Magnetization reversal

II. Non-single-domain effects: Interactions, nanostructures and domain walls

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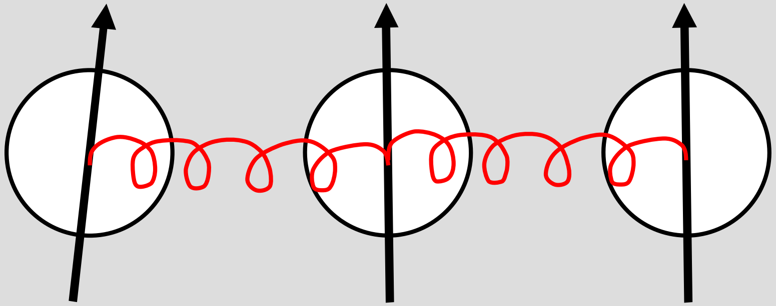
II. Non-single-domain effects

I.1. Dipolar energy

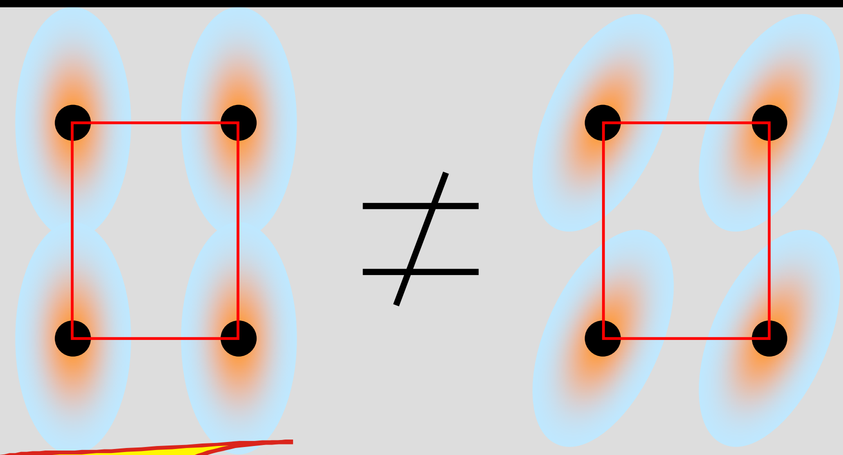
- **1. Treatment of dipolar energy**
- **2. Some consequences of dipolar energy on hysteresis loops**
- **3. Dipolar energy and collective effcts in assemblies**

Echange energy

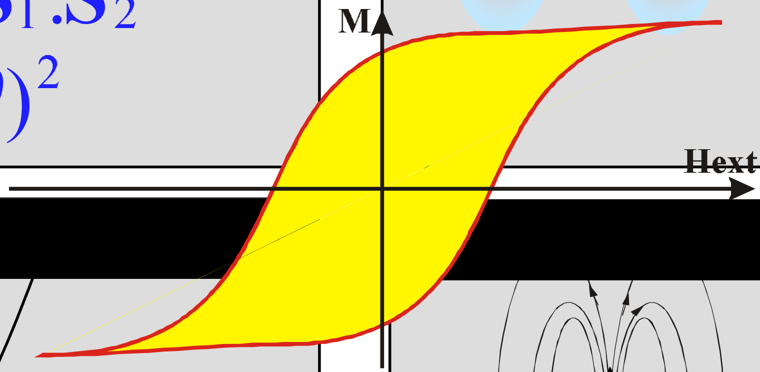


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2$$
$$= A(\nabla\theta)^2$$

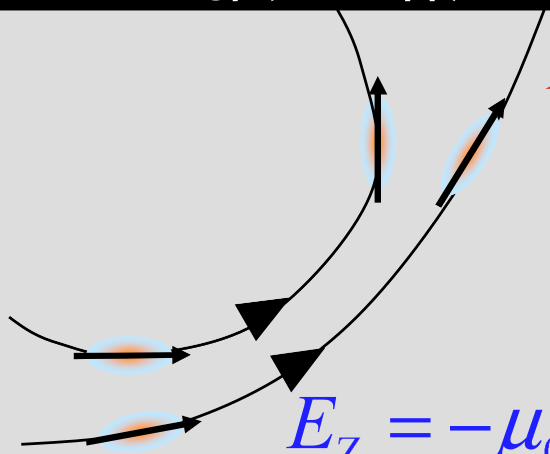
Magnetocrystalline anisotropy energy



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

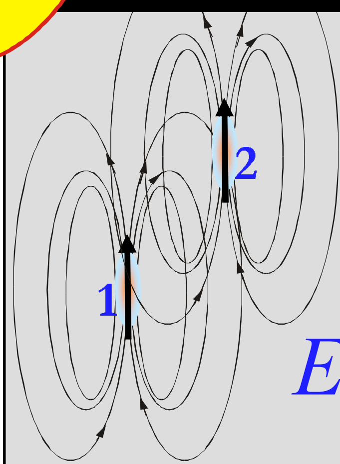


Zeeman energy (enthalpy)



$$E_Z = -\mu_0\,\vec{\mathbf{M}}_S . \vec{\mathbf{H}}$$

Dipolar energy



$$E_d = -\frac{1}{2}\mu_0\,\vec{\mathbf{M}}_S . \vec{\mathbf{H}}_d$$

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: $M_s = M_s(T)$

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

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):

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

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

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

$\sigma(\mathbf{r}) = M_\mathrm{s}\mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$ 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

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

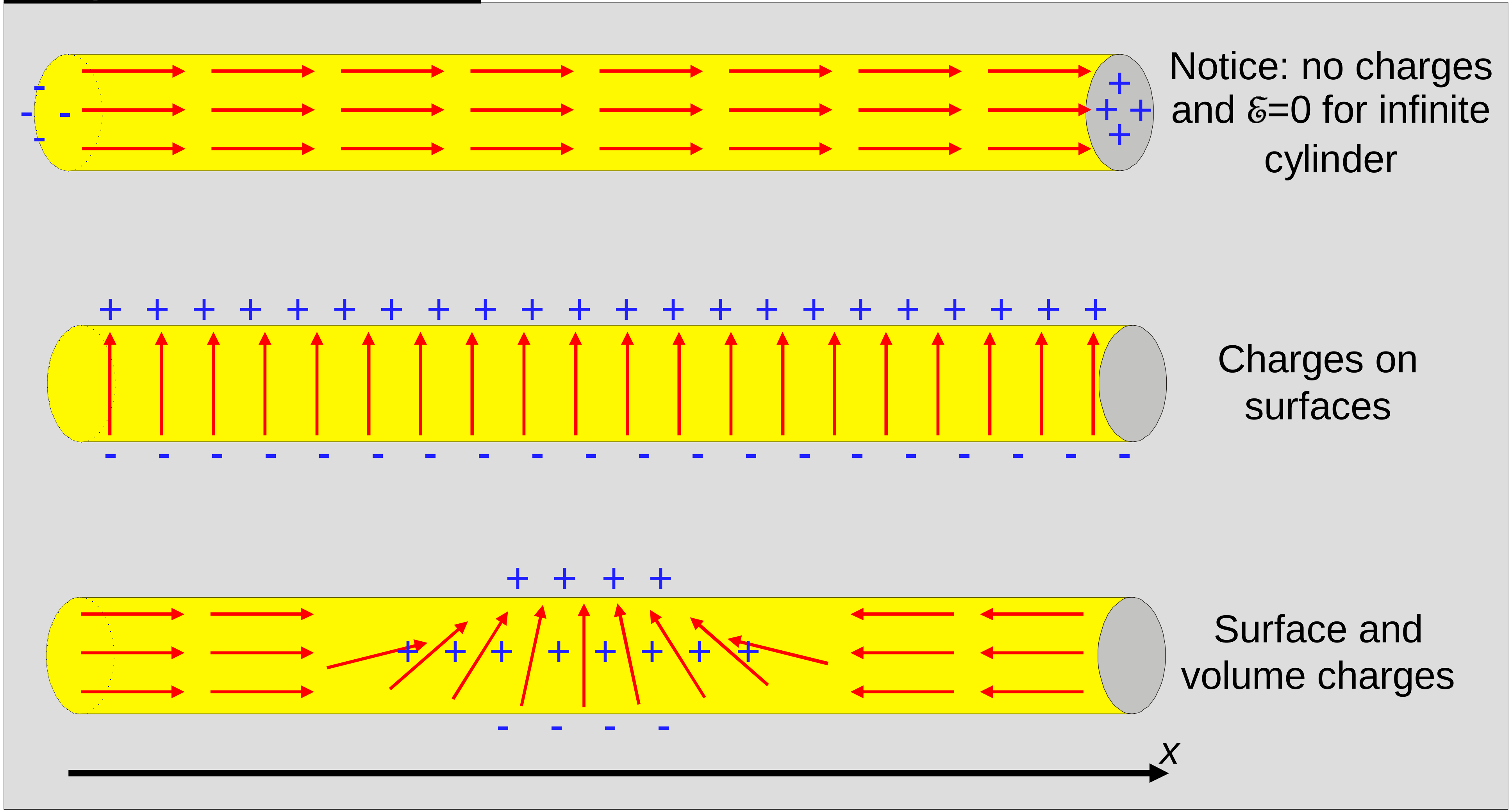
⇨ Significance of (BHmax) for permanent magnets

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

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

Energy available outside the sample, ie usefull for devices

Examples of magnetic charges



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

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

$$= M_\mathrm{s} m_i \iint_\mathrm{sample} \frac{n_i(\mathbf{r}').(\mathbf{r}'-\mathbf{r})}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2 r'$$

$$\mathcal{E}_\mathrm{d} = -\tfrac{1}{2}\mu_0 \iiint_\mathrm{sample} \mathbf{H}_\mathrm{d}(\mathbf{r}).\mathbf{M}.\mathrm{d}^3\mathbf{r}$$

$$= -\tfrac{1}{2}\mu_0 M_\mathrm{s}^2 m_i \iiint_\mathrm{sample} \mathrm{d}^3\mathbf{r} \iint_\mathrm{sample} \frac{n_i(\mathbf{r}').[\mathbf{m}.(\mathbf{r}'-\mathbf{r})]}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2\mathbf{r}'$$

$$= -K_\mathrm{d} m_i m_j \iiint_\mathrm{sample} \mathrm{d}^3\mathbf{r} \iint_\mathrm{sample} \frac{n_i(\mathbf{r}').(r_j'-r_j)}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2\mathbf{r}'$$

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

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

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

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

$$< H_{\mathrm{d},\mathrm{i}}(\mathbf{r}) > = -M_\mathrm{s} N_i$$

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

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

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

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

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

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

Cylinders

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

Magnetization loop of a macrospin along a hard axis

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

Dipolar energy: $H = h.H_a$, $H_a = 2K/\mu_0 M_s$, $K = N_i K_d$

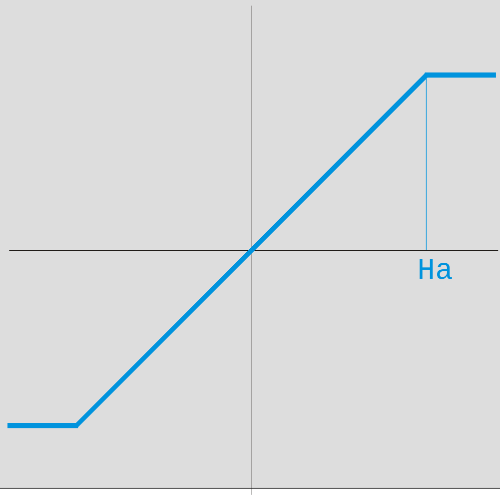
Hard axis: $\theta_H = \pi/2$

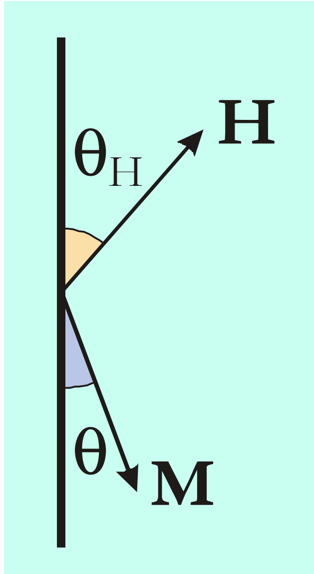
$$e = \sin^2(\theta) - 2h\sin(\theta)$$

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

$$h = \sin\theta = \cos(\theta - \theta_H) = \mathbf{m.u_h}$$

Equilibrium position





Case of a bulk soft magnetic material

Hypotheses:

1. Use an ellipsoid, cylinder or slab along a main direction so that the demagnetizing field may be homogeneous.

2. Domains can be created to yield a uniform and effective magnetization Meff

Density of energy:
$$E_{tot} = E_d + E_Z = \frac{1}{2}\mu_0 N \mathbf{M}_{eff}^2 - \mu_0 \mathbf{M}_{eff} H_{ext}$$

Minimization:
$$\frac{\partial E_{tot}}{\partial \mathbf{M}_{eff}} = \mu_0 N \mathbf{M}_{eff} - \mu_0 H_{ext} \Rightarrow \boxed{\mathbf{M}_{eff} = \frac{1}{N}\mu_0 H_{ext}}$$

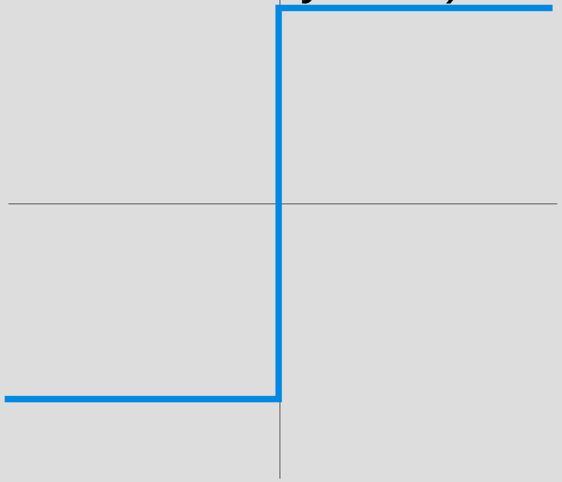
See: V. Pop

Conclusion for soft magnetic materials

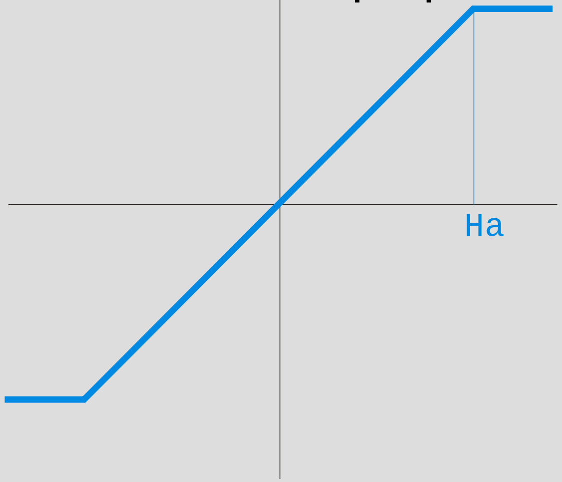
Susceptibility is constant and equal to 1/N

Ideally soft

N=0 (slab, infinite cylinder)

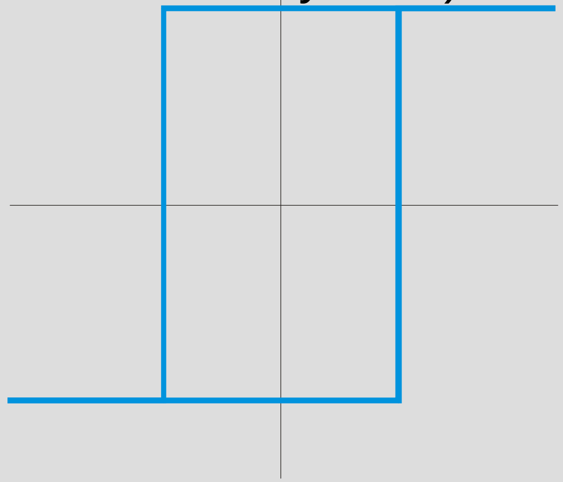


N>0 (here N=1: slab, perpendicular)

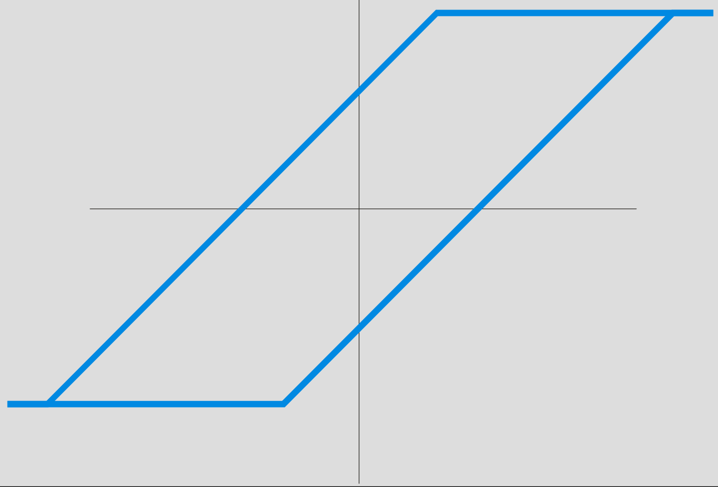


Easy axis, coercitive

N=0 (slab, infinite cylinder)

