Nanomagnetism: born when spintronics was mere science fiction

La caste des métabarons

A. Jodorowsky & J. Gimenez

http://www.humano.com/

A short overview of nanomagnetism

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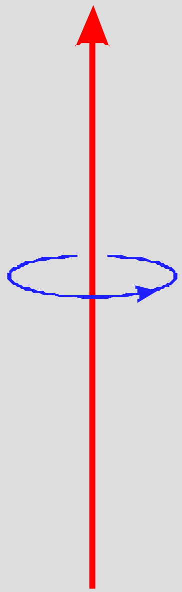
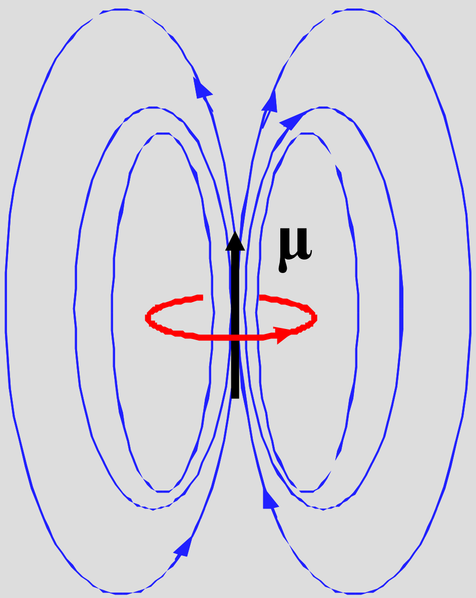
Oersted field



$$B = \frac{\mu_0 I}{2\pi r}$$

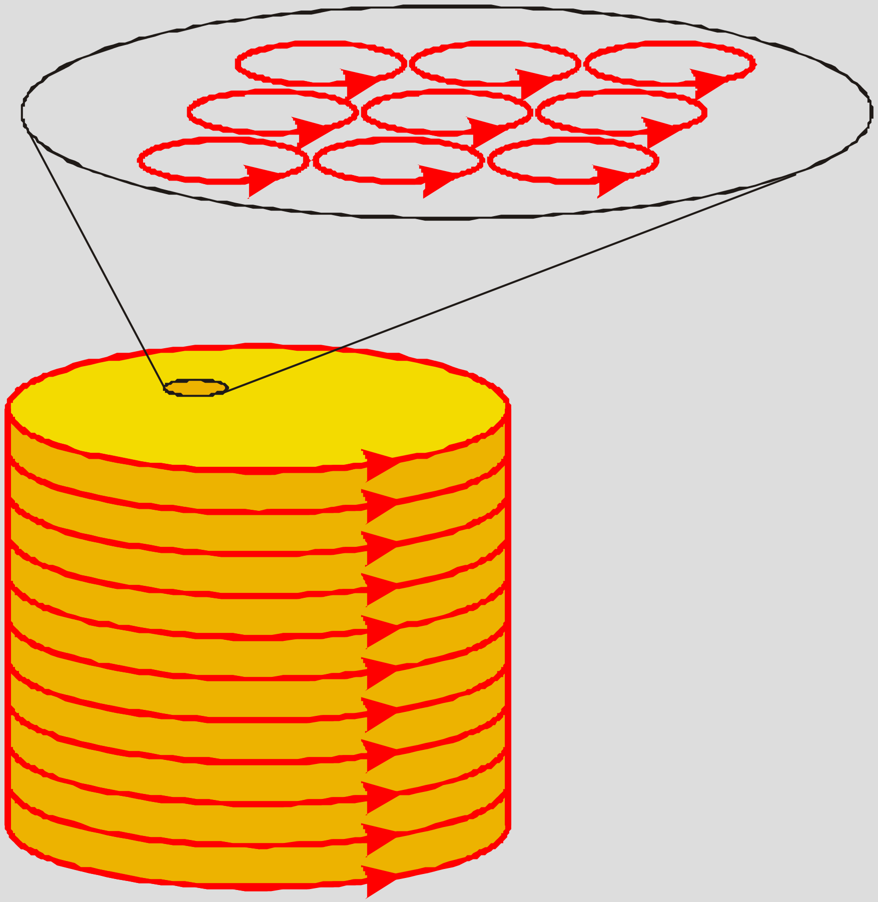
Magnetic dipole



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

Magnetic dipole: $A.m^2$

Magnetic material



Magnetization: $A.m^{-1}$

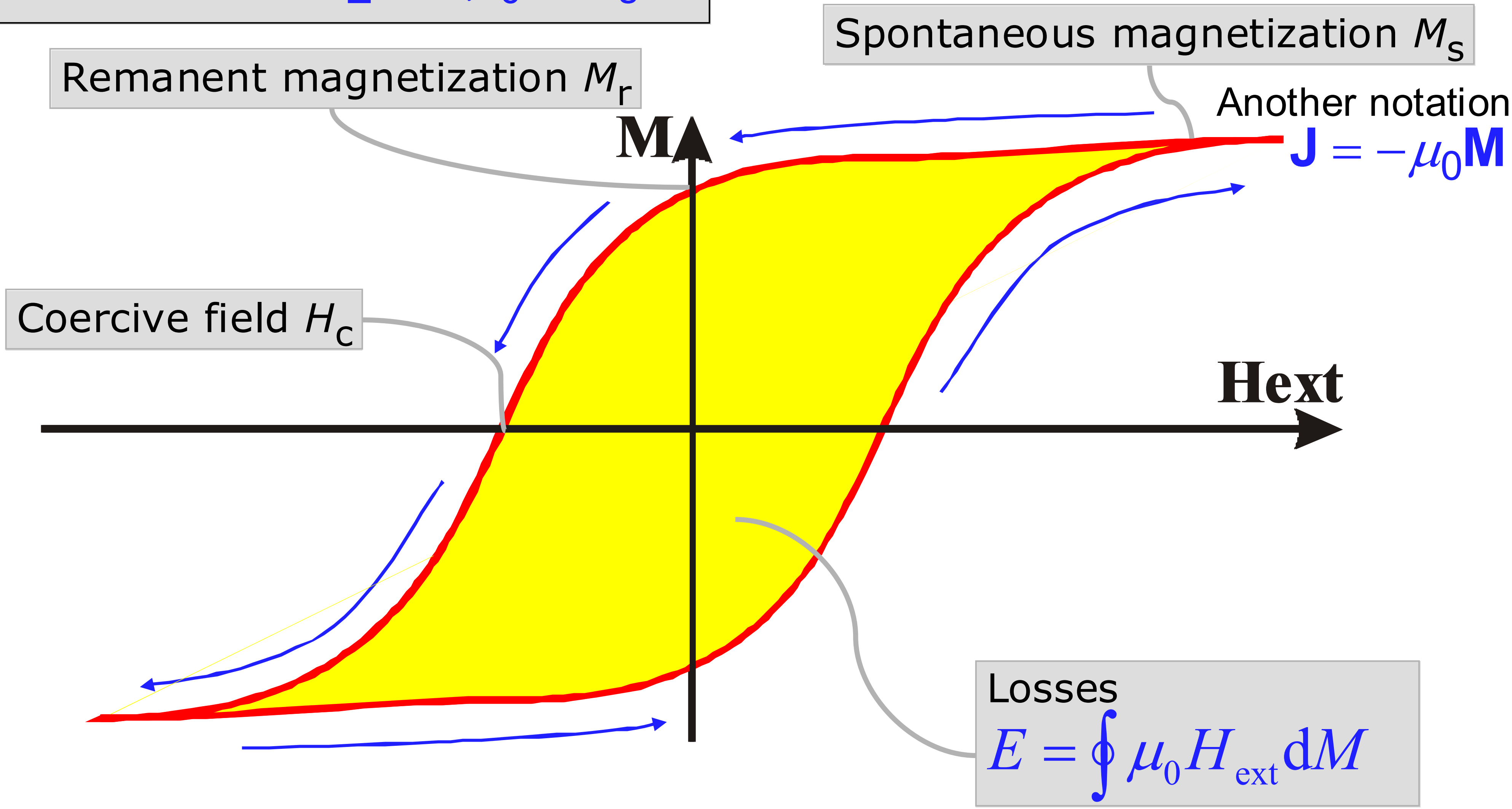
Magnetic moment: $A.m^2$

Manipulation of magnetic materials:

↳ Application of a magnetic field

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

Spontaneous ≠ **S**aturation



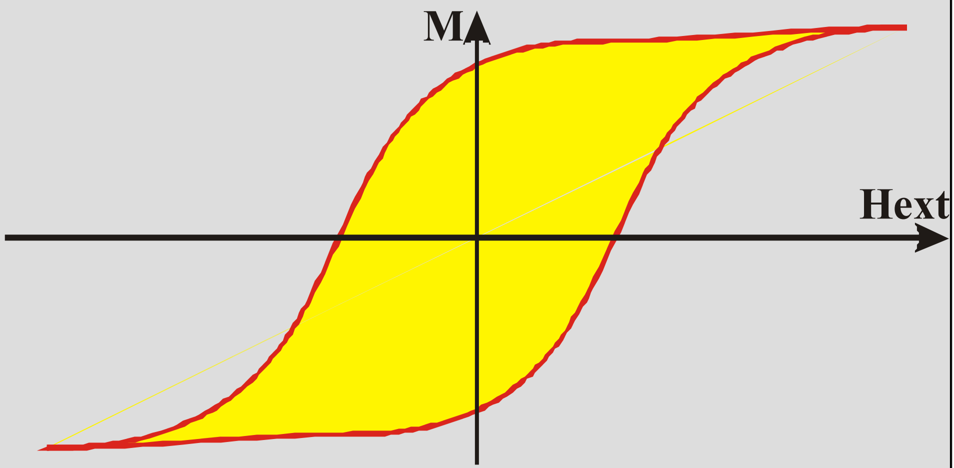
Soft materials

Transformers

Flux guides, sensors

Magnetic shielding

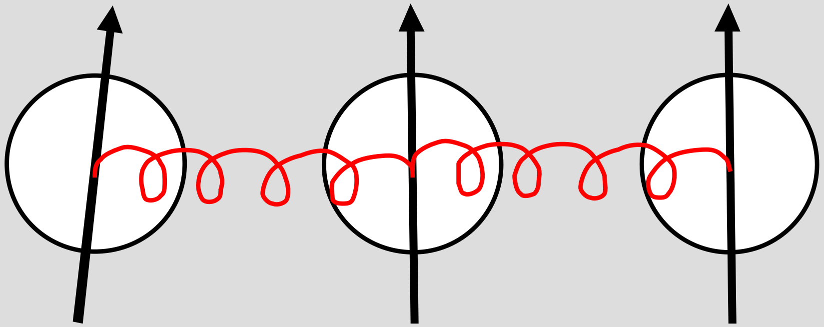
Hard materials



Permanent magnets, motors

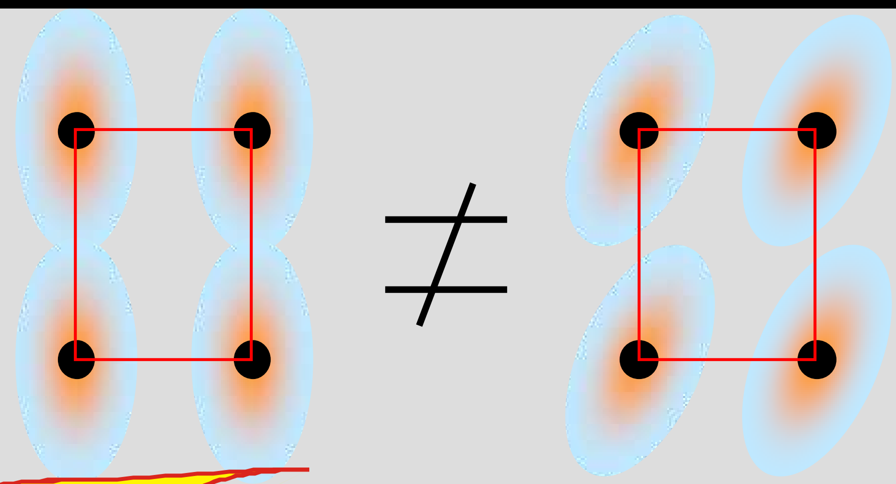
Magnetic recording

Echange energy

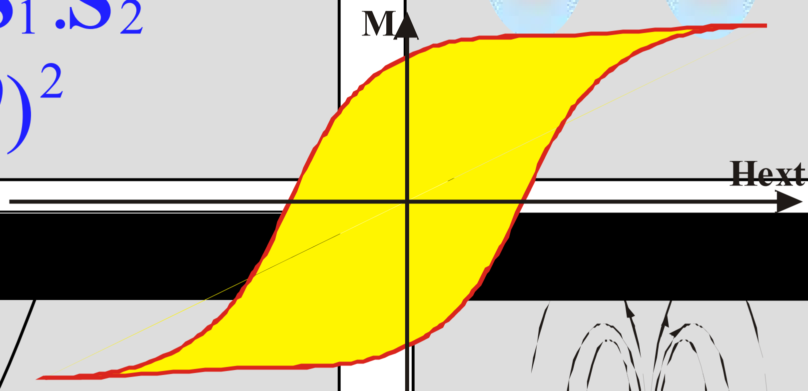


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2 = A(\nabla\theta)^2$$

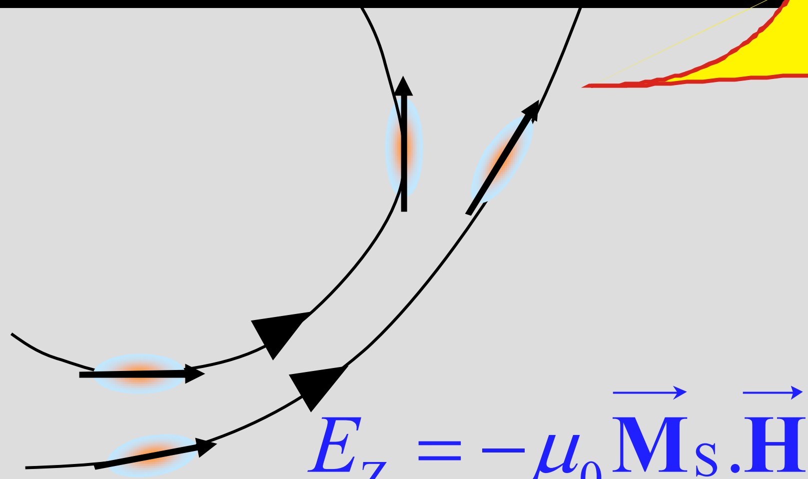
Magnetocrystalline anisotropy energy



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

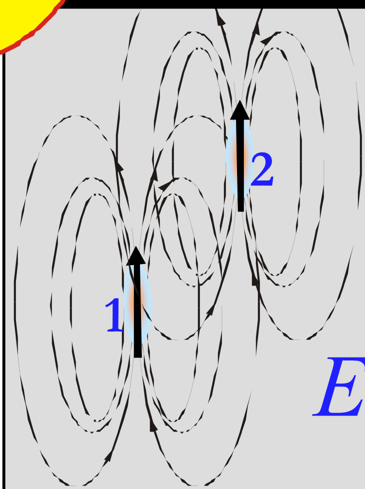


Zeeman energy (enthalpy)



$$E_Z = -\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}$$

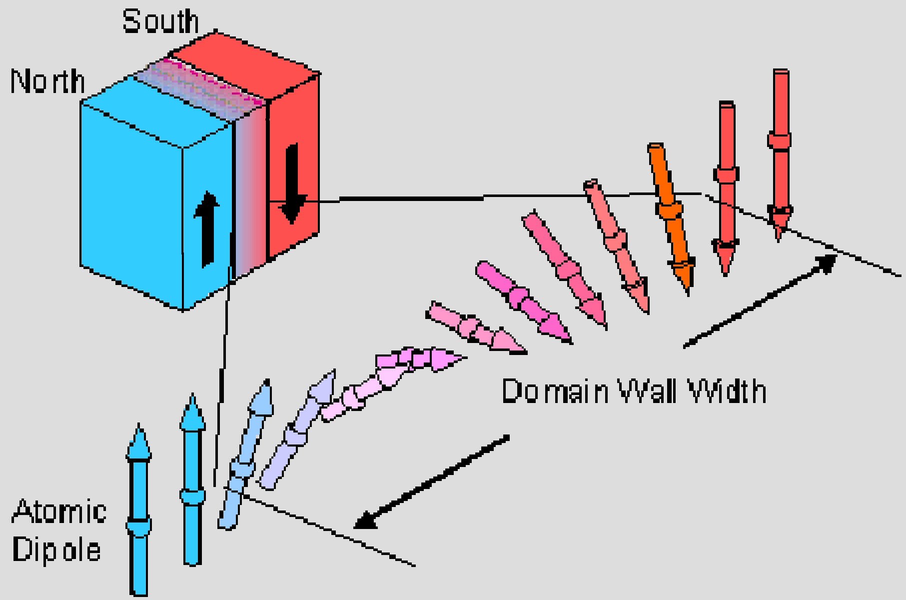
Dipolar energy



Long-ranged

$$E_d = -\frac{1}{2}\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}_d$$

Typical length scale: Bloch wall width λ_B



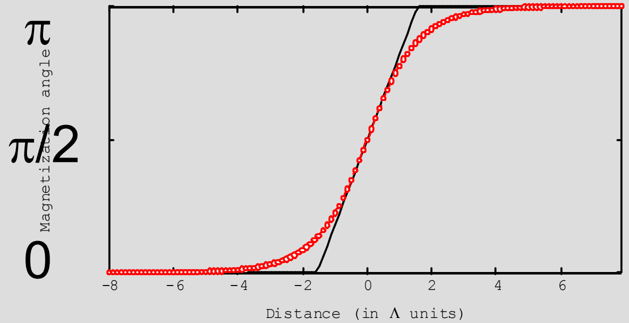
$$e = A(d\theta / dx)^2 + K \sin^2 \theta$$

Exchange $\rightarrow$ J/m

Anisotropy $\rightarrow$ J/m^3

$\Lambda = \sqrt{A/K}$ Wall parameter

Textbook solution and numerical values



$$\theta = 2A\tan[\exp(x/\Lambda)]$$

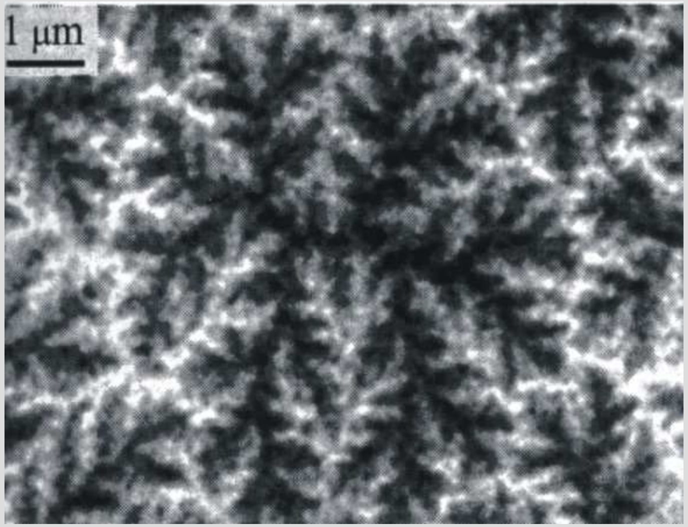
$\pi\sqrt{A/K}$ Wall width (asymptote)

2 – 3 nm $\longrightarrow$ 100 nm

Hard Soft

Bulk material

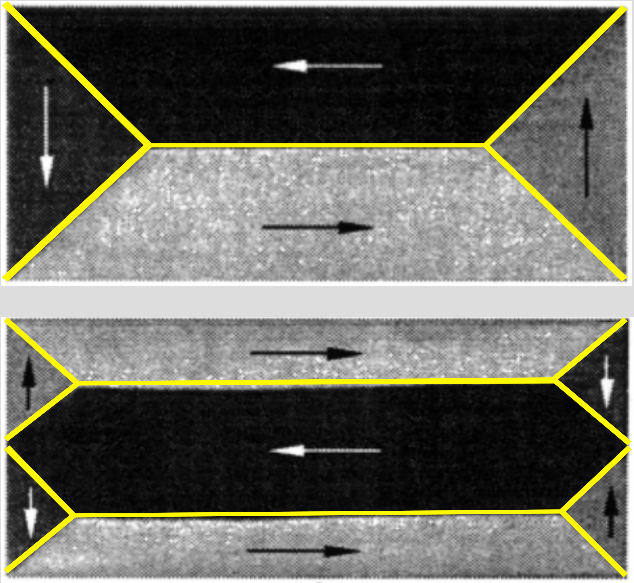
Numerous and complex magnetic domains



Co(1000) crystal – SEMPA
A. Hubert, *Magnetic domains*

Mesoscopic scale

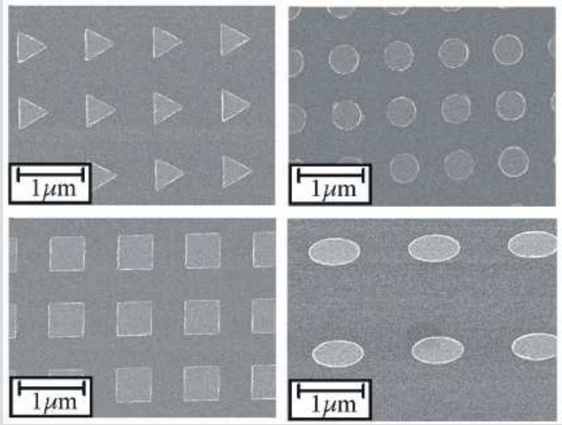
Small number of domains, simple shape

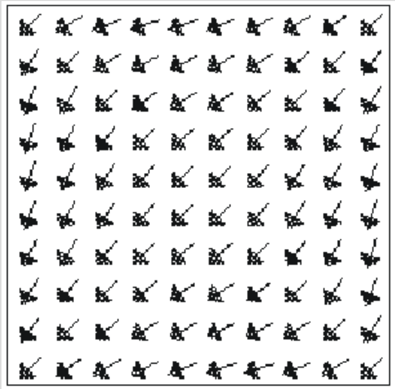


Microfabricated dots
Kerr magnetic imaging
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1 (2000)

↳ Nanomagnetism ≈ mesoscopic magnetism
↳ Size of nanostructures to be compared with a relevant length scale. No universal scale!

