Voyage au pays du Nanomagnétisme

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http://neel.cnrs.fr

Modern applications of magnetism

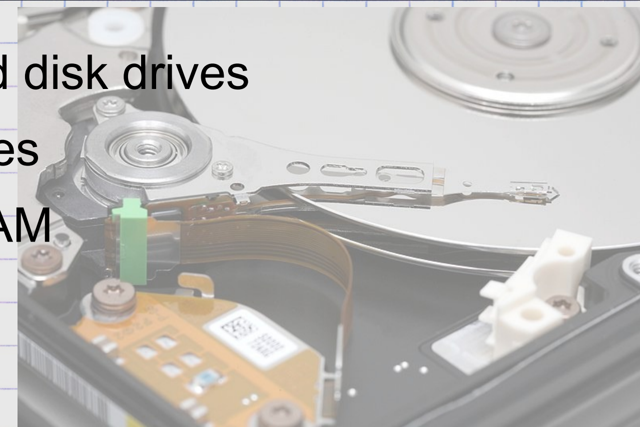
Where does 'nano' contribute ?

Materials

- ⇨ Magnets (→ motors and generators)
- ⇨ Transformers
- ⇨ Magnetocaloric

Data storage

- ⇨ Hard disk drives
- ⇨ Tapes
- ⇨ MRAM

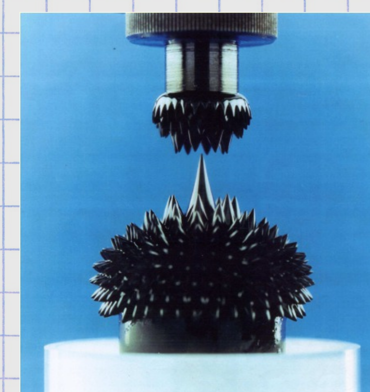


Sensors

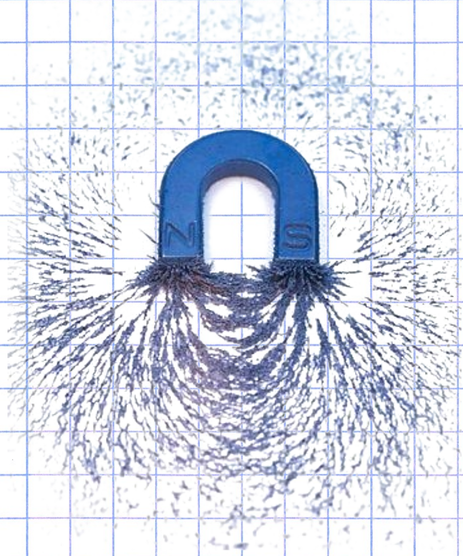
- ⇨ Compass
- ⇨ Field mapping
- ⇨ HDD read heads

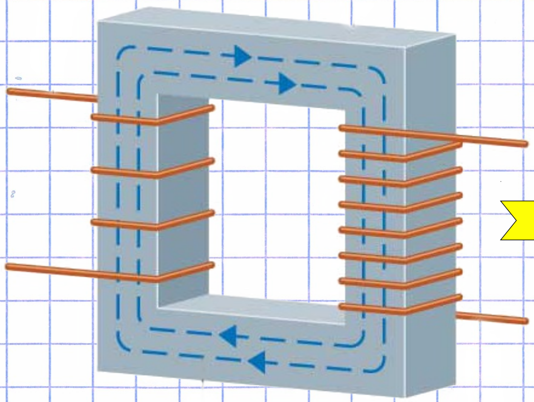
Nanoparticles

- ⇨ Ferrofluids
- ⇨ MRI contrast
- ⇨ Hyperthermia
- ⇨ Sorting & tagging



1. Fields, moments, materials





2. Magnetization processes

3. Low dimensions

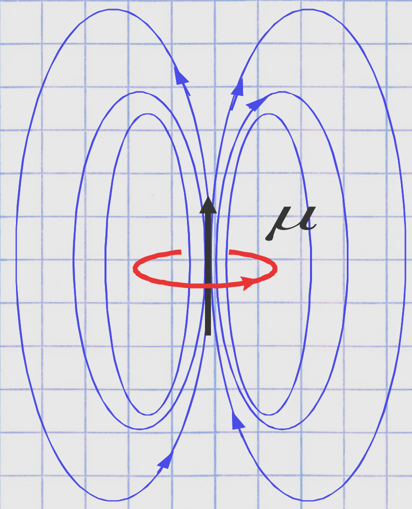
Maxwell equation : $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$

Electric currents produce magnetic fields

Oersted field

$$B_\theta = \frac{\mu_0 I}{2\pi r}$$

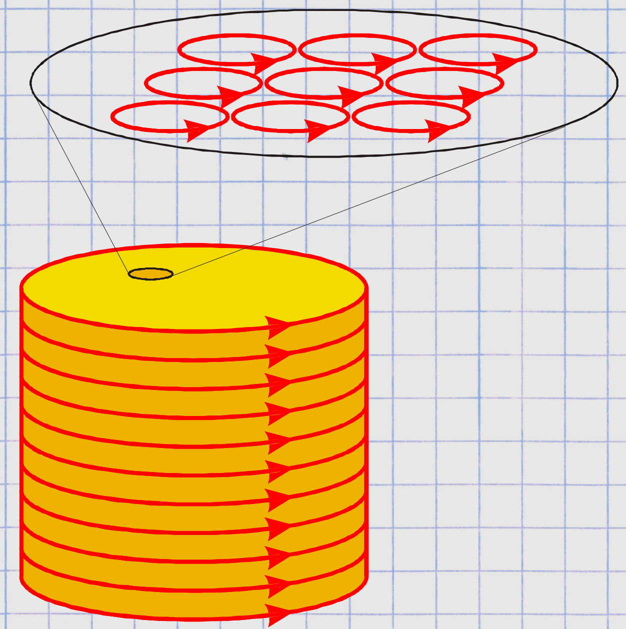
Magnetic dipole



$$\mathbf{B} = \frac{\mu_0}{4\pi r^3} \times \left[\frac{3}{r^2} (\boldsymbol{\mu} . \mathbf{r}) \mathbf{r} - \boldsymbol{\mu} \right]$$

Magnetic dipole $\mathrm{A.m^2}$

Magnetic material



Magnetization $\mathrm{A/m}$

Magnetic moment $\mathrm{A.m^2}$

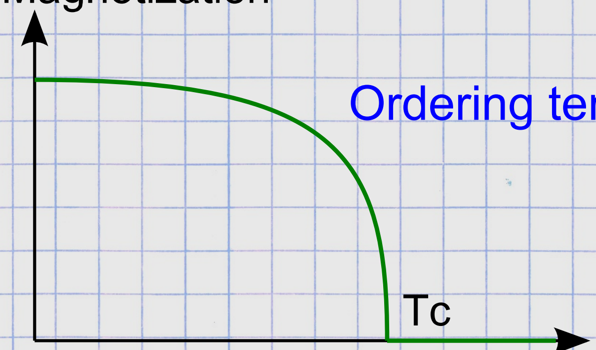
$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$ Induction **B**, Magnetic field **H**, Magnetization **M**

Magnetic ordering

Magnetic exchange

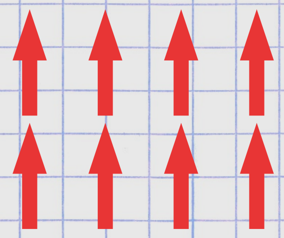
between microscopic moments

$$\mathcal{E} = -2\sum_{i>j} J_{i,j}\,\mathbf{S_i}\cdot\mathbf{S_j}$$



Ferromagnet

$J_{i,j} > 0$



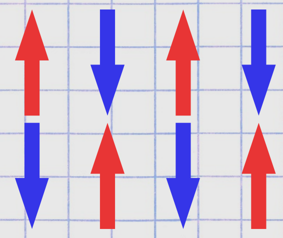
Fe

$T_C = 1043$ K

$M_s = 1.73\times10^6$ A/m

Antiferromagnet

$J_{i,j} < 0$



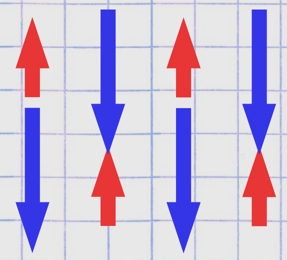
CoO

$T_N = 292$ K

$J = 3/2$

Ferrimagnet

$J_{i,j} < 0$



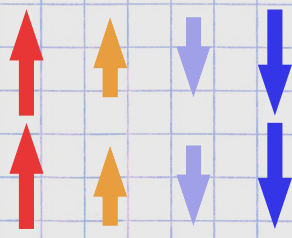
Fe3O4

$T_C = 858$ K

$M_s = 480$ kA/m

Helical

$J_1, J_2 \ldots$

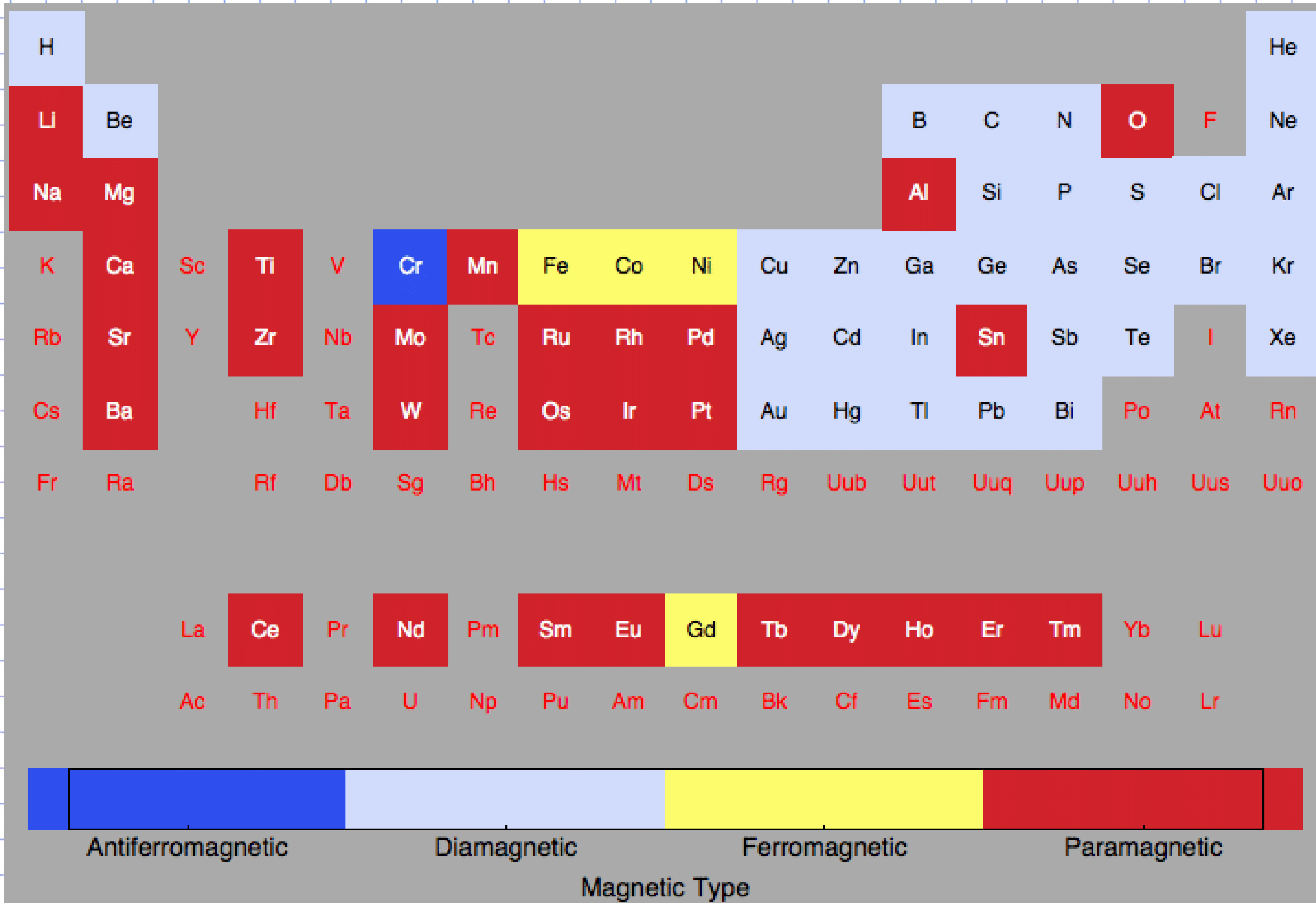


Dy

$T \in 85-179$ K

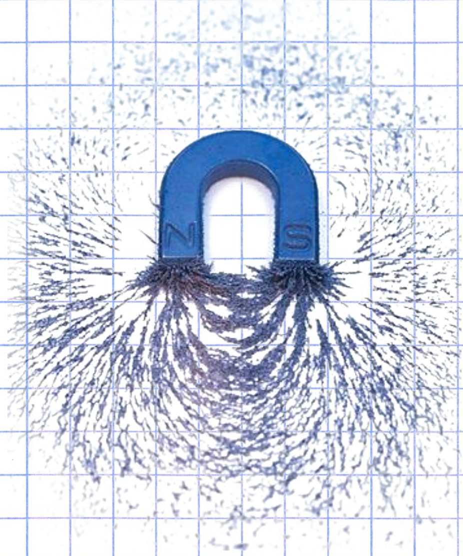
$\mu = 10.4\mu_B$

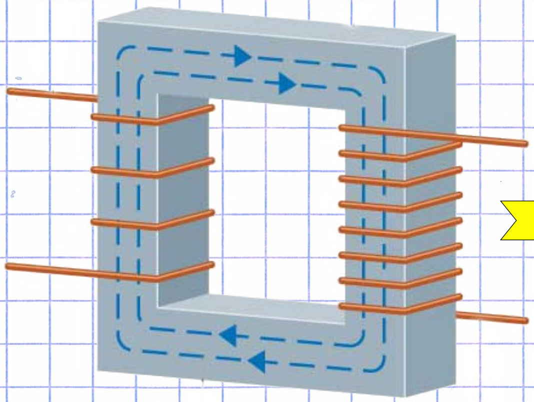
Magnetic properties at room temperature, single elements