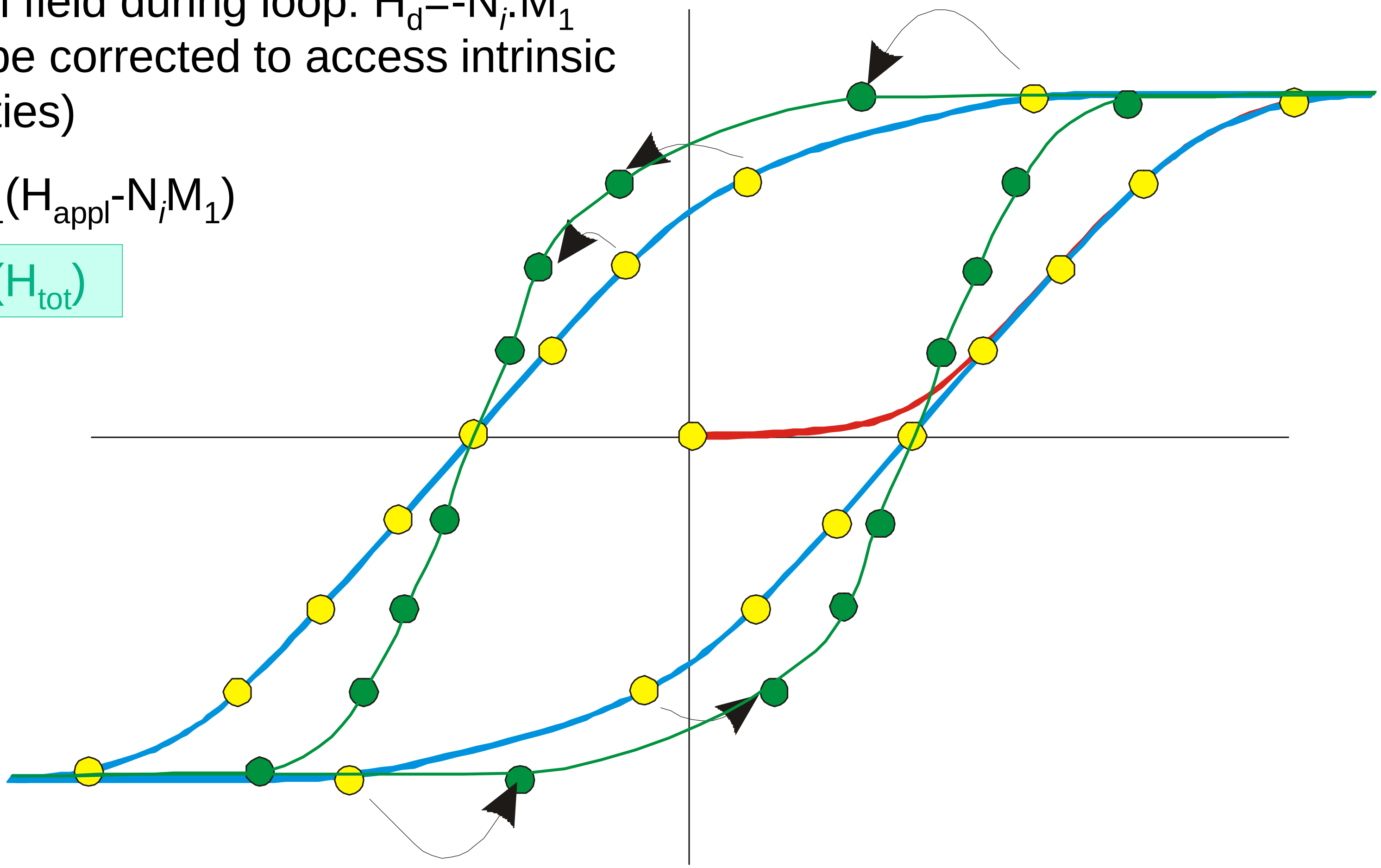


N>0 (here N=1: slab, perpendicular)



1. Measure a hysteresis loop $M_1(H_{appl})$
2. Internal field during loop: $H_d = -N_i . M_1$ (must be corrected to access intrinsic properties)
3. Plot $M_1(H_{appl} - N_i M_1)$

➡ $M_2(H_{tot})$



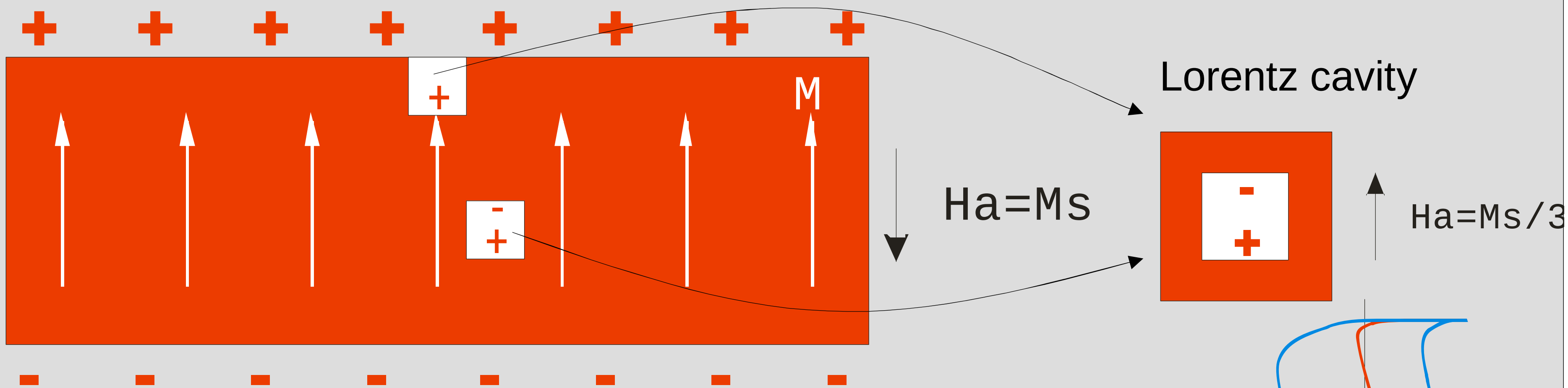
Specific aspects in hard magnetic materials

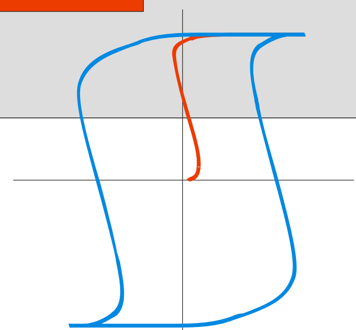
1. The concept of effective magnetization fails, because grains are either up or down.

2. Individual grains have a shape, implying a demagnetizing field that must be taken into account

3. In heteromaterials (ex: hard-soft; magnetic/non-magnetic etc.) the magnetization of both phases has to be taken into account. Depends also on grain size…

Example with cubic grains

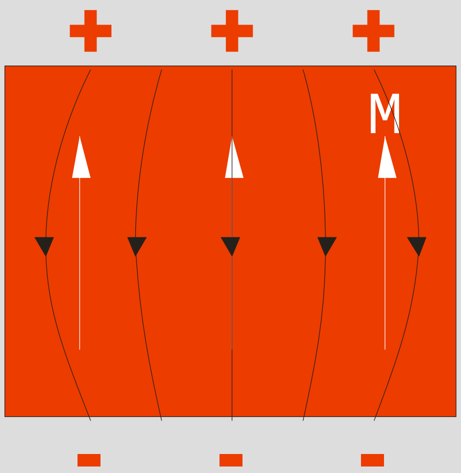




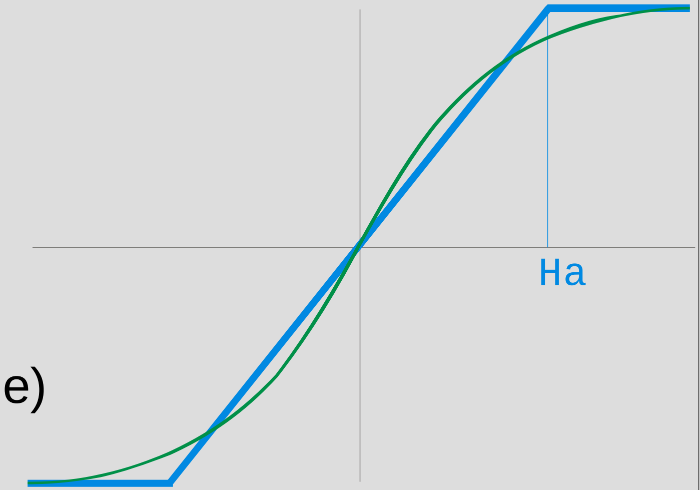
The field felt in the grain if it tries to reverse is -2Ms/3, not –Ms.
The loop is overcompensated if N=1 is used.

See: D. Givord (2005?)

Specific aspects to systems with non-ellipsoidal shapes



In a non-ellipsoidal (or cylindrical, slab) system the demagnetizing field is not homogeneous in magnitude nor direction



1. Initial slope higher than 1/N (demag field smaller than average)

2. Late slope smaller than 1/N (demag field larger than average)

Demagnetizing energy (thus area above loop) is identical $E_\mathrm{d} = \int_0^{M_\mathrm{s}} \mu_0 H_\mathrm{ext} \mathrm{d}M = \frac{1}{2}\mu_0 N M_\mathrm{s}^2$

➪ In a non-ellipsoidal sample (or cylinder, slab) the loop is overcompensated at low magnetization and undercompensated at high field, even for soft magnetic materials.

➪ This effect adds up to the previous effect of grain shape

P. O. Jubert, O. Fruchart et al., Europhys. Lett. 63, 102-108 (2003)

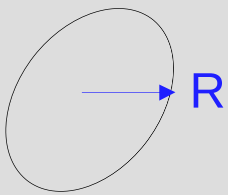
Upper bound for dipolar fields in 2D

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

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

Integration

Local dipole: $1/r^3$

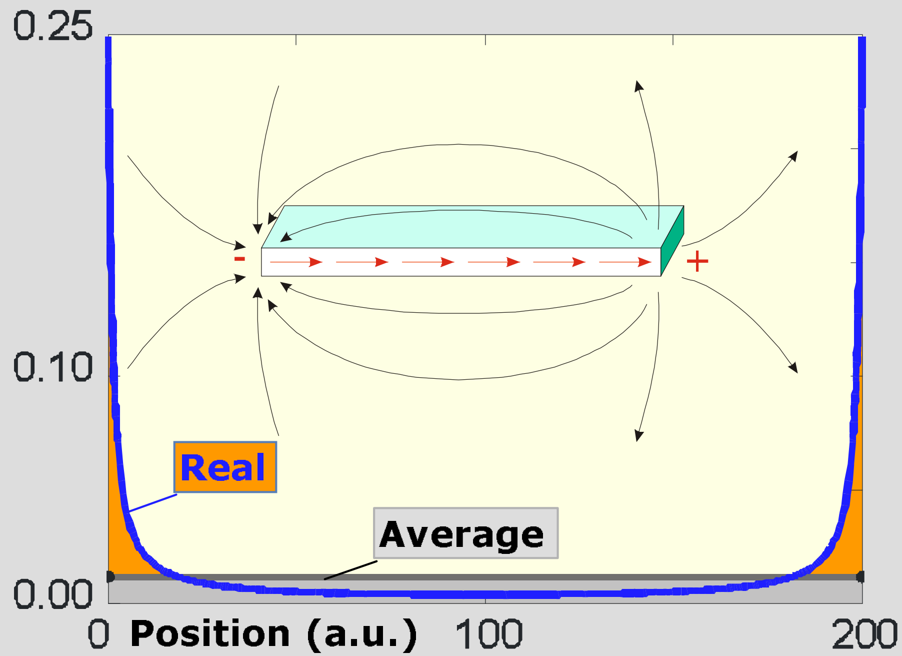


$$\left\|\mathbf{H}_\mathrm{d}(R)\right\| \le \mathrm{Cte} + 1/R$$

Convergence with finite radius (typically thickness)

Non-homogeneity of dipolar fields in 2D

Example: flat stripe with thickness/height = 0.0125

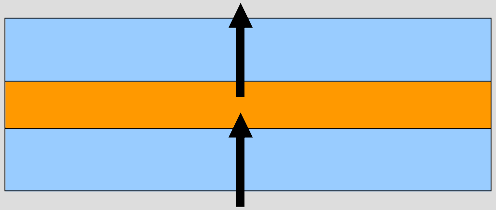


- Dipolar fields are weak and short-ranged in 2D or even lower-dimensionality systems
- Dipolar fields can be highly non-homogeneous in anisotropic systems like 2D
- Consequences on dot’s non-homogenous state, magnetization reversal, collective effects etc.

Stacked dots : dipolar

In-plane magnetization

Out-of-plane magnetization



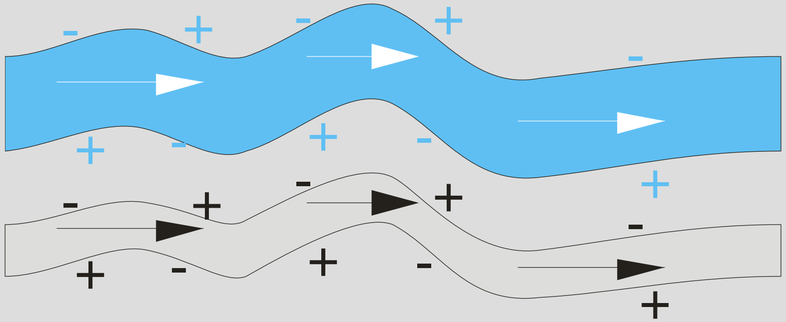
Hint:

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 films)

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)

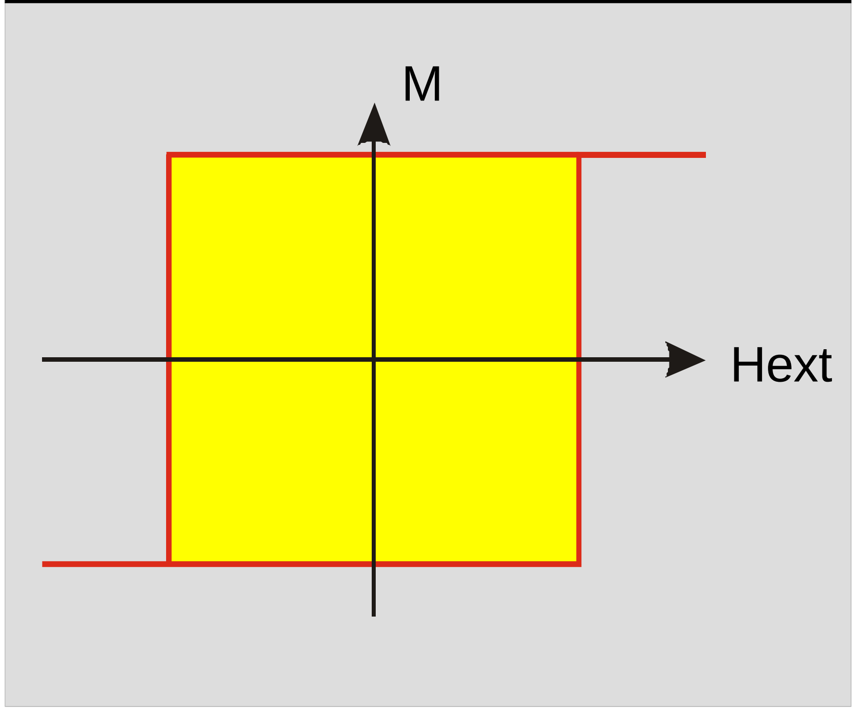
Models for arrays of elements of arbitrary shapes

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)

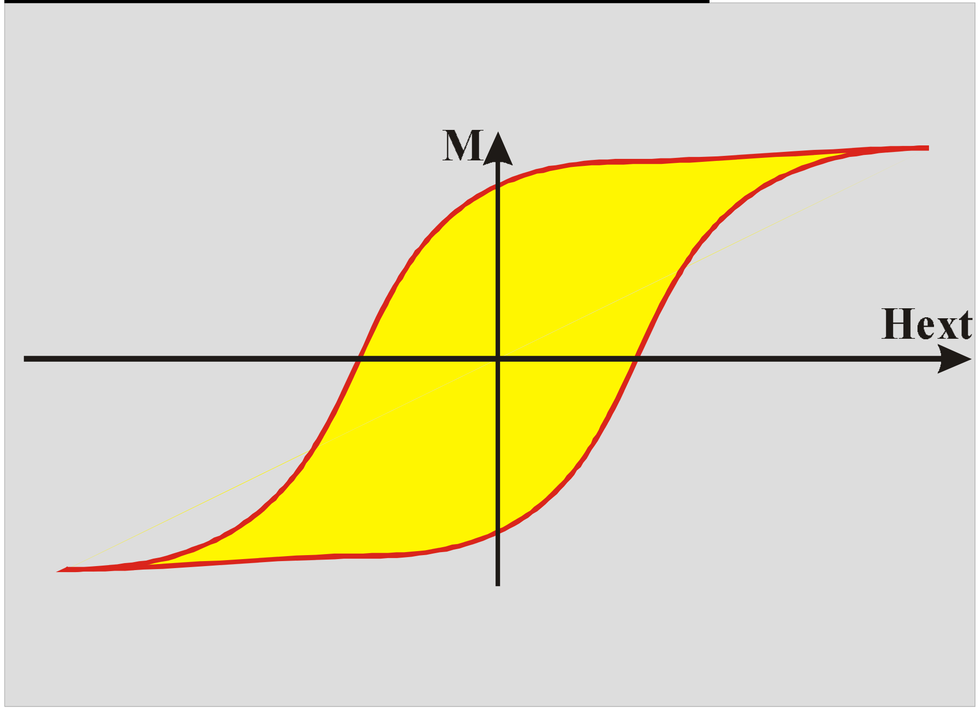
E.Y. Vedmedenko, N. Mikuszeit, H. P. Oepen and R. Wiesendanger, Multipolar Ordering and Magnetization Reversal in Two-Dimensional Nanomagnet Arrays, Phys. Rev. Lett. 95, 207202 (2005)

