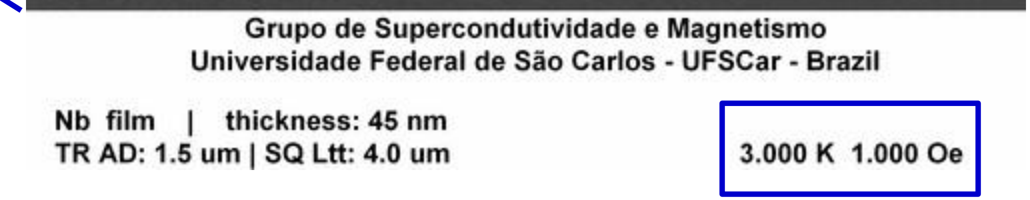
Grupo de Supercondutividade e Magnetismo
Universidade Federal de São Carlos - UFSCar - Brazil

Nb film | thickness: 45 nm
SQ AD: 1.5 um | SQ Ltt: 4.0 um

3.014 K 0.600 Oe

Nb-SQ


1.5 µm
4 µm
500 µm

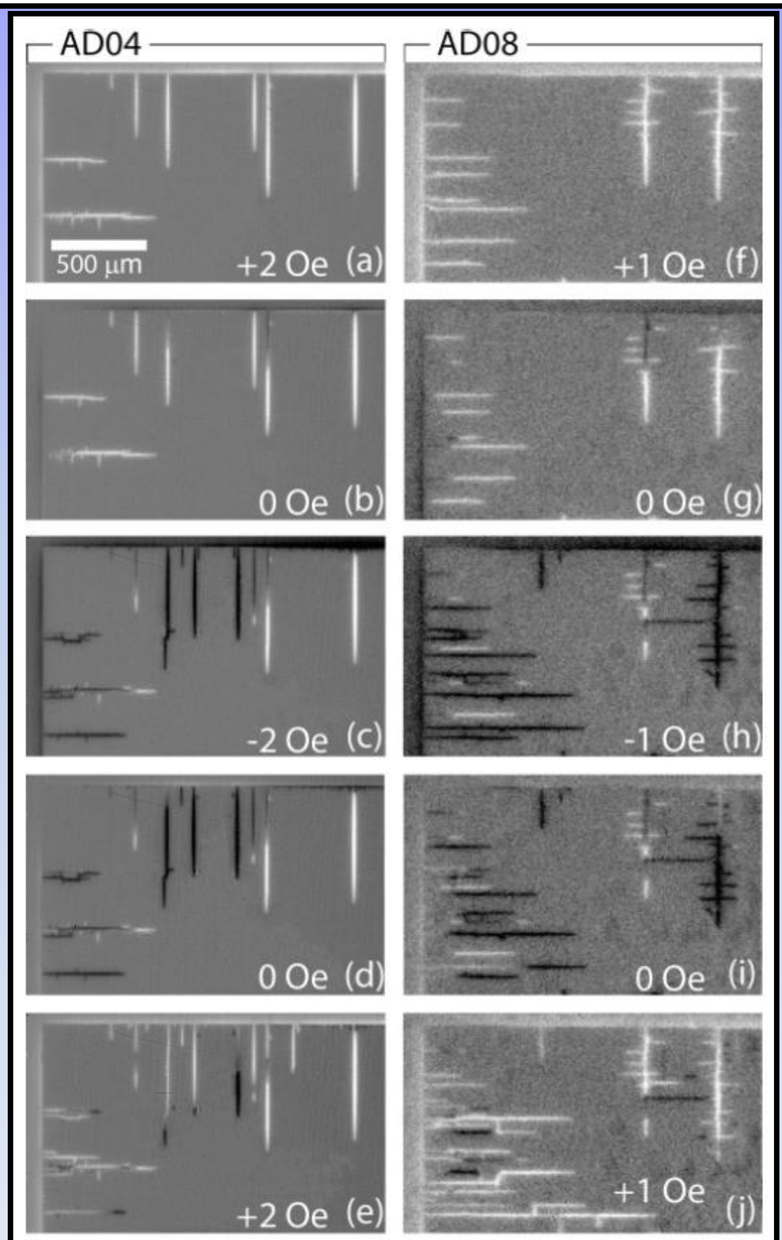

Grupo de Supercondutividade e Magnetismo
Universidade Federal de São Carlos - UFSCar - Brazil
Nb film | thickness: 45 nm
TR AD: 1.5 um | SQ Ltt: 4.0 um
3.000 K 1.000 Oe

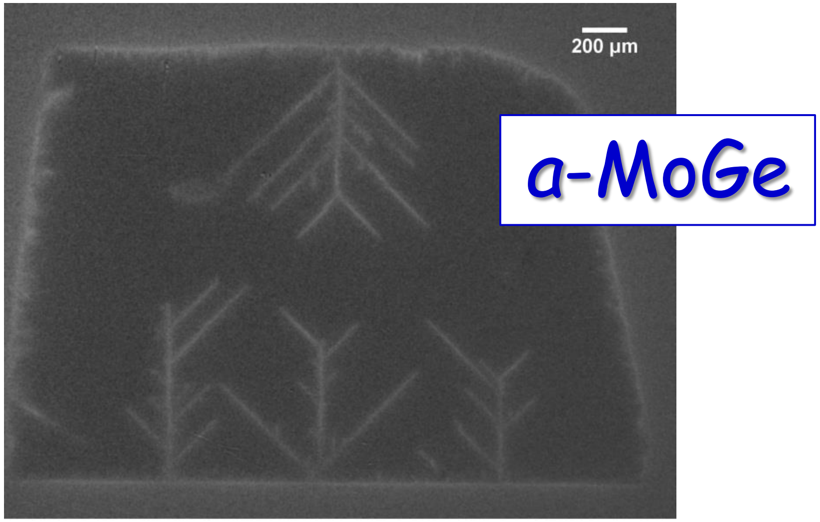
Nb-TR

PHYSICAL REVIEW B **84**, 214529 (2011)

Visualizing the ac magnetic susceptibility of superconducting films via magneto-optical imaging

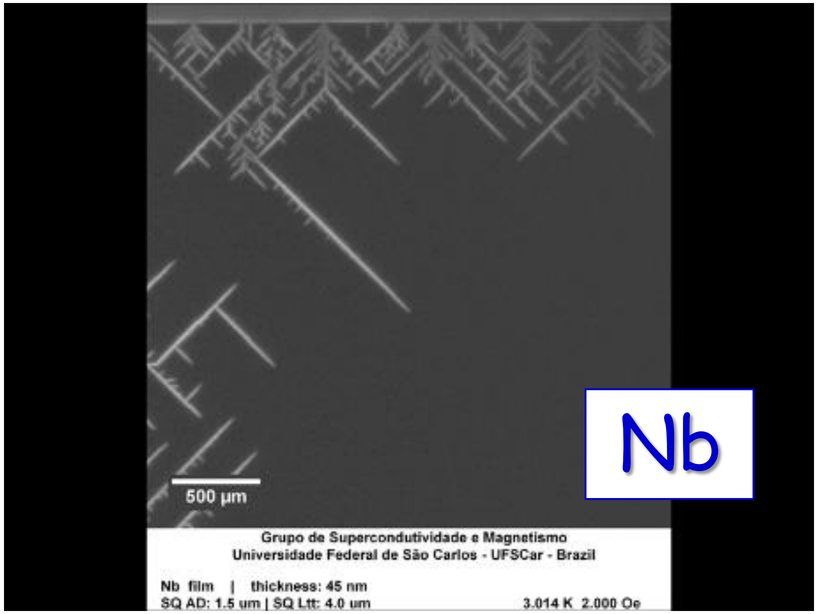
M. Motta,[1] F. Colauto,[1] R. Zadorosny,[1,*] T. H. Johansen,[2,3] R. B. Dinner,[4] M. G. Blamire,[4] G. W. Ataklti,[5] V. V. Moshchalkov,[5] A. V. Silhanek,[5,6] and W. A. Ortiz[1,3]

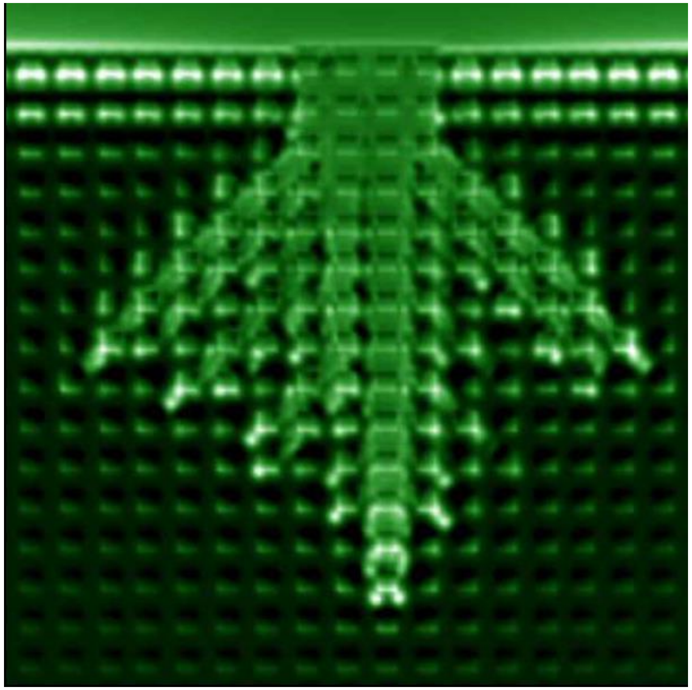




Grupo de Supercondutividade e Magnetismo
Universidade Federal de São Carlos - Brazil

Mo3Ge film | thickness: 25 nm
SQ AD: 0.4 um | SQ Ltt: 1.5 um | 3.000 K 1.0 Oe





Simulation
TMI model
(Johansen 's group)
Square Lattice
Square ADs

PHYSICAL REVIEW B **89**, 134508 (2014)

Controllable morphology of flux avalanches in microstructured superconductors

M. Motta,[1] F. Colauto,[1] J. I. Vestgården,[2] J. Fritzsche,[3] M. Timmermans,[4] J. Cuppens,[4] C. Attanasio,[5] C. Cirillo,[5] V. V. Moshchalkov,[4] J. Van de Vondel,[4] T. H. Johansen,[2,6] W. A. Ortiz,[1] and A. V. Silhanek[7]

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[2]*Department of Physics, University of Oslo, POB 1048, Blindern, 0316 Oslo, Norway*

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[4]*Institute for Nanoscale Physics and Chemistry, Nanoscale Superconductivity and Magnetism Group, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*

[5]*CNR-SPIN Salerno and Dipartimento di Fisica "E. R. Caianiello", Università degli Studi di Salerno, Fisciano (Sa) I-84084, Italy*

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(Received 14 December 2013; revised manuscript received 30 March 2014; published 14 April 2014)

The morphology of abrupt bursts of magnetic flux into superconducting films with engineered periodic pinning centers (antidots) has been investigated. Guided flux avalanches of thermomagnetic origin develop a treelike structure, with the main trunk perpendicular to the borders of the sample, while secondary branches follow well-defined directions determined by the geometrical details of the underlying periodic pinning landscape. Strikingly, we demonstrate that in a superconductor with relatively weak random pinning the morphology of such flux avalanches can be fully controlled by proper combinations of lattice symmetry and antidot geometry. Moreover, the resulting flux patterns can be reproduced, to the finest details, by simulations based on a phenomenological thermomagnetic model. In turn, this model can be used to predict such complex structures and to estimate physical variables of more difficult experimental access, such as the local values of temperature and electric field.

DOI: 10.1103/PhysRevB.89.134508 PACS number(s): 74.25.Ha, 68.60.Dv, 74.78.−w

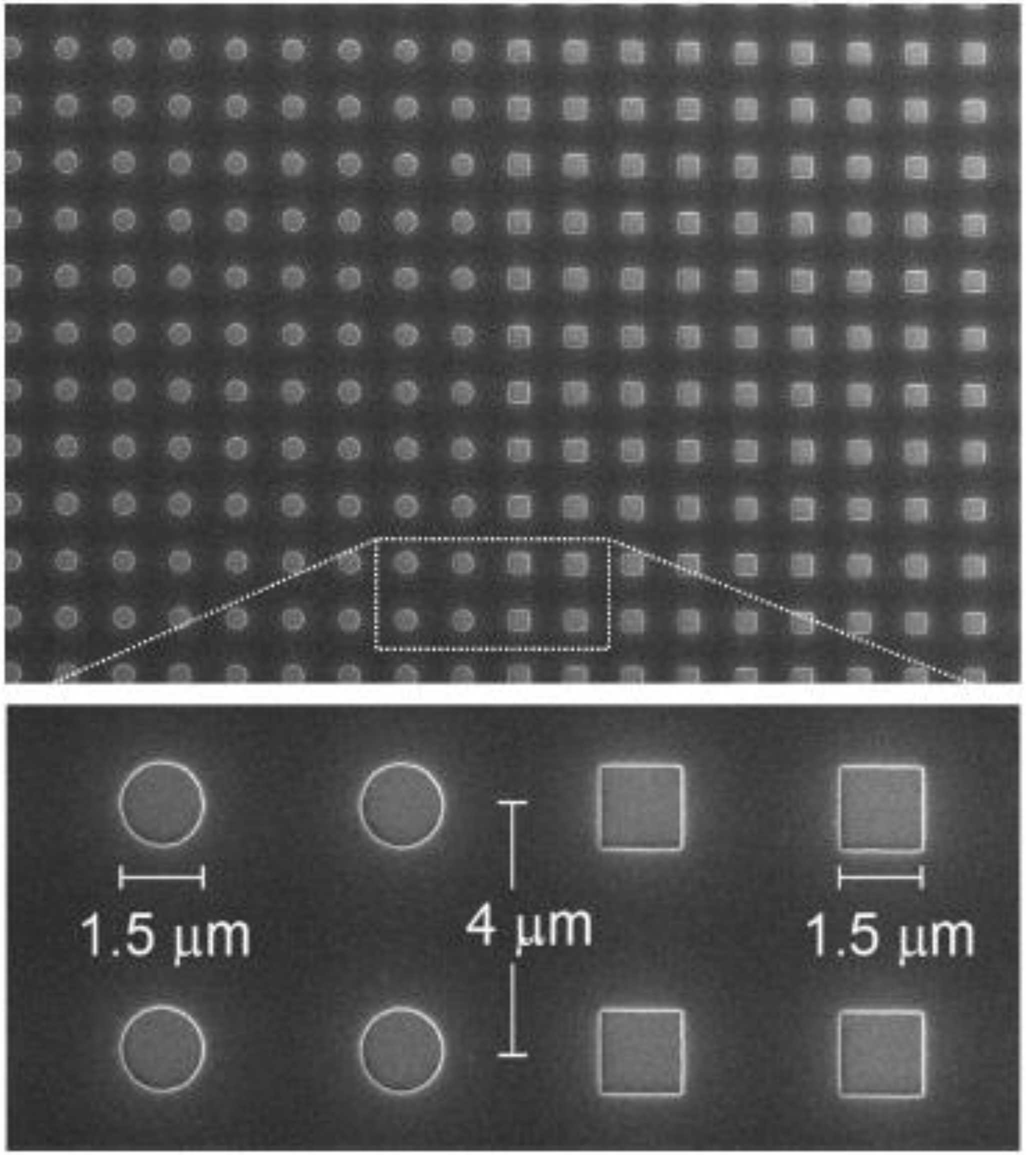


FIG. 1. Scanning electron microscopy image of the central portion of sample Nb-I, showing the abrupt change in antidot geometry, from circle (left) to square (right). Lattice parameter and AD sizes are shown in the zoomed up bottom panel.

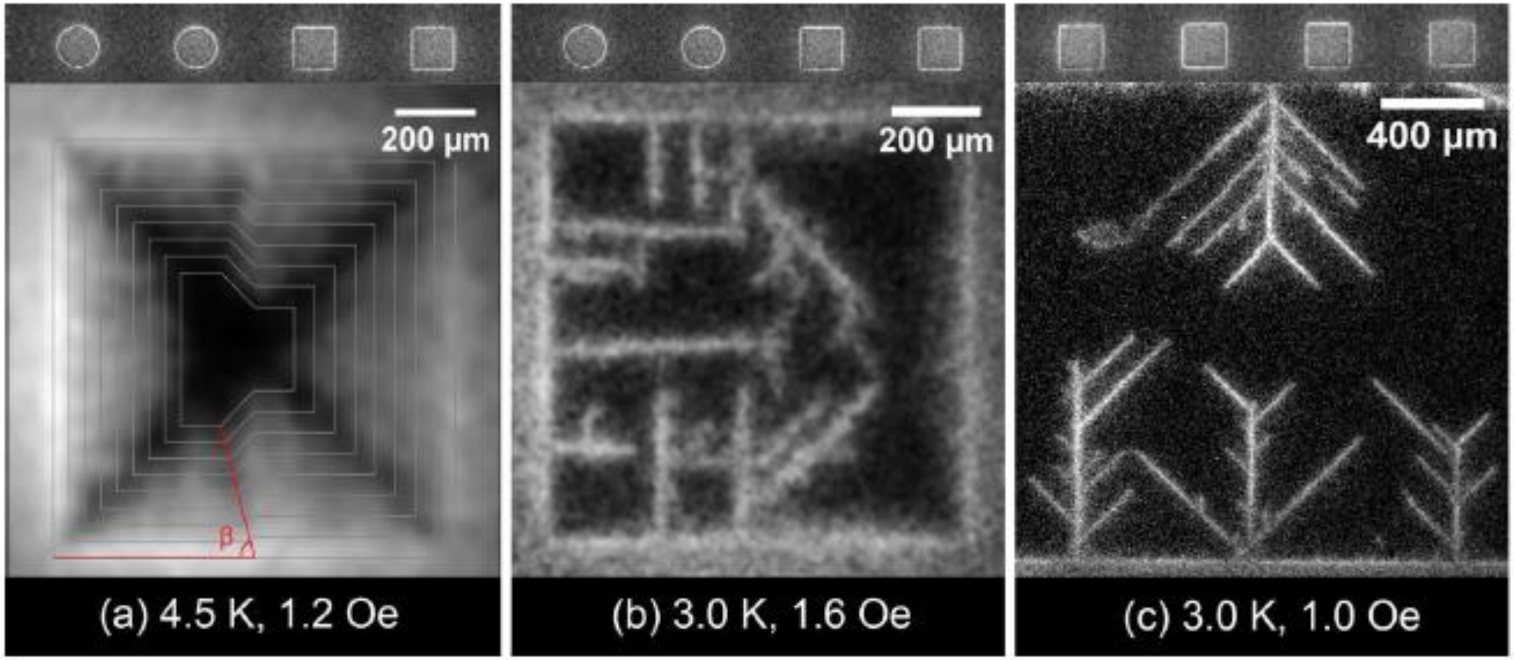


FIG. 2. MO images for sample MoGe-I, with circular (left side) and square (right side) ADs, taken at (a) $T = 4.5$ K and $H = 1.2$ Oe, showing anisotropic flux penetration; and (b) $T = 3$ K and $H = 1.6$ Oe, revealing two different morphologies, depending on the AD geometry. (c) MO image for sample MoGe-II (square lattice of square ADs) taken at $T = 3$ K and $H = 1$ Oe, showing avalanches with the Christmas Tree morphology. In panel (a) a drawing of the streamline pattern of the critical current flow is superimposed to the actual MO image.

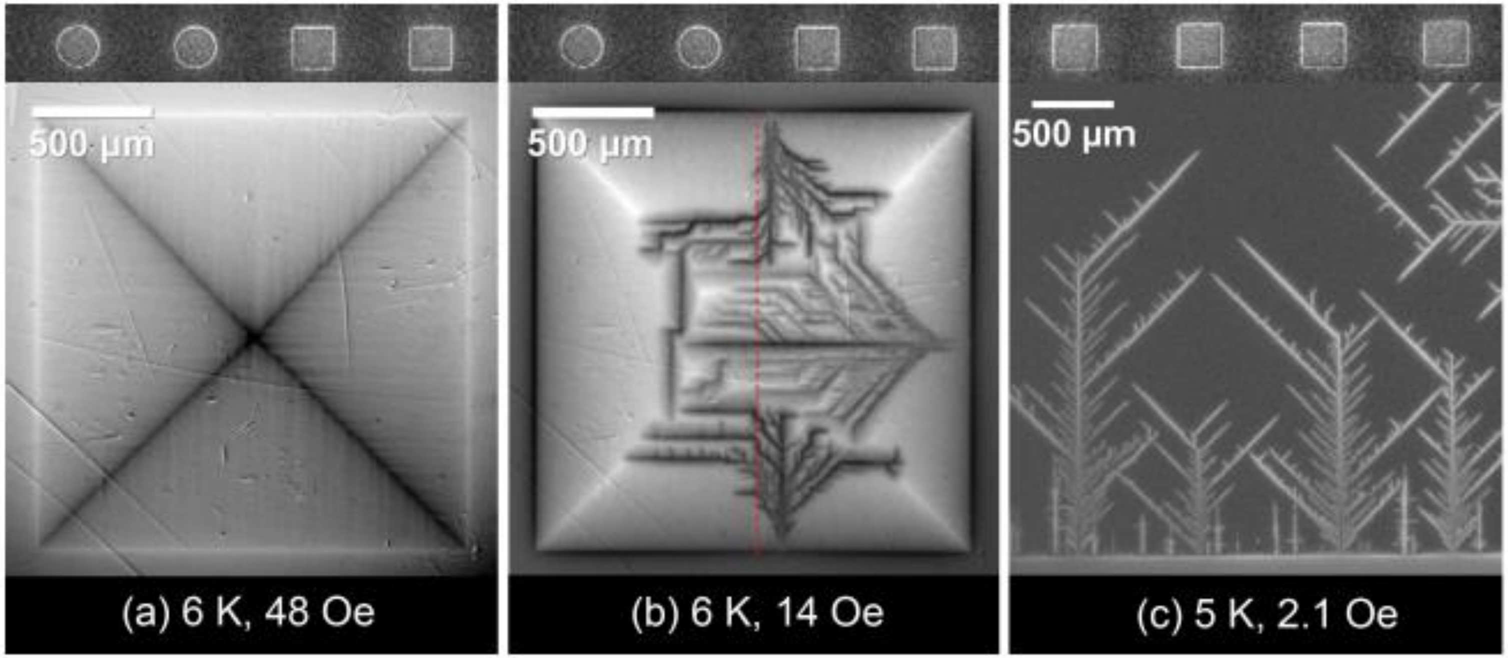


FIG. 3. MO images taken for sample Nb-I, with circular (left side) and square (right side) ADs, taken at (a) $T = 6$ K and $H = 48$ Oe, showing isotropic flux penetration; and (b) decreasing the field from 48 Oe, at $H = 14$ Oe at $T = 6$ K, revealing different morphologies depending on the AD geometry. MO image for sample Nb-II (square lattice of square ADs) taken at $T = 5$ K and $H = 2.1$ Oe, showing avalanches with the Christmas Tree morphology.