Periodictable.com

1. Fields, moments, materials



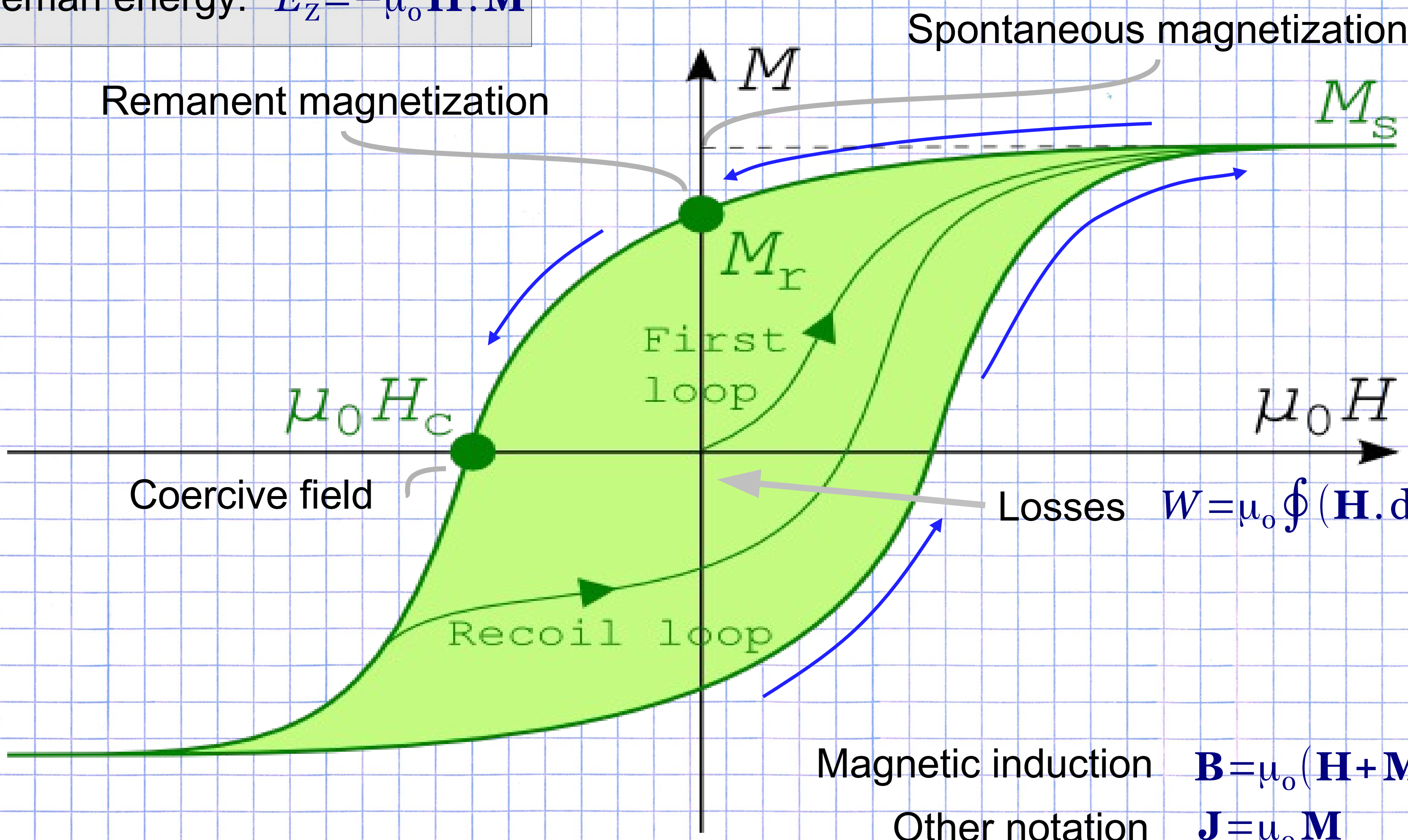


2. Magnetization processes

3. Low dimensions

Manipulation of magnetic materials:
→ Application of a magnetic field

Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}$

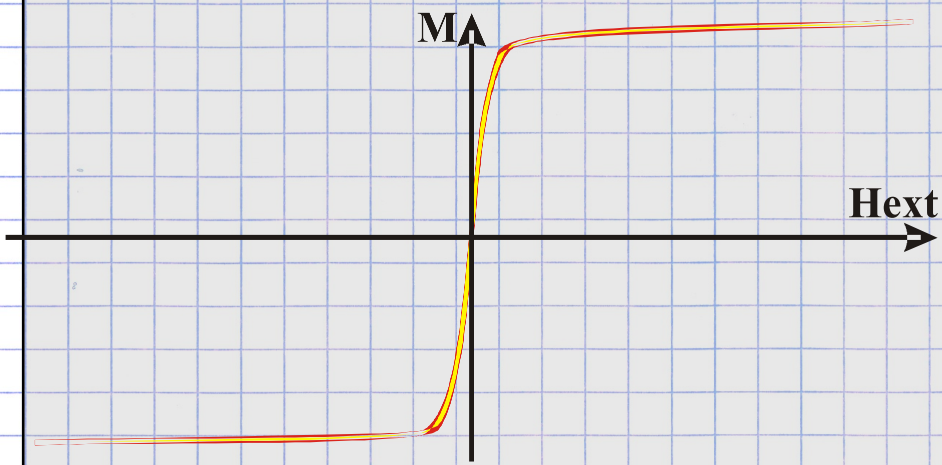


Losses $W = \mu_0 \oint (\mathbf{H}.\mathrm{d}\mathbf{M})$

Magnetic induction $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$

Other notation $\mathbf{J} = \mu_0 \mathbf{M}$

Soft magnetic materials

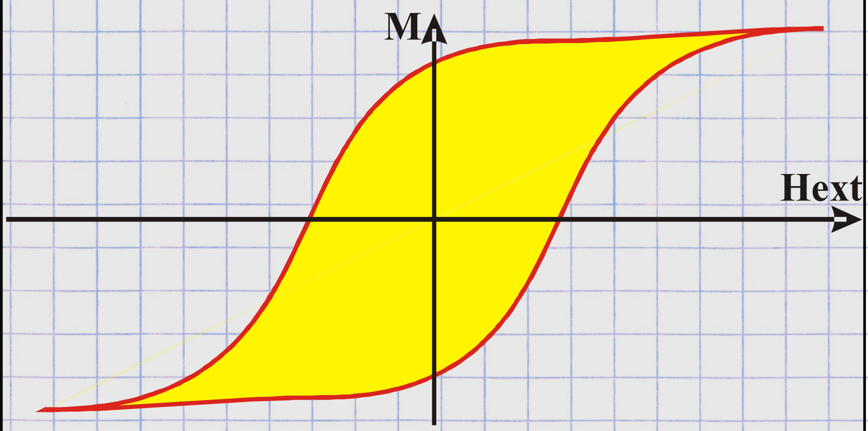


Transformers

Flux guides, sensors

Magnetic shielding

Hard magnetic materials

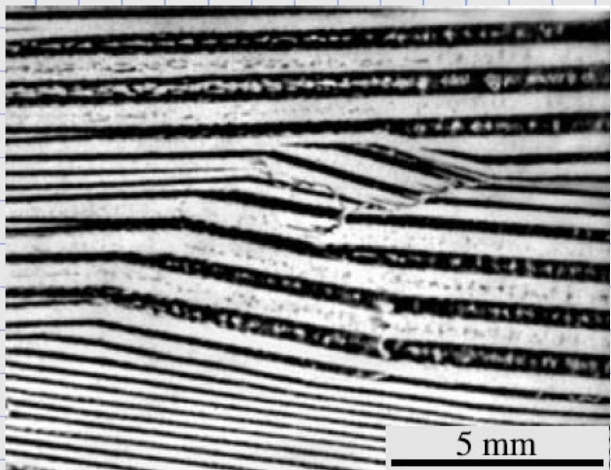


Permanent magnets, motors

Magnetic recording

Bulk material

Numerous and complex magnetic domains

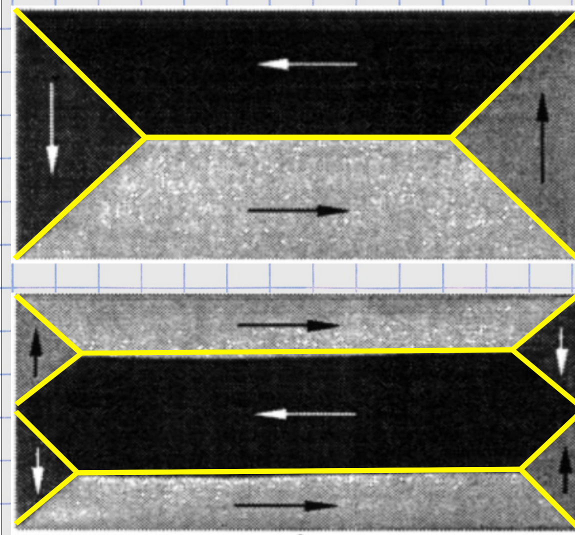


FeSi soft sheet

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

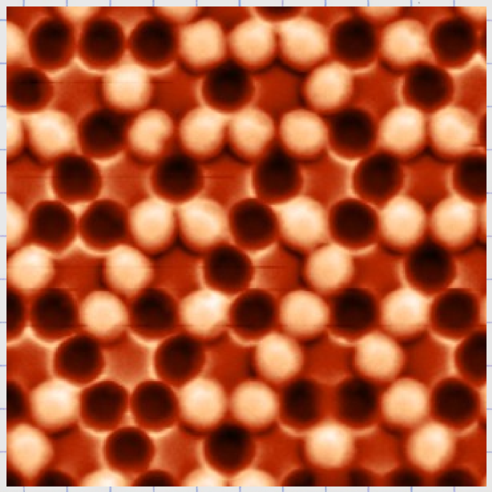


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

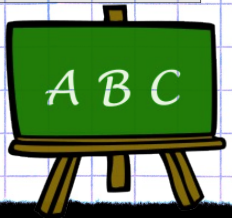
Magnetic single-domain



Nanofabricated dots
MFM

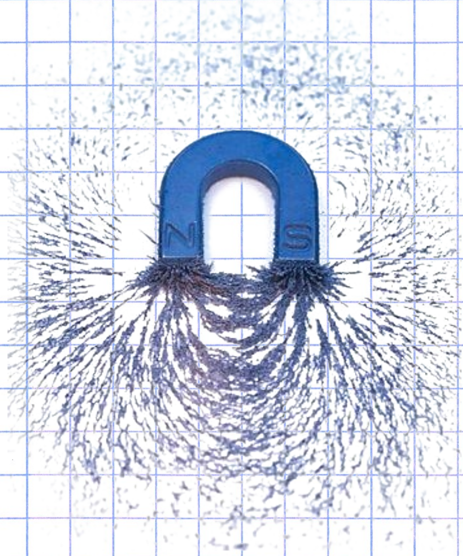
Sample courtesy :
N. Rougemaille, I. Chioar

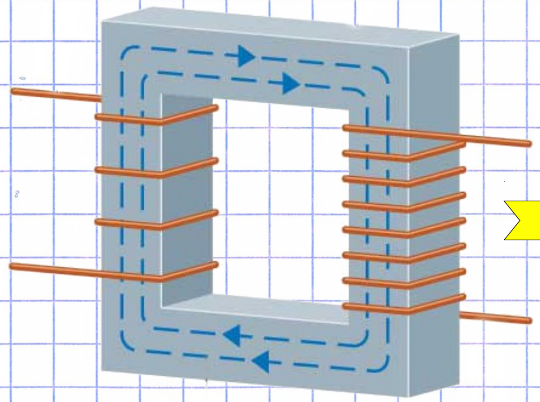
Nanomagnetism ~ mesoscopic magnetism



How small is 'Nano' ?

1. Fields, moments, materials





2. Magnetization processes

3. Low dimensions

Magnetization

Magnetization vector **M** → $\mathbf{M}=\begin{pmatrix}M_x\\M_y\\M_z\end{pmatrix}=M_S\begin{pmatrix}m_x\\m_y\\m_z\end{pmatrix}$

Can vary in time and space.

Modulus is constant
(hypothesis in micromagnetism) → $m_x^2+m_y^2+m_z^2=1$

Mean-field approach possible: $M_S=M_S(T)$

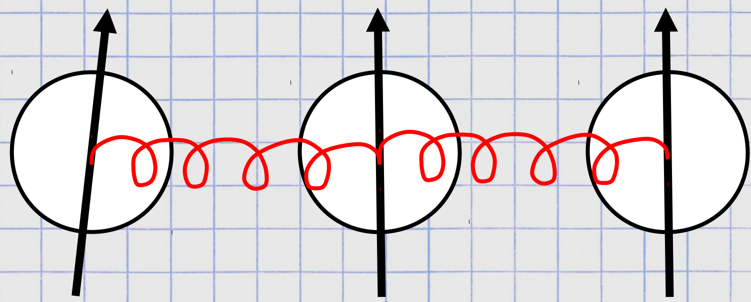
Exchange interaction

Atomistic view : $\mathscr{E}=-2\sum_{i>j} J_{i,j}\mathbf{S_i}.\mathbf{S_j}$ (total energy)

Micromagnetic view : $\mathbf{S_i}.\mathbf{S_j}=S^2\cos\theta_{i,j}\approx S^2(1-\theta_{i,j}^2/2)$

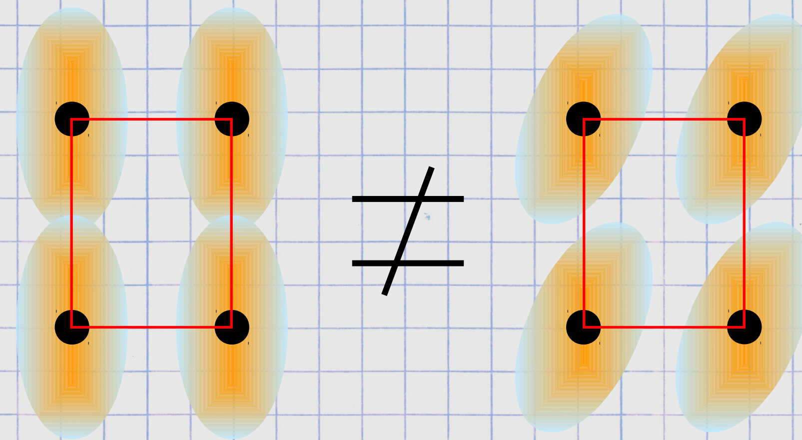
$E=A(\nabla.\mathbf{m})^2$ (energy per unit volume)

Exchange energy



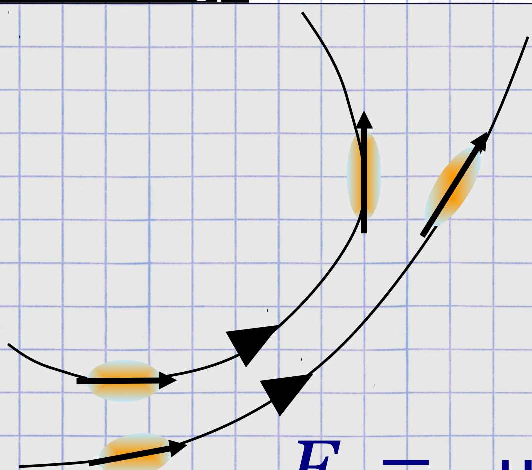
$$E_{ex}=A\left(\nabla.\mathbf{m}\right)^2$$

Magnetocrystalline anisotropy energy



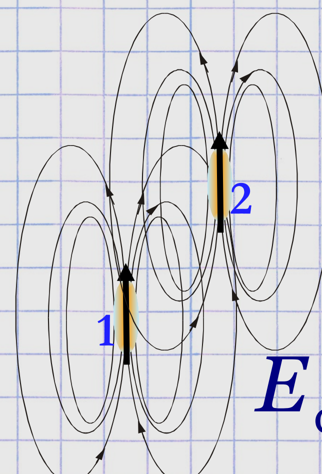
$$E_{mc}=K\sin^2\theta$$

Zeeman energy



$$E_d=-\mu_o\mathbf{M.H}$$

Dipolar energy



$$E_d=-\frac{1}{2}\mu_o\mathbf{M.H_d}$$

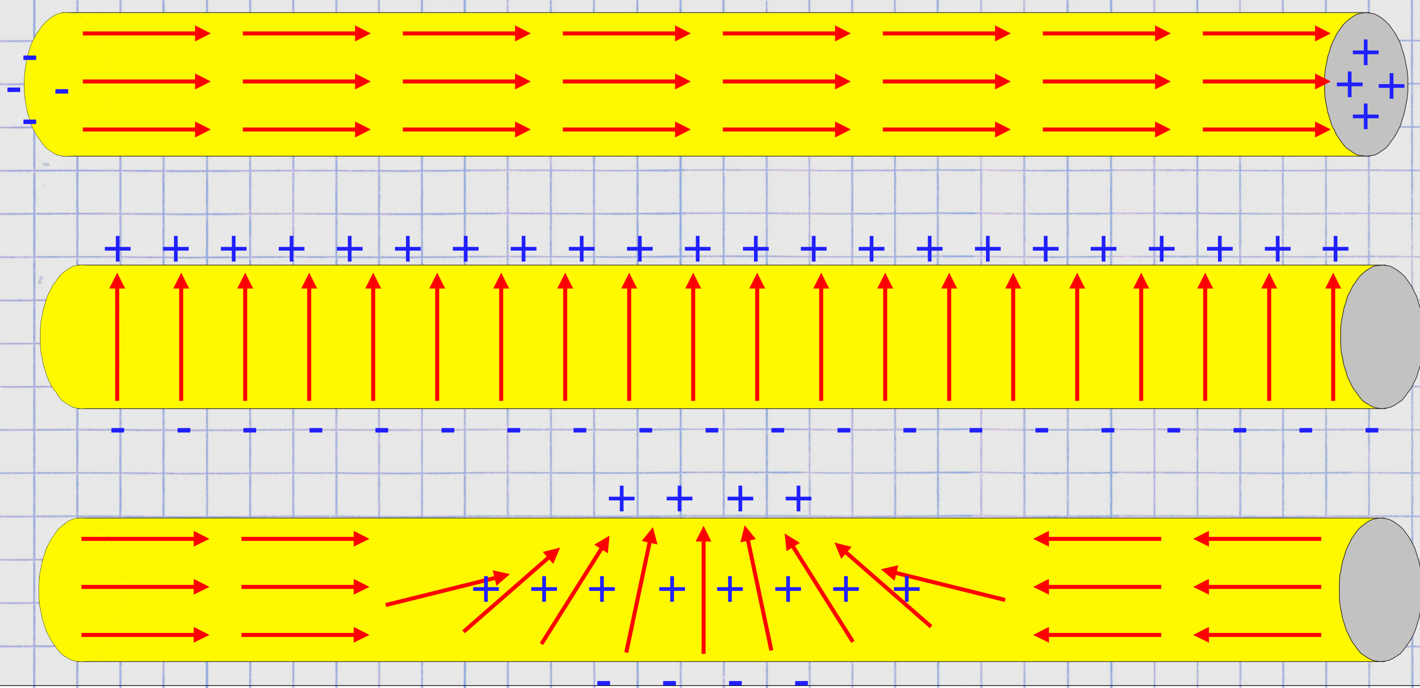
Magnetic charges

Maxwell equation → $\operatorname{div}(\mathbf{H}_\mathrm{d}) = -\operatorname{div}(\mathbf{M})$

$\rho(\mathbf{r}) = -M_\mathrm{s}\operatorname{div}[\mathbf{m}(\mathbf{r})]$ → volume density of magnetic charges

$\sigma(\mathbf{r}) = M_\mathrm{s}\mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$ → surface density of magnetic charges

Examples of magnetic « charges »



Notice: no charges and $\mathcal{E}$=0 for infinite cylinder

Charges on surfaces

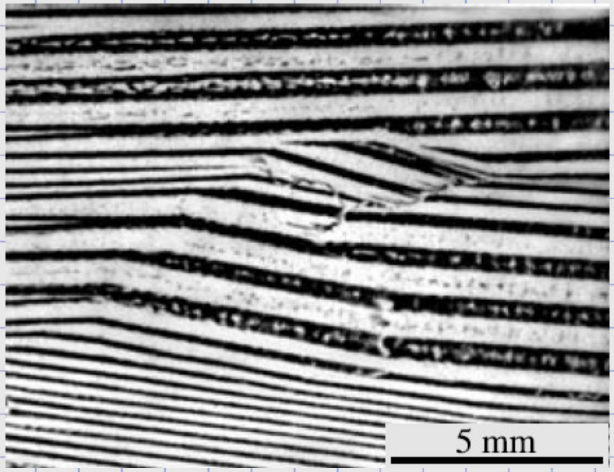
Surface and volume charges

Take-away message

➯ Dipolar energy favors alignement of magnetization with longest direction of sample

Bulk material

Numerous and complex magnetic domains



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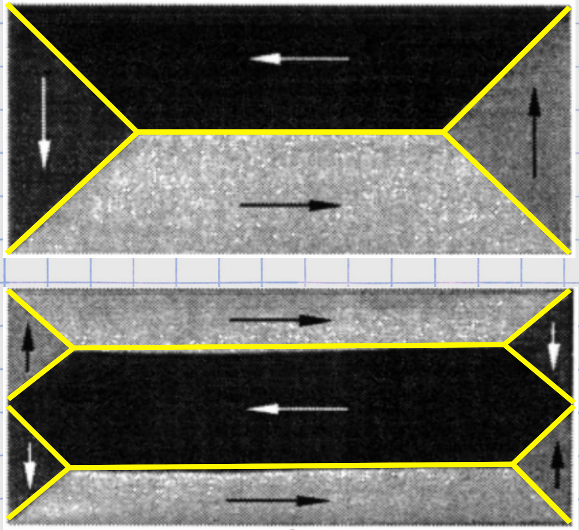
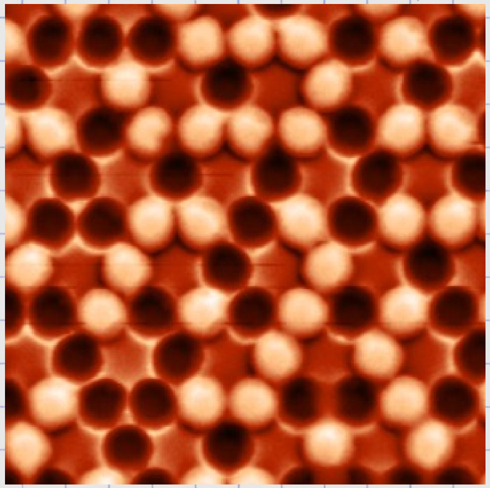


