Nanomagnetism
Part 1 - Macrospins

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Email to esm@magnetism.eu on Aug.19 2009 18:55

hi, i was investigating about magnetism in the human body and i used a speaker with a plug conected to it and then i started touching my body with the plug to hear how it sounds, i realized that when i put the plug in my nipples it made a louder sound wich means that the magnetics were bigger in that area, i have asked about this but i get no answer why, there is no coverage about this subject on the internet either, please if you know about this let me know, my theory is that our nipples are our bridge of expulsing magnetics and electric signal to control the energy outside our bodies, hope this helps with some research, thank you...

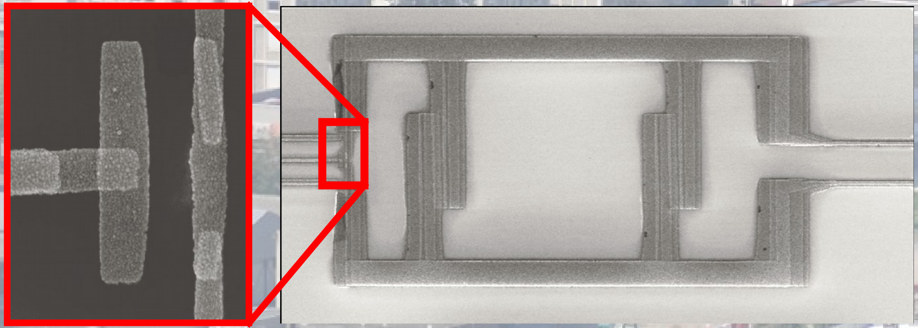
Science and technology area in Grenoble

Facts

- ⇨ Core of Condensed Matter Physics
- ⇨ 180 full-staff scientists, 130 technical staff
- ⇨ 40 PhD / year

Internal structure

- ⇨ Research teams + technological support groups
- ⇨ Three scientific departments
  - Condensed Matter – Low Temperatures
  - Condensed Matter – Functional Materials
  - Nanosciences



Credits: O. Fruchart

New-York

Credits: V. Chaumont

London

Las Vegas

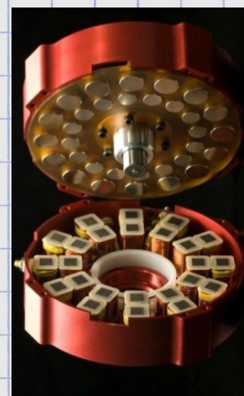
Credits: C. Haranczyk

Modern applications of (Nano)magnetism

Where does 'nano' contribute ?

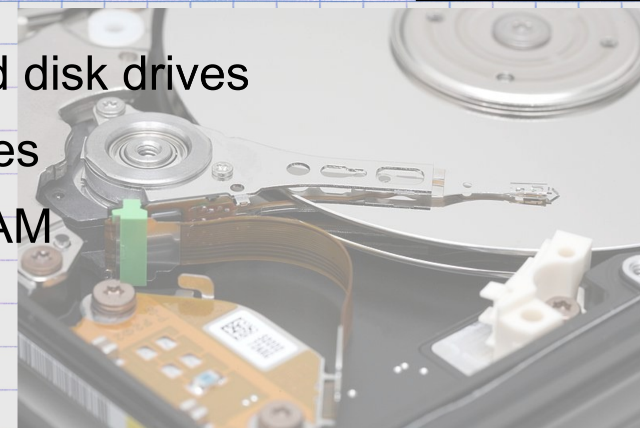
Materials

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



Data storage

- Hard disk drives
- Tapes
- MRAM

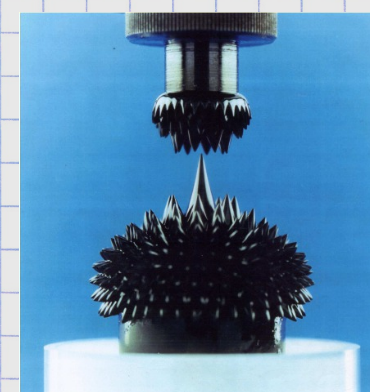


Sensors

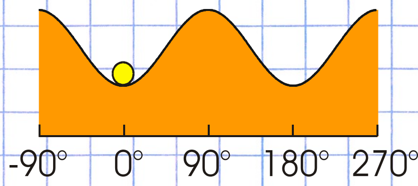
- Compass
- Field mapping
- HDD read heads