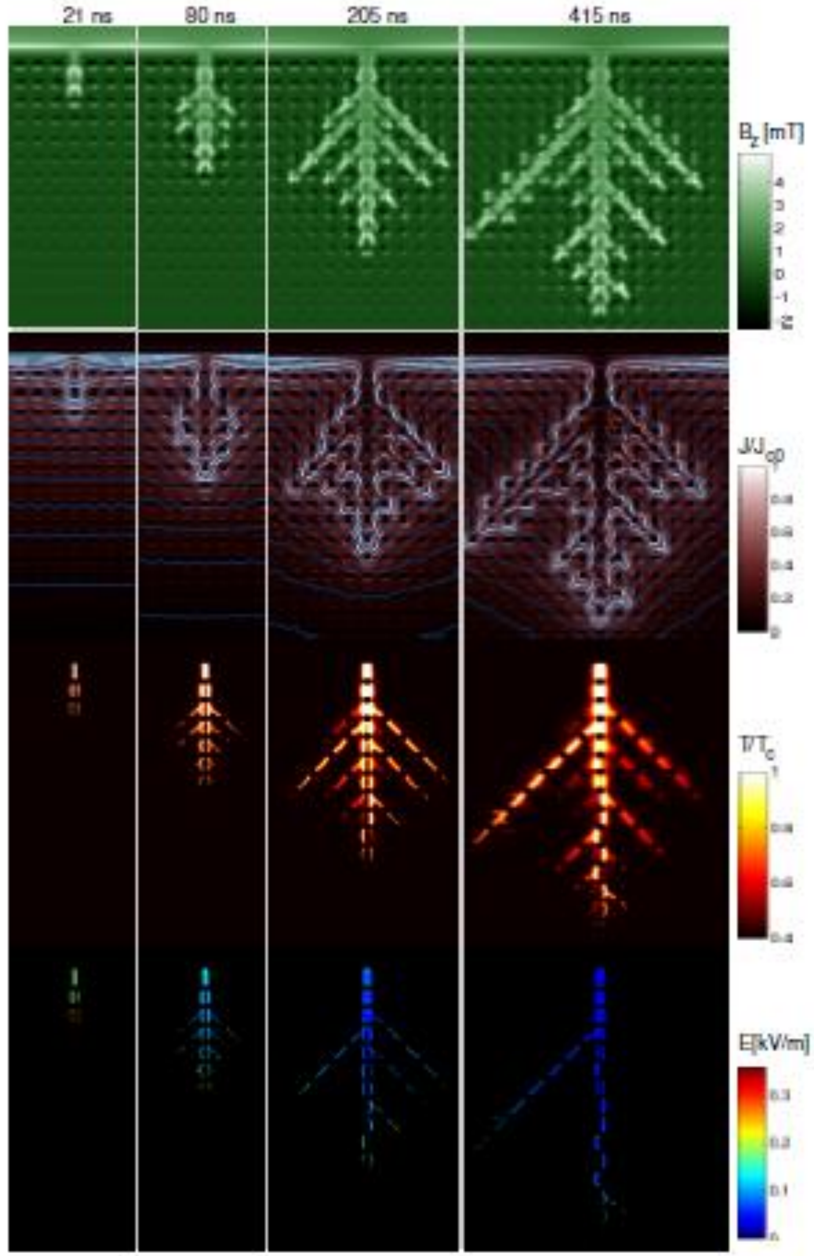


FIG. 4. Flux avalanche in a square array of square antidots, reproducing avalanches with the Christmas Tree morphology (see text) occurring for $T/T_c = 0.4$ and $H = 5.3$ Oe with the typical parameters of a Nb thin film. The first set of panels represents the distribution of the magnetic flux density B_z, the second set shows the induced sheet current J, the third presents the map of the reduced temperature, and the last depicts the space distribution of the electric field. Time evolves from left to right: 21 ns, 80 ns, 205 ns, and 415 ns.

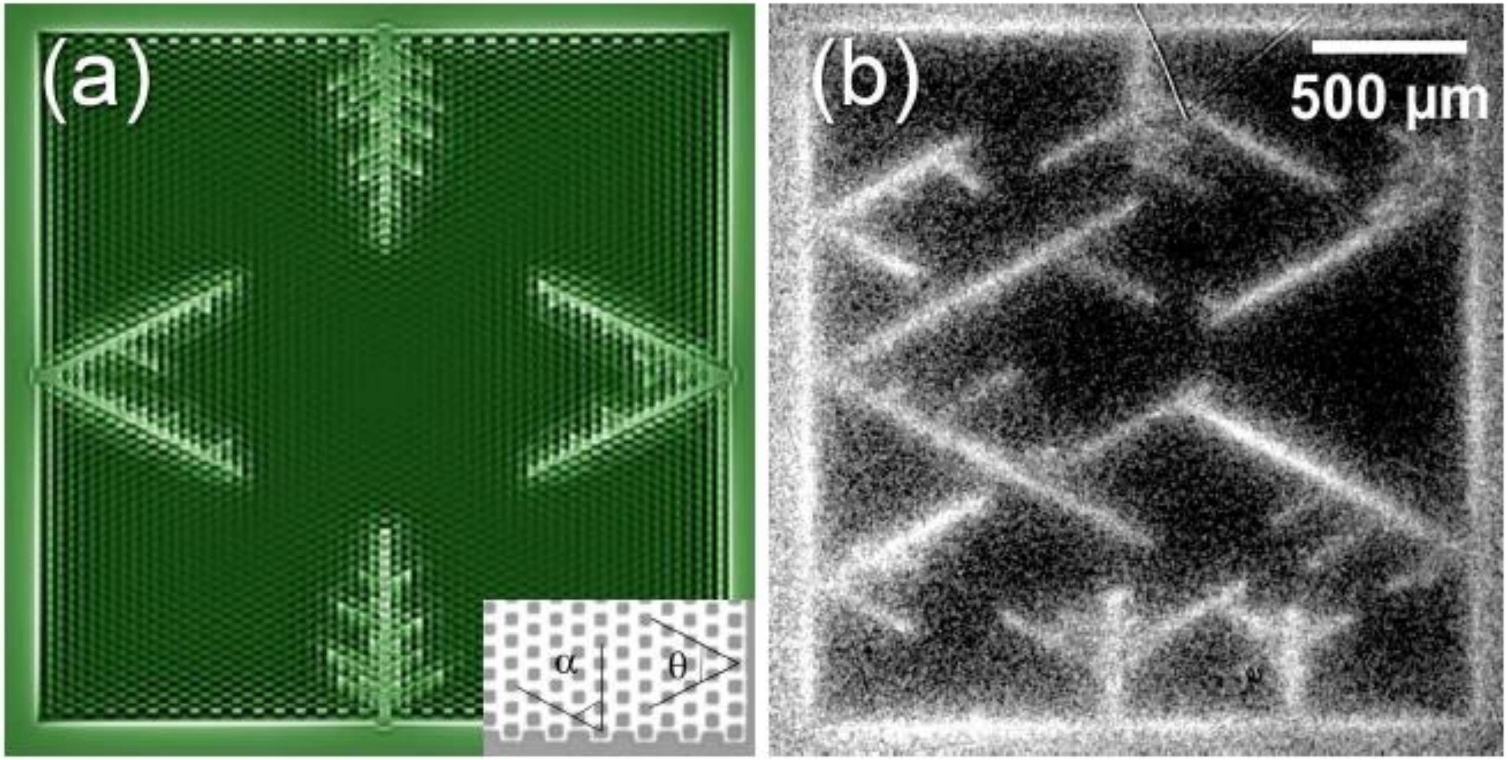
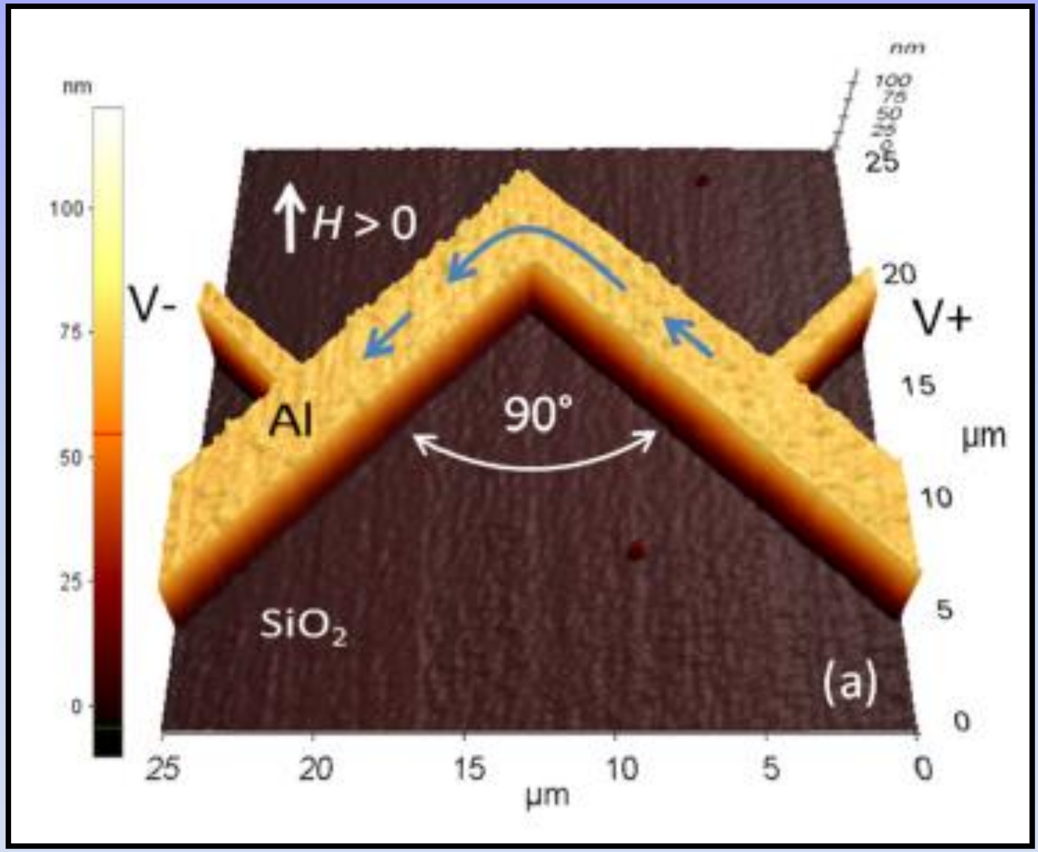


FIG. 5. (a) Magnetic flux distribution for $H = 3.2$ Oe, obtained from simulations for a superconducting film decorated with a centered rectangular 2D Bravais lattice of square ADs, designed to match sample MoGe-III. (b) MO image taken at 3 K and 1.0 Oe for sample MoGe-III. Inset: optical image showing the nominal angles $\alpha = 63.4^\circ$ and $\theta = 53.1^\circ$ of the lattice.

Current crowding effect: vortices enter from the inner corner

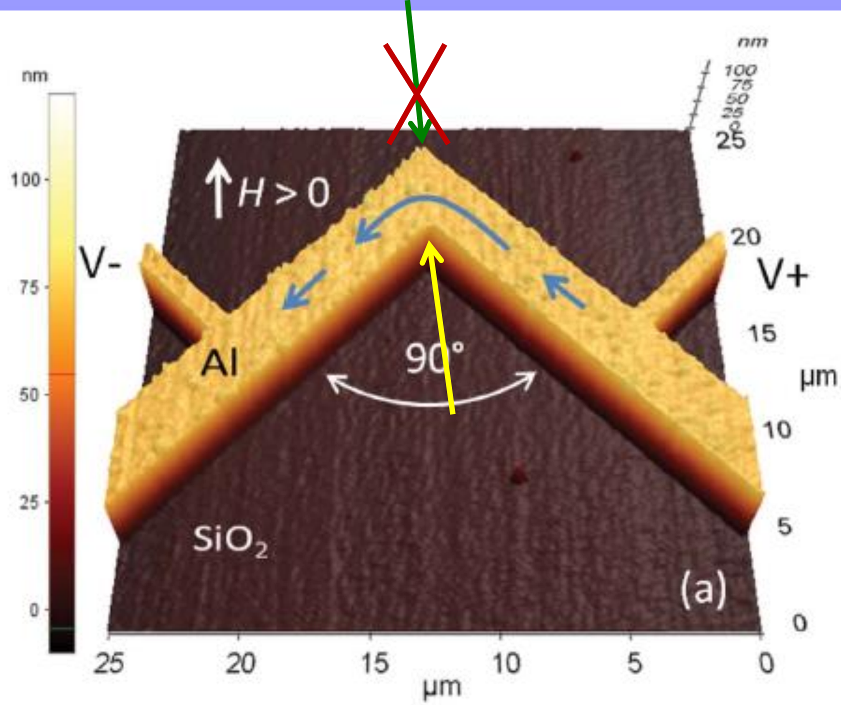


APPLIED PHYSICS LETTERS **102**, 052603 (2013)

CrossMark

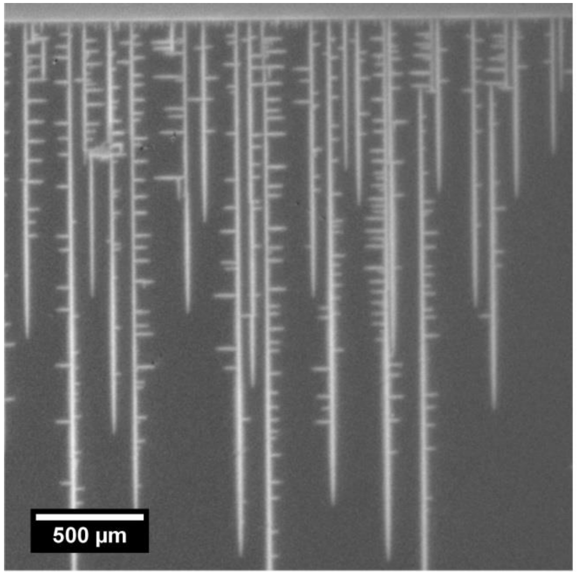
Current crowding effects in superconducting corner-shaped Al microstrips

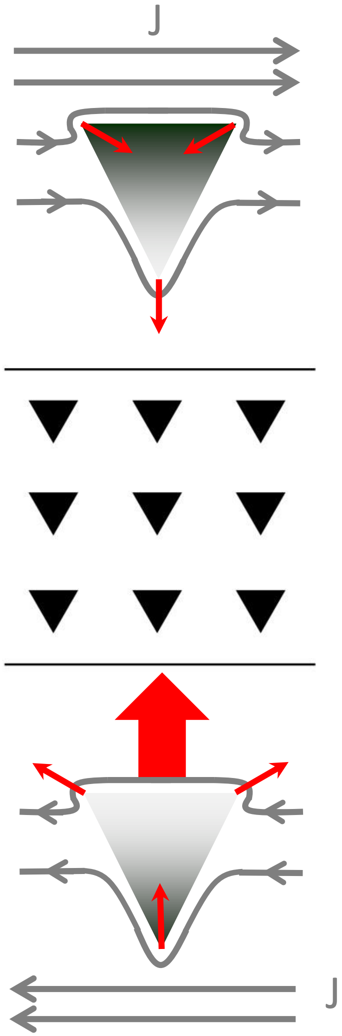
O.-A. Adami,[1,a)] D. Cerbu,[2,a)] D. Cabosart,[3] M. Motta,[4] J. Cuppens,[2] W. A. Ortiz,[4]
V. V. Moshchalkov,[2] B. Hackens,[3] R. Delamare,[5] J. Van de Vondel,[2] and A. V. Silhanek[1]

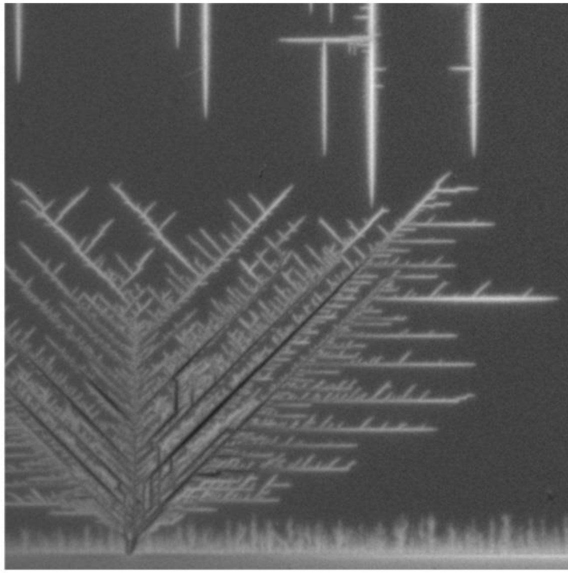


nm
100
75
50
25
0
H > 0
V-
V+
Al
90°
SiO$_2$
(a)
25
20
15
10
5
0
μm

Square lattice with triangles







T = 3 K and H = 3 Oe

Large Holes

APPLIED PHYSICS LETTERS **103**, 032604 (2013)

Limiting thermomagnetic avalanches in superconducting films by stop-holes

F. Colauto,[1] J. I. Vestgården,[2] A. M. H. de Andrade,[3] A. A. M. Oliveira,[1,4] W. A. Ortiz,[1] and T. H. Johansen[2,5]

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[2]*Department of Physics, University of Oslo, P.O. Box 1048 Blindern, 0316 Oslo, Norway*
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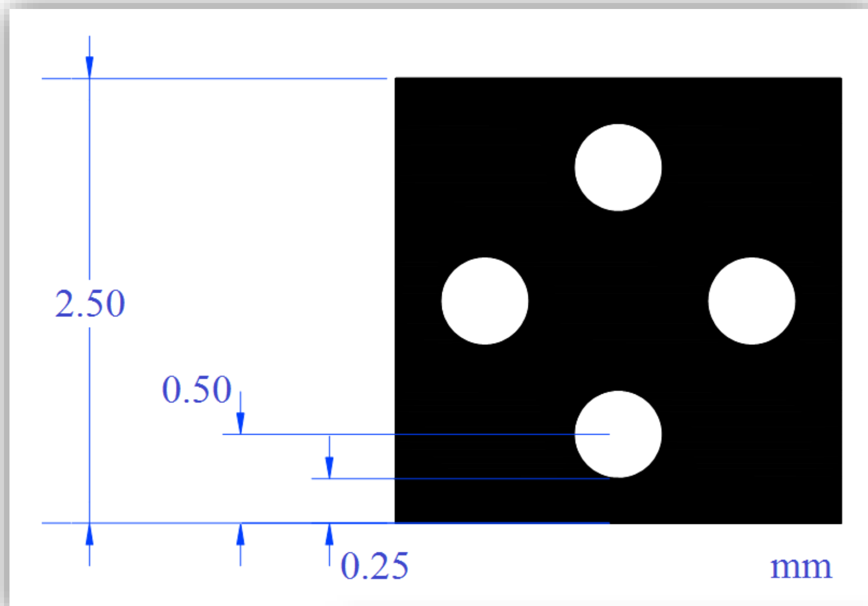
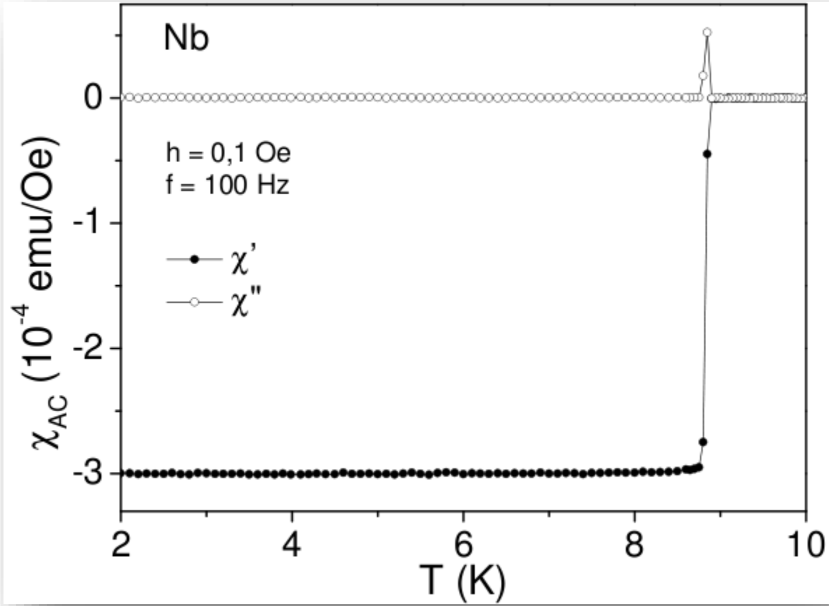
(Received 5 June 2013; accepted 28 June 2013; published online 16 July 2013)

It is demonstrated that circular holes in superconducting films of Nb can arrest the propagation of thermomagnetic avalanches. The effect was found over a range of temperatures where the material is susceptible to this instability. For other hole shapes, like square and triangular, the sharp corners provoke secondary avalanches, thus extending the breakdown. Making use of circular stop-holes can become a practical way to limit thermomagnetic breakdown in superconducting films. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4813908]

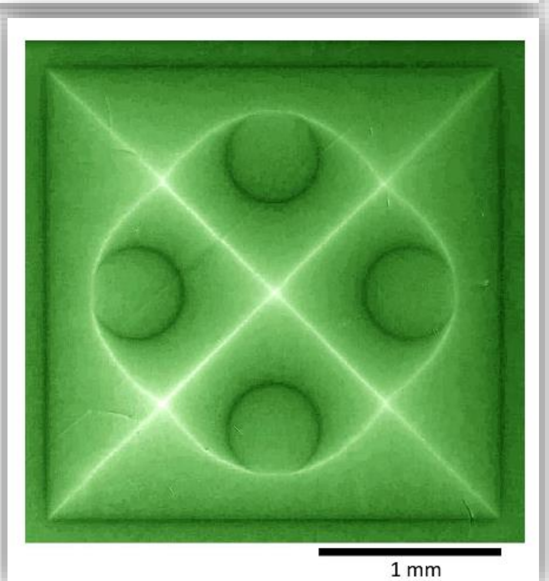
Sample quality





Remanent state
(after field raised up to 48 Oe)

8.0 K

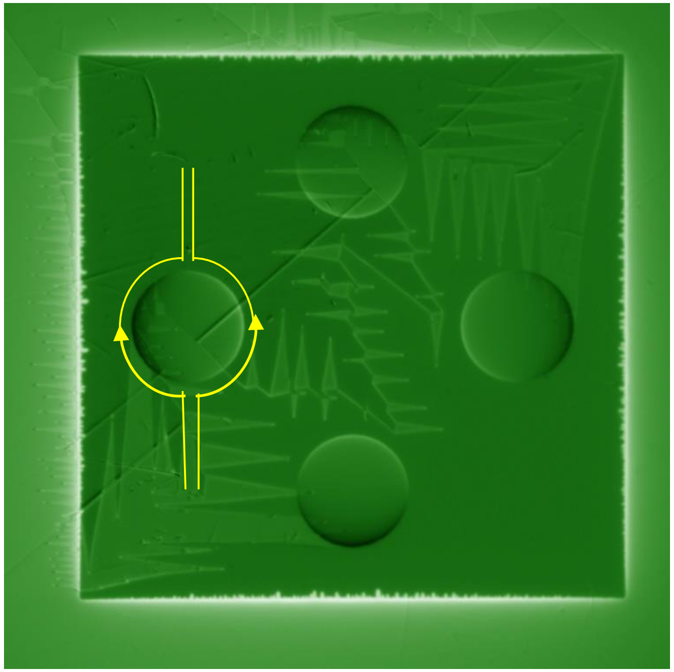


Nb film

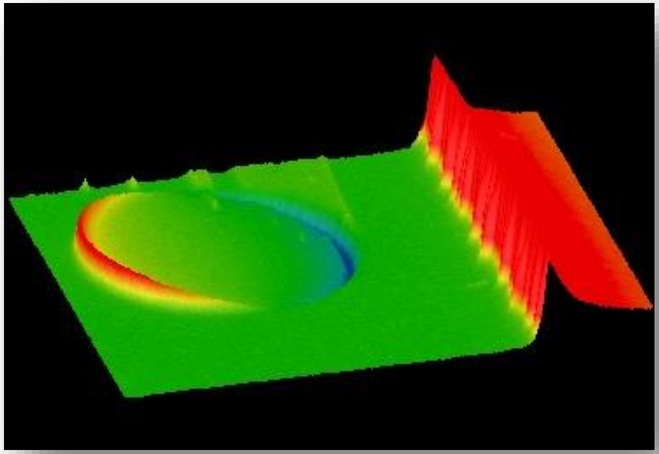
- Niobium film was grown by UHV magnetron sputtering
- Thickness of 200 nm
- Films were shaped using optical lithography
- The material was removed by etching.