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



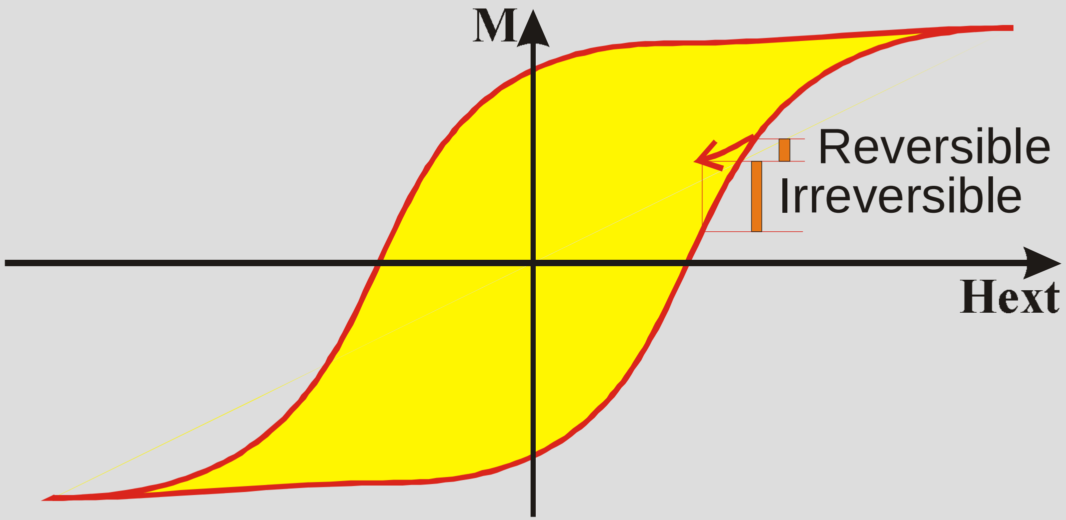
Hysteresis for assemblies of dots



Possible effects

- Distribution of coercive fields
- (Dipolar) interactions

Distribution of properties



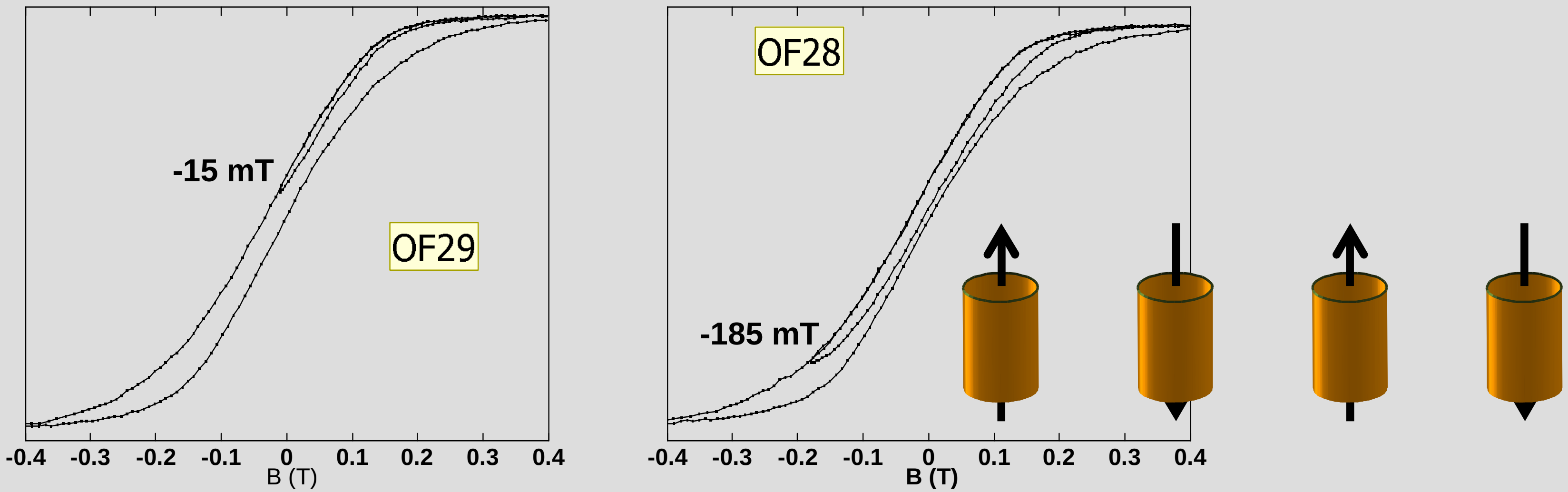
$$\rho(H_r) = \left.\frac{dm}{dH}\right|_{\text{irreversible}}$$

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

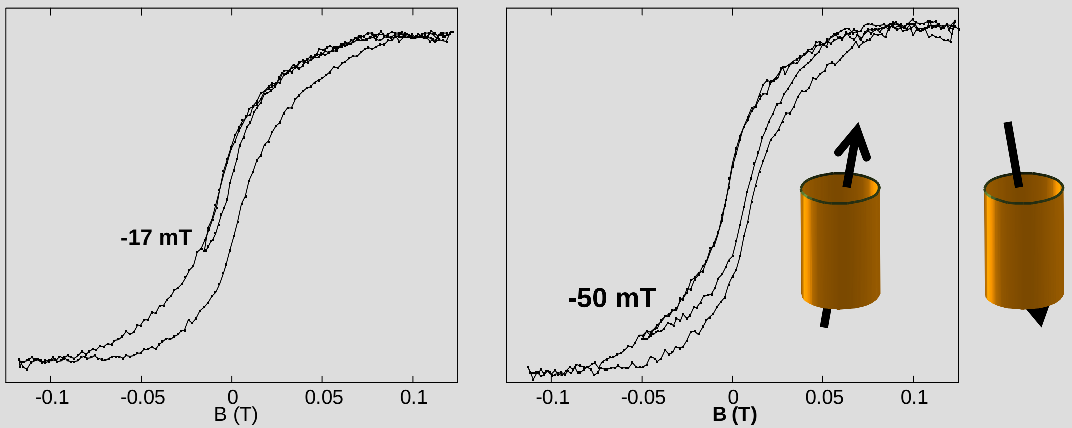
Effect of distributions and dipolar interactions are sometimes difficult to disentangle

Minor loops: negative interactions

Example: dipolar interactions in arrays of Co/Au(111) pillars



Minor loops: negligible interactions



- Faster than Henkel
- Other applications: characterization of exchange bias

O. Fruchart et al., unpublished

Diapositive 23

OF28 mineurPOLAR185.pic
Olivier Fruchart; 09/07/2005

OF29 mineurPOLAR15.pic
Olivier Fruchart; 09/07/2005

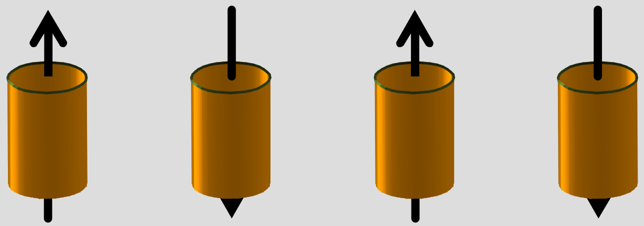
Superparamagnetic regime: plot of inverse susceptibility

- **Brillouin 1/2 function**

$$m = \mathrm{B}_{1/2}\left(\mu_0 \mu_{\mathrm{Co}} N H_{\mathrm{eff.}} / kT\right)$$

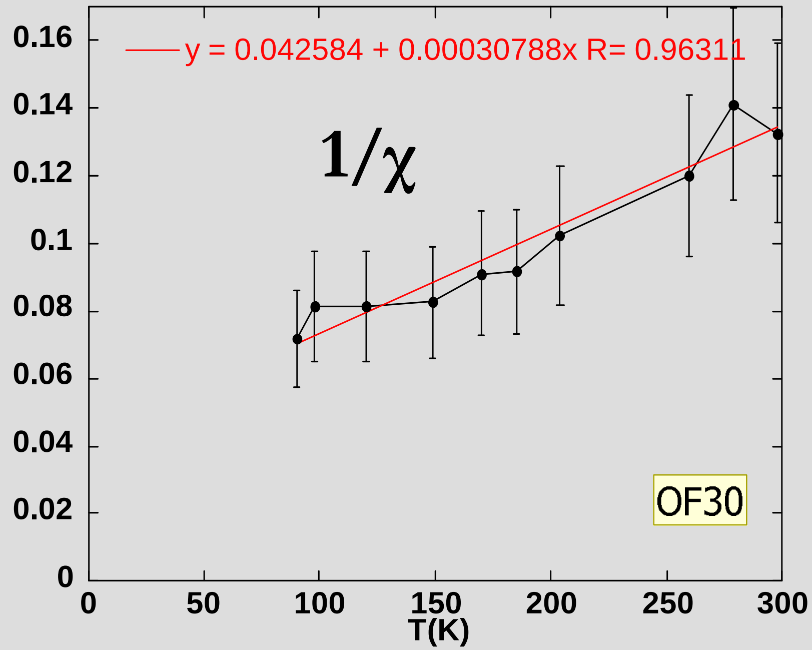
- **Effective field**

$$H_{\mathrm{eff.}} = H + r\, M_{\mathrm{s}}\, m$$



(Demagnetizing dipolar interactions)

(T)



- **First order expansion**:

susceptibility

$$\frac{d(\mu_0 H)}{dm} = \frac{1}{\chi} = -\mu_0 M_S r + \frac{k}{\mu_{\mathrm{Co}} N} T$$

$$\boldsymbol{a} \quad + \quad \boldsymbol{b}\ .\ \boldsymbol{T}$$

O. Fruchart *et al.*, PRL 23, 2769 (1999)

- No need of hysteresis
- Analogy with Curie-Weiss law

Diapositive 24

OF30 UnSurChi.pic

Olivier Fruchart; 09/07/2005

Henkel plots

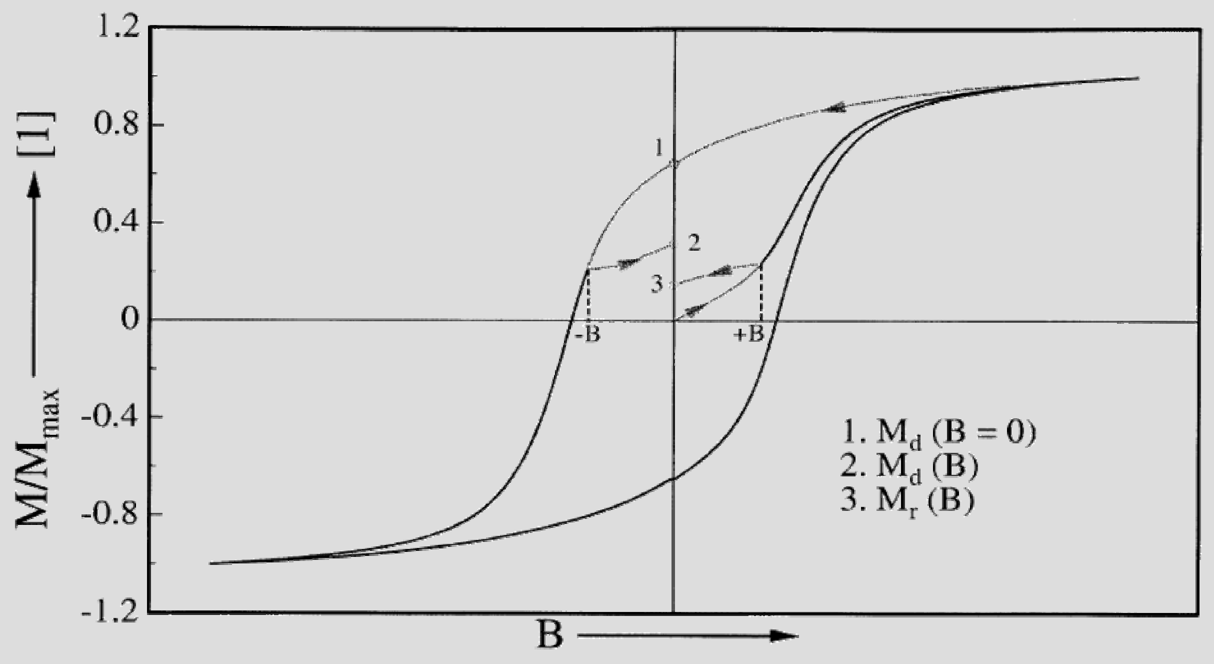


Fig. 1. Explanation of how to measure the two different remanent magnetisations M_r and M_d.

Measure of dipolar interactions

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

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

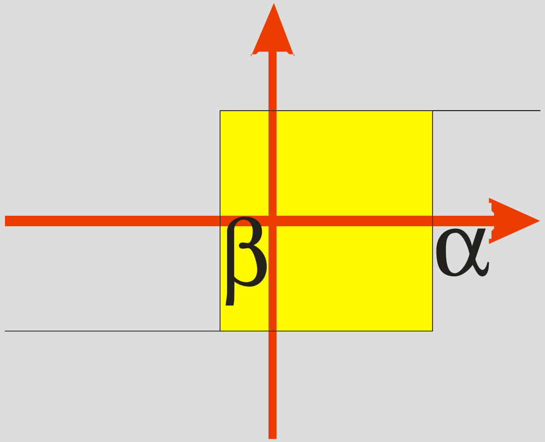
S. Thamm et al.,
JMMM184, 245 (1998)

- 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)

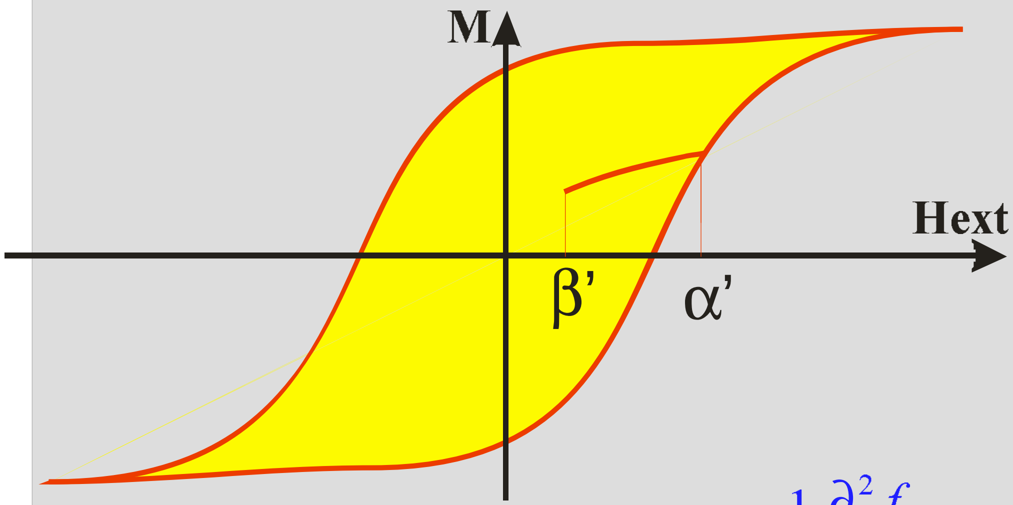


- Distribution function

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

- No true link between real particles and μ

Solving



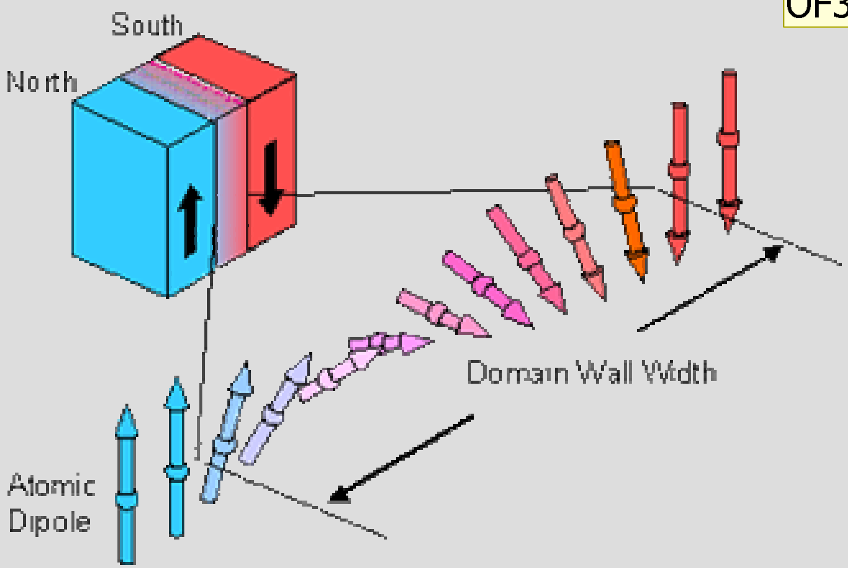
$$\mu(\alpha',\beta') = \frac{1}{2}\frac{\partial^2 f_{\alpha',\beta'}}{\partial\alpha'\partial\beta'}$$

- Long experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions

II.2. Coercivity in patterned elements

Typical length scale: Bloch wall width λ_B

OF31



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

Exchange → $\mathrm{J/m}$

Anisotropy → $\mathrm{J/m^3}$

Numerical values

$$\lambda_B = \pi\sqrt{A/K}$$

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

Hard Soft

$\sqrt{A/K}$ is also often called the Bloch wall parameter. Notice also that several definitions of Bloch wall width have been proposed, e.g. with π or 2 as prefactor

Diapositive 28

OF31 Si temps, refaire schéma en français

Olivier Fruchart; 22/03/2005

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

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

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

Critical size relevant for nanoparticules made of soft magnetic material

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

Generalization for various shapes

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

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

Critical size for hard magnets

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

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

Notice:

Other length scales: with field etc.

