The Abdus Salam
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Educational, Scientific
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Energy Agency

SMR.1766 - 6

**Miniworkshop on
New States of Stable and Unstable Quantum Matter
(14 - 25 August 2006)**

Interplay between Superconductivity and Magnetism in Nanoengineered Superconductor/ Ferromagnet Hybrids

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LEUVEN

Interplay between Superconductivity and Magnetism in Nanoengineered Superconductor/Ferromagnet Hybrids

Victor V. Moshchalkov

In collaboration with:

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A. Aladyshkin, W. Gillijns, K. Vervaeke

INPAC-Institute for Nanoscale Physics and Chemistry,
Nanoscale Superconductivity and Magnetism Group,
University of Leuven, Belgium

Outline

- Introduction
- Magnetic templates for superconductivity
- Magnetic dots for vortex pinning and field compensation
- Magnetic dots for phase shifting
- Domain wall superconductivity in Superconductor/Ferromagnet hybrids
- Conclusion

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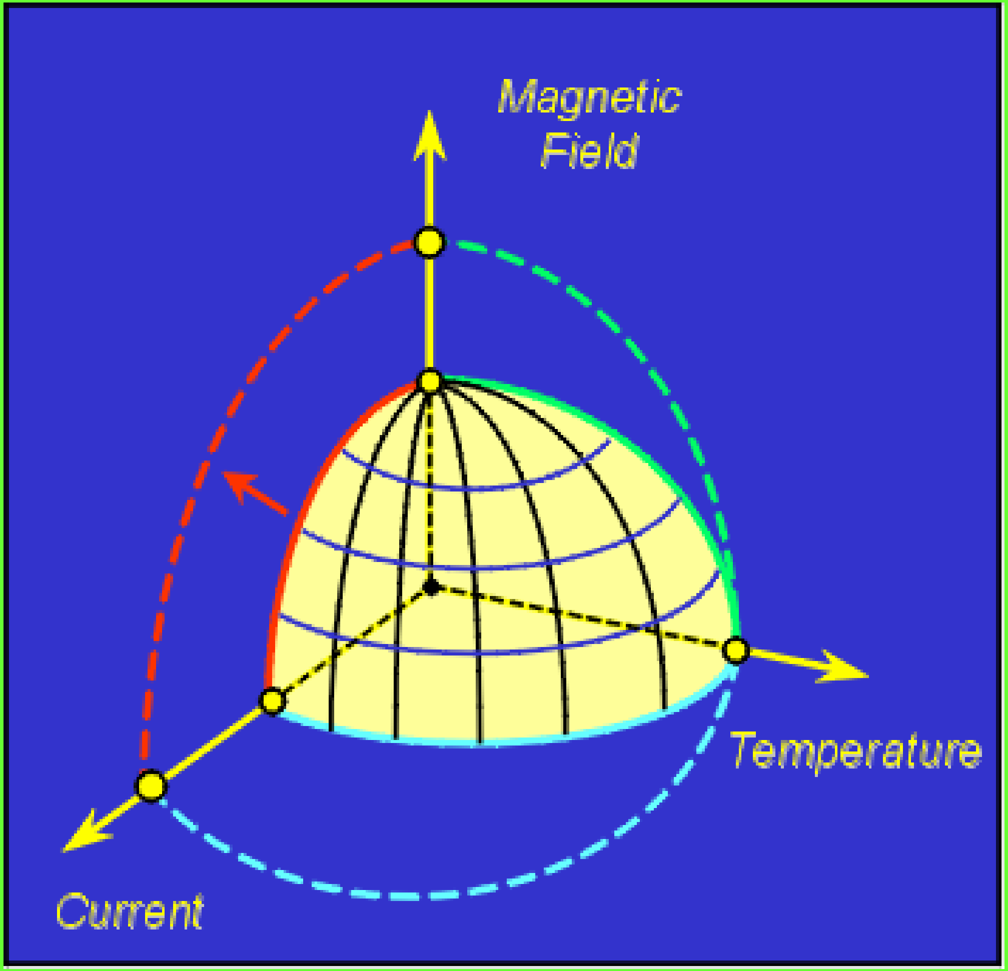
Introduction

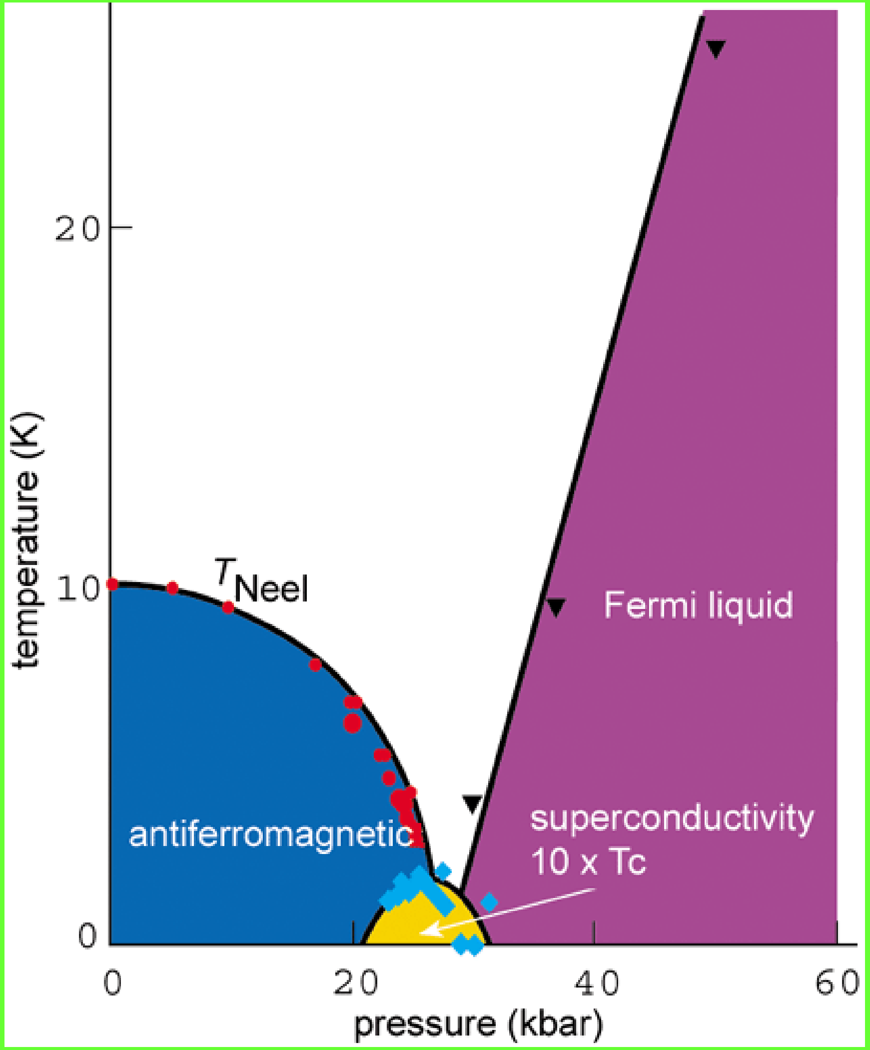


Local fields of nanomagnets for superconductivity:

Destructive or constructive?

Homogeneous vs inhomogeneous ?

First experiments on AF-S (QCP): already in 1982:

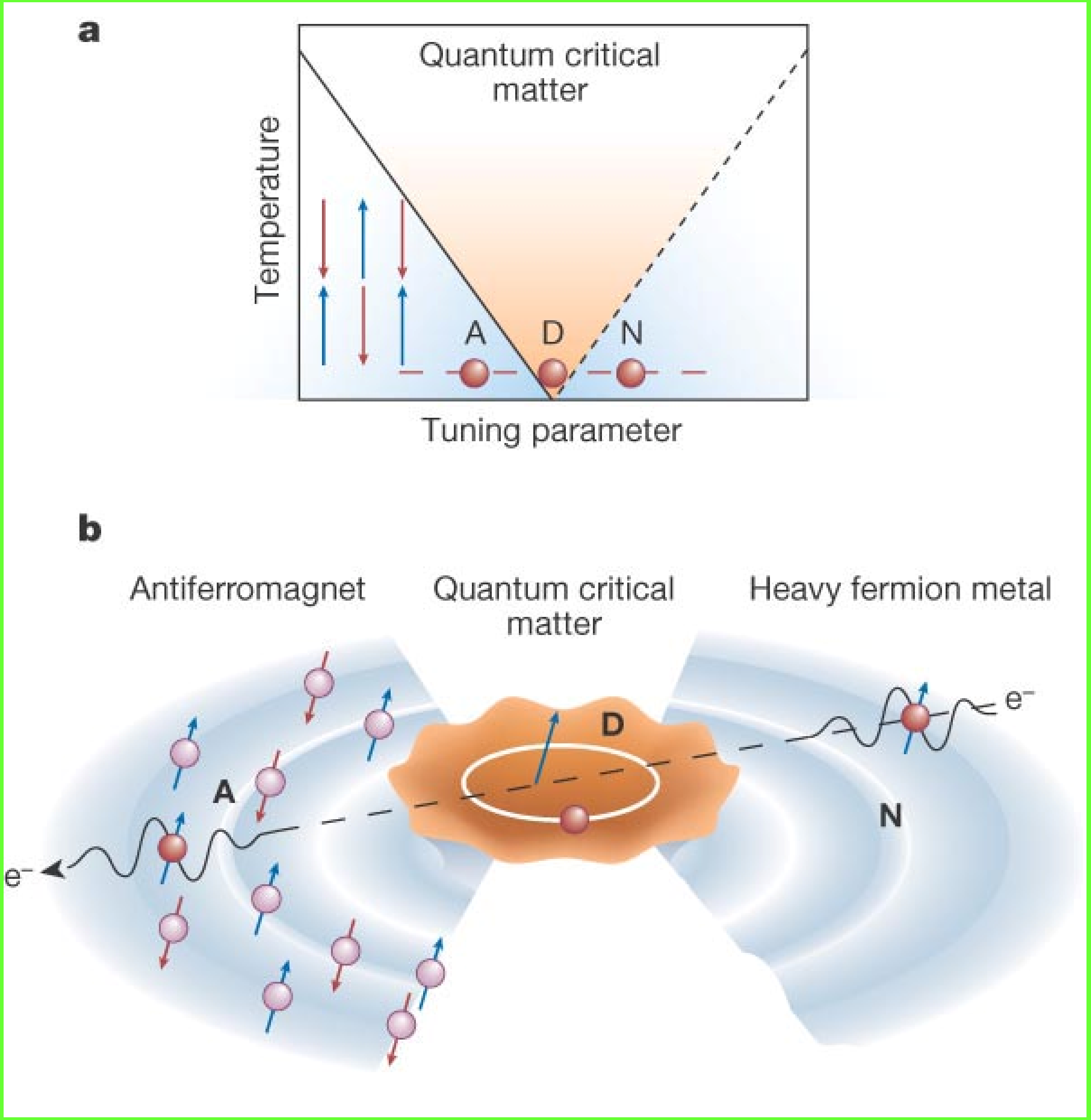


ALIEV FG, BRANDT NB, **MOSHCHALKOV VV**, et al.
PRESSURE TO 140 KBAR EFFECT ON ELECTRIC PROPERTIES OF CECU2SI2
FIZIKA TVERDOGO TELA 24 (10): 3151-3154

1982

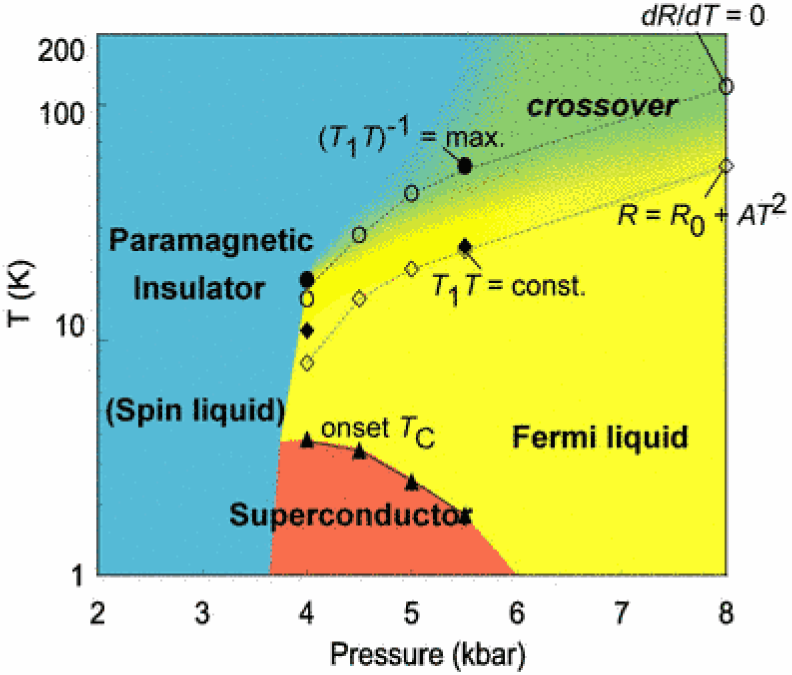
- **ALIEV FG**, BRANDT NB, **MOSHCHALKOV VV**, et al.
  SUPERCONDUCTIVITY IN CECU2SI2
  SOLID STATE COMMUNICATIONS 45 (3): 215-218 1983

  ALIEV FG, BRANDT NB, MOSHCHALKOVov VV, et al.
  SUPERCONDUCTIVITY OF CECU2SI2
  JETP LETTERS 35 (10): 539-542 1982

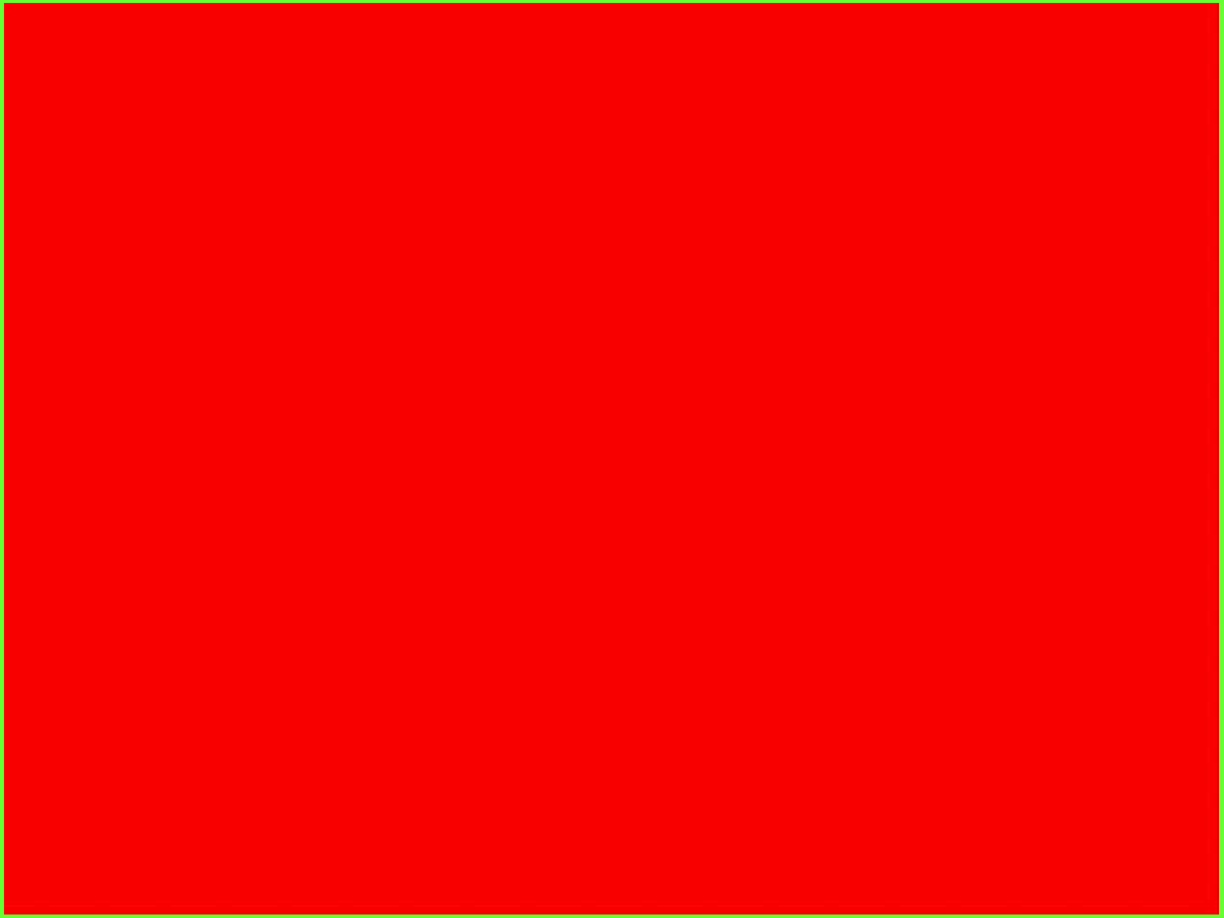


Piers Coleman & Andrew J. Schofield, Nature 2005

Phase diagram of κ-$(ET)_2Cu_2(CN)_3$



Homogeneous



Inhomogeneous

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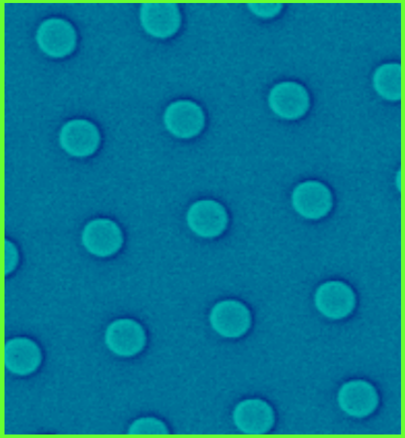
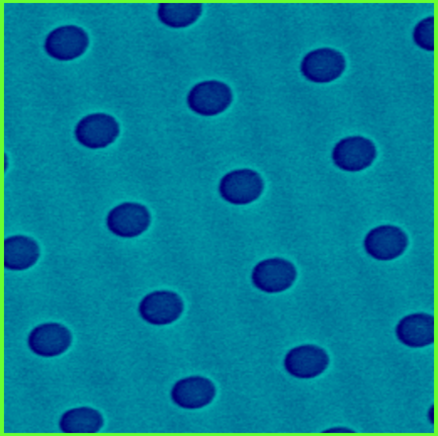
Magnetic force microscopy (MFM)

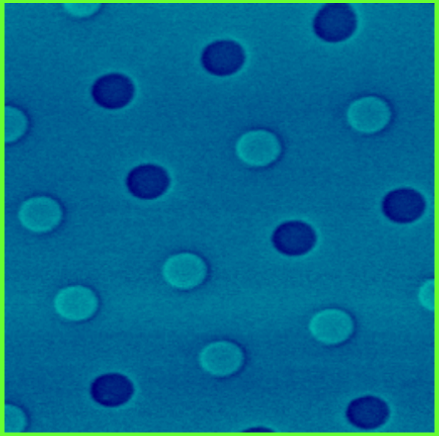
magnetized up



magnetized down

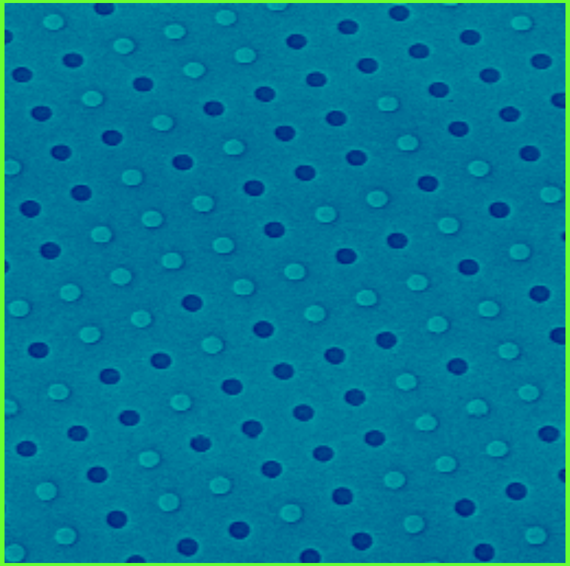


demagnetized

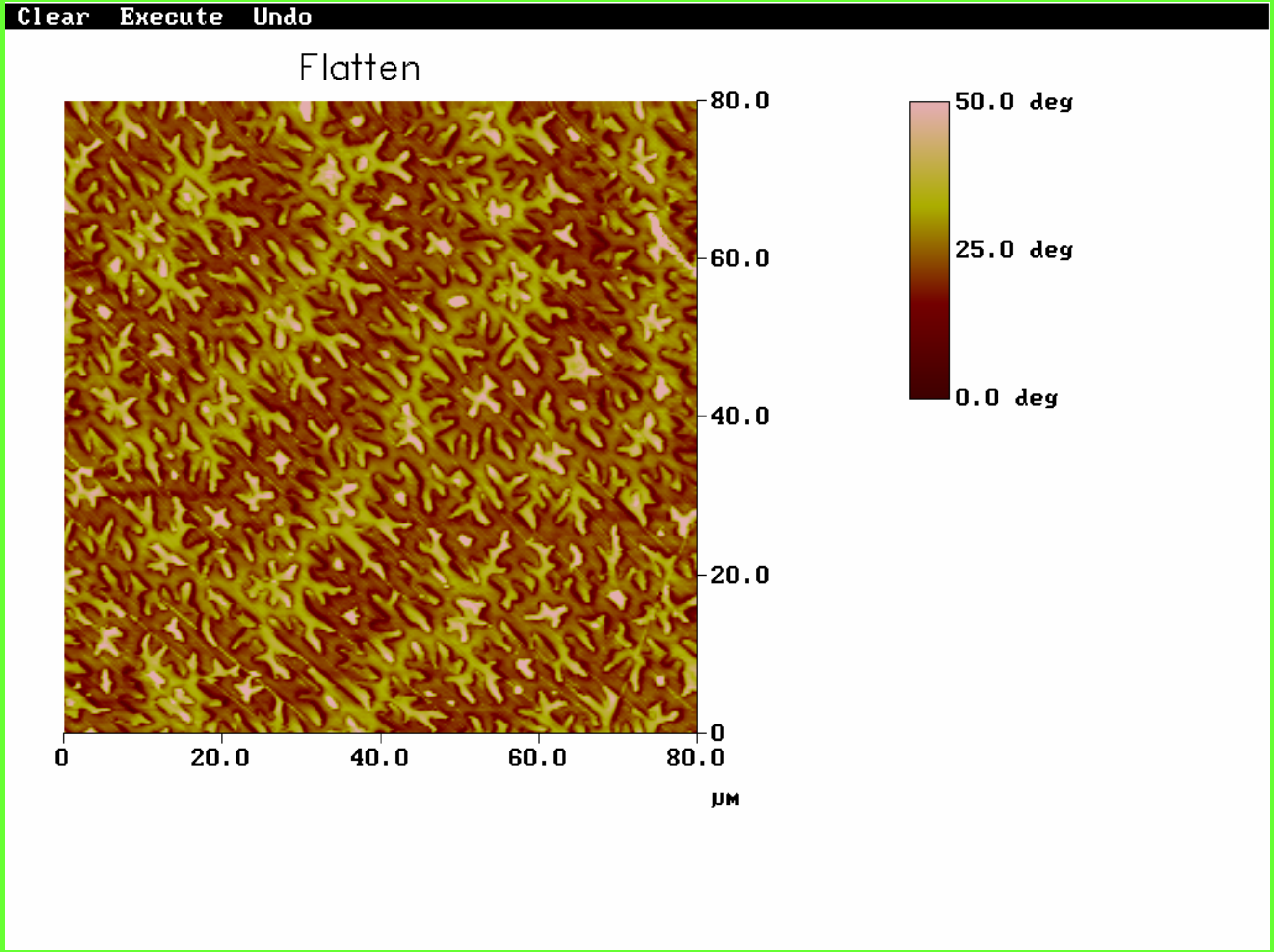


15 x 15 µm² MFM images at
room temperature and H = 0

40 x 40 µm²



Magnetic force microscopy (MFM) @300 K
------*Remanent state*



No evident difference between *demagnetized state* and *remanent state* has been found