Nanoparticles

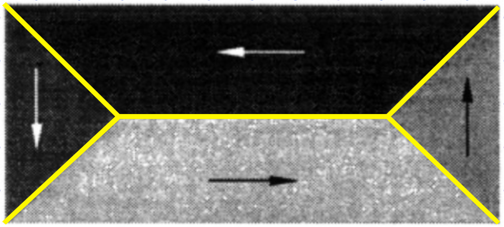
- Ferrofluids
- MRI contrast
- Hyperthermia
- Sorting & tagging



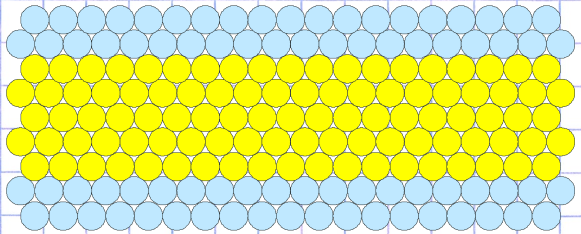
Part 1 : basics of micromagnetism – Simple models of magnetization reversal



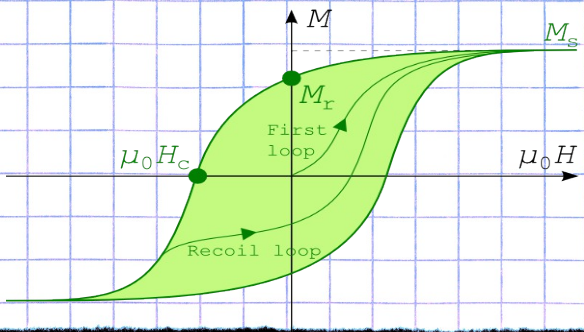
Part 2 : non-uniform magnetization in nanostructure: domains, domain walls



Part 3 : Low-dimensions, interfaces and heterostructures



Part 4 : Learn from hysteresis loops



Definitions

	SI system		cgs-Gauss	
	Meter	m	Centimeter	cm
	Kilogram	kg	Gram	g
	Second	s	Second	s
	Ampere	A	Ab-Ampere	ab-A = 10A
	$\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{M})$		$\mathbf{B}=\mathbf{H}+4\pi\mathbf{M}$	
	$\mu_0=4\pi\times10^{-7}$ SI		$\mu_0=4\pi$	

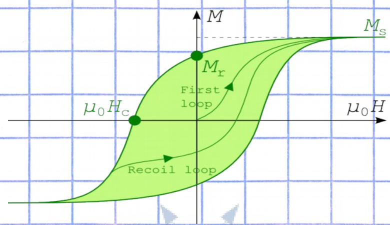
Conversions

Field	$\mathbf{H}$	1 A/m	↔	$4\pi\times10^{-3}$ Oe (Oersted)
Moment	$\boldsymbol{\mu}$	1 $A.m^2$	↔	10^3 emu
Magnetization	$\mathbf{M}$	1 A/m	↔	10^{-3} emu/cm^3
Induction	$\mathbf{B}$	1 T	↔	10^4 G (Gauss)
Susceptibility	$\chi=M/H$	1	↔	$1/4\pi$

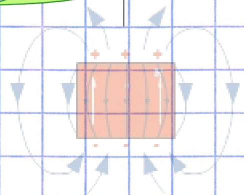
Pratical on units : http://magnetism.eu/esm/2013/abs/fruchart-tutorial.pdf

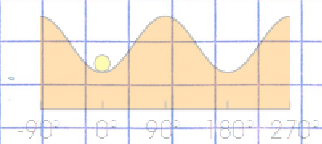
Notations

Microscopic quantity	E	Global quantity	$\mathcal{E}=\iiint E.\mathrm{d}V$
Dimensionless quantity	$e=E/E_0$	Vector quantity	$\mathbf{B}$