Flux polarization inside the hole

Nb film



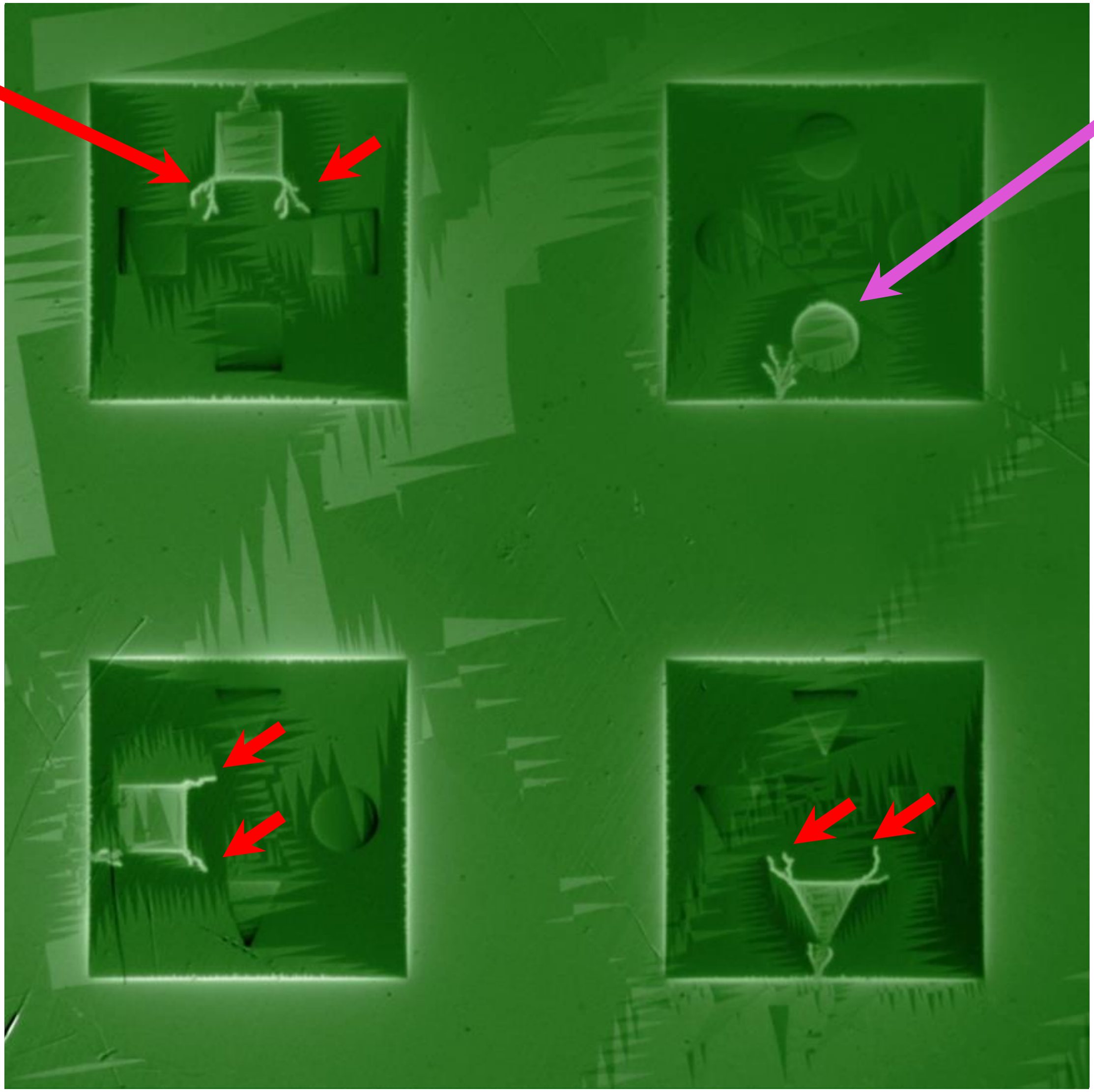
2.5 K
18.5 Oe



Different hole shapes

secondary avalanches

no secondary avalanches



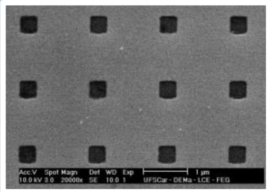
2.5 K

15.5 Oe

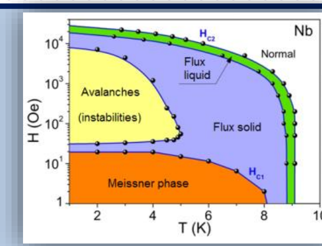
19.0 Oe

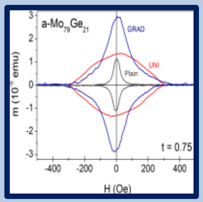
iii. Enhancement of J_c

- ➔ lattice
- ➔ graded array

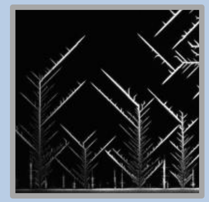


arrays of antidots





Enhancement of J_c



Avalanches

lattice

graded array

suppression

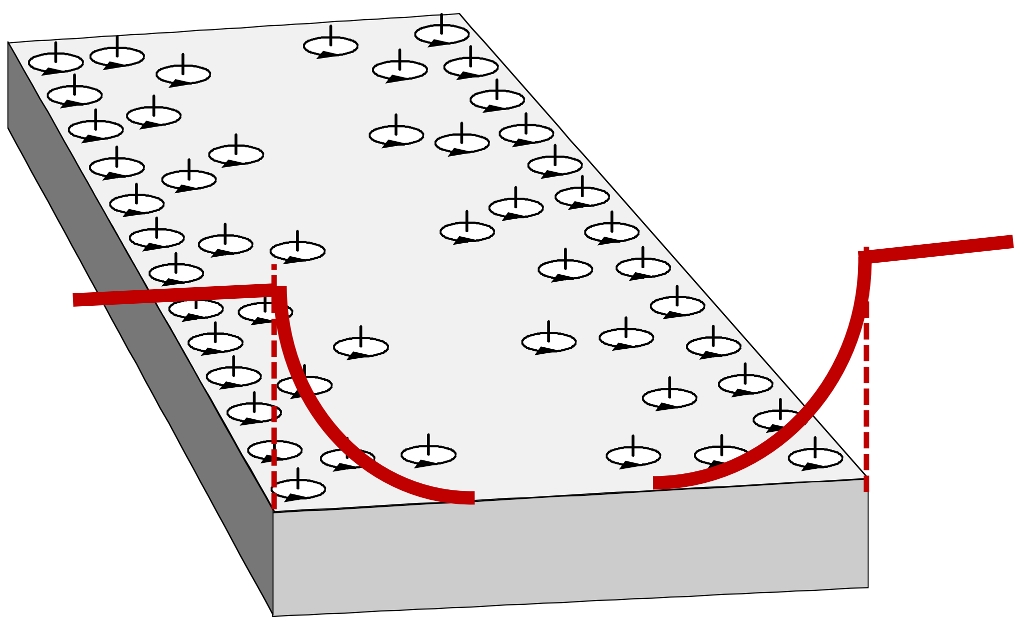
guidance

high-T

low-T

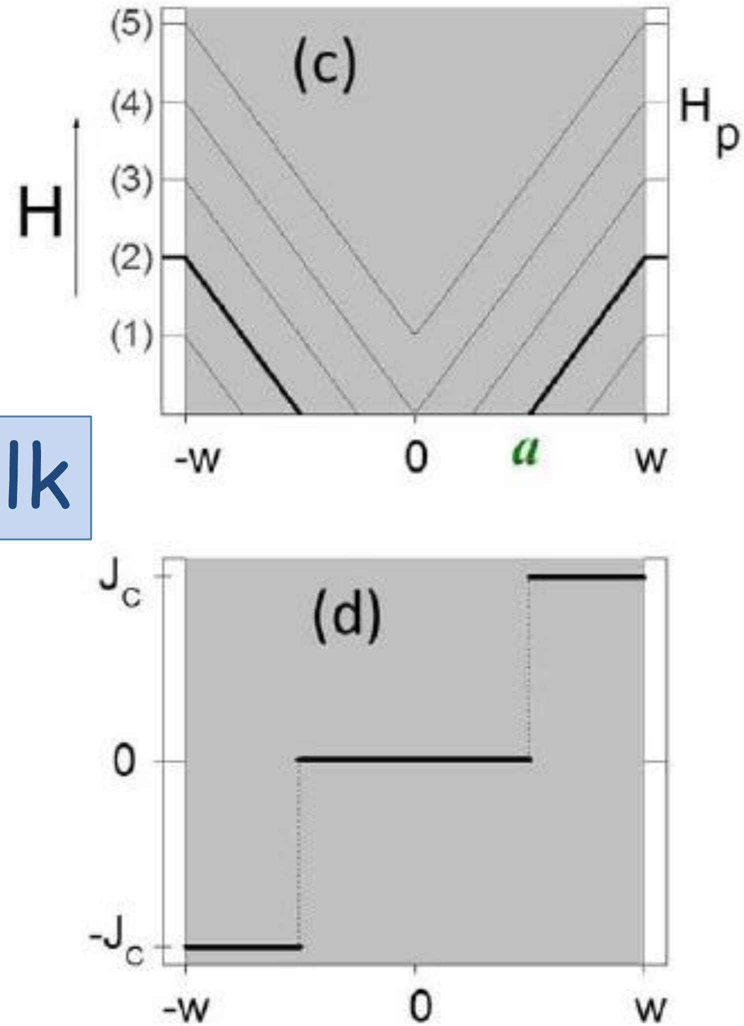
Homogeneous distribution of ADs

For small fields (e.g., at the early stages of penetration): too many holes at the central portion of the sample

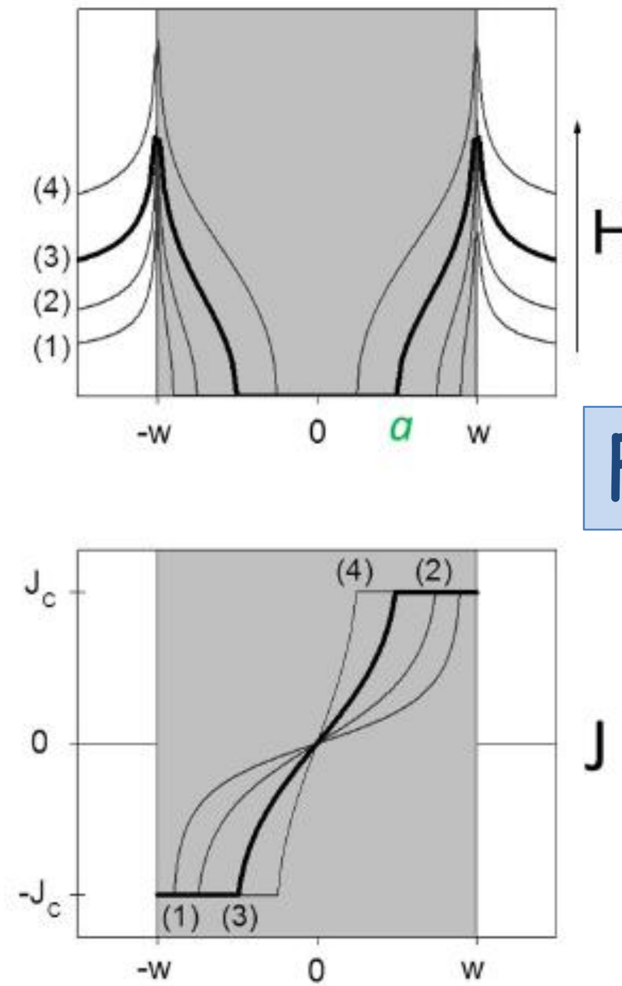


In a film, currents run “everywhere”!

Bulk

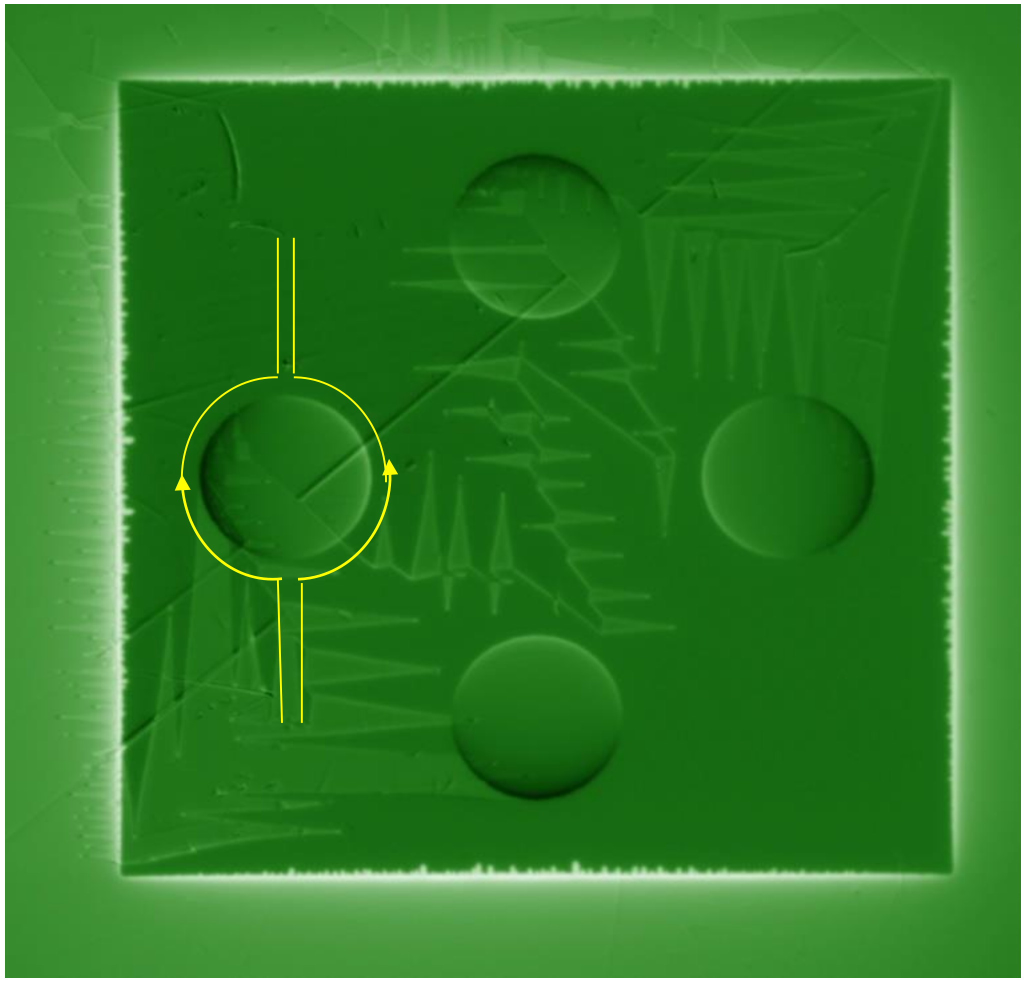


Film



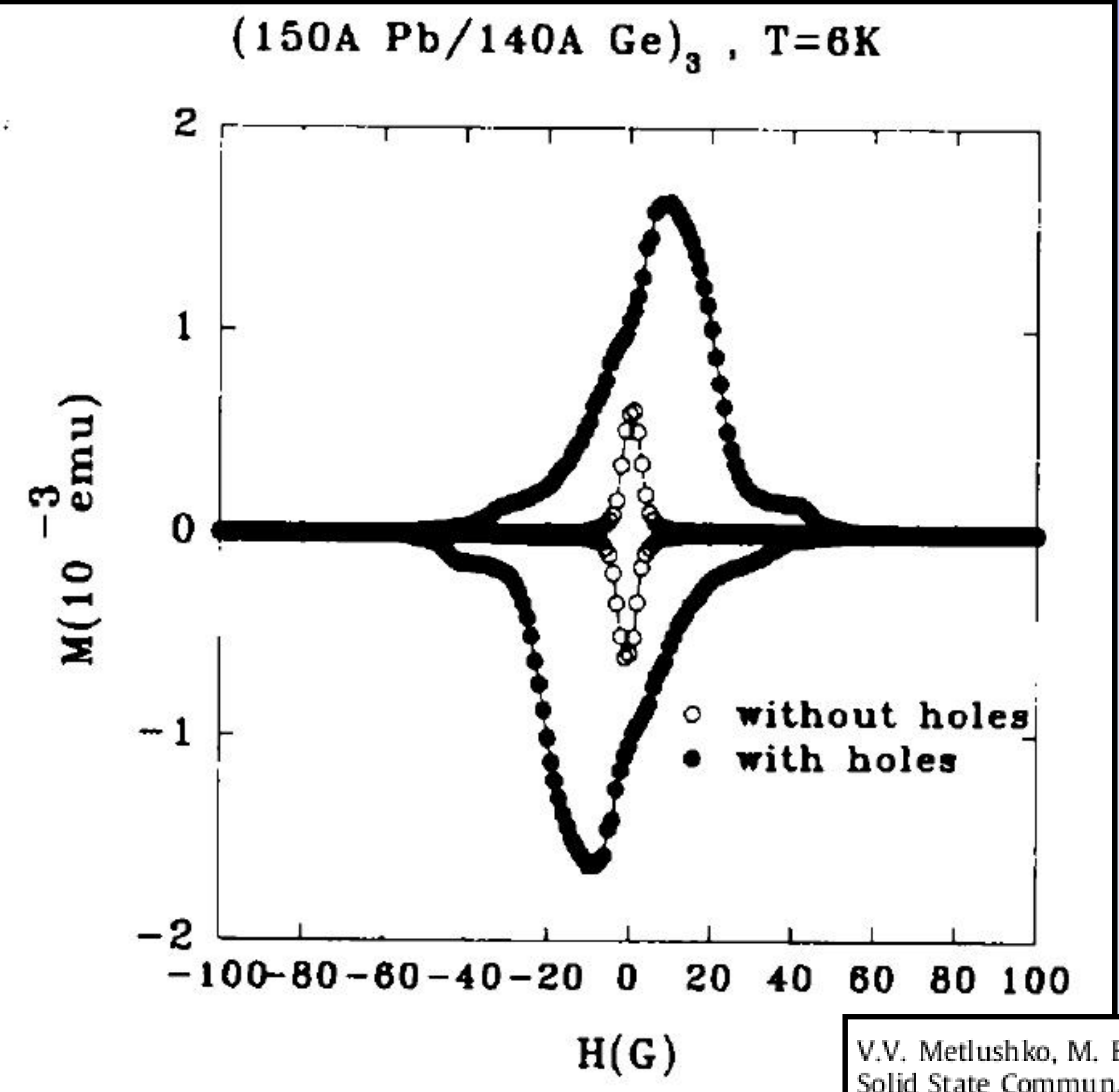
In a film, currents run "everywhere"!