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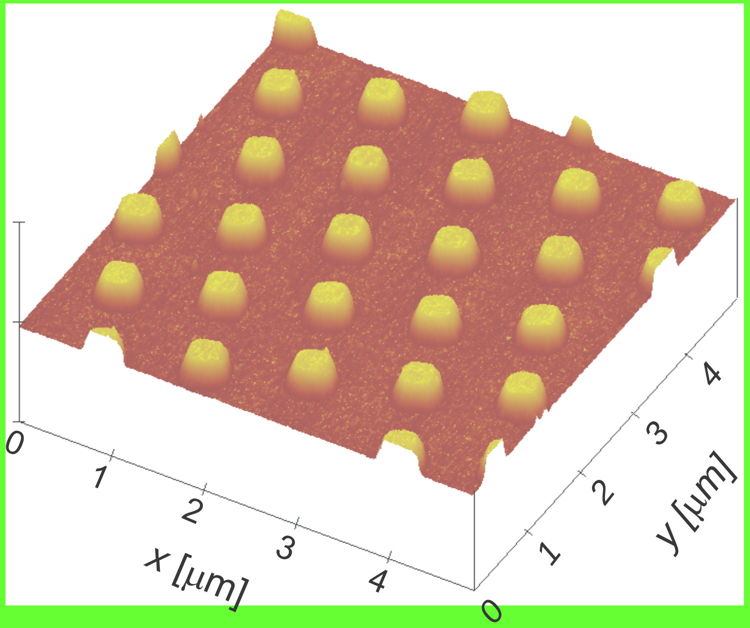
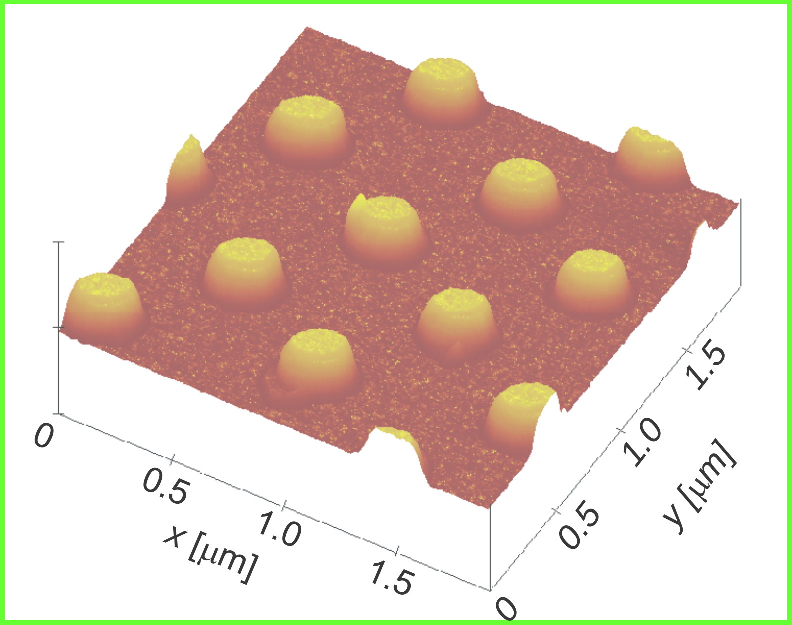
Atomic Force Microscopy

Sample A

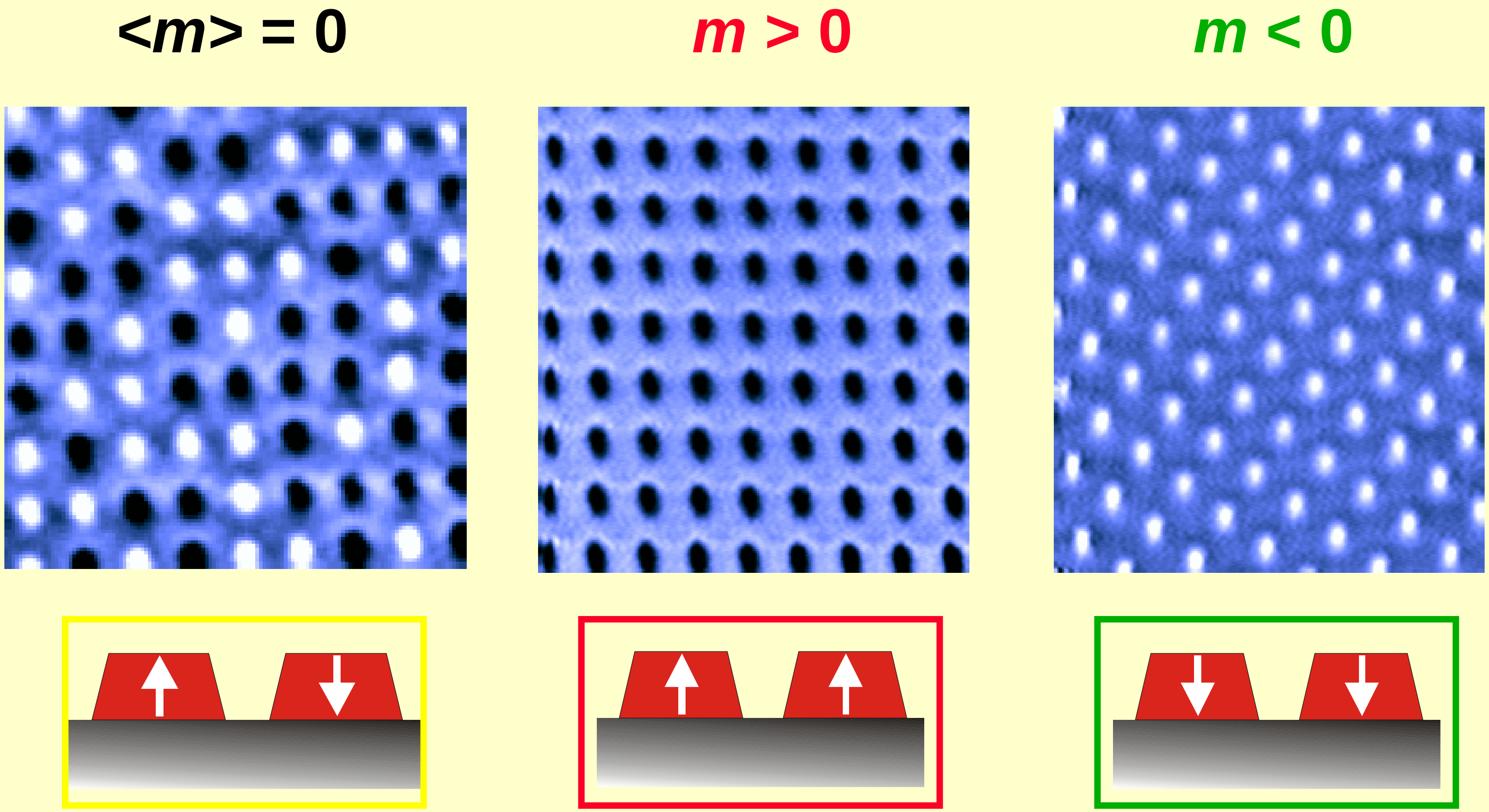


Sample B



Domain structure

5 μm x 5 μm magnetic force microscopy images of small dots at room temperature and $H = 0$



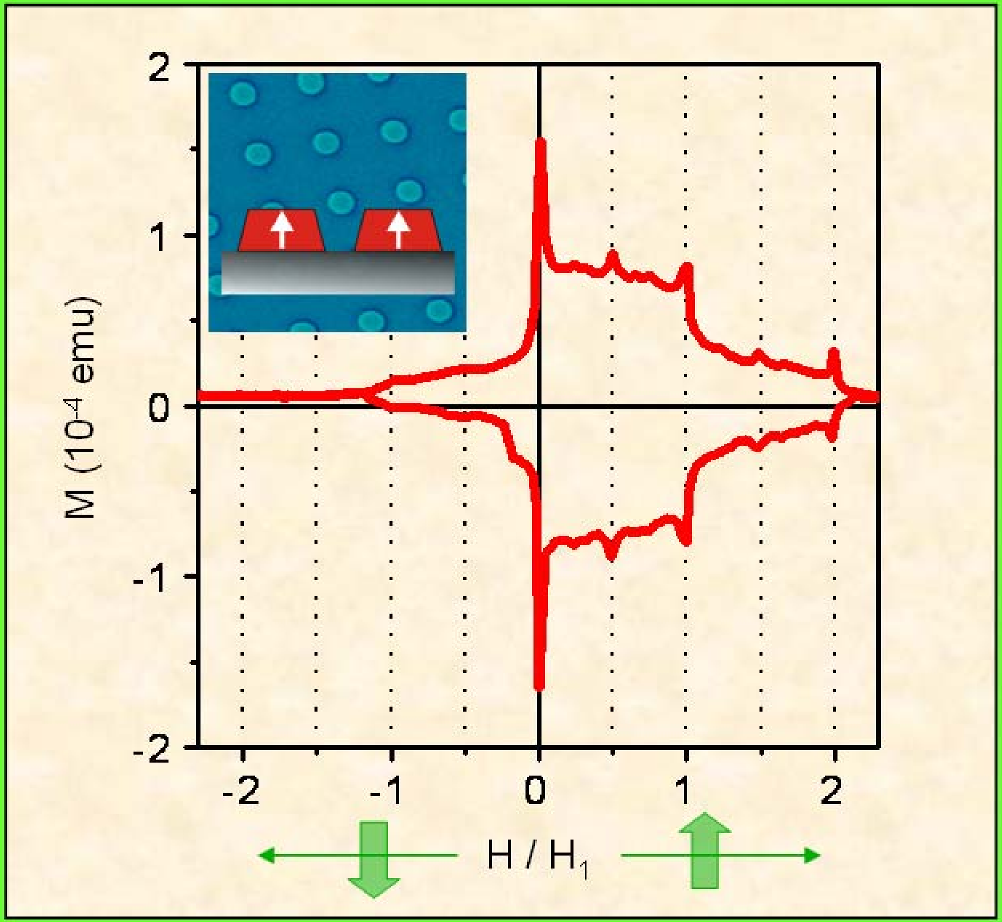
$\langle m \rangle = 0$ $m > 0$ $m < 0$

Vortex pinning by Co/Pt dots

SQUID M(H) loop @ 7.10K

$H_1 = \phi_0 / (1\mu m)^2$
$= 20.68$ Oe

$\Delta M \sim j_C$



Stronger matching peaks and higher j_C at *positive* H

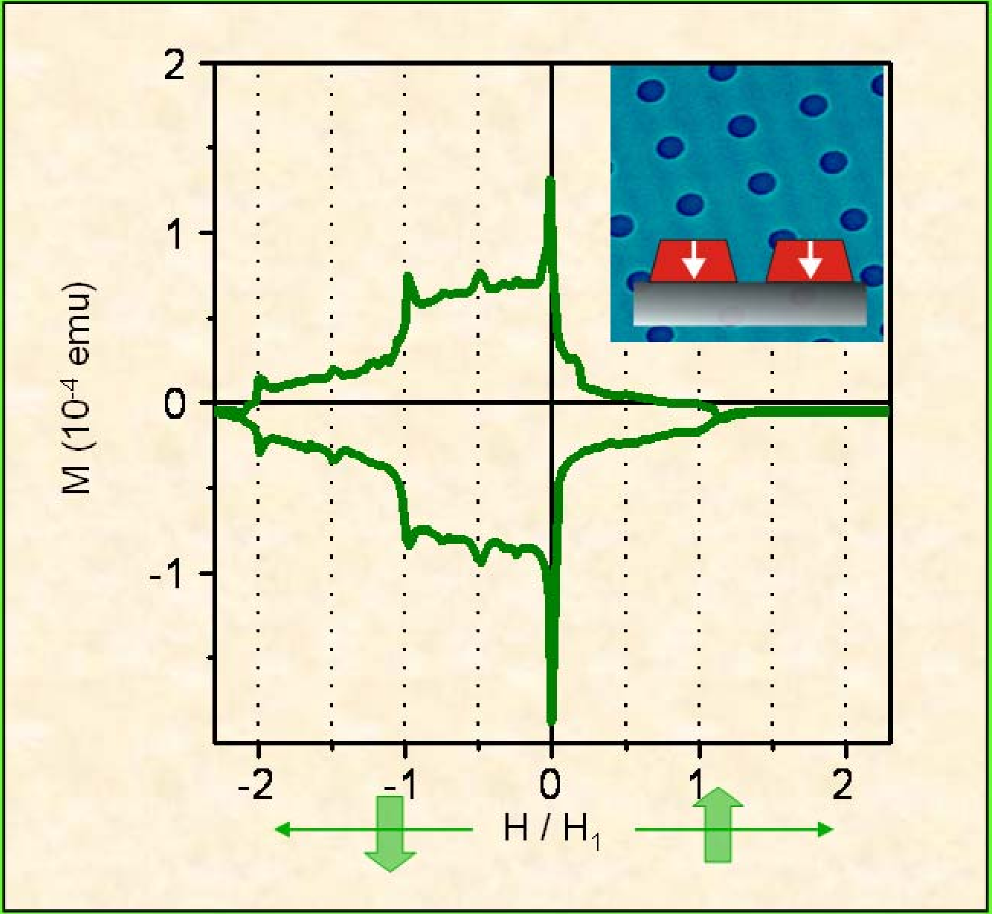
Vortex pinning by Co/Pt dots

SQUID M(H) loop @ 7.10K

$H_1 = \phi_0 / (1\mu m)^2$
$= 20.68$ Oe

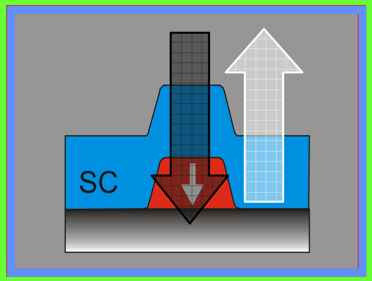
$\Delta M \sim j_C$

Stronger matching peaks and higher j_C at *negative* H



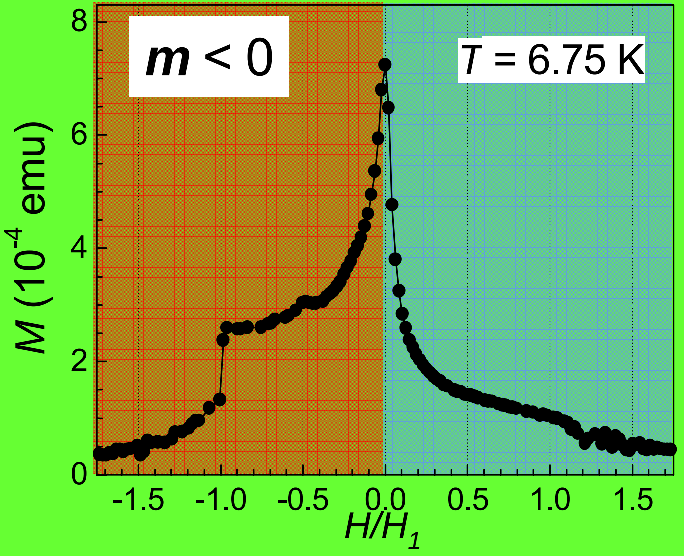
SHPM results on Co/Pt dot array

Macroscopic measurements:
strong asymmetry between
parallel and antiparallel alignment