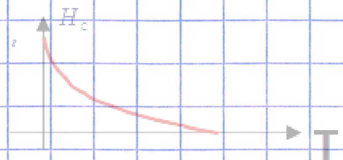


M
M_s
M_r
First loop
$\mu_0 H_c$
$\mu_0 H$
Recoil loop

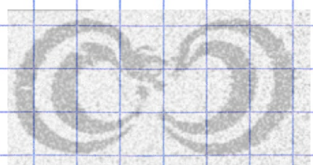


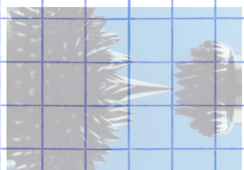


-90°
0°
90°
180°
270°



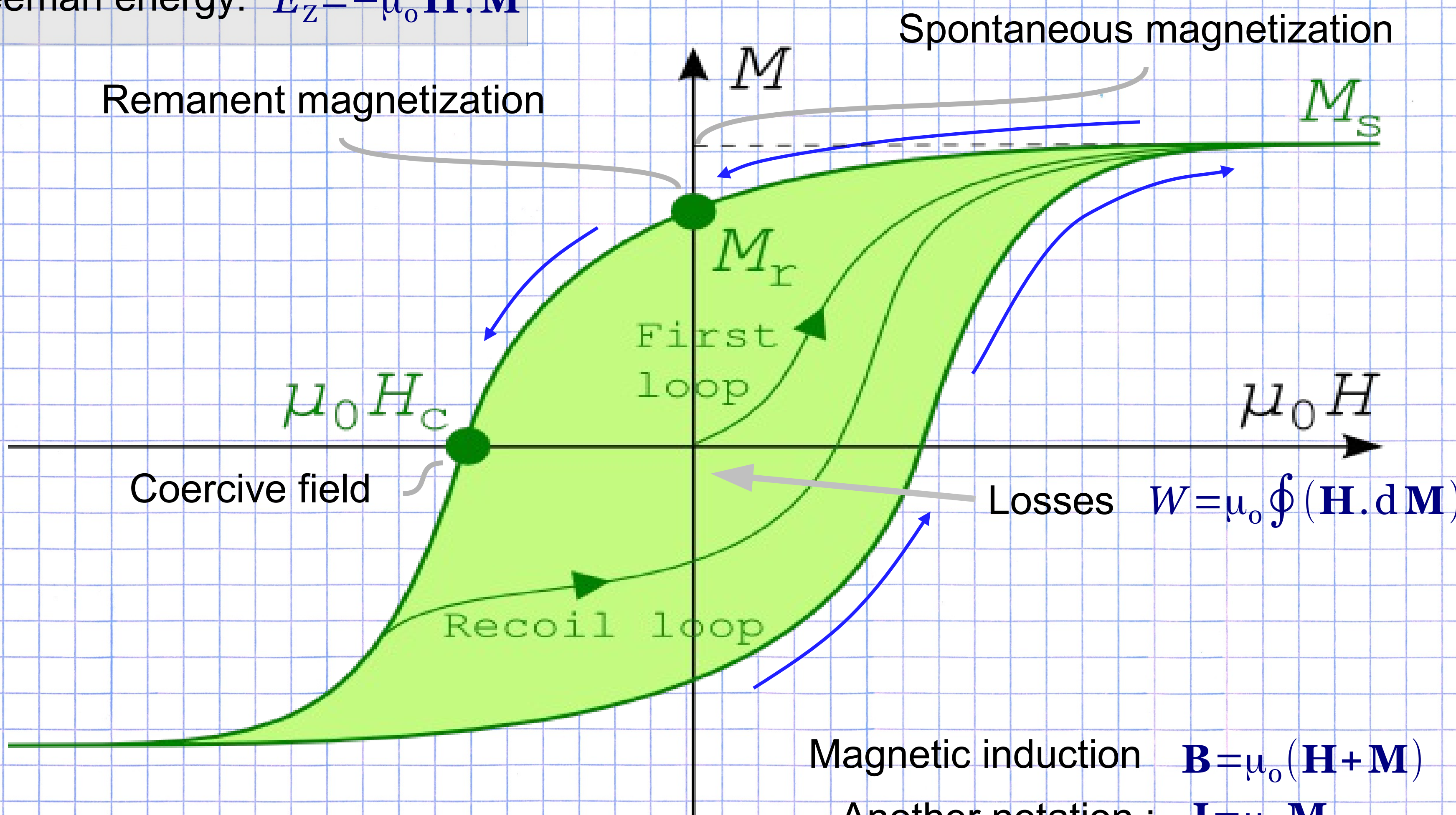
H_c
T





Manipulation of magnetic materials:
→ Application of a magnetic field

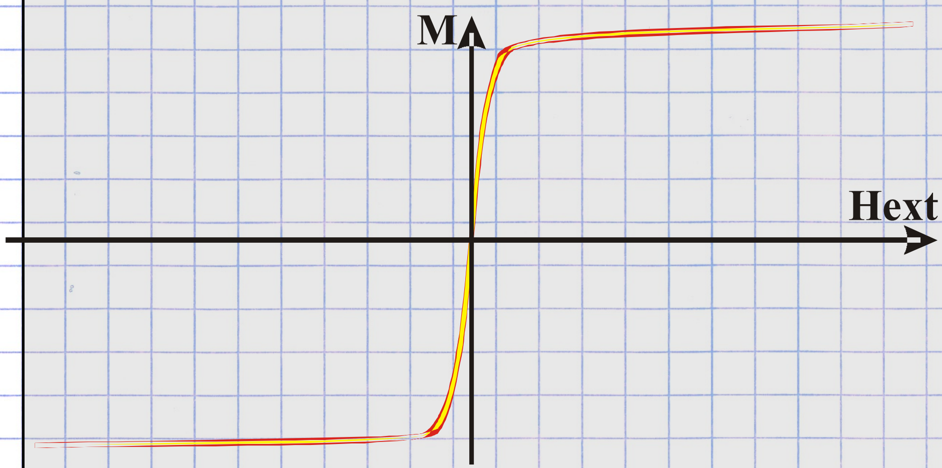
Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}$