Nb film



2.5 K
18.5 Oe

lattice of antidots: enhancement of J_c



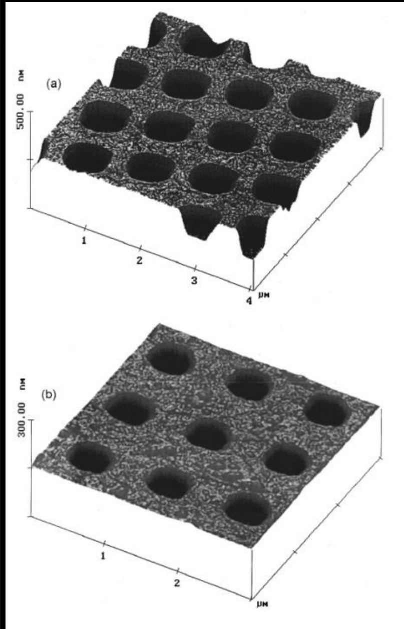
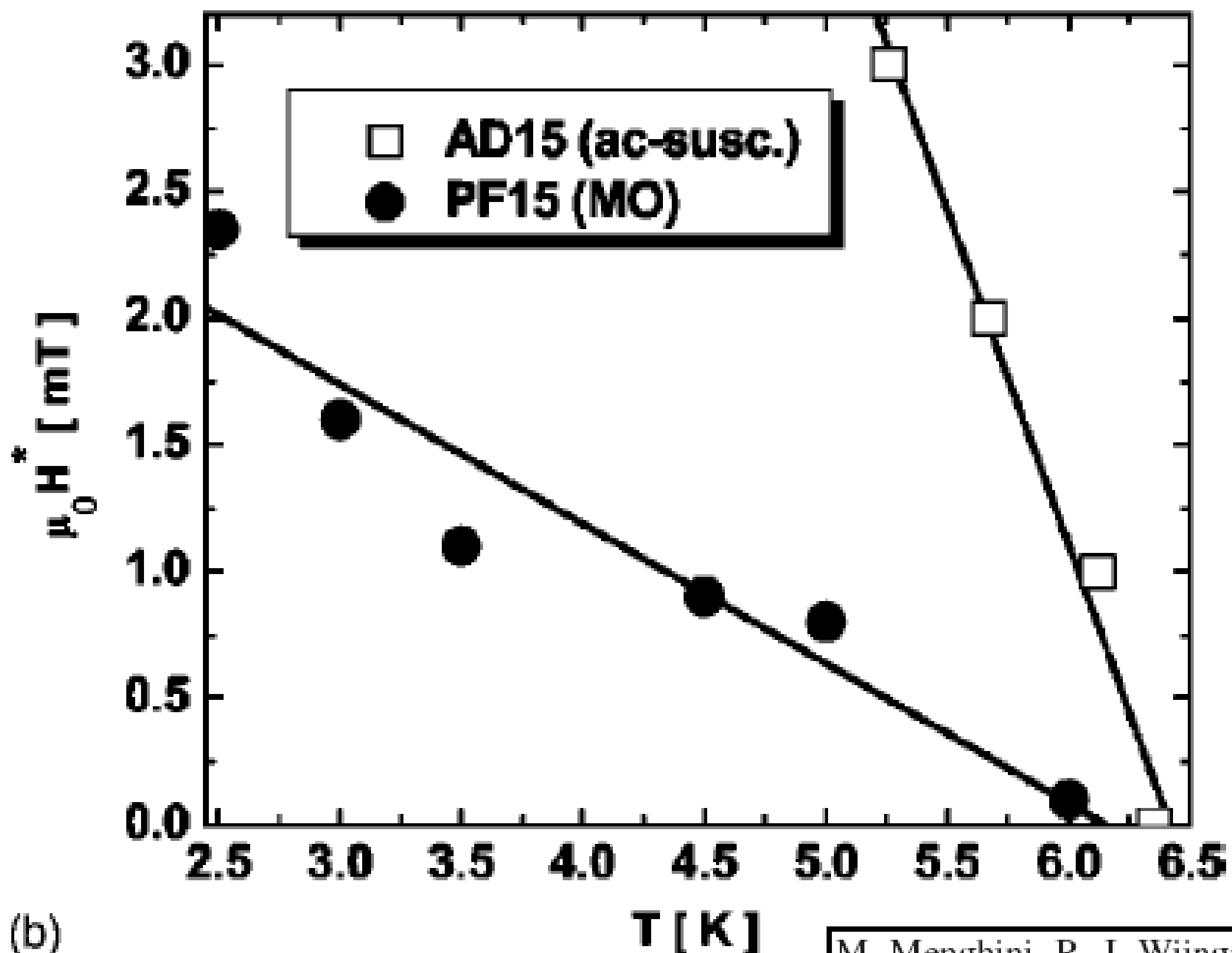


FIG. 1. (a) AFM picture of a [Pb(150 Å)/Ge(140 Å)]$_3$ multilayer with a square "antidot" lattice clearly shows the periodicity of the lattice $d=1$ μm and the shape of the antidots with diameter $D=0.6$ μm. (b) AFM picture of a single WGe(600 Å) film with a square "antidot" lattice ($d=1$ μm and $D=0.35$ μm).

V.V. Metlushko, M. Baert, R. Jonckheere, V.V. Moshchalkov, Y. Bruynseraede, Solid State Commun. 91 (1994) 331.

Lattice of antidots: avalanche inducers



M. Menghini, R. J. Wijngaarden, A. V. Silhanek, S. Raedts, and V. V. Moshchalkov, Phys. Rev. B **71**, 104506 (2005).

Arrays of unevenly distributed pinning centers

APPLIED PHYSICS LETTERS **102**, 212601 (2013)

Enhanced pinning in superconducting thin films with graded pinning landscapes

M. Motta,[1] F. Colauto,[1] W. A. Ortiz,[1] J. Fritzsche,[2] J. Cuppens,[3] W. Gillijns,[3] V. V. Moshchalkov,[3] T. H. Johansen,[4,5] A. Sanchez,[6] and A. V. Silhanek[7]

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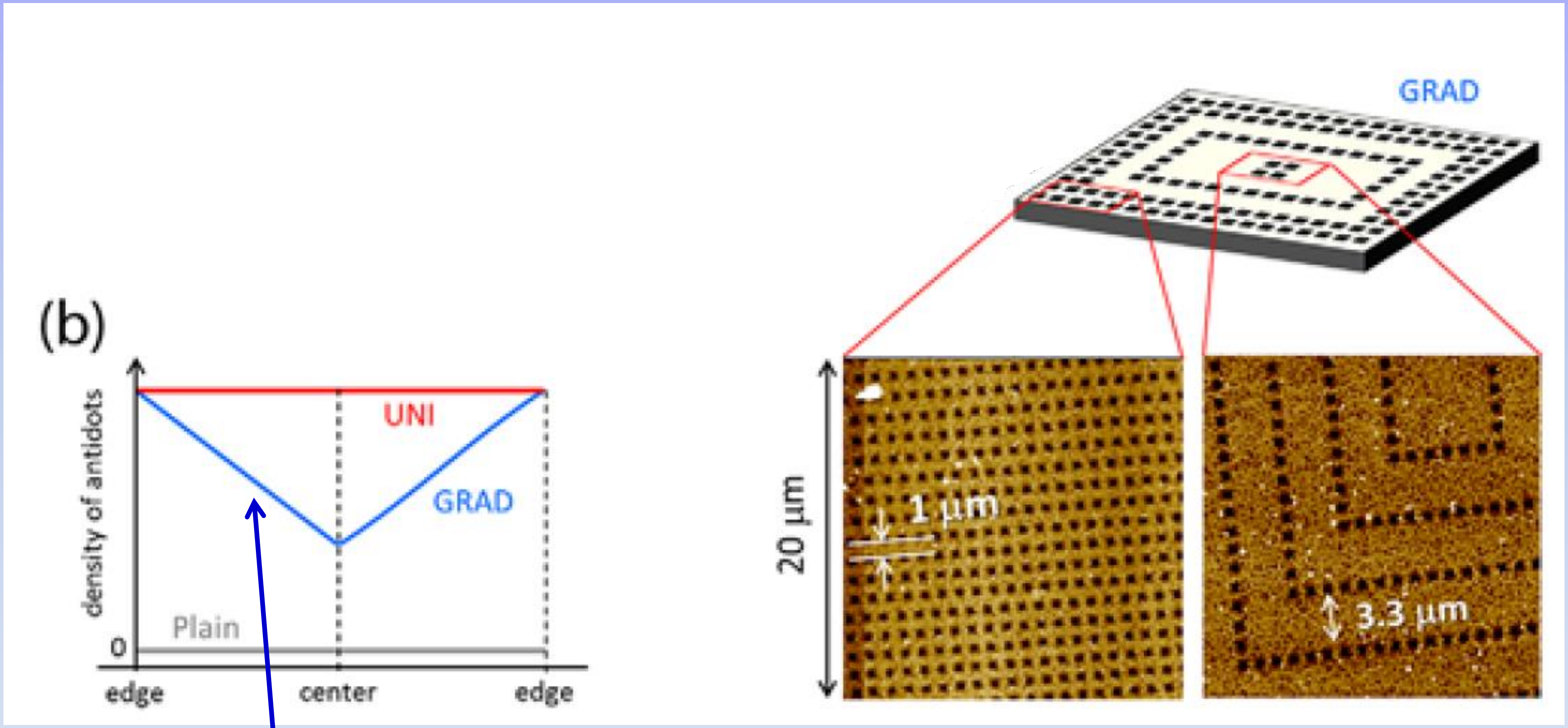
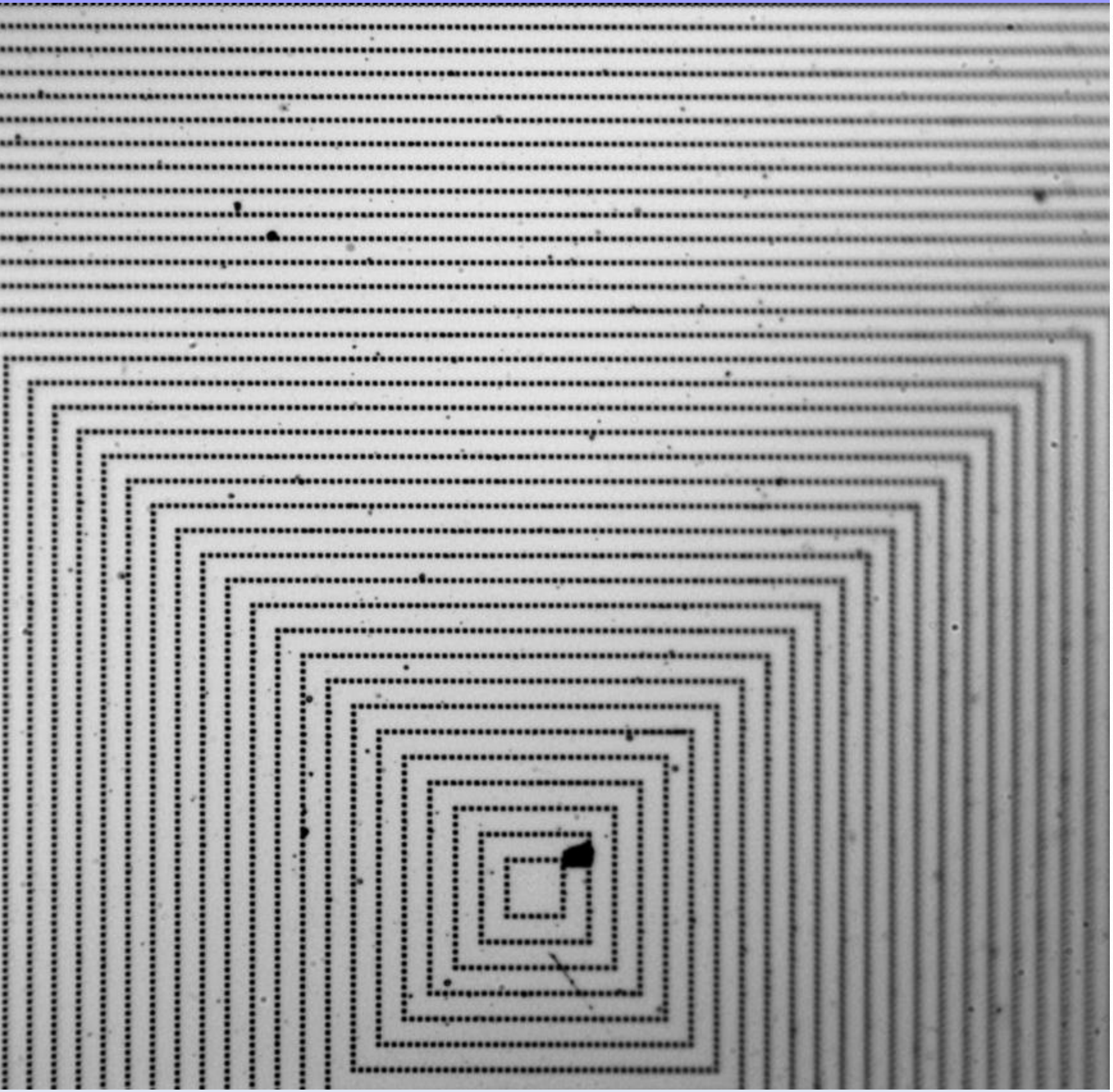
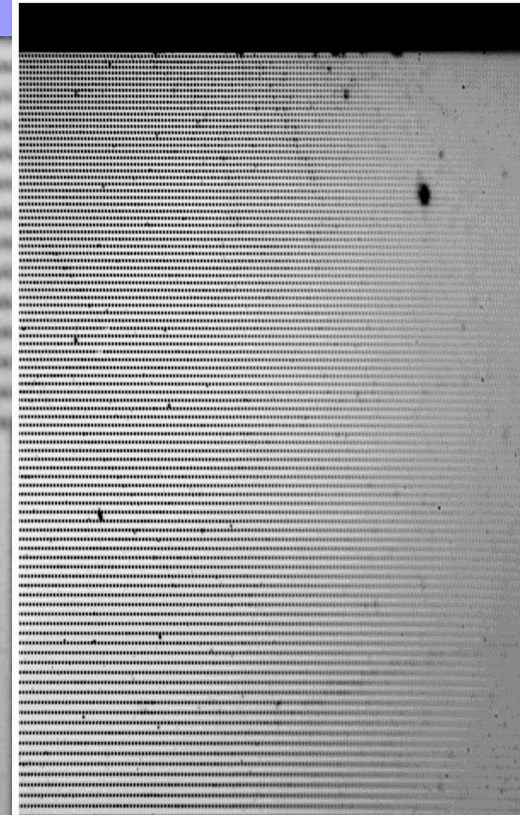
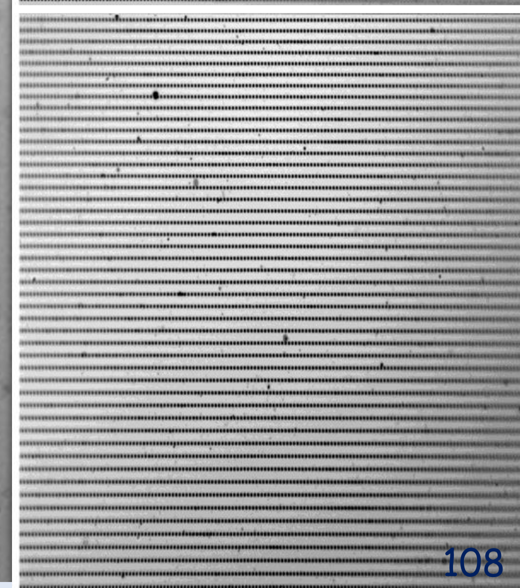
a-$Mo_{79}Ge_{21}$ 1x1 mm^2, 25 nm thick



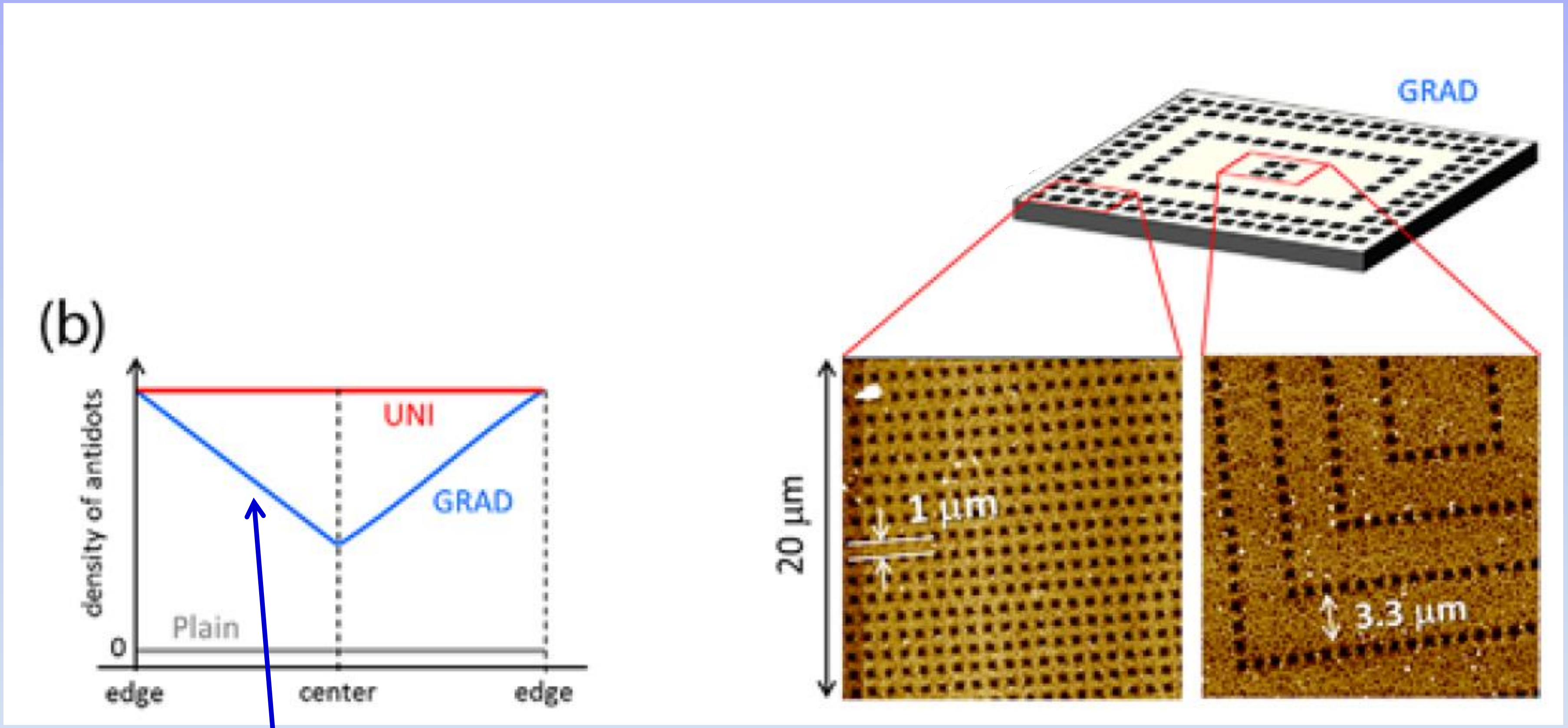
Actual gradient: 0.01 (1%), i.e., 10nm/1μm