Density of dipolar energy $\boxed{E_\mathrm{d}(\mathbf{r}) = -\frac{1}{2}\mu_0 \mathbf{M}(\mathbf{r}).\mathbf{H}_\mathrm{d}(\mathbf{r})}$ $\left(E_\mathrm{Z} = -\mu_0 \vec{\mathbf{M}}_\mathrm{S}.\vec{\mathbf{H}}\right)$

By definition $\mathrm{div}(\mathbf{H}_\mathrm{d}) = -\mathrm{div}(\mathbf{M})$. As $\mathbf{curl}(\mathbf{H}_\mathrm{d}) = \mathbf{0}$ we have (analogy with electrostatics):

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

$\boxed{\rho(\mathbf{r}) = -M_\mathrm{s}\mathrm{div}[\mathbf{m}(\mathbf{r})]}$ is called the volume density of magnetic charges

To lift the divergence that may arise at sample boundaries a volume integration around the boundaries yields:

$$\boxed{\mathbf{H}_\mathrm{d}(\mathbf{r}) = M_\mathrm{s}\left(-\iiint_\mathrm{space} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^3 r' + \iint_\mathrm{sample} \frac{[\mathbf{m}(\mathbf{r}').\mathbf{n}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2 r'\right)}$$

$\boxed{\sigma(\mathbf{r}) = M_\mathrm{s}\mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})}$ is called the surface density of magnetic charges, where n(r) is the outgoing unit vector at boundaries

Do not forget boundaries between samples with different M_s

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http://perso.neel.cnrs.fr/olivier.fruchart/

Some ways to handle dipolar energy

Integrated dipolar energy:

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

Notice: six-fold integral over space: non-linear, long-range, time-consuming.

Bottle-neck of micromagnetic calculations

Usefull theorem for finite samples:

$$\mathcal{E} = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{M}.\mathbf{H}_\text{d}.\text{d}V = \frac{1}{2}\mu_0 \iiint_{\text{space}} \mathbf{H}_\text{d}^2.\text{d}V$$

⇨ $\mathcal{E}$ is always positive

⇨ Significance of $\boxed{\text{(BHmax)}}$ for permanent magnets

$$-\frac{1}{2}\mu_0 \iiint_{\text{sample}} (\mathbf{M}+\mathbf{H}_\text{d}).\mathbf{H}_\text{d}.\text{d}V = \boxed{-\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{B}.\mathbf{H}_\text{d}.\text{d}V}$$

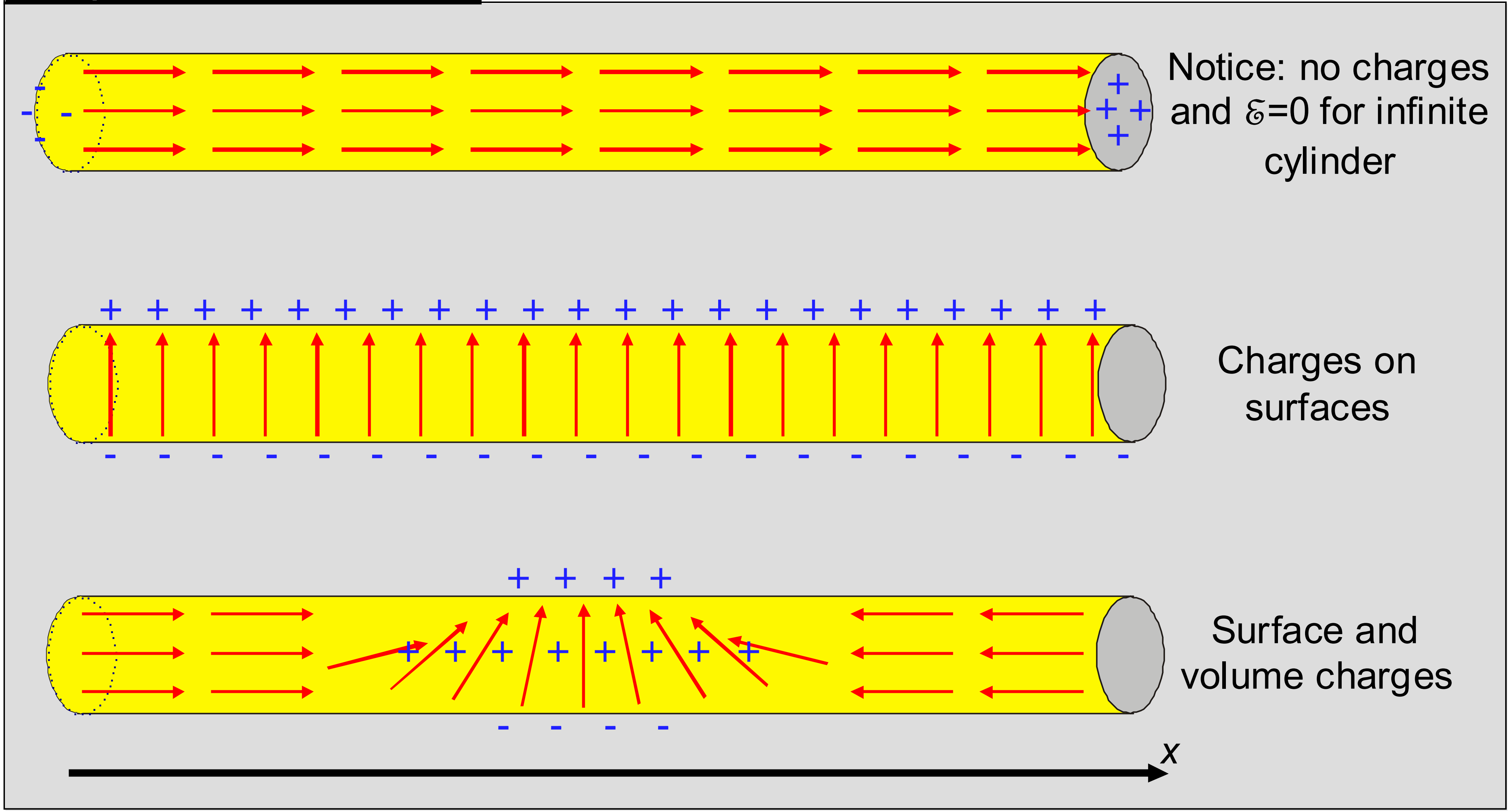
$$= \frac{1}{2}\mu_0 \iiint_{\text{space}\backslash\text{sample}} \mathbf{H}_\text{d}^2.\text{d}V$$

Energy available outside the sample, ie usefull for devices

Volume: $\rho(\mathbf{r}) = -M_s \mathrm{div}[\mathbf{m}(\mathbf{r})]$

Surface: $\sigma(\mathbf{r}) = M_s \mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$

Examples of magnetic charges



Assume uniform magnetization $\mathbf{M}(r) \equiv \mathbf{M} = M_s\left(m_x\mathbf{x} + m_y\mathbf{y} + m_z\mathbf{z}\right) = M_s m_i \mathbf{u}_i$

$$\mathbf{H}_d(\mathbf{r}) = M_s \iint_{\text{sample}} \frac{[\mathbf{m}.\mathbf{n}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi\|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}^2 r'$$
$$= M_s m_i \iint_{\text{sample}} \frac{n_i(\mathbf{r}').(\mathbf{r}'-\mathbf{r})}{4\pi\|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}^2 r'$$

$$\mathcal{E}_d = -\tfrac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{H}_d(\mathbf{r}).\mathbf{M}.\mathrm{d}^3\mathbf{r}$$
$$= -\tfrac{1}{2}\mu_0 M_s^2 m_i \iiint_{\text{sample}} \mathrm{d}^3\mathbf{r} \iint_{\text{sample}} \frac{n_i(\mathbf{r}').[\mathbf{m}.(\mathbf{r}'-\mathbf{r})]}{4\pi\|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}^2\mathbf{r}'$$
$$= -K_d m_i m_j \iiint_{\text{sample}} \mathrm{d}^3\mathbf{r} \iint_{\text{sample}} \frac{n_i(\mathbf{r}').(r_j'-r_j)}{4\pi\|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}^2\mathbf{r}'$$

$$\mathcal{E}_d = K_d V N_{ij} m_i m_j = K_d V \mathbf{m}.\overline{\overline{\mathbf{N}}}.\mathbf{m} \qquad K_d = \tfrac{1}{2}\mu_0 M_s^2$$

See more detailed approach: M. Beleggia and M. De Graef, J. Magn. Magn. Mater. 263, L1-9 (2003)

$$\mathcal{E}_\mathrm{d} = K_\mathrm{d} N_{ij} m_i m_j = K_\mathrm{d}\,{}^t\mathbf{m}.\overline{\overline{\mathbf{N}}}.\mathbf{m}$$

N is a positive second-order tensor

$$< \mathbf{H}_\mathrm{d}(\mathbf{r}) >= -M_\mathrm{s}\overline{\overline{\mathbf{N}}}.\mathbf{m}$$

...and can be defined and diagonalized for any sample shape

$$N = \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$

$$\mathcal{E}_\mathrm{d} = K_\mathrm{d}(N_x m_x^2 + N_y m_y^2 + N_z m_z^2)$$

$$< H_{\mathrm{d},i}(\mathbf{r}) >= -M_\mathrm{s} N_i$$ ← Valid along main axes only!

$$N_x + N_y + N_z = 1$$

What with ellipsoids???

Self-consistency: the magnetization must be at equilibrium and therefore fulfill $\mathbf{m}//\mathbf{H}_\mathrm{eff}$

Assuming $\mathbf{H}_\mathrm{applied}$ and $\mathbf{H}_\mathrm{a}$ are uniform, this requires $\mathbf{H}_\mathrm{d}(\mathbf{r})$ is uniform. This is satisfied only in volumes limited by polynomial surfaces of order 2 or less:
slabs, cylinders, ellisoids (+paraboloïds and hyperboloïds).

J. C. Maxwell, Clarendon 2, 66-73 (1872)

Ellipsoids

$$N_x = \tfrac{1}{2}abc\int_0^\infty \left[(a^2+\eta)\sqrt{(a^2+\eta)(b^2+\eta)(c^2+\eta)}\right]^{-1} \mathrm{d}\eta$$

General ellipsoid: main axes (a,c,c)

$$N_x = \frac{\alpha^2}{1-\alpha^2}\left[\frac{1}{\sqrt{1-\alpha^2}}\,\mathrm{Asinh}\left(\frac{\sqrt{1-\alpha^2}}{\alpha}\right)-1\right]$$

For prolate revolution ellipsoid: (a,c,c) with α=c/a<1

$$N_y = N_z = \tfrac{1}{2}(1-N_x)$$

$$N_x = \frac{\alpha^2}{\alpha^2-1}\left[1-\frac{1}{\sqrt{\alpha^2-1}}\,\mathrm{Asin}\left(\frac{\sqrt{\alpha^2-1}}{\alpha}\right)\right]$$

For oblate revolution ellipsoid: (a,c,c) with α=c/a>1

Cylinders

$$N_x = 0; \quad N_y = c/(b+c); \quad N_z = b/(b+c)$$

For a cylinder along x

J. A. Osborn, Phys. Rev. 67, 351 (1945).

For prisms, see: A. Aharoni, J. Appl. Phys. 83, 3432 (1998)

More general forms, FFT approach: M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)

Framework

Approximation: $\overrightarrow{\mathbf{m}}(\overrightarrow{\mathbf{r}}) = \overrightarrow{\mathbf{M}} = Cte$

(strong!)

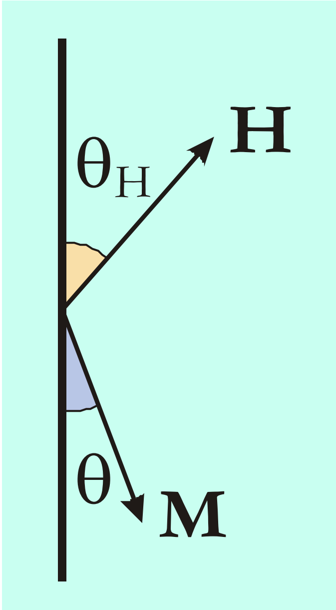
$$E_{tot} = V\left[K_{eff}\sin^2\theta - \mu_0 M_S H_{ext}\cos(\theta-\theta_H)\right]$$

$$K_{eff} = K_{mc} + K_d$$

Dimensionless units:

$$e = \sin^2(\theta) - 2h\cos(\theta-\theta_H)$$

$$\begin{pmatrix} e = E/VK \\ h = H/H_a \\ H_a = 2K/\mu_0 M_S \end{pmatrix}$$



L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

- Uniform rotation / magnetization reversal
- Coherent rotation / magnetization reversal
- Macrospin etc.

$$e = \sin^2(\theta) + 2h\cos(\theta) \qquad (\theta_H = 180°)$$

Equilibrium states

$$\frac{\partial e}{\partial \theta} = 2\sin\theta(\cos\theta - h)$$

$$\frac{\partial e}{\partial \theta} = 0 \quad \Rightarrow \quad \cos(\theta_m) = h$$