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

Another notation : $\mathbf{J} = \mu_0 \mathbf{M}$

Soft magnetic materials

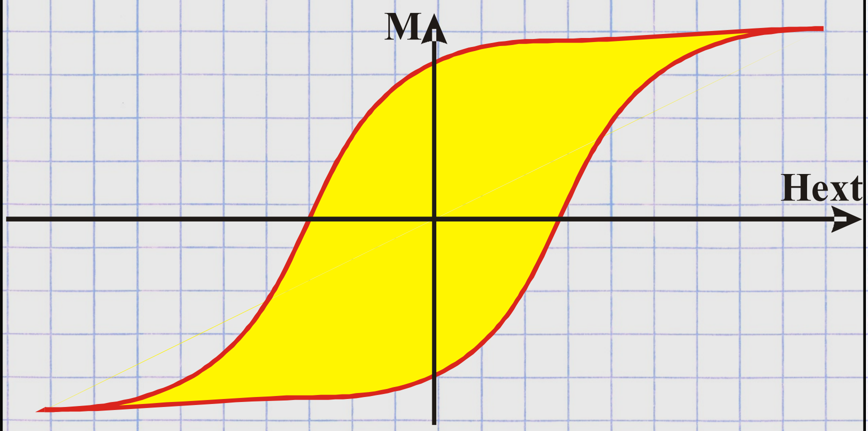


Transformers

Flux guides, sensors

Magnetic shielding

Hard magnetic materials

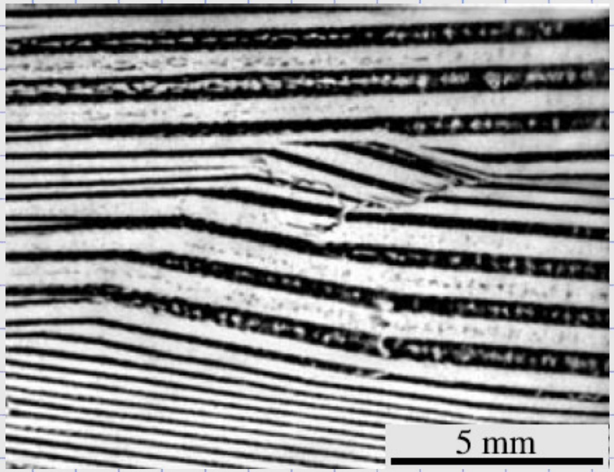


Permanent magnets, motors

Magnetic recording

Bulk material

Numerous and complex magnetic domains

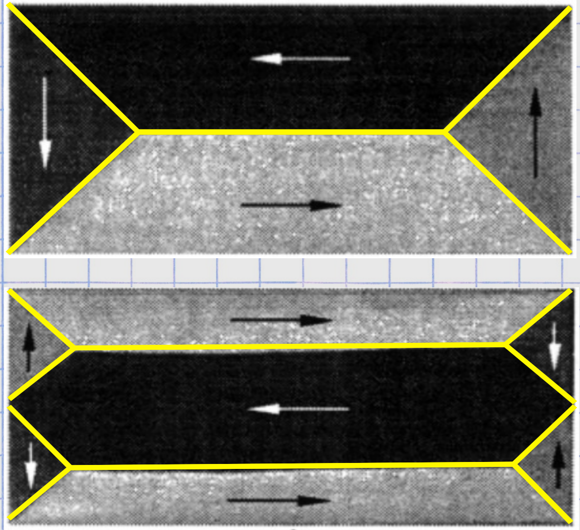


FeSi soft sheet

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

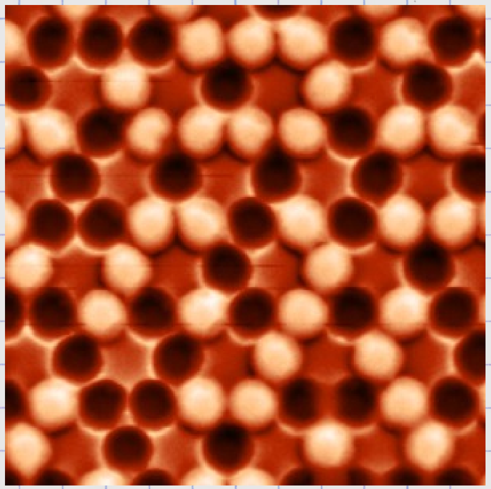


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain



Nanofabricated dots
MFM

Sample courtesy :