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain



Nanofabricated dots
MFM

Sample courtesy :
N. Rougemaille, I. Chioar

↳ Nanomagnetism ~ mesoscopic magnetism

Anisotropy exchange length

$$E = A(\partial_x \theta)^2 + K \sin^2\theta$$

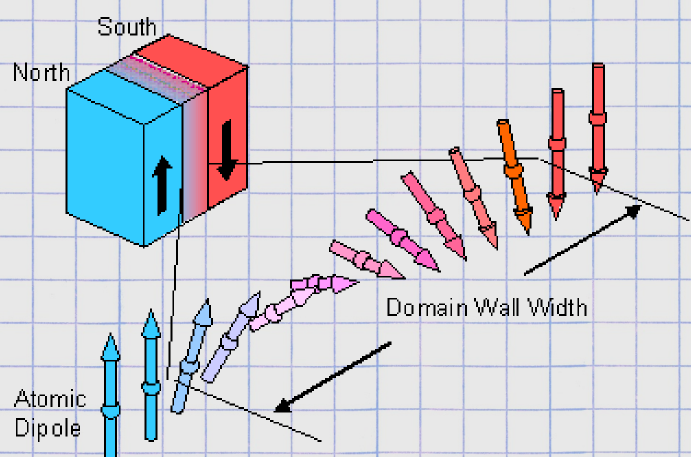
Exchange → J/m

Anisotropy → J/m^3

Anisotropy exchange length:

$\Delta_u \approx 1$ nm → $\Delta_u \geq 100$ nm

Hard Soft



Often called *Bloch parameter* or *domain-wall width*

Dipolar exchange length

$$E = A(\partial_x \theta)^2 + K_d \sin^2\theta$$

Exchange → J/m

Dipolar energy → J/m^3

$$K_d = \frac{1}{2}\mu_0 M_s^2$$

Dipolar exchange length:

$$= \sqrt{2A/\mu_0 M_s^2}$$

$$\Delta_d \approx 3 - 10 \text{ nm}$$

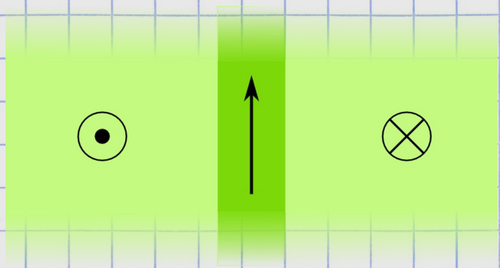
Single-domain critical size relevant for nanoparticules made of soft magnetic material

Often called *Exchange length*

Notice:

Other length scales: with field etc.

Bloch domain wall in the bulk (2D)

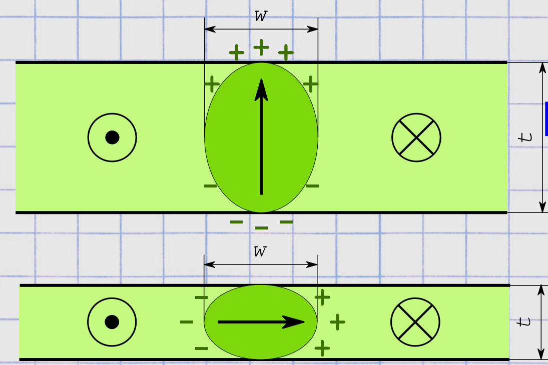


- No magnetostatic energy
- Width $\Delta_u = \sqrt{A/K}$
- Areal energy $\gamma_W = 4\sqrt{AK}$

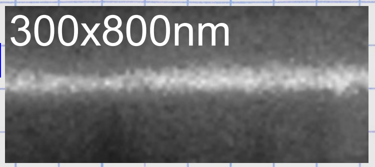
Other angles & anisotropy

F. Bloch, Z. Phys. 74, 295 (1932)

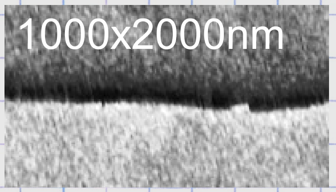
Domain walls in thin films (2D → 1D)



Bloch wall
$t \gtrsim w$



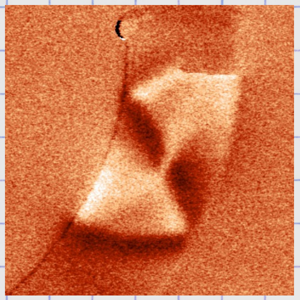
Néel wall
$t \lesssim w$



- Contains magnetostatic energy
- No exact analytics

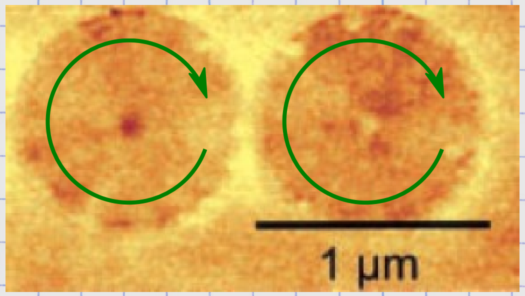
L. Néel, C. R. Acad. Sciences 241, 533 (1956)

Constrained walls (eg : in stripes)



Permalloy (15nm)
Strip 500nm

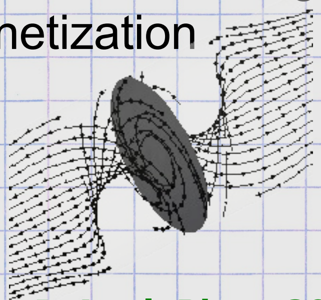
Magnetic vortex (1D → 0D)



T. Shinjo et al., Science 289, 930 (2000)

Bloch point (0D)

- Point with vanishing magnetization

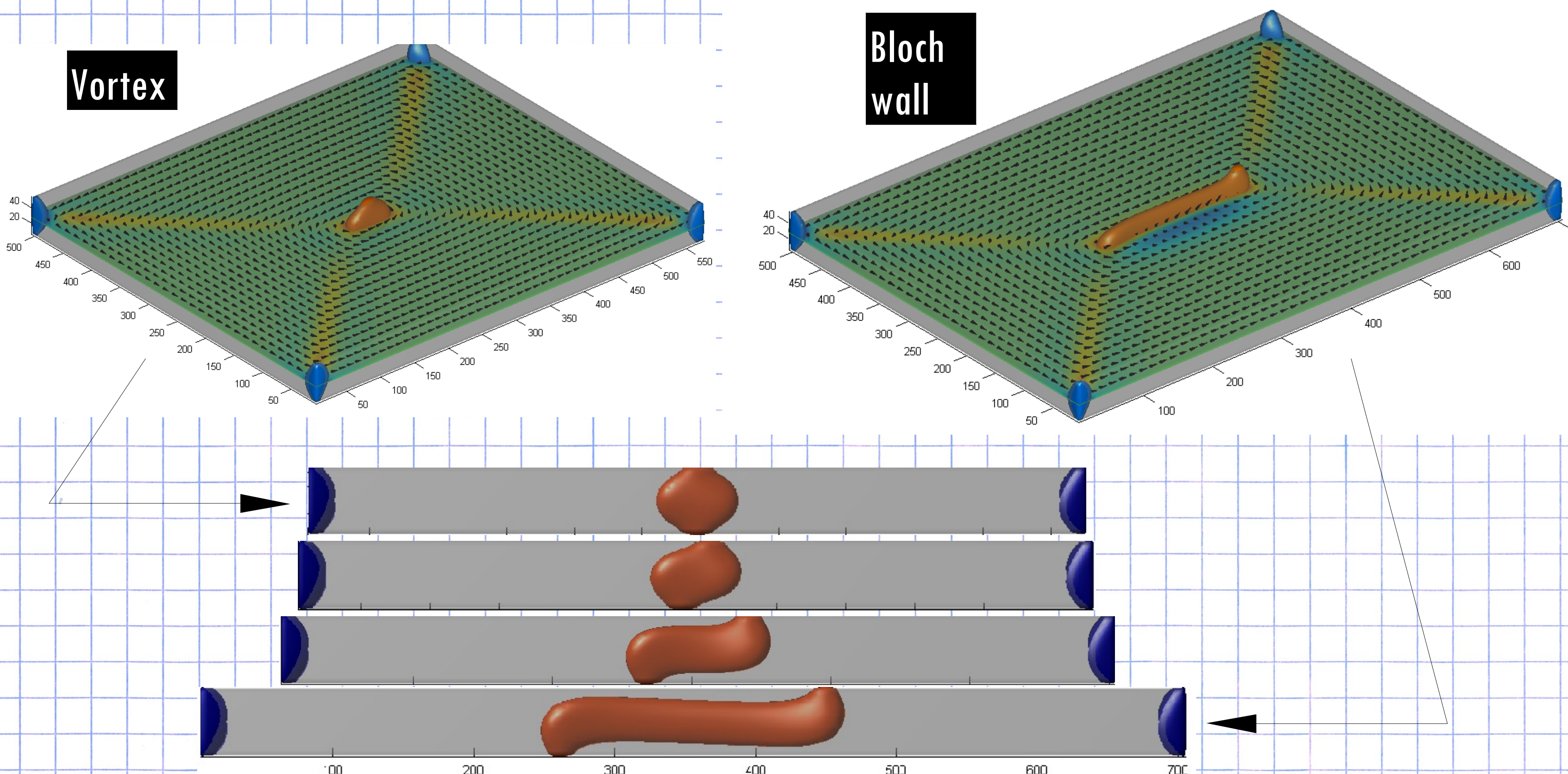


W. Döring, J. Appl. Phys. 39, 1006 (1968)

1. **Low-dimensional structures in nanomagnetism**

2. **What could come next for magnetism in data storage ?**

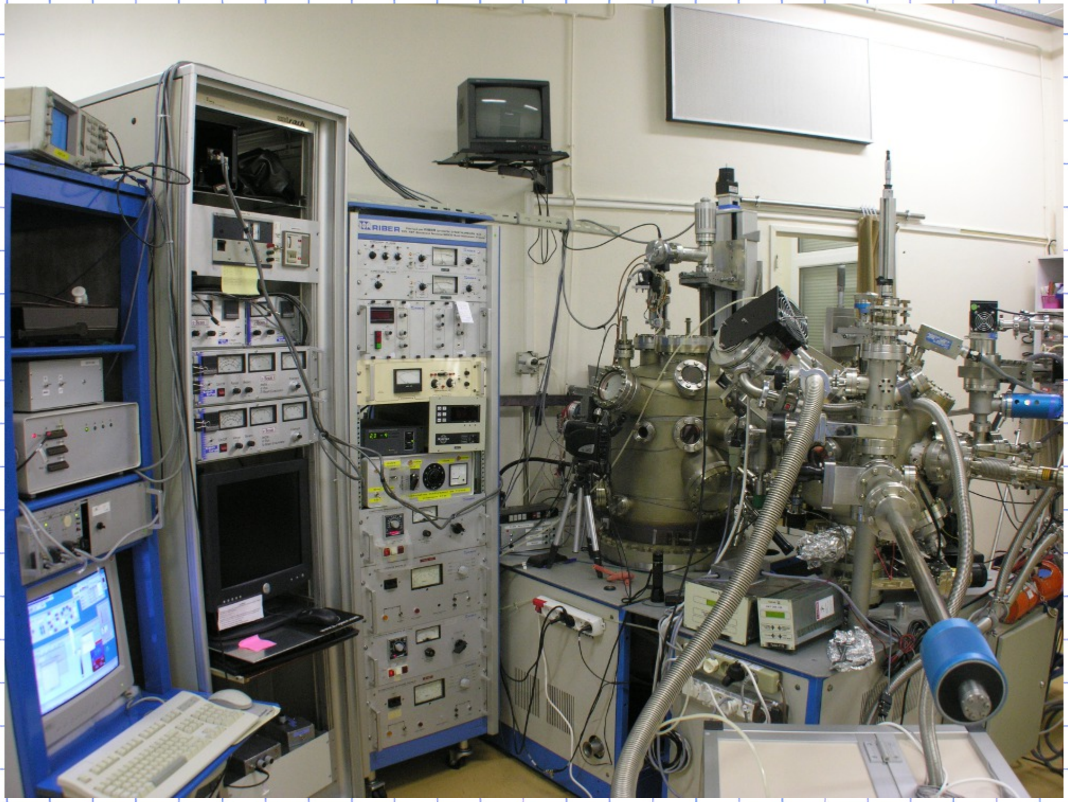
3. **An example of academic study towards 'next'**

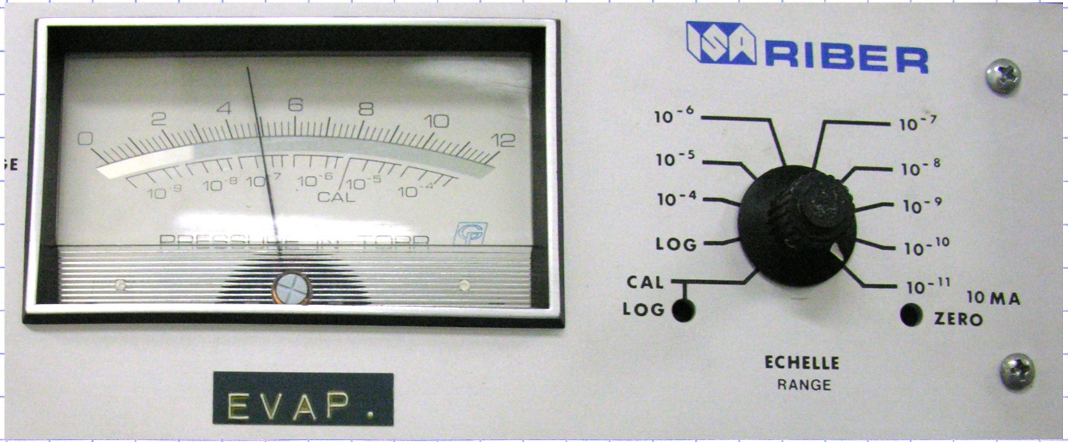


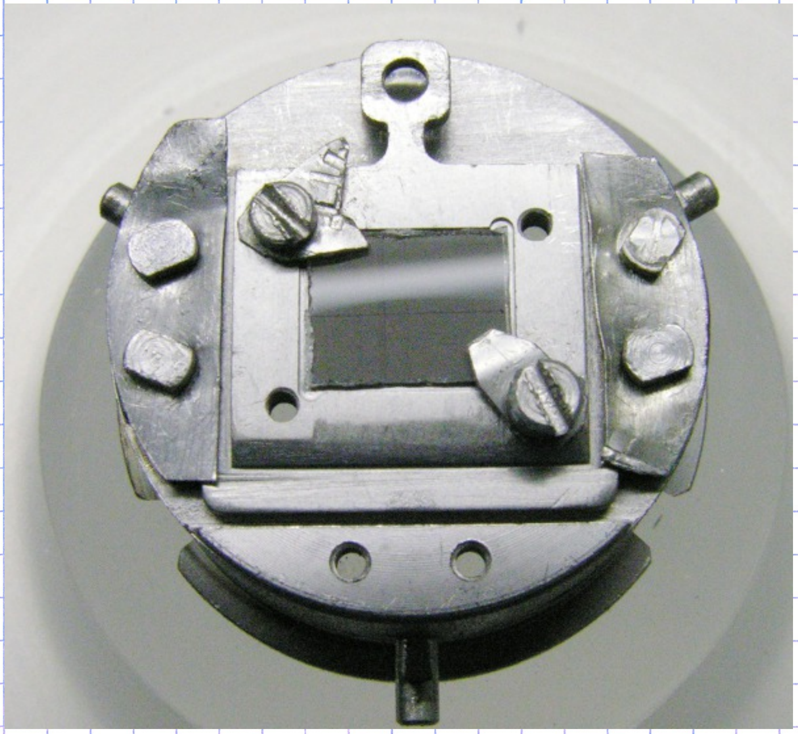
A. Masseboeuf et al., Phys. Rev. Lett. 104, 127204 (2010)

↳ Elongated dots → Breaking of symmetry (2nd order transition) → Order parameter

How does an ultra-high vacuum setup for epitaxy (single-crystal) growth look like ?