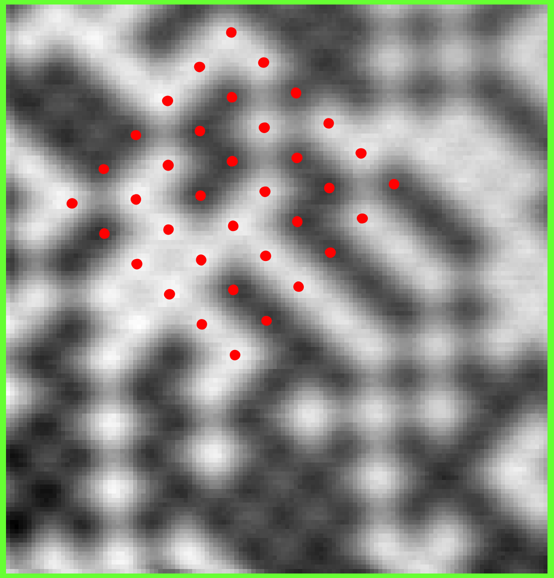
strong pinning

weak pinning

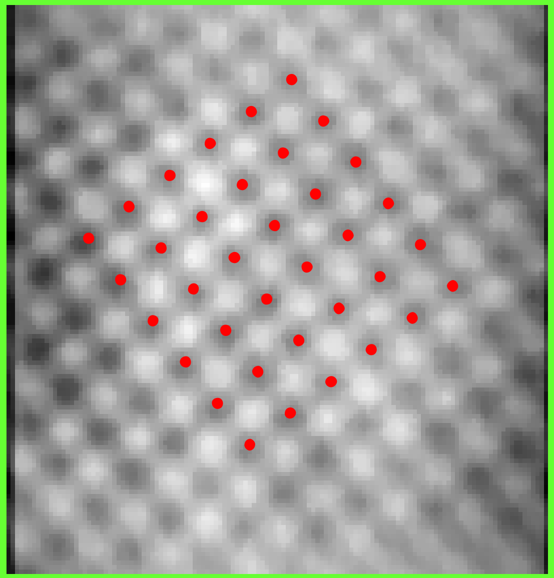


SHPM:
$T > T_c$

demagnetised dot array



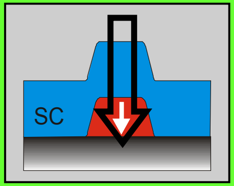
magnetised dot array <0

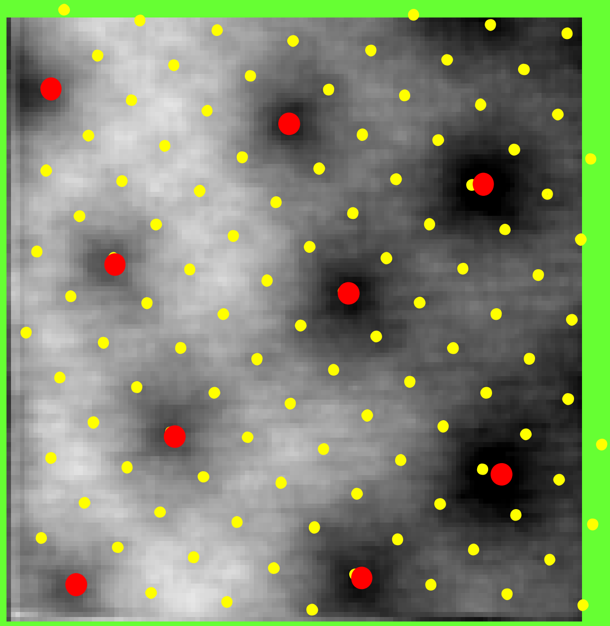


Asymmetric pinning in magnetised Co/Pt dot array

Dots magnetised in negative direction

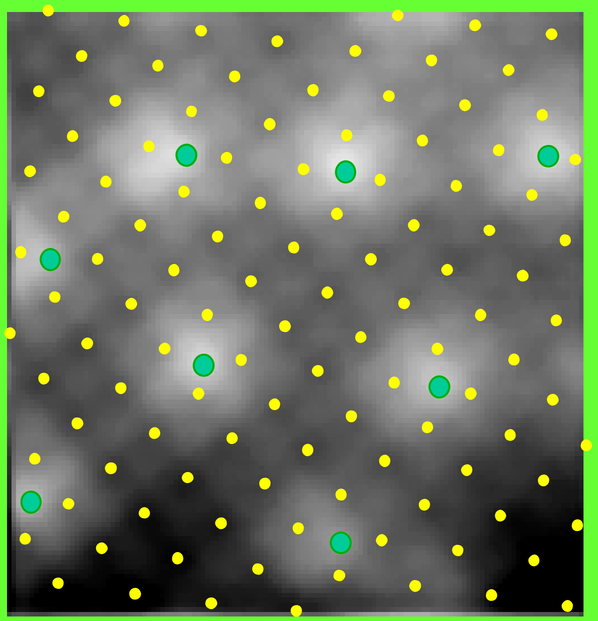
T = 6.8 K H = -1.6 Oe<0

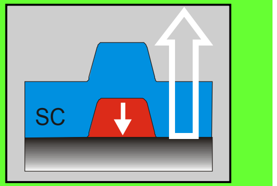




Vortices pinned by dots

T = 6.8 K H = 1.6 Oe >0





Vortices between dots

Vortex-dot interaction: attractive for parallel alignment

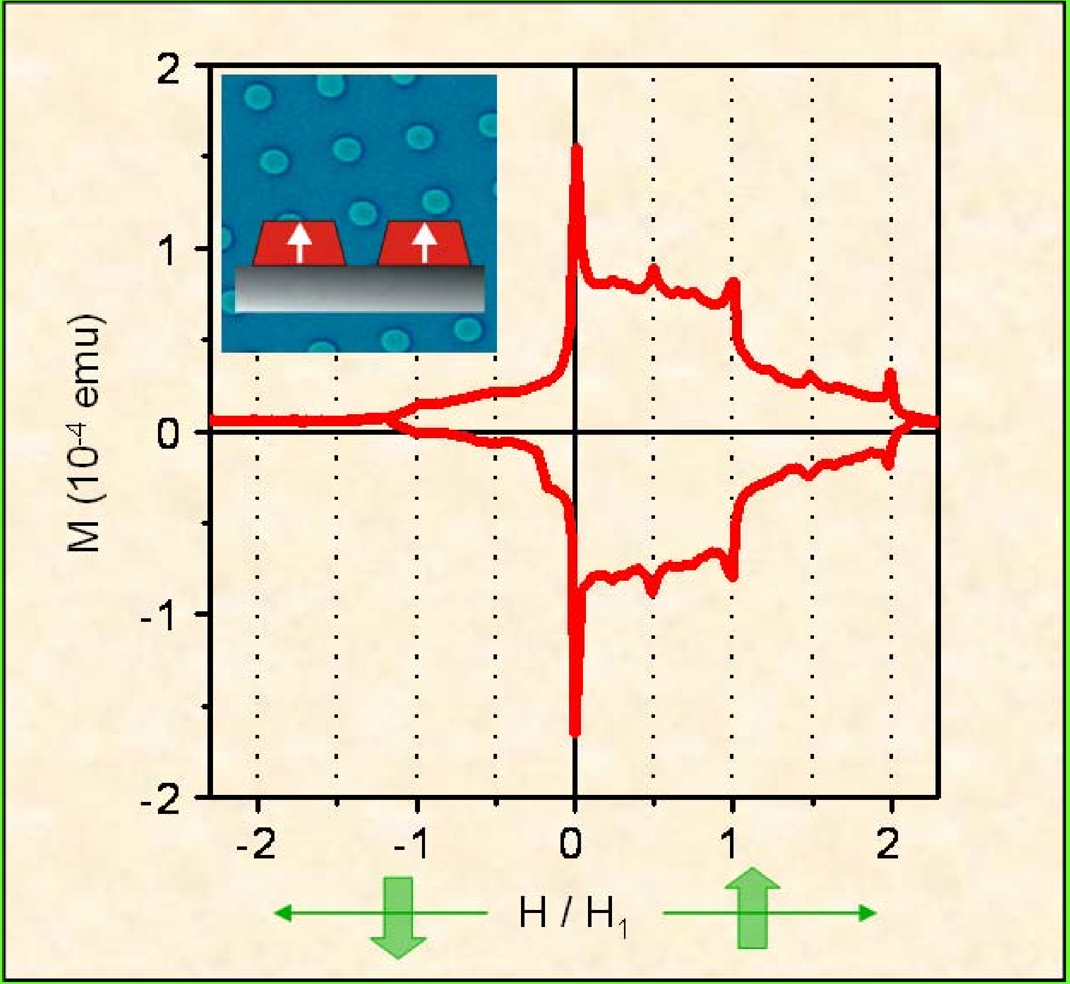
repulsive for anti-parallel alignment

Vortex pinning by Co/Pt dots

SQUID M(H) loop @ 7.10K

$H_1 = \phi_0/(1\mu m)^2$
$= 20.68$ Oe

$\Delta M \sim j_C$



Stronger matching peaks and higher j_C at *positive* H

Vortex pinning by Co/Pt dots

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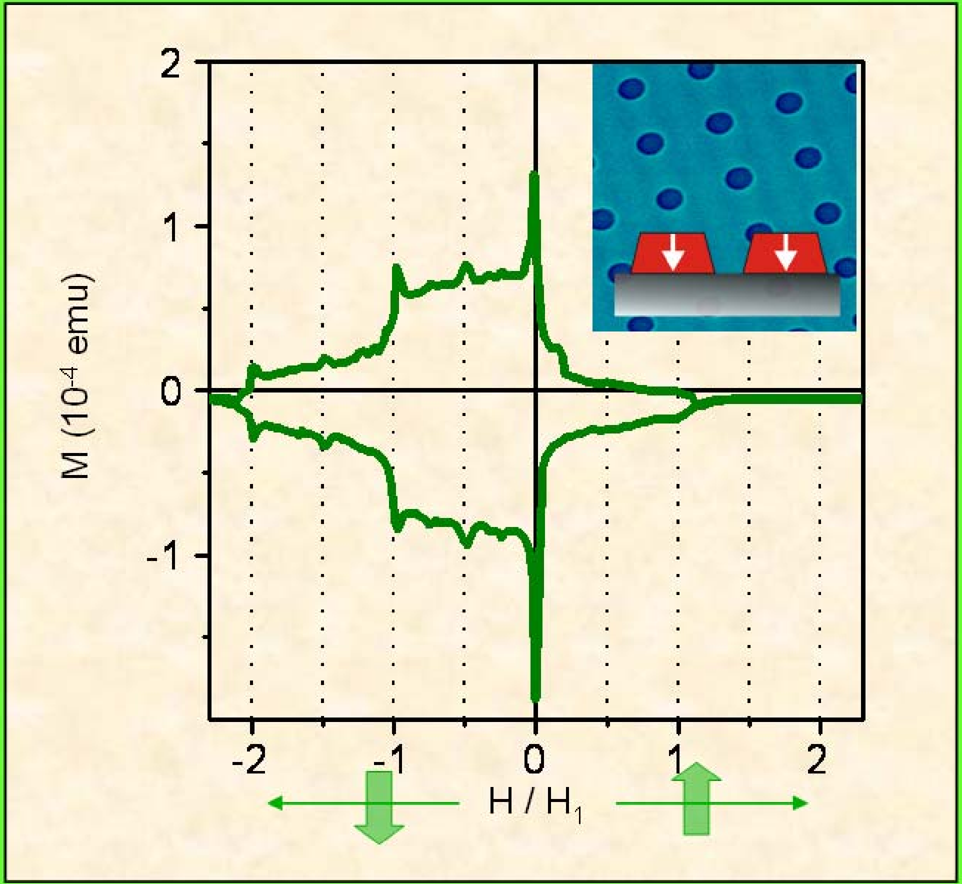


Stronger matching peaks and higher j_C at *negative* H

Conclusion

Vortex manipulation by arrays of magnetic dots:

field polarity dependent

enhanced pinning

Field induced superconductivity

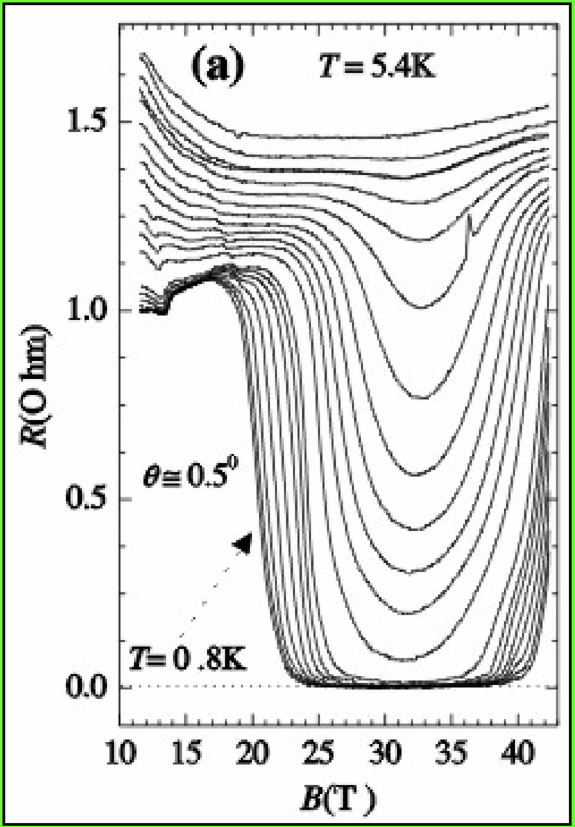
- **Antivortices induced by magnetic dipoles can compensate the applied field**
- **Field-induced superconductivity in films with magnetic dots**
- **Field-polarity dependent and field-selective FIS**

Magnetic - field - induced superconductivity (FIS)

Up to now observed in only three materials:

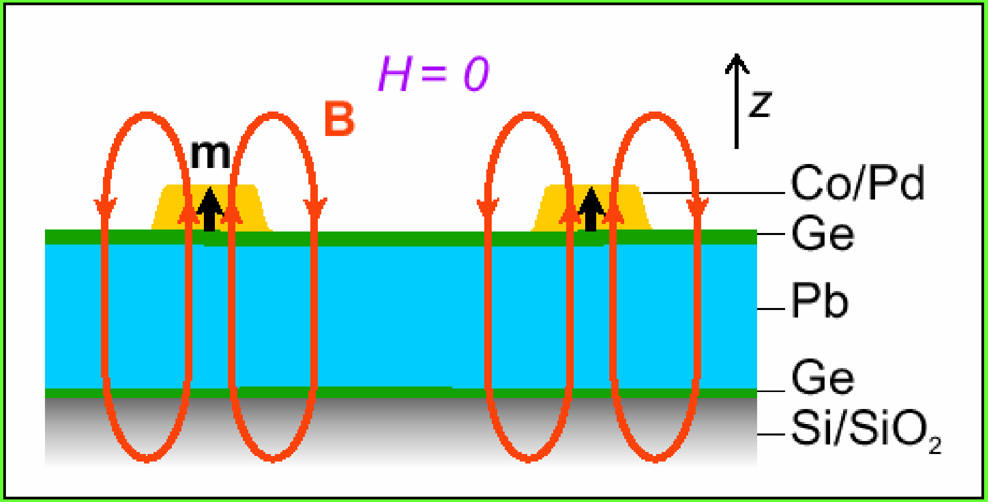
- $(Eu,Sn)Mo_6S_8$, Meul *et al.*, PRL (1984)
- $HoMo_6S_8$, Giroud *et al.*, JLTP (1987)
- λ-$(BETS)_2FeCl_4$, Uji *et al.*, Nature (2001), Balicas *et al.*, PRL (2001)

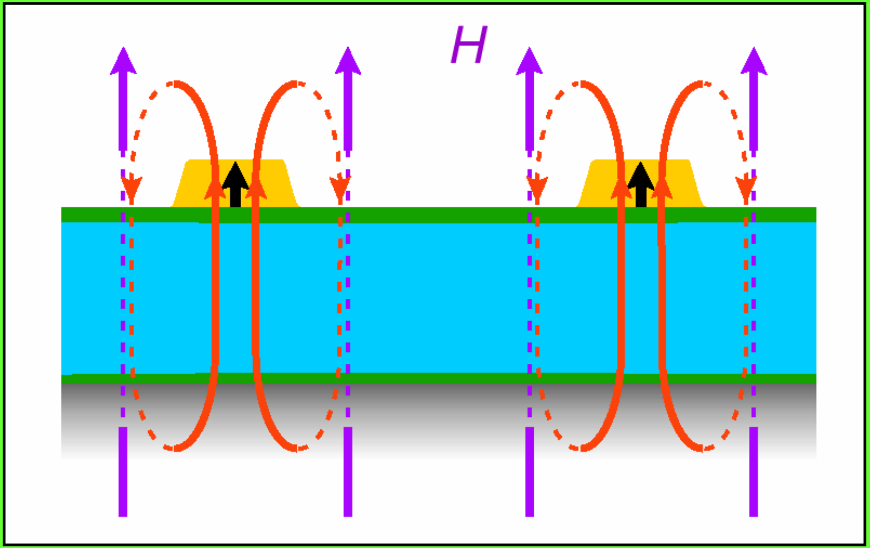
FIS can be explained in terms of field compensation effects (e.g., Jaccarino-Peter effect)



Balicas *et al.*, PRL 2001

FIS in films with magnetic Co/Pd dots



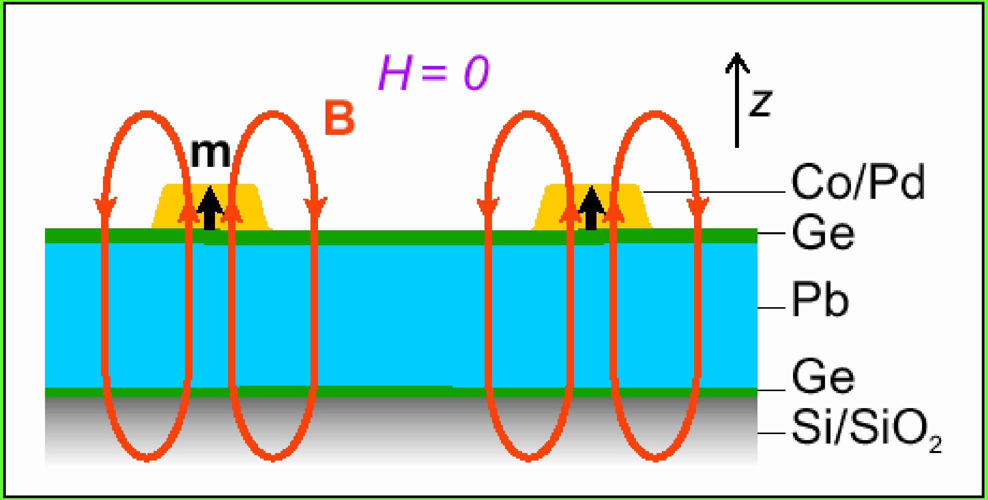


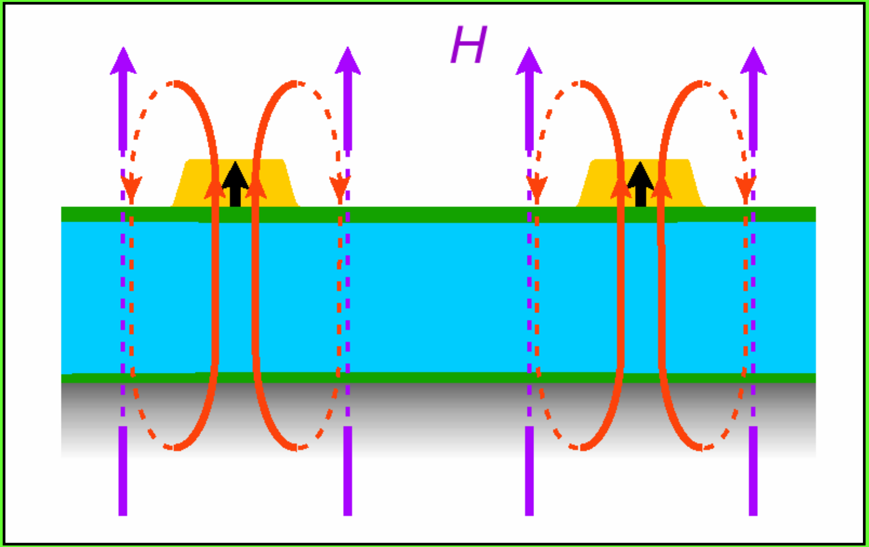
Nanoengineered magnetic-field-induced superconductivity, **PRL 90, 197006 (2003) + Focus**

Let’s make things better…

at the expense of
making them worse elsewhere

FIS in films with magnetic Co/Pd dots

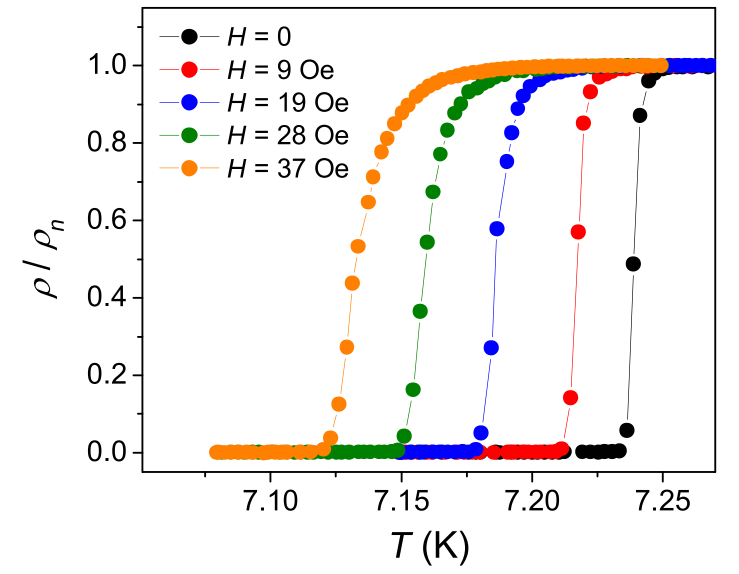




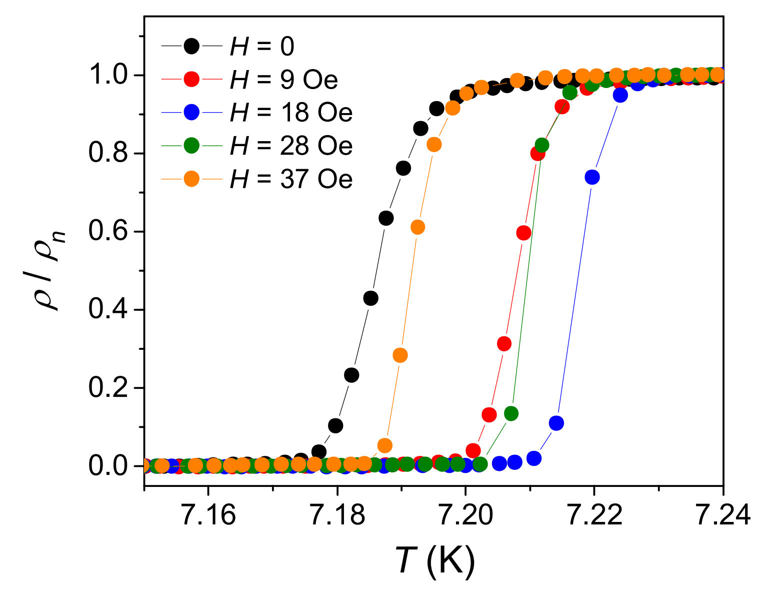
Nanoengineered magnetic-field-induced superconductivity, **PRL 90, 197006 (2003) + Focus**