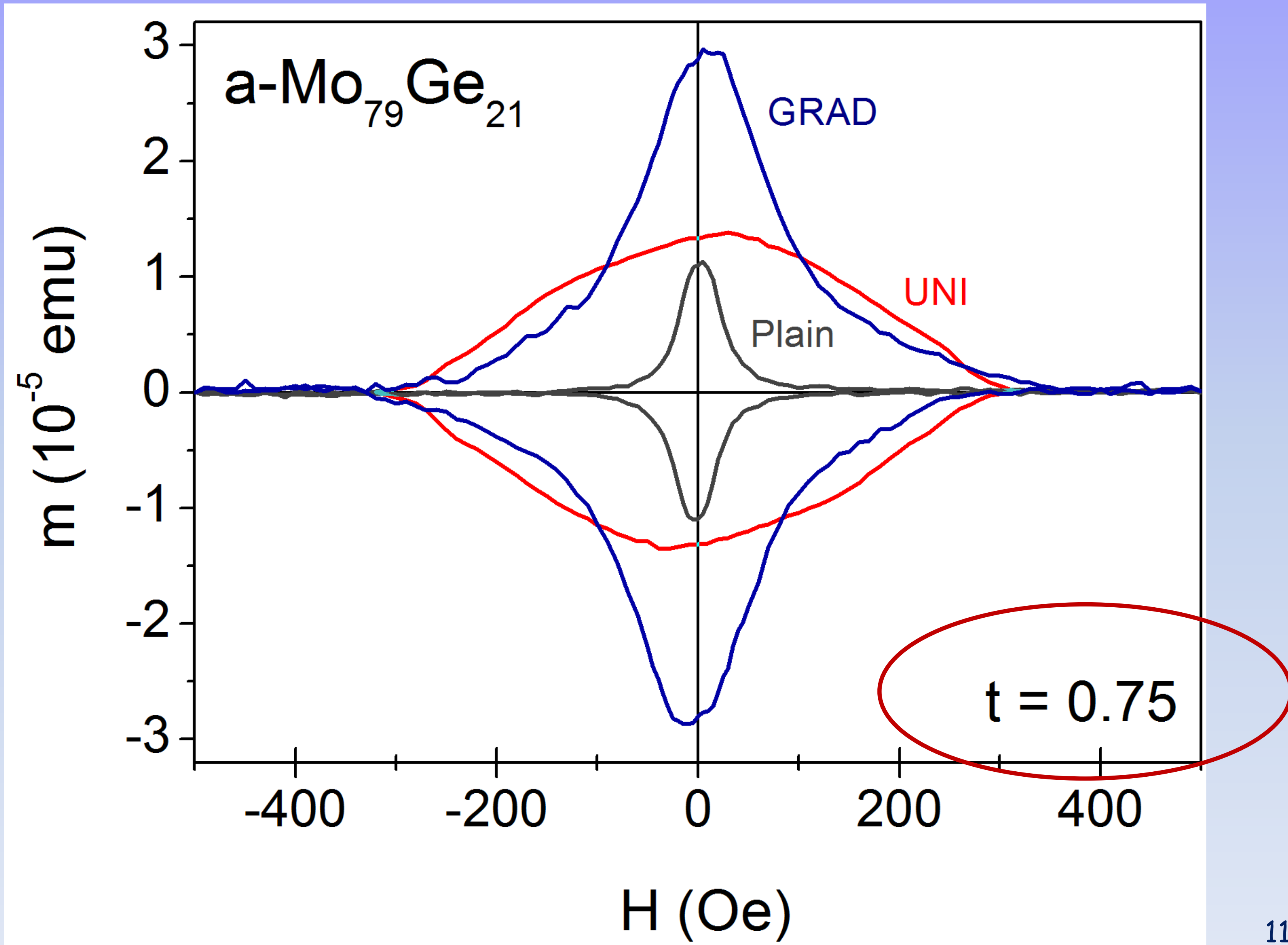


a-$Mo_{79}Ge_{21}$ 1x1 mm^2, 25 nm thick

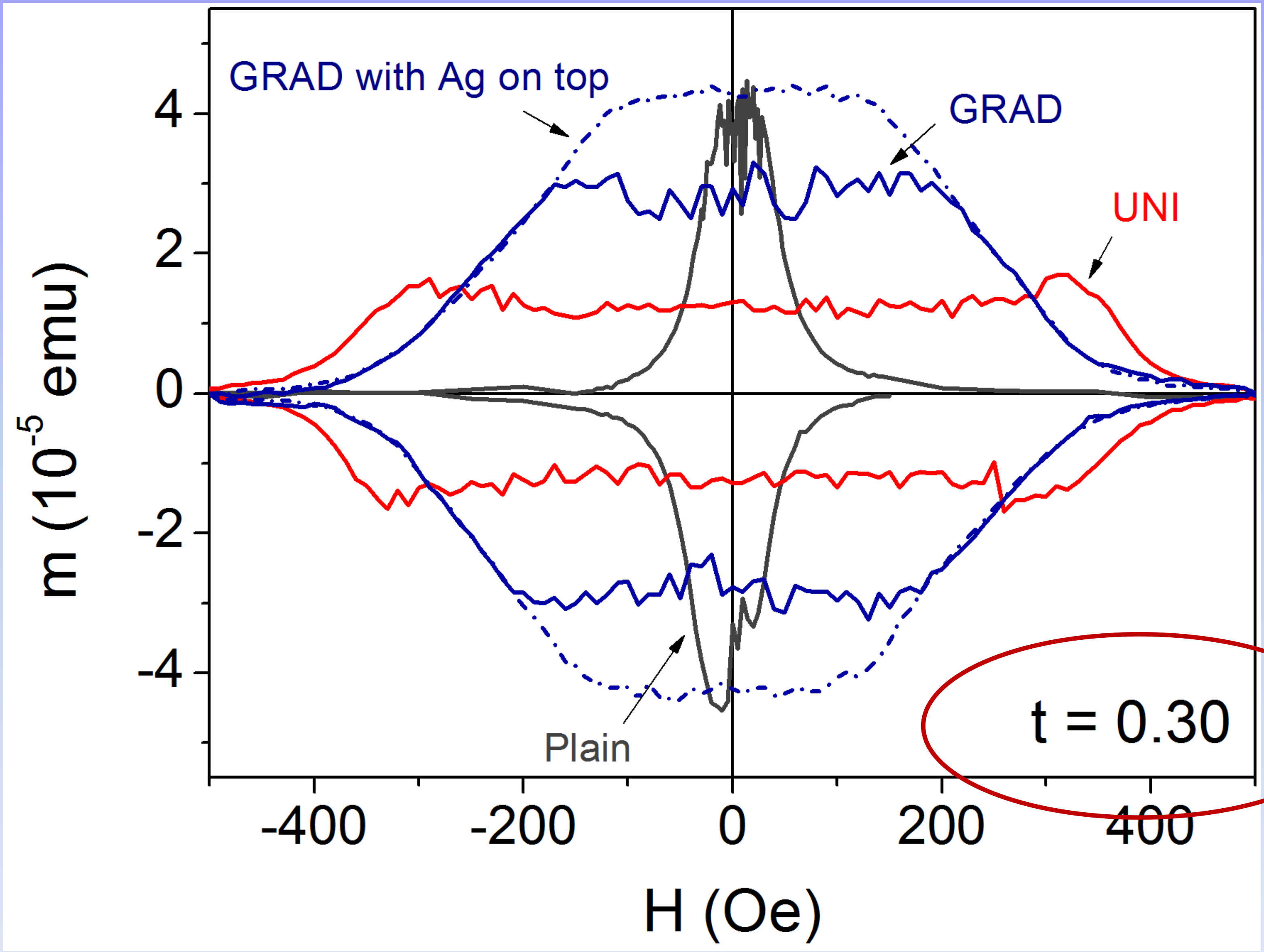


Actual gradient: 0.01 (1%), i.e., 10nm/1µm

$m \times H$ ($J_c \; \alpha \; \Delta m$)



m x H ($J_c \propto \Delta m$)



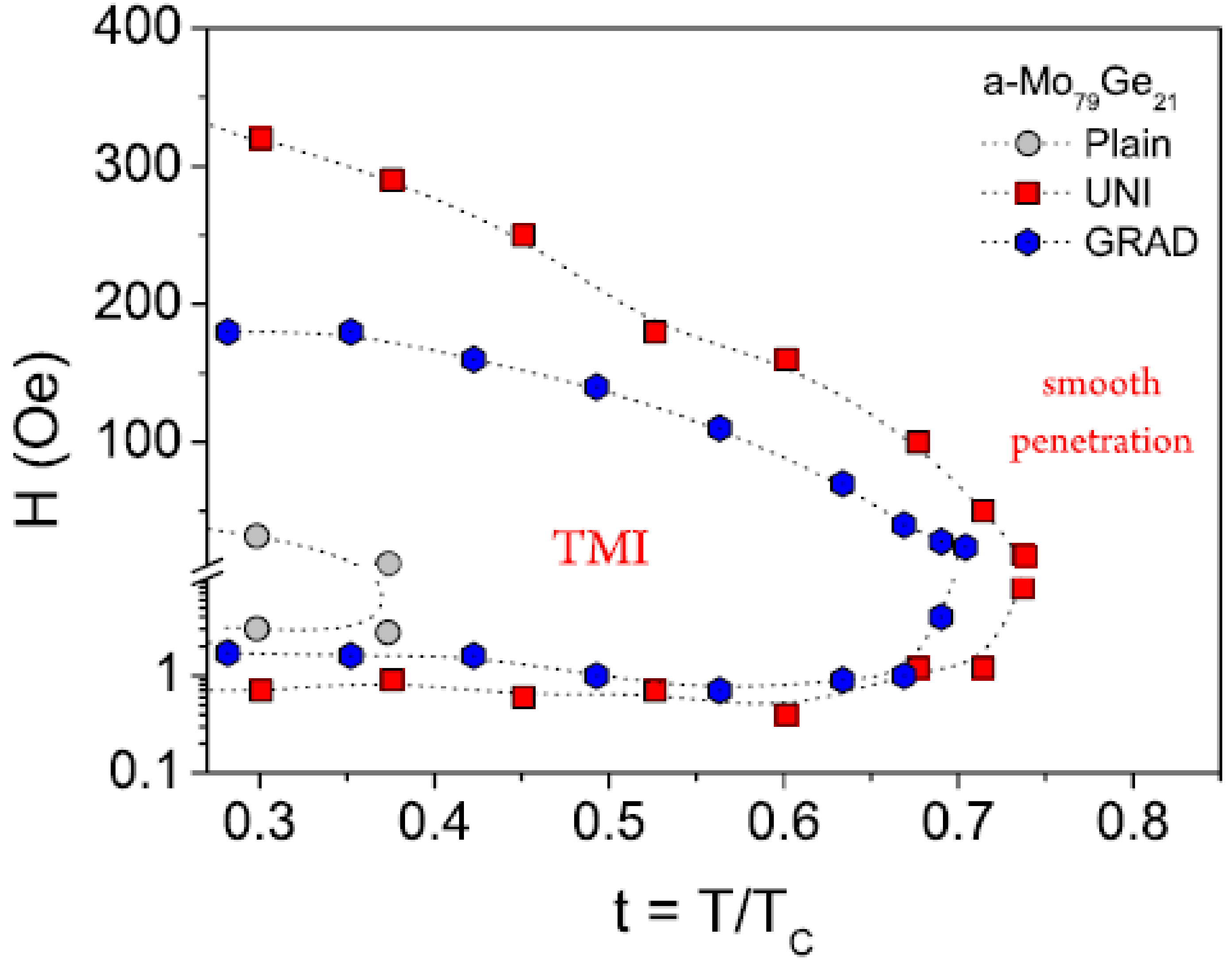
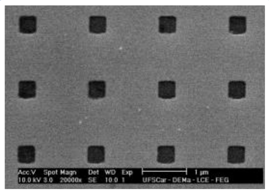
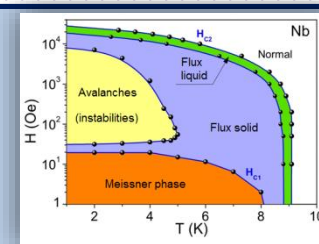
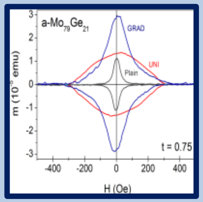


FIG. 3. Boundaries of the instability region of the studied a-$Mo_{79}Ge_{21}$ thin films. Notice the logarithmic scale on the lower portion of the vertical axis.



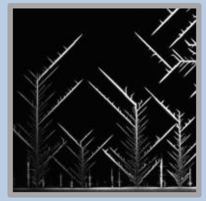
arrays of antidots





Enhancement of J_c

- lattice
- graded array



Avalanches

- suppression
- guidance

high-T

low-T

22 July 2015

Weak-link superconductivity in microstructured films

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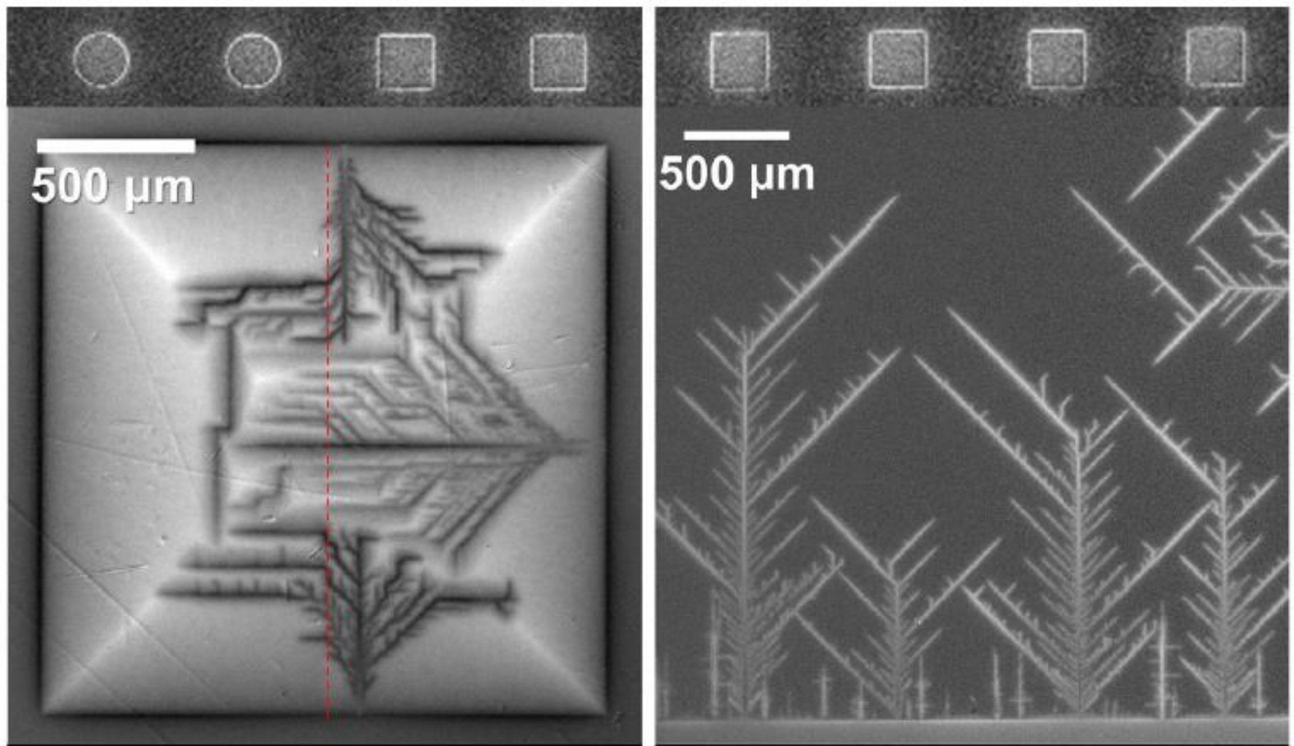
Jørn Inge Vestgården, Tom Henning Johansen
Oslo, Norway

Primary motivation: flux avalanches in the presence of obstacles

PHYSICAL REVIEW B **89**, 134508 (2014)

Controllable morphology of flux avalanches in microstructured superconductors

M. Motta,[1] F. Colauto,[1] J. I. Vestgården,[2] J. Fritzsche,[3] M. Timmermans,[4] J. Cuppens,[4] C. Attanasio,[5] C. Cirillo,[5] V. V. Moshchalkov,[4] J. Van de Vondel,[4] T. H. Johansen,[2,6] W. A. Ortiz,[1] and A. V. Silhanek[7]



(b) 6 K, 14 Oe

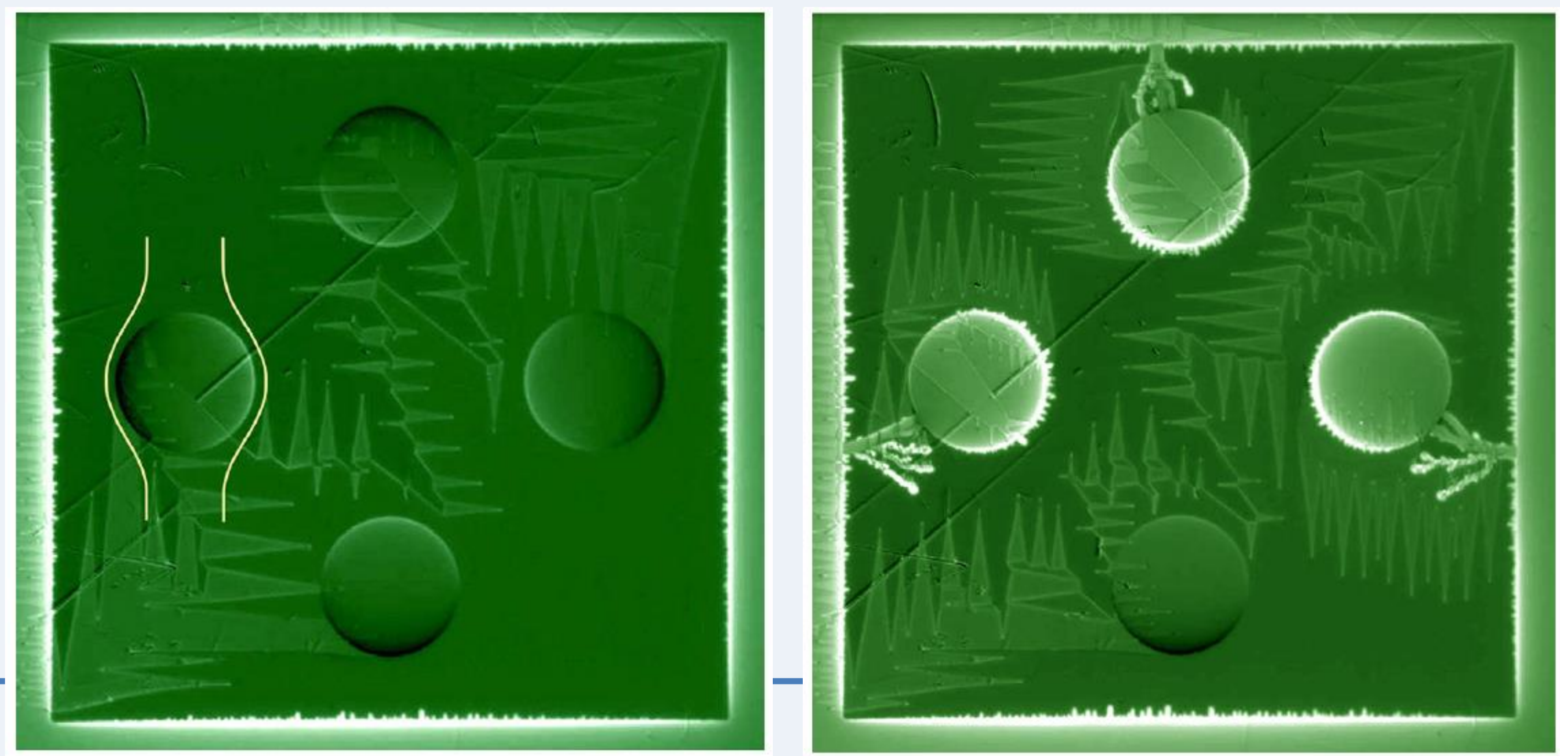
(c) 5 K, 2.1 Oe

Primary motivation: flux avalanches in the presence of obstacles

APPLIED PHYSICS LETTERS **103**, 032604 (2013)

Limiting thermomagnetic avalanches in superconducting films by stop-holes

F. Colauto,[1] J. I. Vestgården,[2] A. M. H. de Andrade,[3] A. A. M. Oliveira,[1,4] W. A. Ortiz,[1] and T. H. Johansen[2,5]



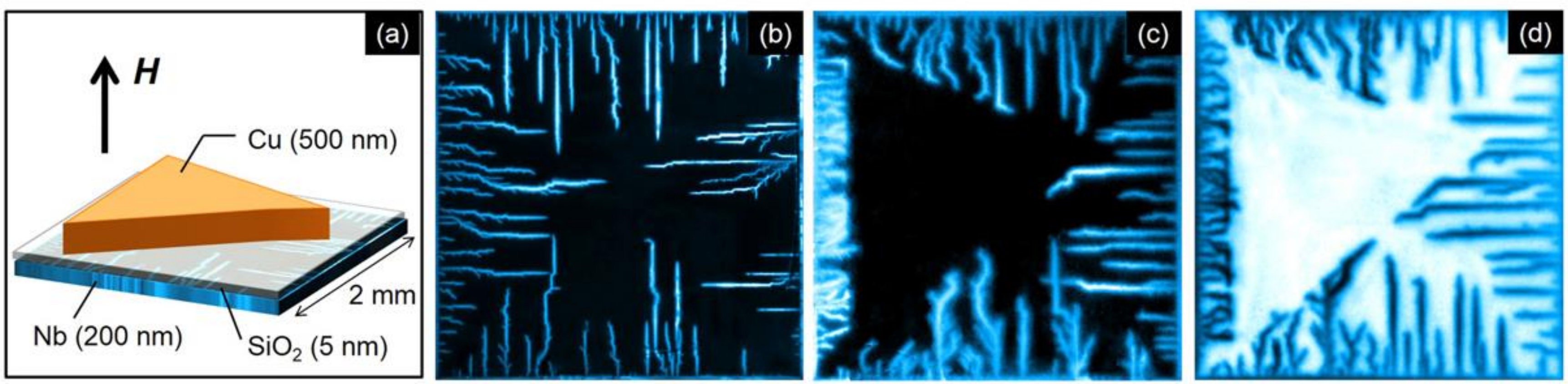
Primary motivation: flux avalanches in the presence of obstacles

New Journal of Physics
The open access journal at the forefront of physics

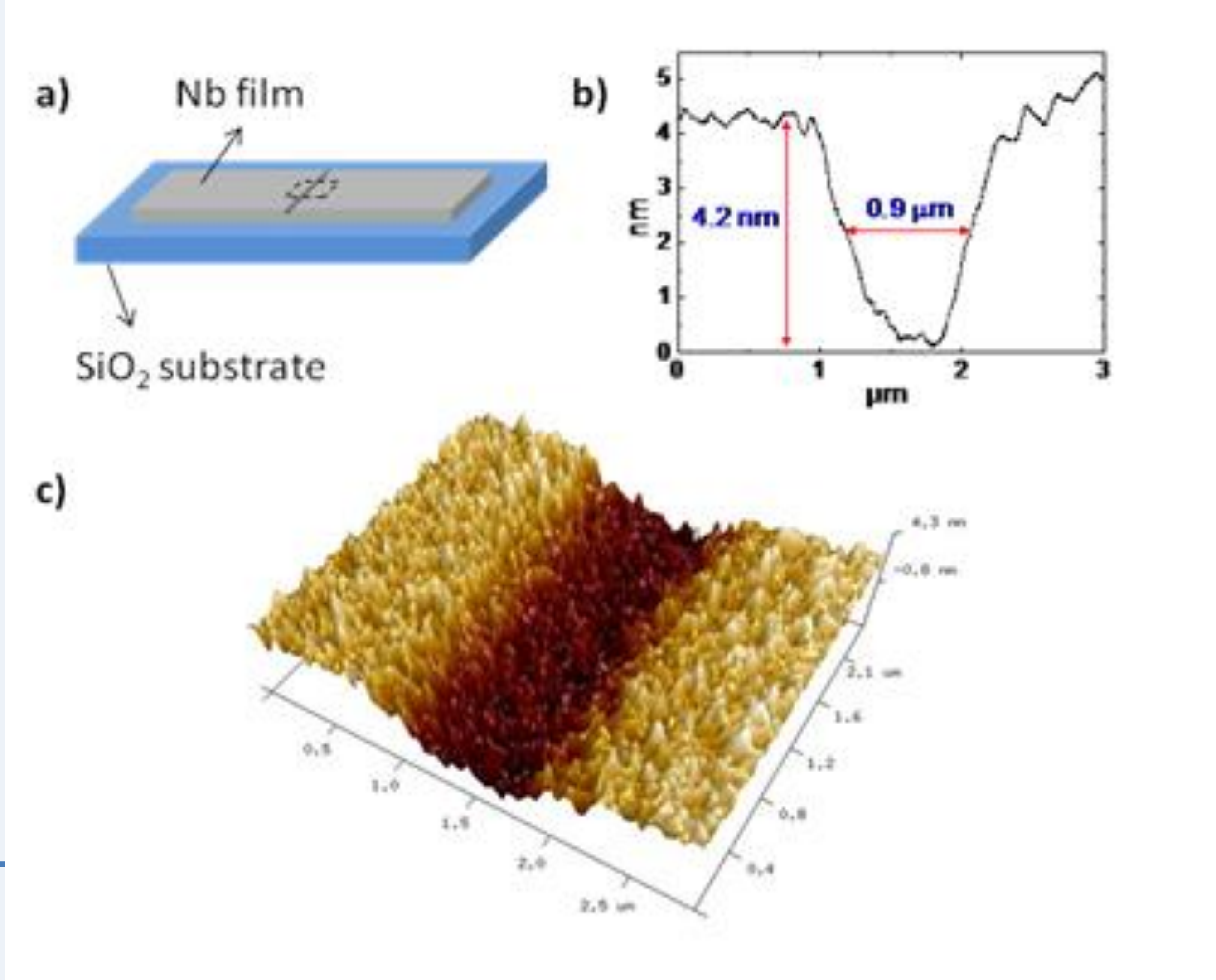
Classical analogy for the deflection of flux avalanches by a metallic layer