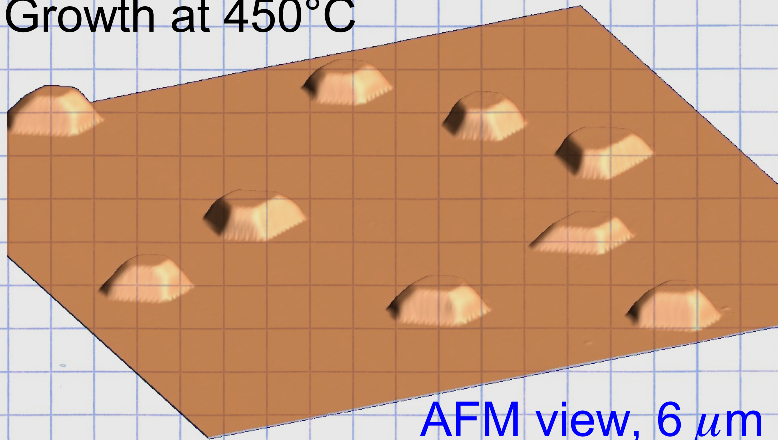




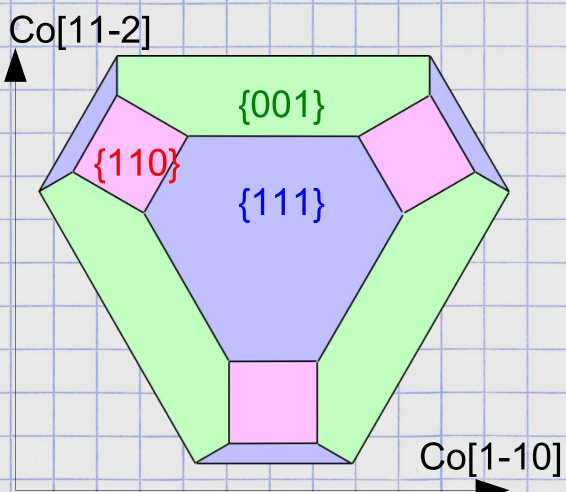


Growth and structure

Stacking: Al2O3(11-20) \ W[10nm] \ Co \ Au
Growth at 450°C



AFM view, 6 μm FoV

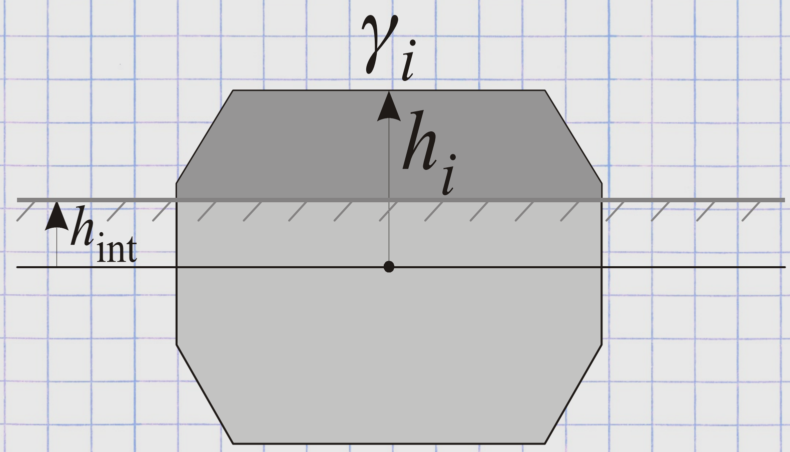


O. Fruchart et al., J. Phys. : Condens. Matter 25, 496002 (2013)

Wulff Kaishev's theorem

Supported crystal (growth on surfaces)

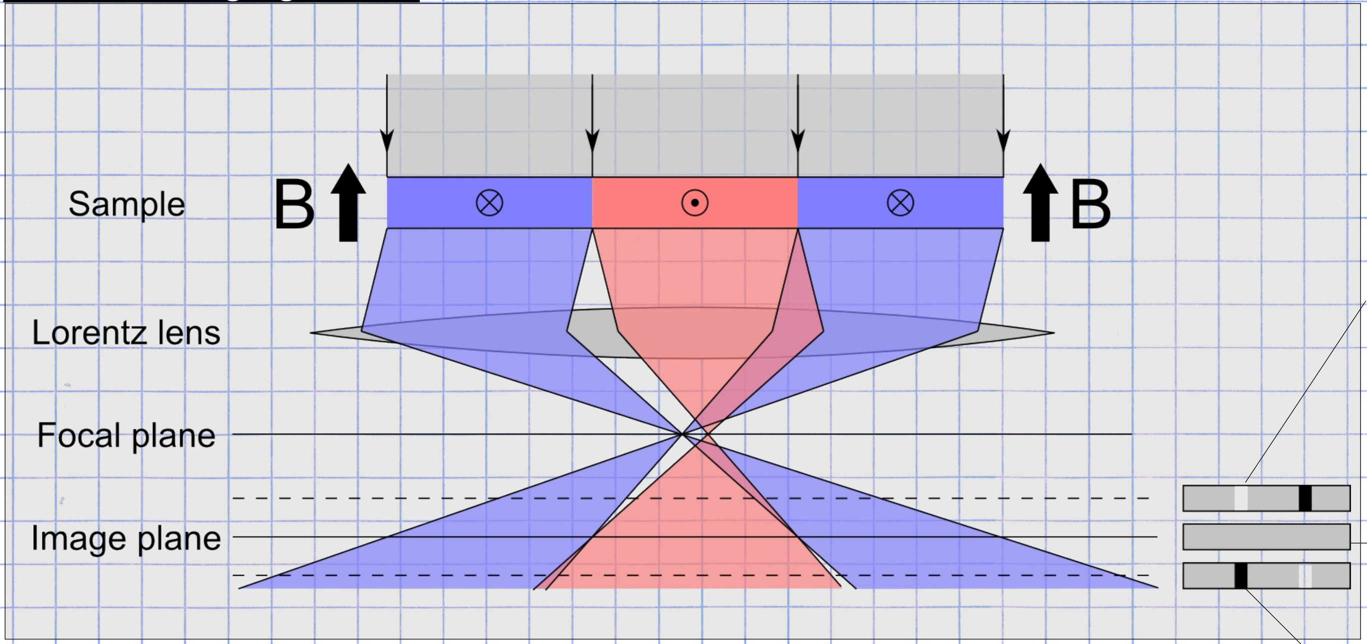
$$\frac{\gamma_i}{h_i} = \frac{\gamma_S - \gamma_{\mathrm{int}}}{h_{\mathrm{int}}} = \mathrm{Constant}$$



Truncated crystal

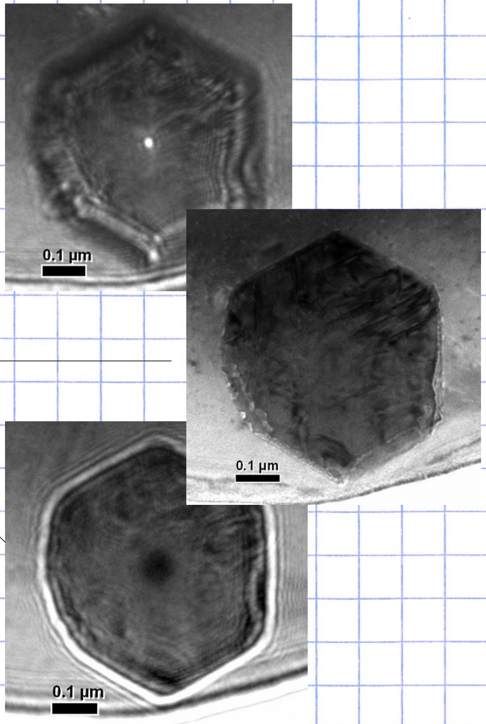
P. Müller and R. Kern, Surf. Sci. 457, 229 (2000) (and incl. ref.)

Fresnel imaging mode



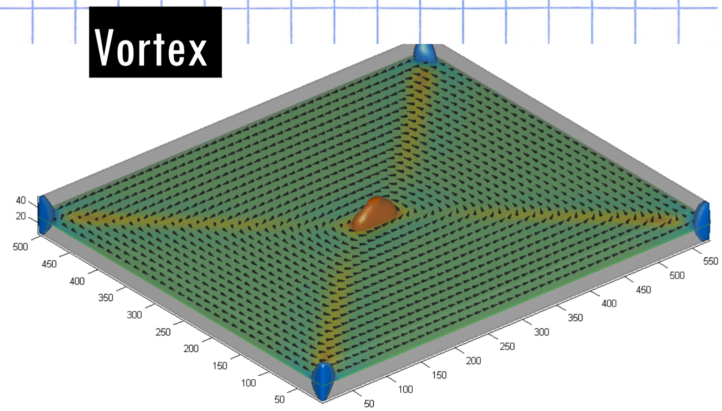
Self-assembled fcc Co dots

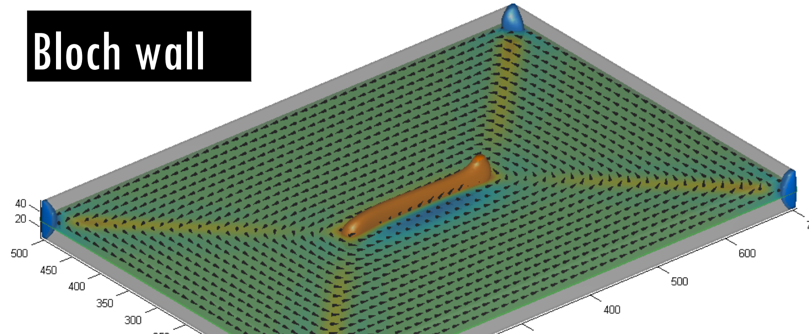
(vortex state)

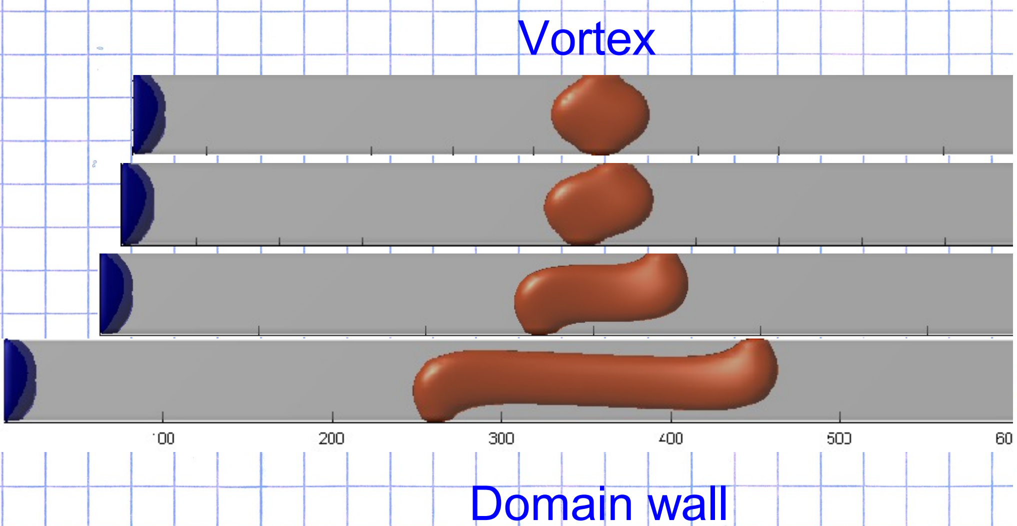


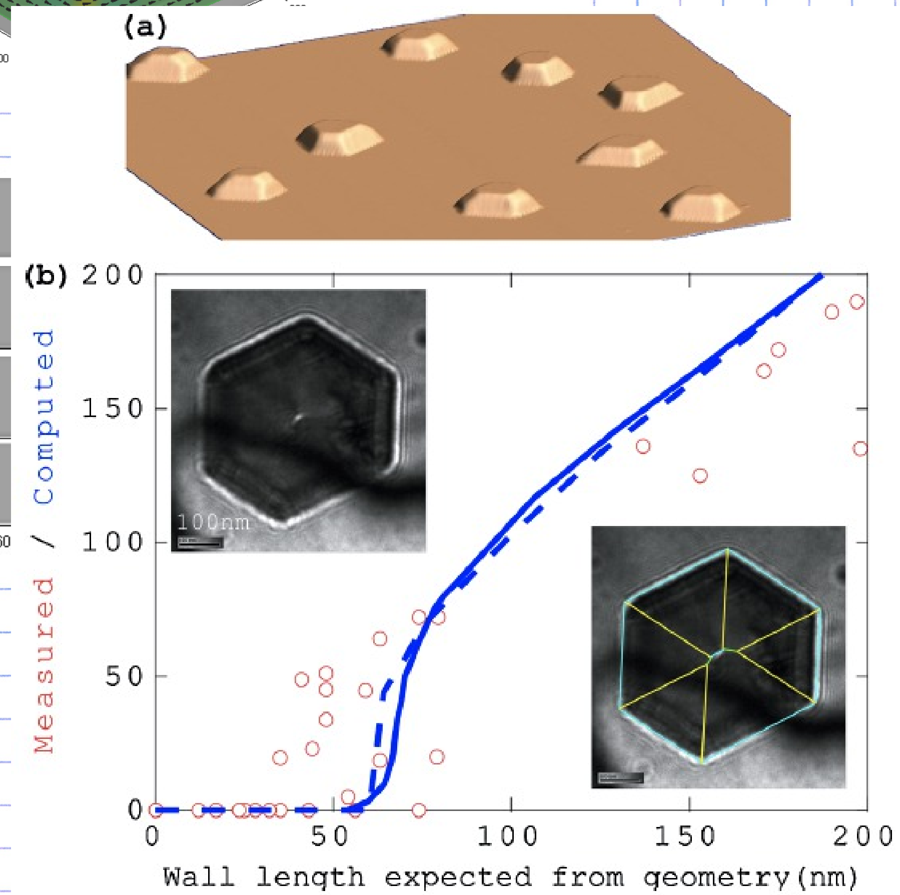
➯ Sensitive mainly to in-plane components of magnetization integrated over the sample's thickness

Pascale Bayle-Guillemaud (INAC)
Aurélien Masseboeuf et al. (INAC → CEMES)