$$\theta \equiv 0\,[\pi]$$

Stability

$$\frac{\partial^2 e}{\partial \theta^2} = 2\cos 2\theta - 2h\cos\theta$$

$$= 4\cos^2\theta - 2 - 2h\cos\theta$$

$$\frac{\partial^2 e}{\partial \theta^2}(0) = 2(1-h)$$

$$\frac{\partial^2 e}{\partial \theta^2}(\theta_m) = 2(h^2 - 1)$$

$$\frac{\partial^2 e}{\partial \theta^2}(\pi) = 2(1+h)$$

Energy barrier

$$\Delta e = e(\theta_{max}) - e(0)$$

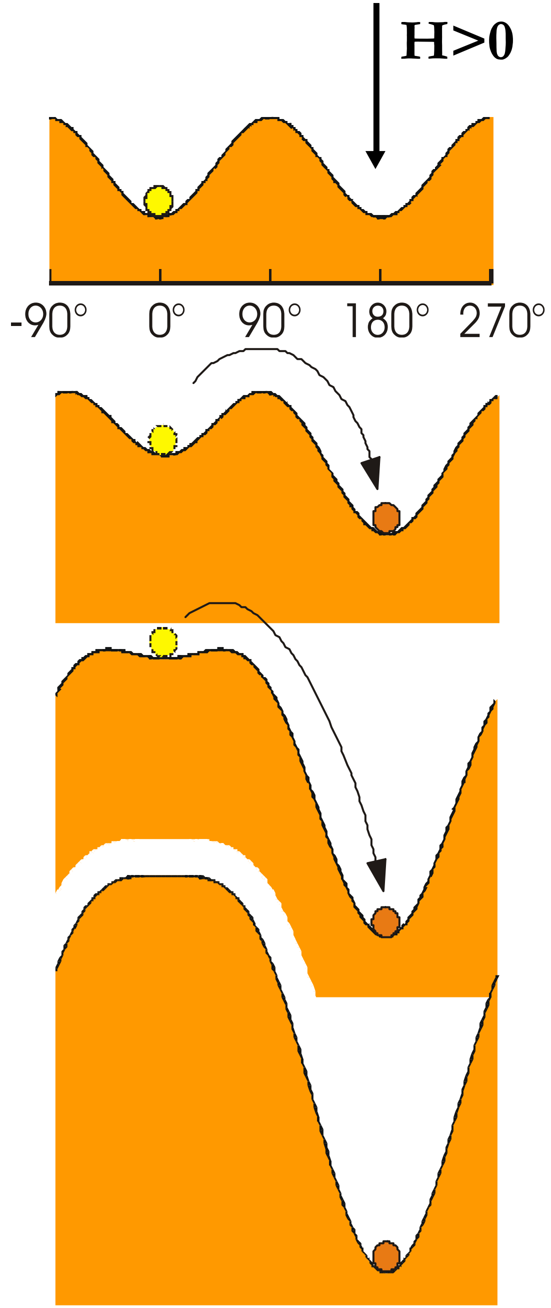
$$= 1 - h^2 + 2h^2 - 2h$$

$$= (1-h)^2$$

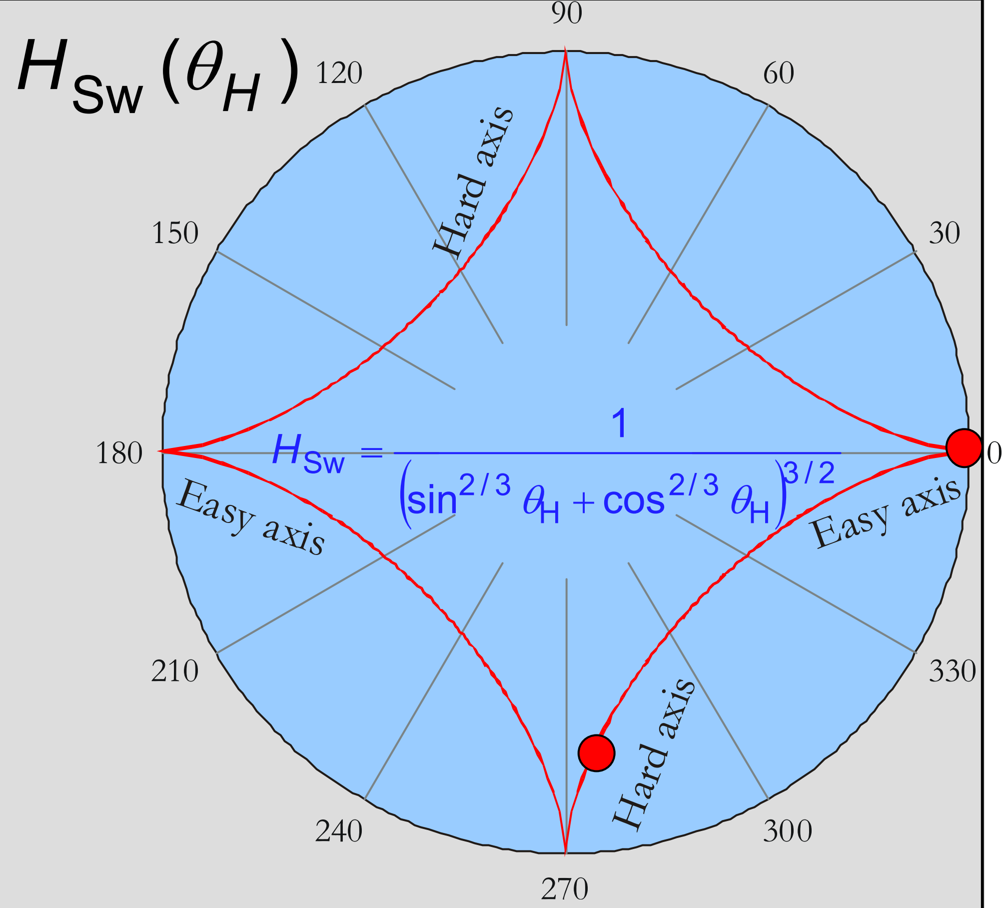
Switching

$$h = 1$$

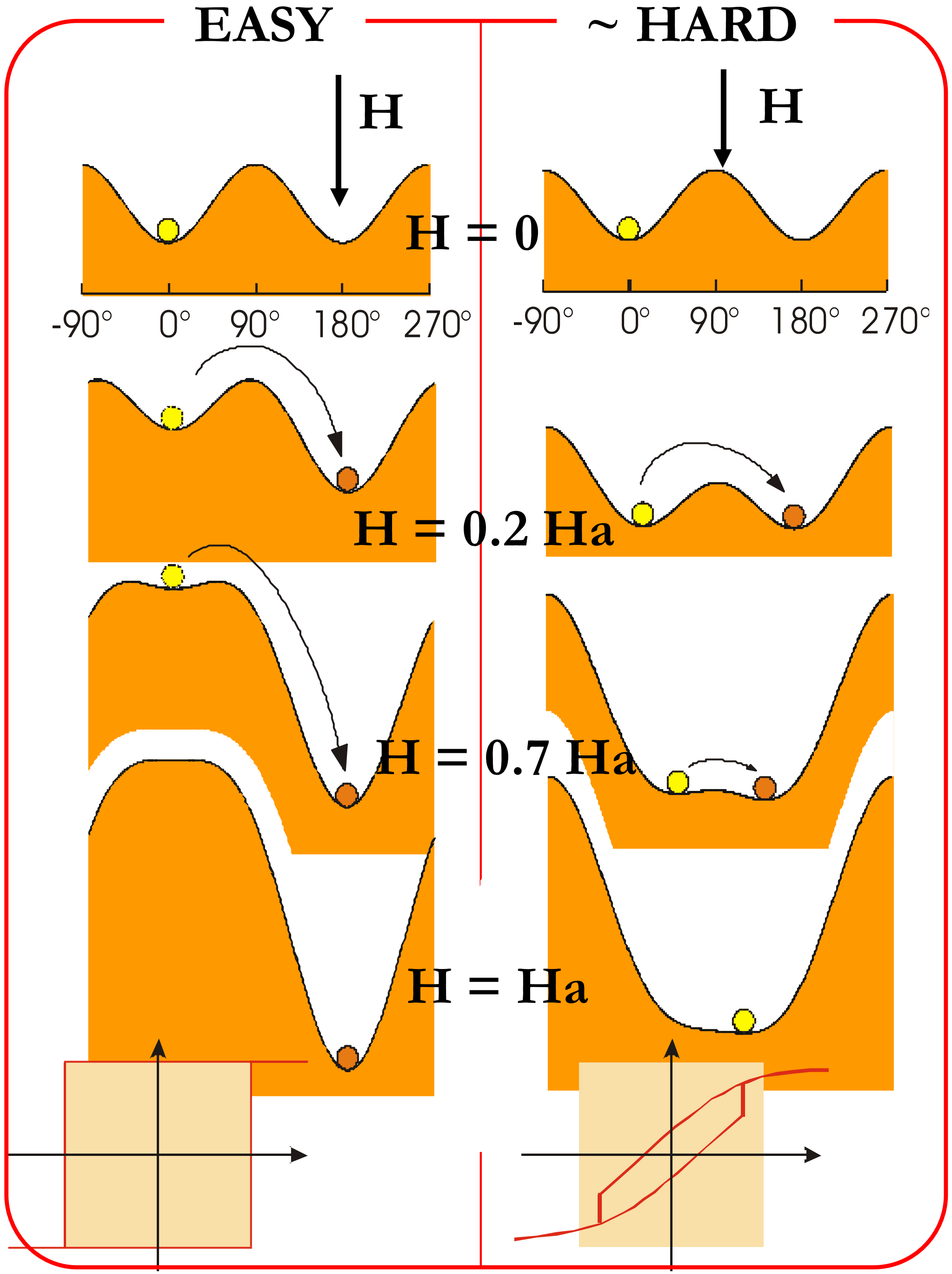
$$H = H_a = 2K/\mu_0 M_s$$



'Astroid' curve



- $H_{Sw}(\theta)$ is only one <u>signature</u> of the reversal mode



J. C. Slonczewski, Research Memo RM 003.111.224, IBM Research Center (1956)

Switching field = Reversal field

A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.

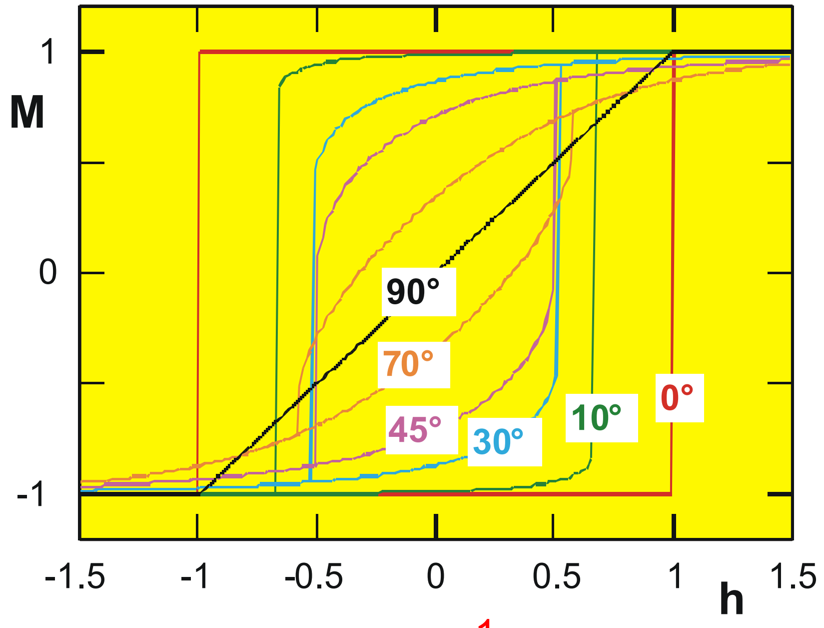
Can be measured only in single particles.

Coercive field

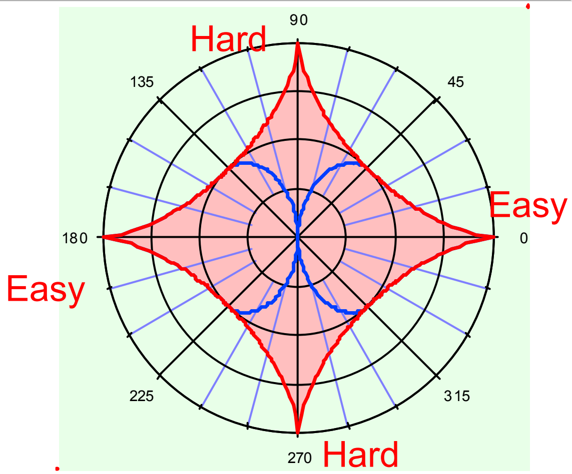
The value of field at which **M.H=0** ($\theta=\theta_H \pm \pi/2$)

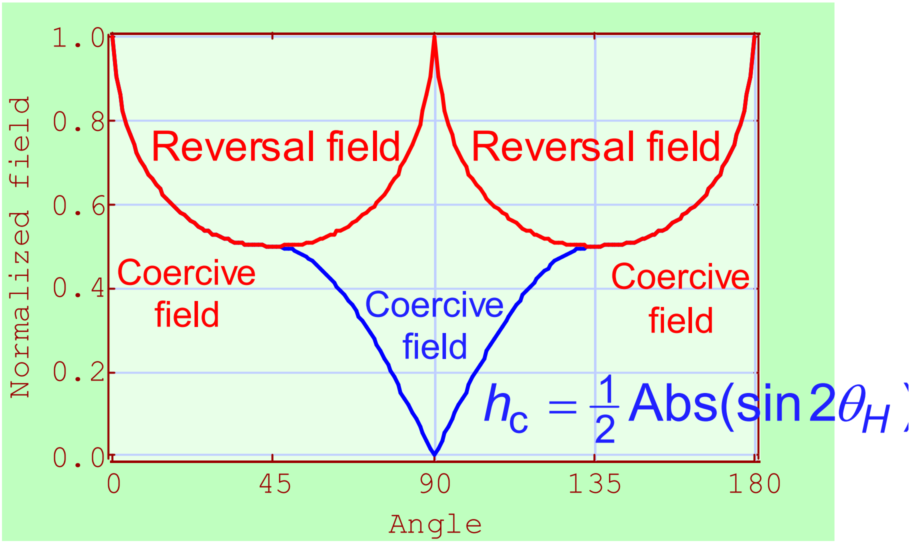
A quantity that can be measured in real materials (large number of 'particles').

<u>**May be or may not be**</u> a measure of the mean switching field at the microscopic level

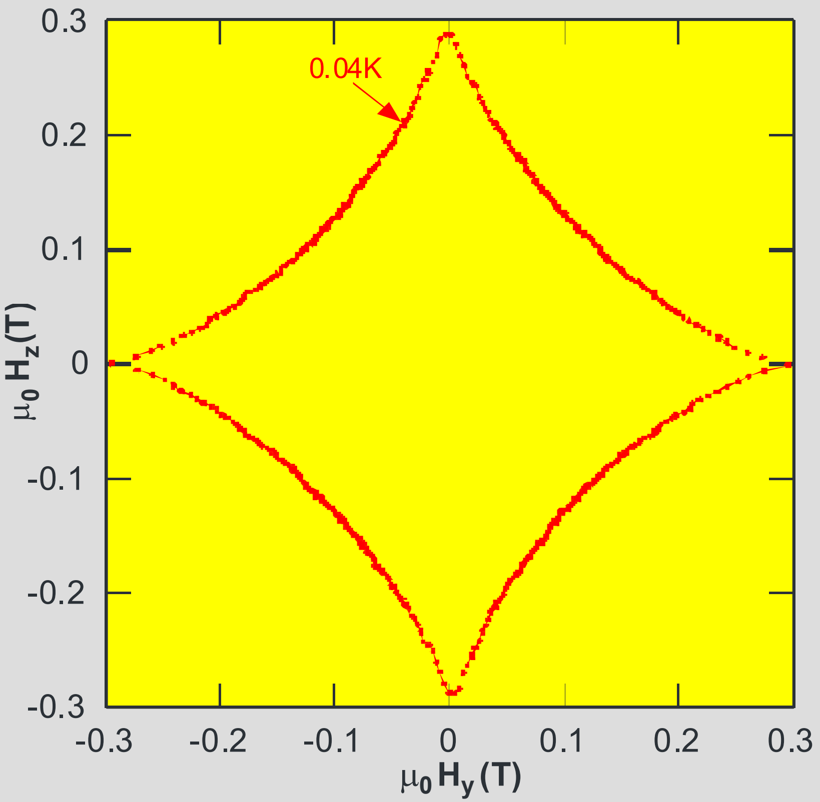


$$h_{Sw} = \frac{1}{\left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{3/2}}$$

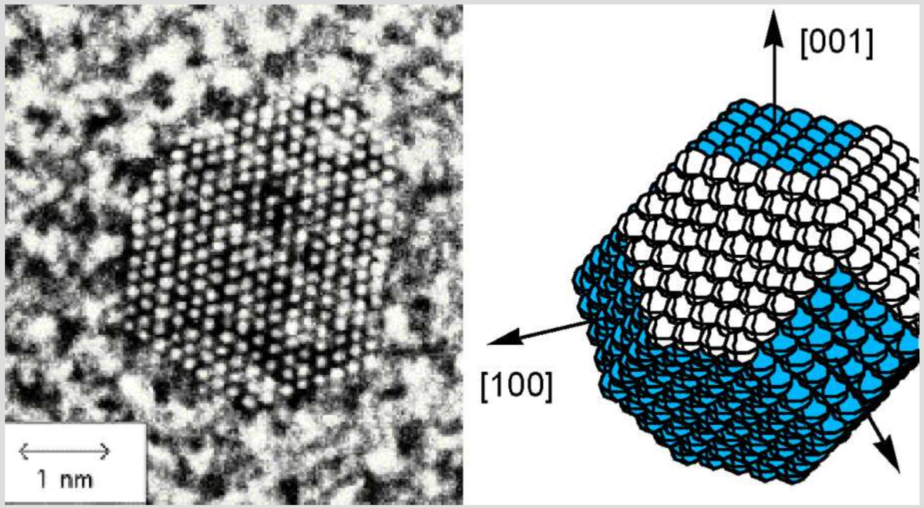




Experimental evidence

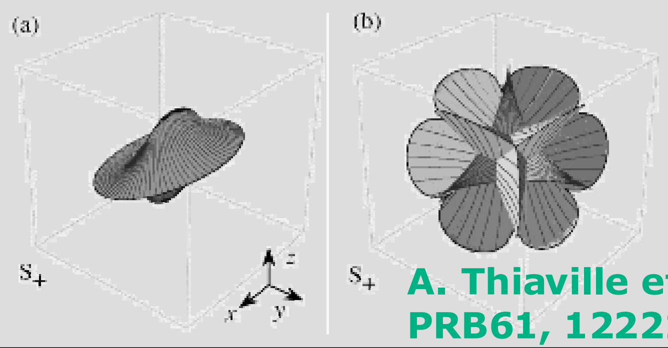


First evidence: **W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)**

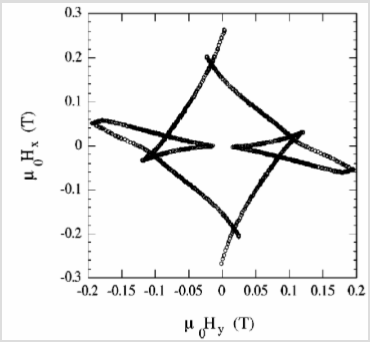


M. Jamet et al., Phys. Rev. Lett., 86, 4676 (2001)

Extensions: 3D, arbitrary anisotropy etc.



A. Thiaville et al., PRB61, 12221 (2000)

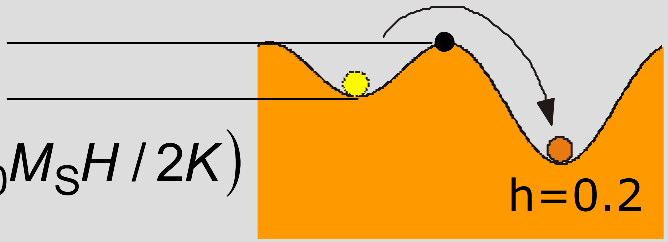


M. Jamet et al., PRB69, 024401 (2004)

Barrier height

$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$

$$\left(h = \mu_0 M_S H / 2K\right)$$



Thermal activation

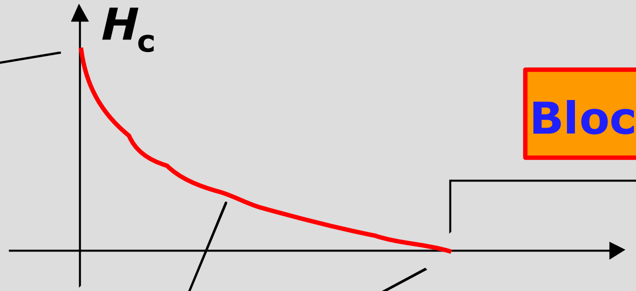
Brown, Phys.Rev.130, 1677 (1963)

$$\tau_0 \approx 10^{-10}\,\mathrm{s}$$

$$\tau = \tau_0 \exp\left(\frac{\Delta E}{k_B T}\right) \Rightarrow \Delta E = k_B T \ln(\tau / \tau_0)$$

Lab measurement : τ = 1s $\quad \sim 25 k_B T$

$$H_c = \frac{2K}{\mu_0 M_S}\left(1 - \sqrt{\frac{25 k_B T}{KV}}\right)$$



Blocking temperature

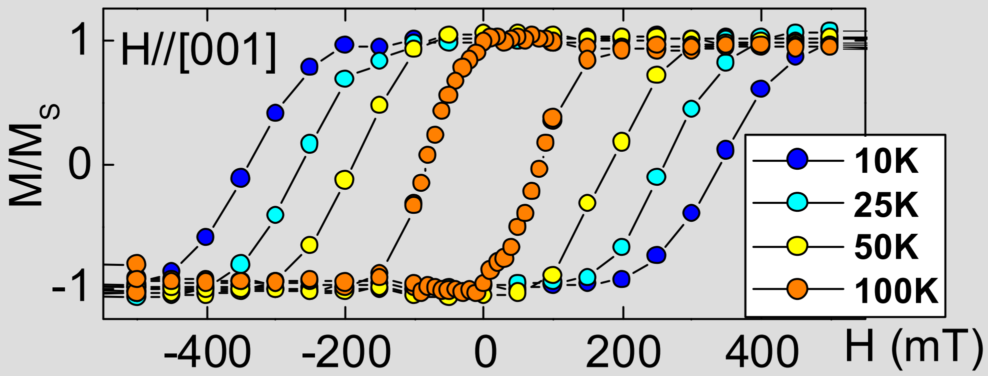
$$T_b \approx KV / 25 k_B$$

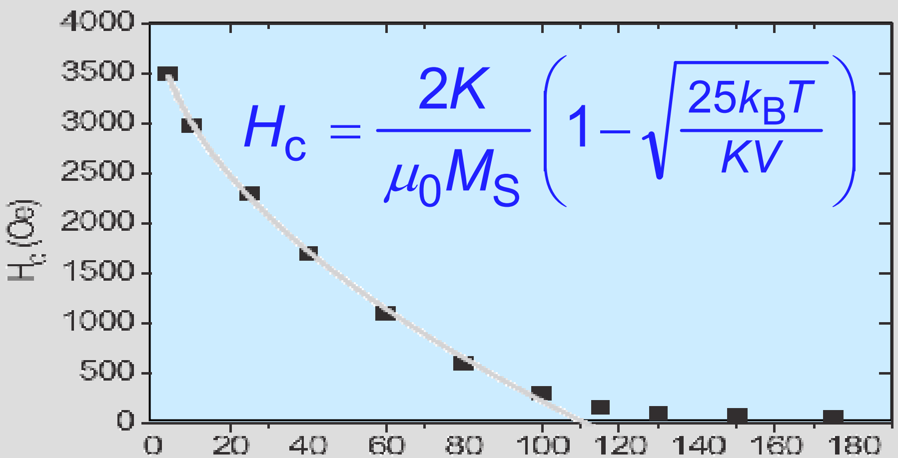
Information about anisotropy density

Information about total effective anisotropy

Notice, for magnetic recording : $t \approx 10^9$s $\quad KV_B \approx 40 - 60\, k_B T$

Hysteresis loops

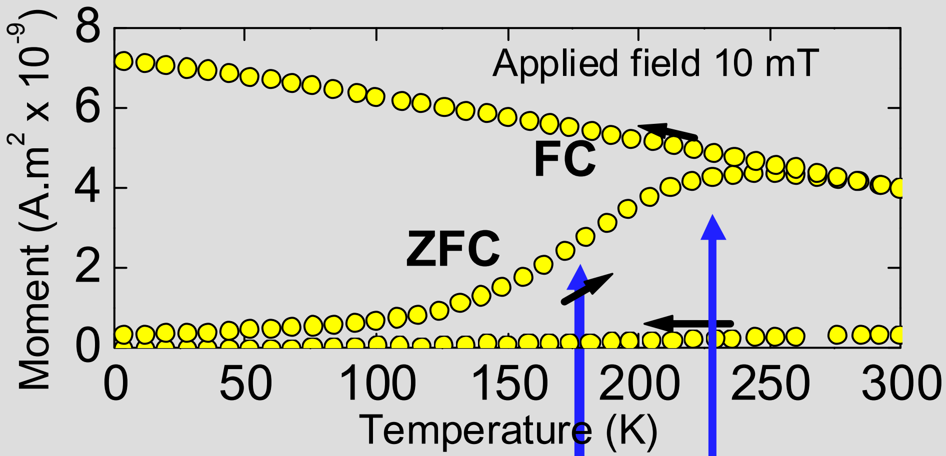




$$H_c = \frac{2K}{\mu_0 M_S}\left(1-\sqrt{\frac{25k_BT}{KV}}\right)$$

FC / ZFC

Field-cooled /
Zero-field-cooled magnetization



Average blocking temperature

Highest blocking temperature

Crude analysis

- T = 0K > effective anisotropy
- Tb > activation volume

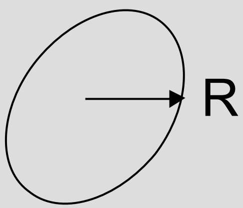
Upper bound for dipolar fields in 2D

Estimation of an upper range of dipolar field in a 2D system

$$\left\|\mathbf{H}_d(R)\right\| \le \oint \frac{2\pi r dr}{r^3}$$

Integration

Local dipole: $1/r^3$

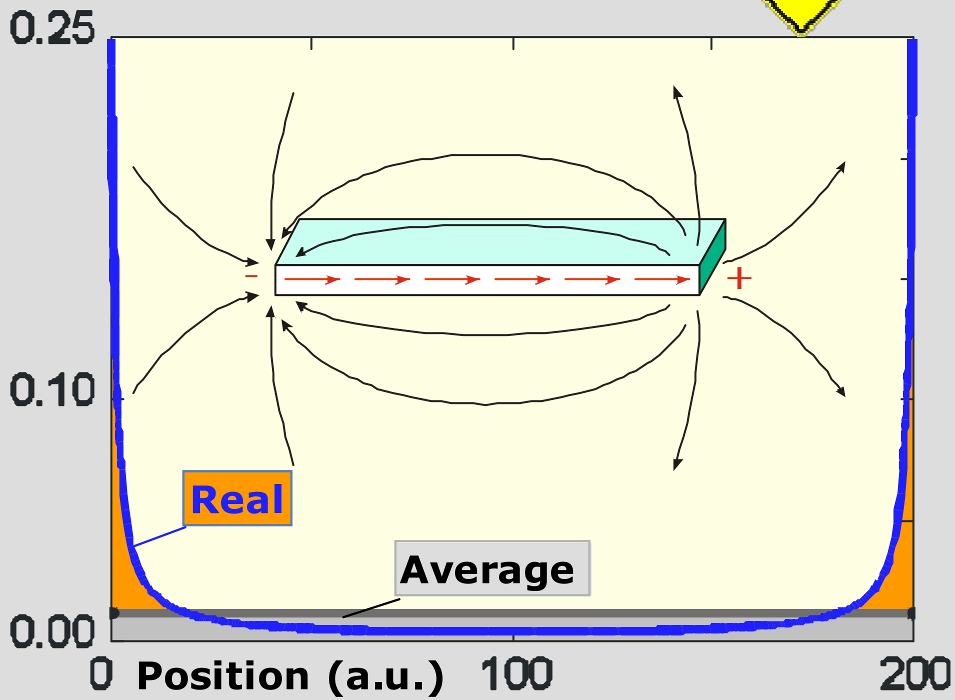


$$\left\|\mathbf{H}_d(R)\right\| \le \mathrm{Cte} + 1/R$$

Convergence with finite radius (typically thickness)

Non-homogeneity of dipolar fields in 2D

Example: flat stripe with thickness/height = 0.0125



- Dipolar fields are weak and short-ranged in 2D or even lower-dimensionality systems
- Dipolar fields can be highly non-homogeneous in anisotropic systems like 2D
- Consequences on dot's non-homogenous state, magnetization reversal, collective effects etc.

