Note: part of the lecture was made on the blackboard, and does not appear here

Magnetization textures
Statics and dynamics

Olivier Fruchart

SPINTEC, Univ. Grenoble Alpes / CNRS / CEA-INAC, France

www.spintec.fr

email: olivier.fruchart@cea.fr

Slides: http://fruchart.eu/slides

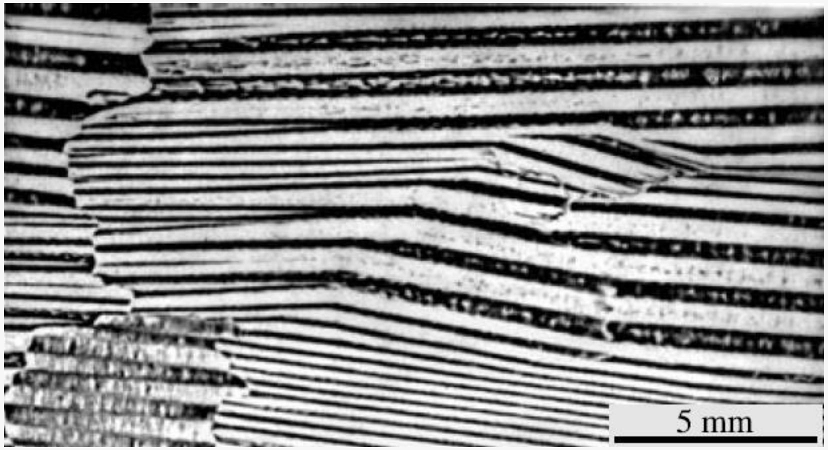
Possible reading: Lecture notes in nanomagnetism: http://fruchart.eu/olivier/publications