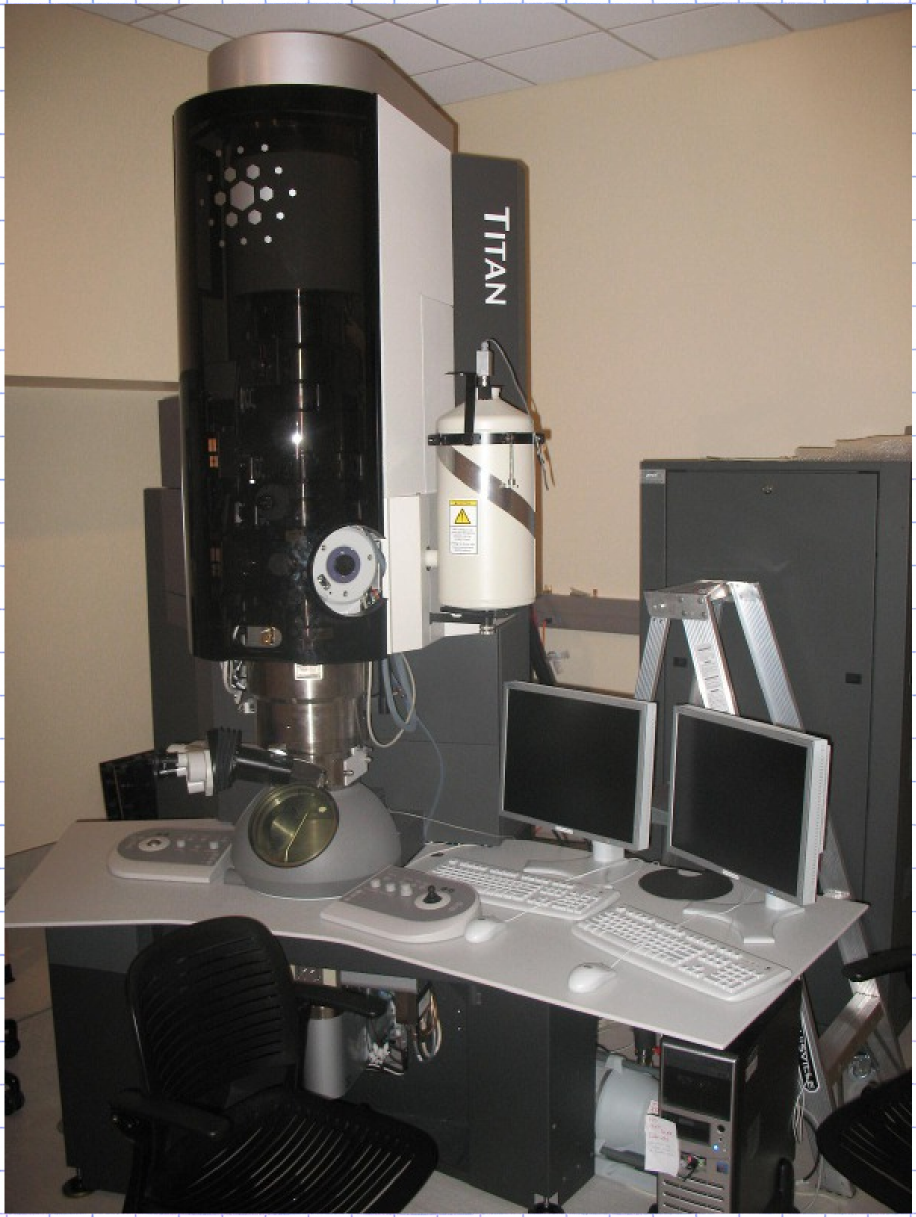




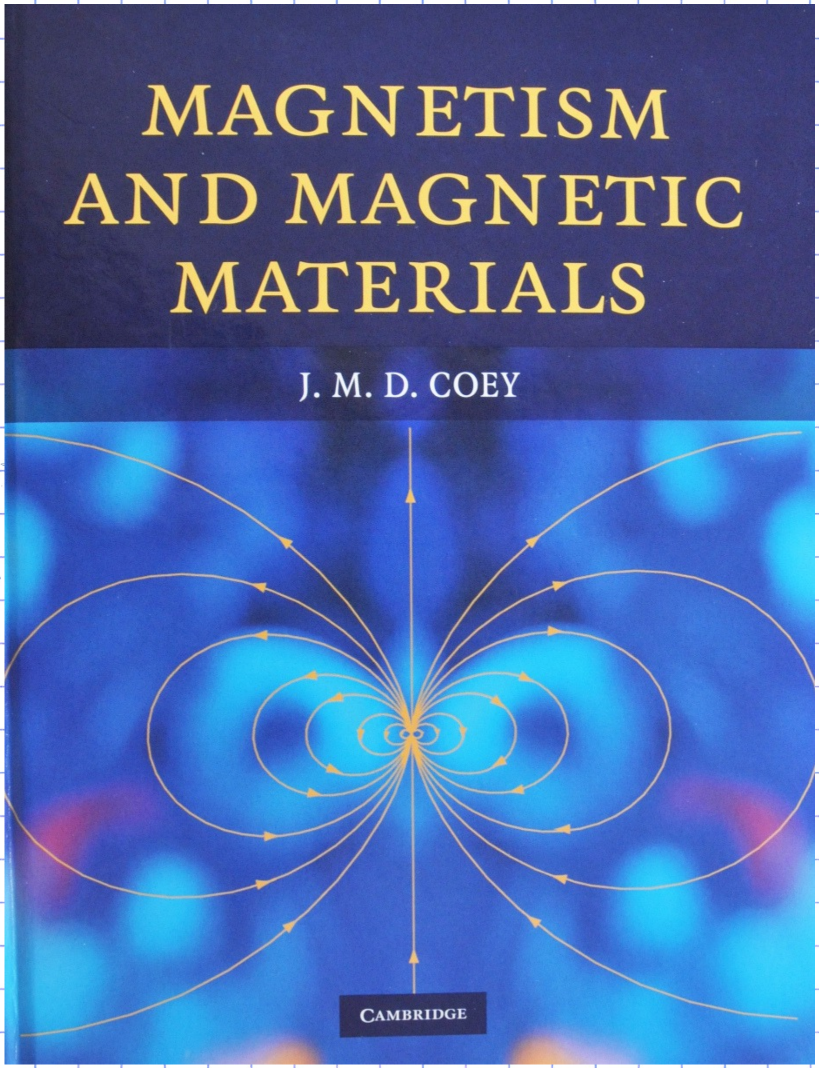


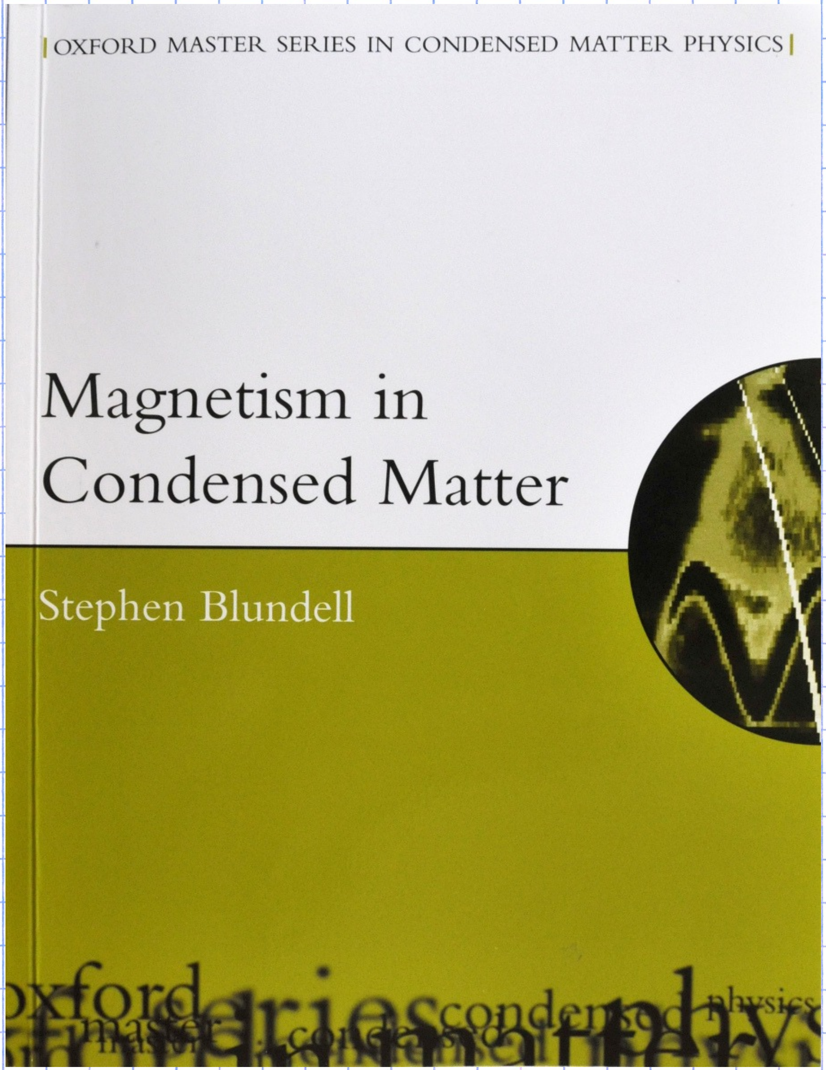
A. Masseboeuf et al., Phys. Rev. Lett. 104, 127204 (2010)

How does a transmission electron microscope look like ?



metsa



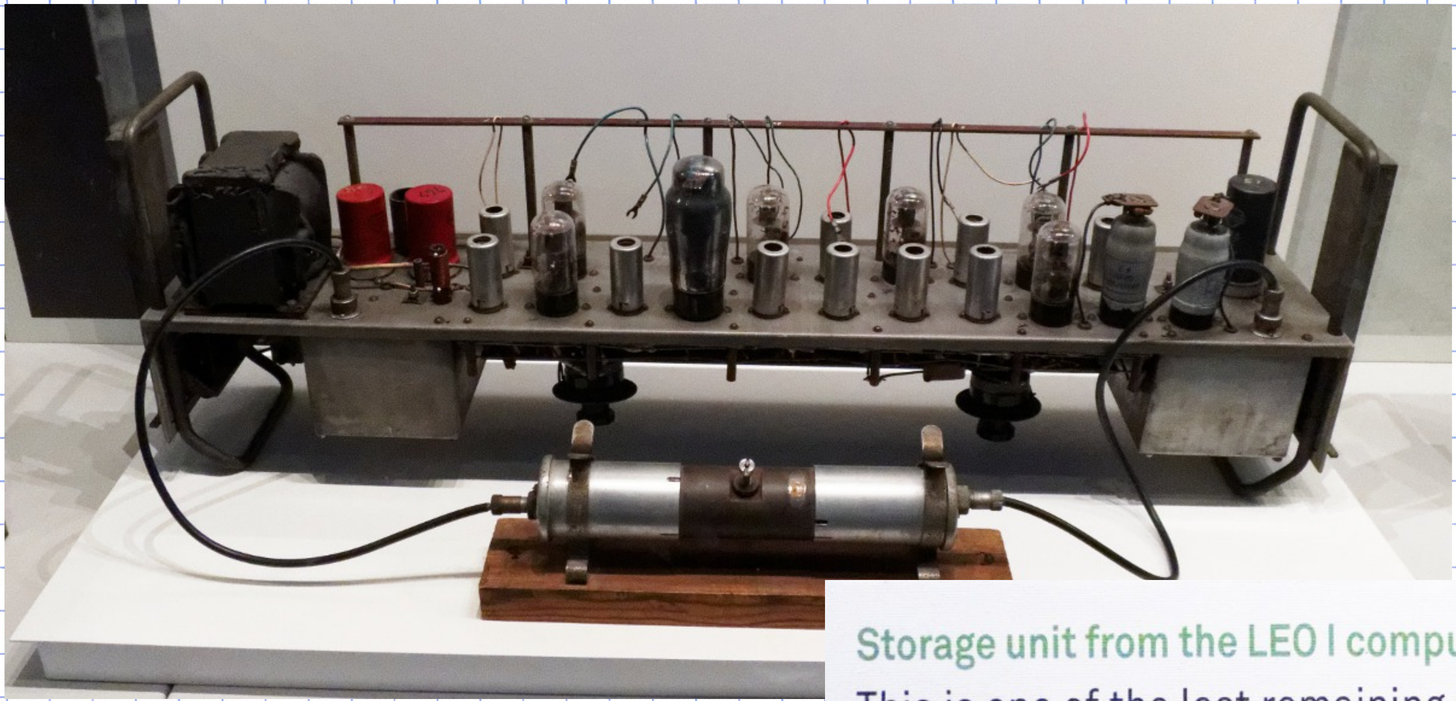


Repository of lectures of the European School on Magnetism: http://magnetism.eu

1. Low-dimensional structures in nanomagnetism

2. What could come next for magnetism in data storage ?

3. An example of academic study towards 'next'

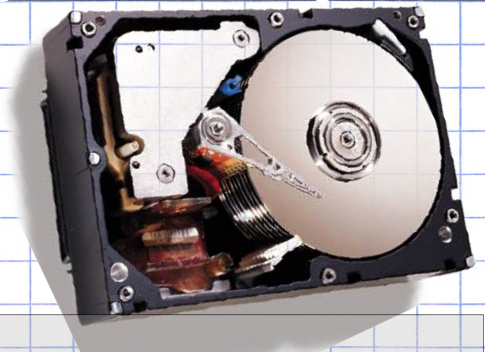


Storage unit from the LEO I computer, 1951

This is one of the last remaining parts of the original Lyons Electronic Office – the first computer built for ordinary business tasks. This storage unit consists of a regeneration chassis and a short mercury delay line. The delay line slowed down, and therefore momentarily stored, electronic signals, and the chassis amplified and 'clocked' the signals.

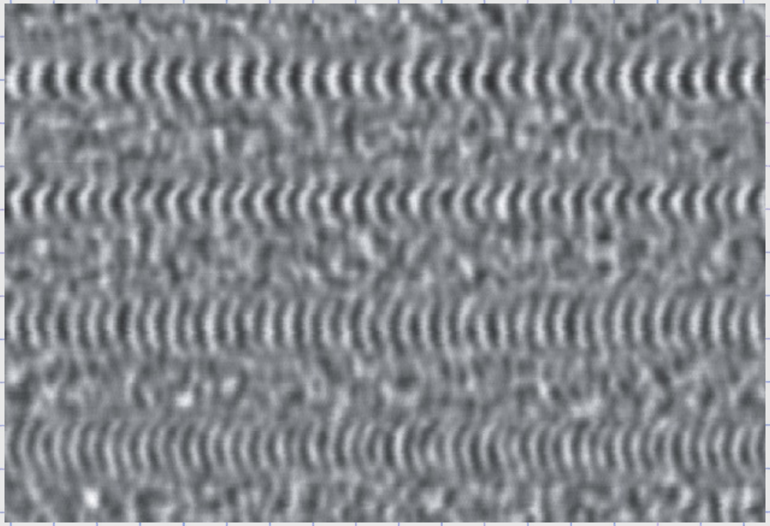
Donated by: J Lyons & Co. Ltd   Object No: 1965-33
Image: Science Museum/SSPL

Current (past?) technology for magnetic data storage



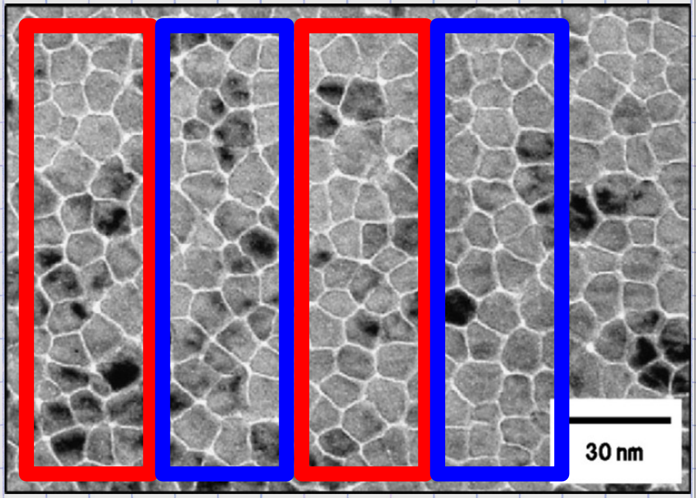
Magnetic bits on Hard Disk Drive

Co-based hard disk media : bits 50nm and below



B. C. Stipe, Nature Photon. 4, 484 (2010)

Underlying microstructure



S. Takenoiri, J. Magn. Magn. Mater. 321, 562 (2009)

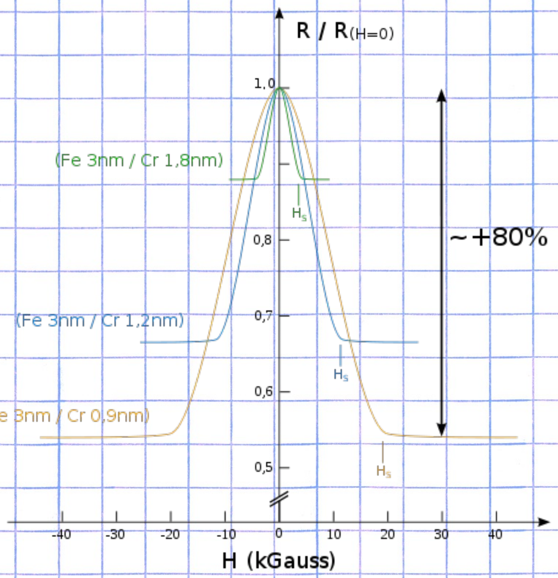
Technological / Physical breakdown

- Compromise time stability, writability, readibility
- Disruptive solutions sought

1956

RAMAC, IBM, first hard disk drive

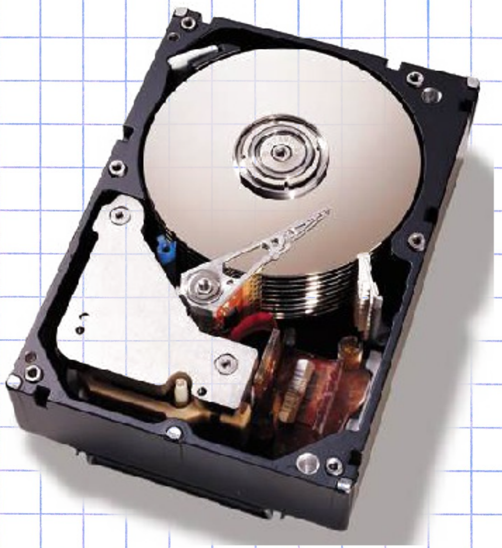
1986



Discovery of Giant Magneto-Resistance

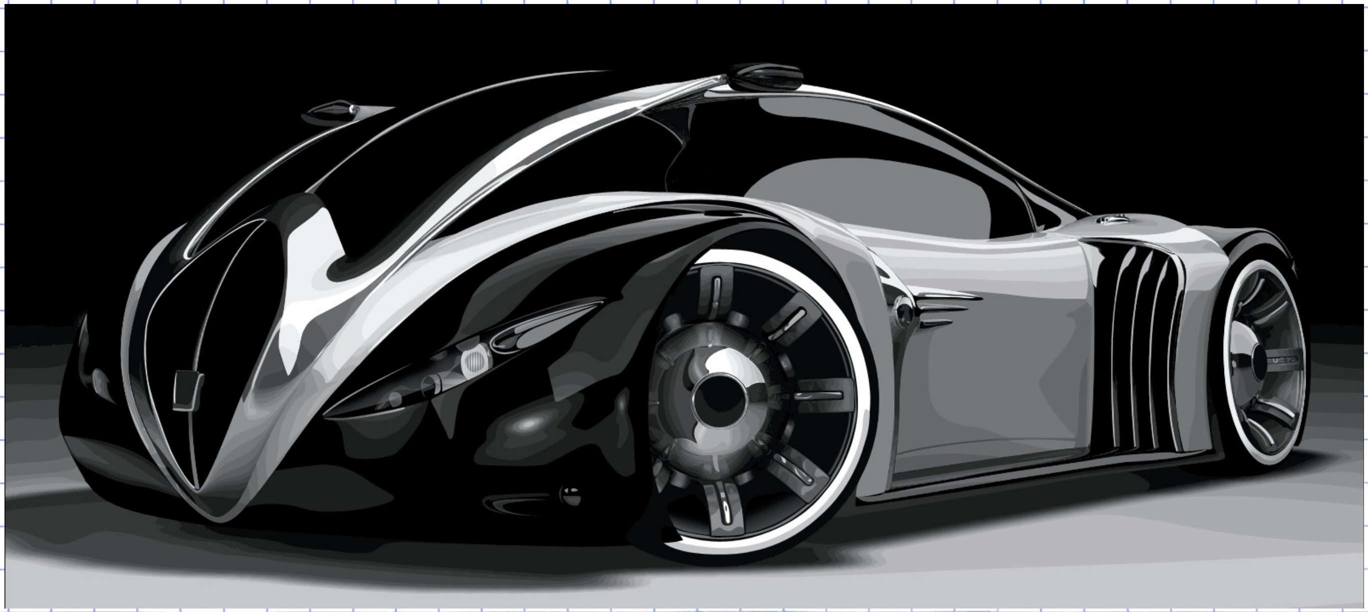
→ Nobel prize in Physics 2007

1998



GMR implemented in HDD read heads

X10^6 increase of density from 1956



Physics (recent)

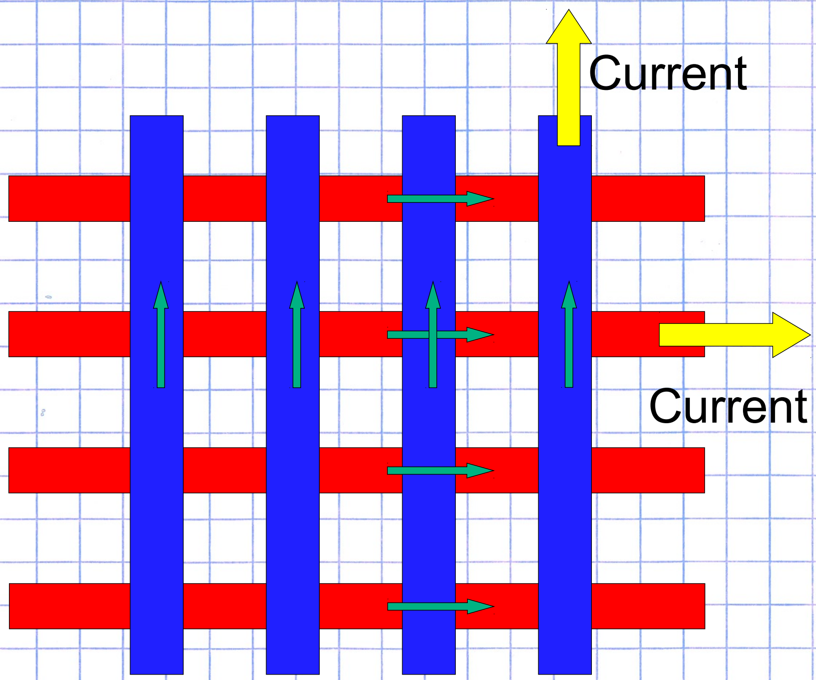
- Spin-transfer torques. Induces magnetization switching, oscillations
- Interfacial effects, chirality