Institut Néel, Grenoble, France

Configurational anisotropy: deviations from single-domain

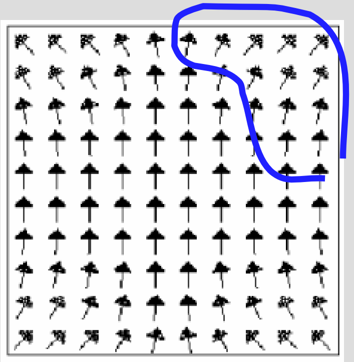
Strictly speaking, 'shape anisotropy' is of second order:

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

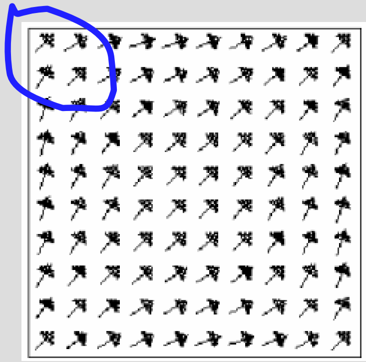
2D: $E_{\mathrm{tot}} = VK_{\mathrm{d}}\sin^2\theta$

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

Num.Calc. (100nm)



Flower state
c/a>2.7



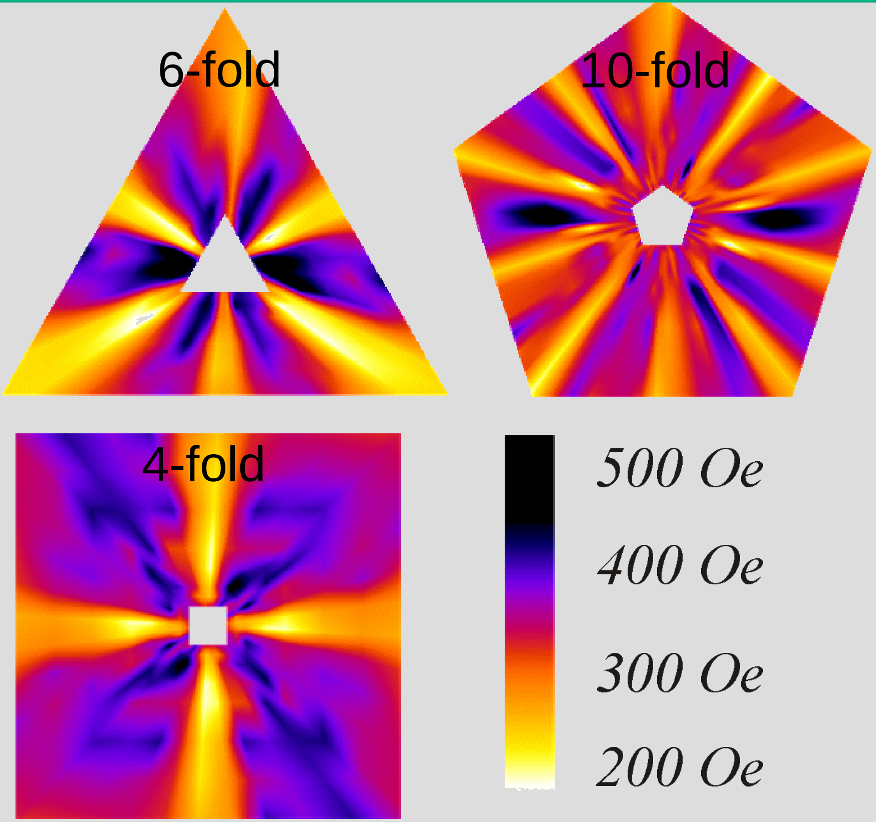
Leaf state
c/a<2.7

Configurational anisotropy may be used to stabilize stable configuration

➯ Higher order contributions to the anisotropy

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

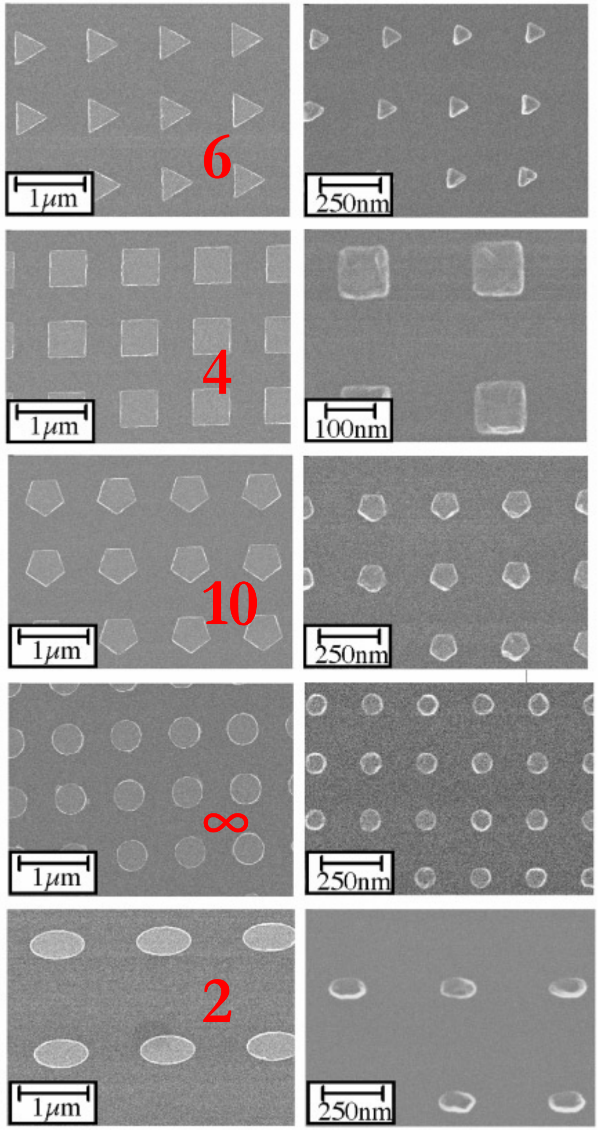
Polar plot of experimental configurational anisotropy with various symmetry



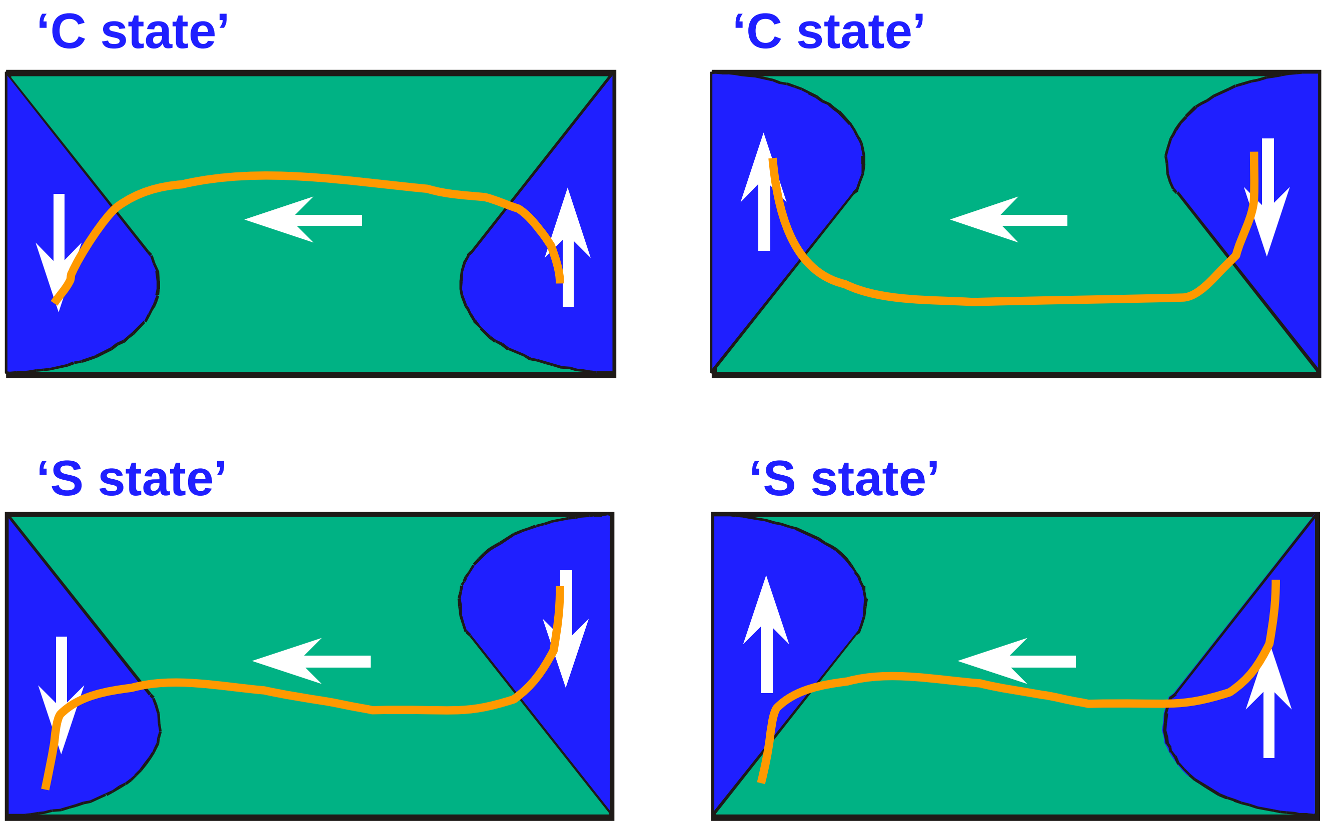
Color code: strength of anisotropy in a given direction

Radius: size of measured pattern

Direction: direction of measurement



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



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

Magnetization is pinned at sharp ends

Experiments **Permalloy** (soft)

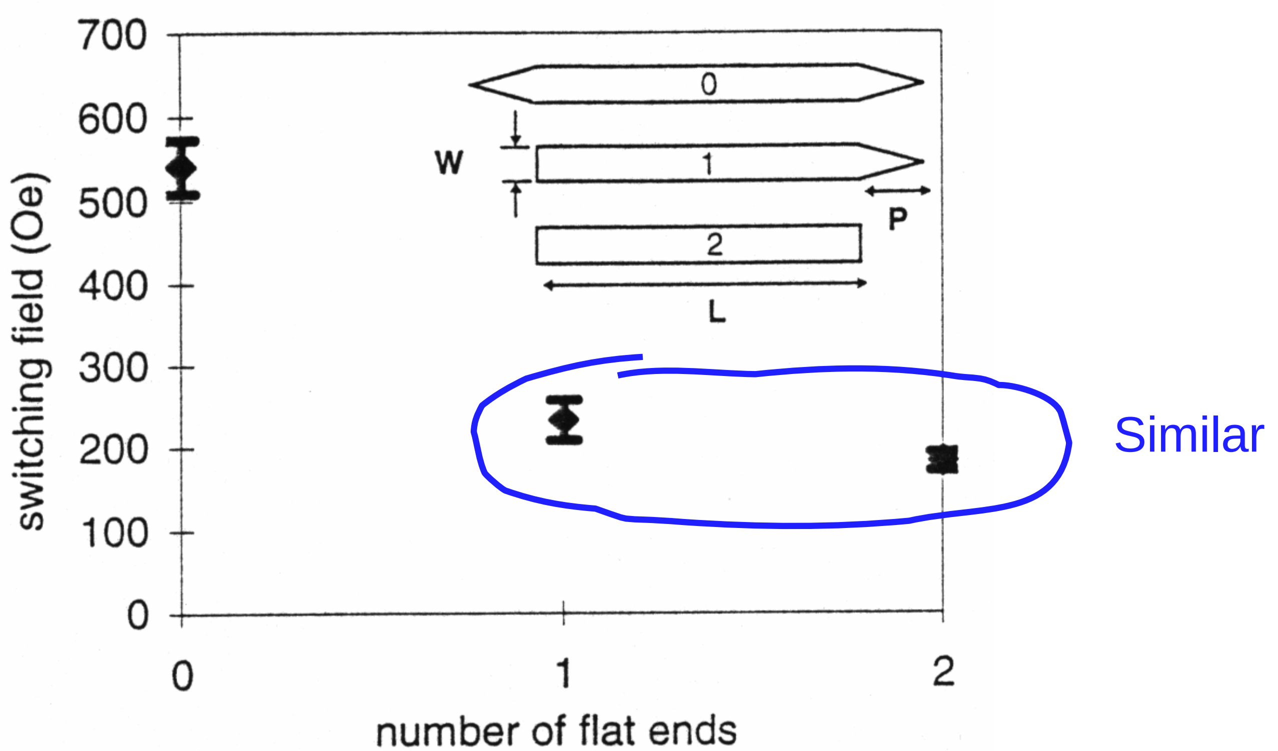


Fig. 8 Dependence of switching field of acicular elements on the number of flat ends. Element geometry is also shown: L=2.5 μm, W=200 nm, P=500 nm.

K.J. Kirk et al., J. Magn. Soc. Jap., 21 (7), (1997)

Magnetization is pinned at sharp ends

Numerical micromagnetic calculation

J.G. Zhu

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

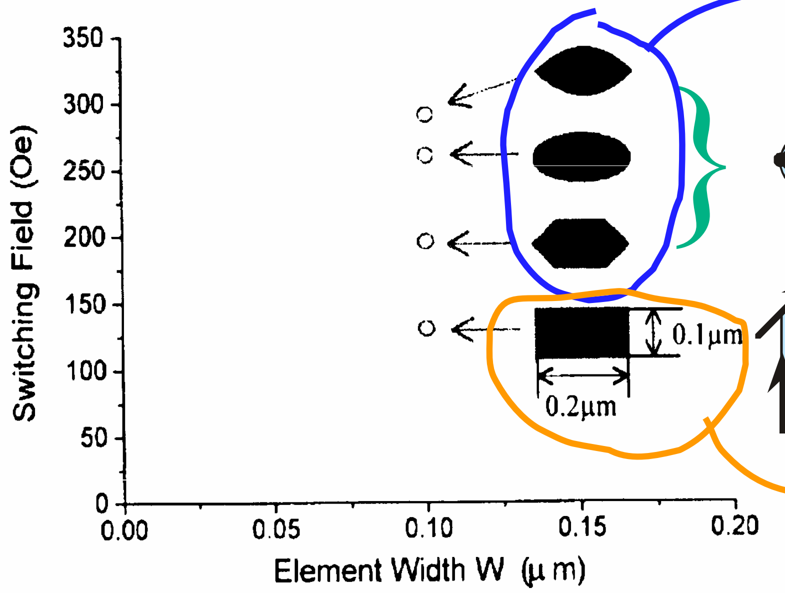
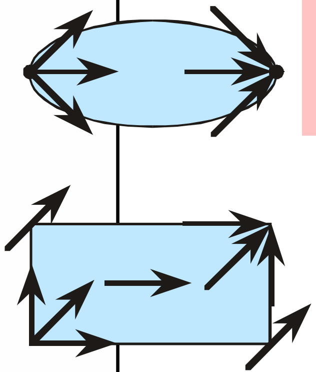


FIG. 11. Calculated switching fields of NiFe film elements with different end shape. All the elements have the same size of 0.2×0.1 μm^2, counting tip-to-tip, and a thickness of 20 Å.