Phase transitions in $\rho(T)$

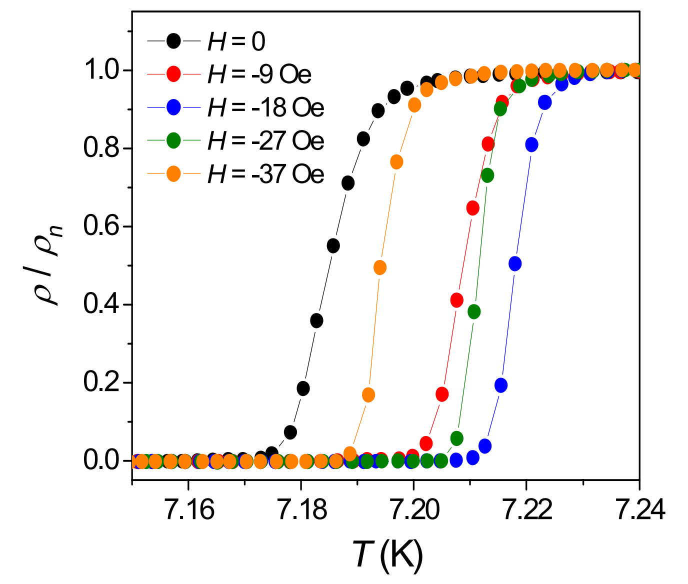
$m = 0$



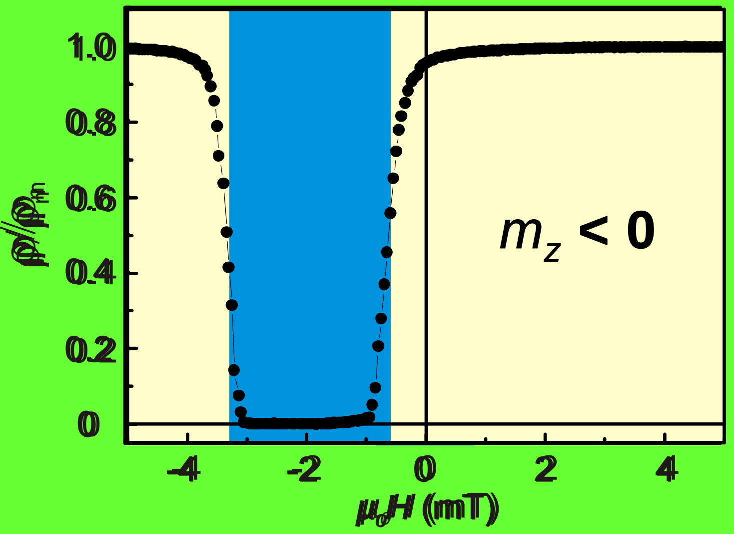
$m_z > 0$

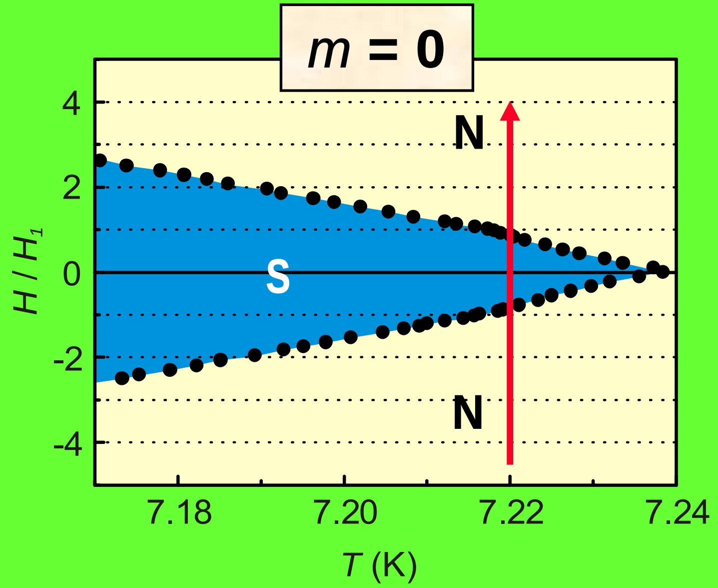


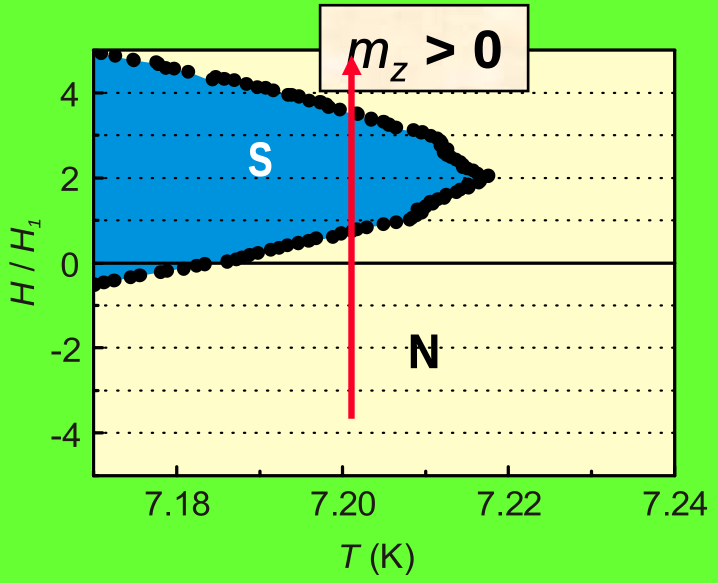
$m_z<0$

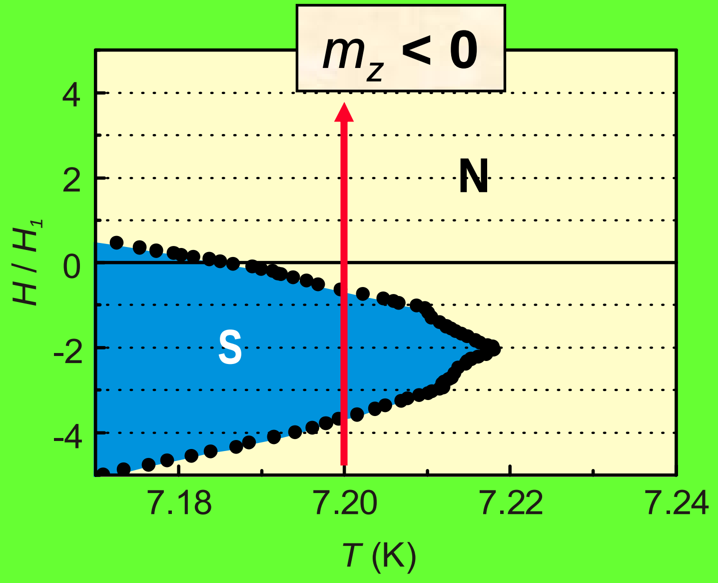


H – T – phase diagrams

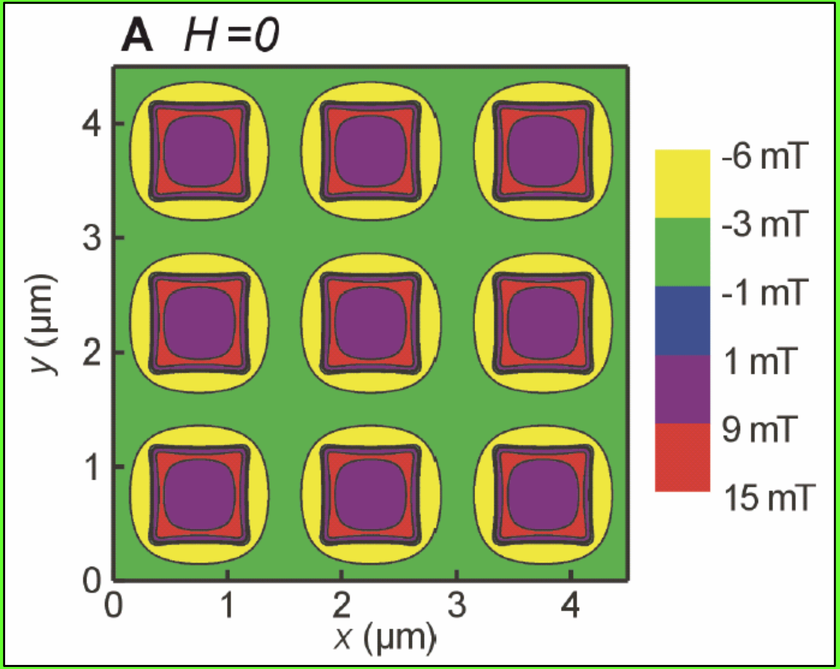








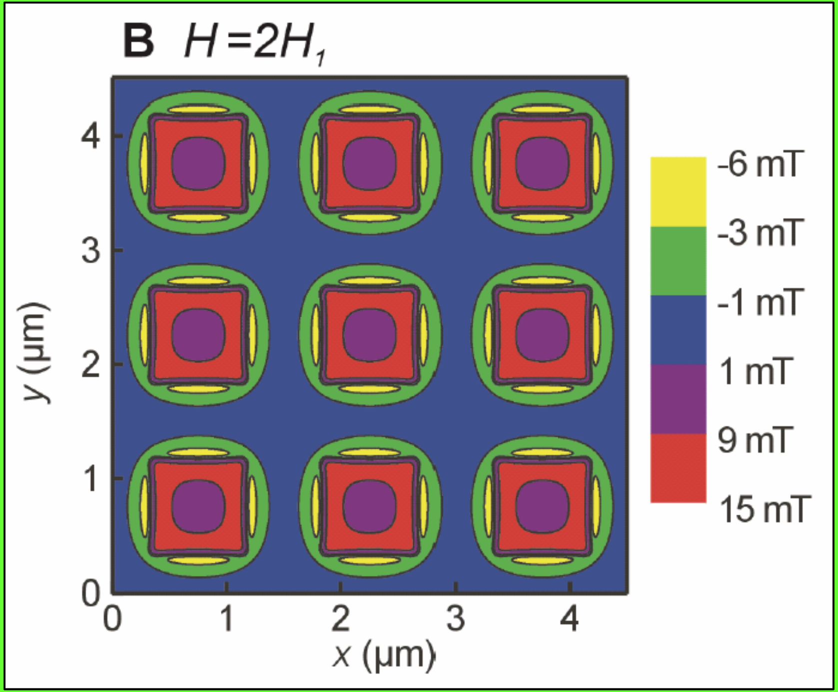
Calculated effective fields in superconductor



Stray field of the dots
suppresses superconductivity

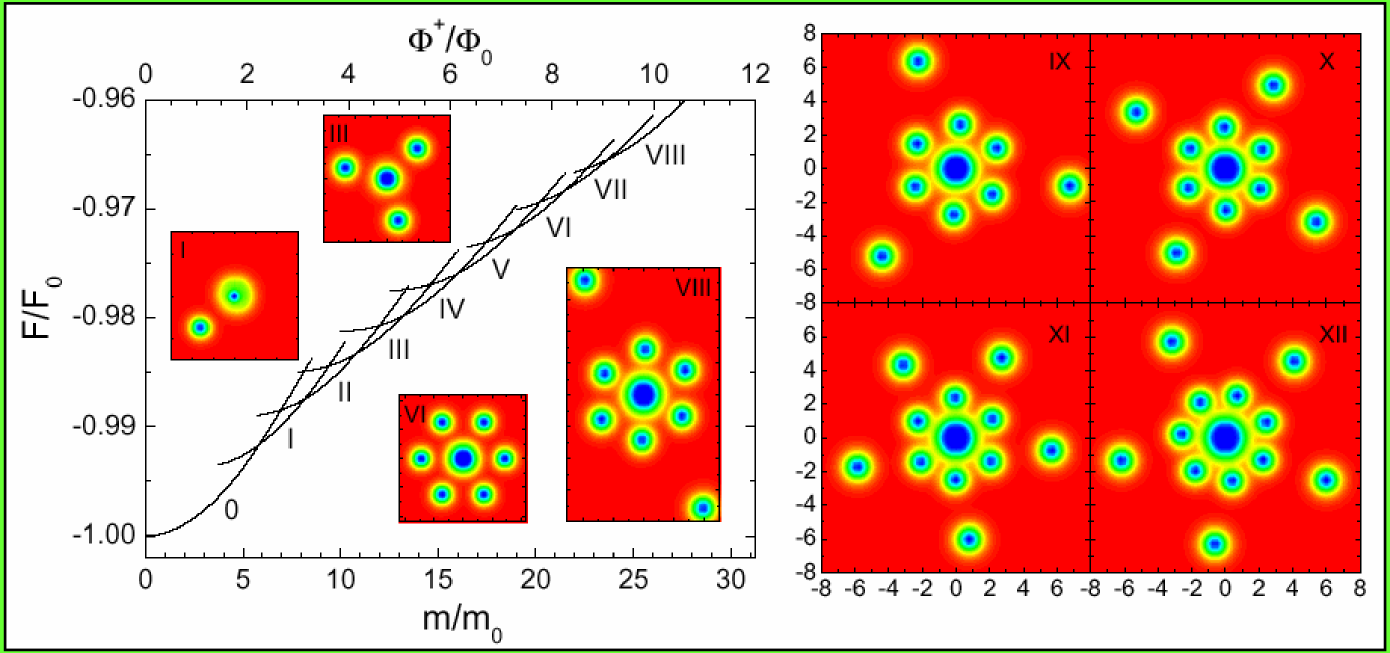
Applied field ($2H_1$= 1.84mT)
compensates stray field
between dots

"superconducting Swiss cheese"



Vortex-Antivortex Pairs

M. V. Milosevic and
F. M. Peeters,
cond-mat/0211547

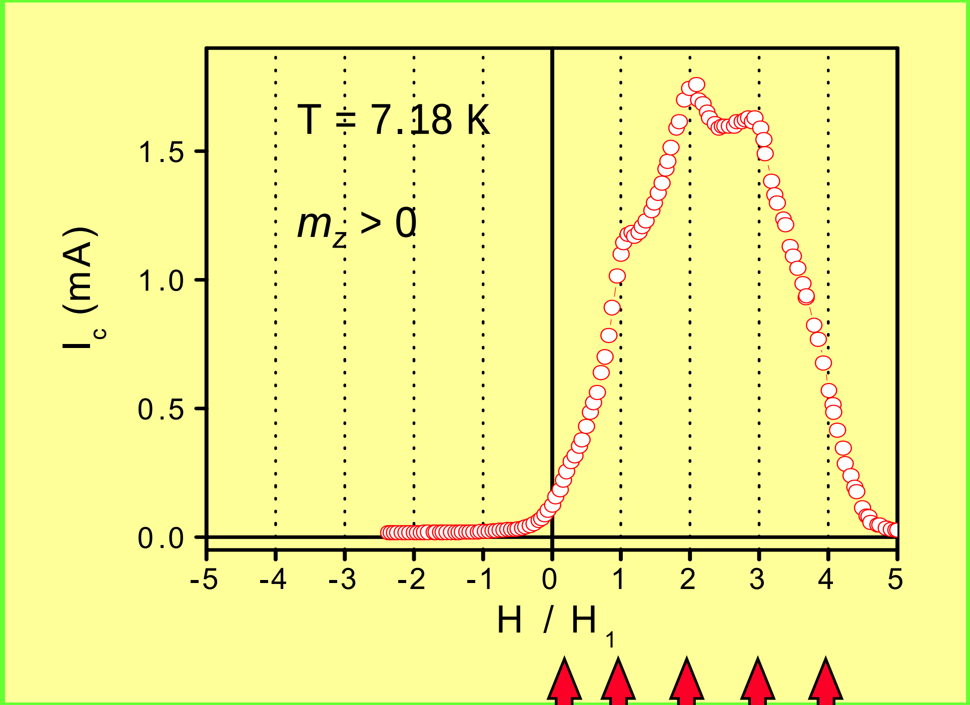


Cooper-pair density (Ginzburg – Landau theory) in a superconducting film with a magnetized dot (radius ξ)

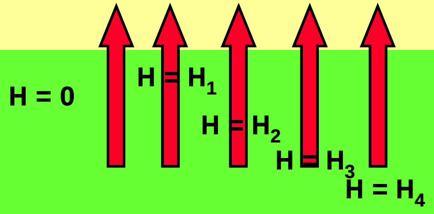
red = high density, blue = low density

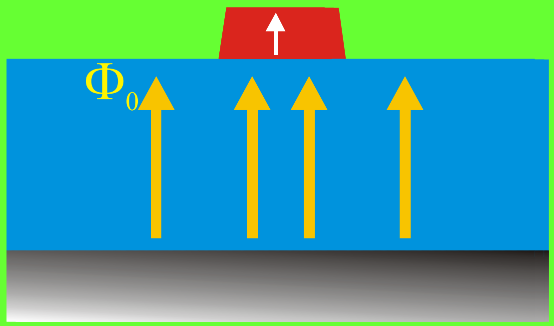
For large magnetic moments the stray field of the dots creates stable vortex – antivortex pairs

Critical current



I_c depends mainly on the mobility of vortices

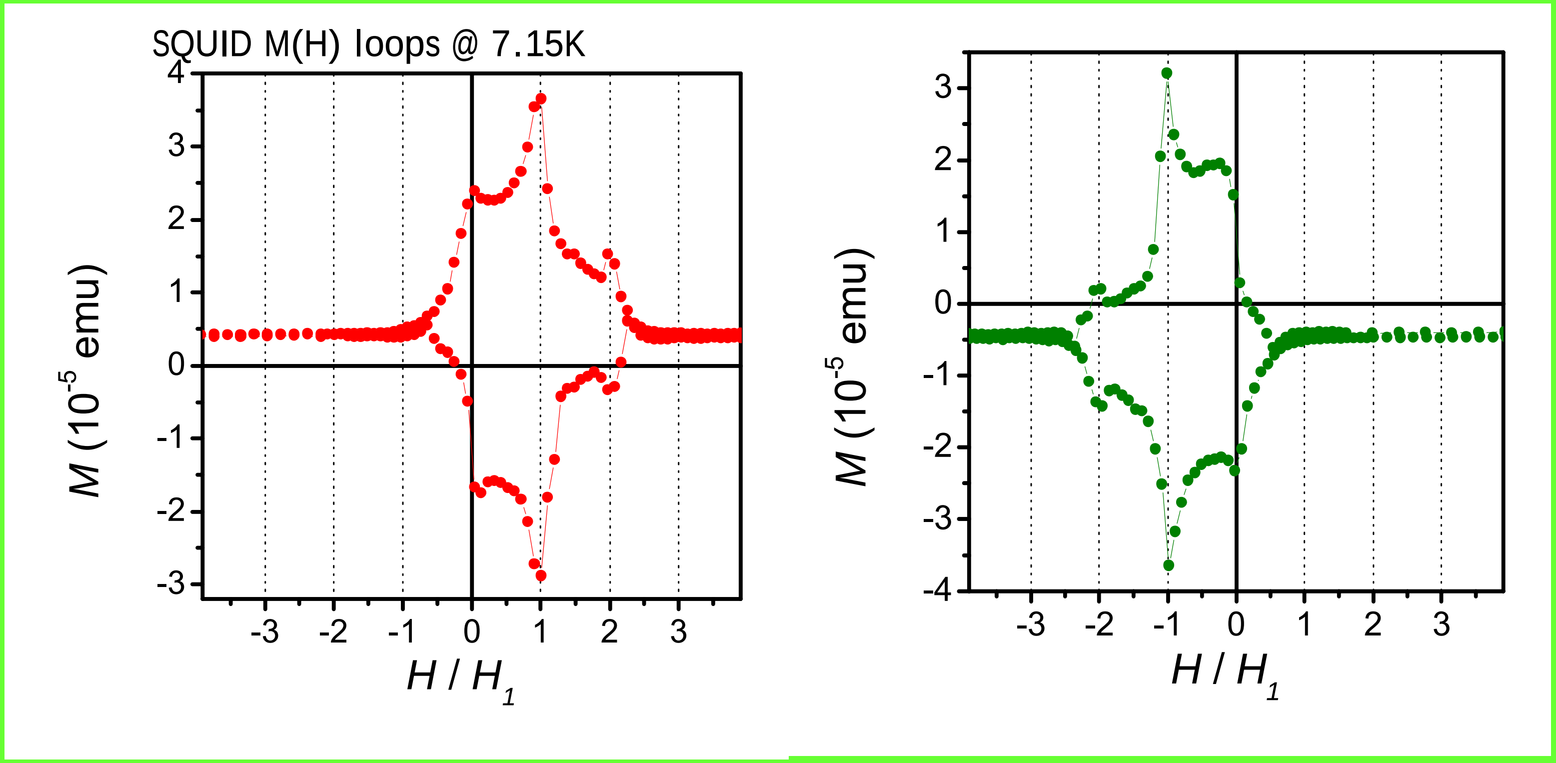




Model can explain qualitatively the asymmetric $I_c(H)$ and M(H) curves

Magnetic dots

$H_1 = \phi_0 / (2\ \mu m)^2$
$= 5.2$ Oe



square array (period 2 µm) of dots with 600 nm diameter
Pd (4 nm) / [Co (0.4 nm) / Pd (1.4 nm)]$_{10}$

Main peak of magnetization curve is shifted to H_1

Conclusion

Vortex manipulation by arrays of magnetic dots:

nano-engineered field-induced superconductivity

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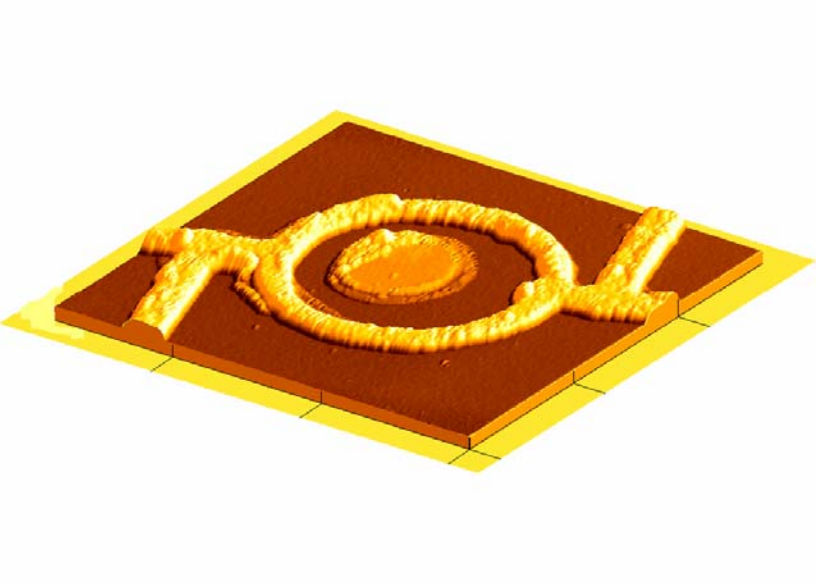
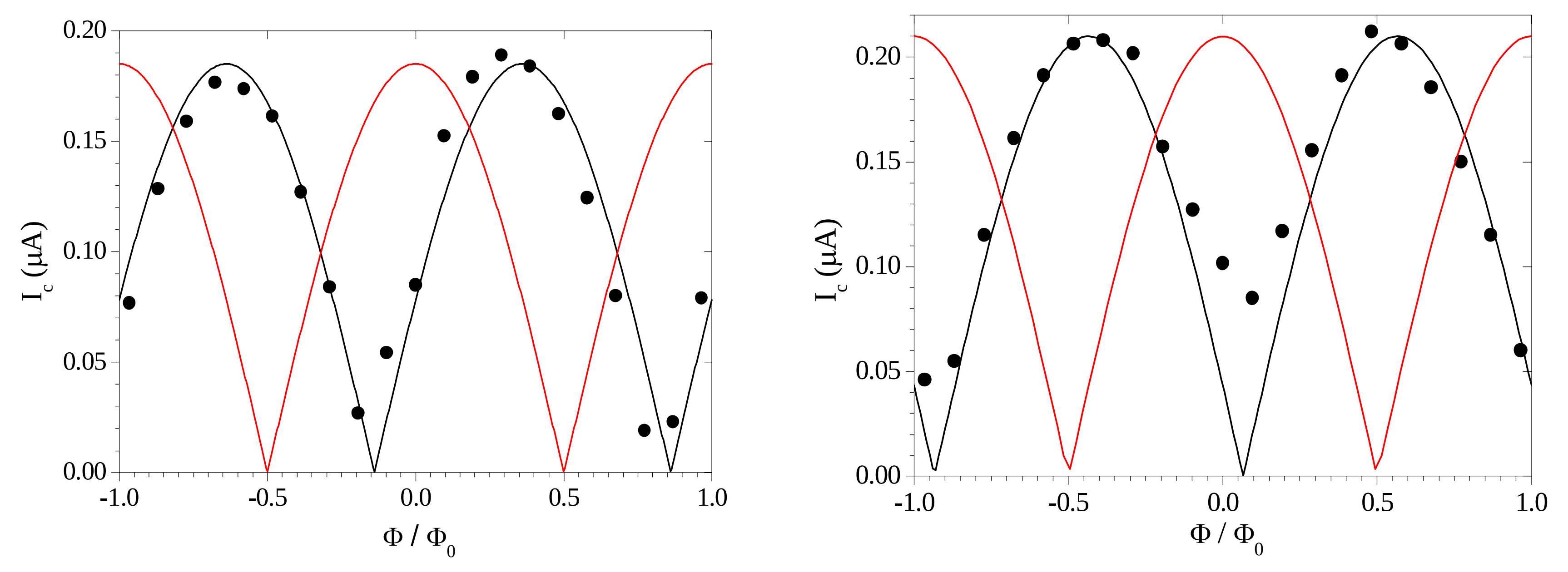
MAGNETIC PHASE SHIFTER FOR QUANTUM COMPUTING