Technology (to come)

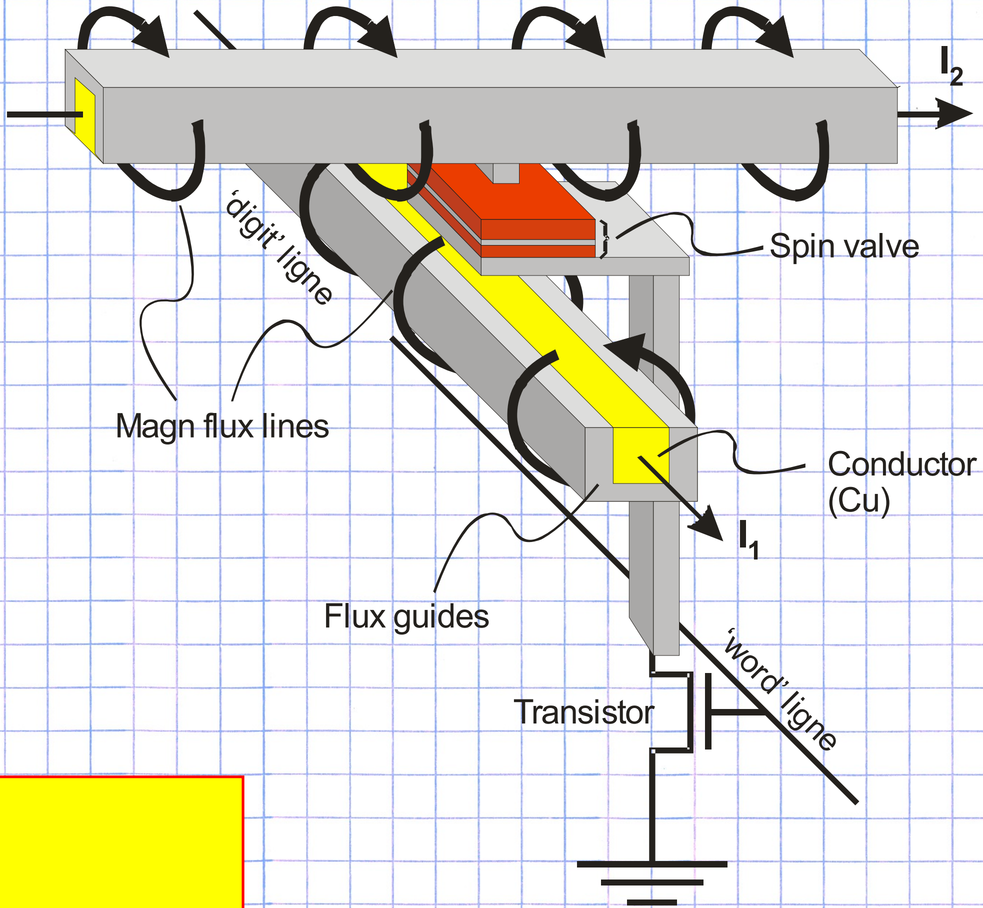
- Magnetic Random Access Memories (dots)
- Logic and memory devices based on domain walls. 3D memories ?

MRAM = Magnetic Random Access Memory

Overview

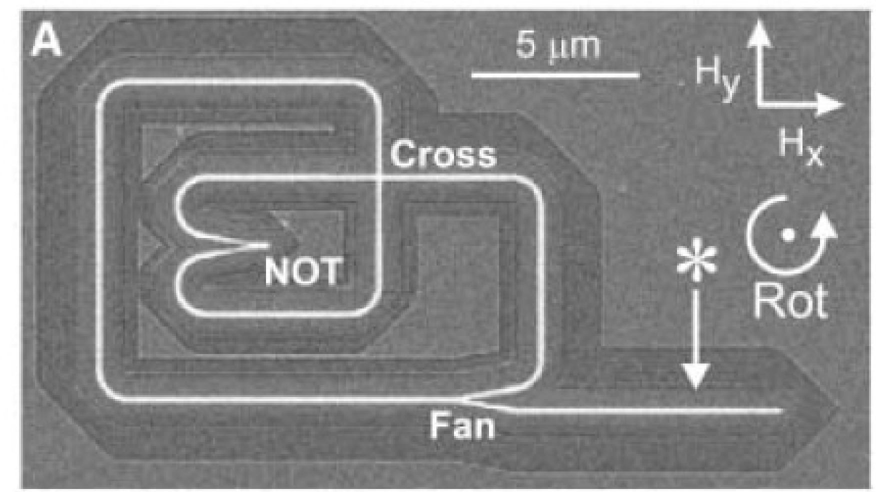


Detail of a cell (very old design)



Main features:
Solid state memory
Non-volatile and fast
Issues being fixed → entered semiconductor roadmap

Magnetic logic with domain walls (Field driven)

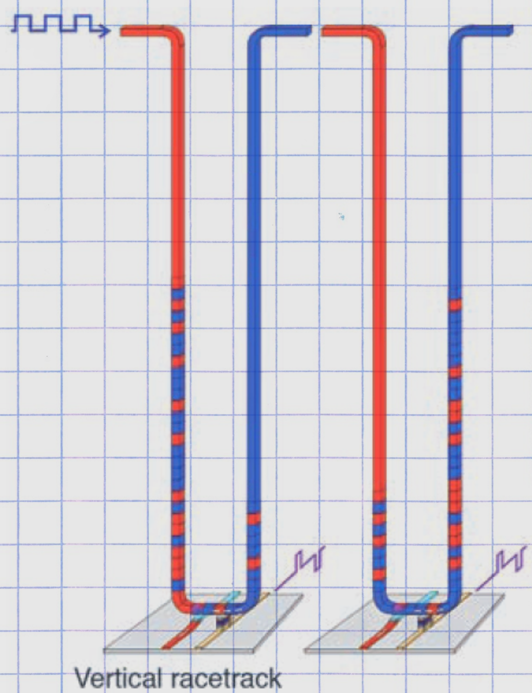


D. A. Allwood et al., Science 309, 1688 (2005)

Limitation:

Requires homogeneous rotating field

Proposal for a race-track memory in 3D



S. S. P. Parkin, Science 320, 190 (2008) + patents (IBM)

- Potentially 3D storage, however technologically challenging
- Cylinders are the 'natural' geometry

1. Low-dimensional structures in nanomagnetism

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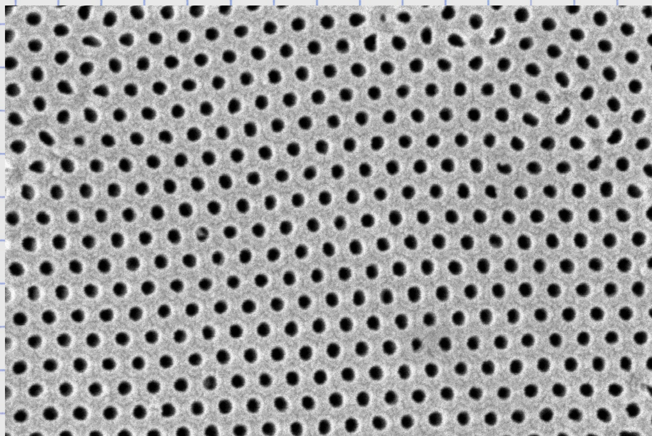
Some of the bottom-up routes implemented at Institut NEEL

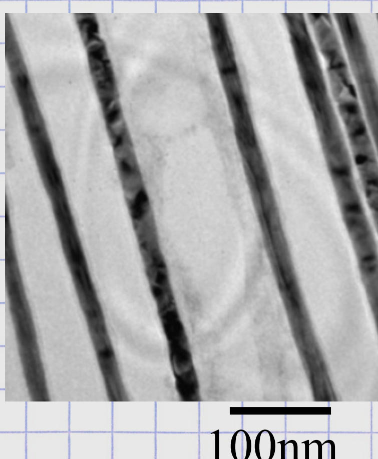
The basics

Anodization of aluminum → template



H. Masuda, Science 268, 1466-1468 (1995)

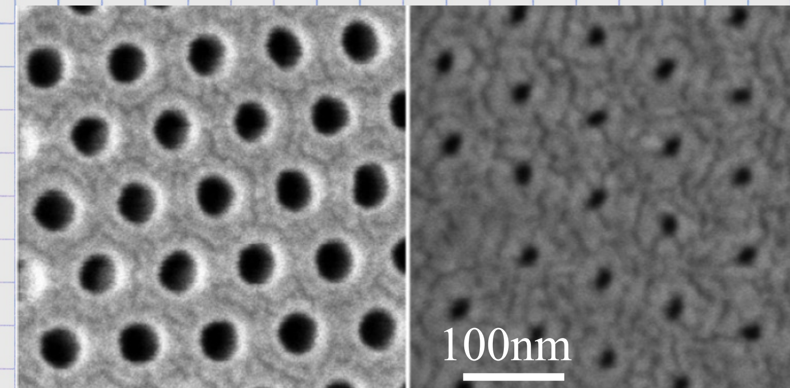
Electroplating → magnetic nanowires



⇨ Simple metals and alloys : Co, Ni, $Fe_{20}Ni_{80}$

Specific aspects

ALD to reduce pore diameter

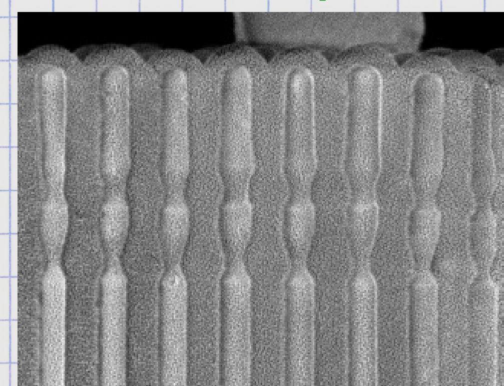


S. Da Col et al., Appl. Phys. Lett. 98, 112501 (2011)

⇨ Decrease dipolar interactions

Modulation of pore diameter

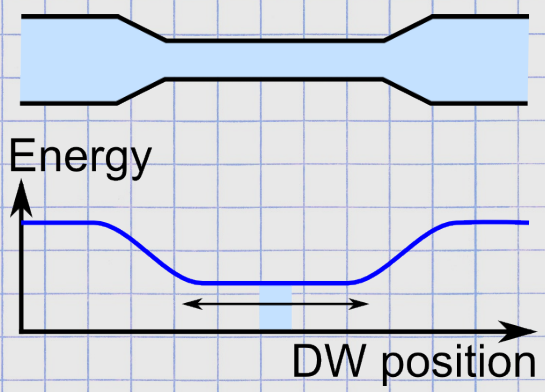
S. Allende et al., Phys. Rev. B 80, 174402 (2009)



⇨ Landscape for domain walls

Nucleate domain-walls – Modulated diameters

Principle

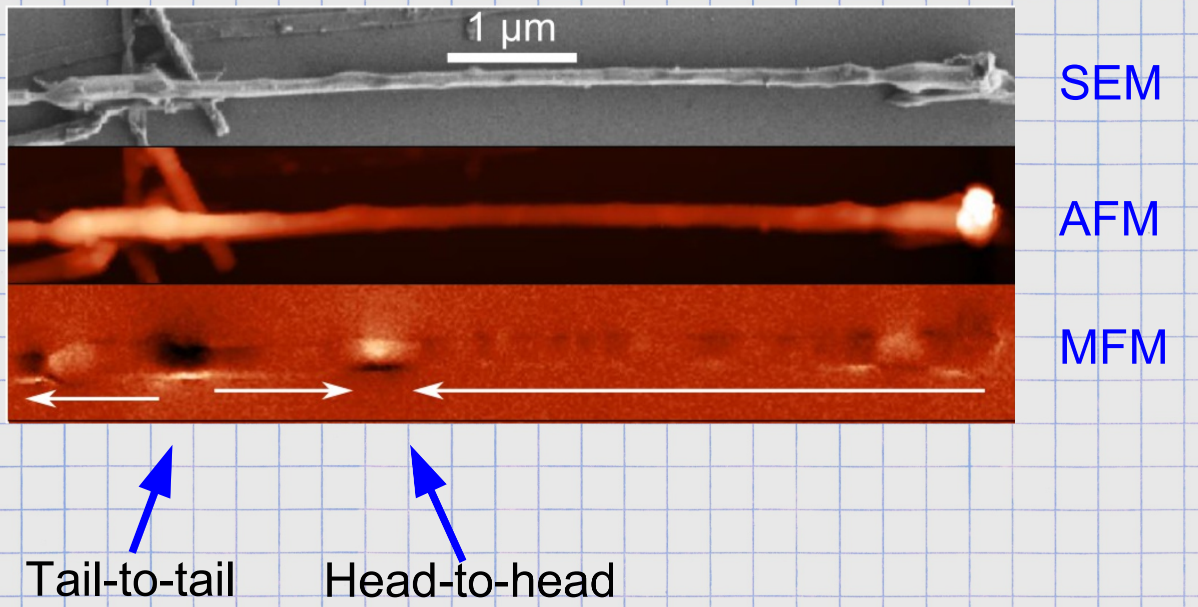


⇨ Provides energy landscape for domain walls

⇨ NB : reports with modulations however no domain walls

K. Pitzschel et al., J. Appl. Phys. 109, 033907 (2011)

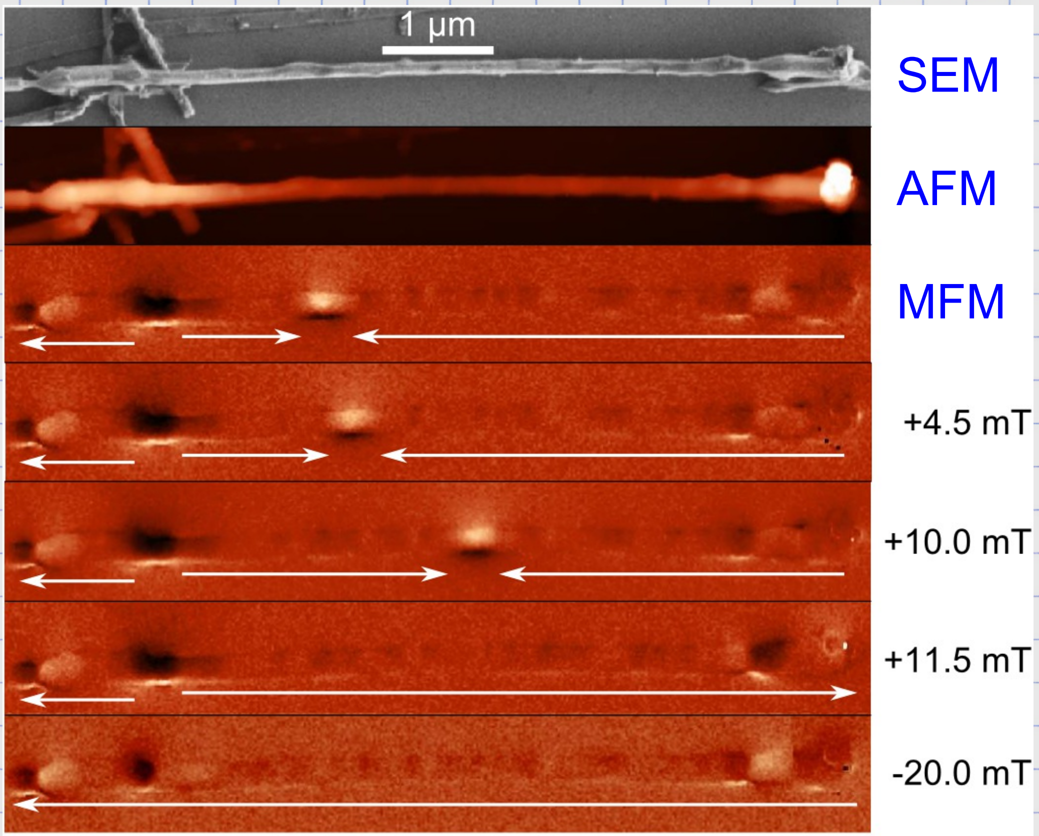
Nucleation of domain walls



⇨ Protrusions create a 'box' for domain walls

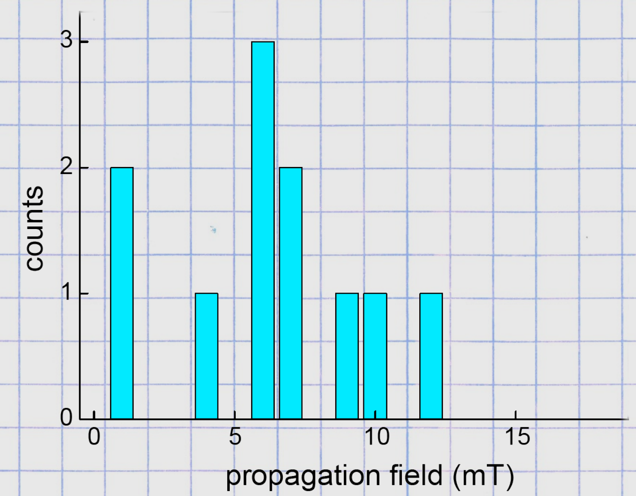
Propagation of domain walls

Experiments



- Domain-wall motion demonstrated (range 1-10mT)
- Pinning at modulations of diameter