Two ground-states each



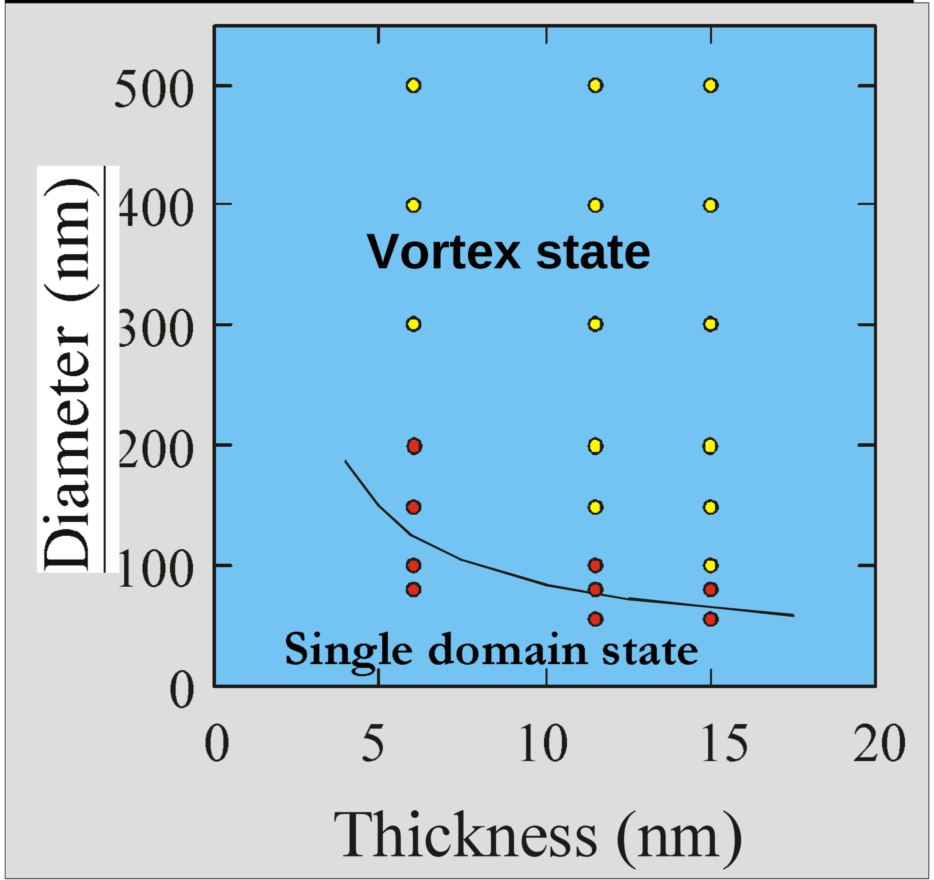
- **GOOD**: Better reproducibility
- **BAD**: Higher switching field

Eight ground-states

Essentially Equivalent Topological Properties

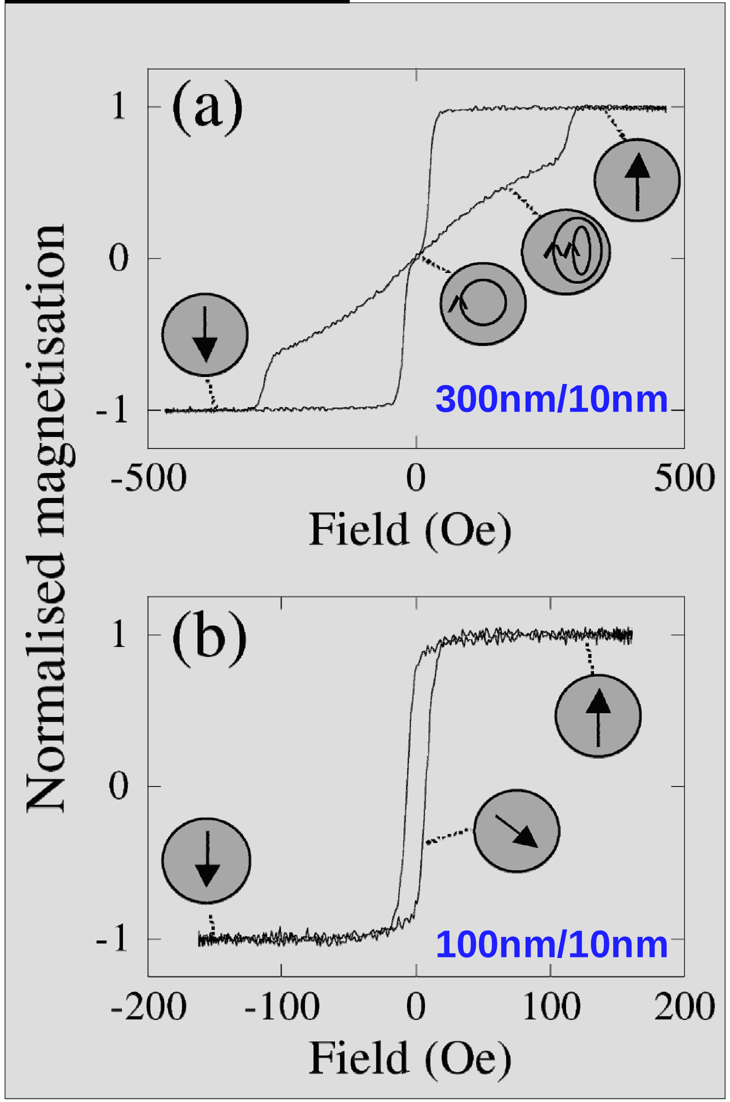
(Images courtesy of J. Miltat - CNRS, Orsay, France)

Phase diagram of macrospin versus vortex



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

Hysteresis loops



Single domain state becomes favorable well above λ_{ex}

Dipolar energy is higher for thicker dots
(think in terms of magnetic charges)

NON-SINGLE DOMAIN EFFECTS – Van den Berg model (1/2)

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)

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

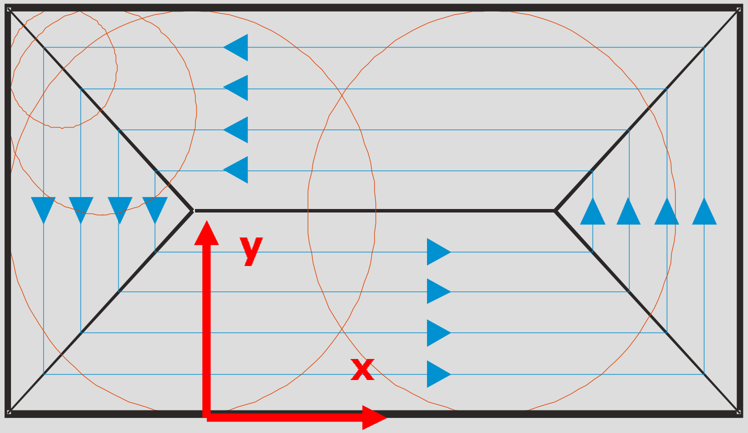
Solution

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

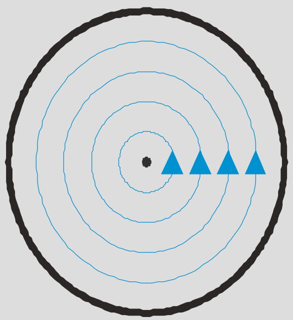
$-\mathrm{div}\mathbf{M} = 0$ (no volume charges)

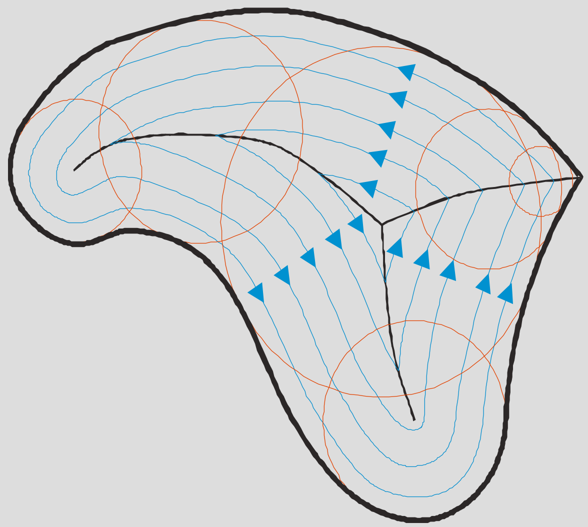
$\mathbf{M}.\mathbf{n} = 0$ (no surface charges)

« Flux closure »



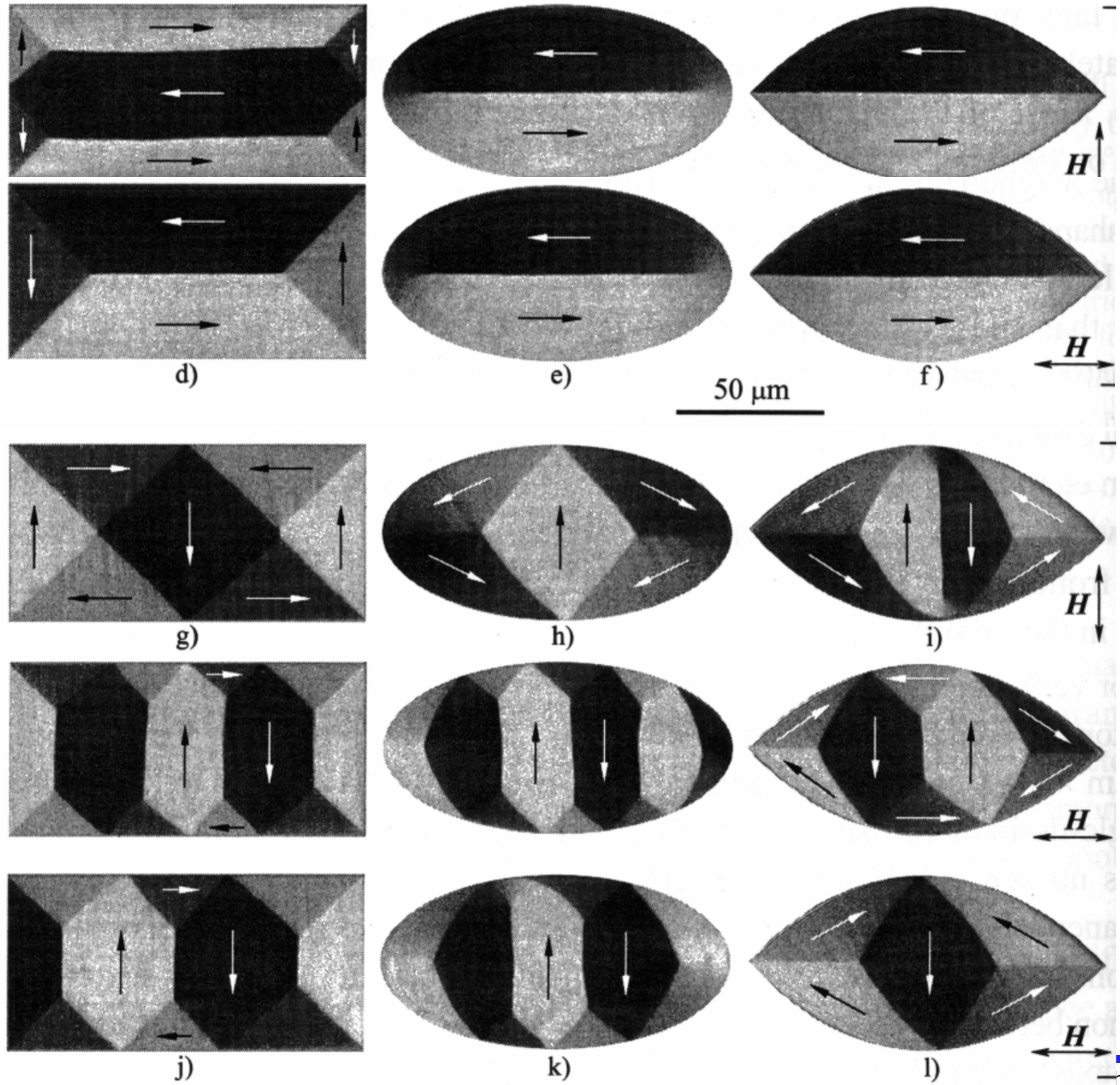
$$\mathrm{div}\mathbf{M} = \frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y}$$





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

Sandpiles for simulating flux-closure patterns



Easy axis of **weak** magnetocrystalline anisotropy

Easy axis of **weak** magnetocrystalline anisotropy

Large dots

- many degrees of freedom
- many possible states
- history is important
- even slight perturbations can influence the dot (anisotropy, defects, etc.).

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)

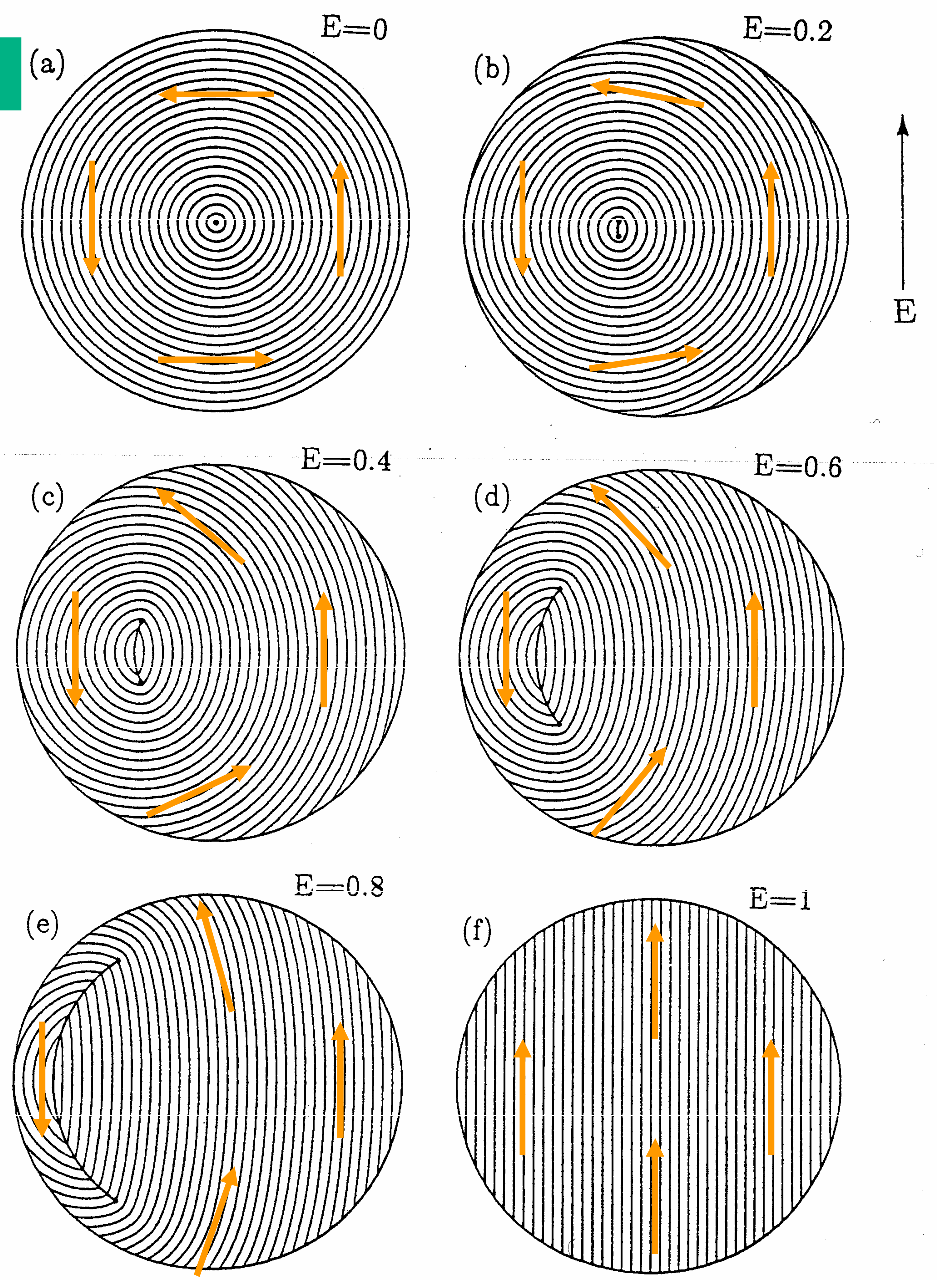
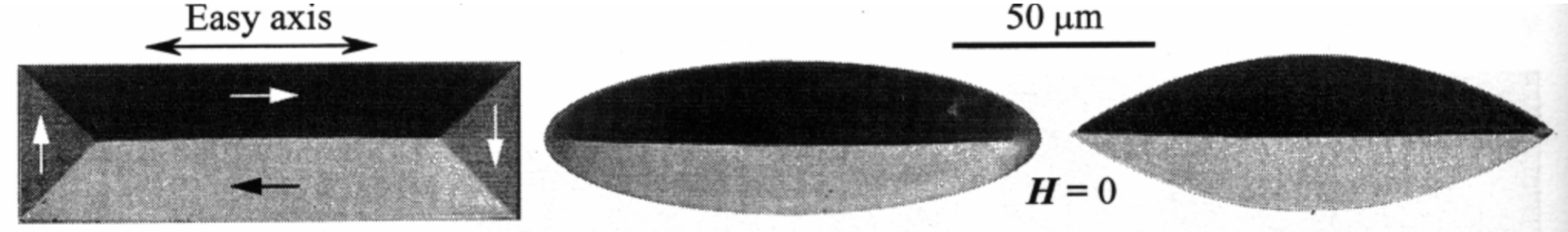


Figure 3

In the following, many pictures taken from Hubert's book

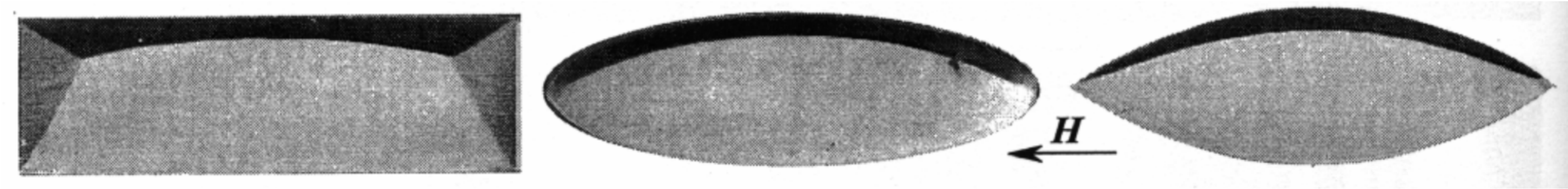
Zero field : agreement with Van den Berg's model

Material : $Ni_{80}Fe_{20}$
'Permalloy', Py.