J Brisbois[1], B Vanderheyden[2], F Colauto[3], M Motta[3], W A Ortiz[3], J Fritzsche[4], N D Nguyen[1], B Hackens[5], O-A Adami[1] and A V Silhanek[1]

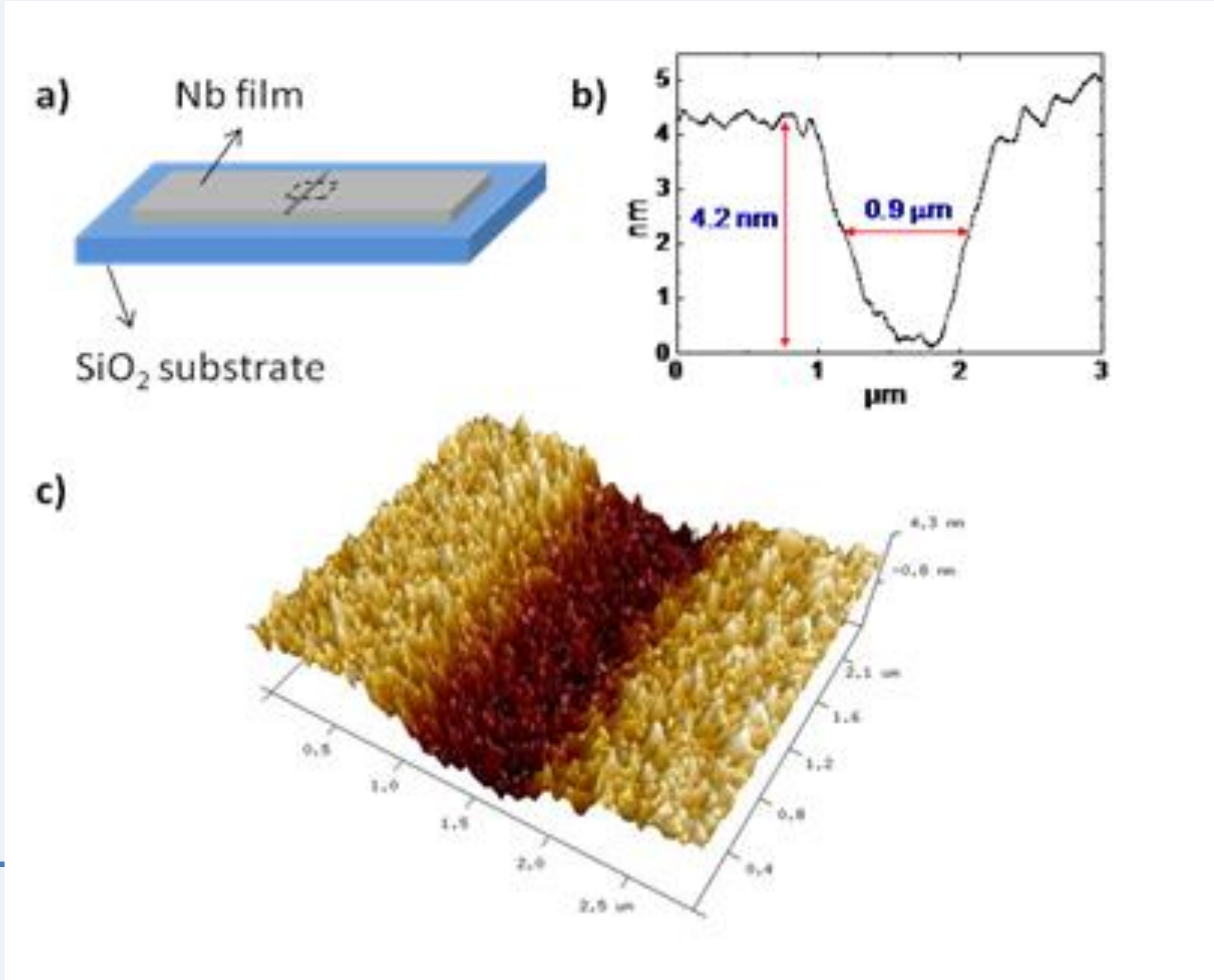
New J. Phys. **16** (2014) 103003 J Brisbois *et al*



A shallow valley in the middle of a superconducting film



Joint: 2 grains linked by a constriction (with or without a SC frame)



- Building pieces for Granular SCs (HTCS) as well as for Large Applications (big pieces joined);

- MOI is powerful tool, but maps the vicinity of the surface (not the volume) [besides, not every lab has access to imaging];

➔ Using thin films, we developed a method to determine Transparency using MMs (assisted by MOI).

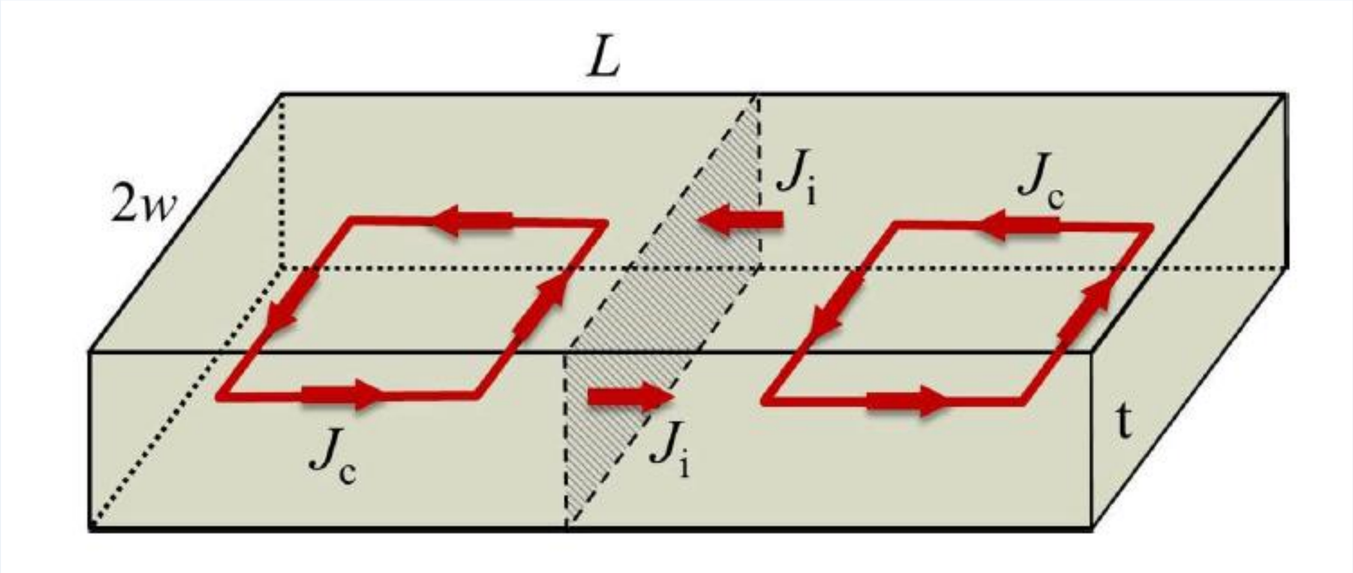
- Transparency of a joint

- Transparency and magnetic moment (critical-state)

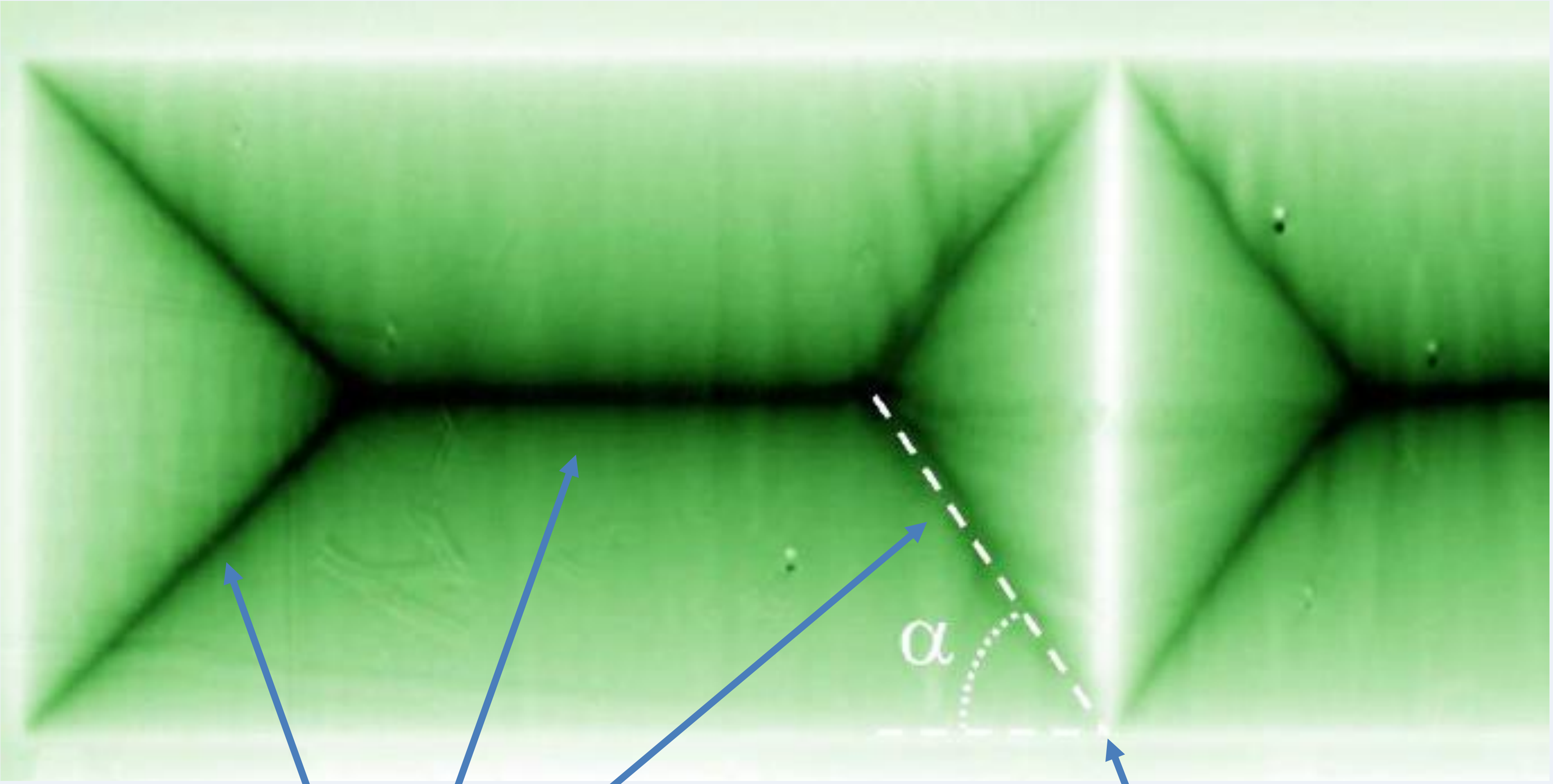
- Anomalous hysteresis loop of unprotected joints

Transparency of a joint

$$\tau \equiv \frac{J_i}{J_c}$$



200 nm thick Nb film with WL

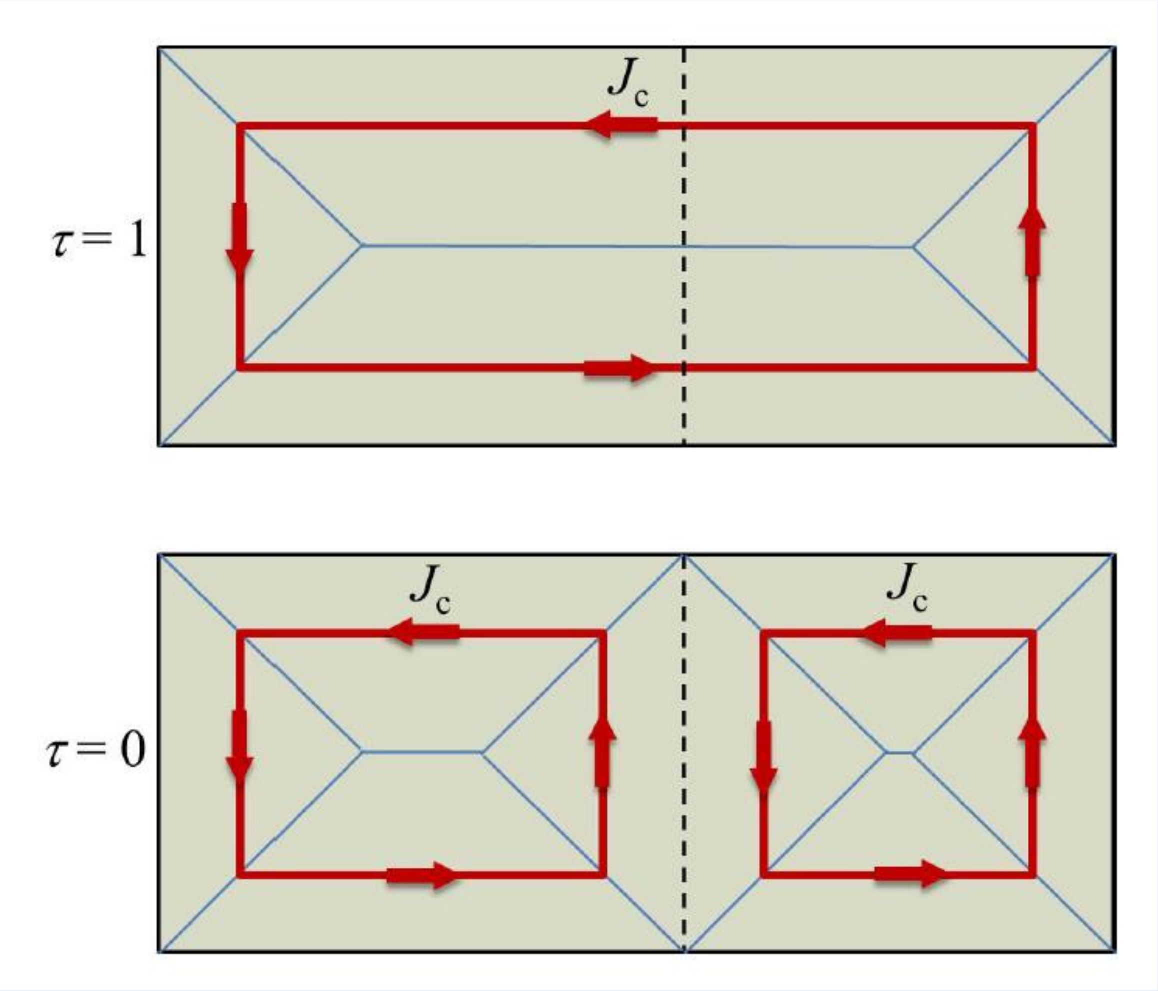


d-lines

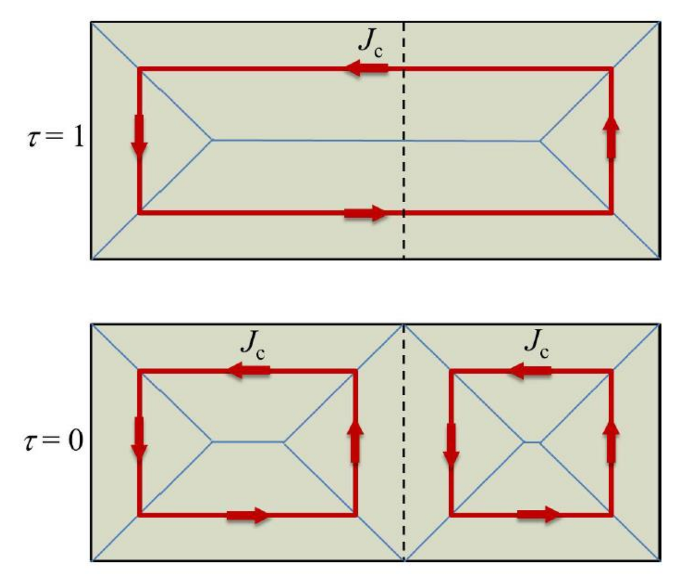
WL (FIB)

Critical-state analysis ➔ transparency and magnetic moment

$$\tau \equiv \frac{J_i}{J_c}$$



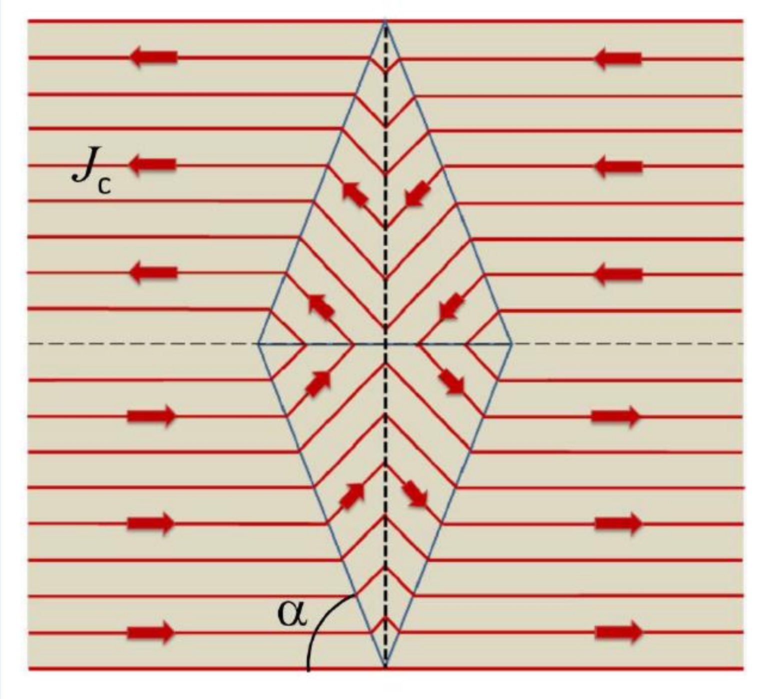
$$m(\tau = 1) = J_c t w^2 L \left(1 - \frac{2w}{3L}\right)$$



$$m(\tau = 0) = J_c t w^2 L \left(1 - \frac{4w}{3L}\right)$$

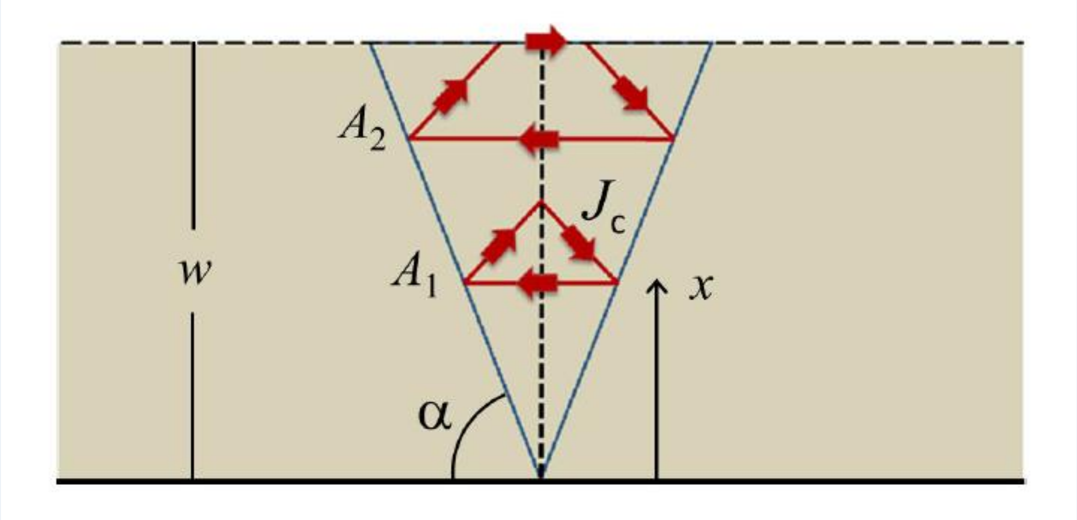
$$m(\tau) = J_c t w^2 L \left(1 - \frac{2w}{3L} f(\tau)\right)$$