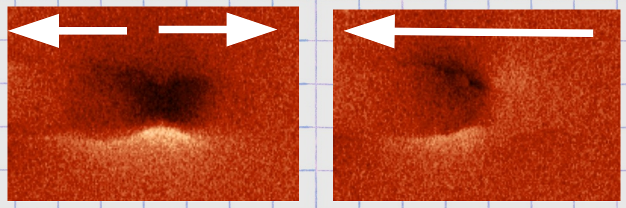
Straight sections



- Distribution of propagation fields, range 1-10mT
- Similar to the case of strips

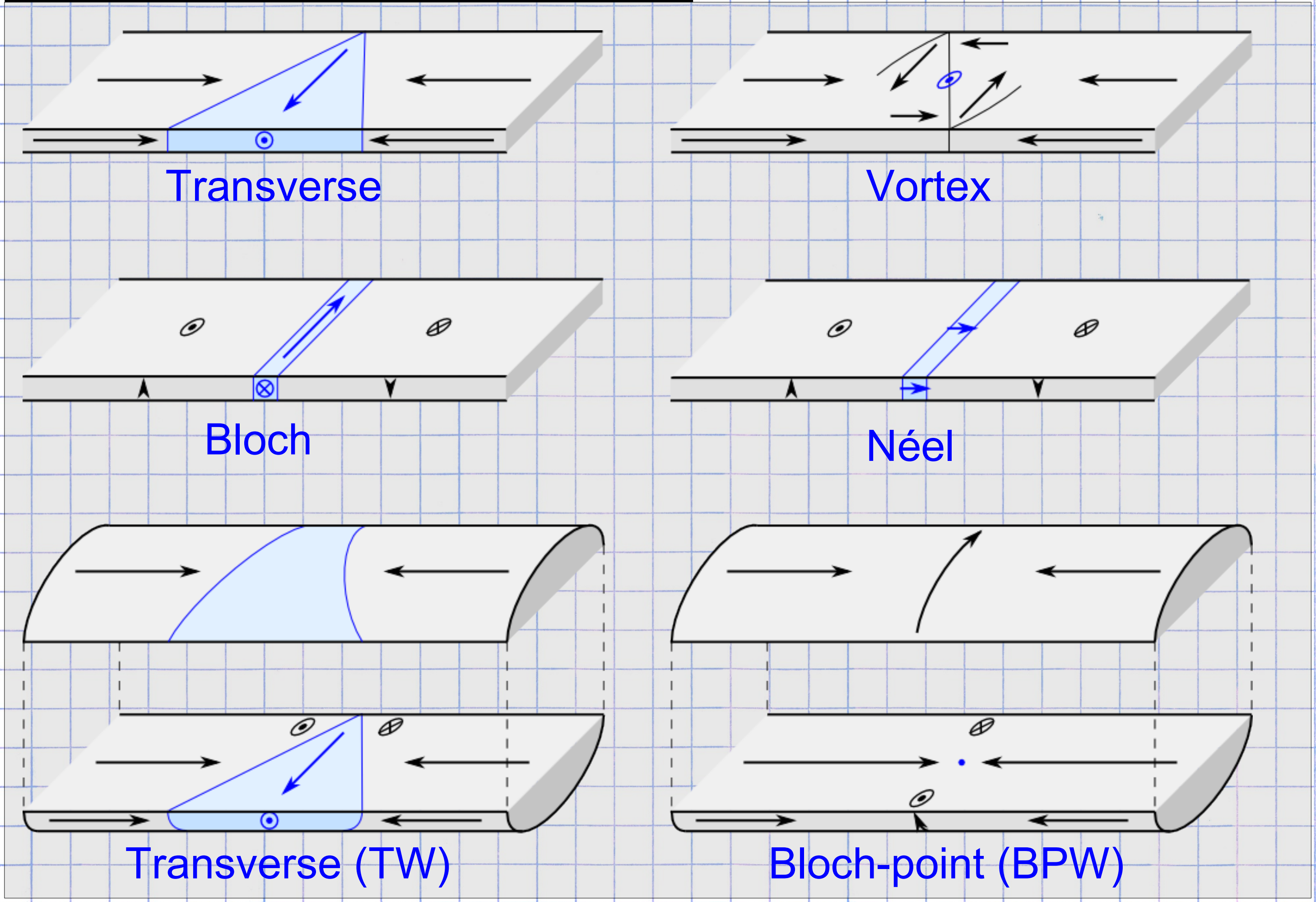
J. Sampaio et al., J. Appl. Phys. (2013)

Protrusions and constrictions



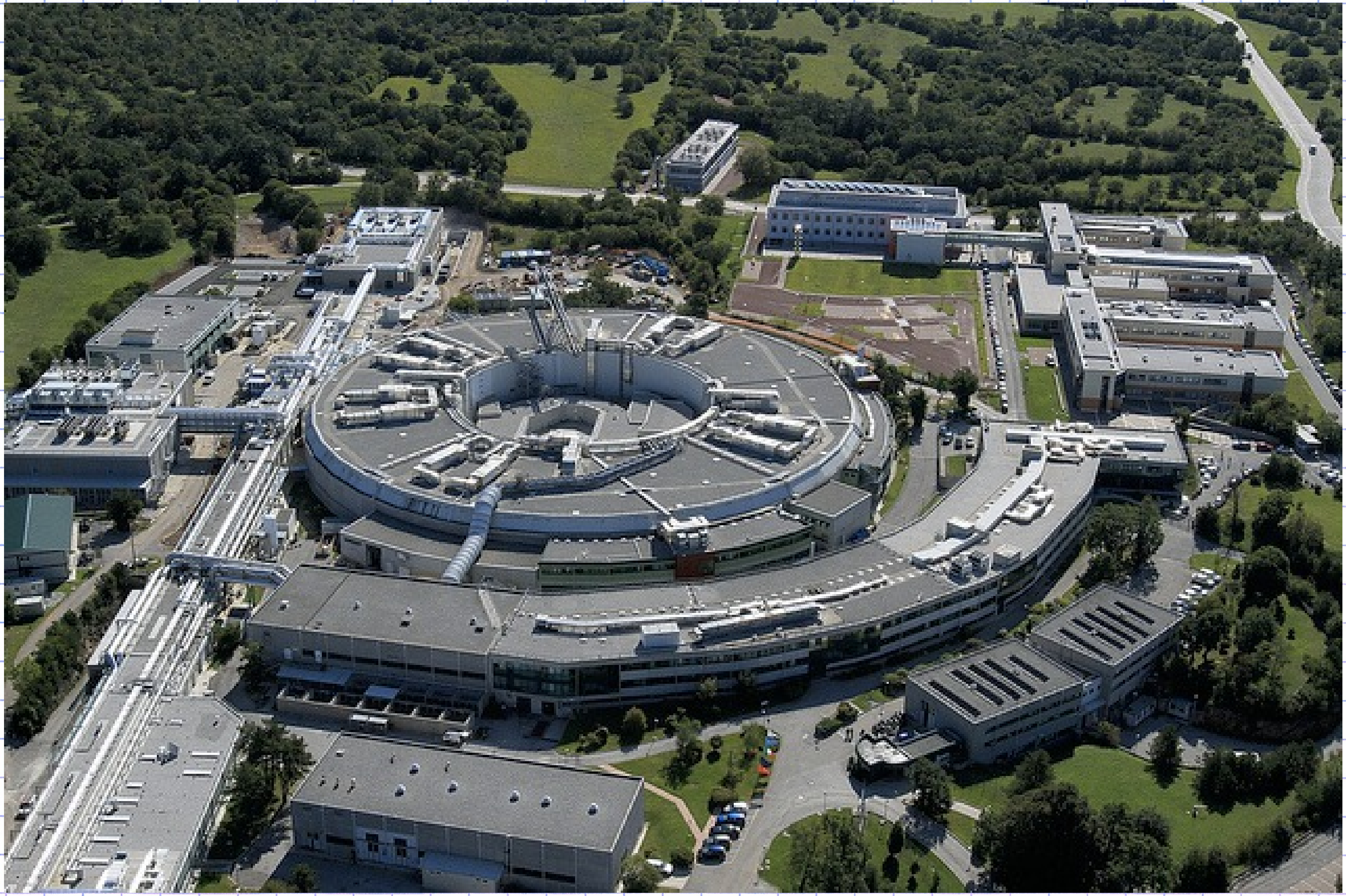
- Pinning field ~30mT

Domain walls in one-dimensional systems



Need for advanced magnetic microscopies to identify domain walls

⇨ Elettra synchrotron, Trieste, Italy



elettra

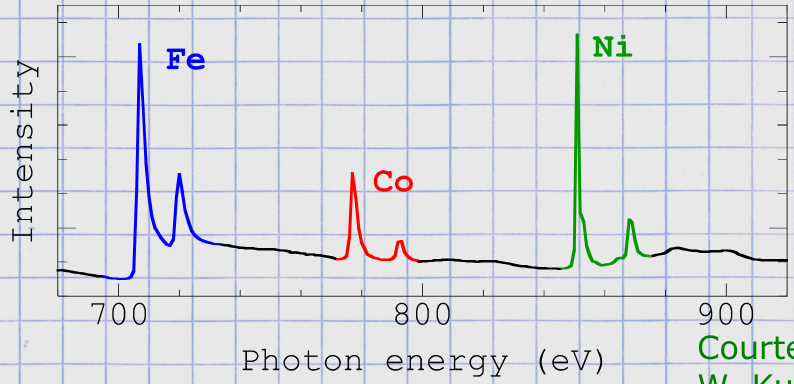
Inside a synchrotron ring

⇨ Swiss Light Source (SLS), close to Zürich

XMCD

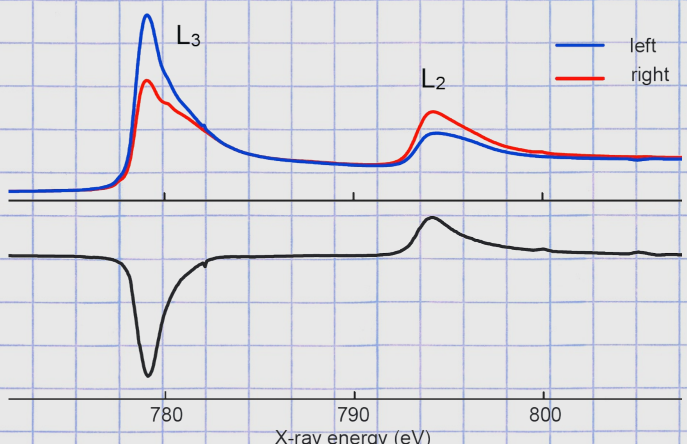
X-ray Magnetic Circular Dichroism

⇨ Element selectivity



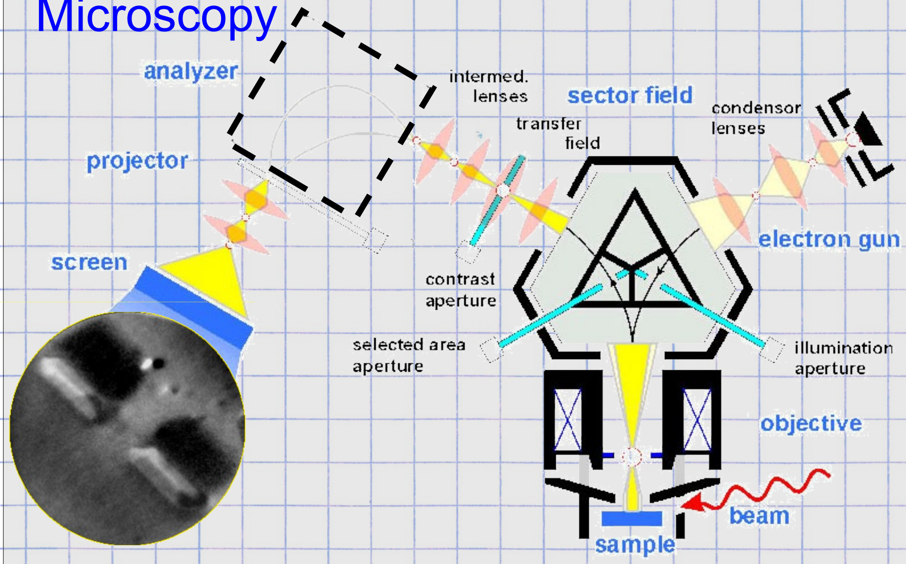
Courtesy: W. Kuch

⇨ Magnetic sensitivity



PEEM

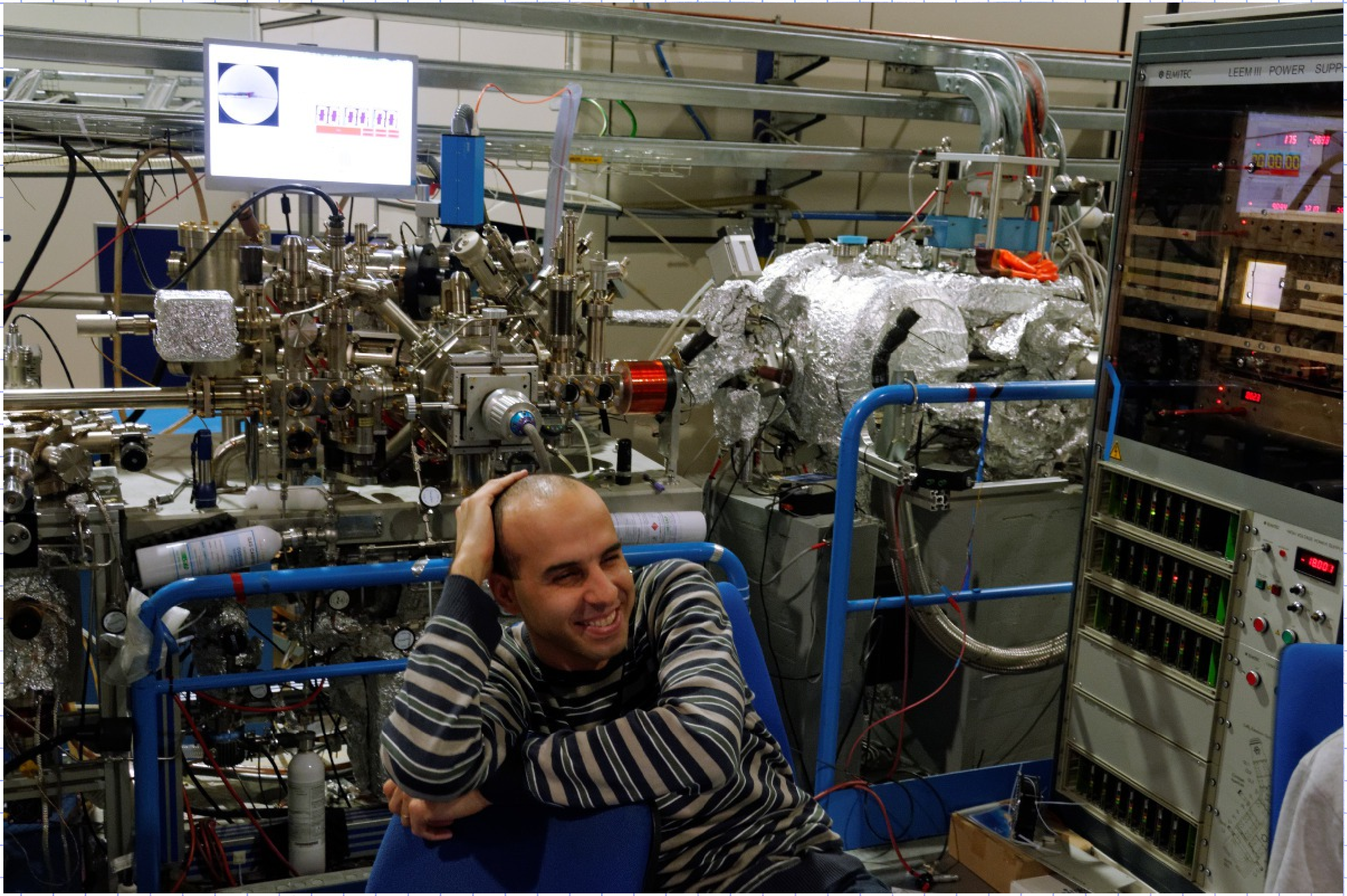
Photo-Emission Electron Microscopy



Features

- Secondary electrons → surface sensitive
- Spatial resolution : 25nm

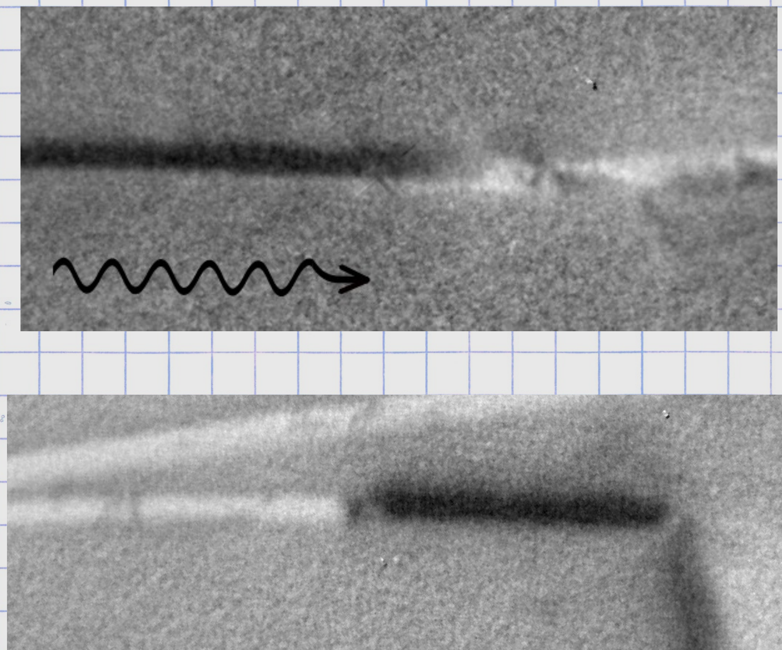
What does a Photo-Emission Electron Microscope look like ?