D. S. Golubovic, W. V. Pogosov, M. Morelle and
V. V. Moshchalkov, PRL *92, 177904 (2004)*
Also cond-mat/0403315

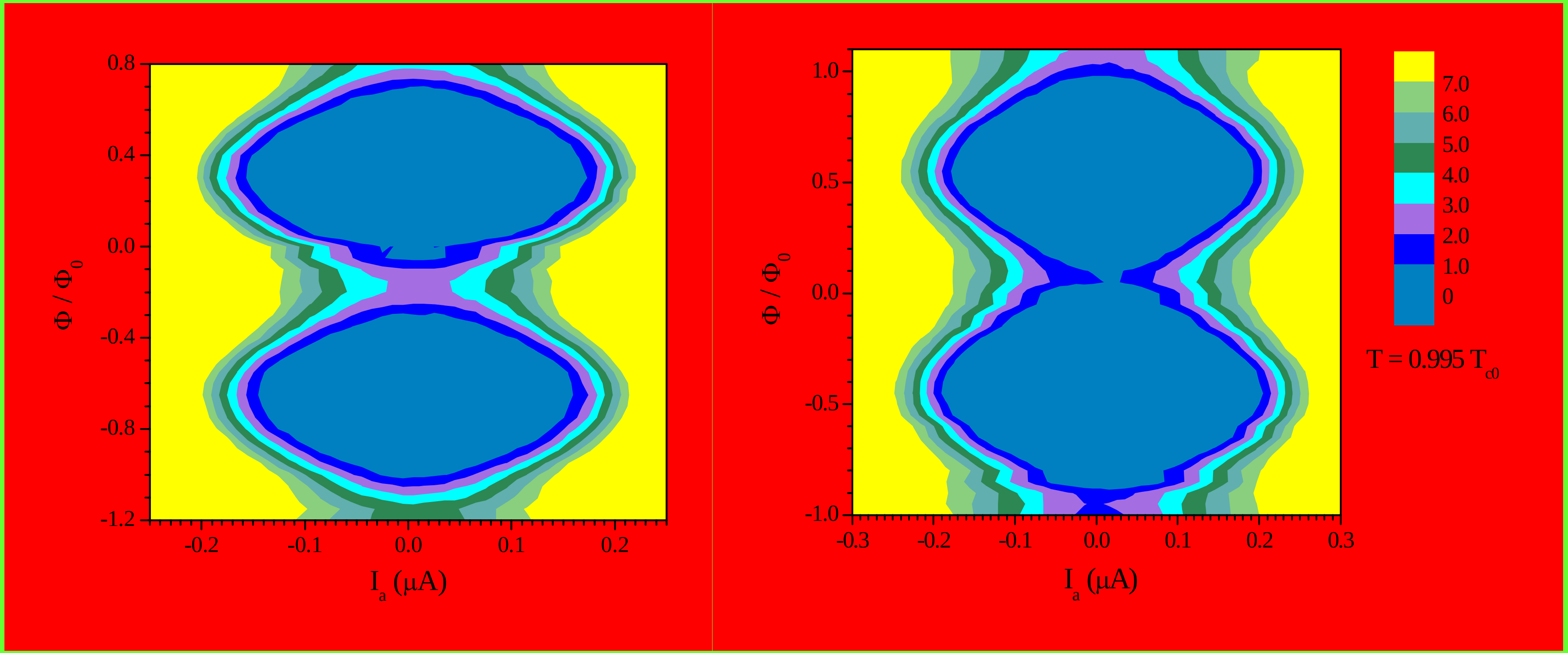
PHASE SHIFT

Φ_{m1} Φ_{m2}



D. S. Golubovic, W. V. Pogosov, M. Morelle and V. V. Moshchalkov, PRL, *92, 177904 (2004),* also cond-mat/0403315

PHASE SHIFT



Φ_{m1} Φ_{m2}

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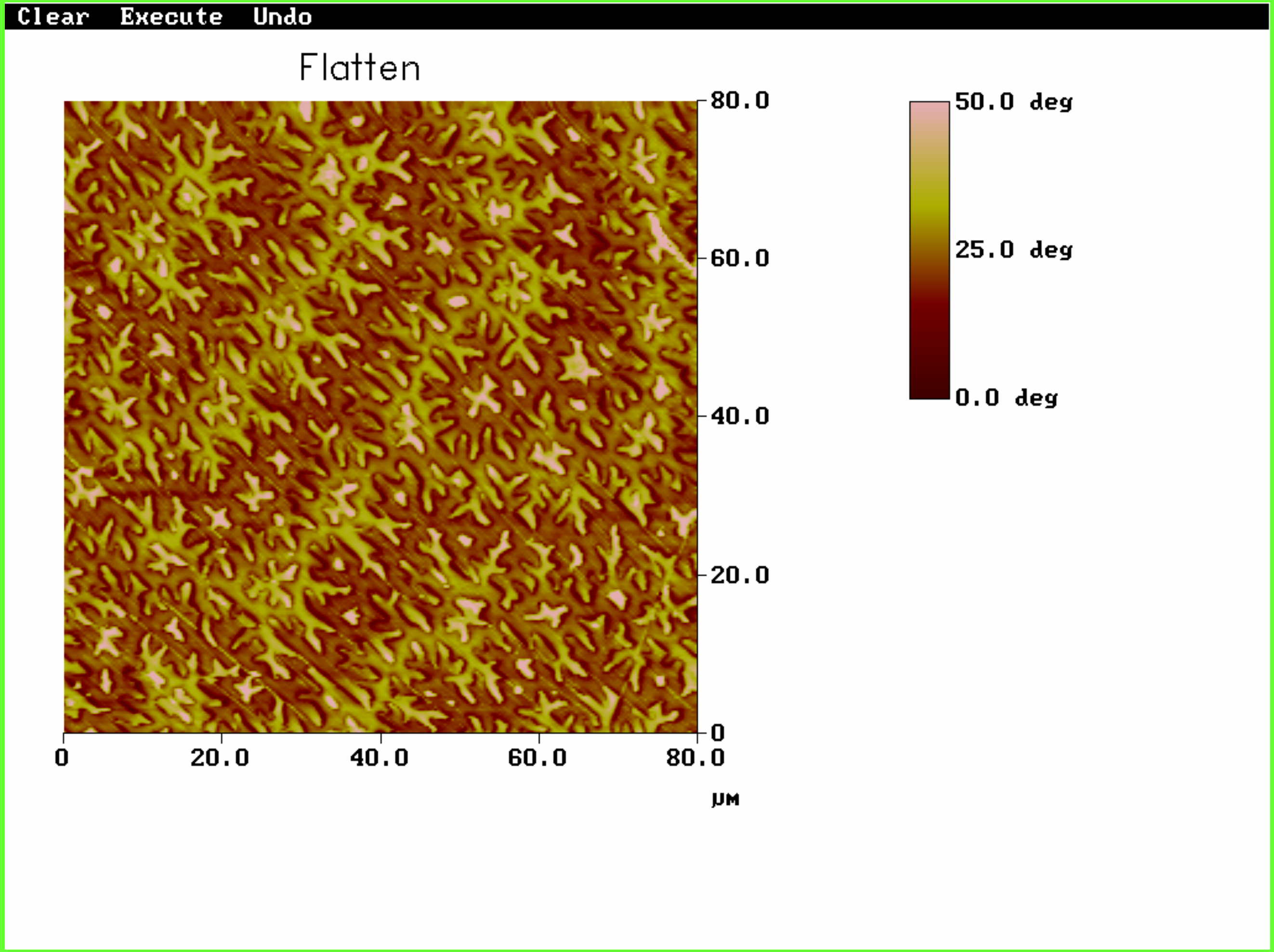
------*Remanent state*



No evident difference between *demagnetized state* and *remanent state* has been found

Introduction and motivation

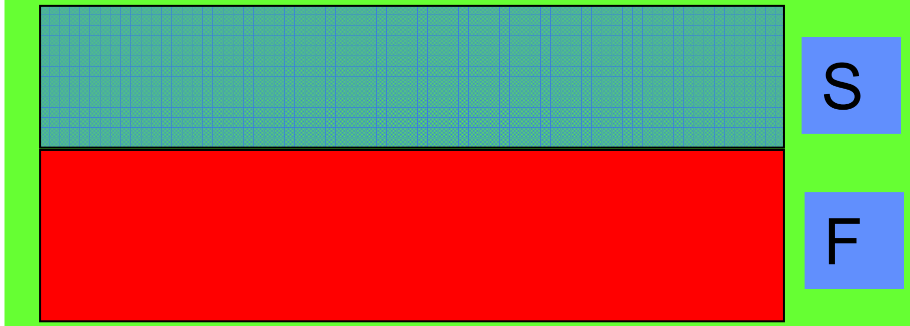
------------domain wall superconductivity (DWS)

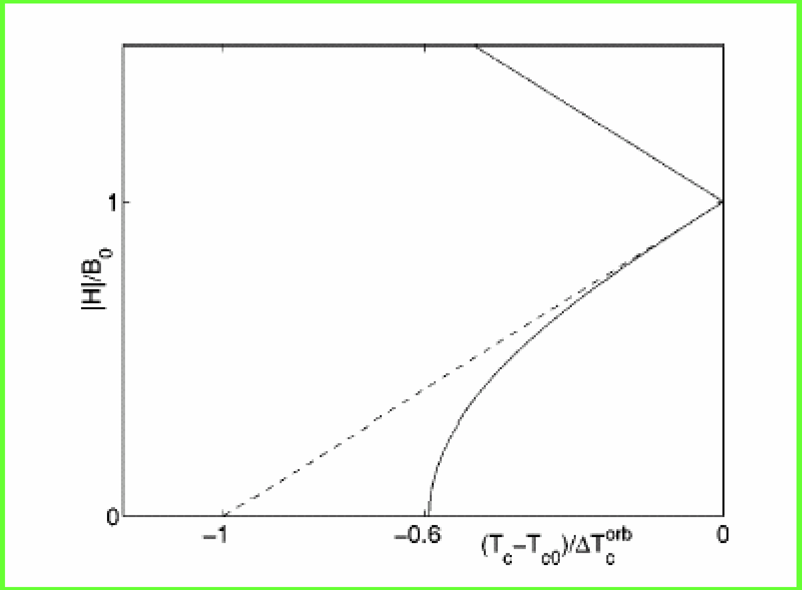
Superconductivity ←antagonistic→ Ferromagnetism

Coexistence (?)

Superconductivity in a ferromagnet is more favorable to exist near a domain wall

Hybrid superconductor/ferromagnet structure

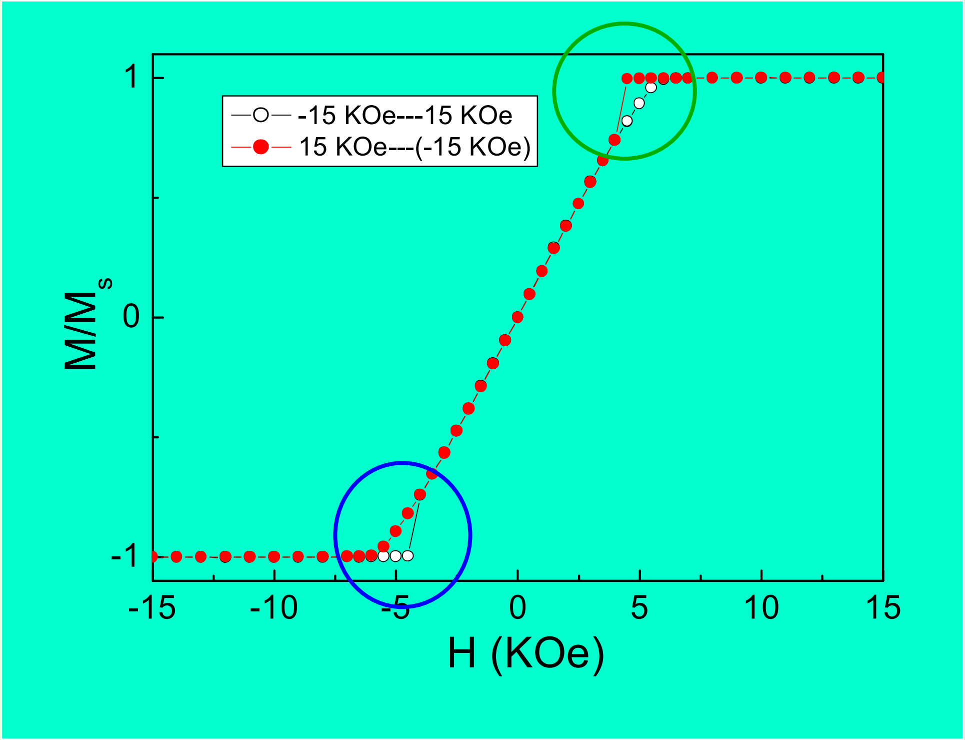


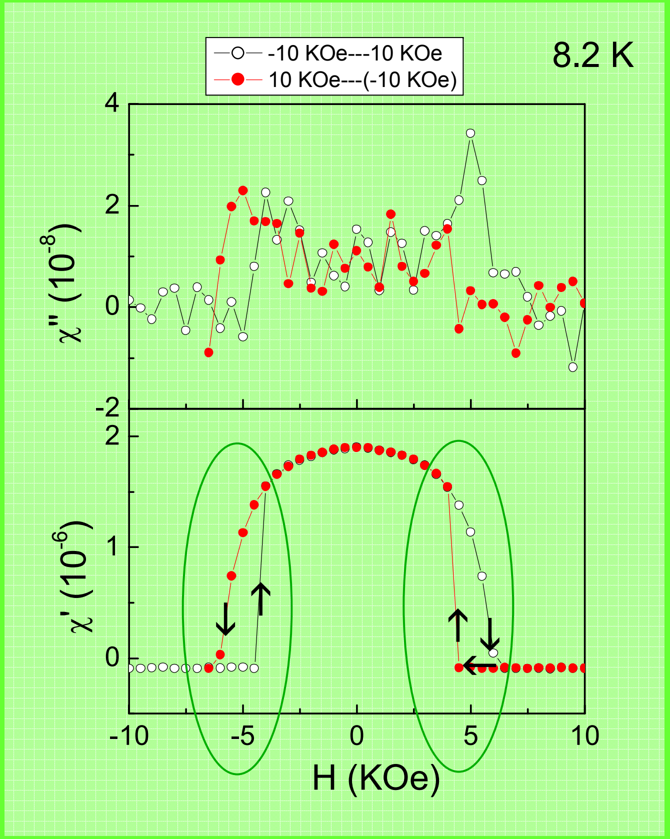


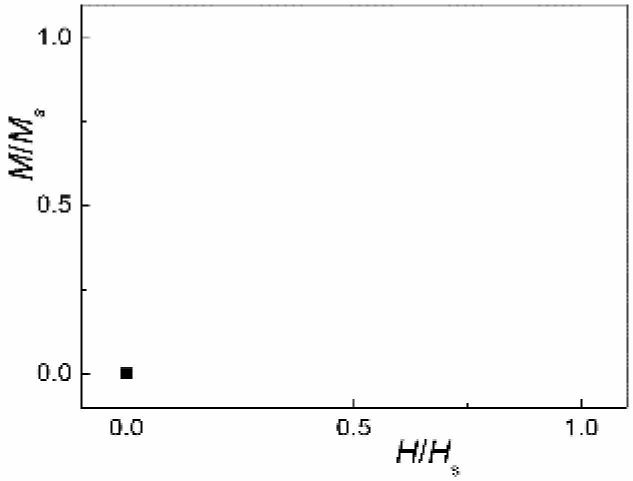
A. Yu. Aladyshkin, et al.,
Phys. Rev. B **68**, 184508 (2003)

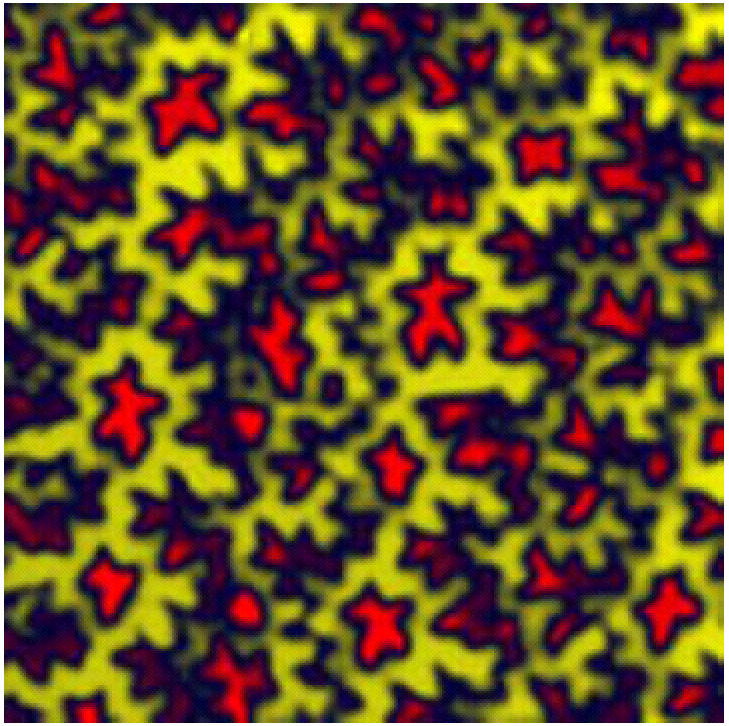
Magnetic properties of $BaFe_{12}O_{19}$ single crystal

- The easy axis is along [0001] direction
- Hexagonal structure with uniaxial anisotropy
- We used the [0001] substrate