View details

Longitudinal applied field

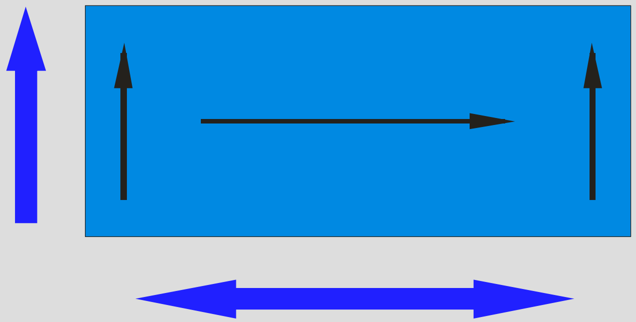


The domains with magnetization parallel to the applied field are favored

II.3. Manipulating domain walls

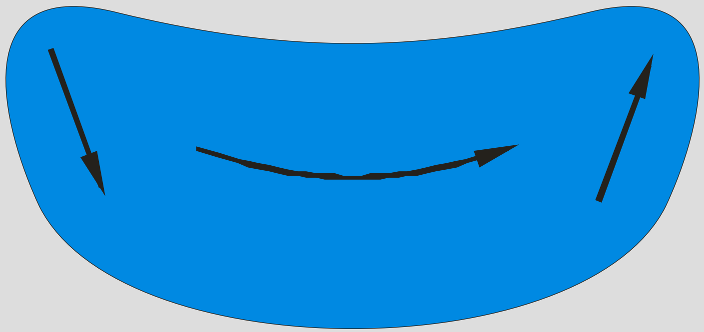
Preparation of 'S' state

Transverse field to keep end domains aligned parallel to each other



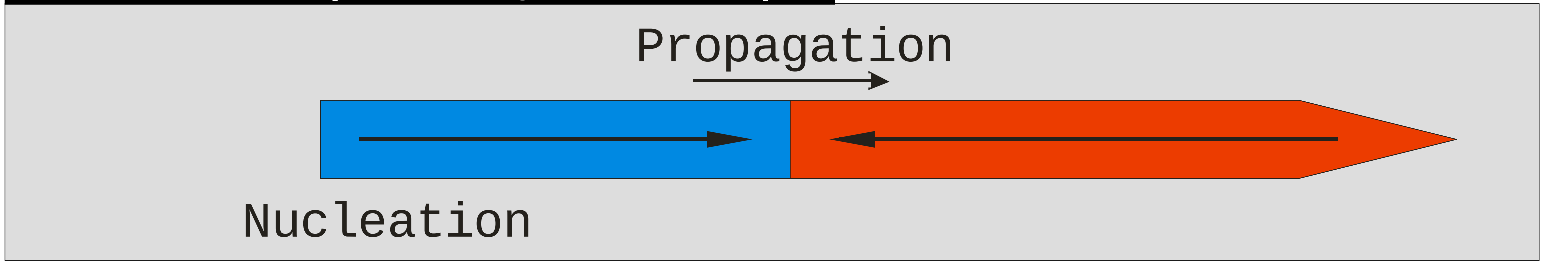
Longitudinal field to reverse the magnetization

Preparation of 'S' state

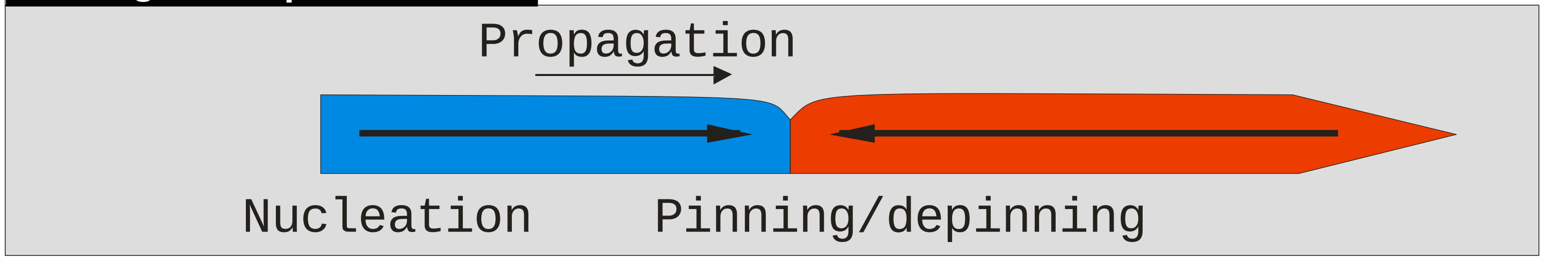


End domains aligned mainly antiparallel owing to a dipolar shape effect

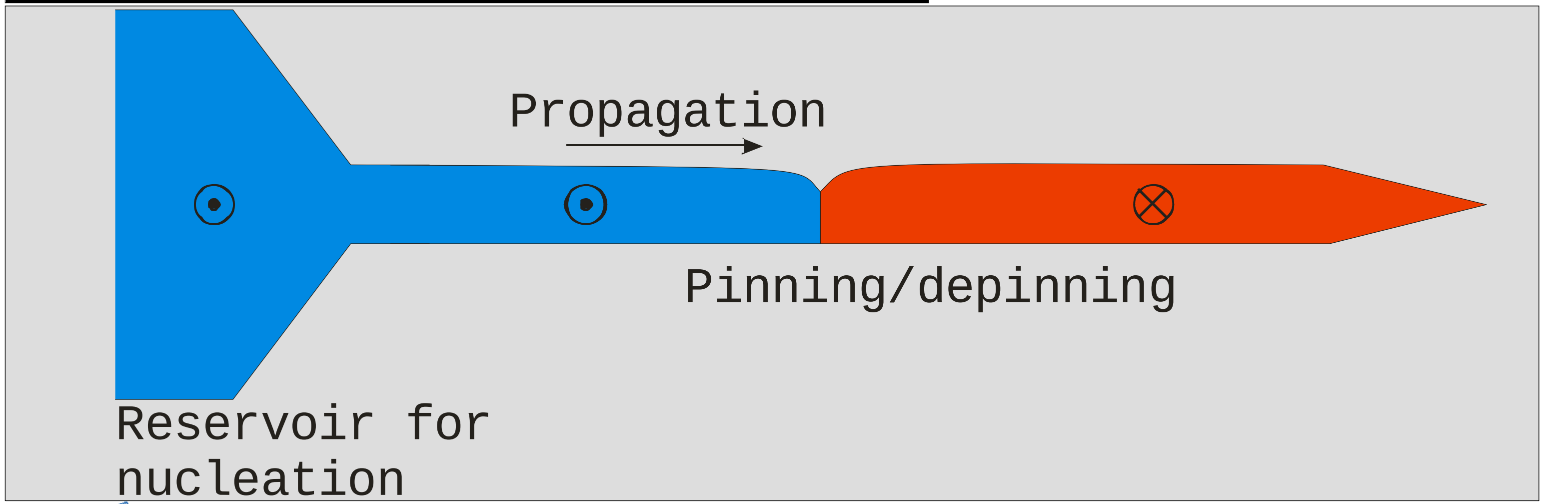
Nucleation in in-plane magnetized stripes



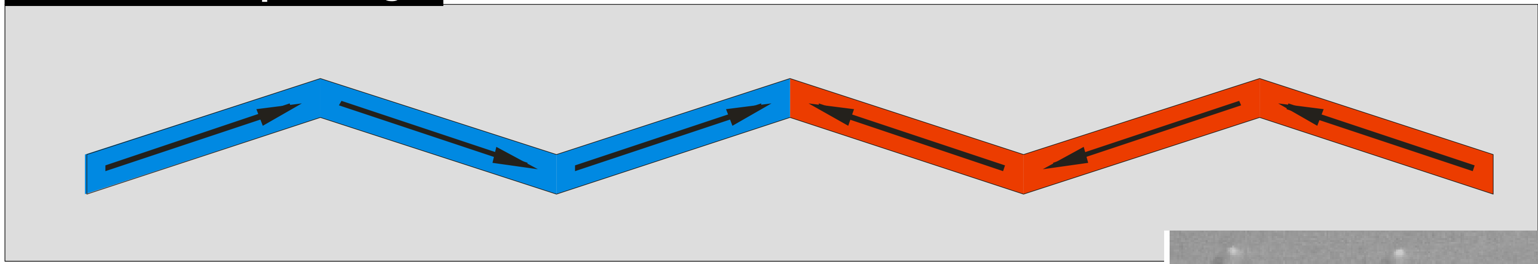
Pinning in stripes: notches

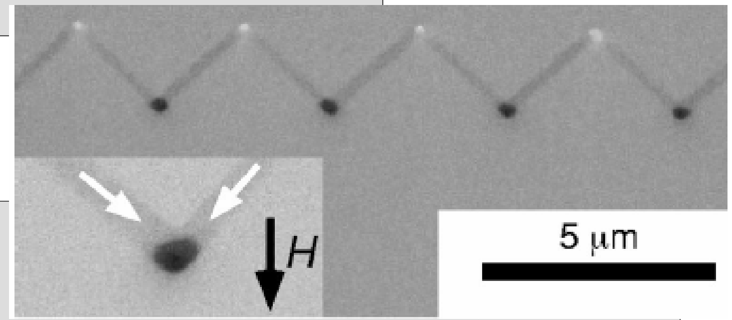


Nucleation in out-of-plane magnetized stripes

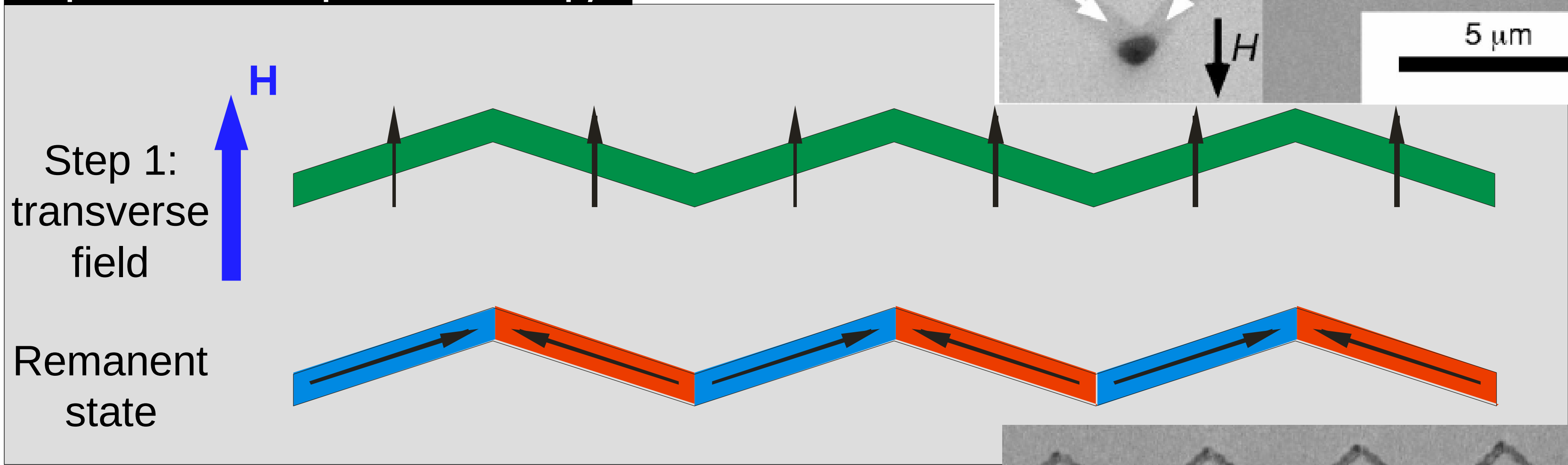


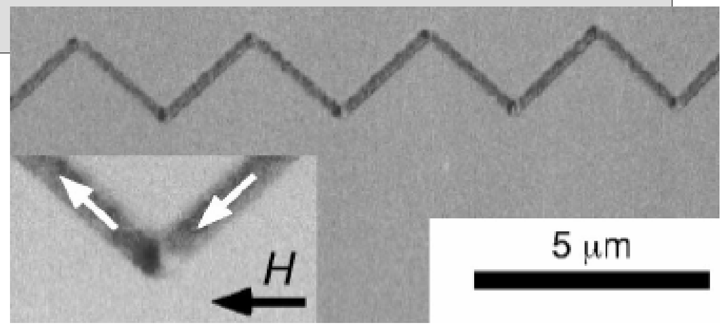
Geometrical pinning





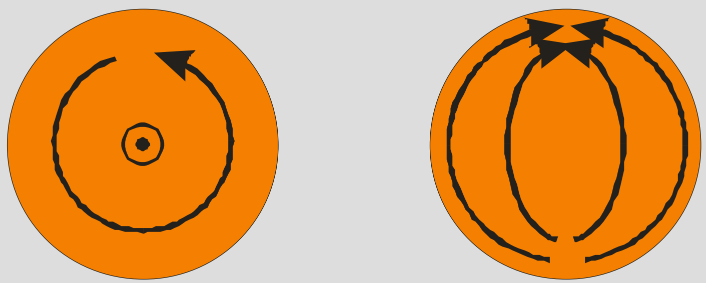
Preparation for in-plane anisotropy





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

Disks



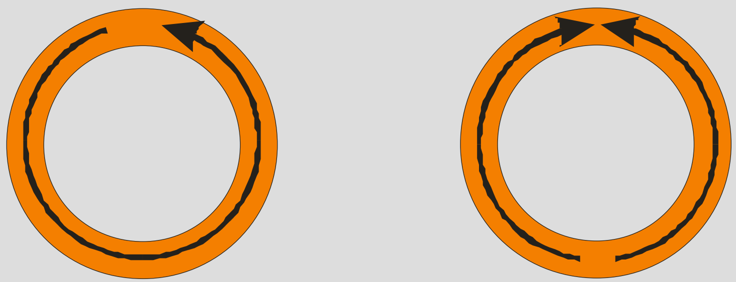
Vortex state

Near single-domain (leaf state)

Aspect ratio D/t

Large diameter D

Rings

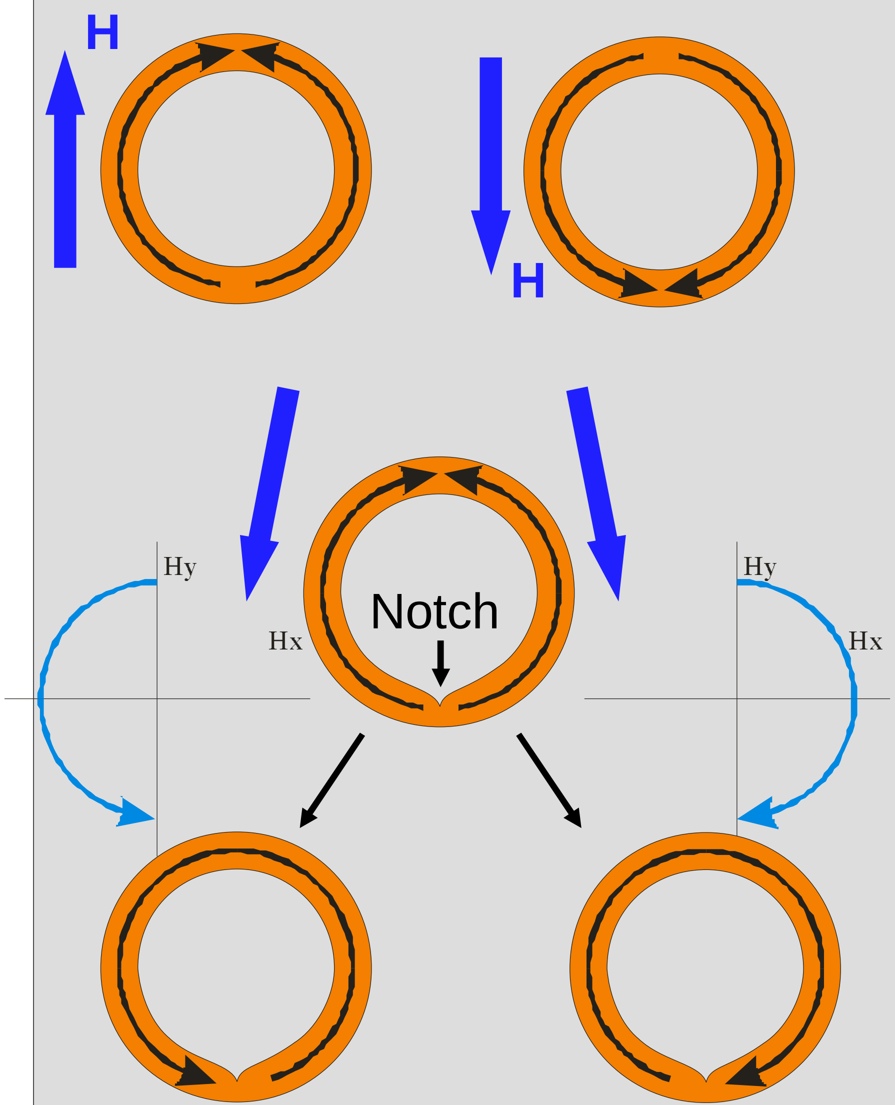


Vortex state

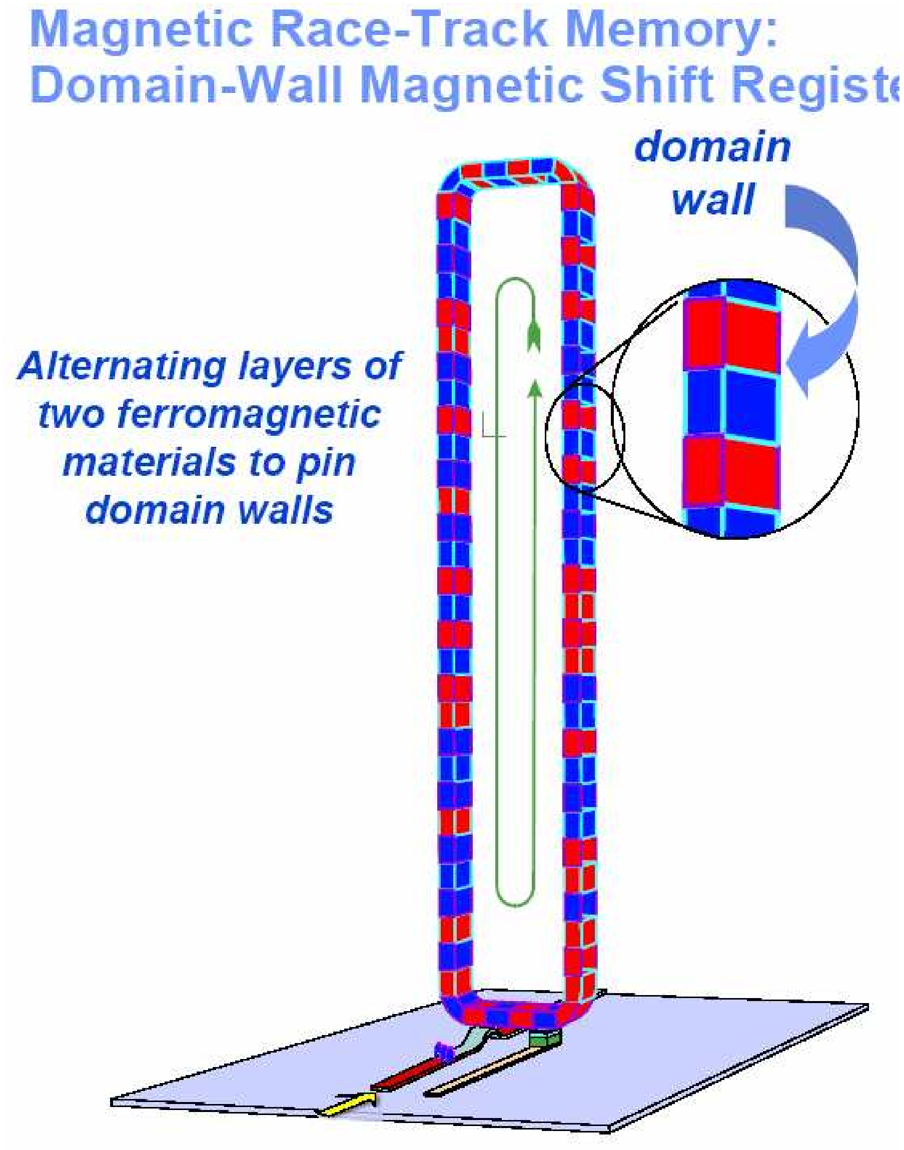
Onion state

Stability less dependent on geometry (no vortex energy)