Two examples

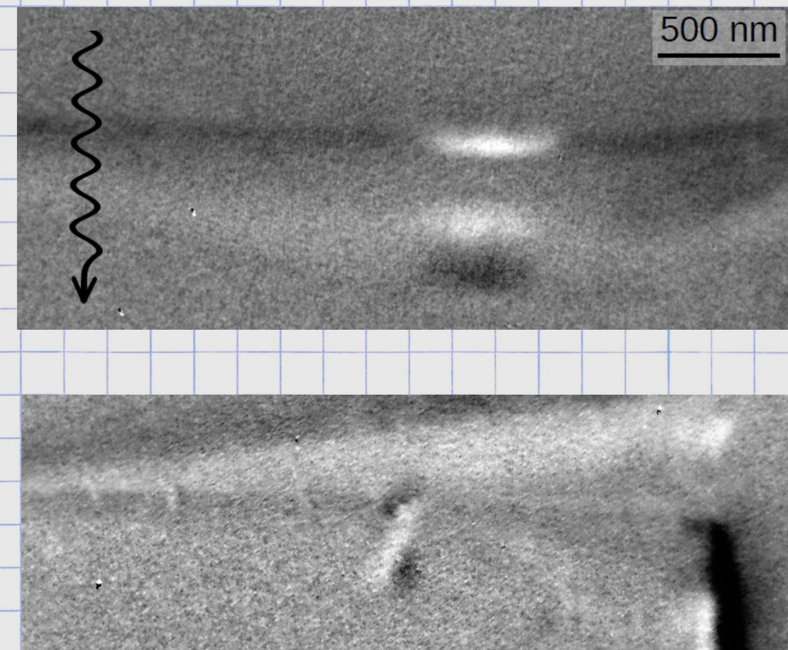
Beam along wire

⇨ Locate domain walls



Beam across wire

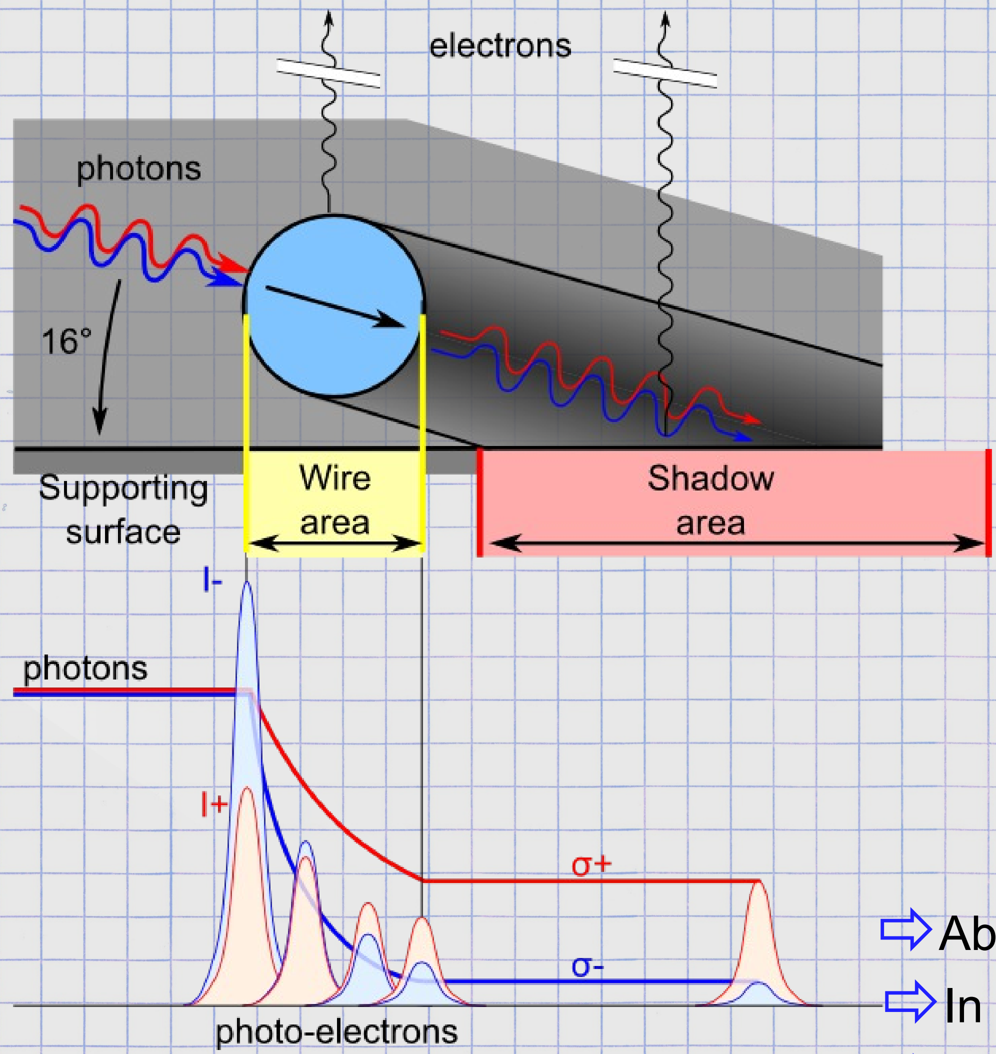
⇨ Inspect domain wall

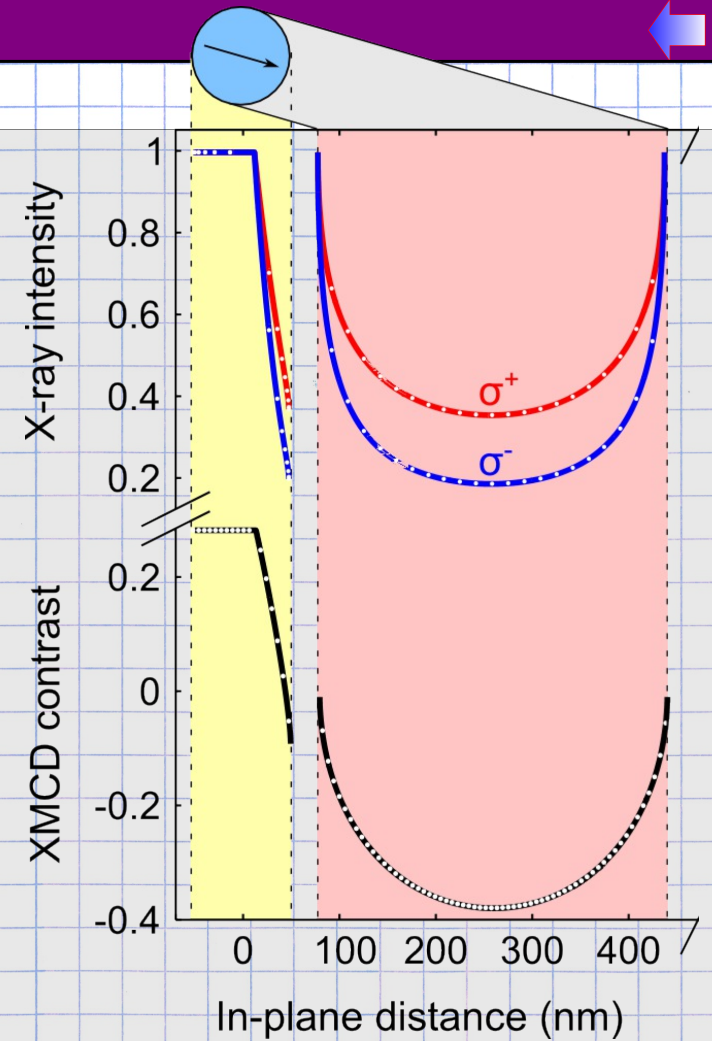


↳ Several non-trivial patterns
↳ Need for modelling

Test case : uniform transverse magnetization

Schematics





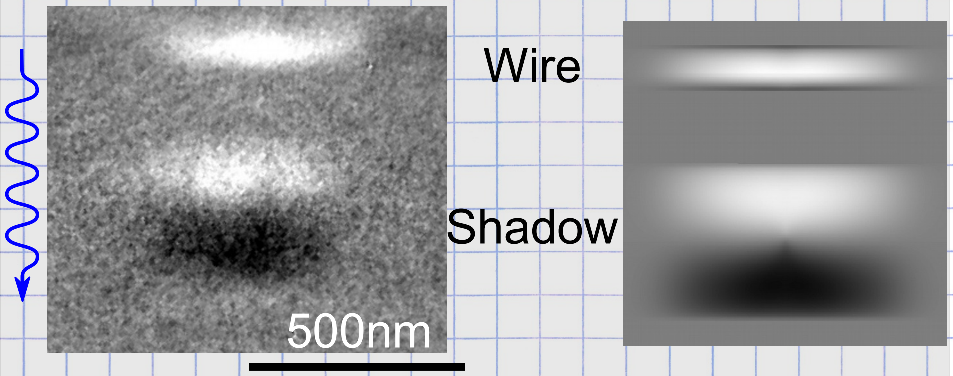
- Above wire : surface magnetization
- In the shadow : volume magnetization
- Non-linear, even change of sign

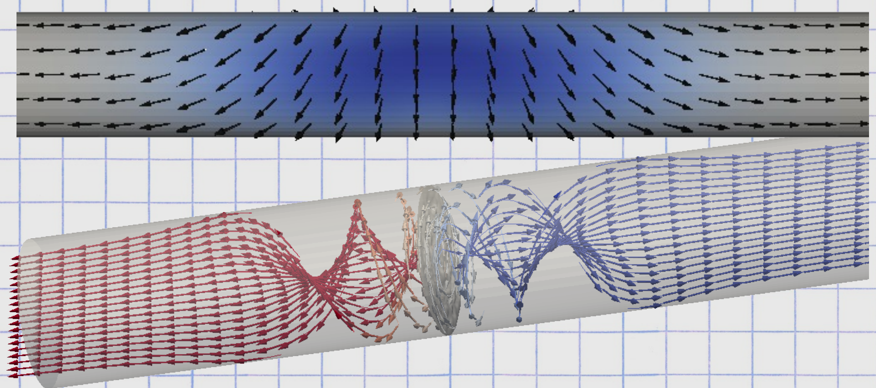
Formal identification of domain walls

Bloch-Point Wall (BPW)

Wire diameter : 95nm

Experiment   Simulation



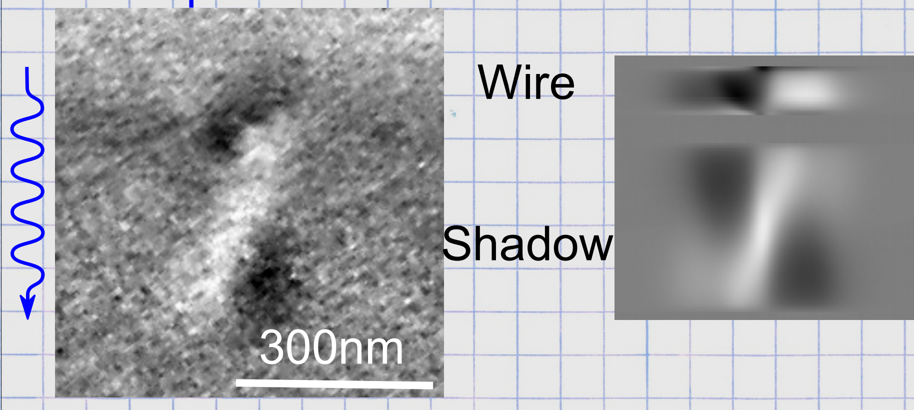


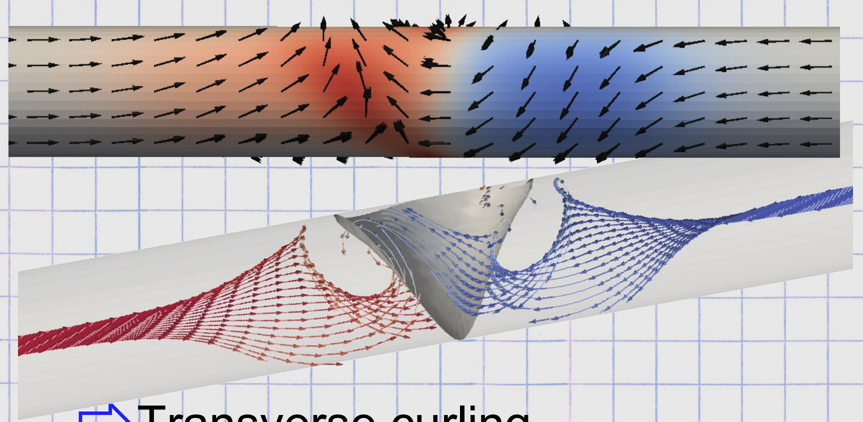
- ⇨ Orthoradial curling
- ⇨ Symmetry with respect to plane perpendicular to axis

Transverse Wall (TW)

Wire diameter : 70nm

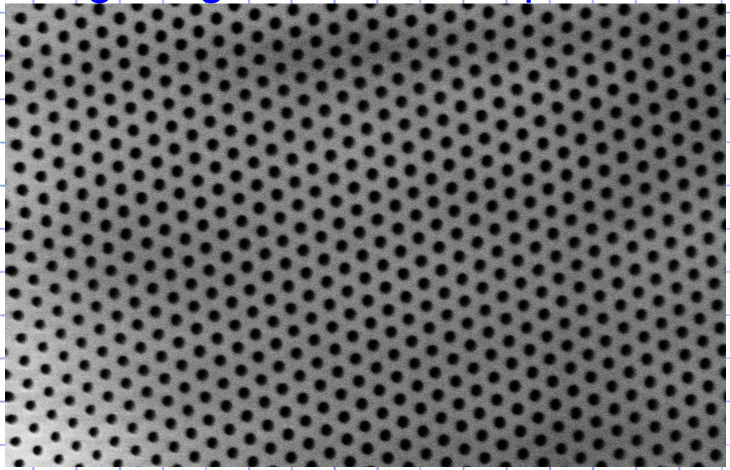
Experiment   Simulation



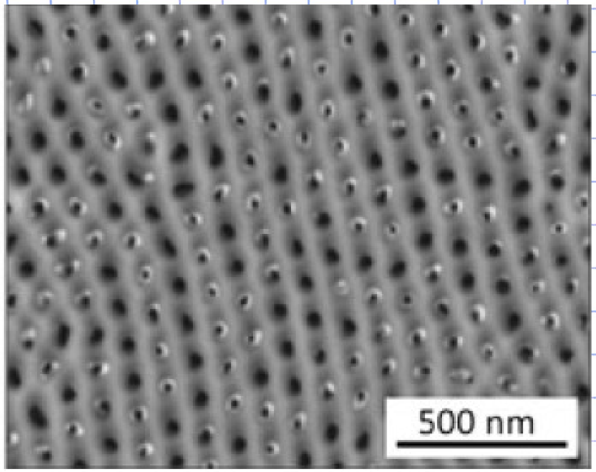


- ⇨ Transverse curling
- ⇨ Loss of symmetry with respect to plane perpendicular to axis

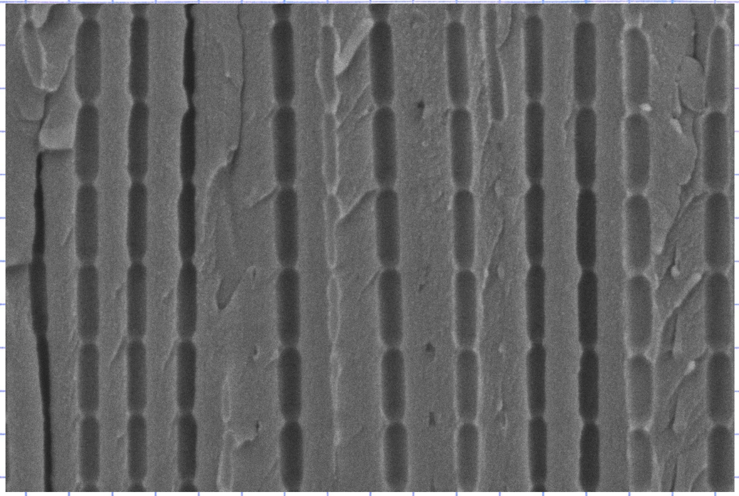
Long-range ordered templates



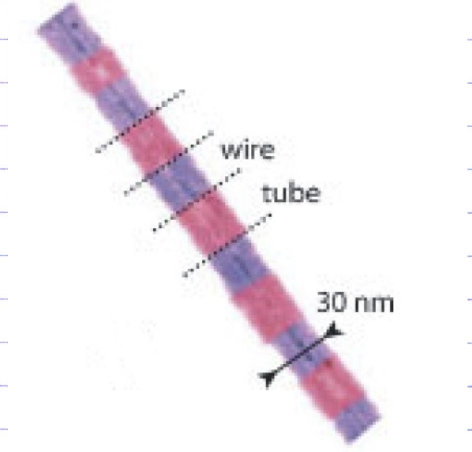
Nanotubes



Pre-defined bits



Multilayered structures



Areal density

- Prospects for HDD : $1\,\mathrm{Tbit/in^2}$
  $\approx 1.5\times 10^{11}\,\mathrm{bit/cm^2}$
- Pitch 100nm → $10^{10}\,\mathrm{wire/cm^2}$
- Need 100 bits/wire to overcome HDD
- Goal 1bit/200nm → $20\,\mu\mathrm{m}$

Power

- Current for spin-torque $10^{12}\,\mathrm{A/m^2}$
- Resistivity $10^{-7}\,\Omega.\mathrm{m}$
- Power consumption $10\,\mathrm{mW}$
- Energy per bit $10-100\,\mathrm{pJ}$

Speed

- Shift wire registers in parallel
  → not a limiting factor
- Determined by R/W (planar) device
- Similar to 2D competitors

Cost per bit

- 2D patterning → similar to flash

Scalability

- 2D cost + 3D scalability
  → cost/bit decreases
- No limitation for 3D fabrication
- Practical limitation for energy consumption

Collaborative work !

- Perform experiments (or simulations, theory)
- Develop instrumentation, codes etc.
- Reading recent and less recent publications, books etc.
- Go to conferences : learn and disseminate
- Seeking funding → Grants, equipment, travel etc.
- Do some teaching
- Organize the lab : scientific life, technical versus scientific activity etc.