Lecture in Sevilla, Spain

spintec SPIN IN ELECTRONICS

Magnetic domains

- Numerous and complex shape of domains

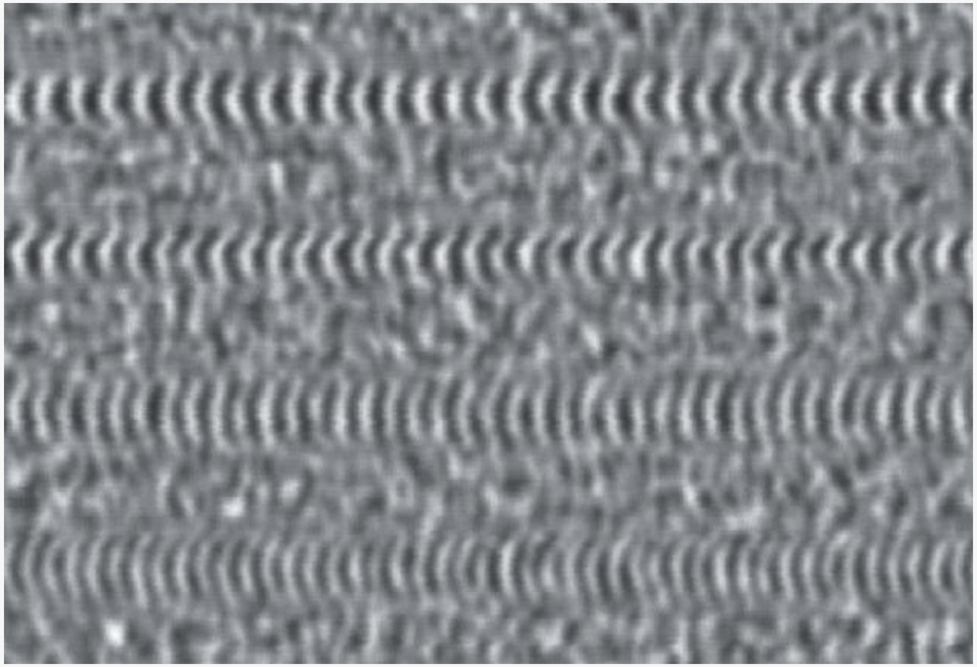


History: Weiss domains

Practical: improve material properties

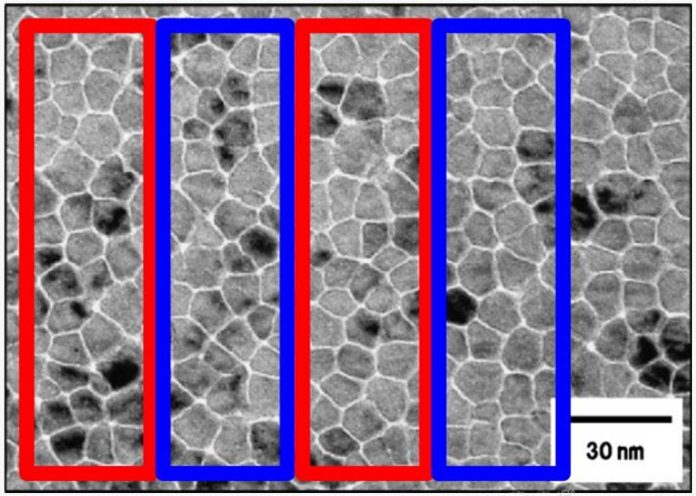
Magnetic bits on hard disk drives

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

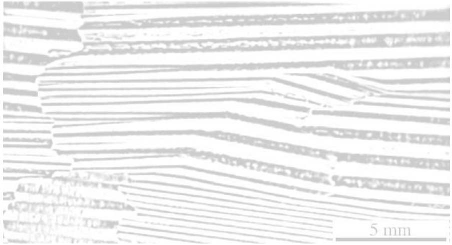


B. C. Stipe, Nature Photon. 4, 484 (2010)

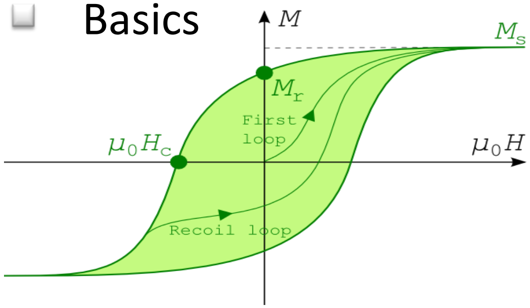
Underlying microstructure



- Motivation

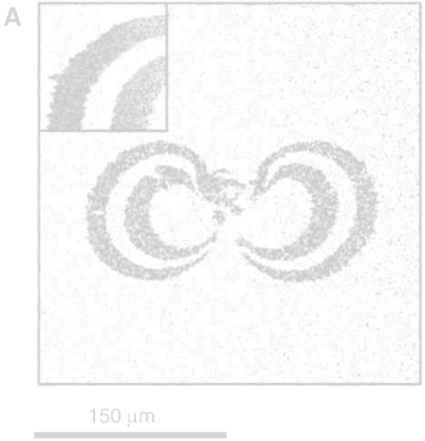


- Basics



- Statics

- Dynamics

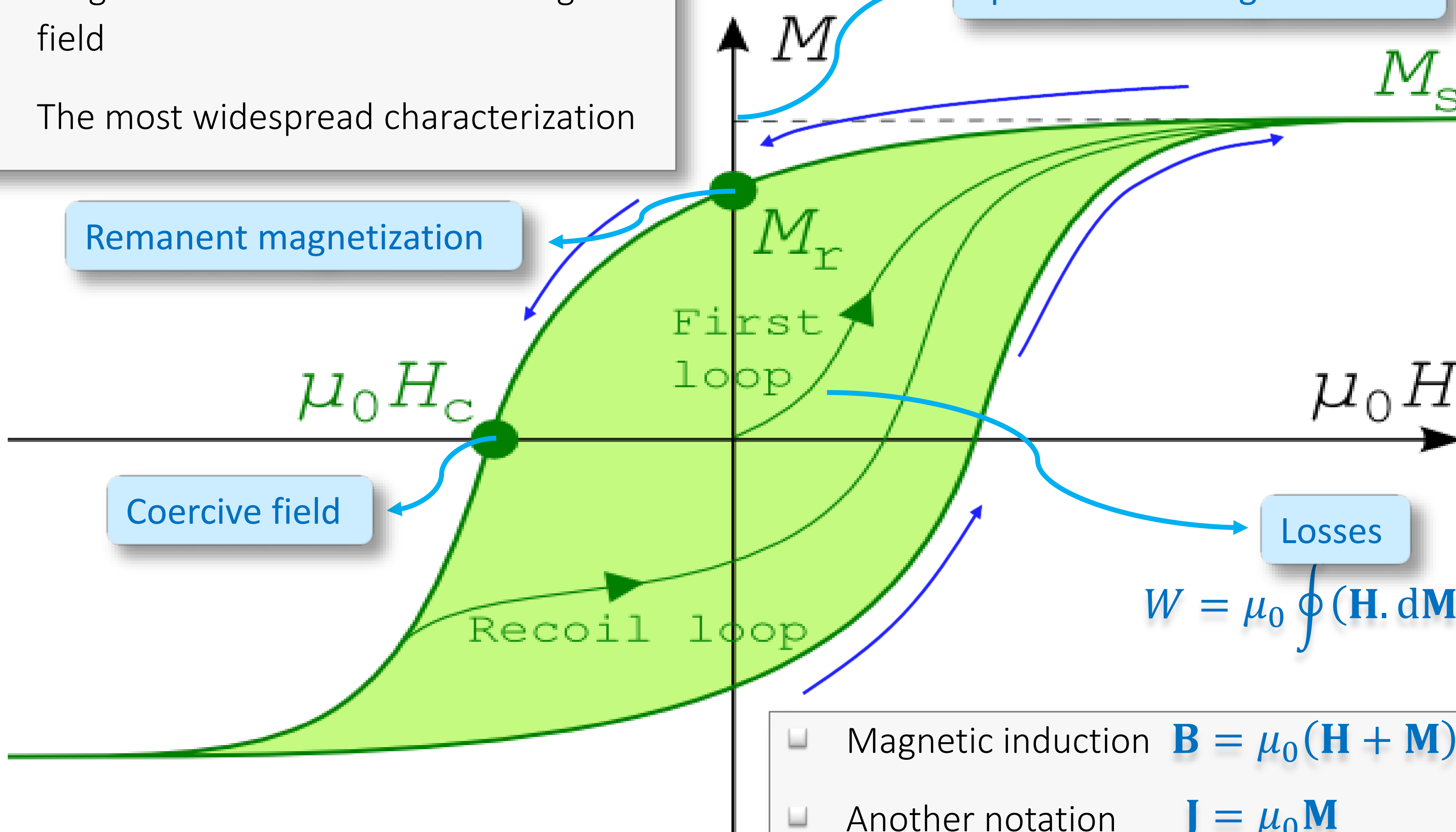


BASICS – CONTROL MAGNETIZATION REVERSAL

The hysteresis loop

- Magnetization reversal under magnetic field
- The most widespread characterization

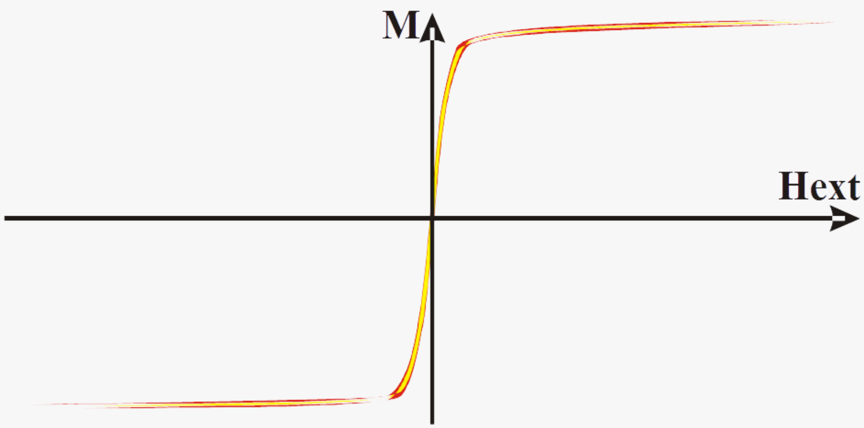
Spontaneous ≠ **S**aturation



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

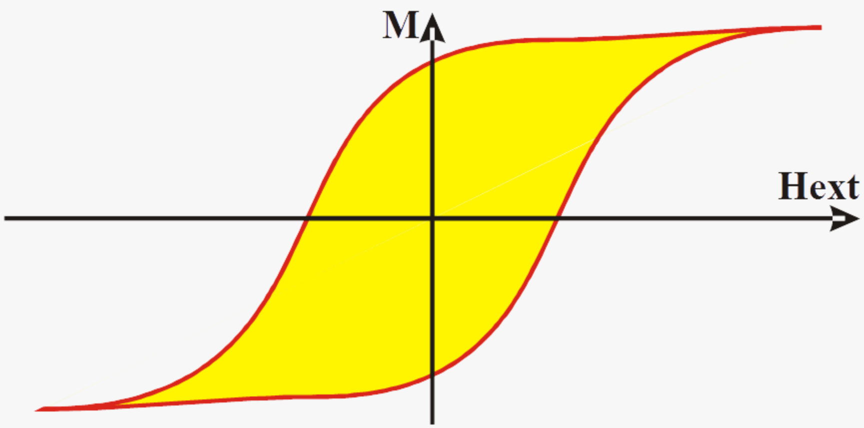
- Magnetic induction $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$
- Another notation $\mathbf{J} = \mu_0\mathbf{M}$

Soft magnetic material



- Transformers
- Magnetic shielding, flux guides
- Magnetic sensors

Hard magnetic material



- Magnetic recording
- Permanent magnets

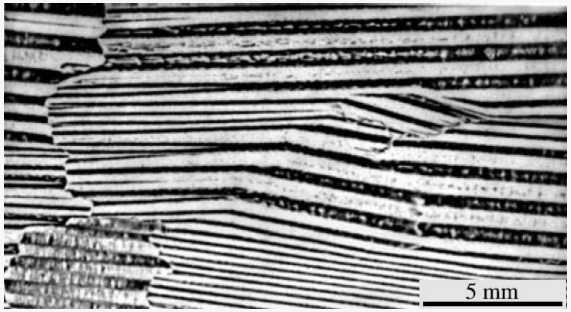
What determines hysteresis loops?