N. Rougemaille, I. Chioar

Nanomagnetism ~ mesoscopic magnetism

Magnetization

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

May vary over time and space

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

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

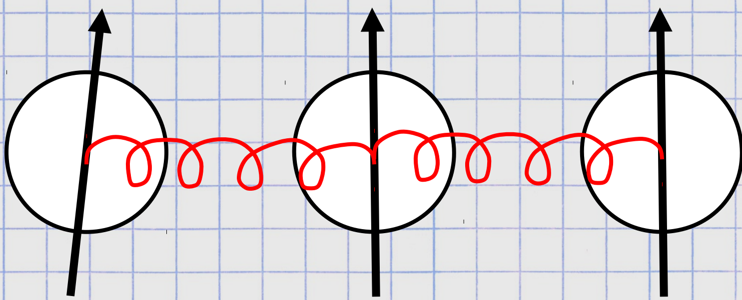
Exchange interaction

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

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

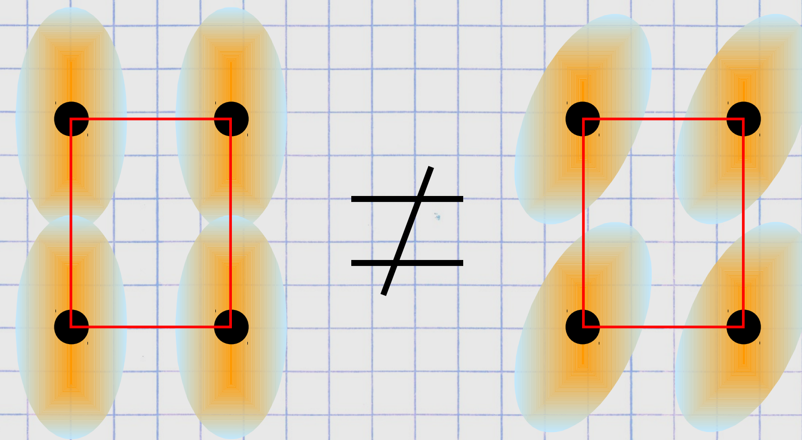
$E=A(\nabla.\mathbf{m})^2$ (energy per unit volume)

Exchange energy



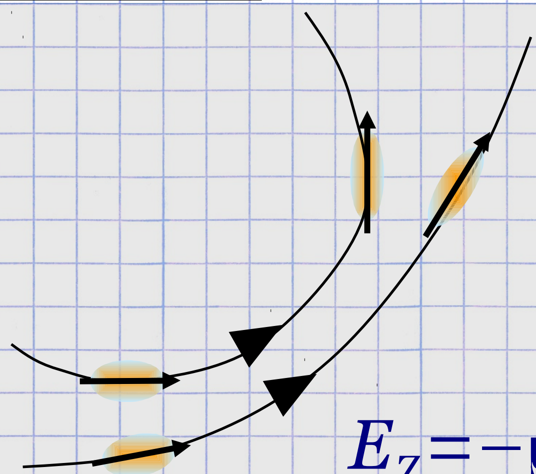
$$E_{ex} = A(\nabla.\mathbf{m})^2 = A\sum_{i,j}\frac{\partial m_i}{\partial x_j}$$