Configurational anisotropy: deviations from single-domain

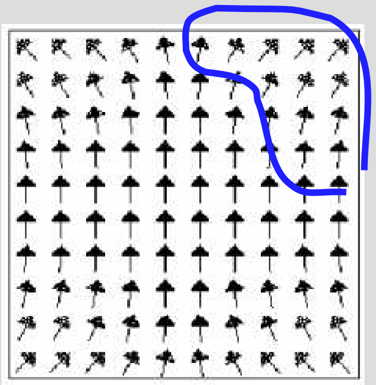
Strictly speaking, 'shape anisotropy' is of second order:

$$E_{\mathrm{d}} = \frac{1}{2}\mu_0\left(N_x M_x^2 + N_y M_y^2 + N_z M_z^2\right)$$

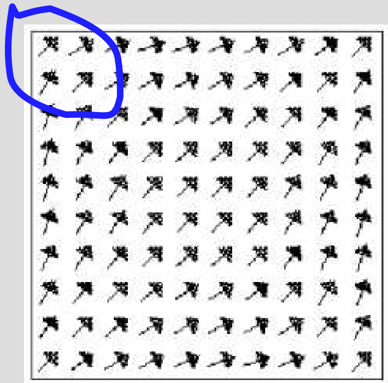
2D: $E_{\mathrm{tot}} = VK_{\mathrm{d}}\sin^2\theta$

In real samples magnetization is never perfectly uniform: competition between exchange and dipolar

Num.Calc. (100nm)



Flower state
c/a>2.7



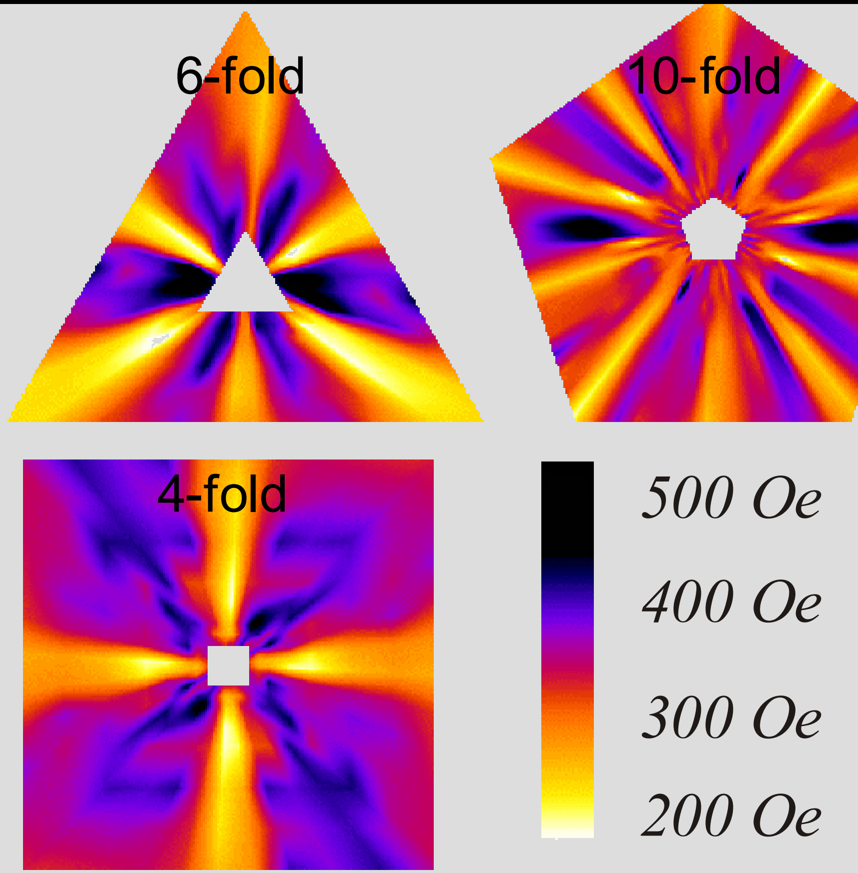
Leaf state
c/a<2.7

Configurational anisotropy may be used to stabilize stable configurations

Higher order contributions to the anisotropy of the total energy

M. A. Schabes et al., JAP 64, 1347 (1988) R.P. Cowburn et al., APL 72, 2041 (1998)

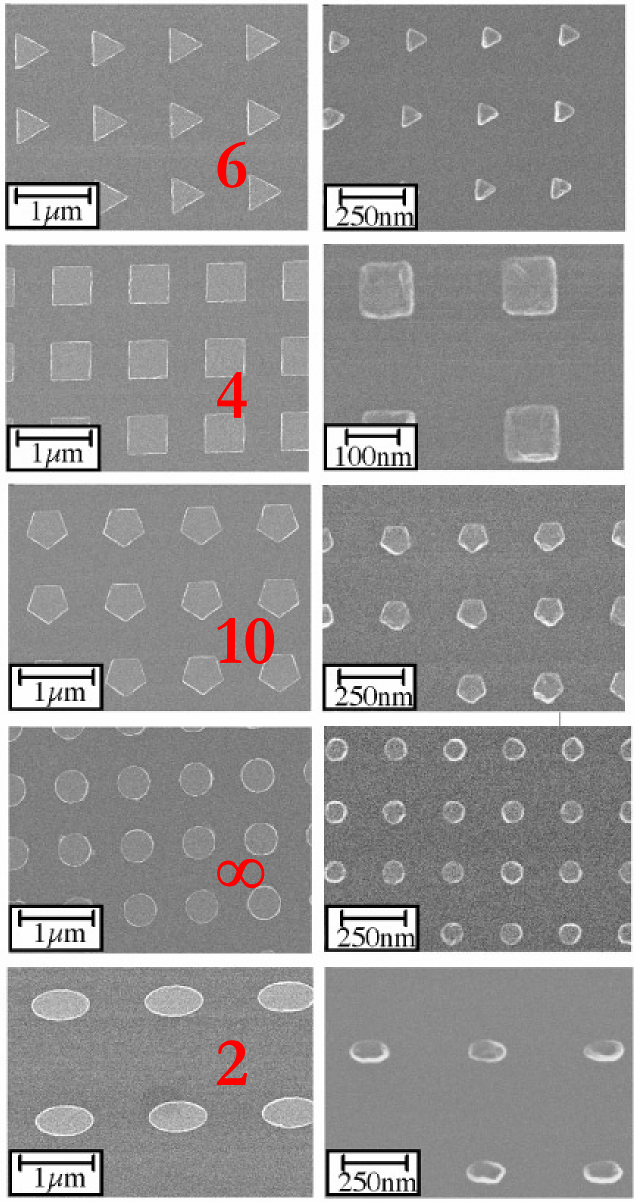
Polar plot of experimental configurational anisotropy with various symmetry



Color code: strength of anisotropy in a given direction

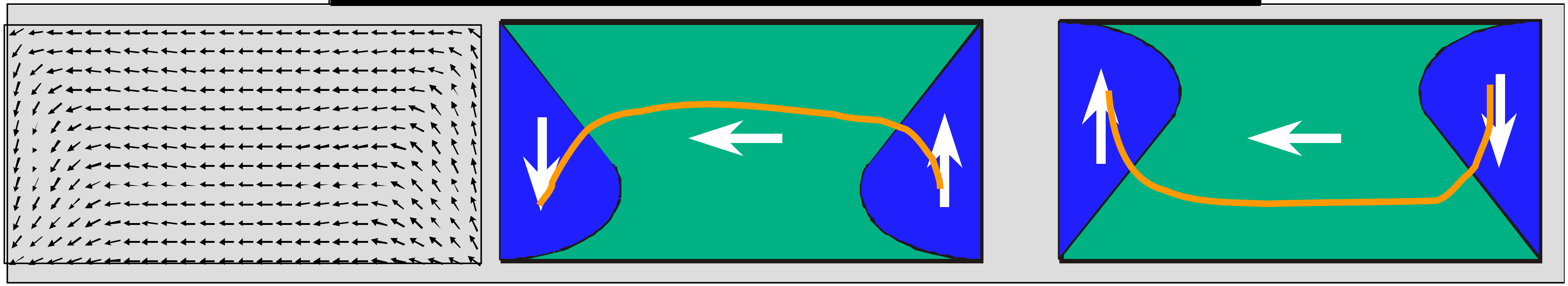
Radius: size of measured pattern

Direction: direction of measurement

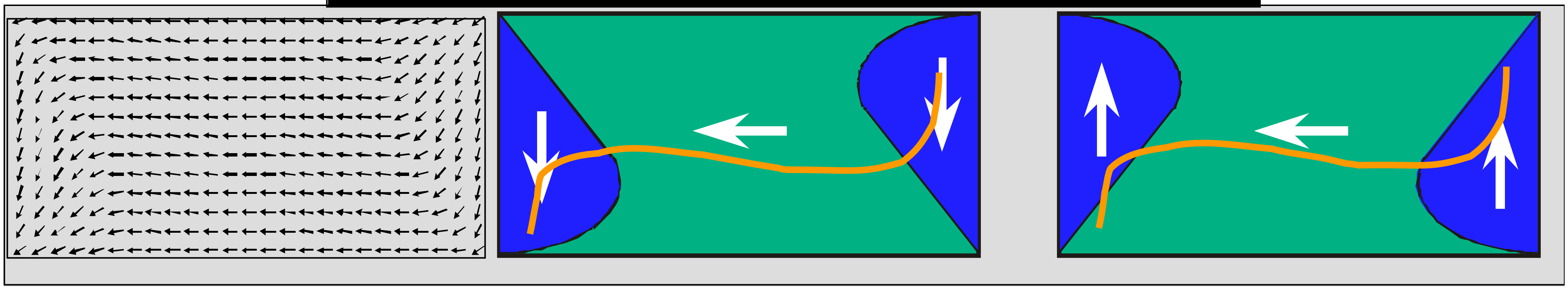


R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1-R16 (2000)

'C' state



'S' state

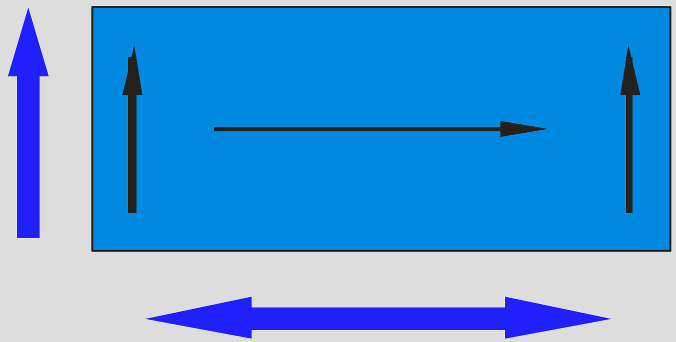


↳ At least 8 nearly-equivalent ground-states for a rectangular dot

↳ Issue for the reproductibility of magnetization reversal

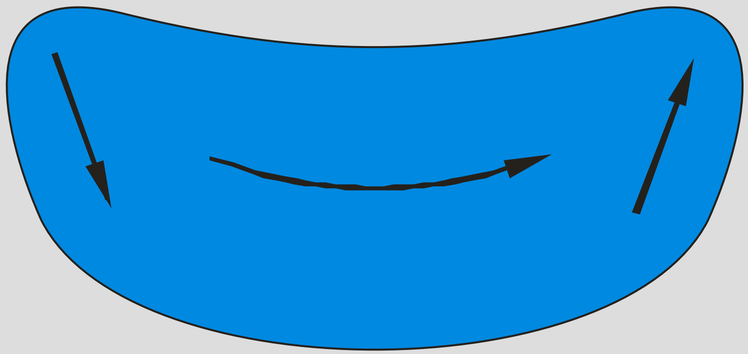
Preparation of 'S' state

Transverse field to keep end domains aligned parallel to each other



Longitudinal field to reverse the magnetization

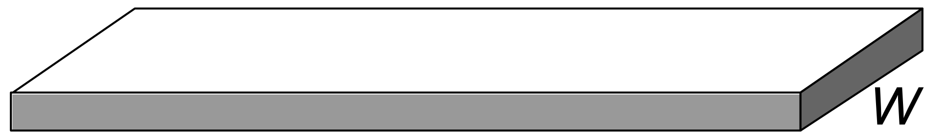
Preparation of 'C' state



End domains aligned mainly antiparallel owing to a dipolar shape effect

Purpose

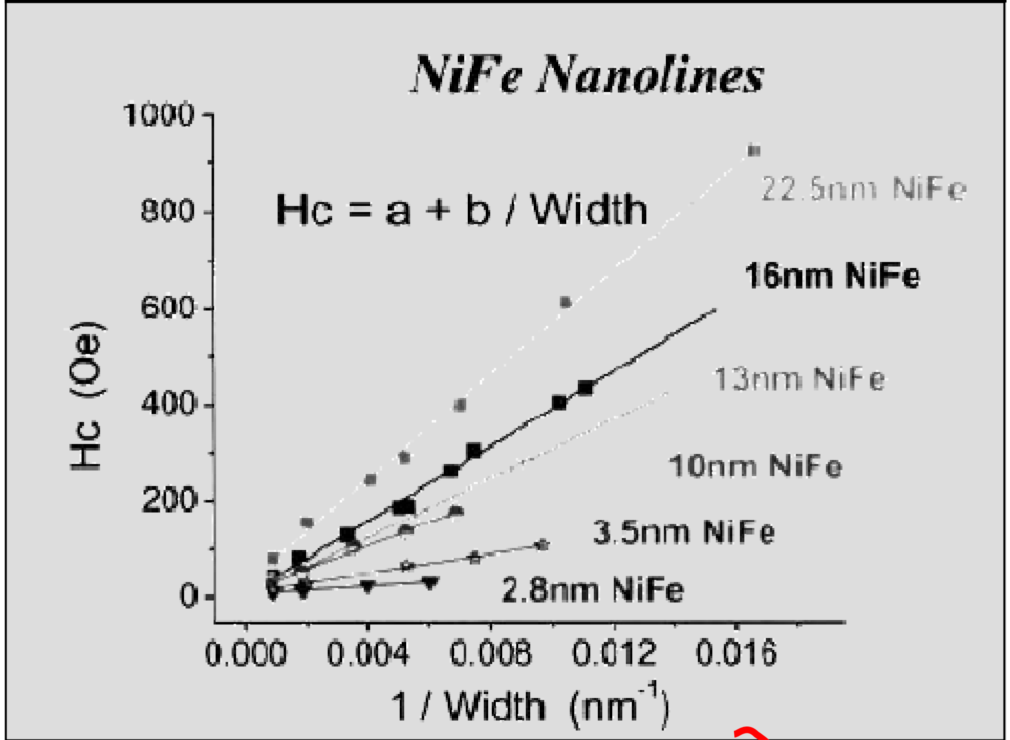
Avoid the formation of 180° domain walls during magnetization reversal



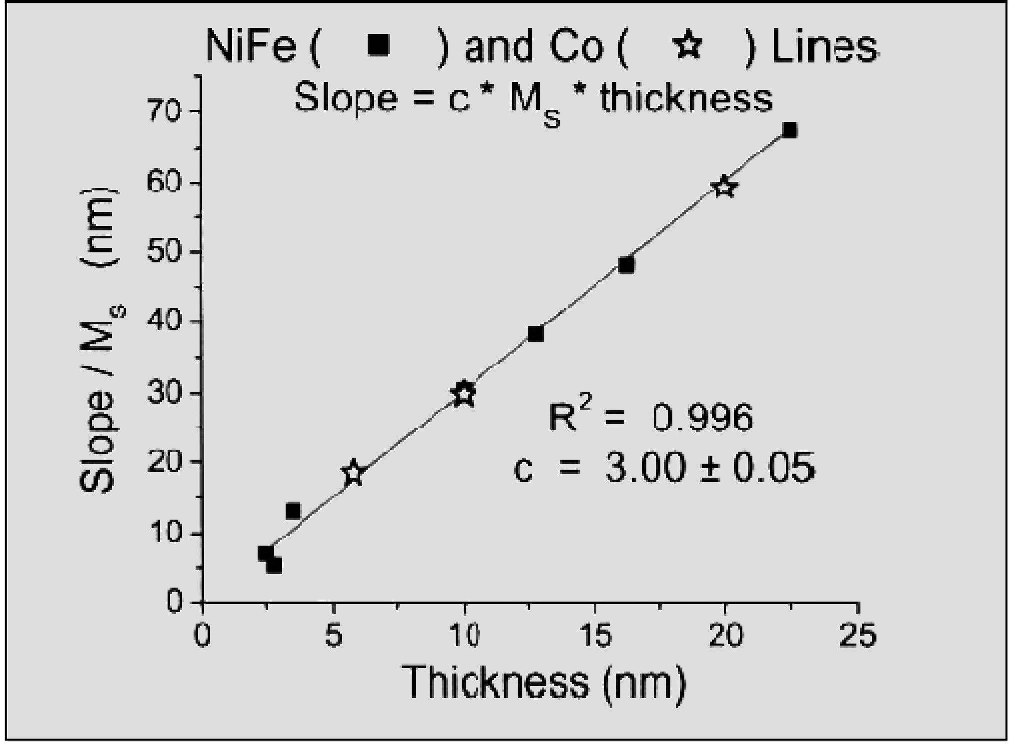
Hypotheses

- Soft magnetic material
- Not too small neither too large nanostructures

Hc ~1/Width



Hc ~Ms * Thickness



$$H_c = a + 3M_S \frac{t}{W}$$

~Lateral demagnetizing coefficient of the stripe

W. C. Uhlig & J. Shi,
Appl. Phys. Lett. 84, 759 (2004)

Magnetization is pinned at sharp ends

Numerical micromagnetic calculation

J.G. Zhu

6672 J. Appl. Phys., Vol. 87, No. 9, 1 May 2000

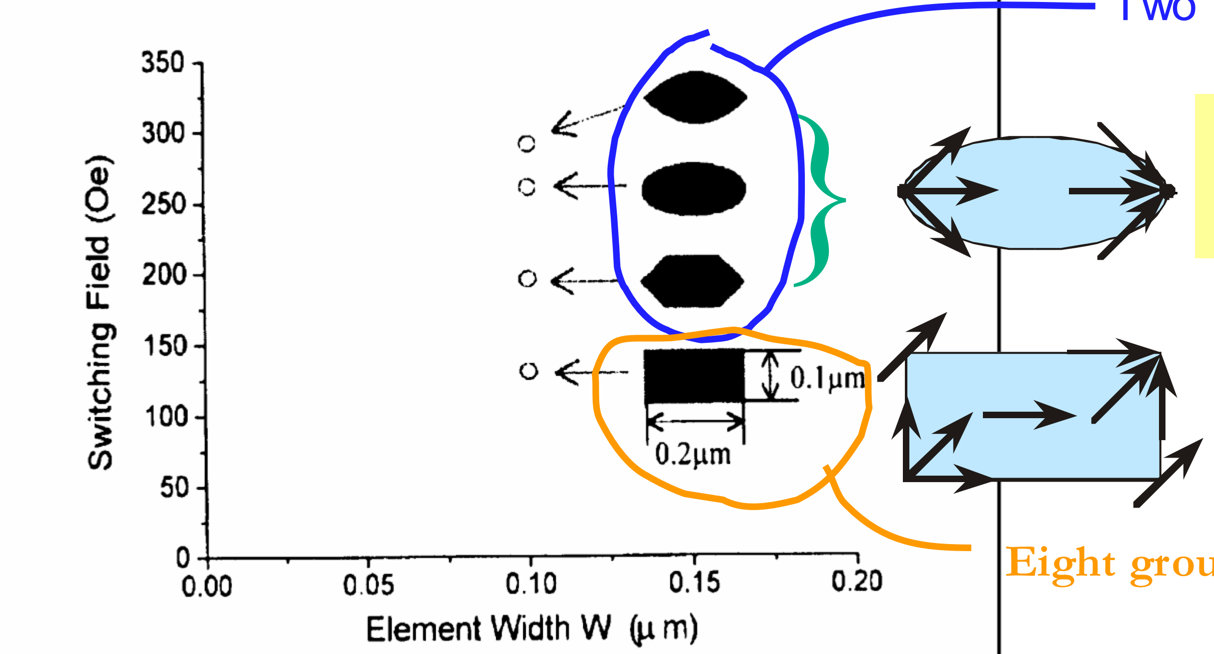


FIG. 11. Calculated switching fields of NiFe film elements with different end shape. All the elements have the same size of $0.2\times0.1\ \mu m^2$, counting tip-to-tip, and a thickness of 20 Å.