- Material composition and crystal structure
- Microstructure

BASICS – DOMAINS, FROM BULK TO NANO

Bulk material

Numerous and complex shape of domains

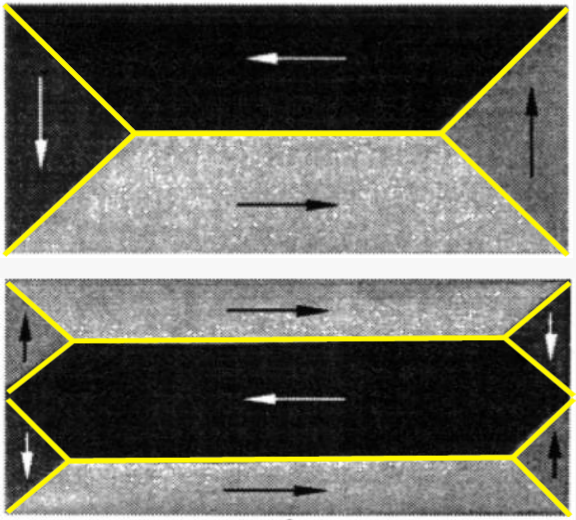


FeSi soft magnetic sheet

A. Hubert, Magnetic domains

Mesoscopic scale

Small number of domains, simple shape

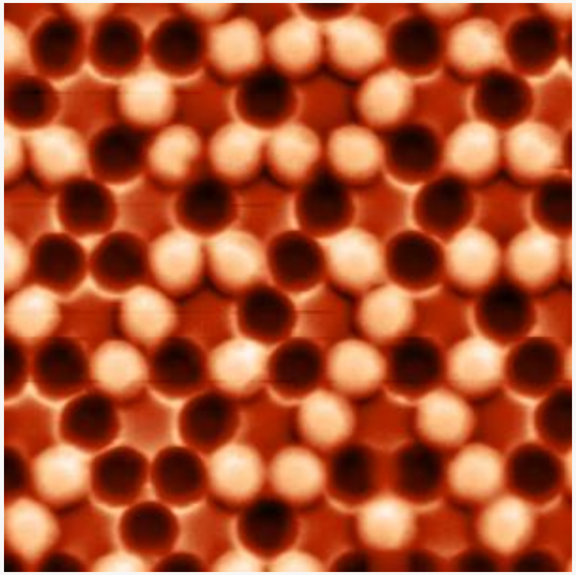


Microfabricated elements
Kerr microscopy

A. Hubert, Magnetic domains

Nanoscopic scale

Magnetic single domain



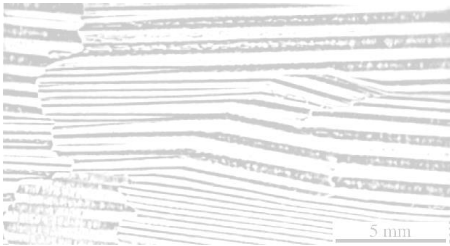
Nanofabricated dots
MFM

Sample courtesy: I. Chioar, N.Rougemaille

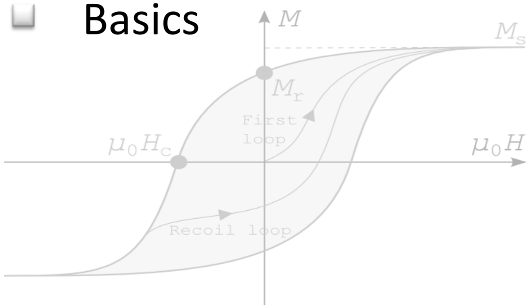
- Nanomagnetism ≈ Mesomagnetism

TABLE OF CONTENTS

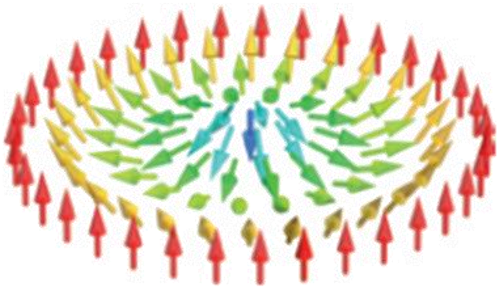
- Motivation



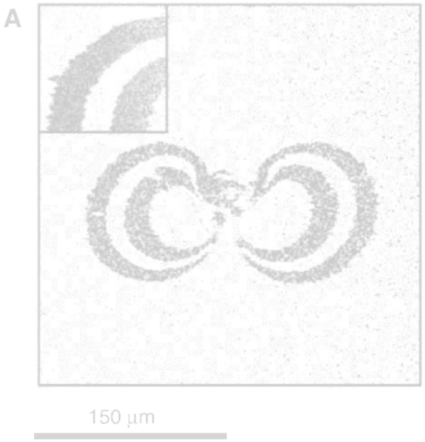
- Basics



- Statics



- Dynamics



Magnetization

Magnetization vector **M**

- Continuous function
- May vary over time and space
- Modulus is constant and uniform (hypothesis in micromagnetism)

$$\mathbf{M}(\mathbf{r}) = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = M_s \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

$$m_x^2 + m_y^2 + m_z^2 = 1$$

Mean field approach is possible: $M_s = M_s(T)$

Exchange interaction

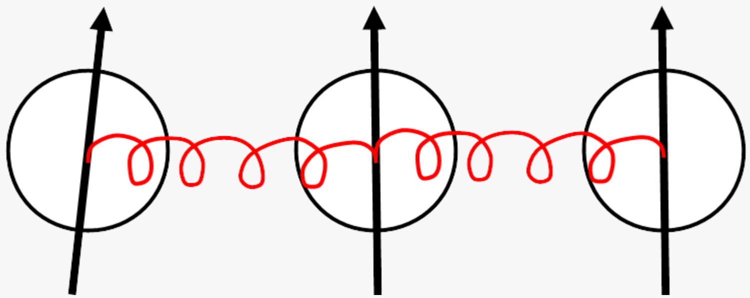
- Atomistic view $\mathcal{E} = -\sum_{i \neq j} J_{i,j} \mathbf{S}_i . \mathbf{S}_j$ (total energy, J)
- Micromagnetic view

$$\mathbf{S}_i . \mathbf{S}_j = S^2 \cos(\theta_{i,j}) \approx S^2 \left(1 - \frac{\theta_{i,j}^2}{2}\right)$$

$$E_{\mathrm{ex}} = A(\boldsymbol{\nabla}.\mathrm{m})^2 = A \sum_{i,j} \left(\frac{\partial m_i}{\partial x_j}\right)^2$$

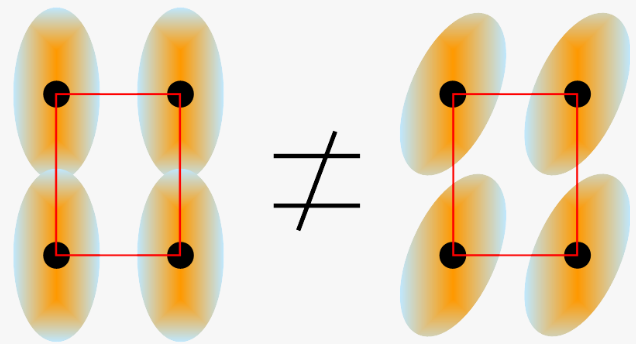
STATICS – THE VARIOUS TYPES OF MAGNETIC ENERGY

Exchange energy



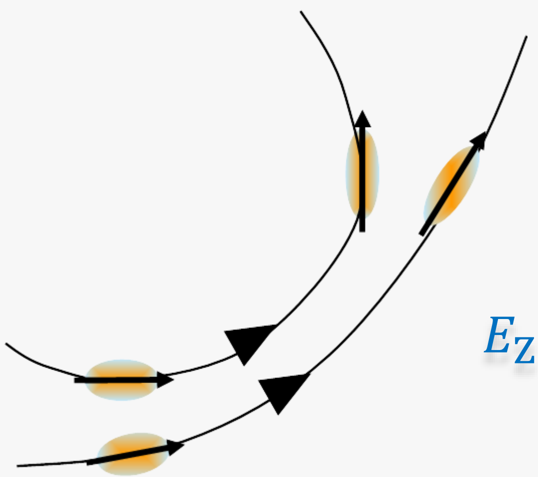
$$E_{\mathrm{ex}} = A(\boldsymbol{\nabla}.\mathrm{m})^2 = A\sum_{i,j}\left(\frac{\partial m_i}{\partial x_j}\right)^2$$

Magnetocrystalline anisotropy energy



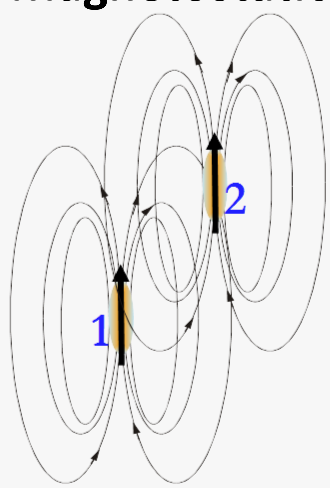
$$E_{\mathrm{mc}} = K\, f(\theta,\varphi)$$

Zeeman energy (→ enthalpy)



$$E_{\mathrm{Z}} = -\mu_0 \mathbf{M}.\mathbf{H}$$

Magnetostatic energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0 \mathbf{M}.\mathbf{H}_{\mathrm{d}}$$

Analogy with electrostatics

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

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = -M_\mathrm{s} \iiint_\mathrm{space} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}V'$$

To lift the singularity that may arise at boundaries, a volume integration around the boundaries yields:

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = \iiint \frac{\rho(\mathbf{r}').(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}V' + \oiint \frac{\sigma(\mathbf{r}').(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}S'$$