Magnetocrystalline anisotropy energy



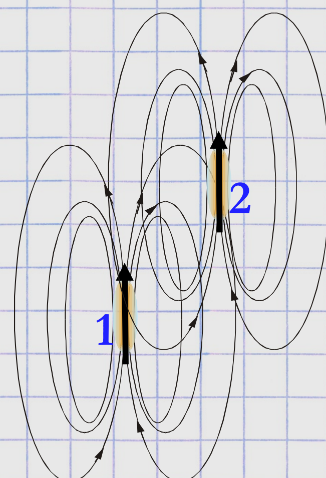
$$E_{mc} = A\,f(\theta,\varphi)$$

Zeeman energy

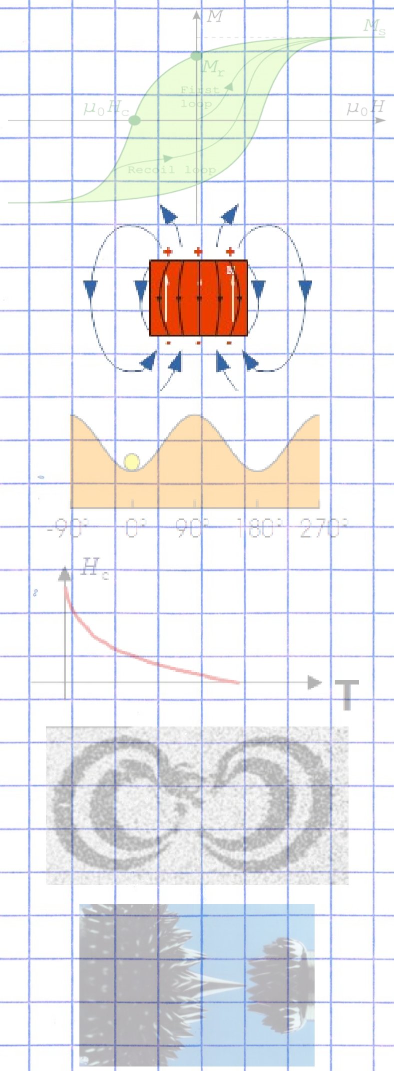


$$E_Z = -\mu_0\,\mathbf{M.H}$$

Dipolar energy



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



Analogy with electrostatics (synonym : magnetostatic energy)

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 singulaity that may arise at boundaries, a volume integration around the boundaries yields:

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

Usefull expressions

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

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

- ⇨ Dipolar energy is always positive
- ⇨ Zero energy means a minimum

Magnetic charges

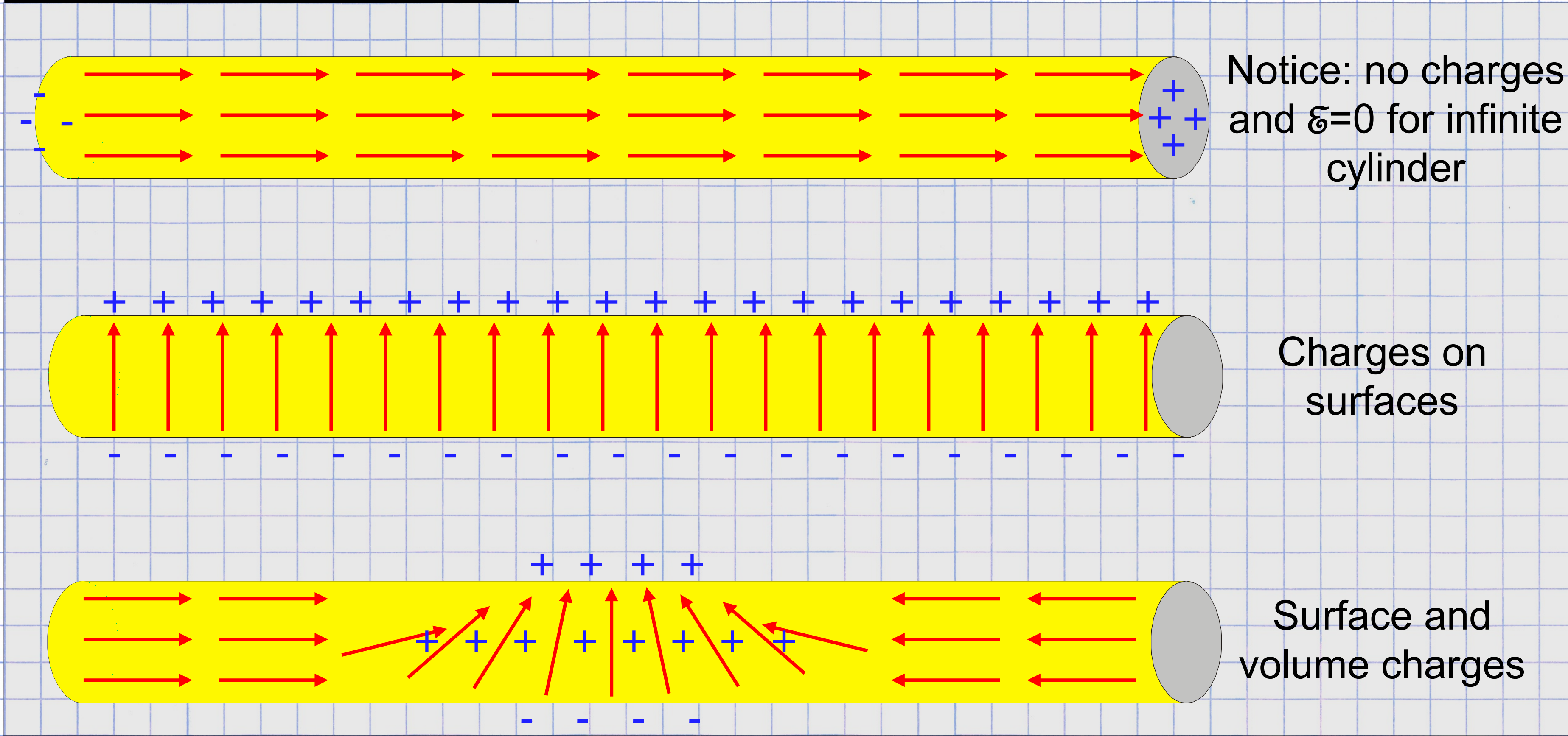
$\rho(\mathbf{r}) = -M_\mathrm{s}\,\mathrm{div}[\mathbf{m}(\mathbf{r})]$ → volume density of magnetic charges