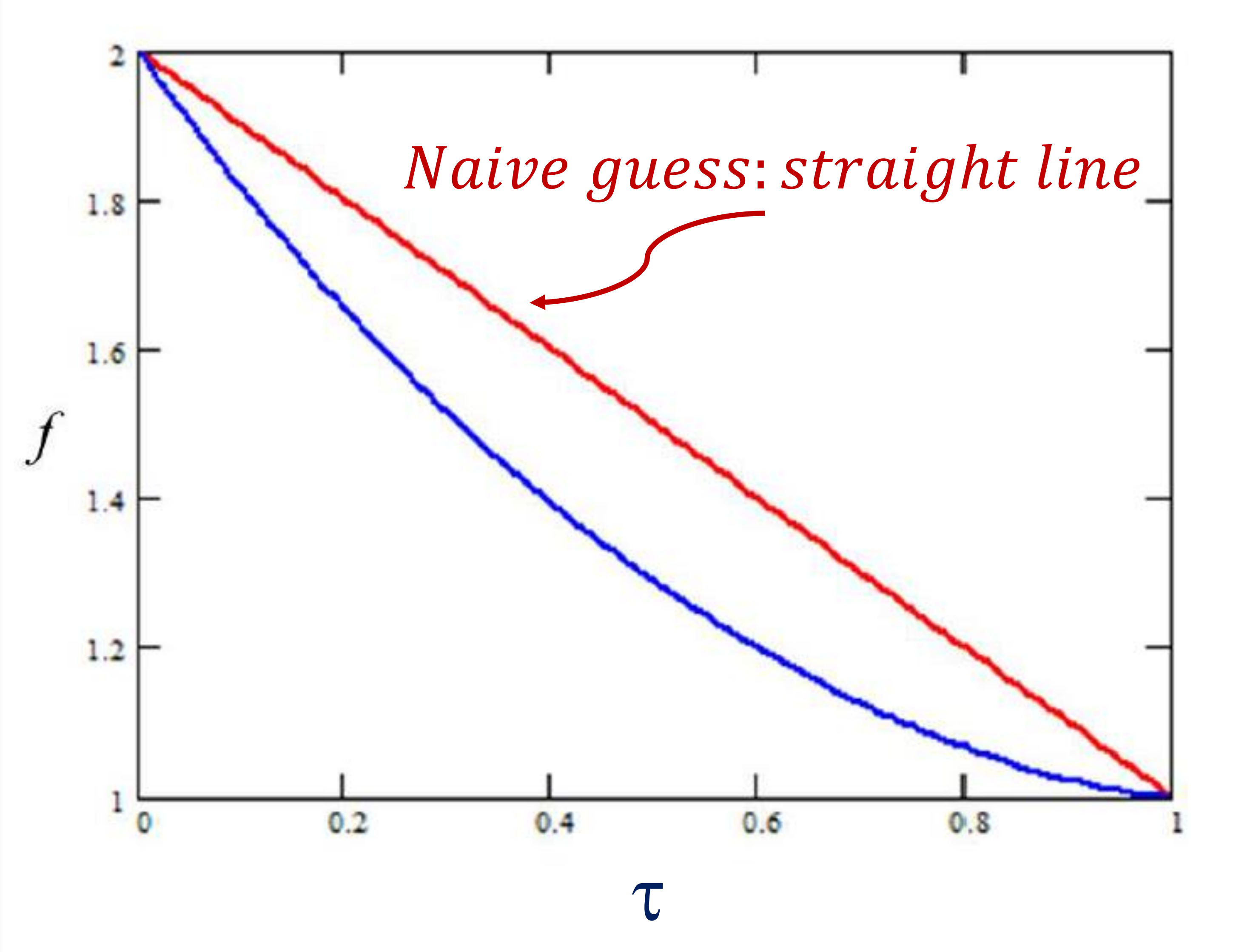
$$f(0) = 2; f(1) = 1$$



$$-\cos 2\alpha = \tau.$$

$$f(\tau) = 1 + \frac{1-\tau}{1+\tau}\sqrt{1-\tau^2}$$

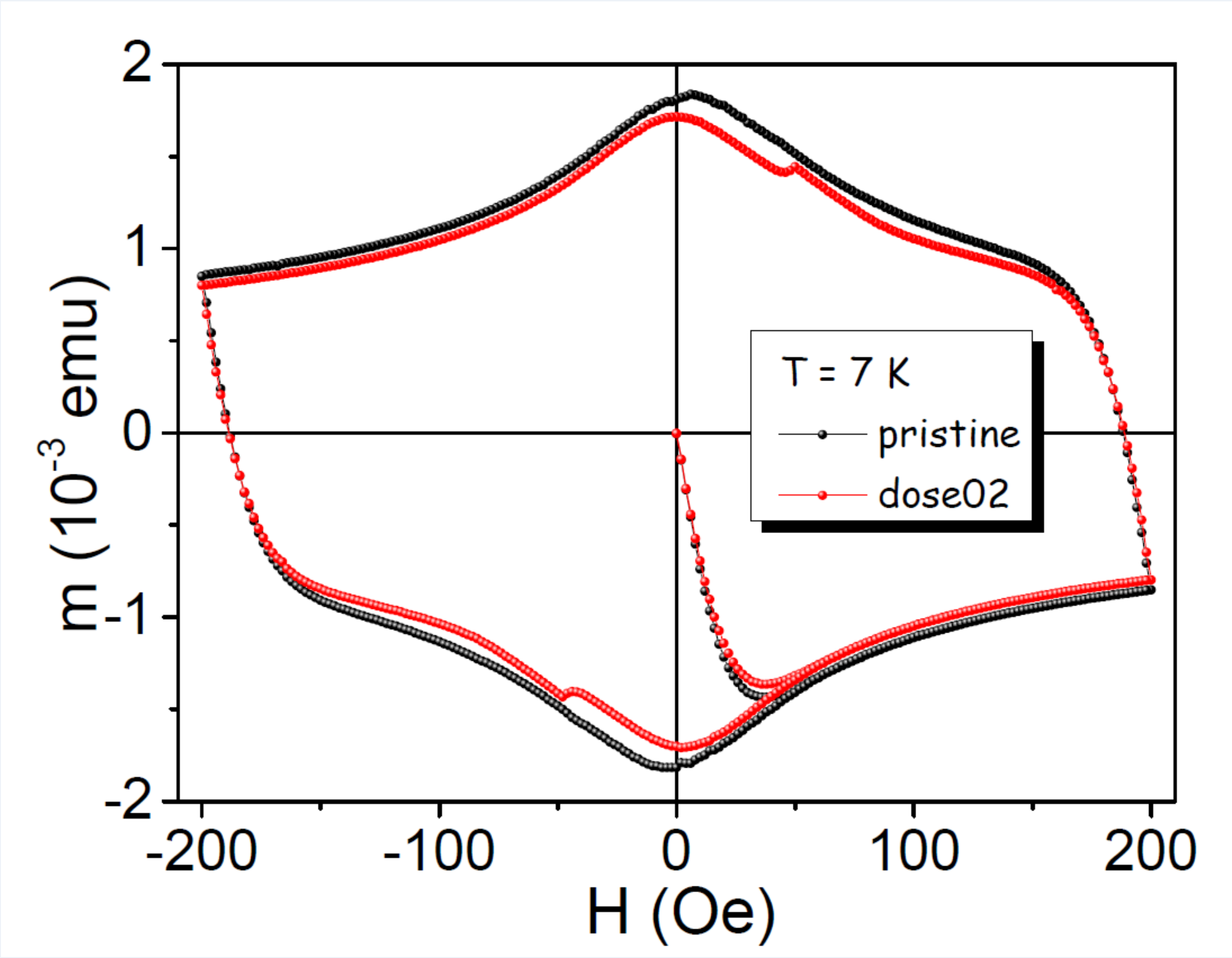


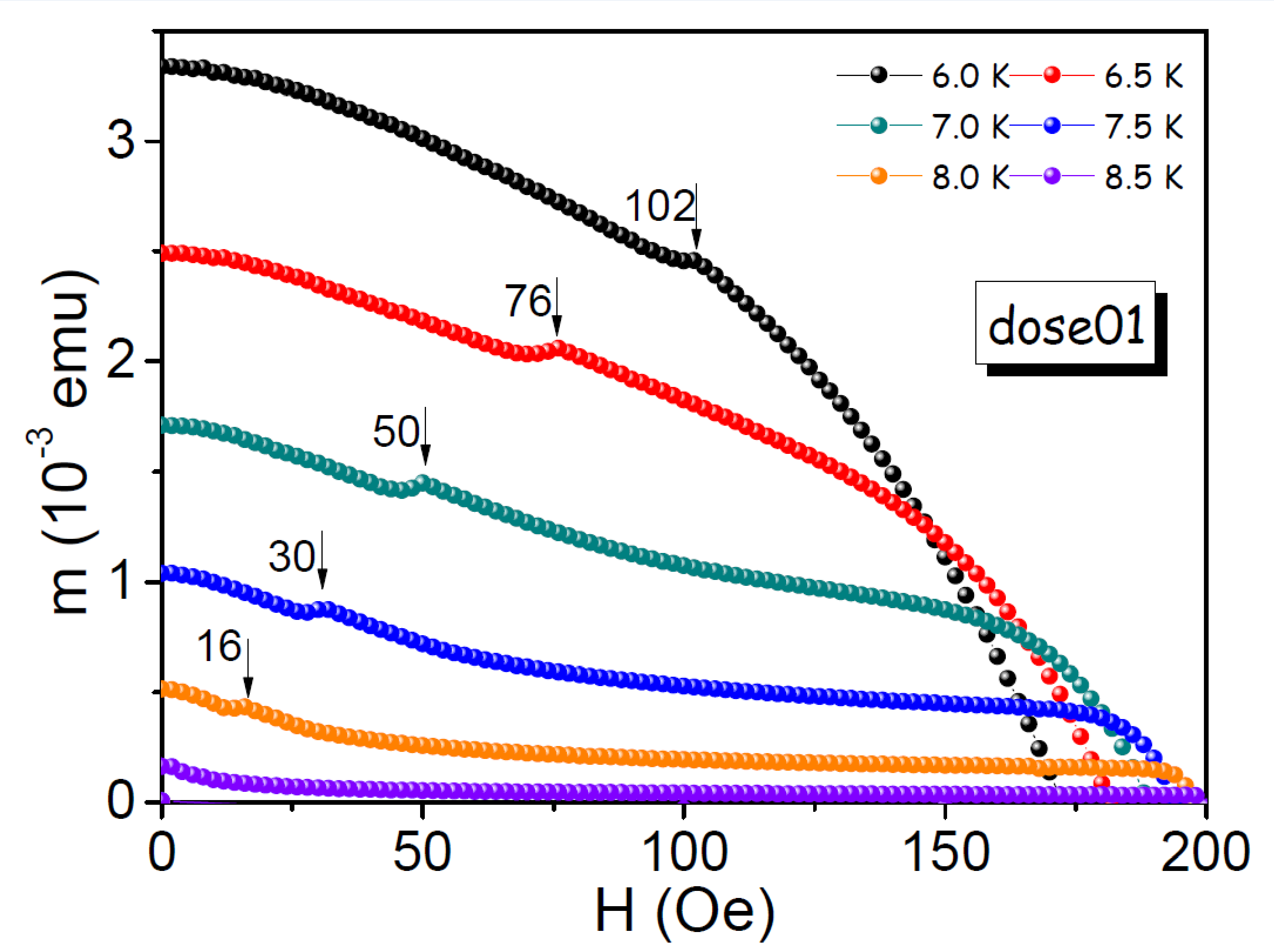


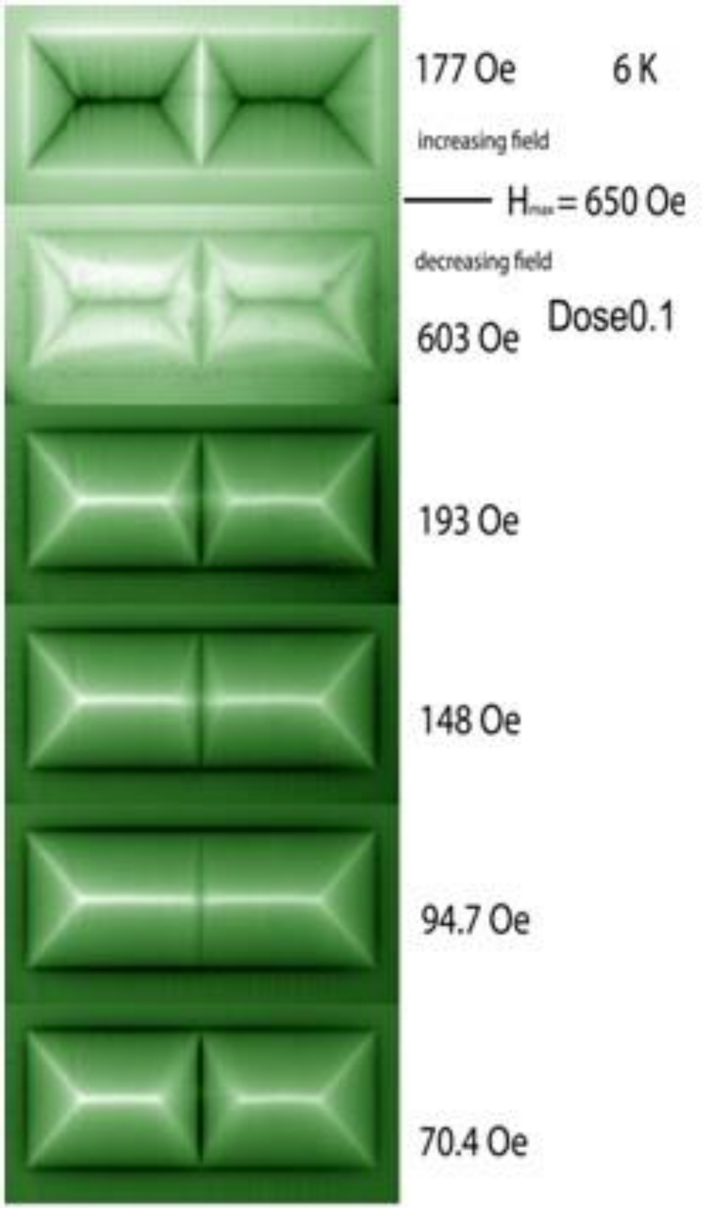
Naive guess: straight line
2
1.8
1.6
1.4
1.2
1
0
0.2
0.4
0.6
0.8
1
f
τ

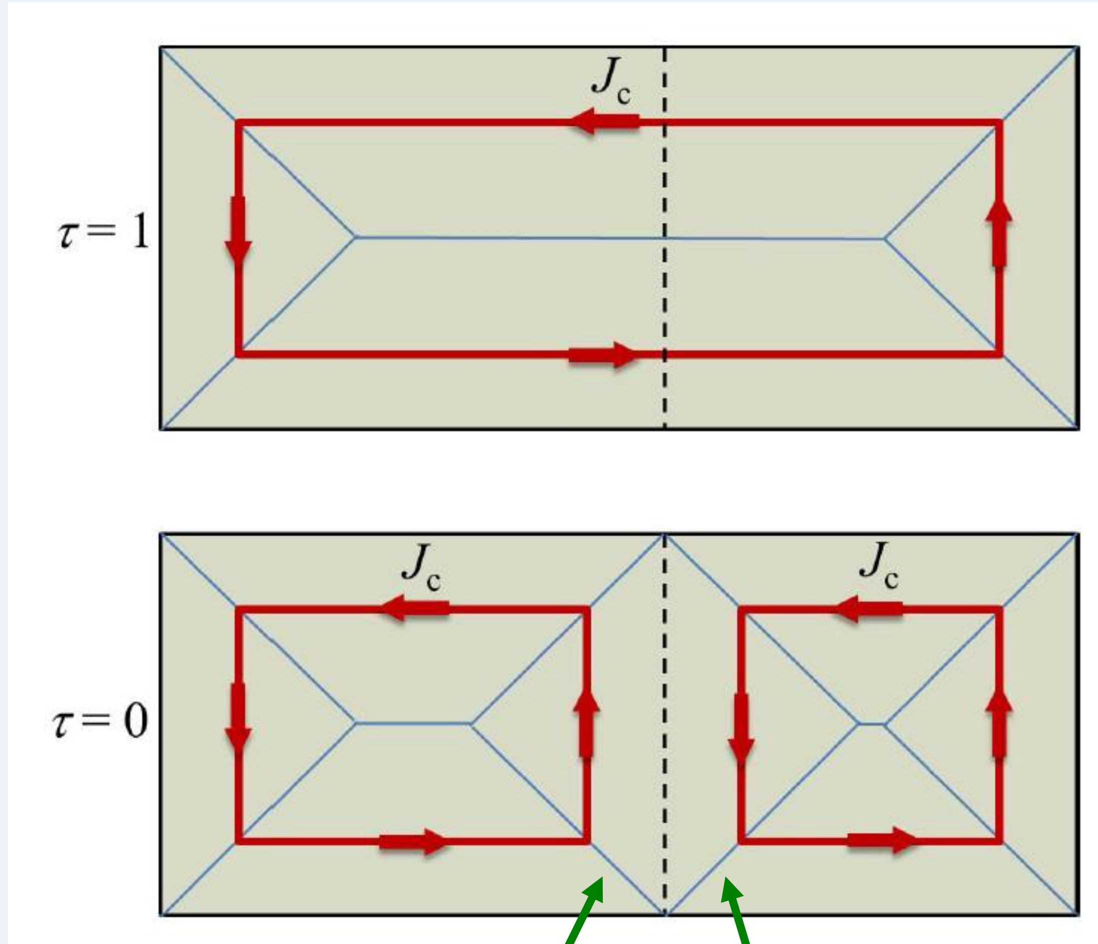
Anomalous hysteresis loop for unprotected joint

(pristine and protected joints give equal loops)