GOOD: Better reproducibility

BAD: Higher switching field

Essentially Equivalent Topological Properties

(Images courtesy of J. Miltat - CNRS, Orsay, France)

Hypothesis

Van den Berg model

Infinitely soft material (K=0) $e_{\mathrm{mc}} = 0$

Zero external magnetic field $e_{\mathrm{Z}} = 0$

2D geometry (neglect thickness)

Size >> all magnetic length scales (wall width)

$e_{\mathrm{ex}} \longrightarrow 0$

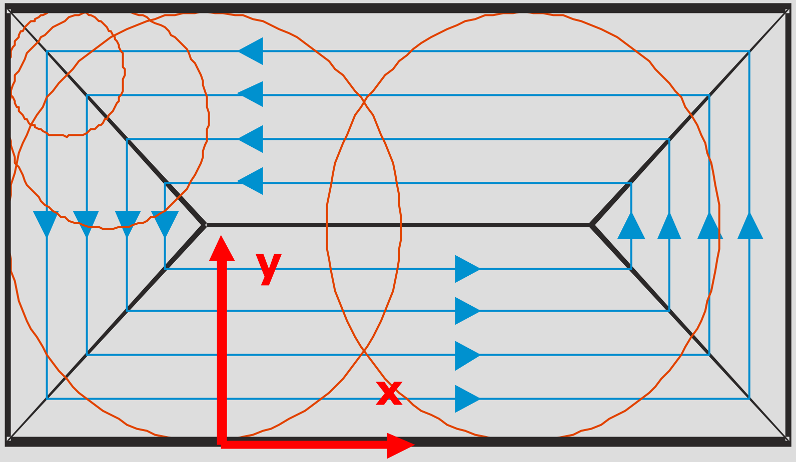
Solution

Looking for a solution with : $e_{\mathrm{d}} = 0$

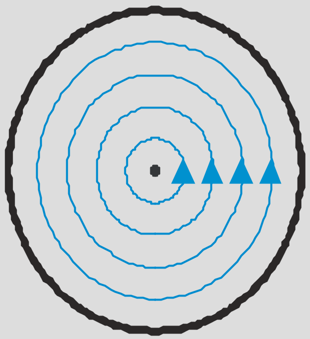
$-\mathrm{div}\mathbf{M} = 0$ (no volume charges)

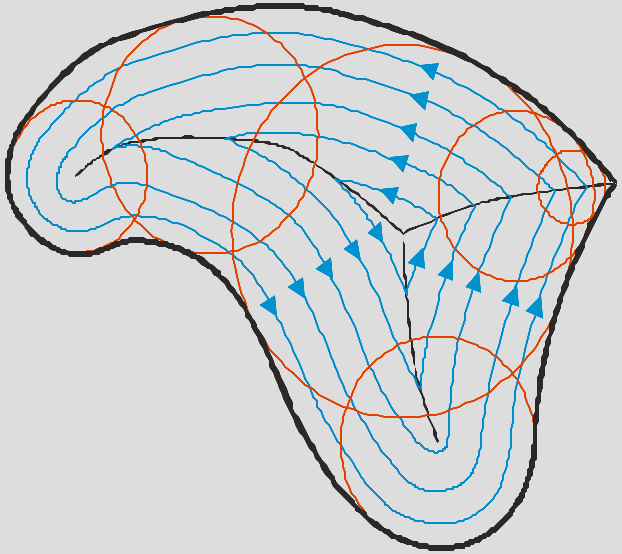
$\mathbf{M.n} = 0$ (no surface charges)

« Flux closure »



$$\mathrm{div}\mathbf{M} = \frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y}$$

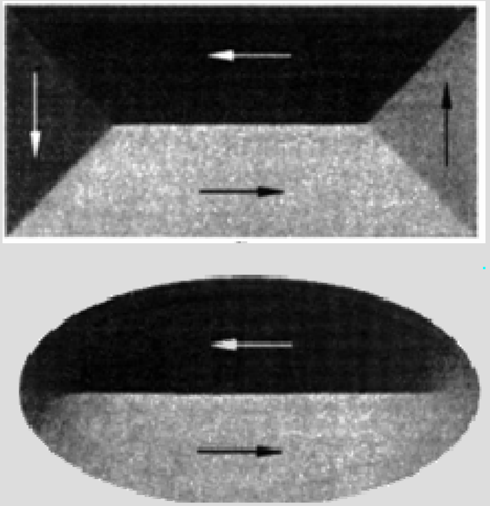


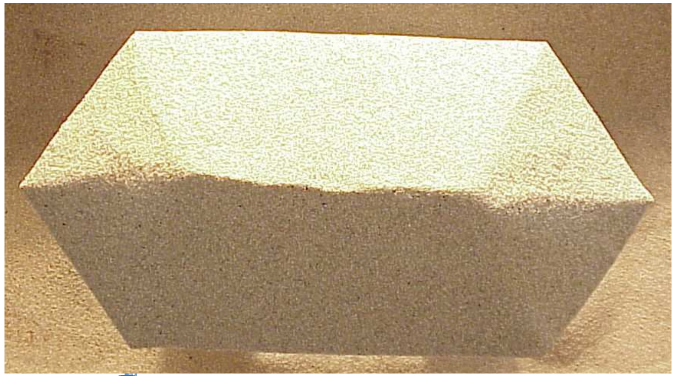


H. A. M. Van den Berg, *J. Magn. Magn. Mater.* 44, 207 (1984)

Sandpiles for simulating flux-closure patterns

Experiments





Generalization for non-zero field

The domains with magnetization parallel to the applied field are favored

P. Bryant et al., *Appl. Phys. Lett.* 54, 78 (1989)

See further extension to field arbitrarily-close to the saturation field:

A. DeSimone, R. V. Kohn, S. Müller, F. Otto & R. Schäfer, Two-dimensional modeling of soft ferromagnetic films, Proc. Roy. Soc. Lond. A457, 2983-2991 (2001)

A. DeSimone, R. V. Kohn, S. Müller & F. Otto, A reduced theory for thin-film micromagnetics, Comm. Pure Appl. Math. 55, 1408-1460 (2002)

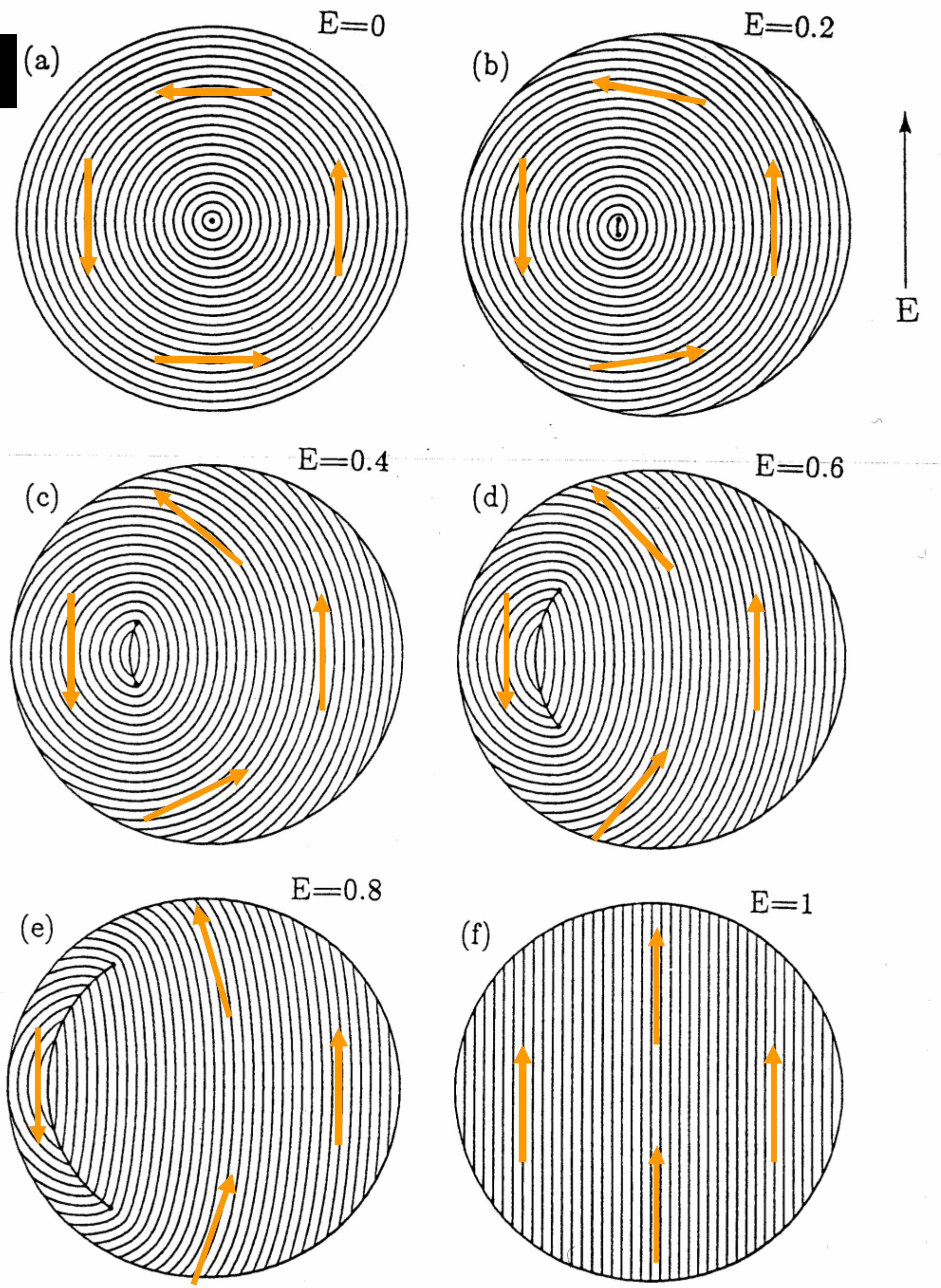
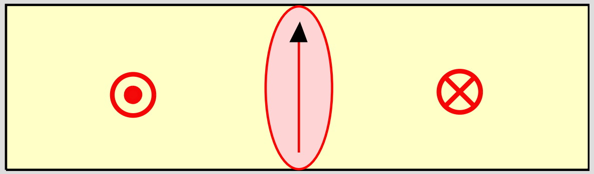


Figure 3

Bloch versus Néel wall

Crude model: wall is a uniformly-magnetized cylinder with an ellipsoid base

Bloch wall

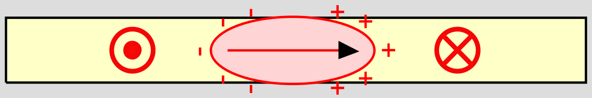


$$E_d = K_d \frac{W}{2t}$$

Thickness t

Wall width W

Néel wall



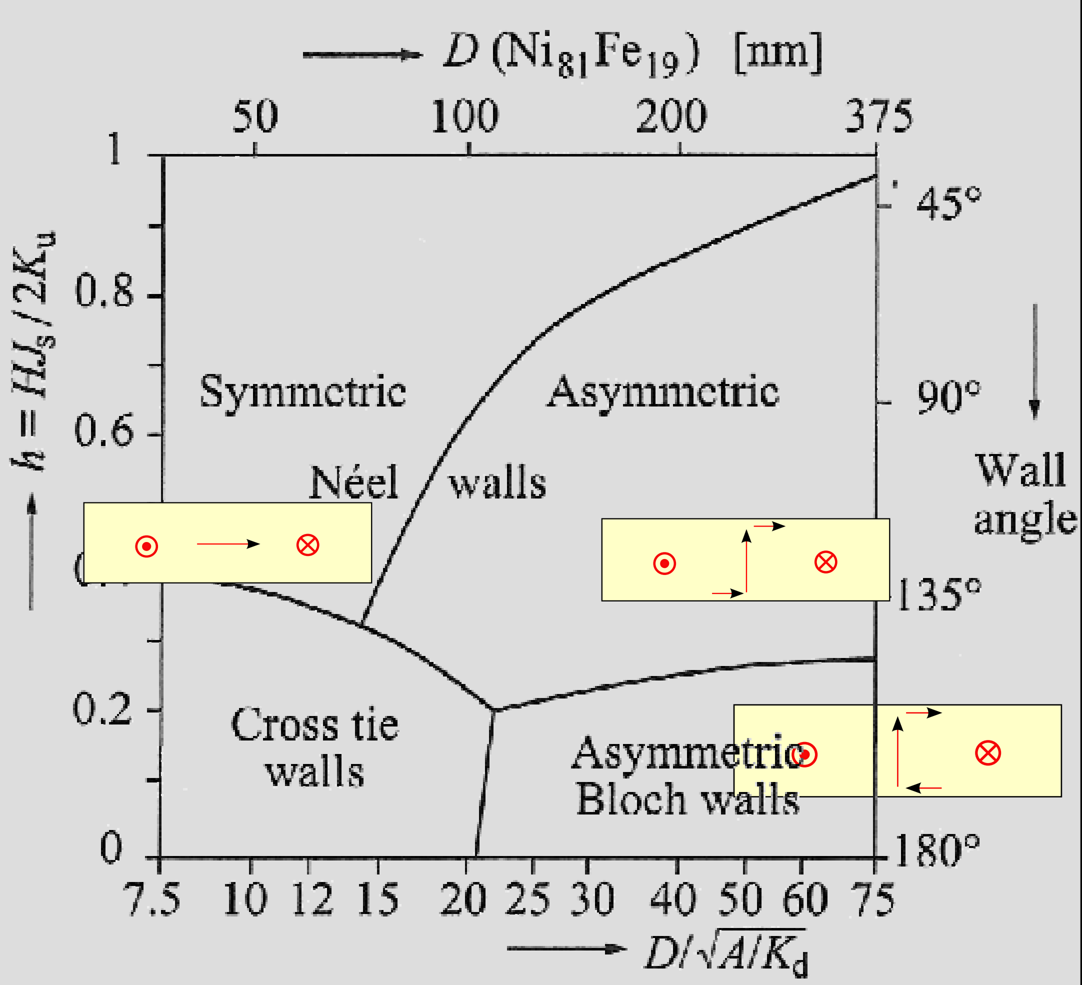
$$E_d = K_d \frac{t}{2W}$$

L. Néel, Énergie des parois de Bloch dans les couches minces, C. R. Acad. Sci. 241, 533-536 (1955)

Conclusion

- At low thickness (roughly $t \approx W$) Bloch domain walls are expected to turn their magnetization in-plane > Néel wall
- Model needs to be refined
- Domain walls not changed for films with perpendicular magnetization

Refined phase diagram of domain walls

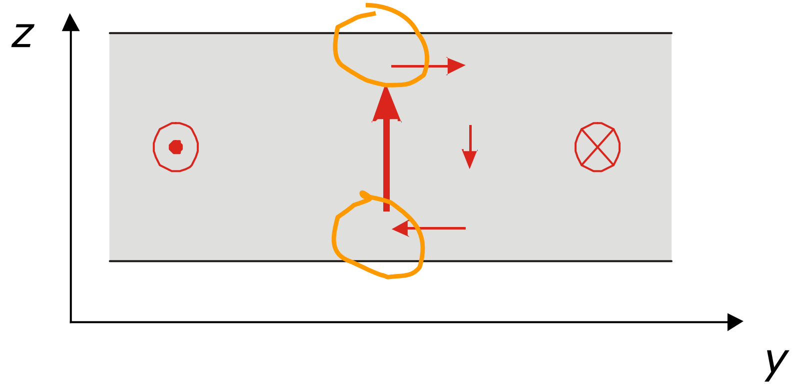


A. Hubert and R. Schäfer, Magnetic domains, Springer (1999)

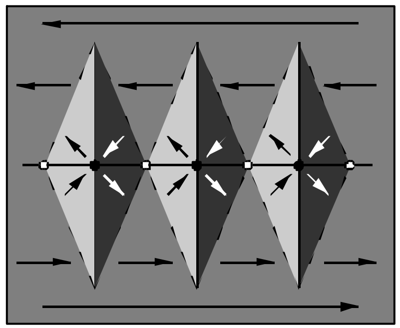
Néel caps occur atop Bloch walls to reduce surface and volume magnetic charges

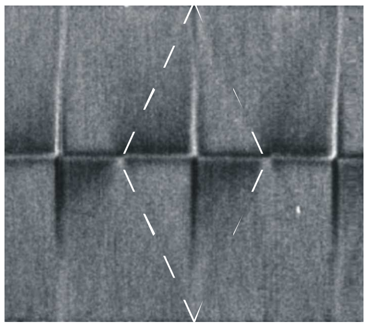
$$\mathbf{M.n} = 0$$

$$-\operatorname{div}\mathbf{M} = -\frac{\partial M_x}{\partial x} - \frac{\partial M_y}{\partial y} - \frac{\partial M_z}{\partial z}$$