Usefull expressions

$$\mathcal{E}_\mathrm{d} = -\frac{1}{2}\mu_0 \iiint_\mathrm{Sample} \mathbf{M}.\mathbf{H}_\mathrm{d}\mathrm{d}V$$

$$\mathcal{E}_\mathrm{d} = \frac{1}{2}\mu_0 \iiint_\mathrm{Space} \mathbf{H}_\mathrm{d}^2\mathrm{d}V$$

- Always positive
- Zero means minimum

Magnetic charges

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

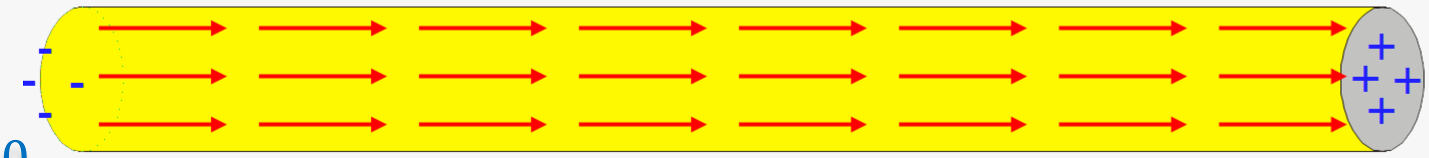
$\sigma(\mathbf{r}) = M_\mathrm{S}\mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$ → surface density of magnetic charges

- Hd depends on shape, not size
- Synonym: dipolar, magnetostatic

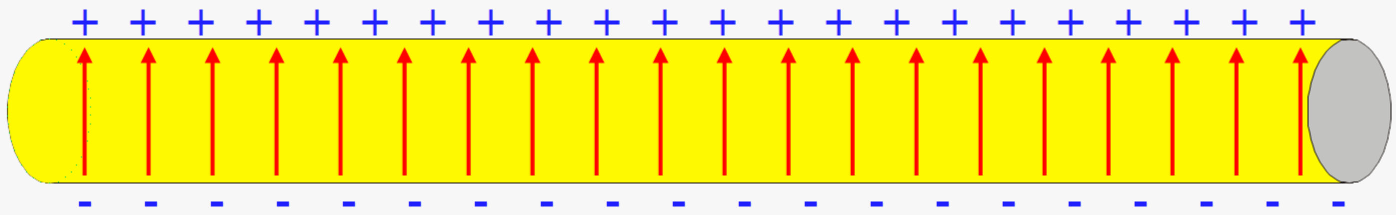
STATICS – MAGNETIC CHARGES

Examples of magnetic charges

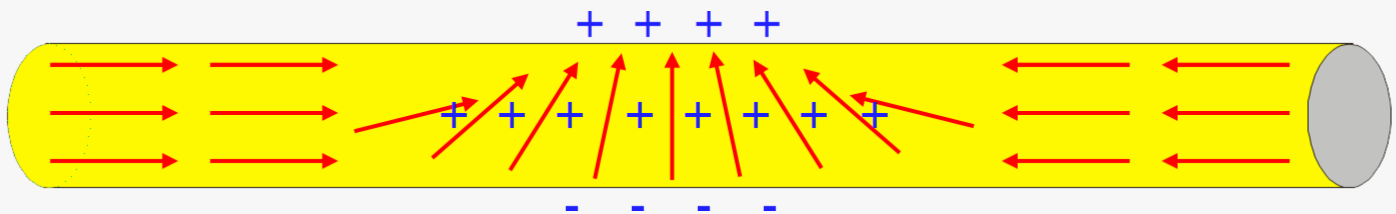
- Note for infinite cylinder:
  no charge $\mathcal{E} = 0$