1.0
0.5
0.0
M/M_s
0.0
0.5
1.0
H/H_s

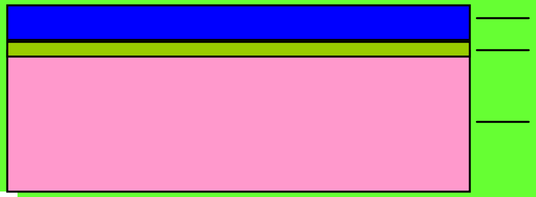


R-T curves

Nb 50 nm

Si 10 nm

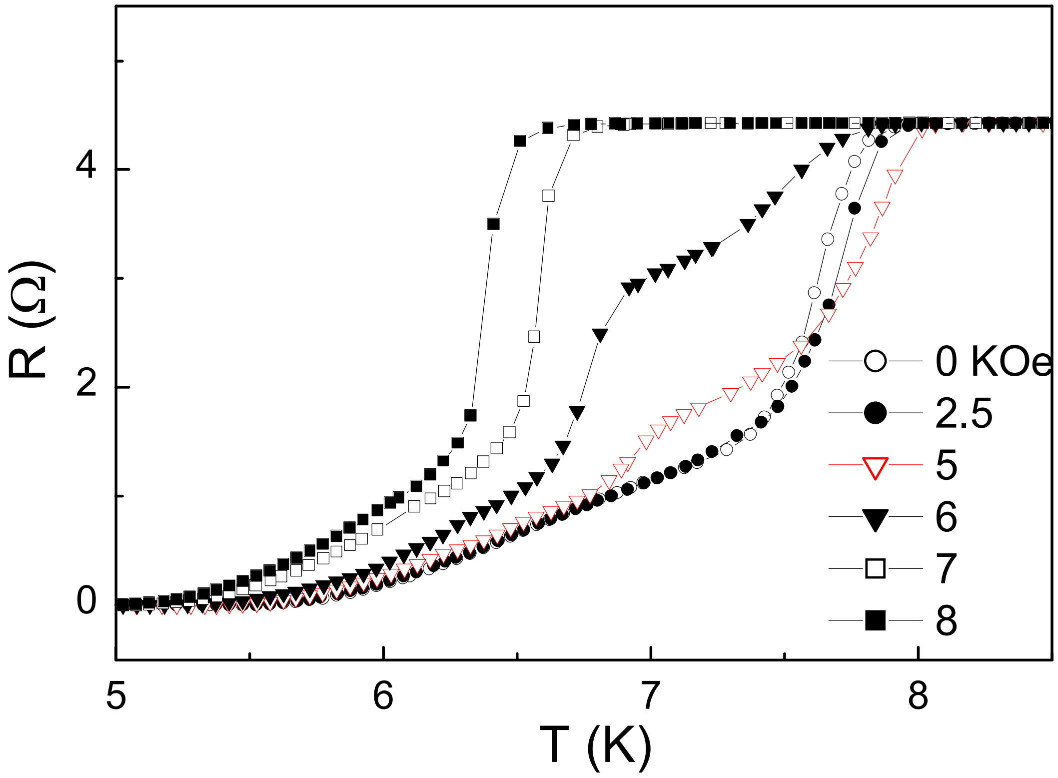
$BaFe_{12}O_{19}$

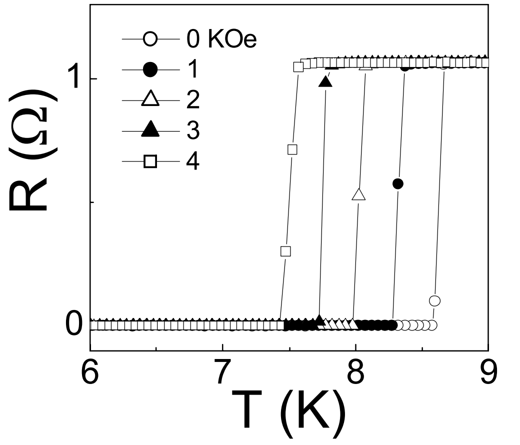


Nb 50 nm

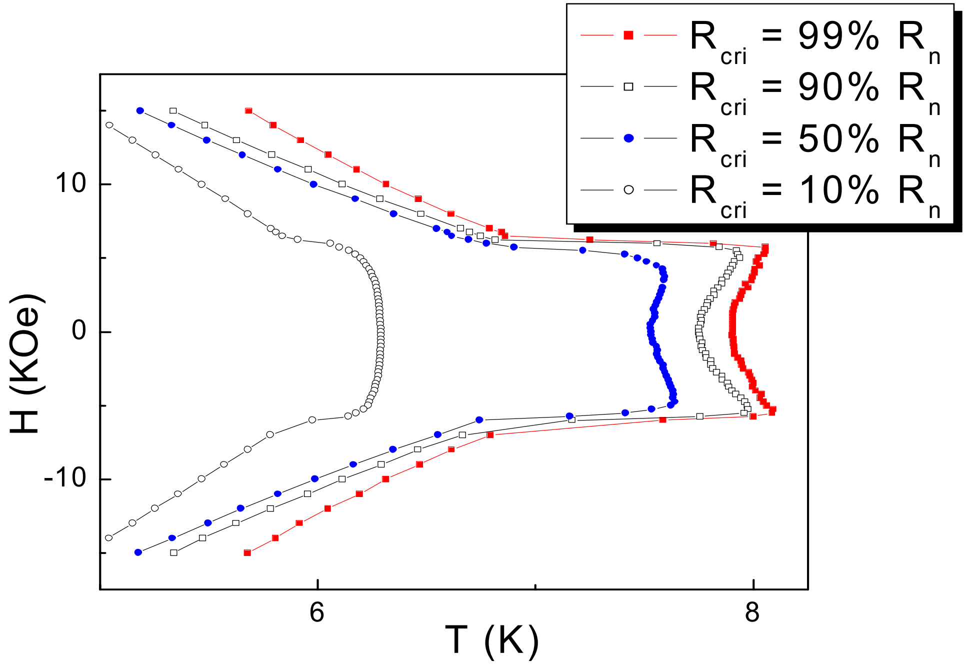
Si 10 nm

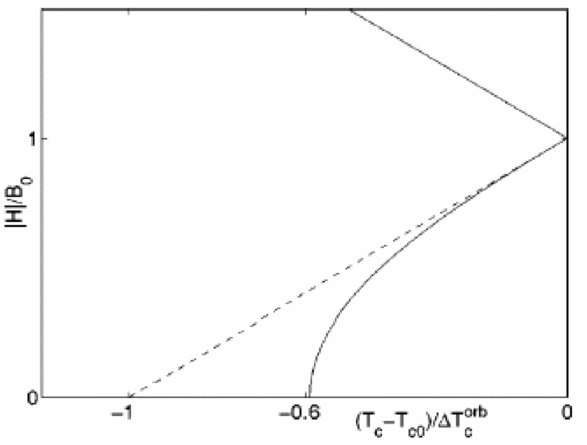
Si/SiO_2

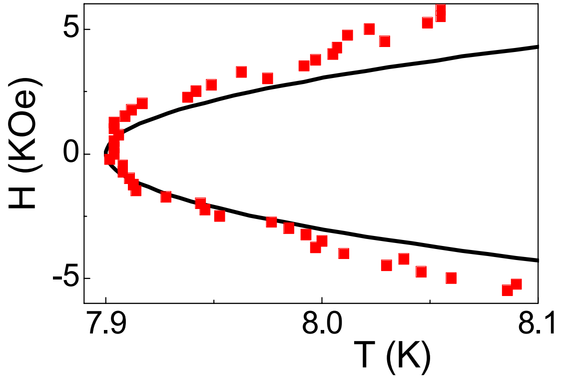




H – *T* – phase diagrams







***R**$_{cri}$* **= 99%** ***R**$_{n}$*

Nature Materials, ***3****, 793 (2004)*

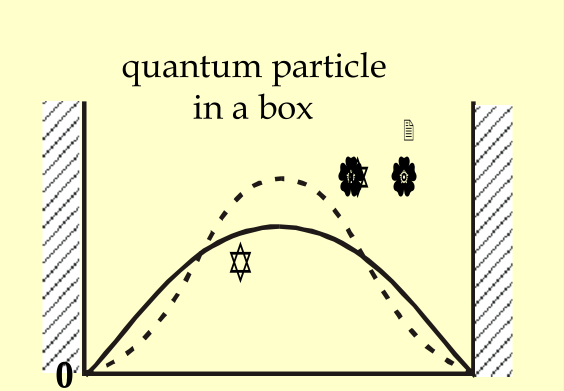
Introduction

- Schrödinger equation particle in magnetic field H :

$$\boxed{\frac{1}{2m}\left(-i\hbar\vec{\nabla}-e\vec{A}\right)^{2}\Psi = E\,\Psi}$$

$$rot\,\vec{A} = \mu_0\,\vec{H}$$

- Particle wavefunction Ψ



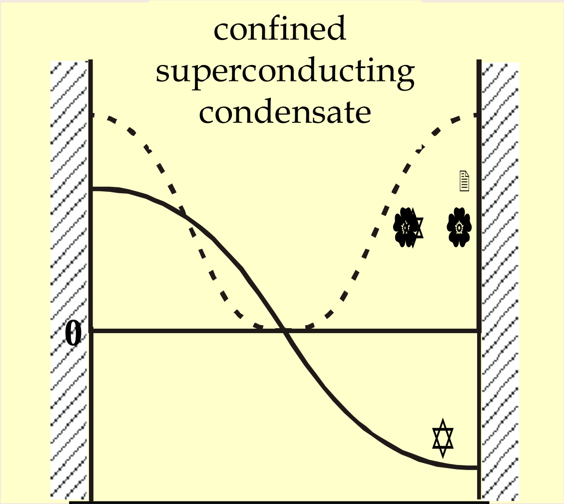
$$\boxed{\Psi = 0}$$

- Dirichlet boundary condition

- Linearised Ginzburg-Landau equation :

$$\boxed{\frac{1}{2m^{*}}\left(-i\hbar\vec{\nabla}-2e\vec{A}\right)^{2}\Psi \propto \left(1-\frac{T}{T_{c0}}\right)\Psi}$$

- Complex order parameter Ψ



$$\boxed{\left.\left(-i\hbar\vec{\nabla}-2e\vec{A}\right)\Psi\right|_{\perp} = 0}$$

- Neumann boundary condition

Mesoscopic superconductors

- Size of the structure smaller than length scale x(*T*) :

$$\xi(T) \sim (0.1 - 1)\ \mu\mathrm{m} \qquad \boxed{S \le \xi^2(T)}$$

- Confinement effects in mesoscopic structures (Moshchalkov et al, Nature 373, 319(1995) :

bulk :

$$\boxed{1-\frac{T_c(H)}{T_{c0}} \propto H\left(N+\frac{1}{2}\right), \quad N=0}$$

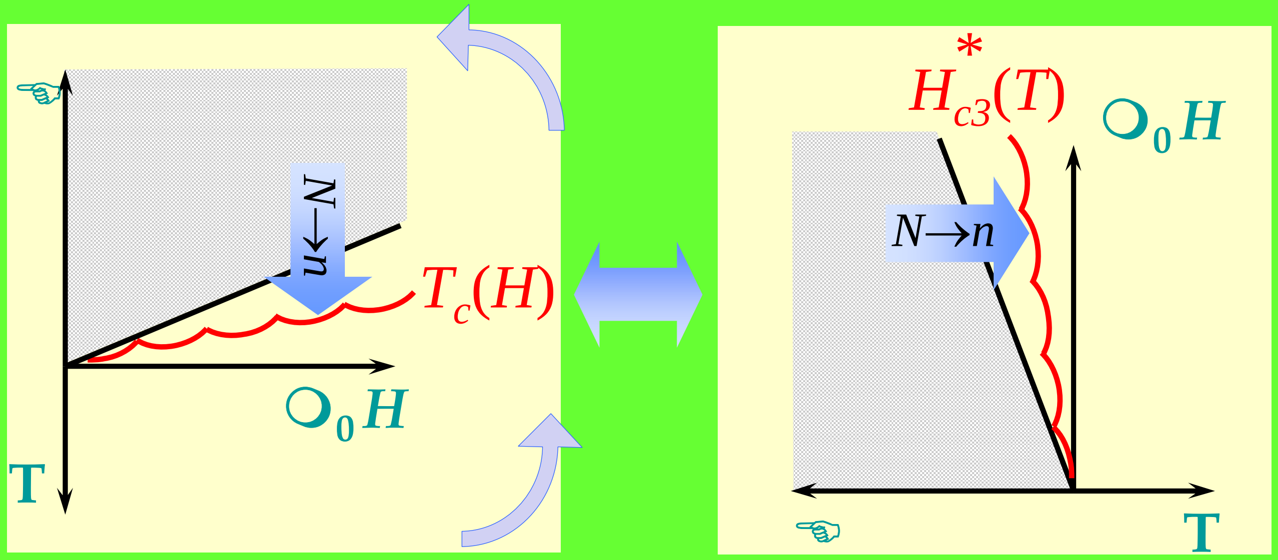
$N \rightarrow n$

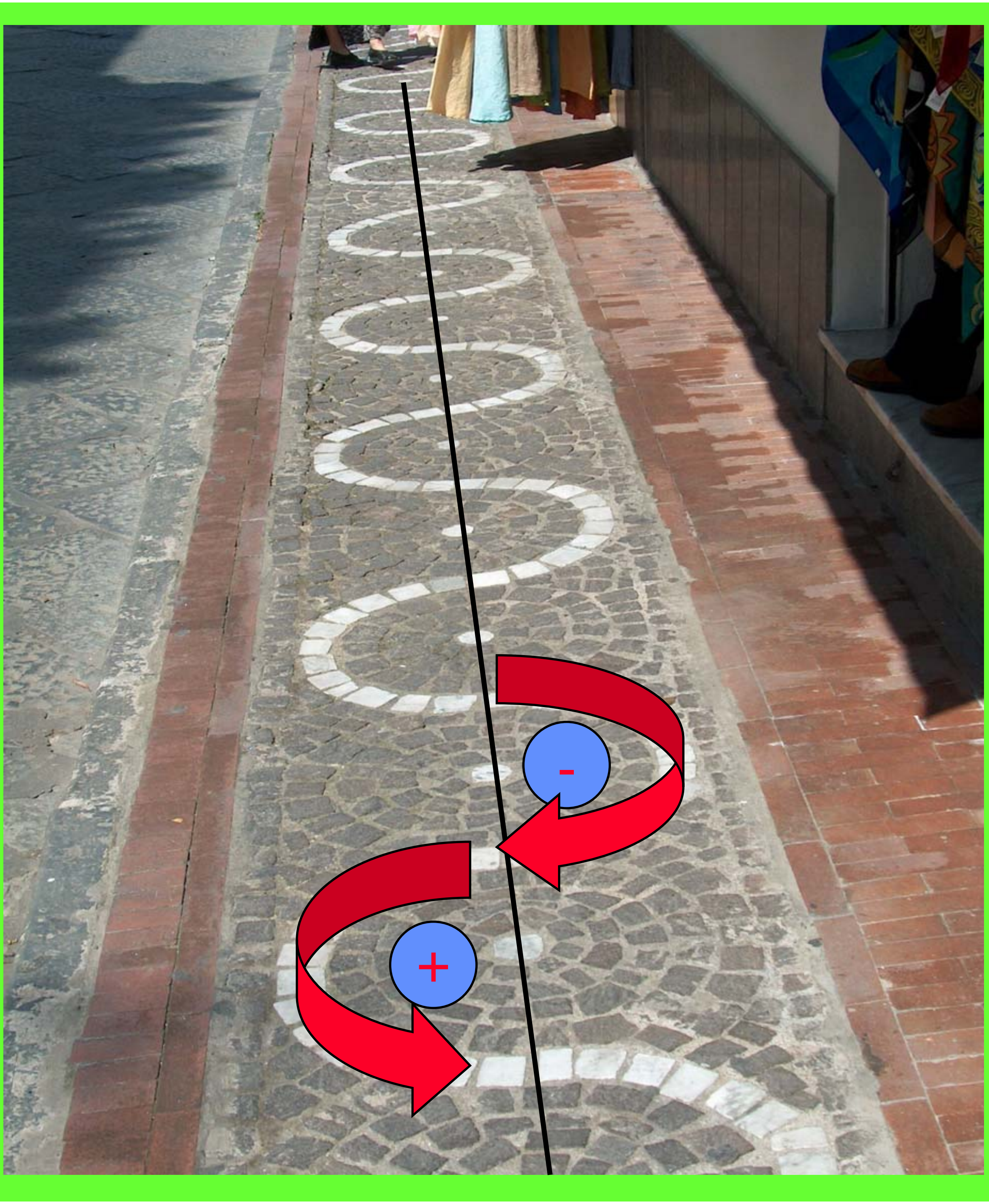
boundary conditions

mesoscopic superconductors :

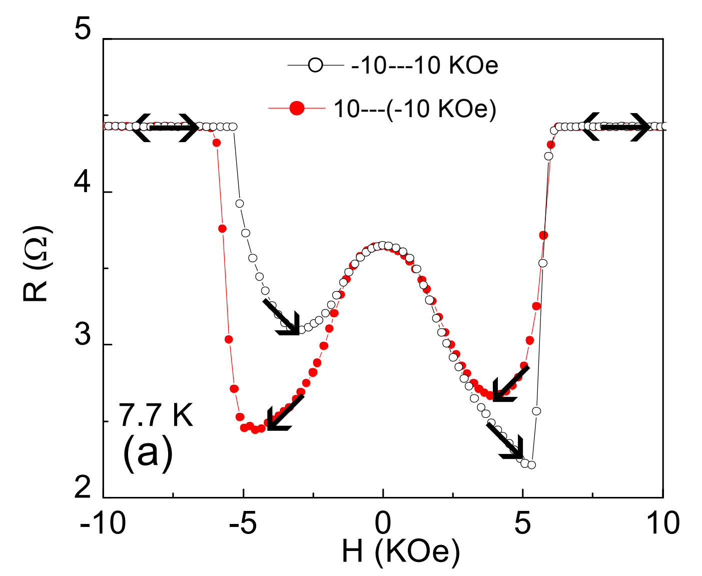
$$\boxed{1-\frac{T_c(H)}{T_{c0}} = \xi^2(0)\frac{\mu_0 H}{\Phi_0}4\pi\left(n+\frac{1}{2}\right), \quad n<0}$$

$n=f\,(S,H,\ldots)$





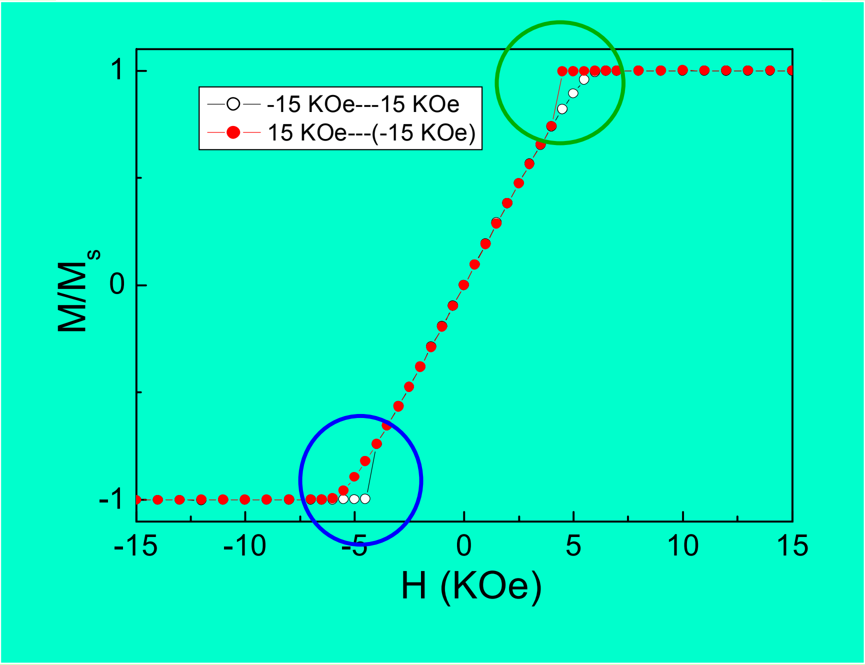
Magnetoresistance



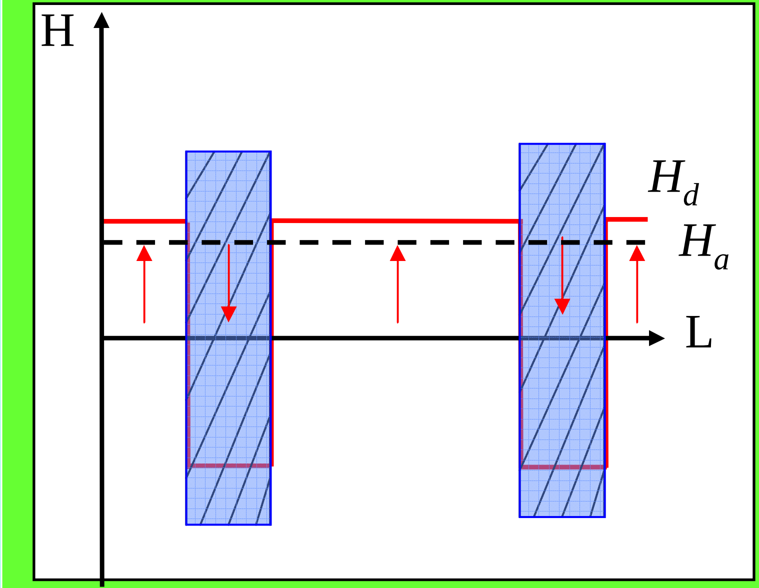
$H_a > +H_s$

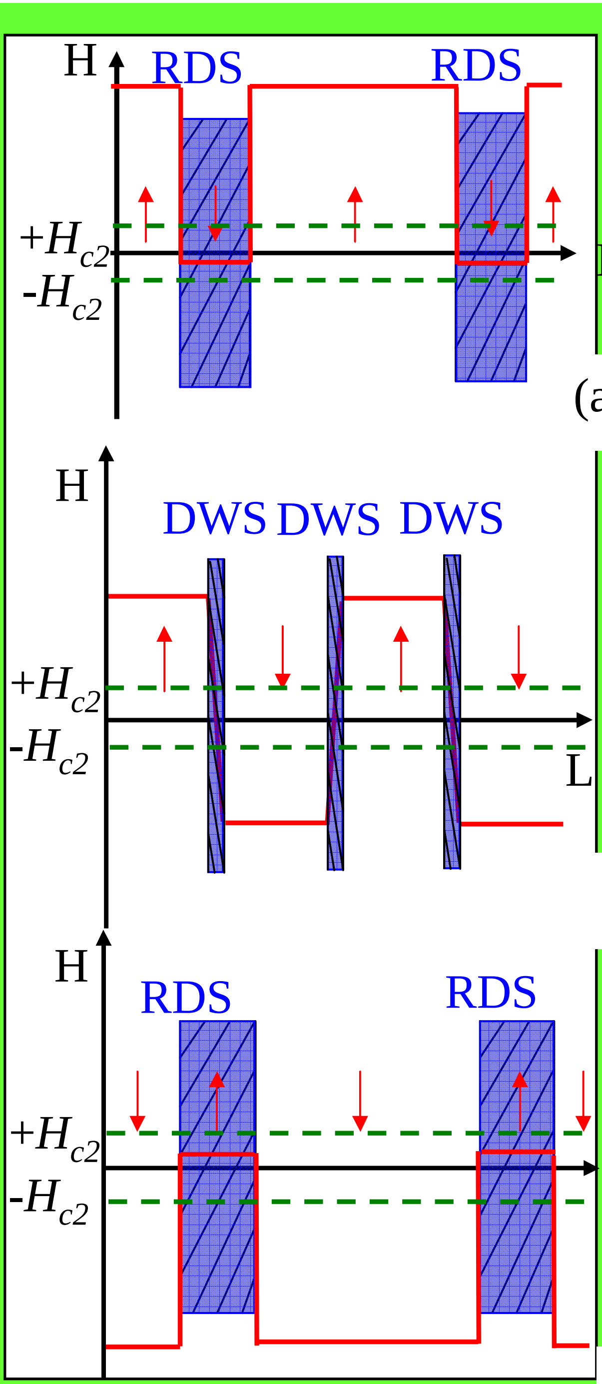
All domains are magnetized along the applied field