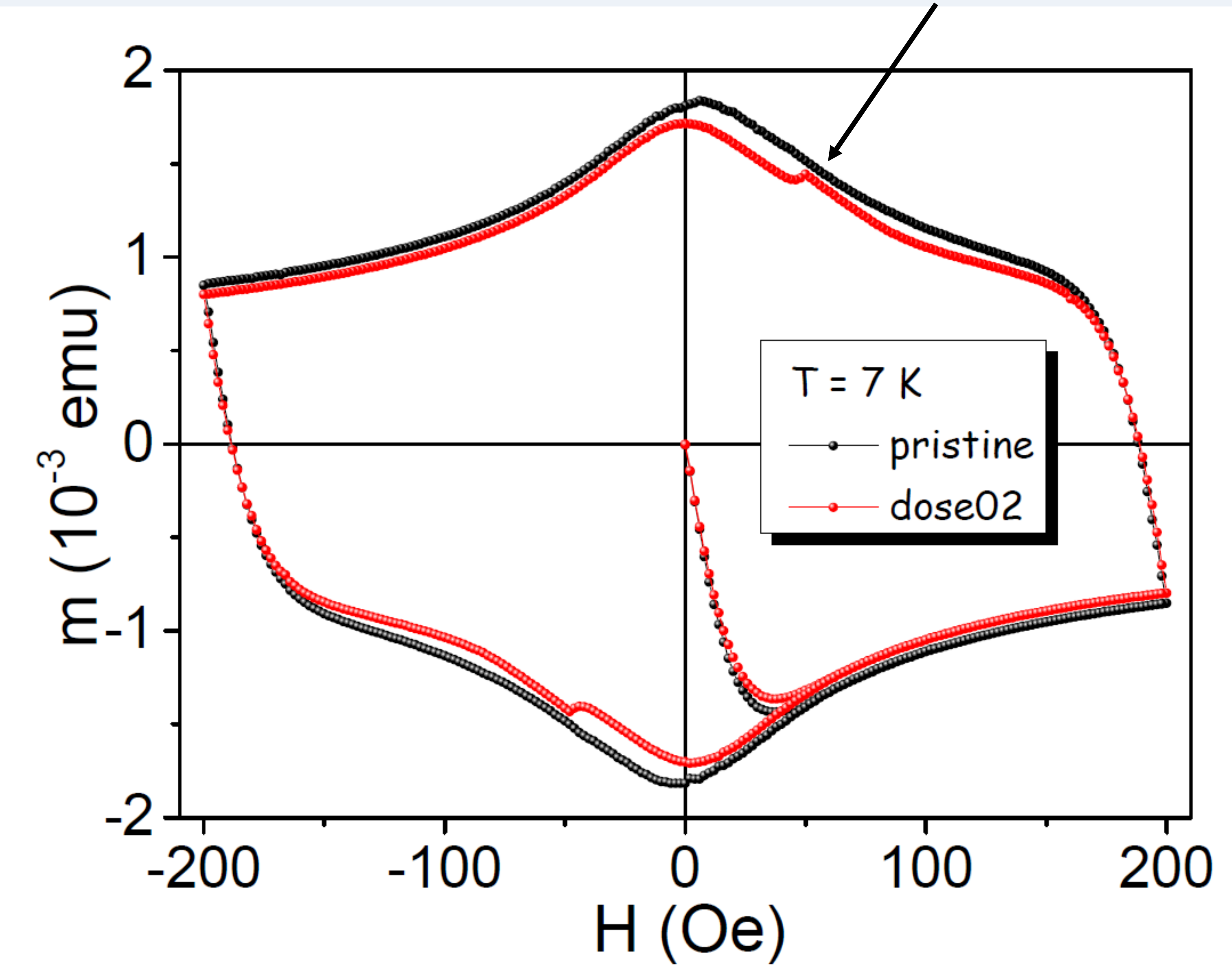

6.0 K
6.5 K
7.0 K
7.5 K
8.0 K
8.5 K
dose01
102
76
50
30
16
m (10^-3 emu)
H (Oe)
0
1
2
3
0
50
100
150
200


177 Oe
6 K
increasing field
H_max = 650 Oe
decreasing field
603 Oe
Dose0.1
193 Oe
148 Oe
94.7 Oe
70.4 Oe

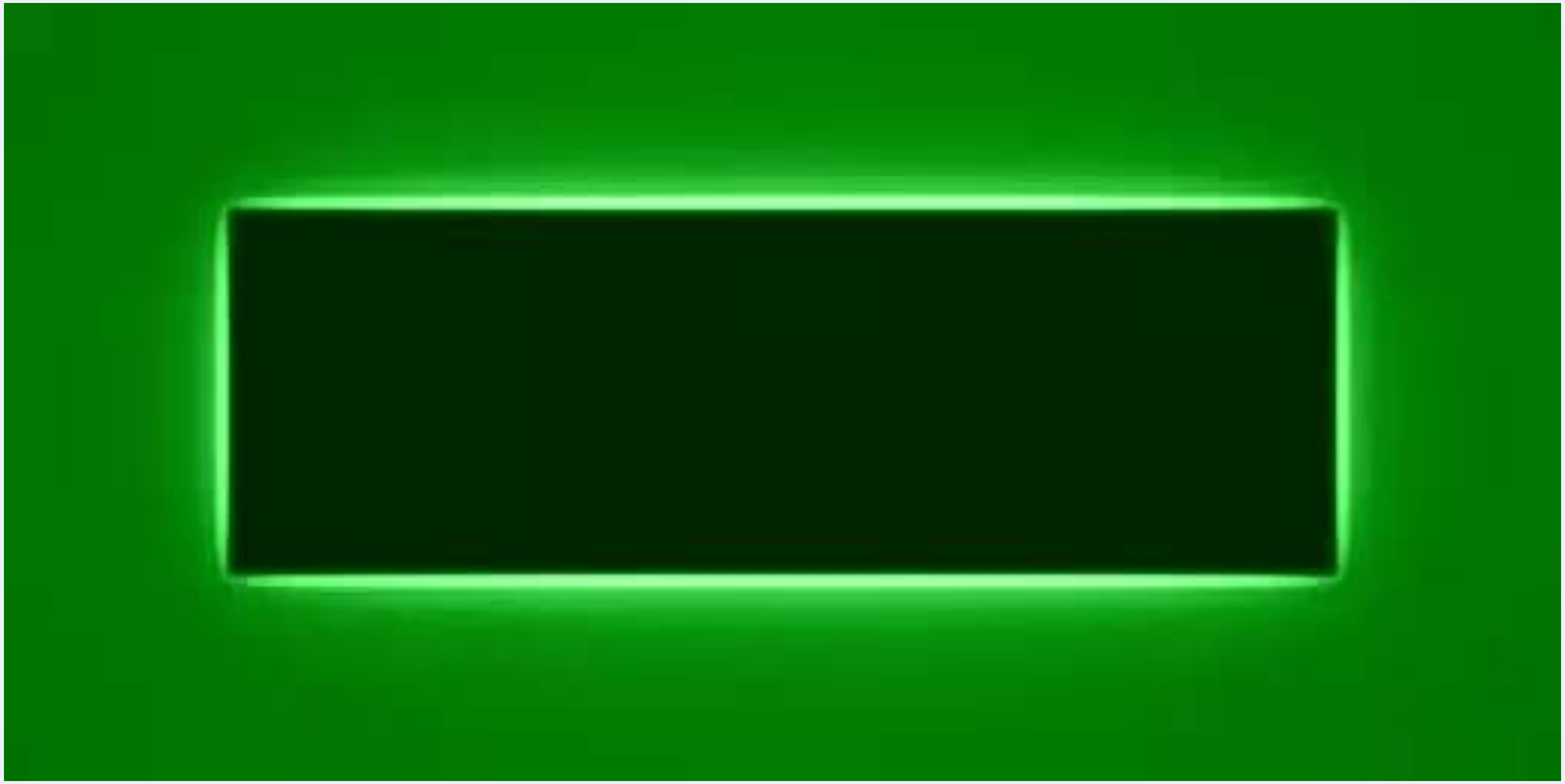

J_c
$\tau = 1$
J_c
J_c
$\tau = 0$

d-lines

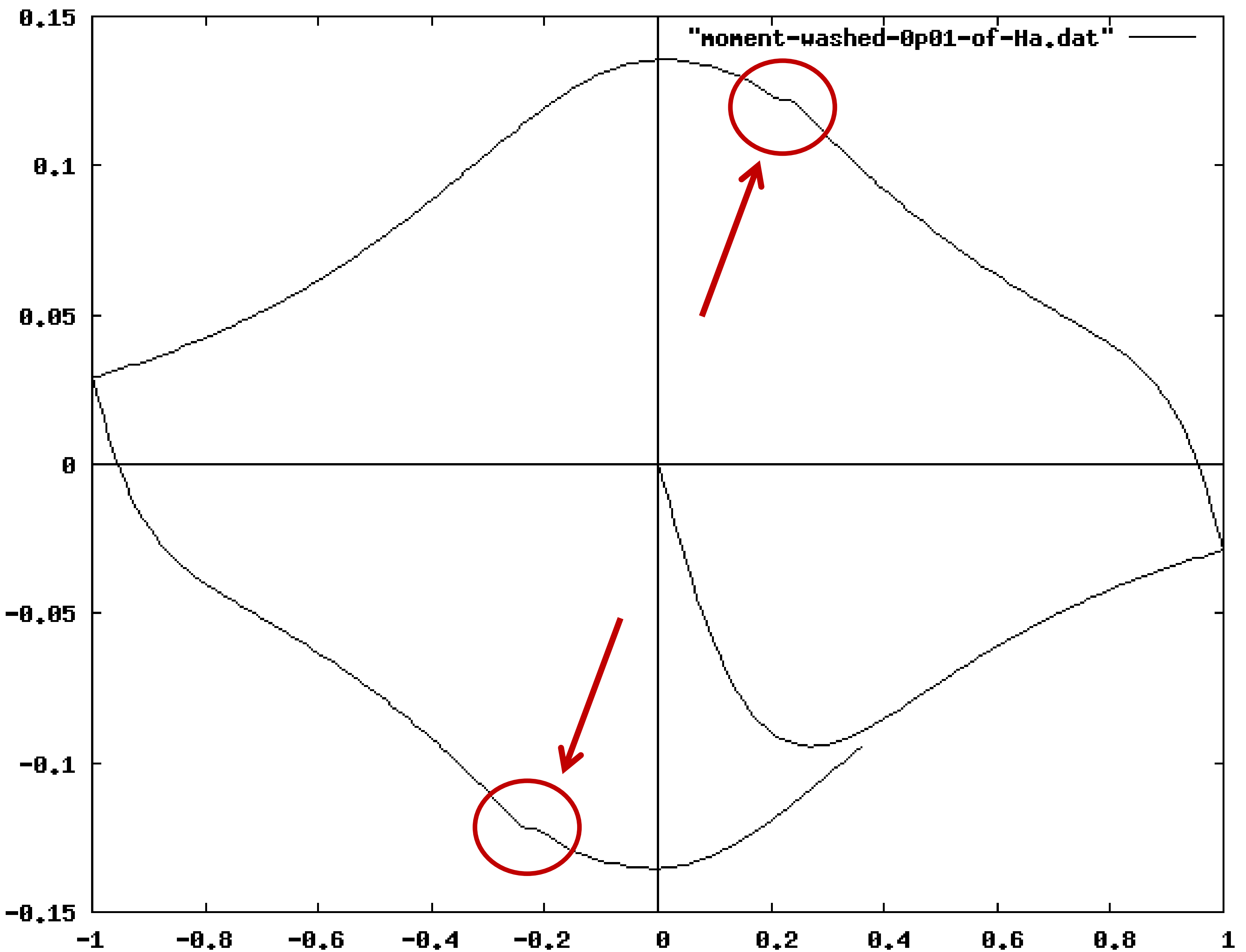
$\tau \sim 1$



Field-dependent J_c is needed to get the fading out of the d-lines



$$J_c(B_z) = J_{c0} e^{-\frac{B_z}{B_0}}; \; B_0 = 0.5\mu_0 J_{c0}$$


"moment-washed-0p01-of-Ha.dat"
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

22 July 2015

Controlling flux avalanches in superconducting films: choosing where and when

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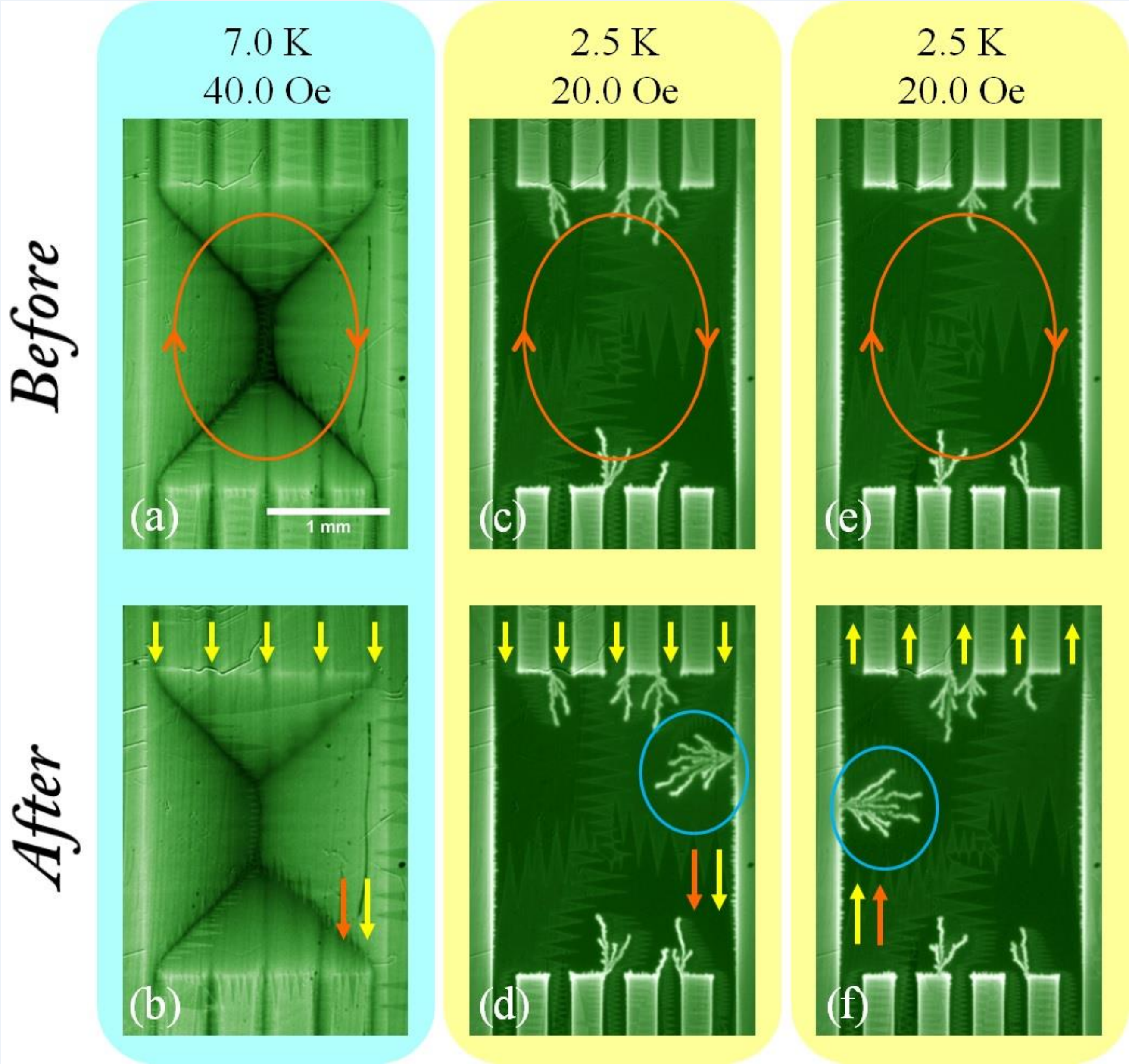
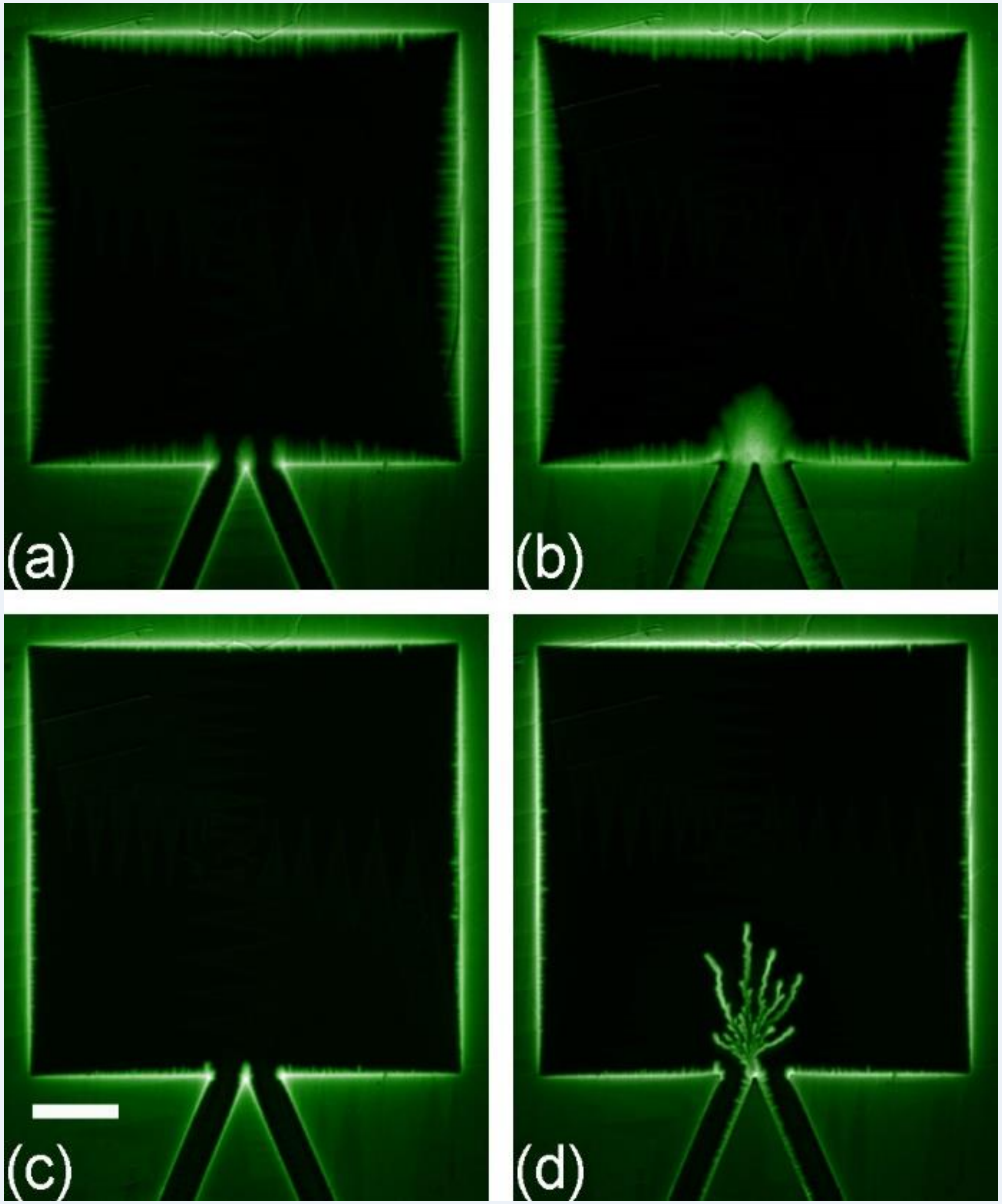
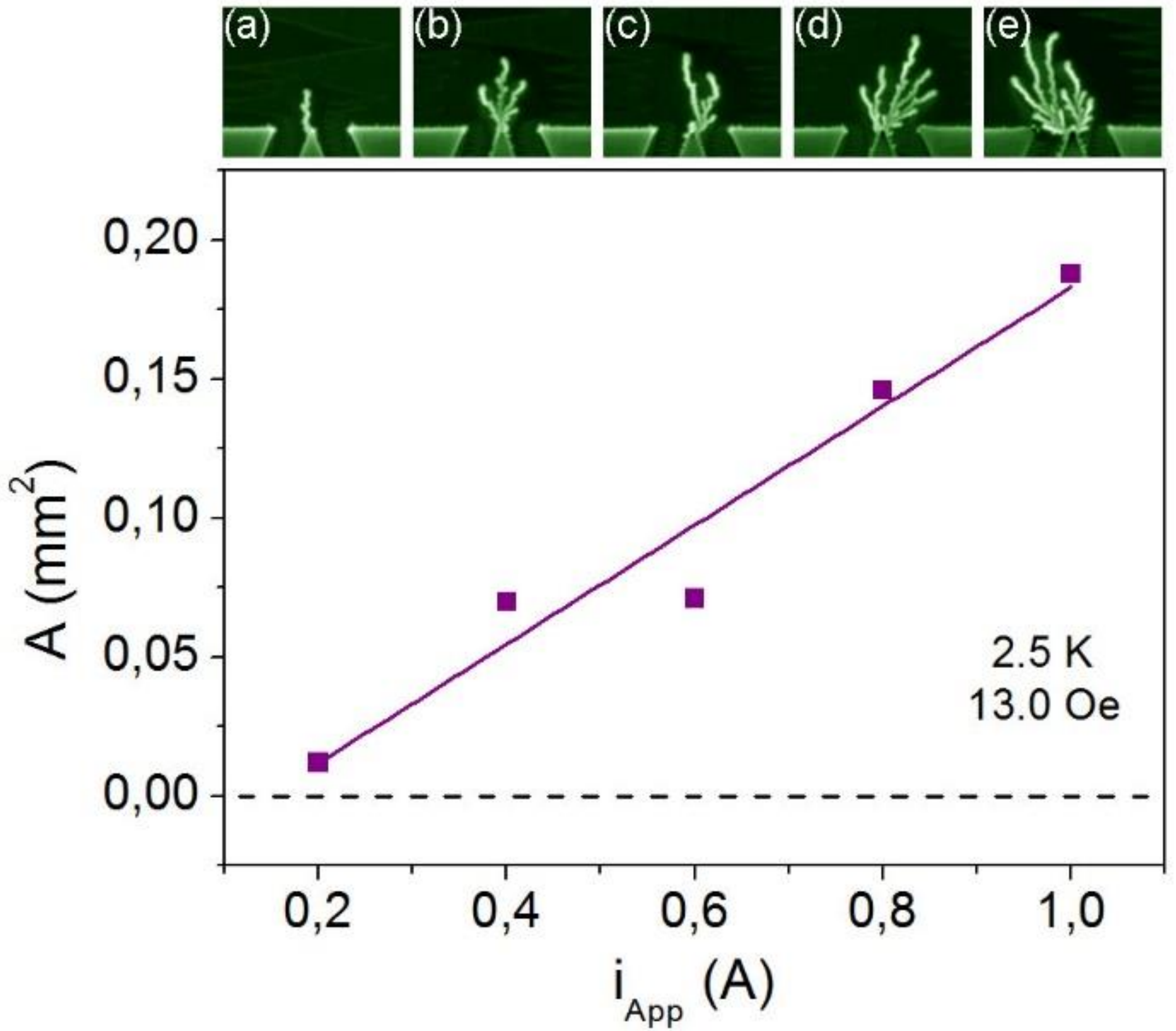
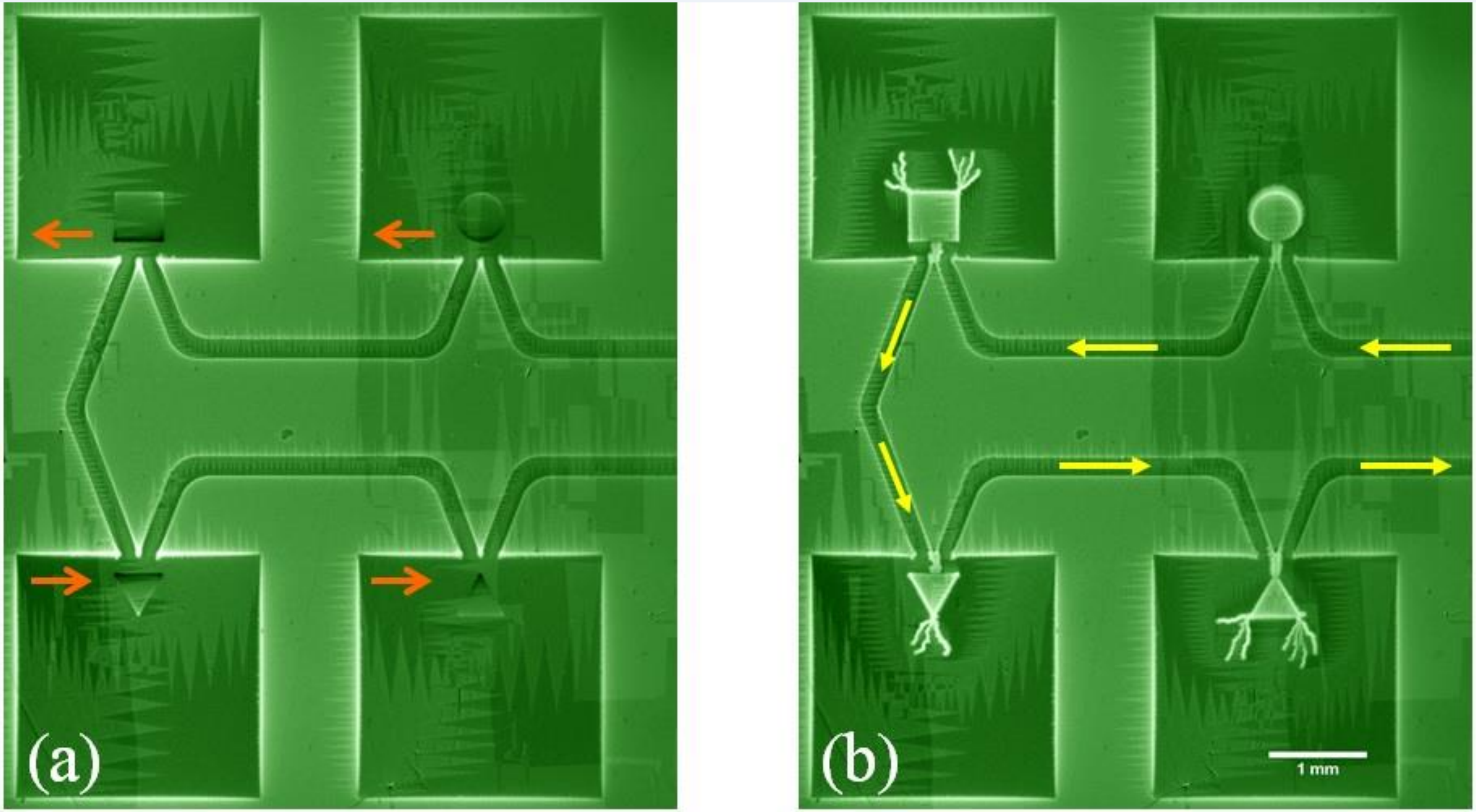
Tom Henning Johansen
Oslo, Norway


7.0 K
40.0 Oe
2.5 K
20.0 Oe
2.5 K
20.0 Oe
Before
After
(a)
1 mm
(b)
(c)
(d)
(e)
(f)


(a)
(b)
(c)
(d)



(a)
(b)
(c)
(d)
(e)
0,20
0,15
0,10
0,05
0,00
A (mm^2)
2.5 K
13.0 Oe
0,2
0,4
0,6
0,8
1,0
i_{App} (A)


(a)
(b)
1 mm