- Charges on side surfaces

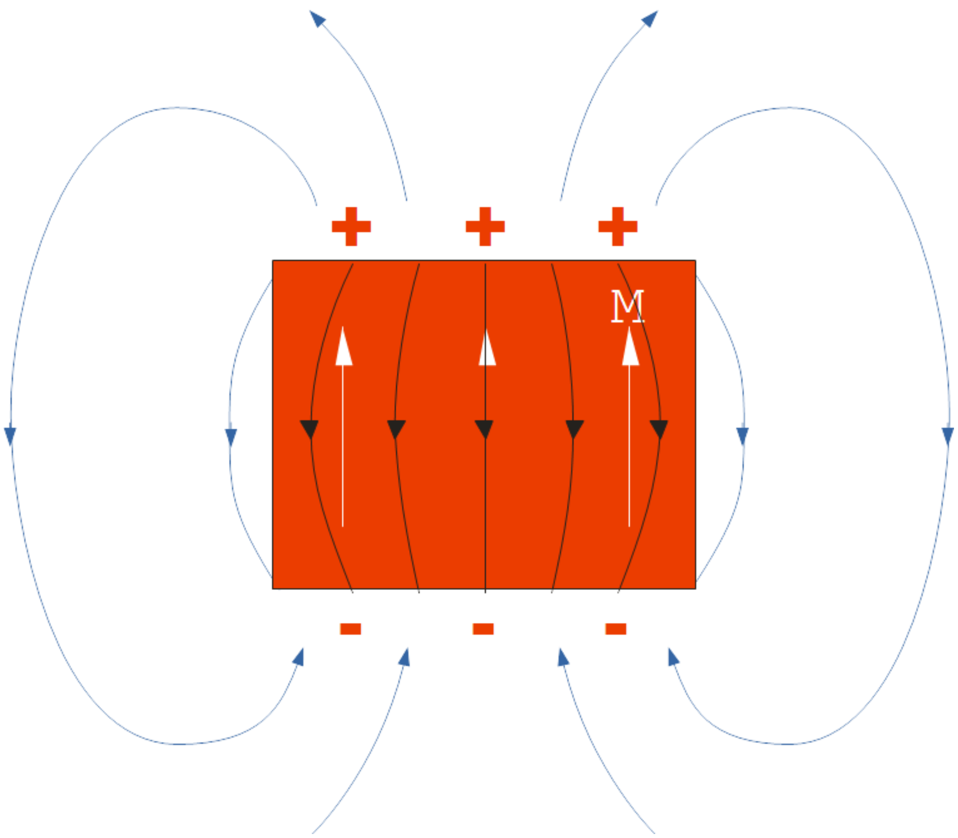


- Surface and volume charges



Take-away message

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



Vocabulary

- Generic names

  Magnetostatic field
  Dipolar field

- Inside material

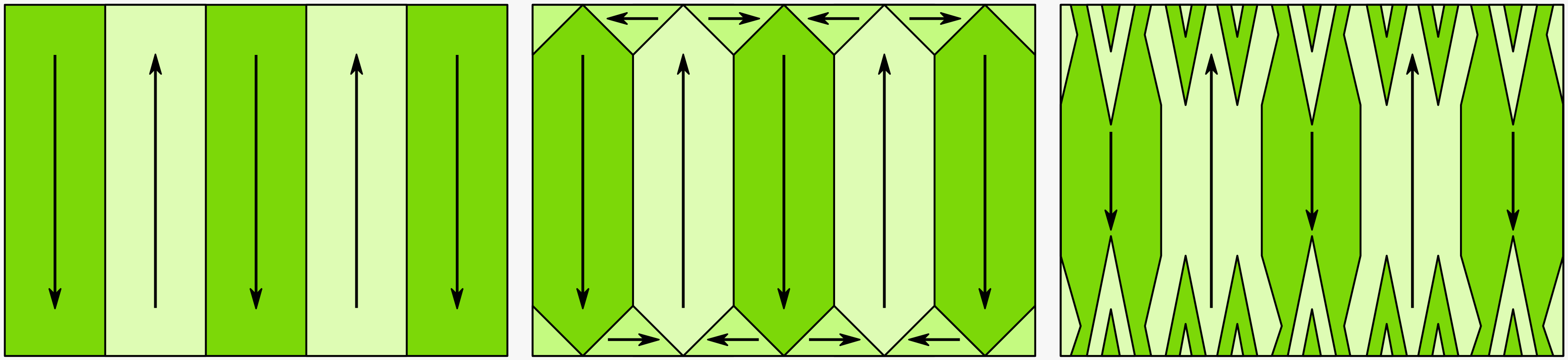
  Demagnetizing field

- Oustide material

  Stray field

Films with easy axis out-of-the-plane: Kittel domains

Principle: compromise between gain in dipolar energy, and cost in wall energy

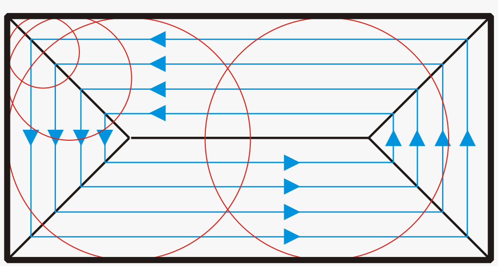


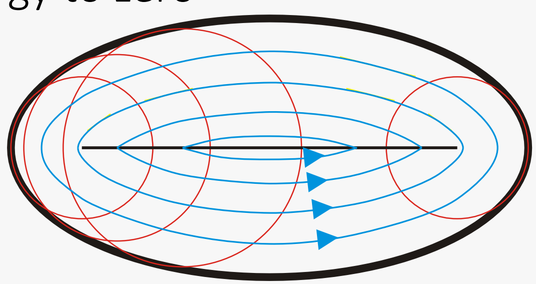
C. Kittel, Physical theory of ferromagnetic domains, Rev. Mod. Phys. 21, 541 (1949)

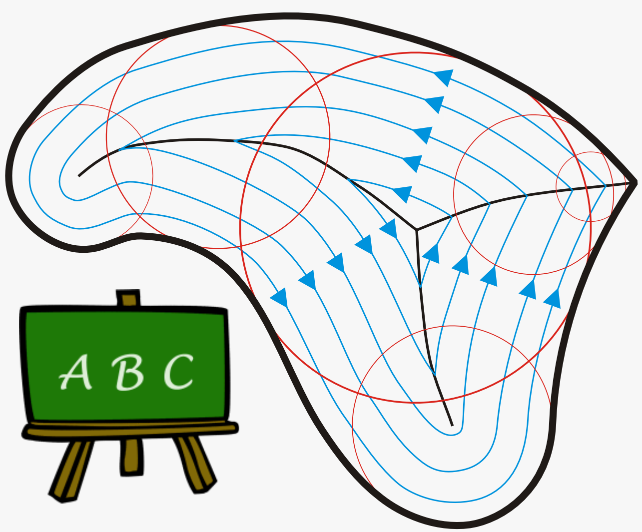
Nanostructures with in-plane magnetization

Van den Berg theorem

Principle: Reduce dipolar energy to zero







H. A. M. van den Berg, J. Magn. Magn. Mater. 44, 207 (1984)

The dipolar exchange length

When: anisotropy and exchange compete

$$E = \underbrace{A\left(\frac{\partial m_i}{\partial x_j}\right)^2}_{\text{Exchange},\ \mathrm{J/m}} + \underbrace{K_\mathrm{d}\sin^2\theta}_{\text{Dipolar},\ \mathrm{J/m^3}}$$

$$K_\mathrm{d} = \frac{1}{2}\mu_0 M_\mathrm{s}^2$$

$$\boxed{\Delta_\mathrm{d} = \sqrt{A/K_\mathrm{d}} = \sqrt{2A/\mu_0 M_\mathrm{s}^2}}$$

$$\Delta_\mathrm{d} \simeq 3 - 10\ \mathrm{nm}$$

Critical single-domain size, relevant for small particles made of soft magnetic materials

Often called: exchange length

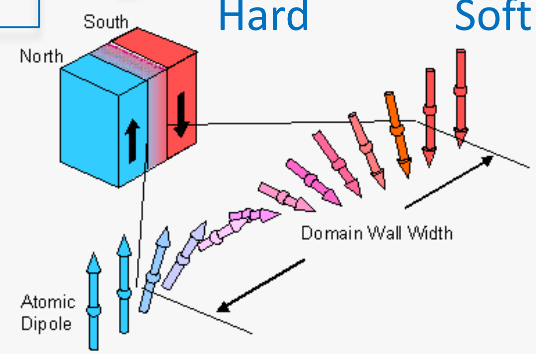
The anisotropy exchange length

When: anisotropy and exchange compete

$$E = \underbrace{A\left(\frac{\partial m_i}{\partial x_j}\right)^2}_{\text{Exchange},\ \mathrm{J/m}} + \underbrace{K\sin^2\theta}_{\text{Anisotropy},\ \mathrm{J/m^3}}$$

$$\boxed{\Delta_\mathrm{u} = \sqrt{A/K}}$$

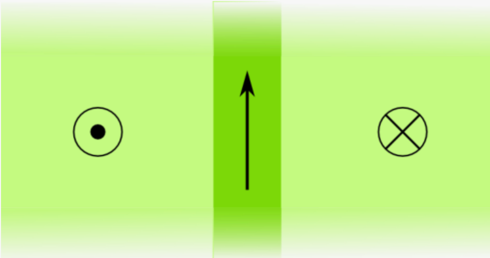
$\Delta_\mathrm{u} \simeq 1\ \mathrm{nm}$ (Hard) $\rightarrow$ $100\ \mathrm{nm}$ (Soft)



Sometimes called: Bloch parameter, or wall width

Note: Other length scales can be defined, e.g. with magnetic field

Bloch wall in the bulk (2D)

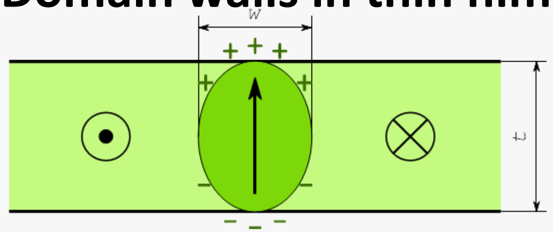


- No magnetostatic energy
- Width $\Delta_u = \sqrt{A/K}$
- Energy $\gamma_W = 4\sqrt{AK}$

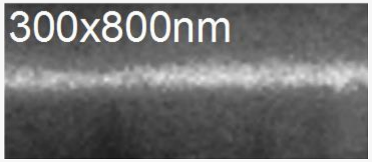
Other angles & anisotropy

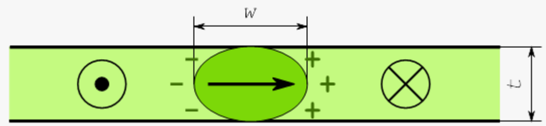
F. Bloch, Z. Phys. 74, 295 (1932)

Domain walls in thin films (towards 1D)

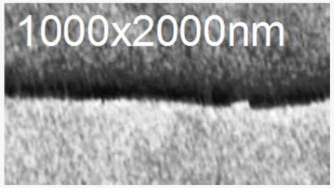


Bloch wall
$t \gtrsim w$





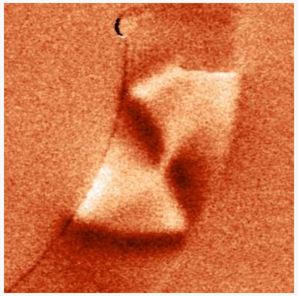
Néel wall
$t \lesssim w$



- Implies magnetostatic energy
- No exact analytic solution

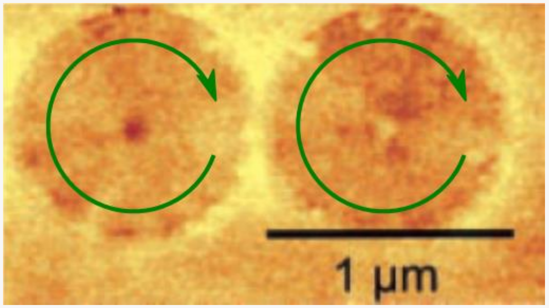
L. Néel, C. R. Acad. Sciences 241, 533 (1956)

Constrained walls (eg in strips)