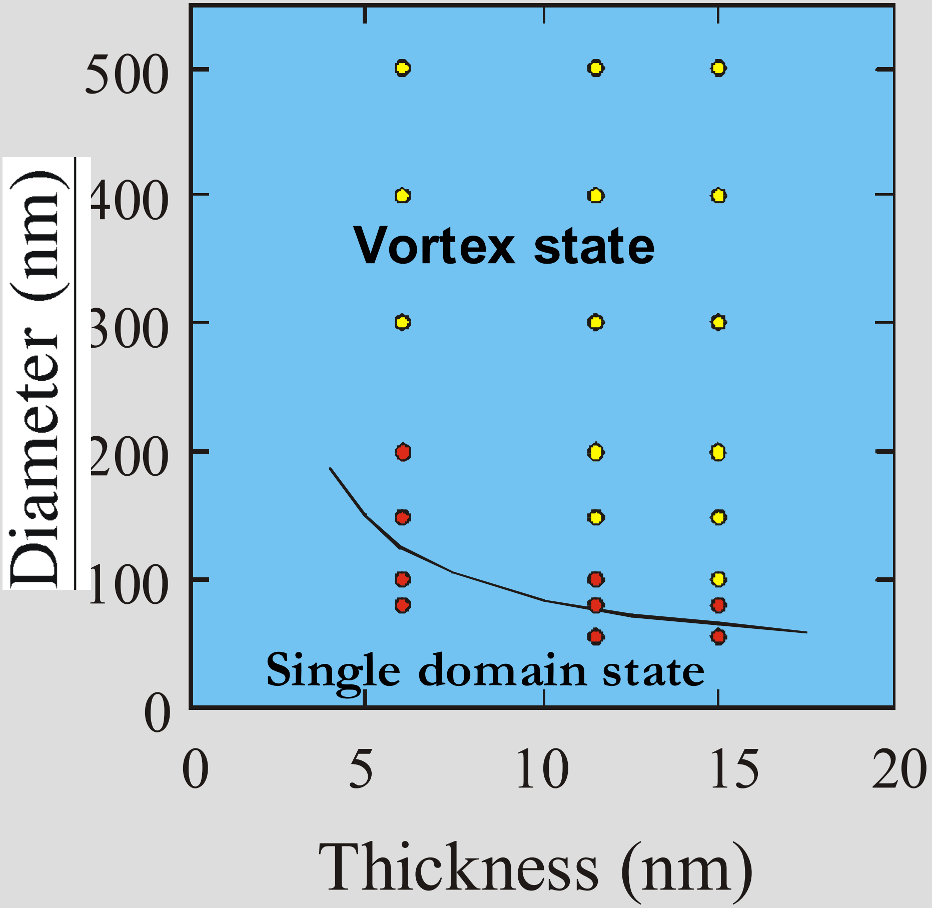


From Néel walls to cross-tie walls



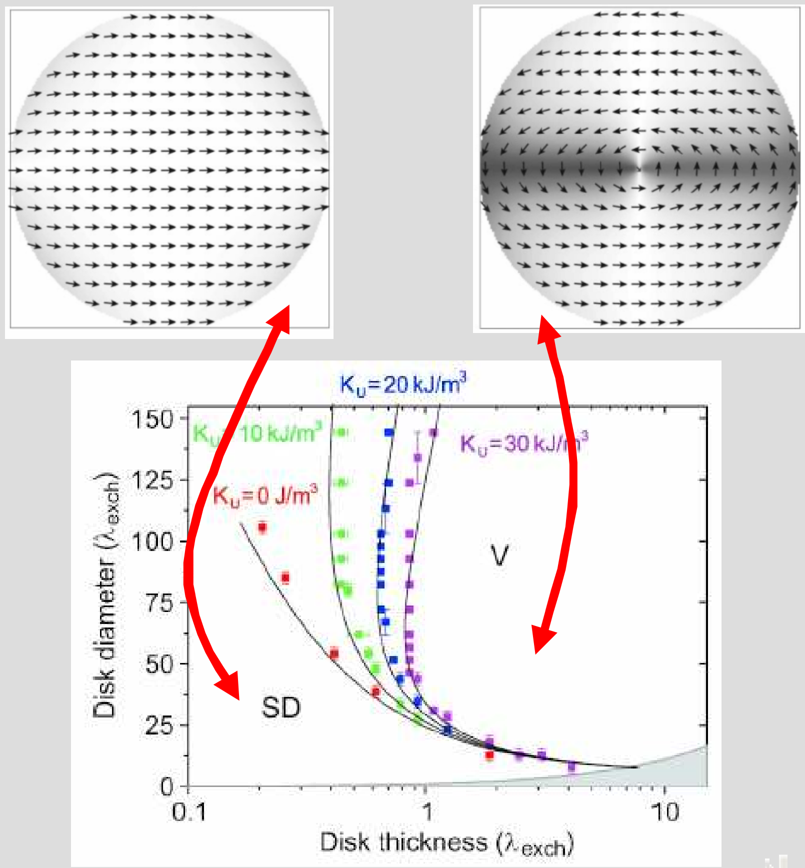


Experiments



R.P. Cowburn,
J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Theory / Simulation



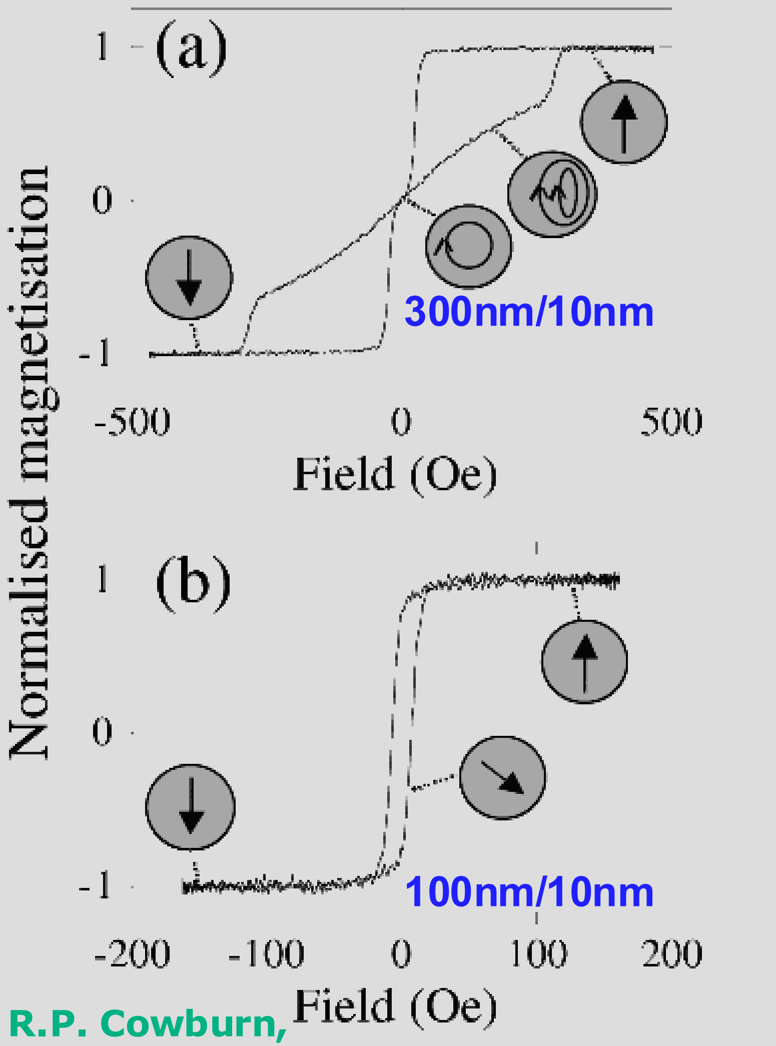
P.-O. Jubert & R. Allenspach,
PRB 70, 144402/1-5 (2004)

Zero-field cross-over

$$t.D \approx 20\lambda_{ex}^2$$

- Vortex state (flux-closure) dominates at large thickness and/or diameter
- The size limit for single-domain is much larger than the exchange length
- Experimentally the vortex may be difficult to reach close to the transition (hysteresis)

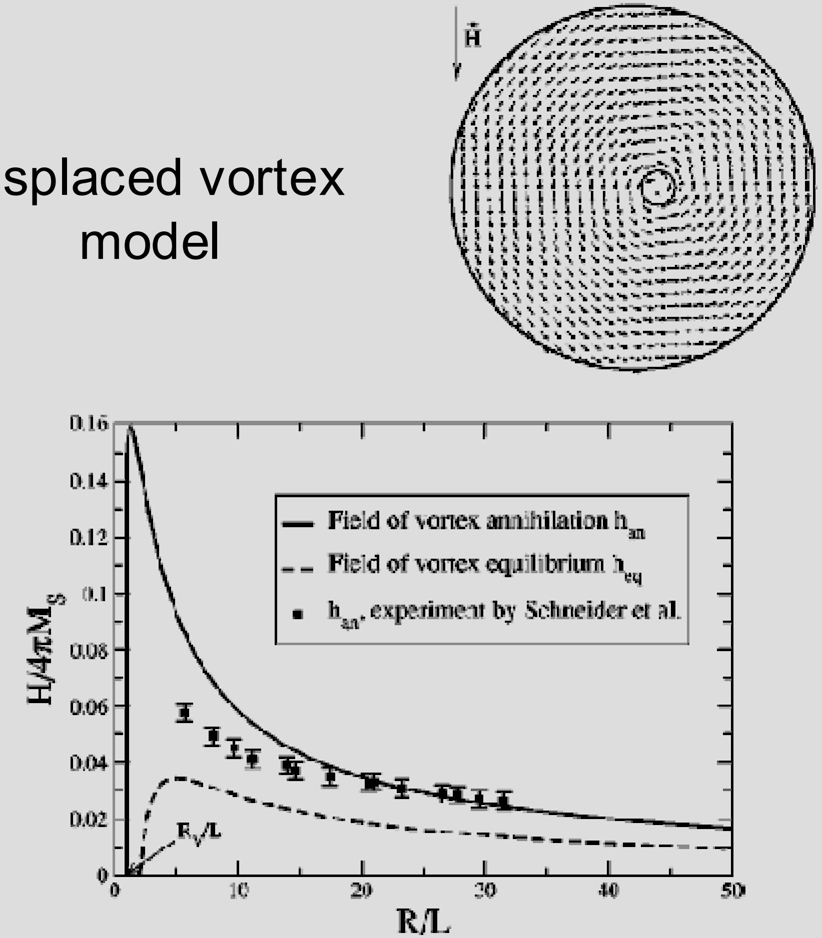
Experiments



R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Theory / Simulations

Displaced vortex model



Calculation of the equilibrium line and the annihilation line

K. Y. Guslienko & K. L. Metlov, PRB 63, 100403(R) (2001)

- Typical loops for flux-closure states
- Energy of the vortex state can be computed from the anhysteretic above-loop area.

Closure domains (flat)

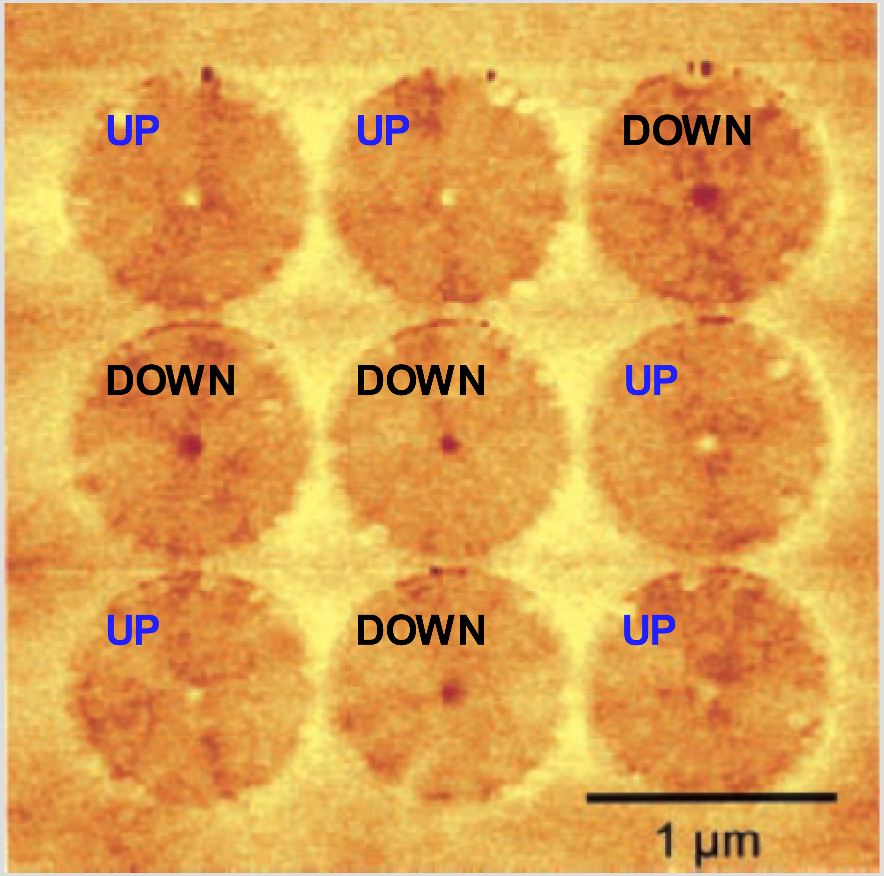


Fig. 2. MFM image of an array of permalloy dots 1 µm in diameter and 50 nm thick.

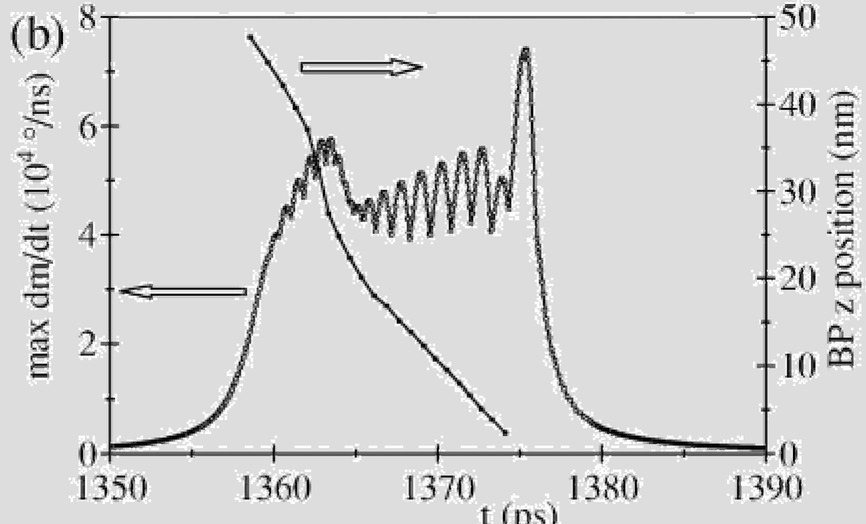
The central magnetic vortex can be magnetized up or down using a perpendicular field

T. Shinjo et al., Science 289, 930 (2000)
T. Okuno et al., JMMM240, 1 (2002)

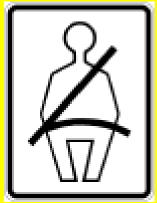
Theory and simulation

Micromagnetic simulation

A. Thiaville et al., Phys. Rev. B 67, 094410 (2003)



Requires a Bloch point:
Not well described
in micromagnetism



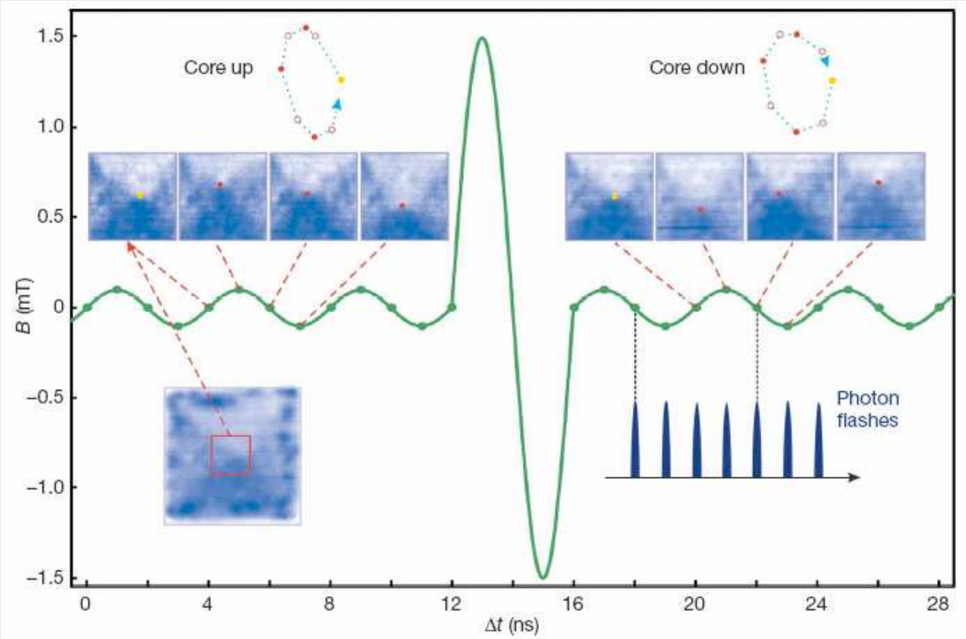
First theoretical insight in Bloch points

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

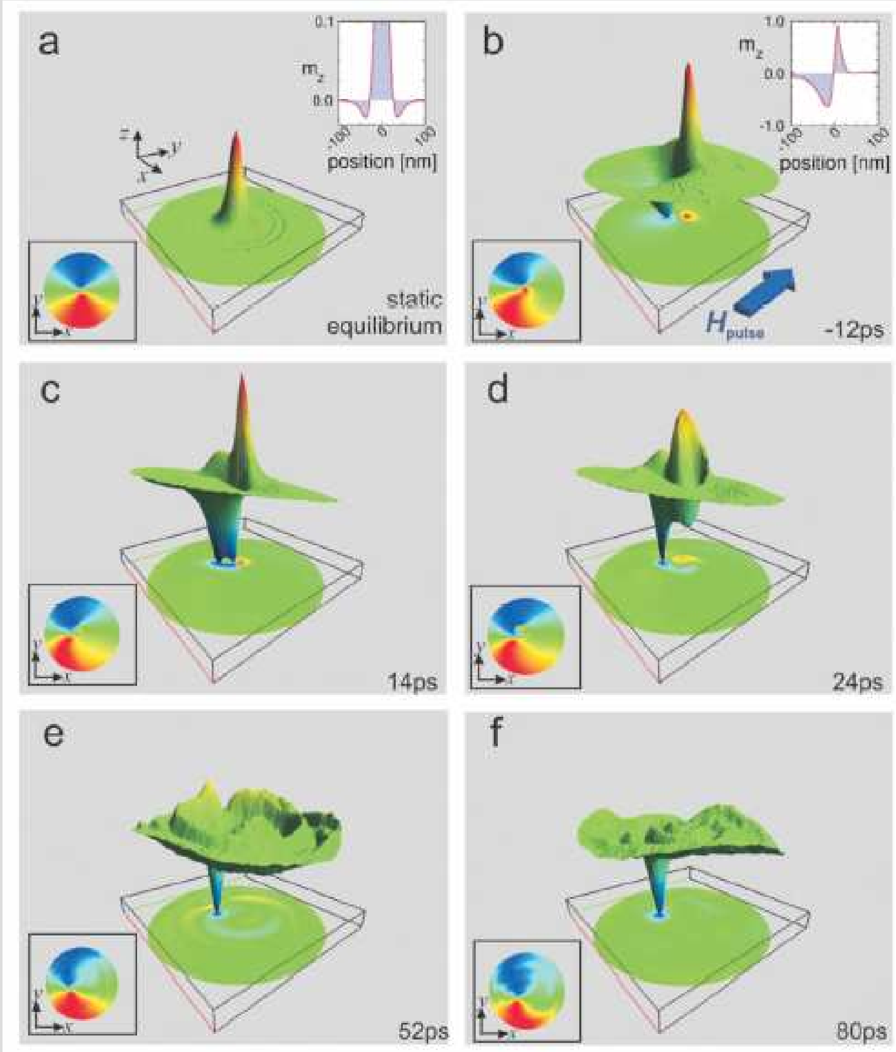
Magnetic vortex core reversal by excitation with short bursts of an alternating field

B. Van Waeyenberg et al., Nature 444, 461 (2007)

R. Hertel et al., Phys. Rev. Lett. 98, 117201 (2007)



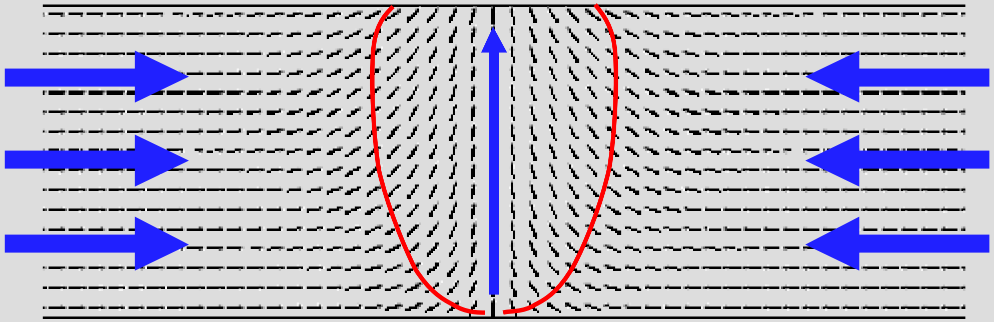
Resonant phenomenon



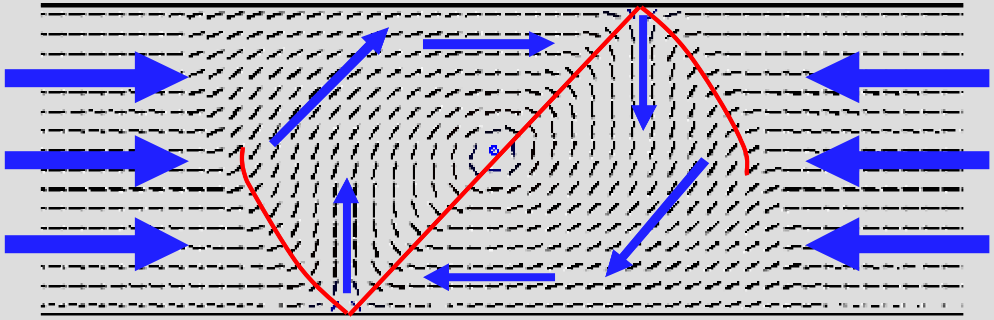
Non-resonant phenomenon

Transverse versus vortex wall

Thin and narrow stripes



Thick and large stripes



Transition for: $\boxed{t.W \approx 75\lambda_{ex}^2}$

R. McMichael & M. Donahue,
IEEE Trans. Mag. 33, 4167 (1997)

Handwavy argument

Energy of transverse wall:

Area x Demag. coeff.

$$\frac{t}{W}W^2 = tW$$

Energy of vortex

Constant to first approx.