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

Notice

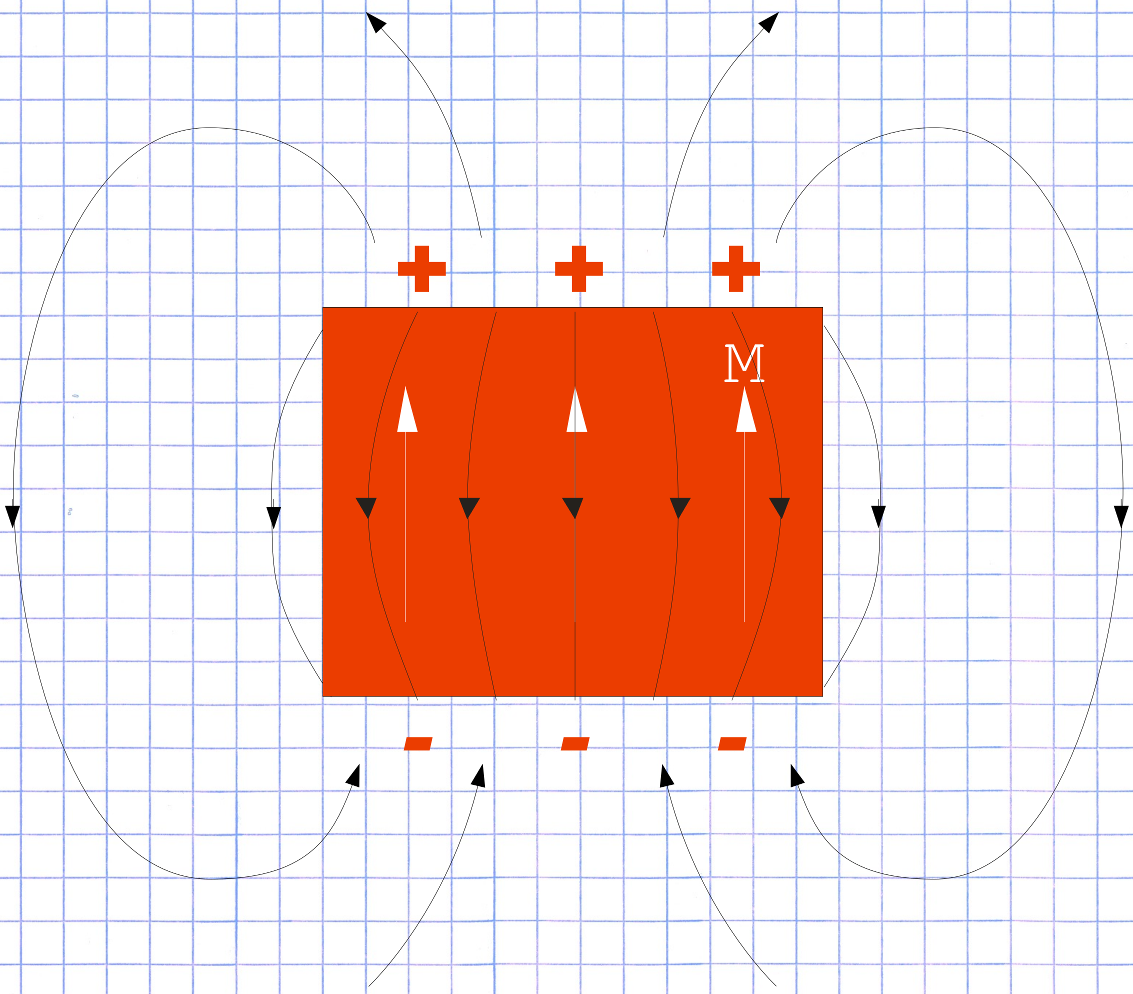
- Hd depends on sample shape, not size
- Synonym : dipolar ↔ magnetostatic