Permalloy (15nm)
Strip width 500nm

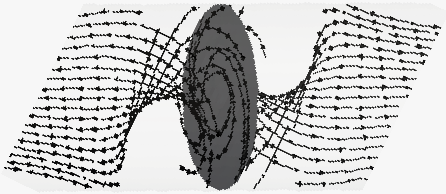
Vortex (1D → 0D)



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

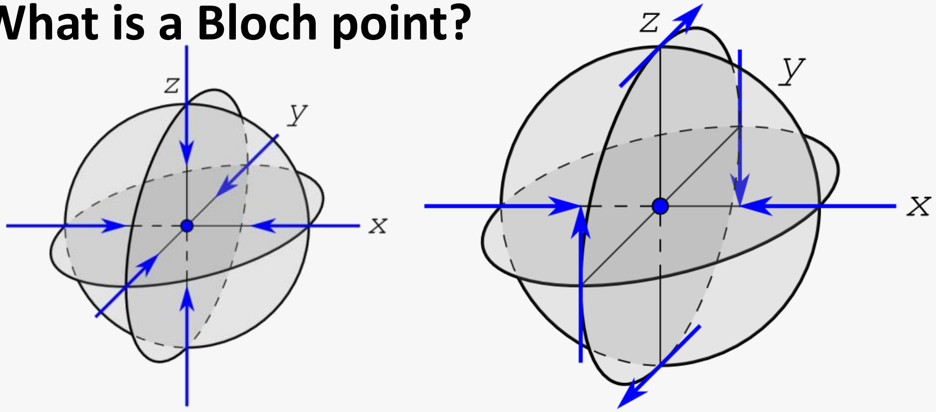
Bloch point (0D)

- Point with vanishing magnetization



W. Döring, JAP 39, 1006 (1968)

What is a Bloch point?

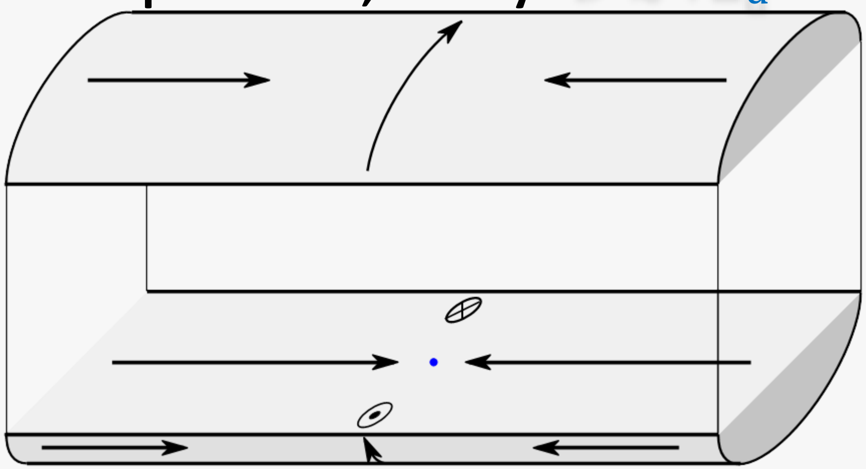


A magnetization texture with local cancellation of the magnetization vector

R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

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

Bloch-point wall, theory $D \gtrsim 7\Delta_{\mathrm{d}}^2$

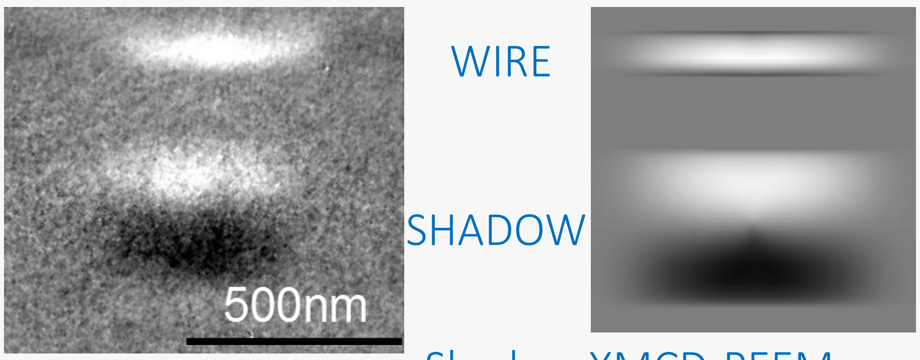


H. Forster et al., J. Appl. Phys. 91, 6914 (2002)

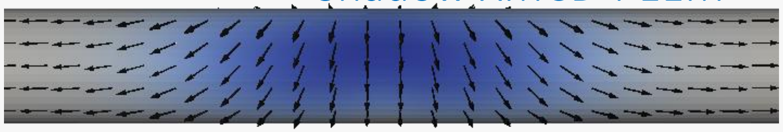
A. Thiaville, Y Nakatani, Spin dynamics in confined magnetic structures III, 101, 161-206 (2006)

Bloch-point wall, experiments

Experiment Simulation



Shadow XMCD-PEEM



S. Da-Col et al., PRB (R) 89, 180405, (2014)

The Dzyaloshinskii-Moriya interaction

- Usual magnetic exchange

$$\mathcal{E}_{i,j} = -J_{i,j}\mathbf{S}_i.\mathbf{S}_j$$

Promotes ferromagnetism (or antiferromagnetism)

- The DM interaction

$$\mathcal{E}_{\mathrm{DMI}} = -\mathbf{d}_{i,j}.\left(\mathbf{S}_i \times \mathbf{S}_j\right)$$

Requires: loss of inversion symmetry

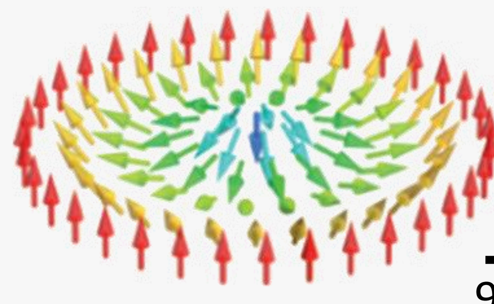
Promotes spirals and cycloids

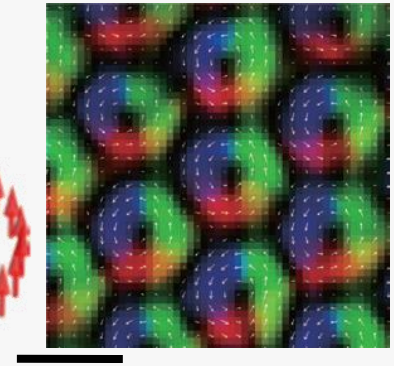
I. Dzyaloshiinsky, J. of Phys. Chem. Solids 4, 241 (1958)

T. Moriya, Phys. Rev. 120, 91 (1960)

A.Fert and P.M.Levy, PRL 44, 1538 (1980)