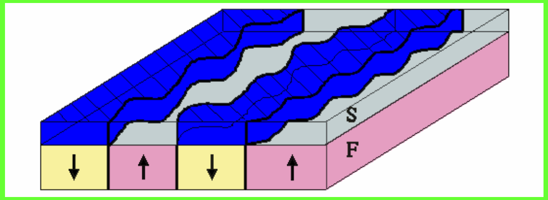
$$\vec{H} = \vec{H}_a + \vec{H}_d$$



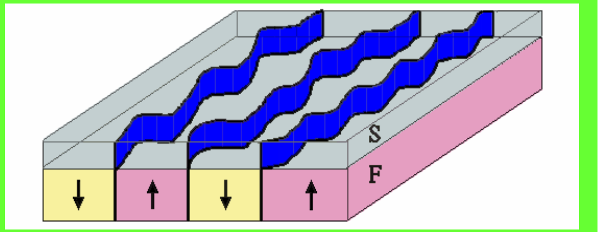
$H_a \approx +H_s$



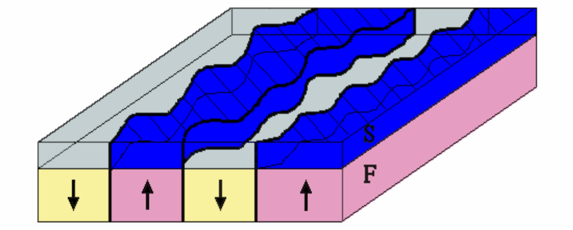




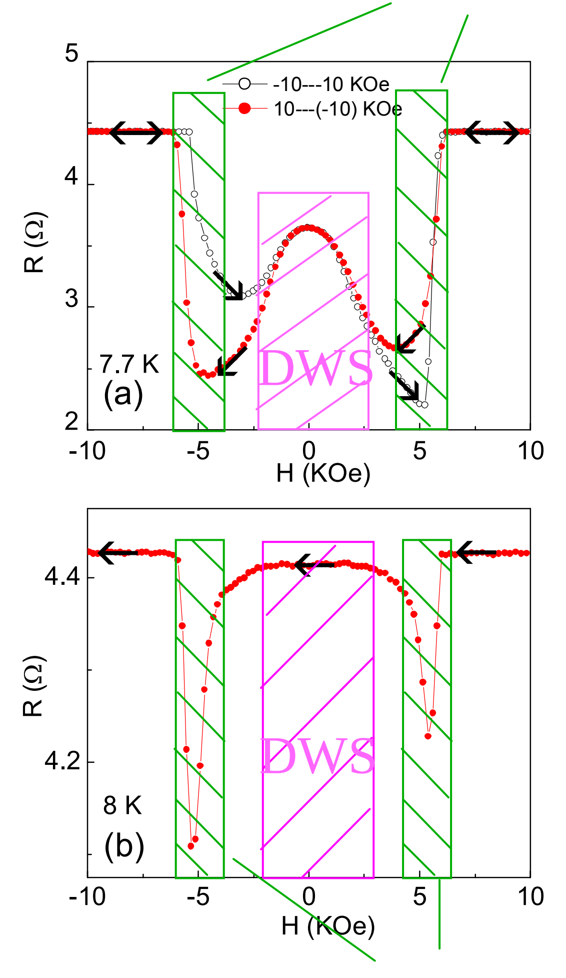
(a). $H_a \approx +H_s$



(b). $H_a \approx 0$

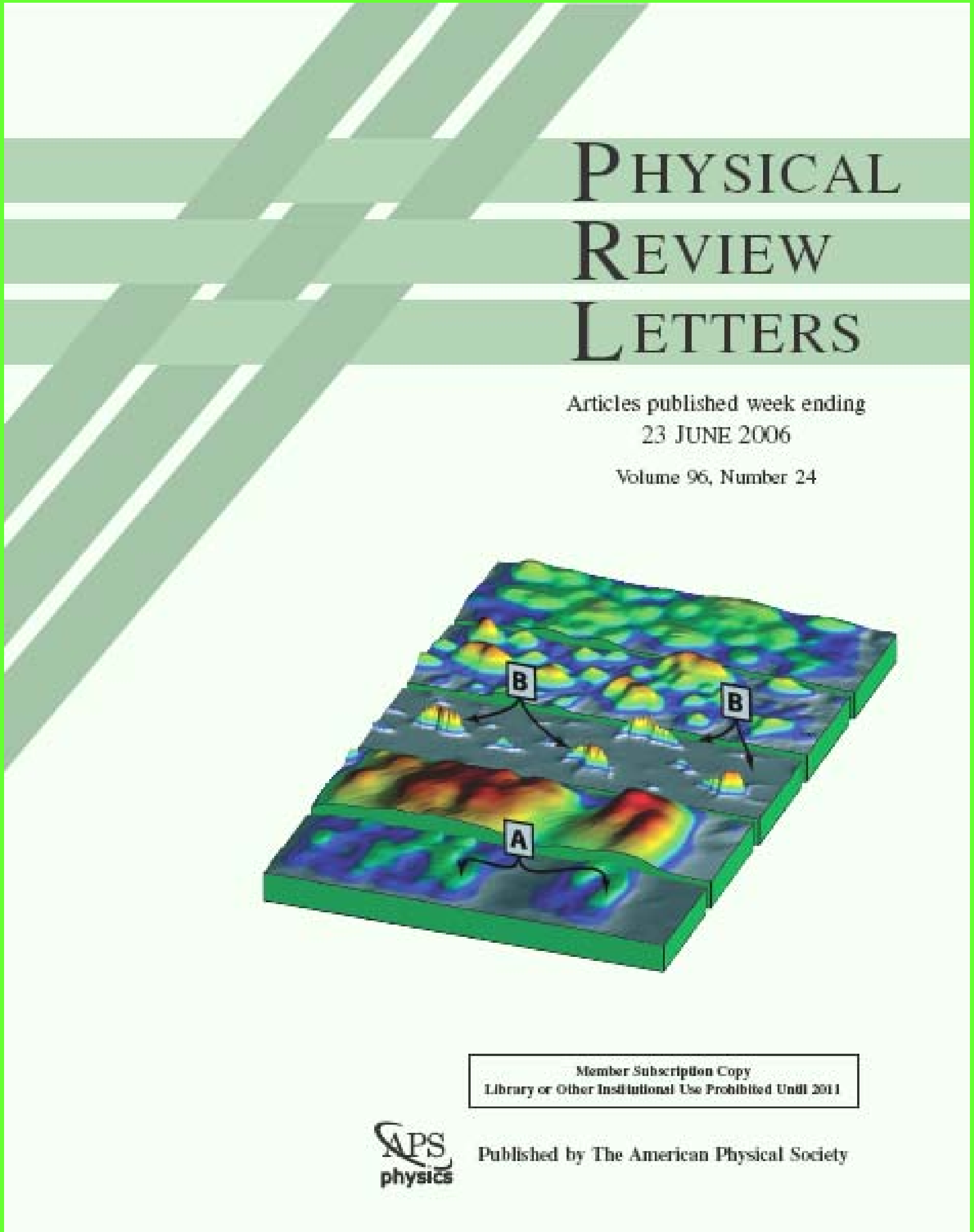


(c). $H_a \approx -H_s$



RDS

RDS



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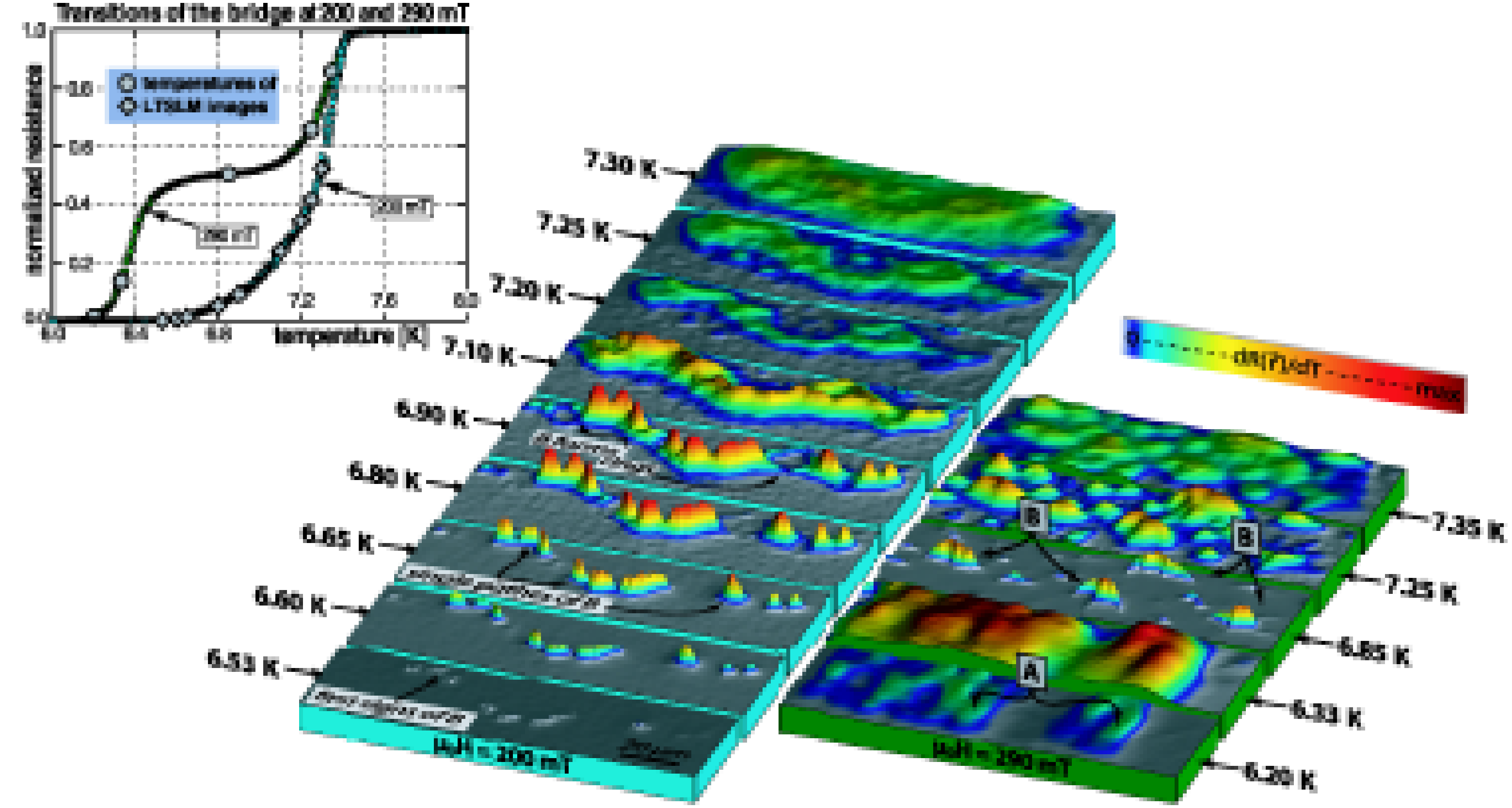
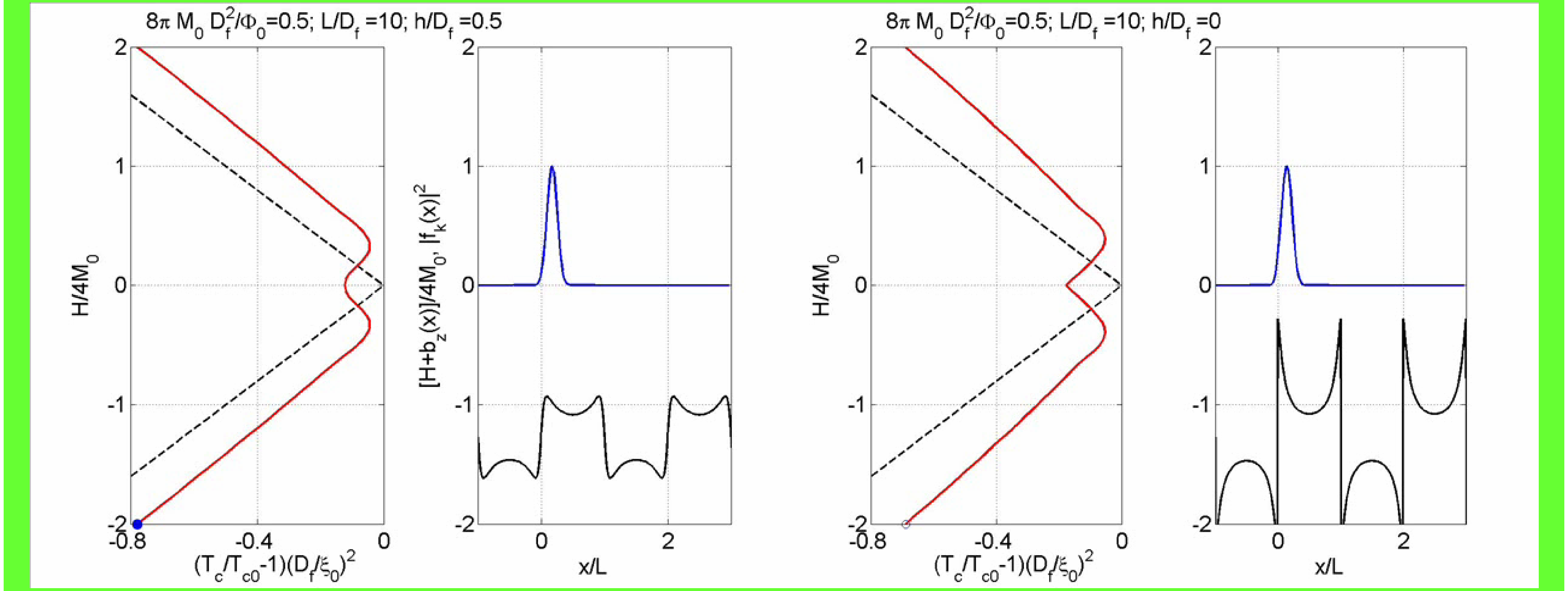


FIG. 3 (color online). Diagram: normalized resistance of the bridge vs temperature at 200 mT and 290 mT. Gray circles and diamonds indicate the temperatures at which the LTSLM images were taken. Images: temperature dependence of the LTSLM $dR(F)/dT$ signal of the Nb bridge at 200 mT (left series) and 290 mT (right series).

Evolution of superconductivity in external magnetic field



Vortex Manipulation by Magnetic Templates in F/S/F Structures

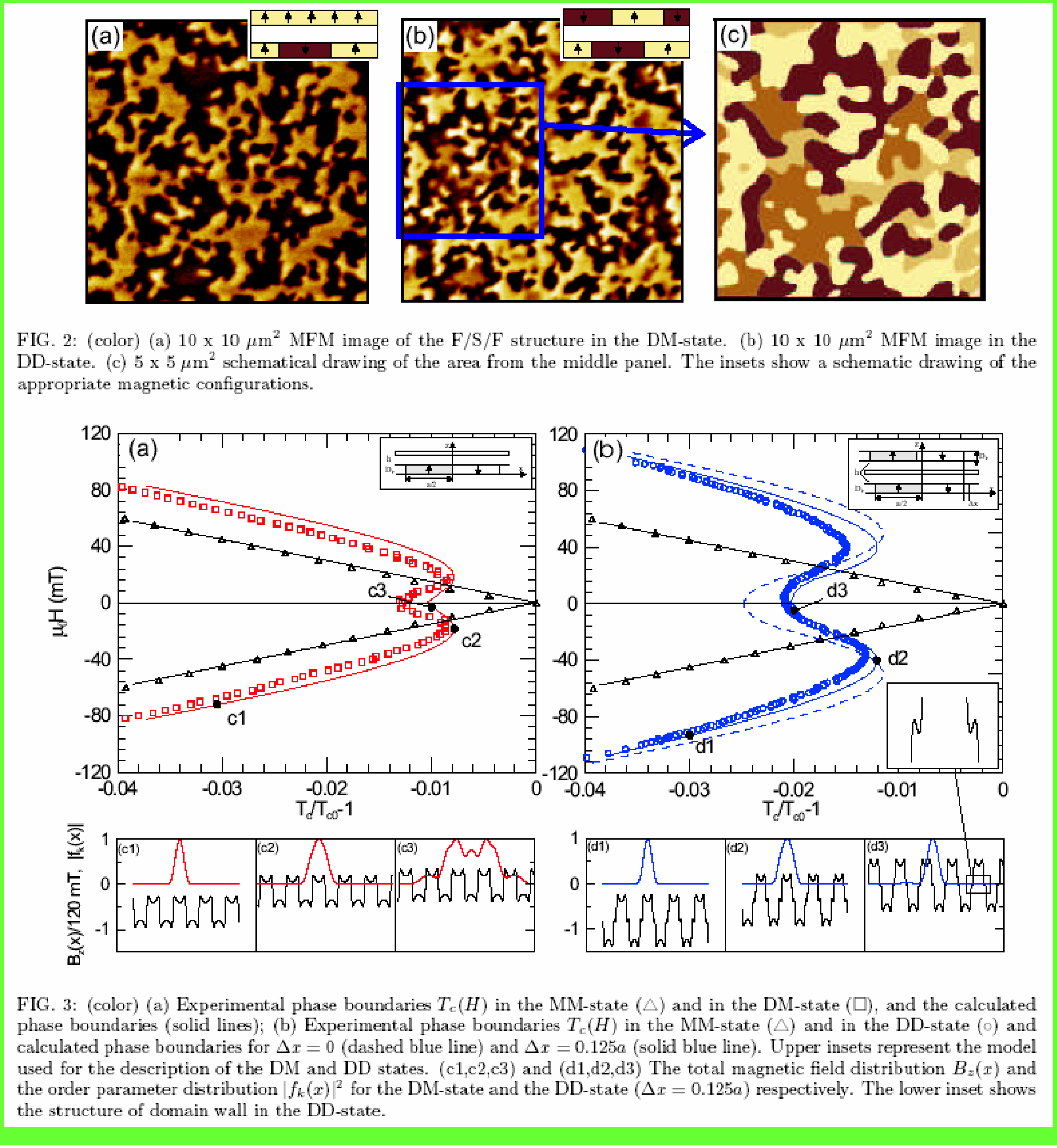


FIG. 2: (color) (a) 10 x 10 μm^2 MFM image of the F/S/F structure in the DM-state. (b) 10 x 10 μm^2 MFM image in the DD-state. (c) 5 x 5 μm^2 schematical drawing of the area from the middle panel. The insets show a schematic drawing of the appropriate magnetic configurations.

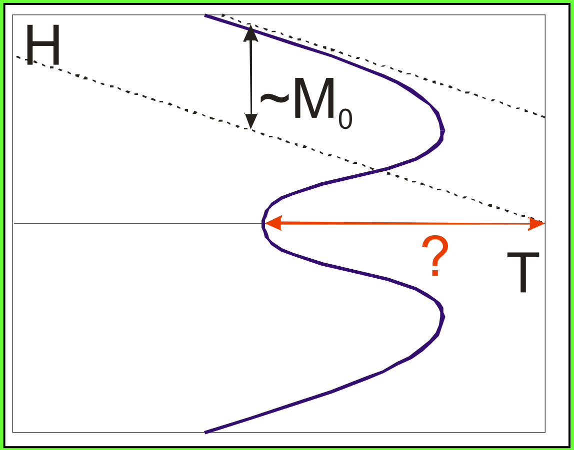
FIG. 3: (color) (a) Experimental phase boundaries $T_c(H)$ in the MM-state (△) and in the DM-state (□), and the calculated phase boundaries (solid lines); (b) Experimental phase boundaries $T_c(H)$ in the MM-state (△) and in the DD-state (○) and calculated phase boundaries for $\Delta x = 0$ (dashed blue line) and $\Delta x = 0.125a$ (solid blue line). Upper insets represent the model used for the description of the DM and DD states. (c1,c2,c3) and (d1,d2,d3) The total magnetic field distribution $B_z(x)$ and the order parameter distribution $|f_k(x)|^2$ for the DM-state and the DD-state ($\Delta x = 0.125a$) respectively. The lower inset shows the structure of domain wall in the DD-state.