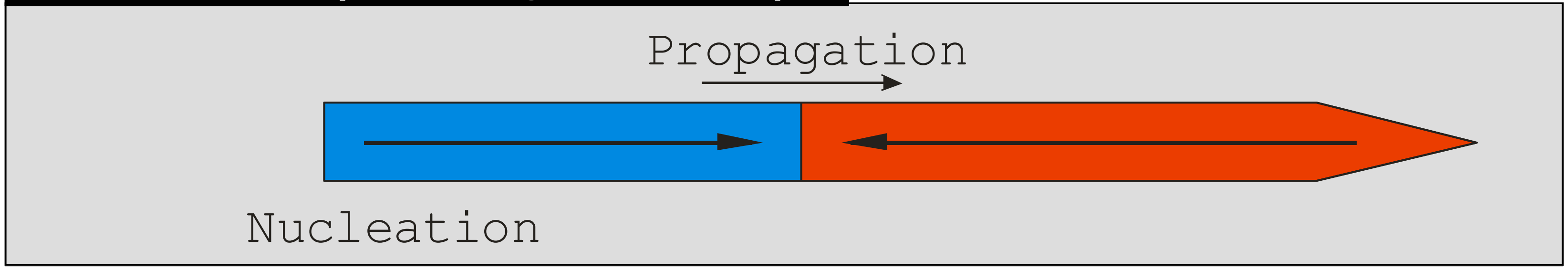
Cross-over for t.W ≈ Cte

Refinement

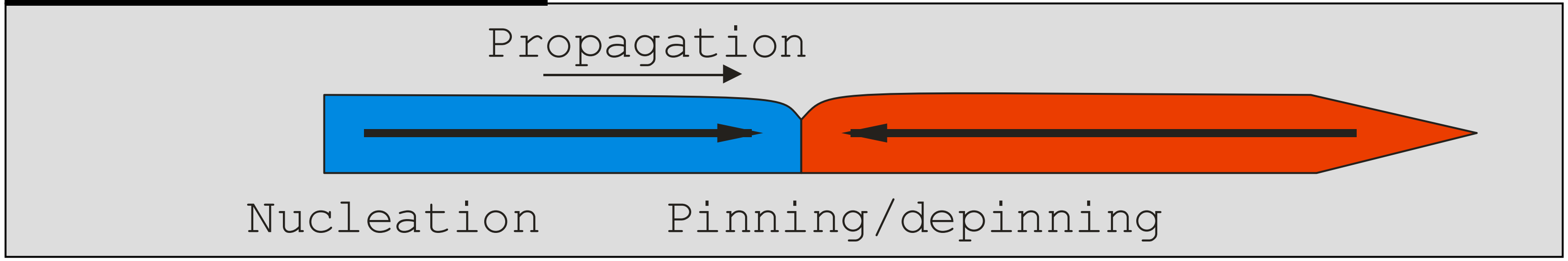
Precision, step size,
assymetric transverse wall

Y. Nakatani, A. Thiaville & J. Miltat,
J. Magn. Magn. Mater. 290-291, 750 (2005)

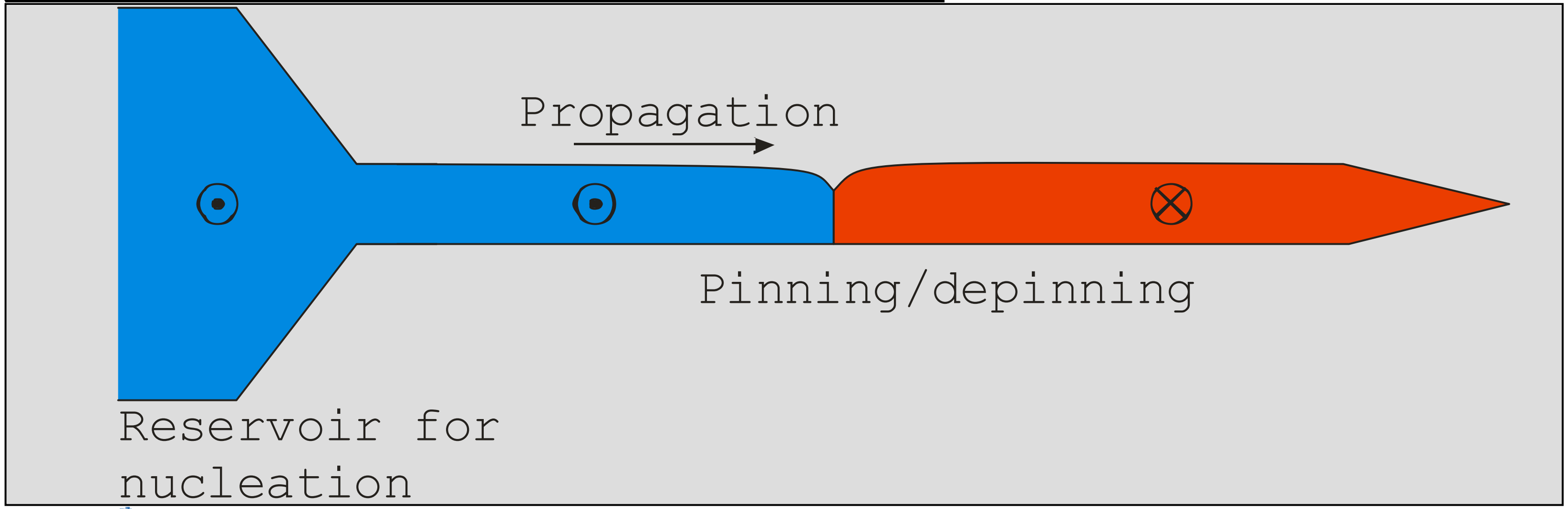
Nucleation in in-plane magnetized stripes



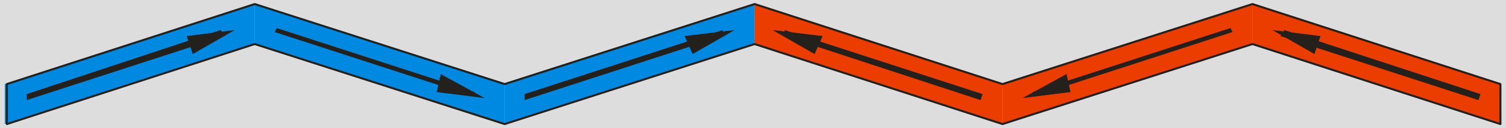
Pinning in stripes: notches

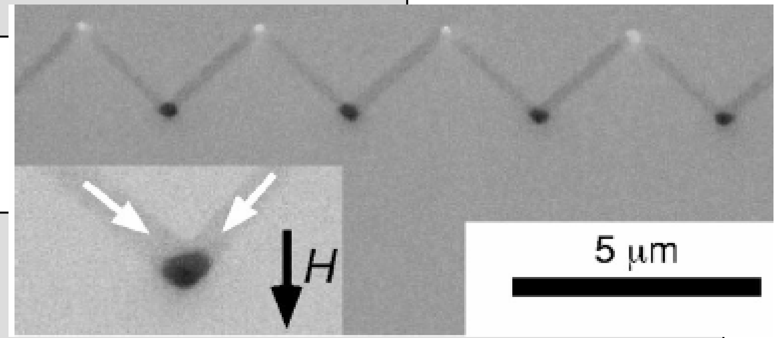


Nucleation in out-of-plane magnetized stripes



Geometrical pinning

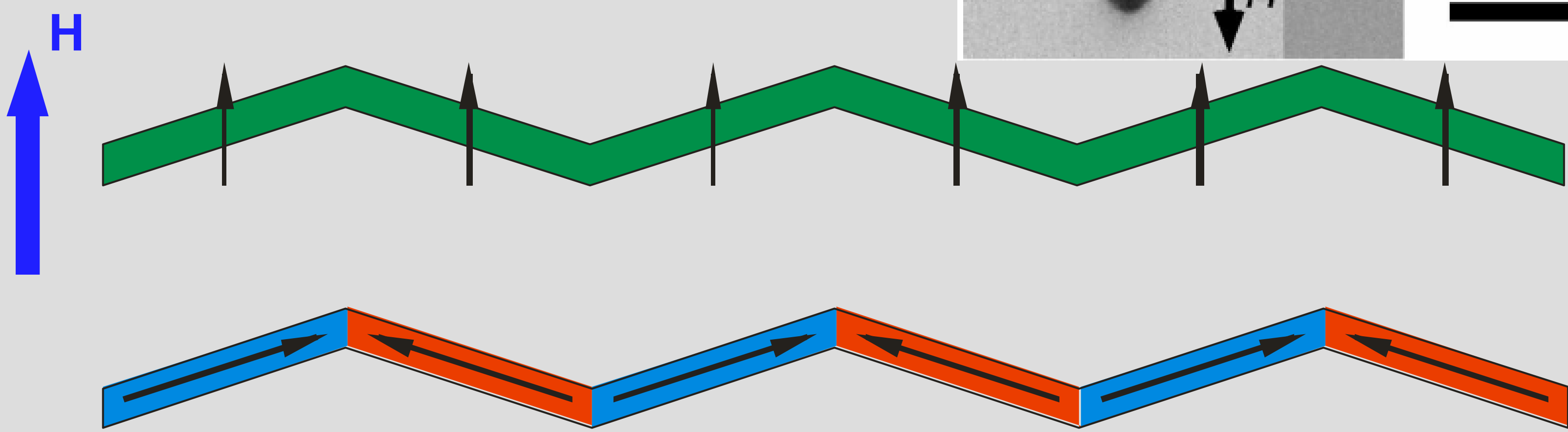


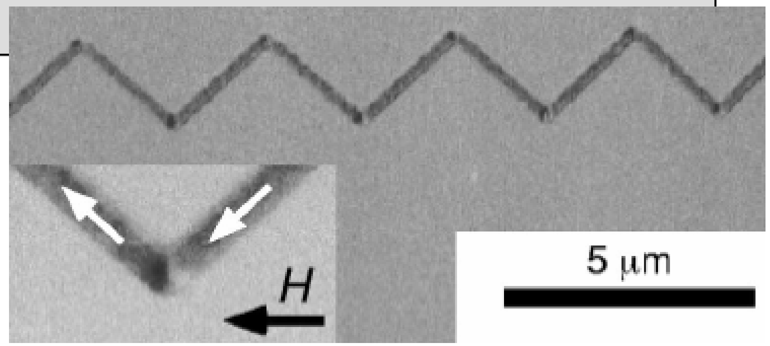


Preparation for in-plane anisotropy

Step 1: transverse field

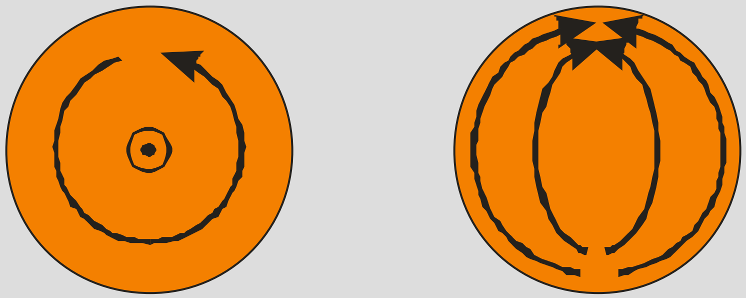
Remanent state





T. Taniyama et al., APL76, 613 (2000)

Disks



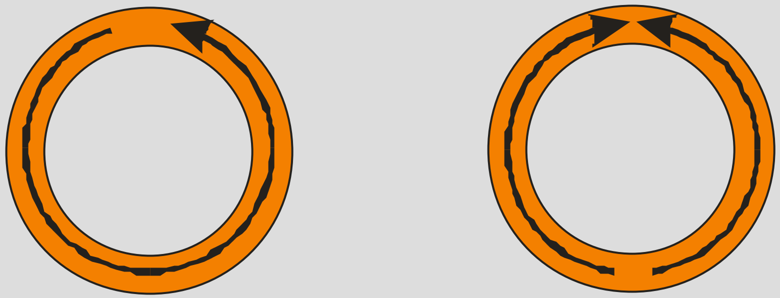
Vortex state

Near single-domain (leaf state)

Large thickness t

Large diameter D

Rings

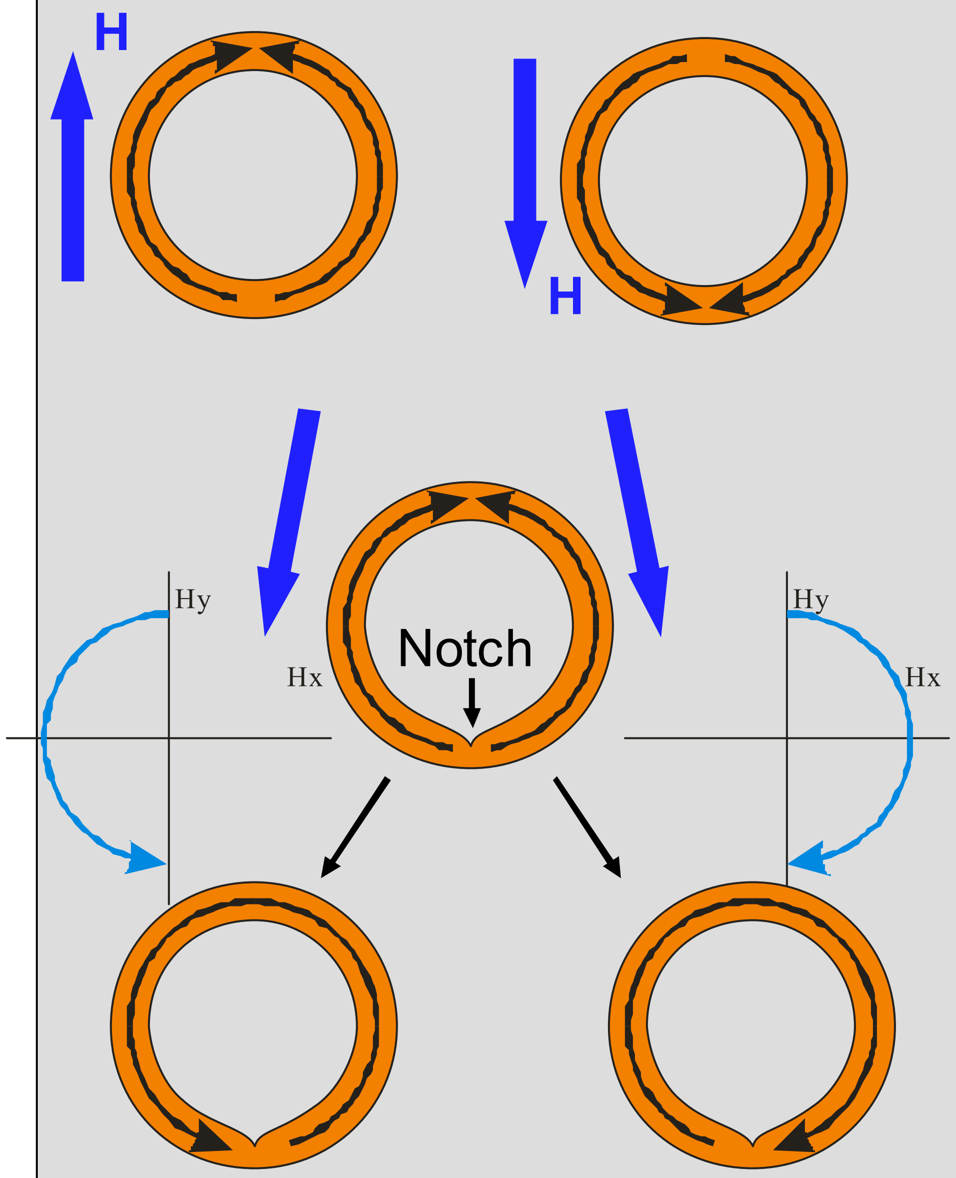


Vortex state

Onion state

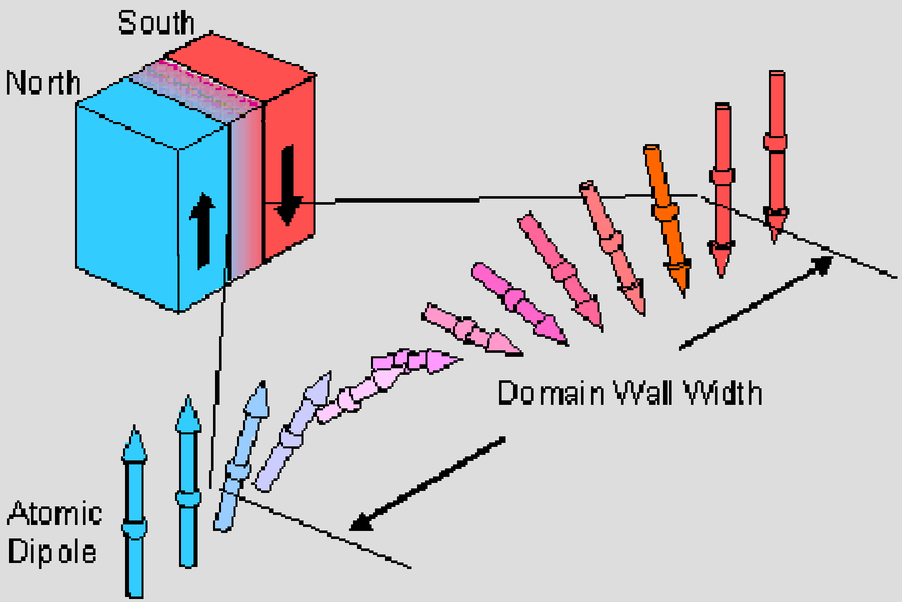
Stability less dependent on geometry (no vortex energy)

Control of ring states



Ex: M. Klaüi et al., APL78, 3268 (2001)

Typical length scale: Bloch wall width λ_B



$$e = A(d\theta/dx)^2 + K\sin^2\theta$$

Exchange → J/m

Anisotropy → J/m^3

Numerical values

$$\Lambda = \sqrt{A/K}$$ Bloch wall parameter

$$\lambda_B = \pi\sqrt{A/K}$$ Bloch wall width

$\lambda_B = 2-3\text{ nm}$ ⟶ $\lambda_B \geq 100\text{ nm}$

Hard — Soft

There are several other definitions are used for measuring the width of walls, implying 2 or other prefactor

Typical length scale: Exchange length λ_{ex}

$$e = A(d\theta/dx)^2 + K_d \sin^2\theta$$

Exchange: J/m — Dipolar energy: J/m^3

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

$$\lambda_{ex} = 3 - 10\ \mathrm{nm}$$

Critical size relevant for nanoparticules made of soft magnetic material: vortex etc.

$$D_c \approx \pi\sqrt{3}\lambda_{ex}$$

Generalization for various shapes

$$D_c \approx \pi\sqrt{6A/(N\mu_0)M_s^2}$$

Critical size for hard magnets

$$D_c \approx 6E_w/K_d \approx 2.5Q\lambda_B$$

$E_w \approx 4\sqrt{AK}$ for hard magnetic materials

Quality factor Q

$$e = -K\sin^2\theta + K_d\sin^2\theta$$

m.c.: J/m — Dipolar energy: J/m^3

$$Q = K/K_d$$

Relevant e.g. for stripe domains in thin films with perpendicular magnetocristalline anisotropy

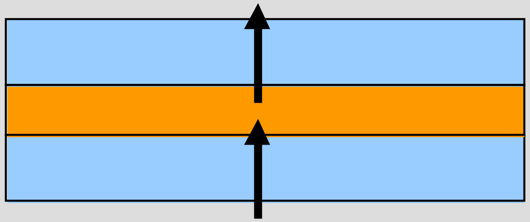
Notice:

Other length scales: with field etc.