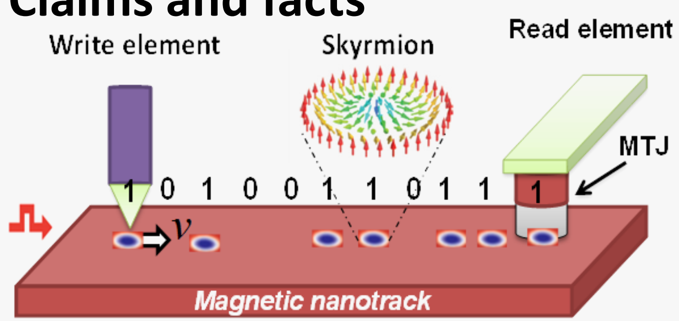
Magnetic skyrmions

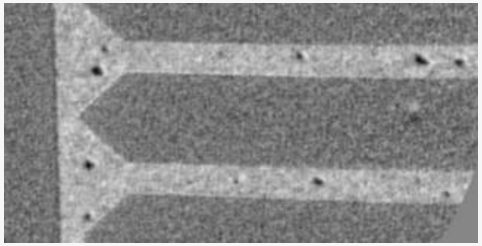




Bulk FeCoSi
Lorentz microscopy

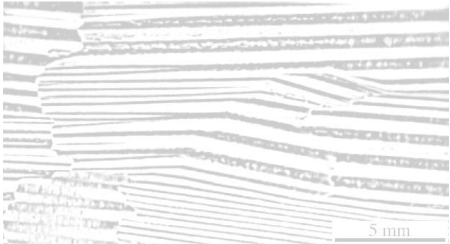
Claims and facts



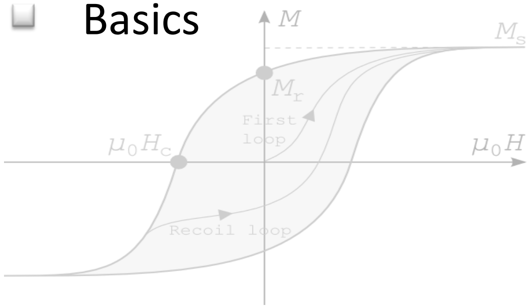


O. Boulle et al., Nat. Nanotech., 11, 449 (2016)

- Motivation

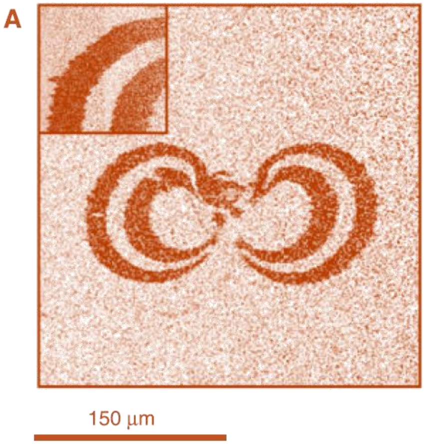


- Basics



- Statics

- Dynamics



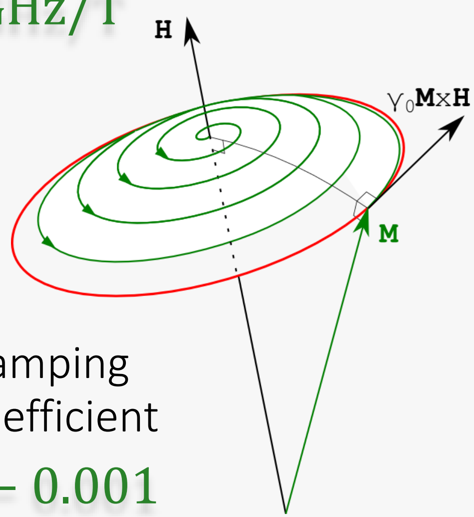
LLG equation

- Describes: precessional dynamics of magnetic moments
- Applies to magnetization, with phenomenological damping

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = \gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