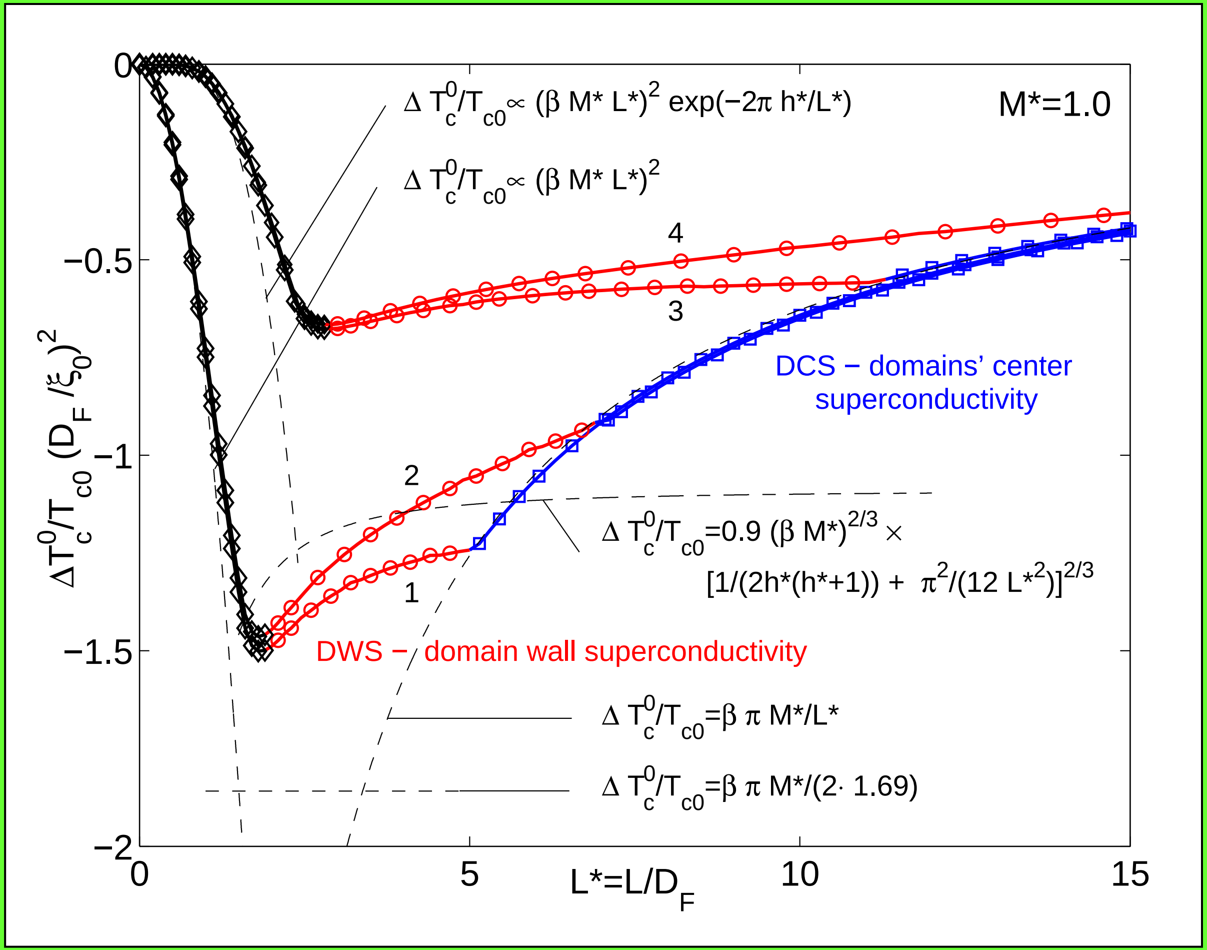
W. Gillijns, A. Aladyshkin, M. Lange, M. Van Bael, V.V. Moshchalkov, *Phys. Rev. Lett.*, 2005,

Conclusions

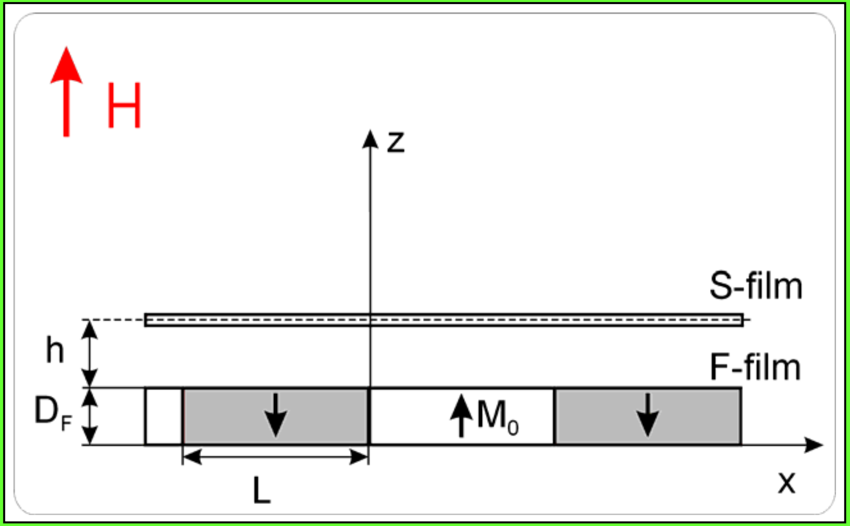
- DWS and RDS have been studied in S/F and F/S/F hybrids
- Hysteretic resistive transitions and field compensation effects have been observed
- “Magnetic protection” of superconductivity works

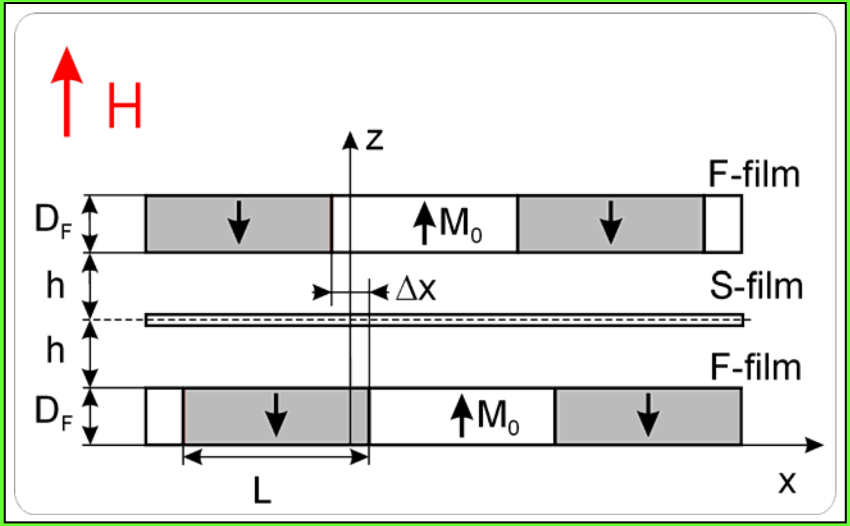
The nucleation in hybrids at H=0





S/F hybrids with one-dimensional periodical magnetic field





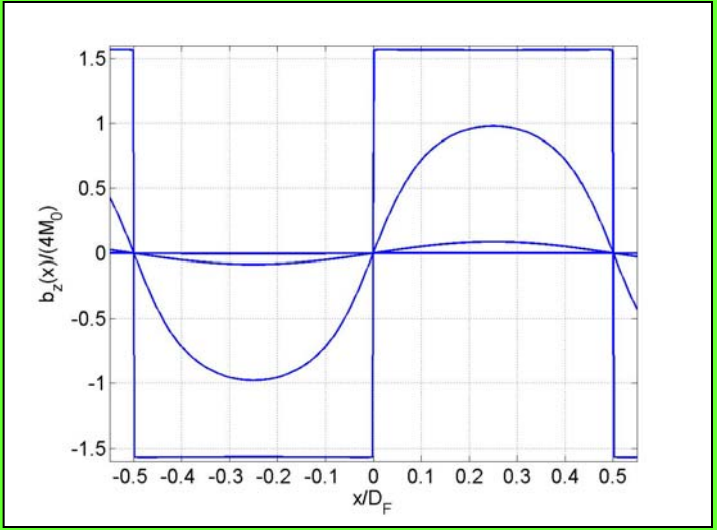
$$-\left(\nabla+\frac{2\pi i}{\Phi_0}\mathbf{A}\right)^2\Psi=\frac{1}{\xi^2(T)}\Psi$$

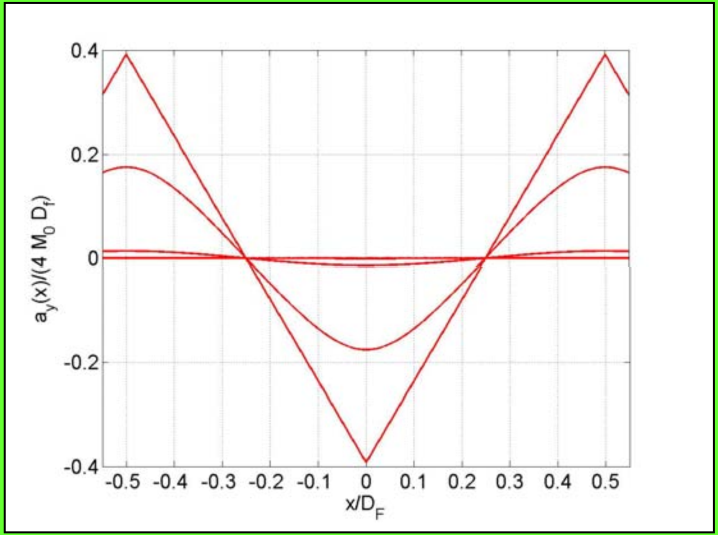
$$A_y(x,z)=Hx+a_y(x,z)$$

The magnetic field distribution depends strongly on the ratios

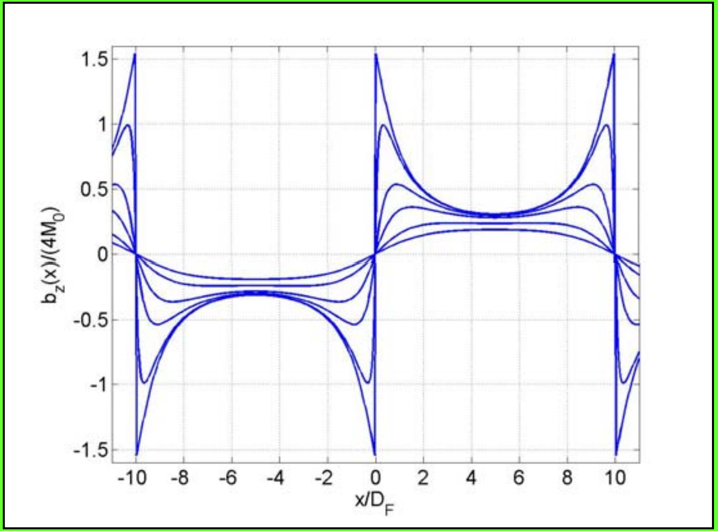
L/D_F and h/D_F

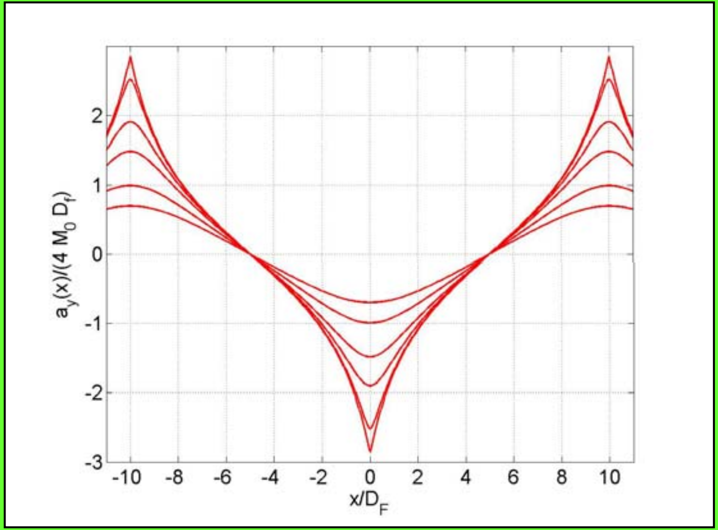
Thick ferromagnetic films, $L/D_F \ll 1$

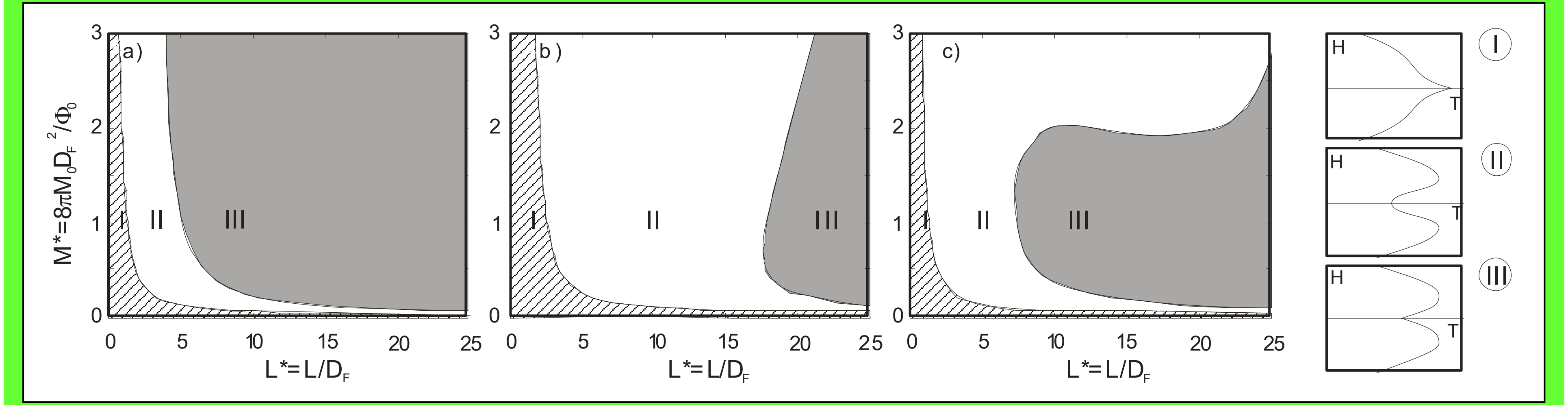


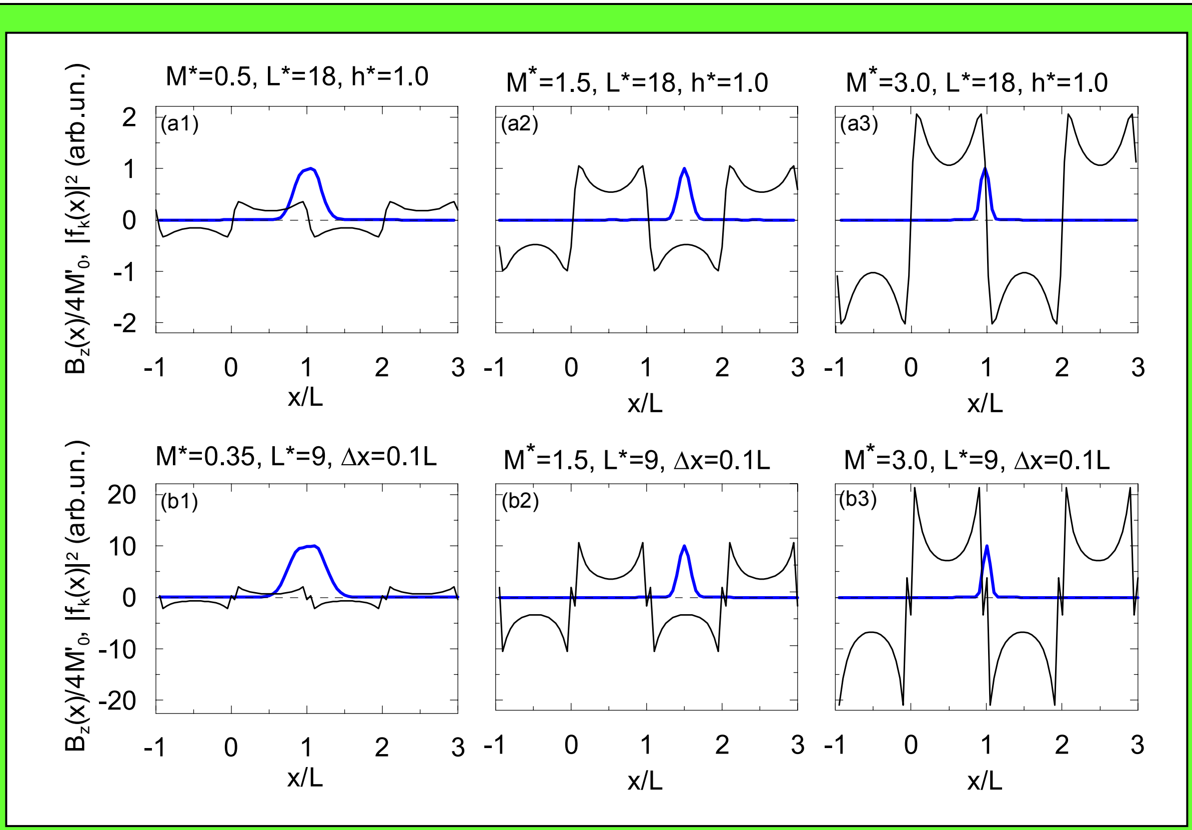


Thin ferromagnetic films, $L/D_F \gg 1$

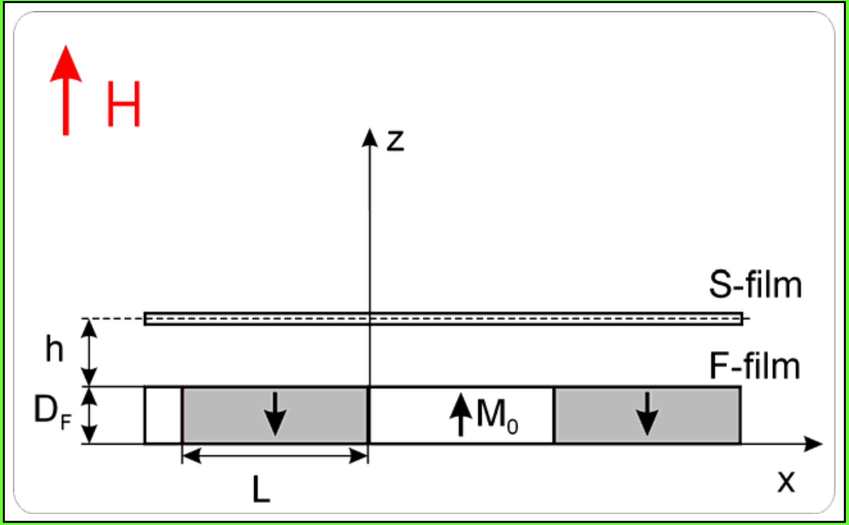





a)
b)
c)
I
II
III
M*=8πM$_0$D$_F$^{2}/Φ$_0$
L*=L/D$_F$
0
1
2
3
0
5
10
15
20
25
H
T
I
II
III


M*=0.5, L*=18, h*=1.0
M*=1.5, L*=18, h*=1.0
M*=3.0, L*=18, h*=1.0
(a1)
(a2)
(a3)
M*=0.35, L*=9, Δx=0.1L
M*=1.5, L*=9, Δx=0.1L
M*=3.0, L*=9, Δx=0.1L
(b1)
(b2)
(b3)
B$_z$(x)/4M'$_0$, |f$_k$(x)|^2 (arb.un.)
x/L
-1
0
1
2
3
-2
-20
-10
10
20

The further plans



$M^{*}=8\pi\, M_0 D_F^{\,2}/\Phi_0$

$L^{*}=L/D_F$

$h^{*}=h/D_F$

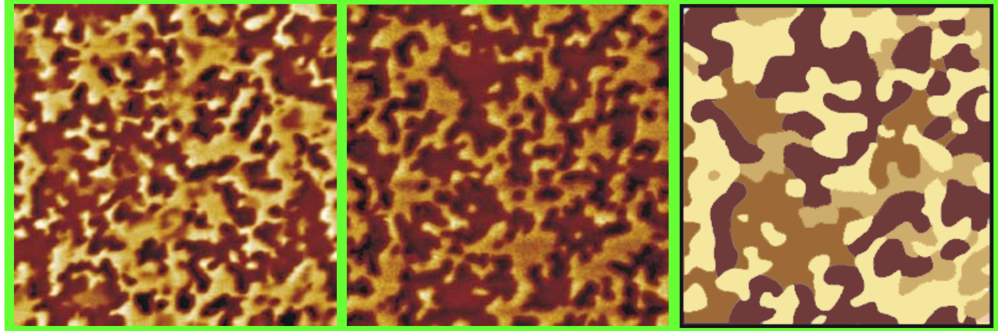
Physical realization + magnetic properties:

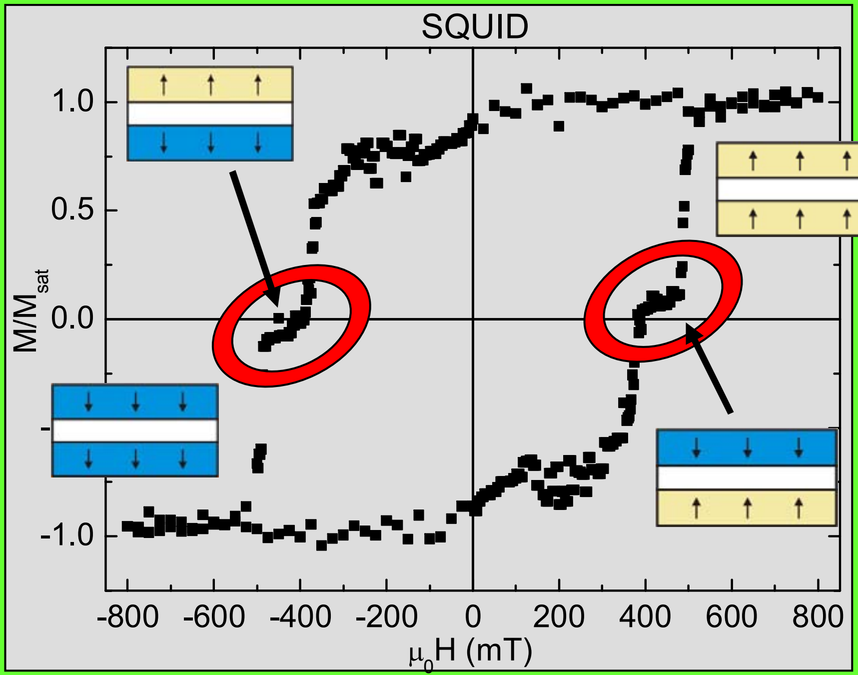
$[Co(0.8nm) / Pd(1.5nm)]_{10}$

$Nb(35nm)$

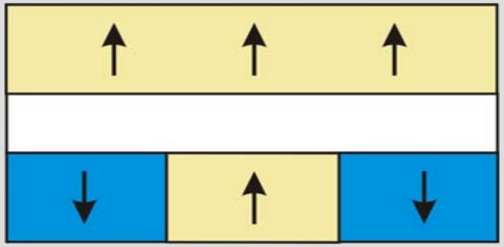
$[Co(0.8nm) / Pd(1.2nm)]_{10}$

Possibility to create three different magnetic states:

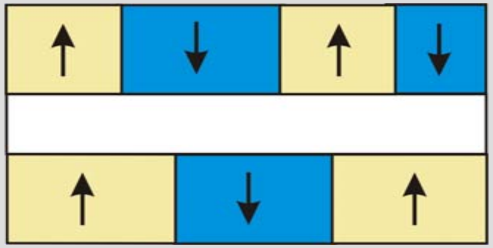




Half Demagnetized State (HDS):



Fully Demagnetized State (FDS):



Magnetized State (MS):