Stacked dots : dipolar

In-plane magnetization

Out-of-plane magnetization



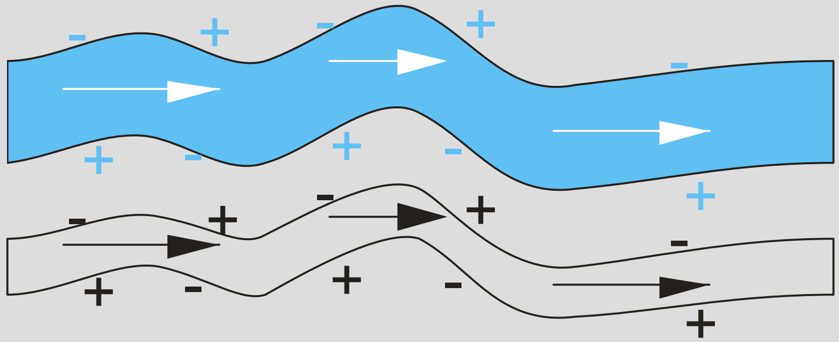
Hint:

An upper bound for the dipolar coupling is the self demagnetizing field

Notice: similar situation as for RKKY coupling

Stacked dots : orange-peel coupling

In-plane magnetization



Always parallel coupling

L. Néel, C. R. Acad. Sci. 255, 1676 (1962)

(valid only for thick films)

J. C. S. Kools et al.,
J. Appl. Phys. 85, 4466 (1999)
(valid for any film)

Out-of-plane magnetization

May be parallel or antiparallel

J. Moritz et al., Europhys. Lett. 65, 123 (2004)

Models for arrays of single-domain planar rectangular dots

E. Y. Tsymbal, Theory of magnetostatic coupling in thin-film rectangular magnetic elements, Appl. Phys. Lett. 77, 2740 (2000)

R. Álvarez-SÁnchez at el., Analytical model for shape anisotropy in thin-film nanostructured arrays: Interaction effects, J. Magn. Magn. Mater. 307, 171-177 (2006)

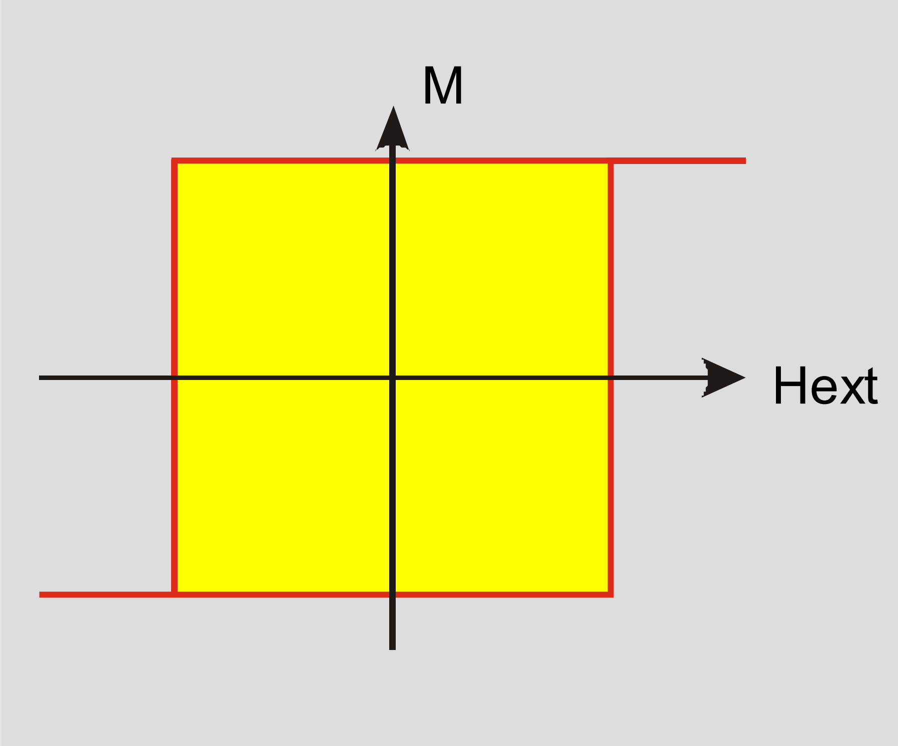
Models for arrays of elements of arbitrary shapes

M. Beleggia and M. De Graef, On the computation of the demagnetization tensor field for an arbitrary particle shape using a Fourier space approach, J. Magn. Magn. Mater. 263, L1-9 (2003)

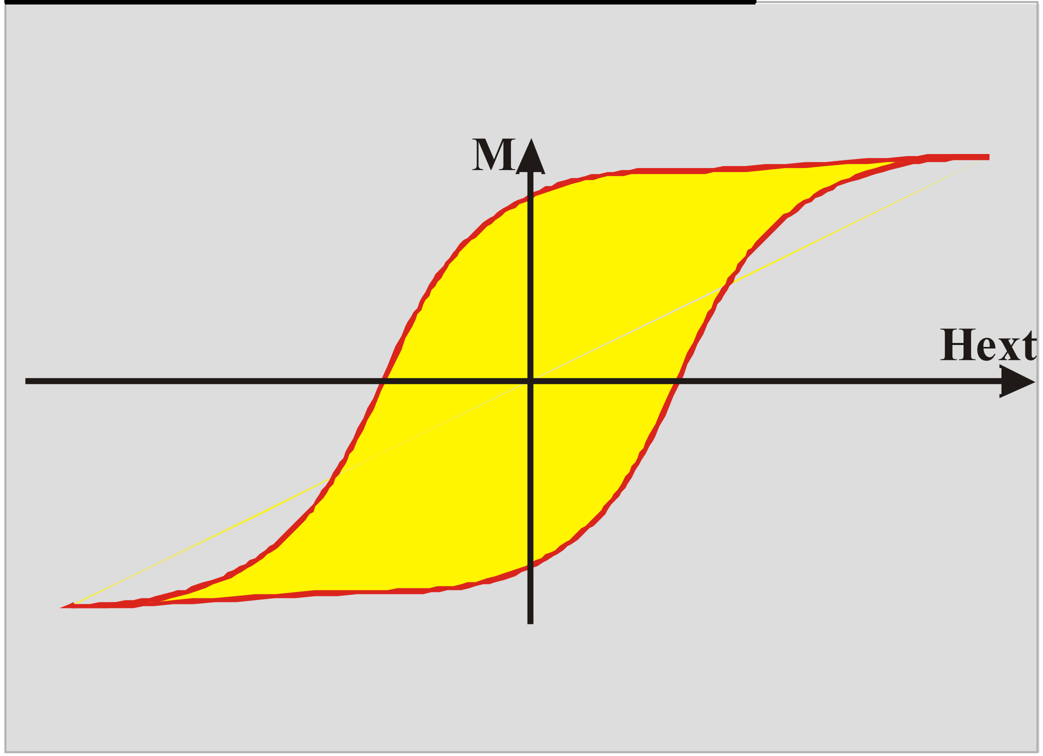
E.Y. Vedmedenko, N. Mikuszeit, H. P. Oepen and R. Wiesendanger, Multipolar Ordering and Magnetization Reversal in Two-Dimensional Nanomagnet Arrays, Phys. Rev. Lett. 95, 207202 (2005)

N. Mikuszeit, E. Y. Vedmedenko & H. P. Oepen, Multipole interaction of polarized single-domain particles, J. Phys. Condens. Matter 16, 9037-9045 (2005)

Expected hysteresis loop for macrospins



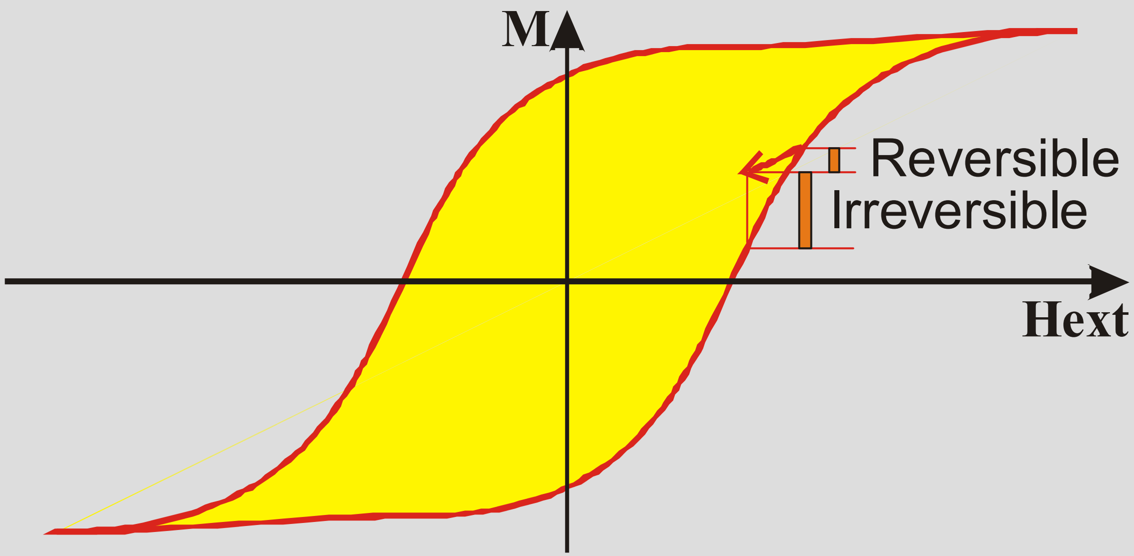
Hysteresis for assemblies of dots



Possible effects

- Distribution of coercive fields
- (Dipolar) interactions

Distribution of properties



$$\rho(H_r) = \left.\frac{dm}{dH}\right|_{\text{irreversible}}$$

Hc(T) for a given population of the distribution can be studied at a given stage of the reversal (10%, 20% etc.)

Example (among many others): O. Fruchart et al., Phys. Rev. B 57, 2596-2606 (1998)

Effect of distributions and dipolar interactions are sometimes difficult to disentangle

Henkel plots

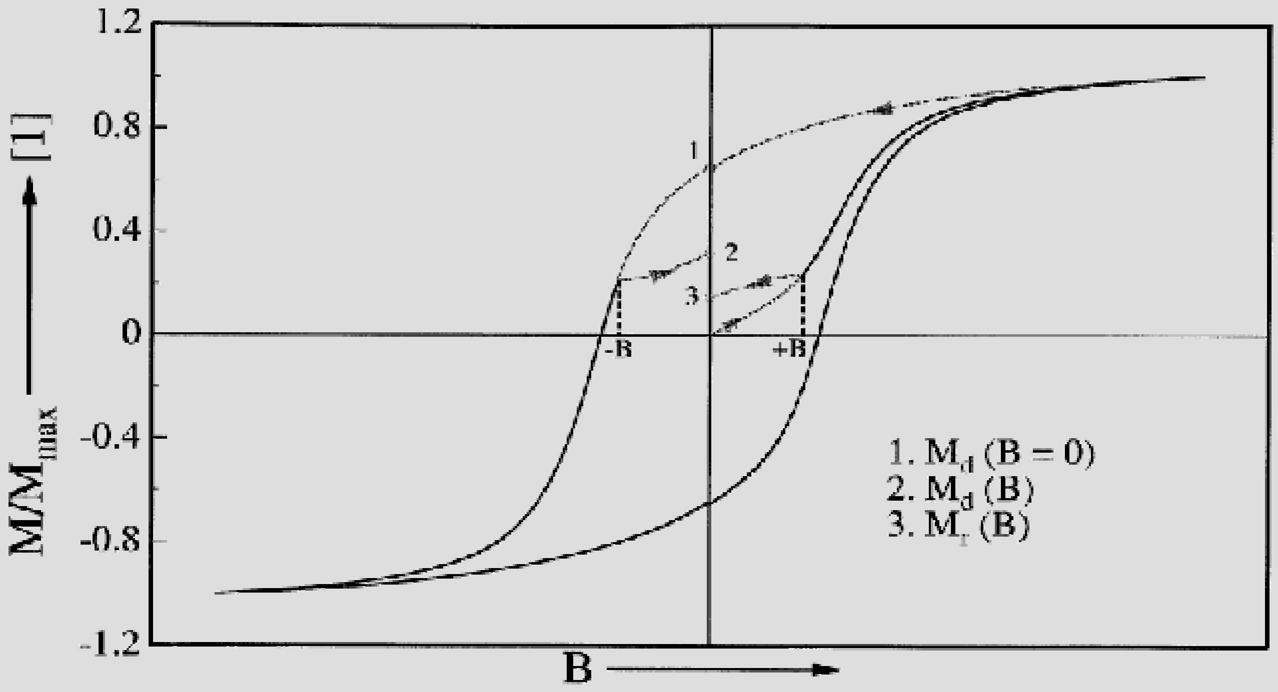


Fig. 1. Explanation of how to measure the two different remanent magnetisations M_r and M_d.

Measure of dipolar interactions

$$\Delta M_H(x) = M_d(x) - [1 - 2M_r(x)]$$

O. Henkel, Phys. Stat. Sol. 7, 919 (1964)

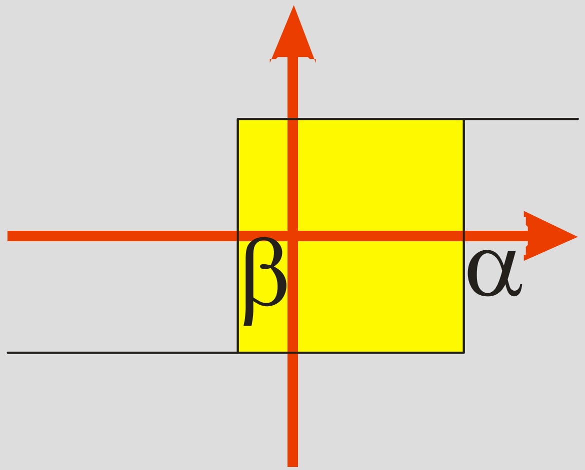
S. Thamm et al., JMMM184, 245 (1998)

- Long experiments (ac demagnetization)
- Better physical meaning than Preisach

Preisach model

G. Biorci et al., Il Nuov. Cim. VII, 829 (1958)

I. D. Mayergoyz, Mathematical models of hysteresis, Springer (1991)

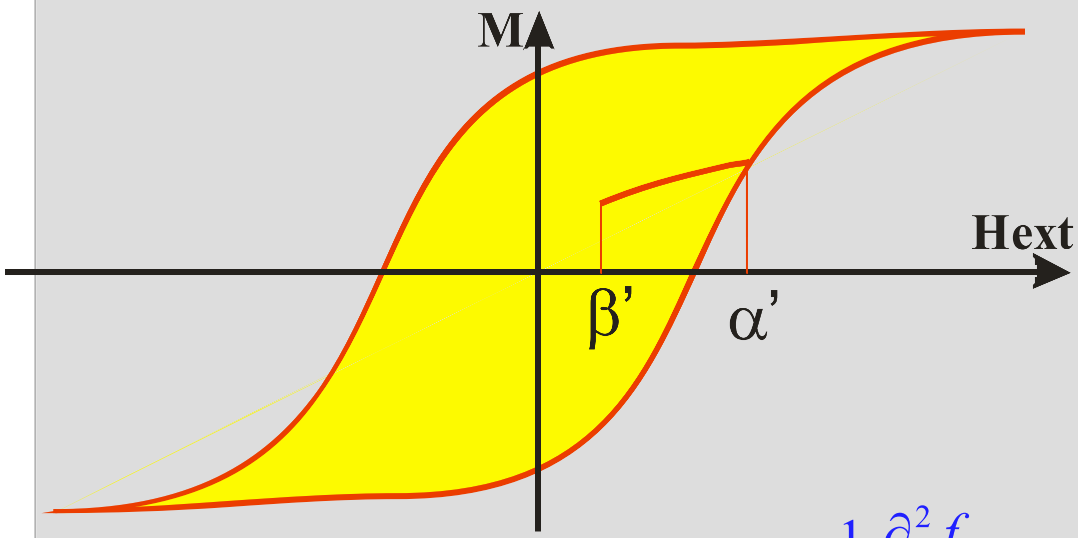


- Distribution function

$$\mu(\alpha,\beta) \text{ with } \alpha > \beta$$

- No true link between real particles and μ

Solving



$$\mu(\alpha',\beta') = \frac{1}{2}\frac{\partial^2 f_{\alpha',\beta'}}{\partial\alpha'\partial\beta'}$$

- Time-s=consuming experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions

Not covered in this lecture

Dimensional effects

Not covered in this lecture

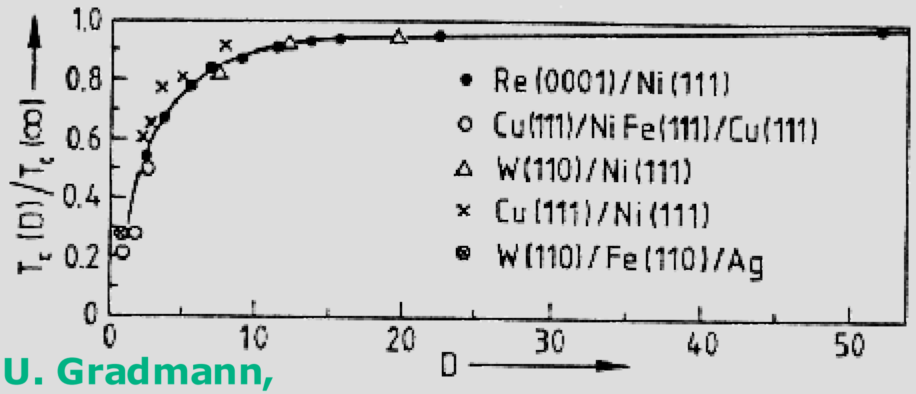
Relevant length scale: inter-atomic distance, Fermi wavelength etc. ≈1nm

Mostly relevant for thin films or self-organized nanostructures at surfaces

Effect on magnetization at interfaces

⇨ Change of ground-state interface Ms due to hybridization (often an increase)

⇨ Enhanced decay of magnetization due to a lower mean number of neighbors



U. Gradmann, Handbook of Magn. Mater. Vol.7, ch.1 (1993)

Interface magnetic anisotropy

⇨ Origin: breaking of symmetry at interfaces
L. Néel, J. Phys. Radium 15, 15 (1954)

⇨ Phenomenology: often a 1/*t* dependence of the density of anisotropy
W. A. Jesser et al., Phys. Stat. Sol. 19, 95 (1967)
C. Chappert and P. Bruno., JAP64, 5736 (1988)

⇨ Consequence: possibility of films with perpendicular magnetization
U. Gradmann and J. Müller, Phys. Status Solidi 27, 313 (1968)

U. Gradmann, Handbook of Magn. Mater. Vol.7, ch.1 (1993)

See OF lecture: ESM 2003, Brasov, Romania

SOME READING

[1] ***Magnetic domains***, A. Hubert, R. Schäfer, Springer (1999)

[2] J.I. Martin et coll., ***Ordered magnetic nanostructures: fabrication and properties***, J. Magn. Magn. Mater. **256**, 449-501 (2003).

[3] R. Skomski, ***Nanomagnetics***, J. Phys.: Cond. Mat. **15,** R841–896 (2003).

[4] O. Fruchart, A. Thiaville, ***Magnetism in reduced dimensions***, C. R. Physique **6**, 921 (2005) [Topical issue, Spintronics].

[5] O. Fruchart, ***Couches minces et nanostructures magnétiques***, Techniques de l'Ingénieur, E2 150/E2 151.

[6] G. Chaboussant, **Nanostructures magnétiques**, Techniques de l'Ingénieur, revue 10-9 (RE51) (2005)

[7] Lecture notes from undergraduate lectures, plus various slides:
http://perso.neel.cnrs.fr/olivier.fruchart
* European School on Magnetism 2003: **low-dimensional magnetism**
* European School on Magnetism 2007: **magnetization reversal, basics and nanostructures**