$\gamma_0 = \mu_0 \gamma < \mathbf{0}$ Gyromagnetic ratio

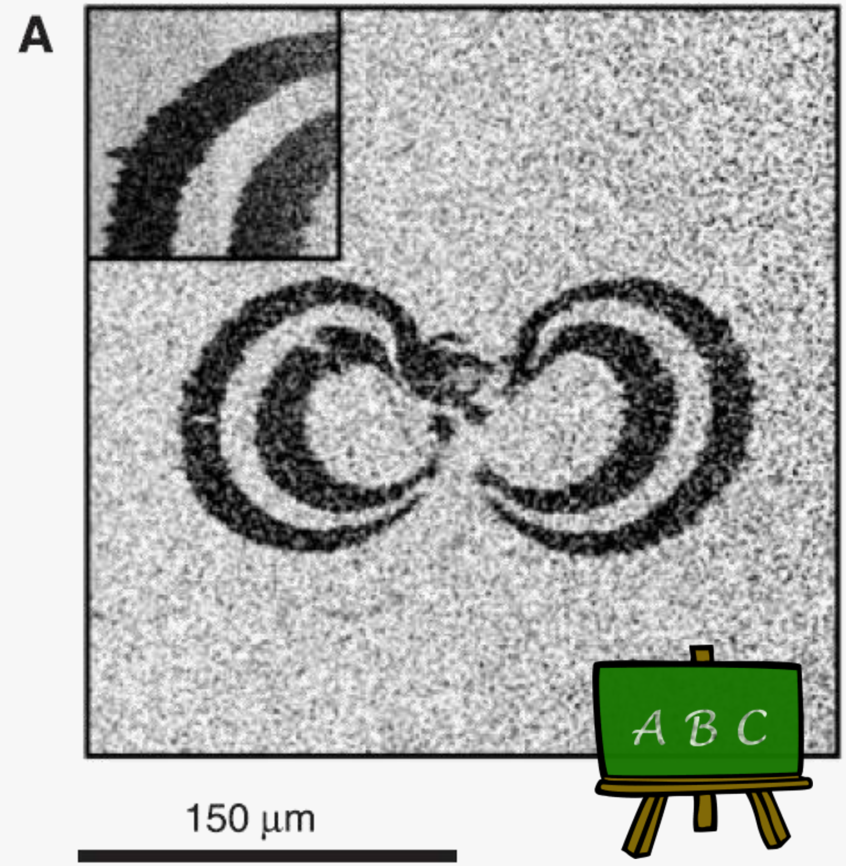
$\gamma_s = 28\ \mathrm{GHz/T}$



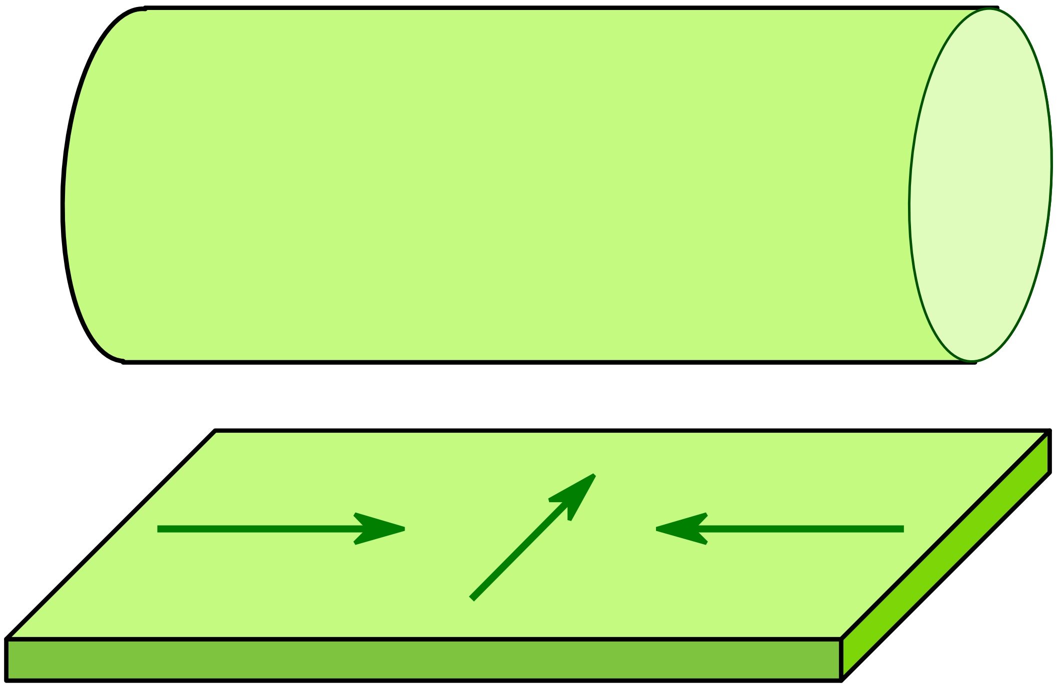
$\alpha > 0$ Damping coefficient

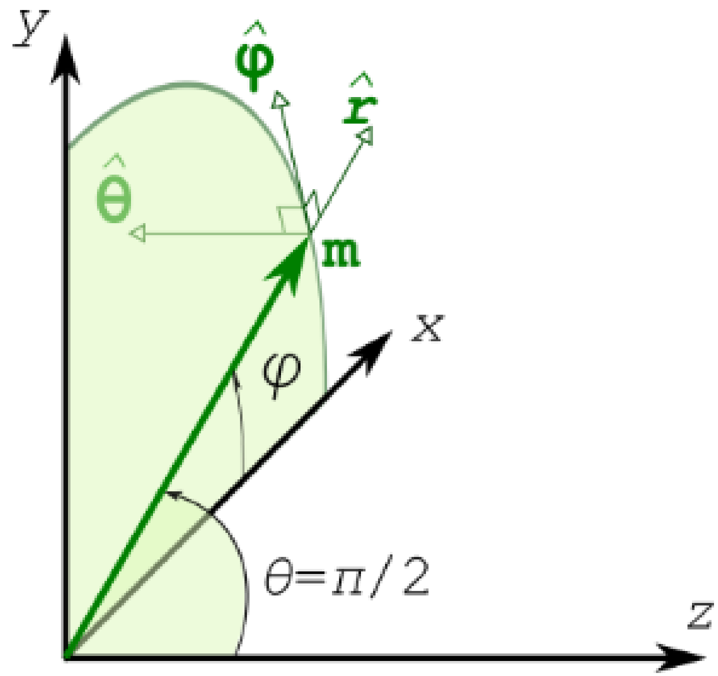
$\alpha = 0.1 - 0.001$

Pioneering experiment of precessional magnetization reversal



C. Back et al., Science 285, 864 (1999)

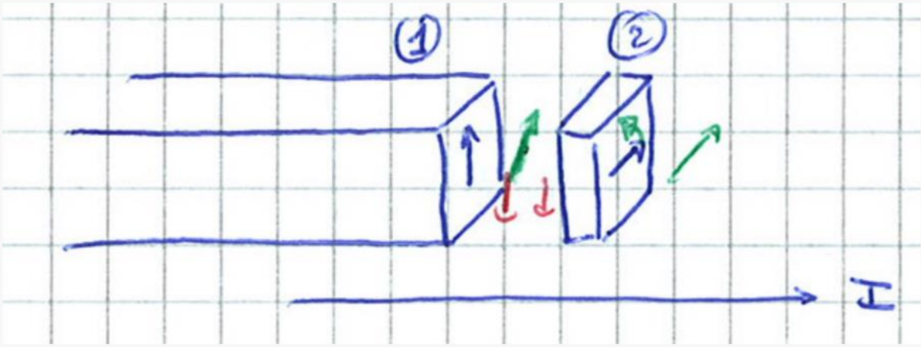




Precessional dynamics under field

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = \gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

Macrospins (1d model)



$$\frac{\mathrm{d}\mathbf{M}_2}{\mathrm{d}t} = \gamma_0 \mathbf{M}_2 \times \mathbf{H}_{\mathrm{eff}} + \alpha \frac{\mathbf{M}_2}{M_{s,2}} \times \frac{\mathrm{d}\mathbf{M}_2}{\mathrm{d}t} - P_{\mathrm{trans}} \mathbf{M}_2 (\mathbf{M}_2 \times \mathbf{M}_1)$$

$$P_{\mathrm{trans}} \sim P \frac{J}{|e|}$$

Number of spin-polarized per unit time

J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996)

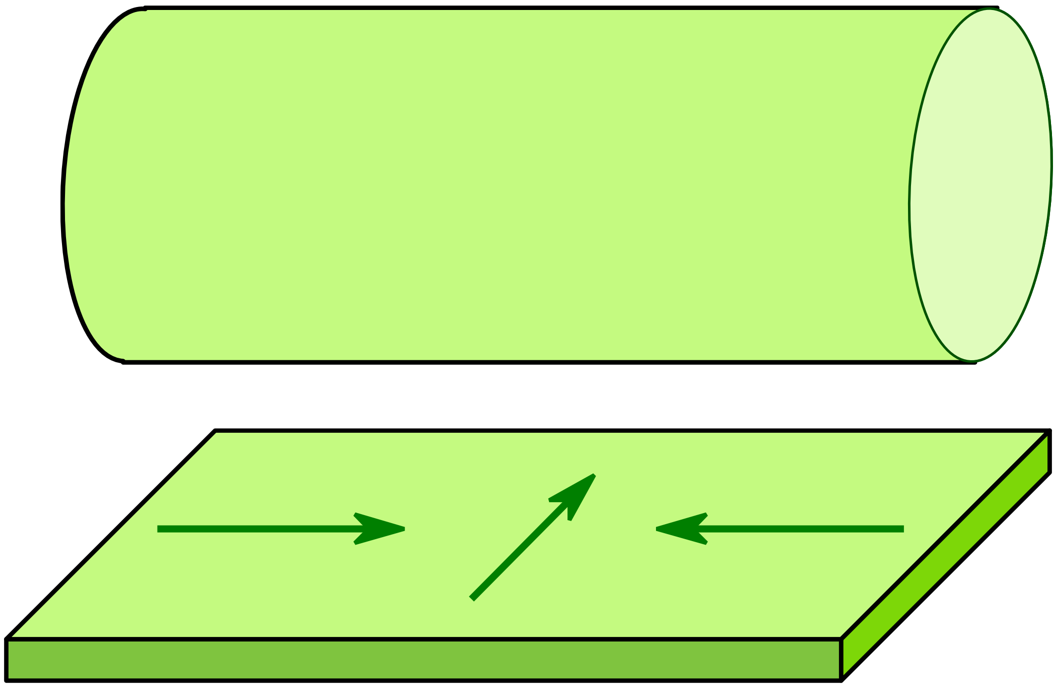
L. Berger, Phys. Rev. B 54, 9353 (1996)

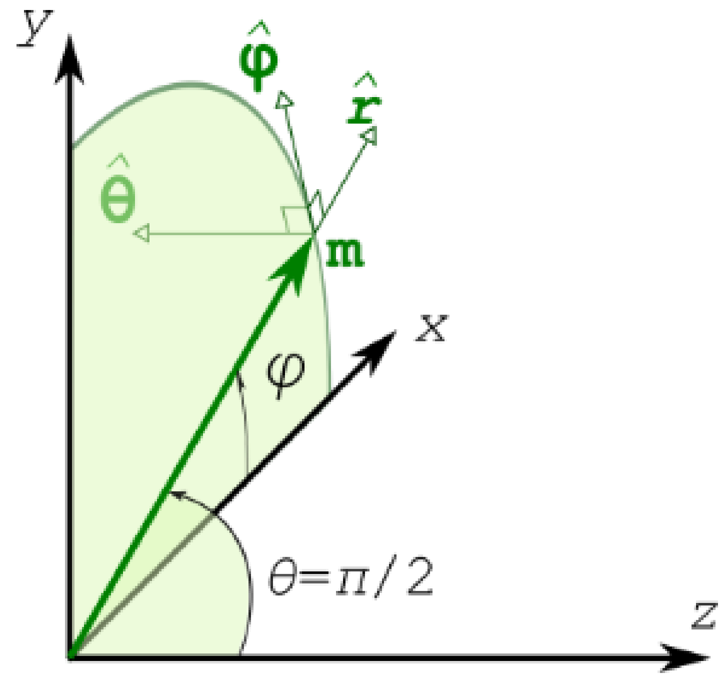
Magnetization texture (domain wall etc.)

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = \gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} - \overbrace{(\mathbf{u}.\boldsymbol{\nabla})\mathbf{m}}^{\text{Transfer}} + \overbrace{\beta \mathbf{m} \times [(\mathbf{u}.\boldsymbol{\nabla})\mathbf{m}]}^{\text{Field-like}}$$

A. Thiaville, Y. Nakatani, Micromagnetic simulation of domain wall dynamics in nanostrips, in *Nanomagnetism and Spintronics*, Elsevier (2009)

Dynamics – Motion of domain walls





Precessional dynamics under current

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = \gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} - (\mathbf{u}.\boldsymbol{\nabla})\mathbf{m} + \beta \mathbf{m} \times [(\mathbf{u}.\boldsymbol{\nabla})\mathbf{m}]$$

Thank you for your attention !

www.spintec.fr

email: olivier.fruchart@cea.fr

Slides: http://fruchart.eu/slides