Control of ring states



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



S. S. P. Parkin, IBM-Almaden
U.S. patents 6834005, 6898132, 6920062

D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson,
D. Petit & R. P. Cowburn,
Magnetic domain-wall logic, Science 309, 1688 (2005)

Closure domains (flat)

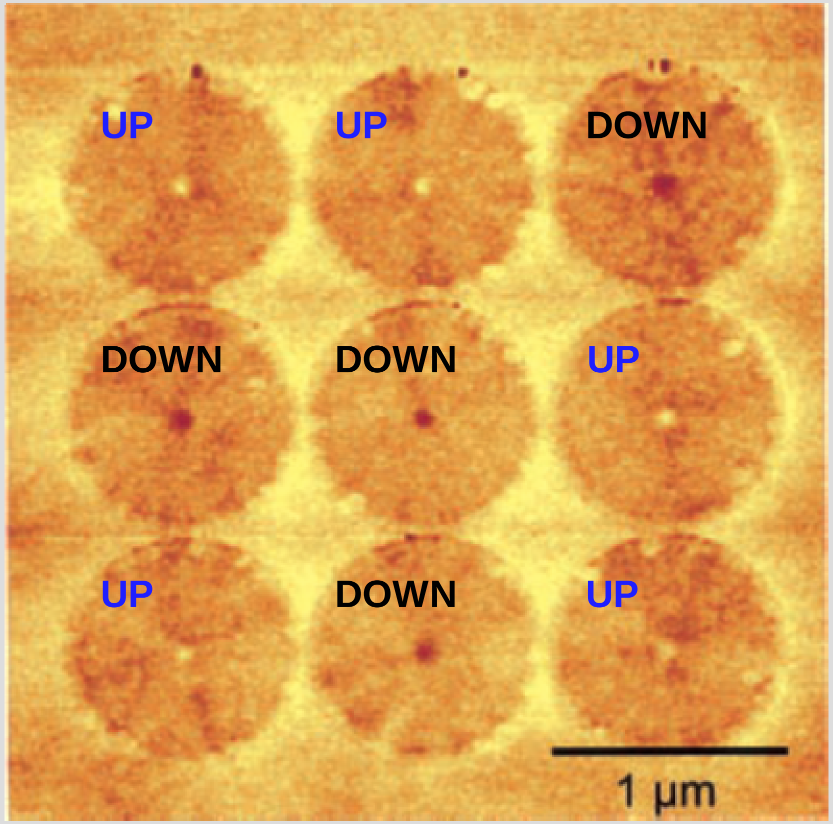


Fig. 2. MFM image of an array of permalloy dots 1 μm in diameter and 50 nm thick.

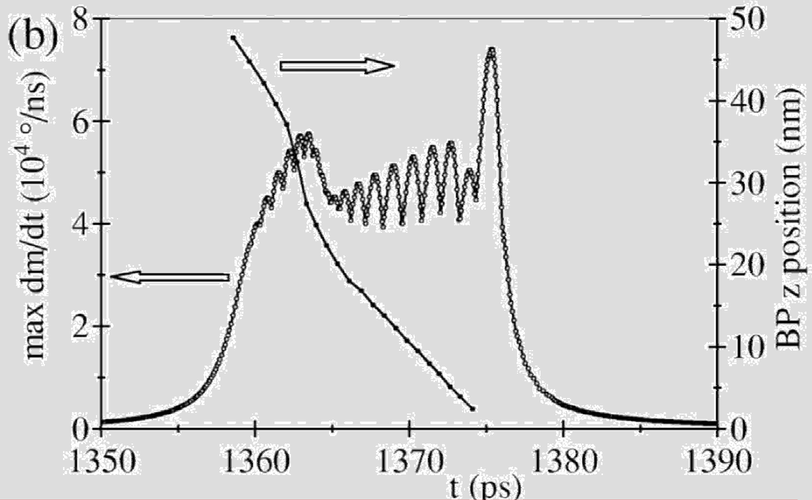
The central magnetic vortex can be magnetized up or down using a perpendicular field

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)



Require a Bloch point:

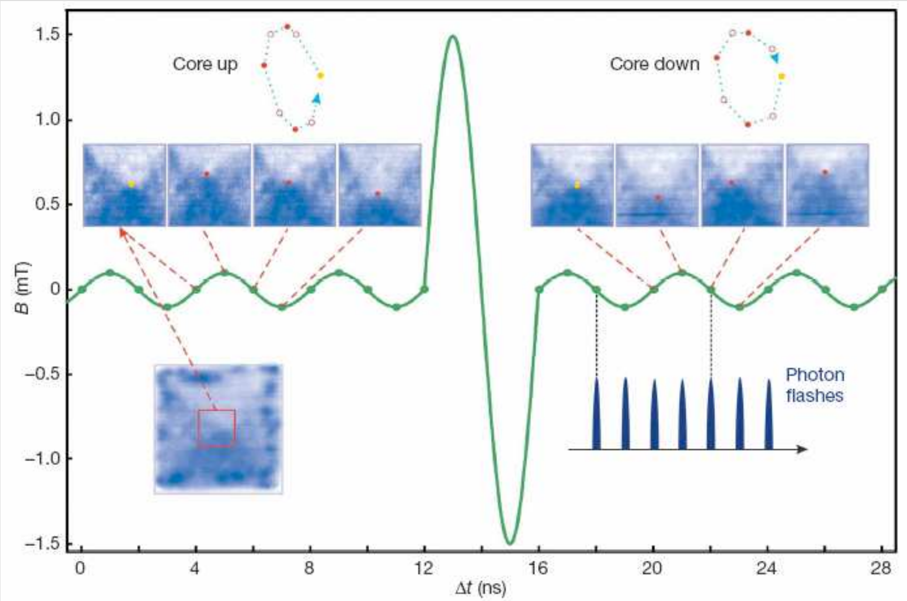
Not well described in micromagnetism

First theoretical insight in Bloch points

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

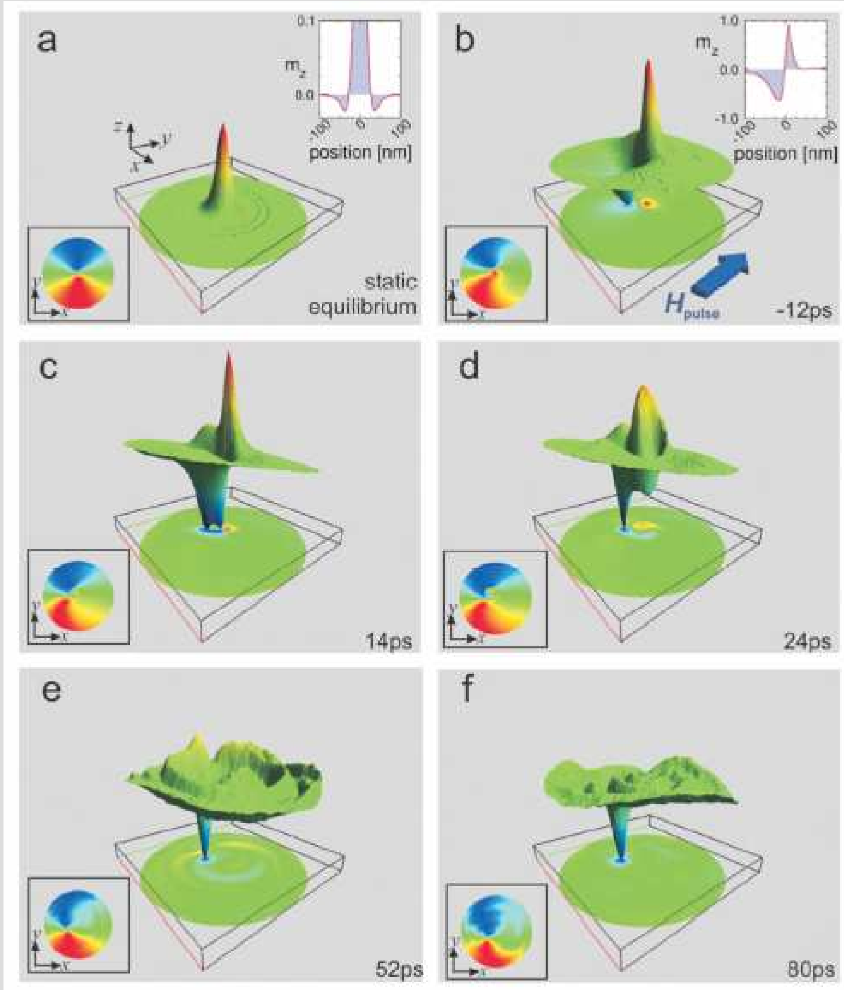
Magnetic vortex core reversal by excitation with short bursts of an alternating field

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



Resonant phenomenon

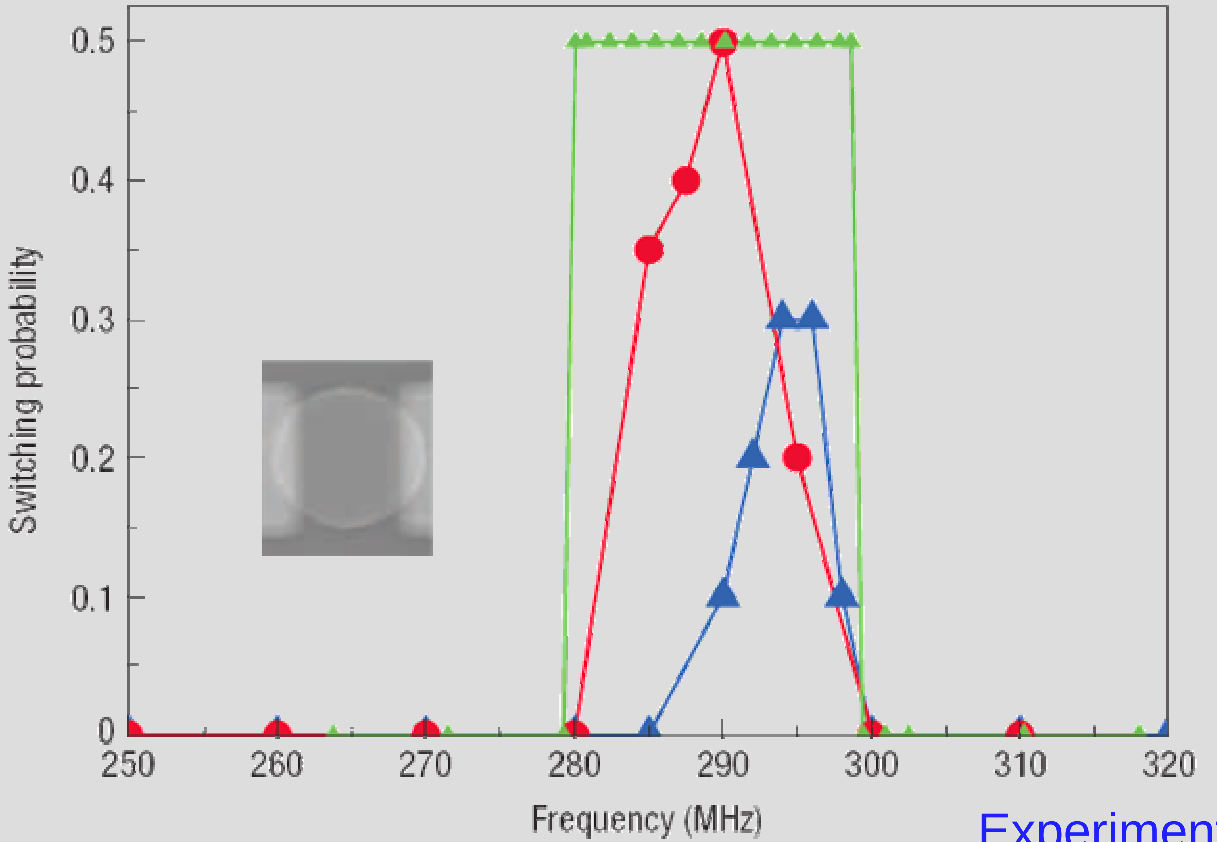
R. Hertel et al., Phys. Rev. Lett. 98, 117201 (2007)



Non-resonant phenomenon

Electrical switching of the vortex core in a magnetic disk

K. Yamada et al., Nat. Mater. 6 (2007)



Experiment $2.4x10^{11}A/m^2$

Experiment $3.5x10^{11}A/m^2$

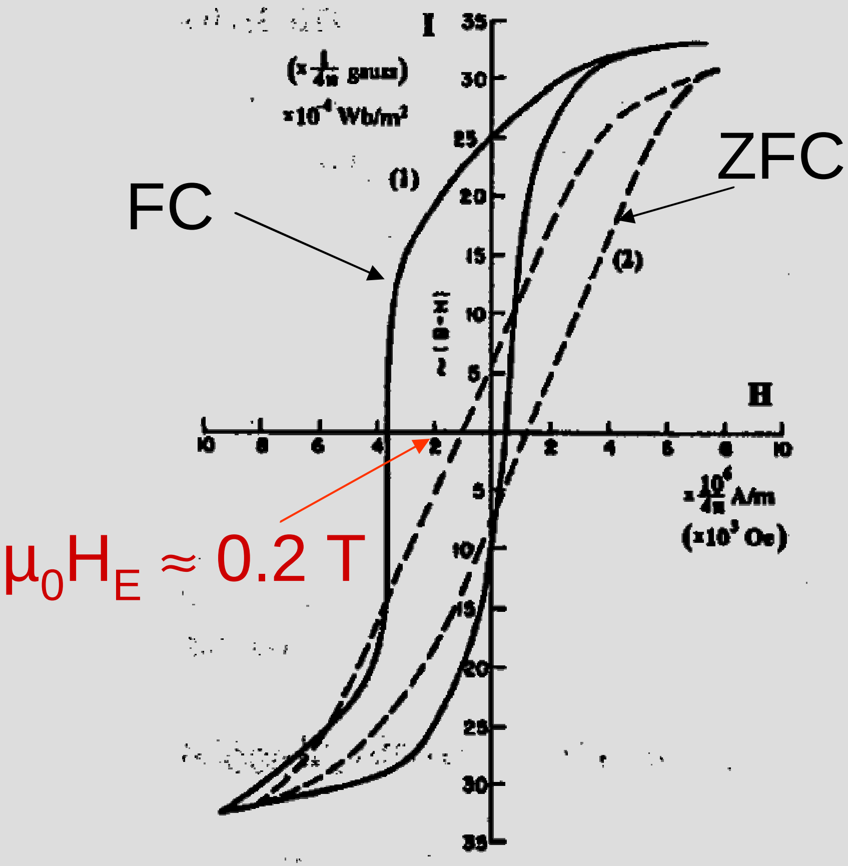
Simulation $3.88x10^{11}A/m^2$

(resonant phenomenon)

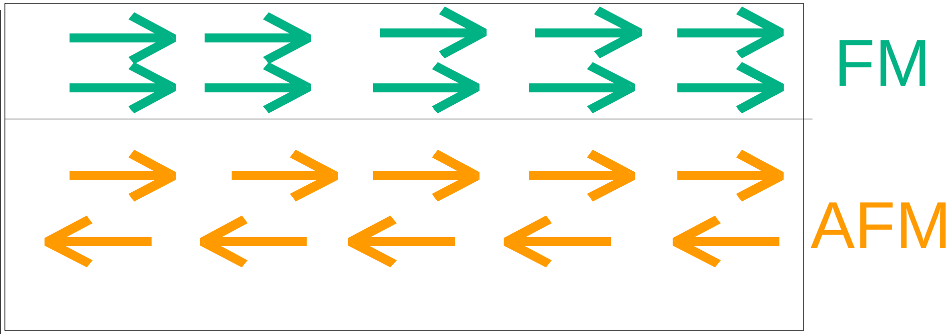
II.4. Interfacial effects on magnetization reversal

Seminal studies

Oxidized Co nanoparticles



Meiklejohn and Bean,
Phys. Rev. 102, 1413 (1956),
Phys. Rev. 105, 904, (1957)



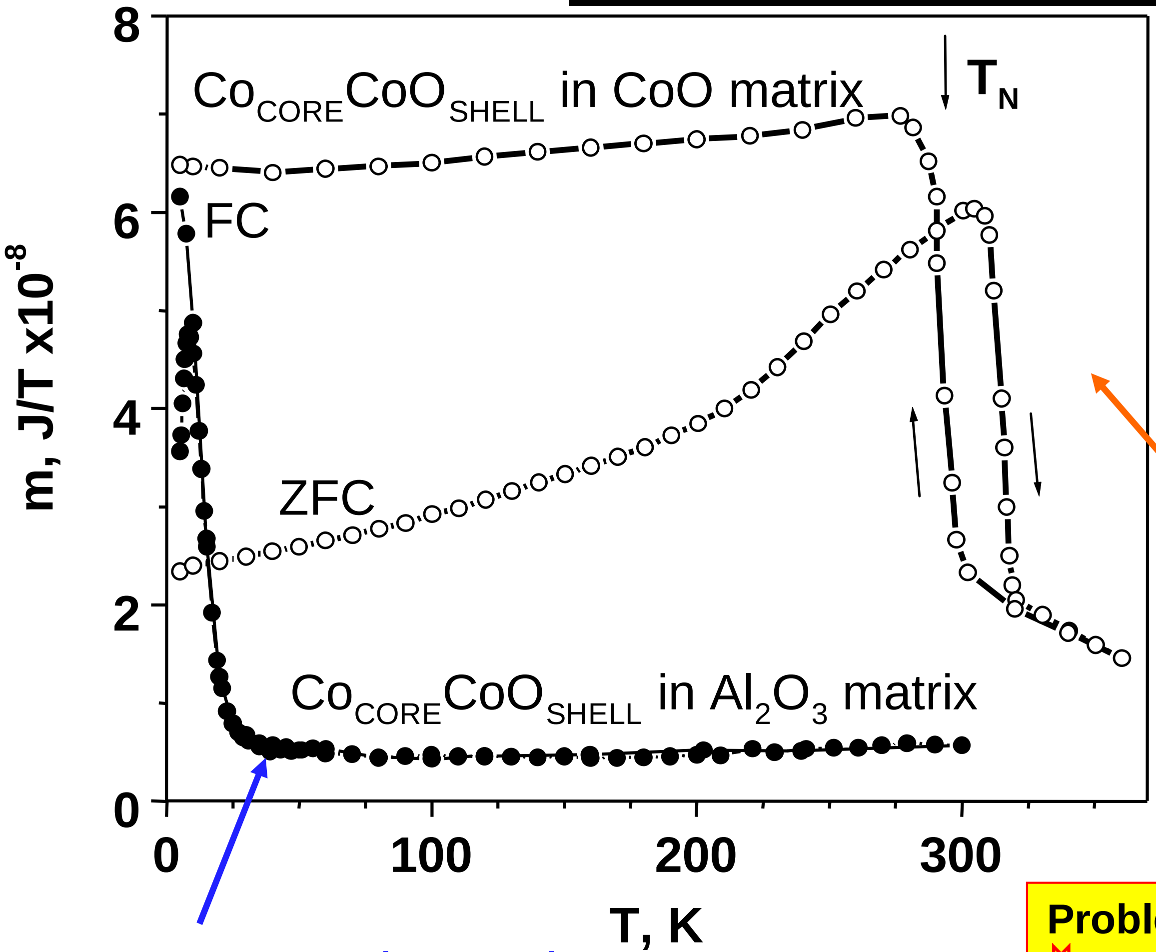
Field-cooled hysteresis loops:

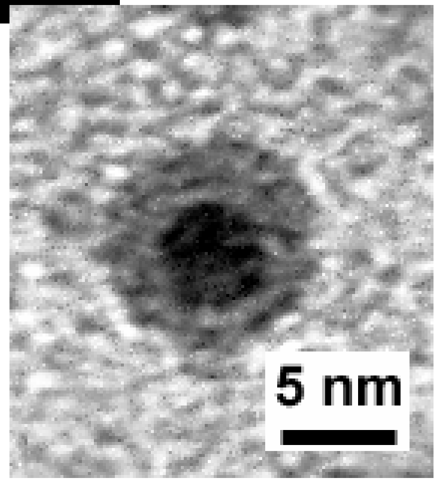
- **Increased coercivity**
- **Shifted in field**

Exchange bias
J. Nogués and Ivan K. Schuller
J. Magn. Magn. Mater. 192 (1999) 203

Exchange anisotropy—a review
A E Berkowitz and K Takano
J. Magn. Magn. Mater. 200 (1999)

Dependence of the blocking temperature on the nature of the matrix





AFM matrix

$T_B \approx T_N$ CoO

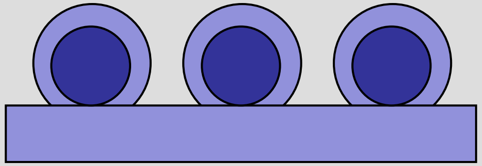
Non-magnetic matrix : $T_B \approx 30K$

V.Skumryev, et al., Nature 423, 850 (2003)

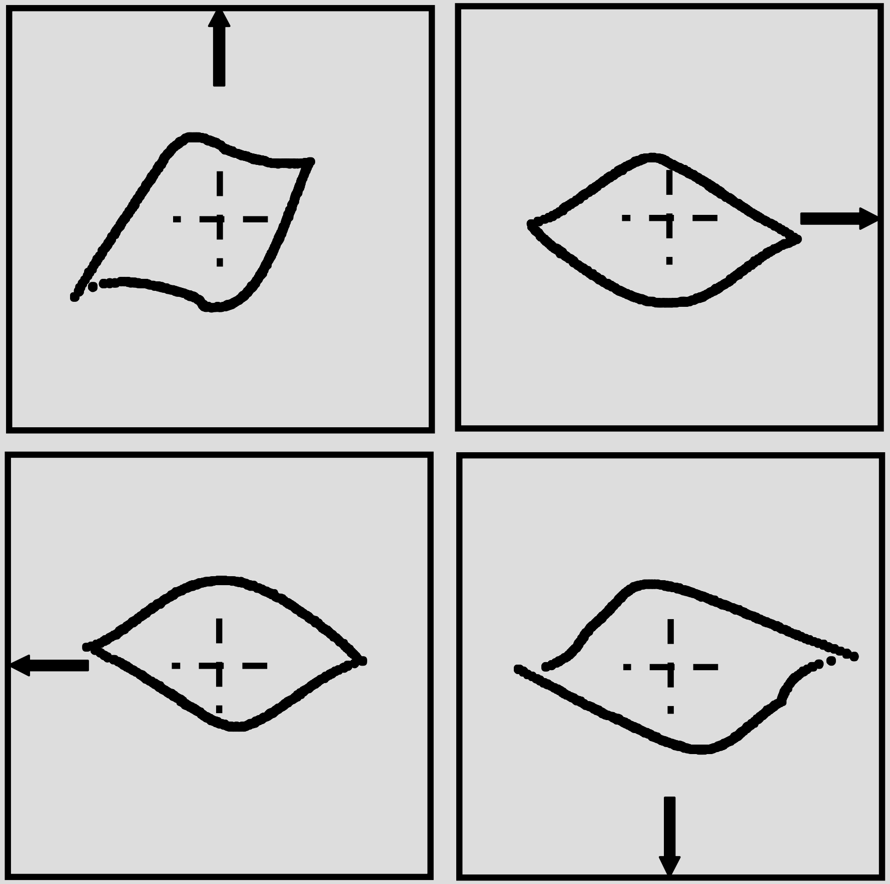
Problems remain:

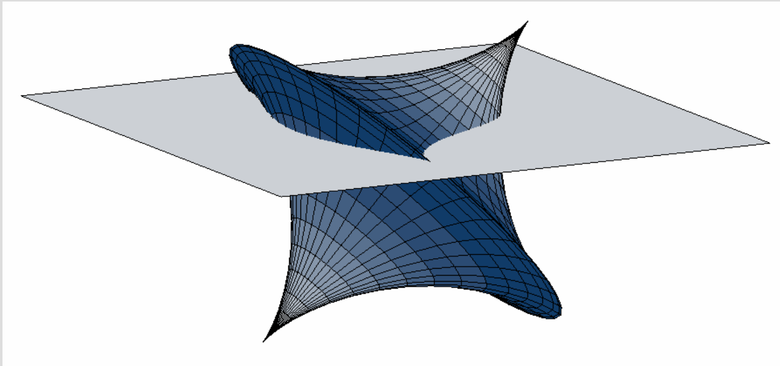
- **Not all features understood**
- **Very sensitive on fabrication**

Astroids of single particles with Ferro/Antiferro exchange



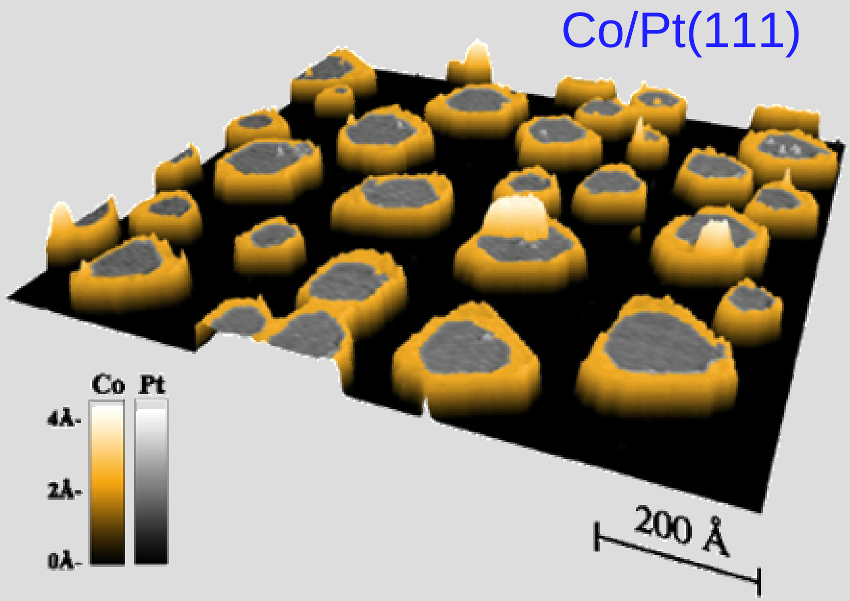
Core-shell CoO cluster on CoO





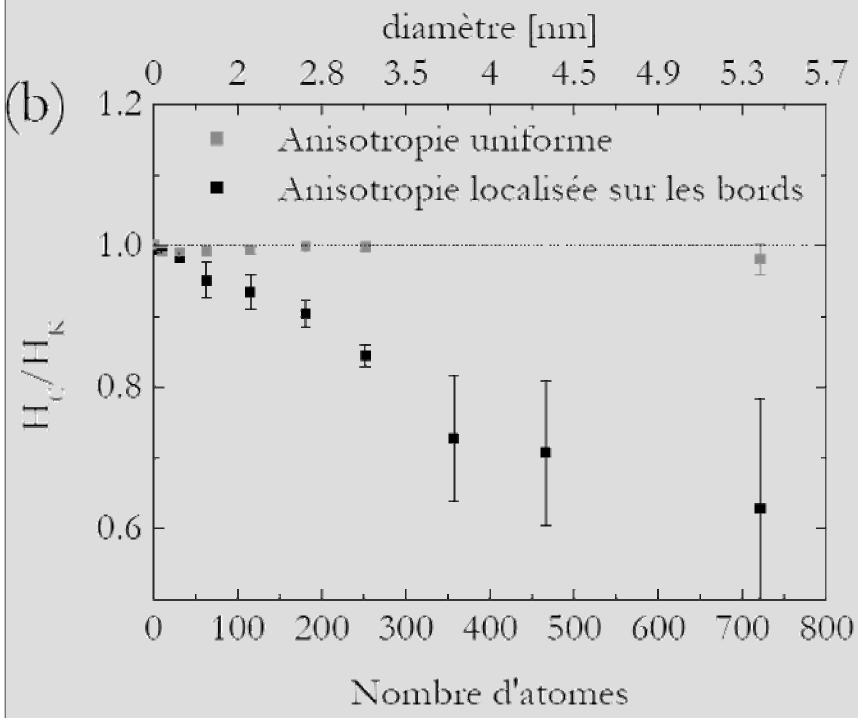
A. Brenac et al., CEA-Grenoble,
W. Wernsdorfer, Institut Néel
unpublished

Experiments



S. Rusponi et al., Nature Mater. (2003):
« The remarkable difference between surface and step atoms in the magnetic anisotropy of two-dimensional nanostructures”

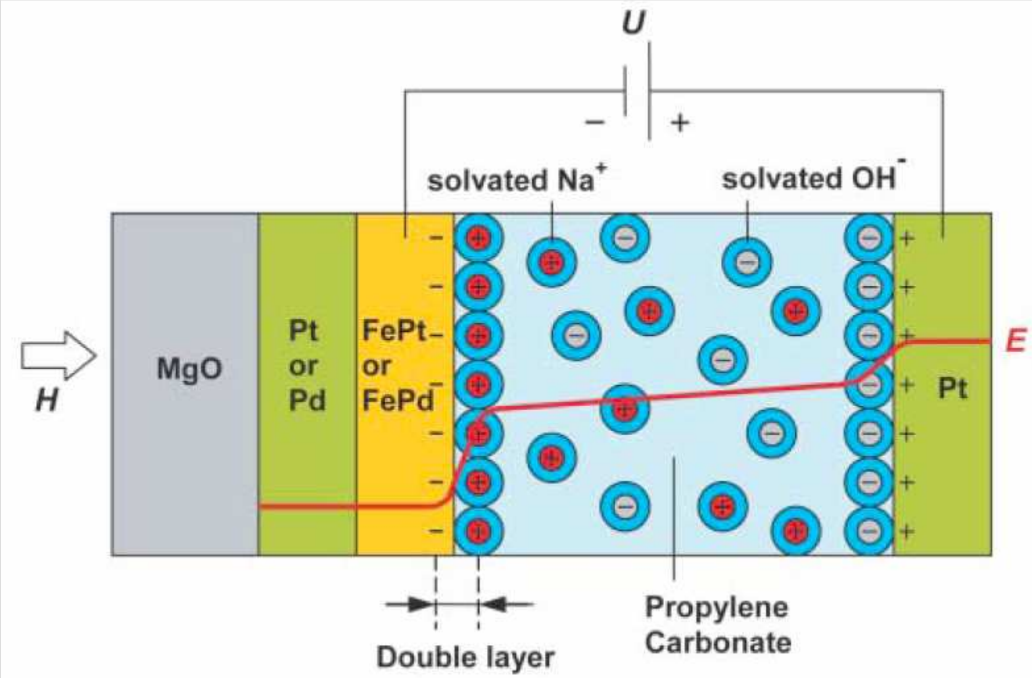
Simulation/Theory

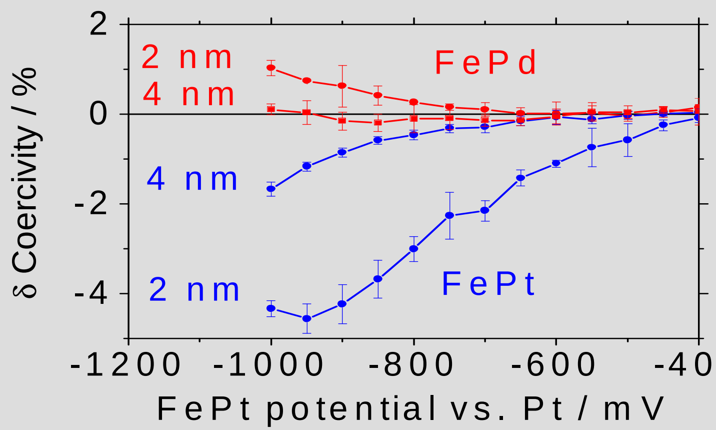


S. Rohart, PhD Thesis (2005)

S. Rohart, A. Thiaville, unpublished

Electric modification of intrinsic properties





M. Weisheit et al., Science 315, 349 (2007)

See also: magnetic semiconductors, multiferroics etc.

SOME READING

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

[2] O. Fruchart, *Couches minces et nanostructures magnétiques*, Techniques de l'Ingénieur, REF.

[3] Lecture notes from undergraduate lectures, plus various slides: http://lab-neel.grenoble.cnrs.fr/themes/couches/ext/slides/

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

[6] Magnetic domains, A. Hubert, R. Schäfer, Springer (1999, reed. 2001)

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

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