Examples of magnetic charges



Take-away message

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



Names

- Generic names
  - Magnetostatic field
  - Dipolar field
- Within sample
  - Demagnetizing field
- Outside sample
  - Stray field

Principle

Goal : evaluate strength of demagnetizing field and energy

Assume uniform magnetization $\mathbf{M}(\mathbf{r})=\mathbf{M}=M_\mathrm{s}(m_x\mathbf{u}_x+m_y\mathbf{u}_y+m_z\mathbf{u}_z)=M_\mathrm{s}m_i\mathbf{u}_i$

Demagnetizing coefficients

(Easy to prove, however not done here)

$\langle\mathbf{H}_\mathrm{d}(\mathbf{r})\rangle=-M_\mathrm{s}\bar{\bar{\mathbf{N}}}.\mathbf{m}=-N_iM_\mathrm{s}m_i$

$\mathcal{E}_\mathrm{d}=K_\mathrm{d}V\,\mathbf{m}.\bar{\bar{\mathbf{N}}}.\mathbf{m}=K_\mathrm{d}VN_{ij}m_im_j$

$K_\mathrm{d}=\frac{1}{2}\mu_0M_\mathrm{s}^2$ Dipolar constant (J/m³)

$\bar{\bar{\mathbf{N}}}$ Demagnetizing tensor

Notice: Valid for any shape

$N_x+N_y+N_z=1$

cgs: $\langle\mathbf{H}_\mathrm{d}\rangle=-4\pi\bar{\bar{\mathbf{N}}}.\mathbf{M}$, $\bar{\bar{\mathbf{D}}}=4\pi\bar{\bar{\mathbf{N}}}$

Model cases : slabs, cylinders and ellipsoids

(Not easy to prove, mathematics...)

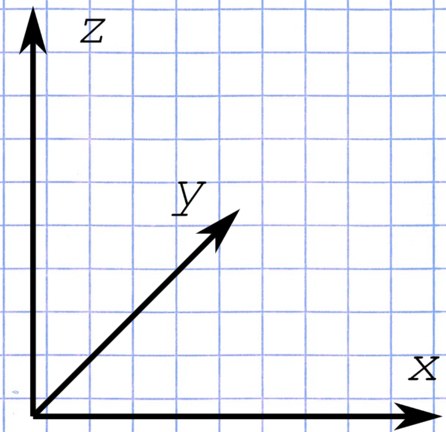
Hd is uniform for surfaces of polynomial boundary with order <=2 $\mathbf{H}_\mathrm{d}=-M_\mathrm{s}\bar{\bar{\mathbf{N}}}.\mathbf{m}$

Along all three main directions : $H_i=-N_iM_\mathrm{s}m_i$ and $\mathcal{E}_\mathrm{d}=K_\mathrm{d}VN_im_i^2$

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

Dipolar energy contributes to magnetic anisotropy with second-order term

Example : $\mathcal{E}_\mathrm{d}=VK_\mathrm{d}(N_xm_x^2+N_ym_y^2)=VK_\mathrm{d}(N_x-N_y)\cos^2\theta$



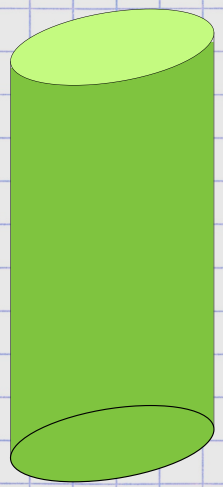
Slabs (infinite thin films)

$L_x = L_y = \infty$

$N_x = N_y = 0$

$N_z = 1$

Cylinders (infinite)



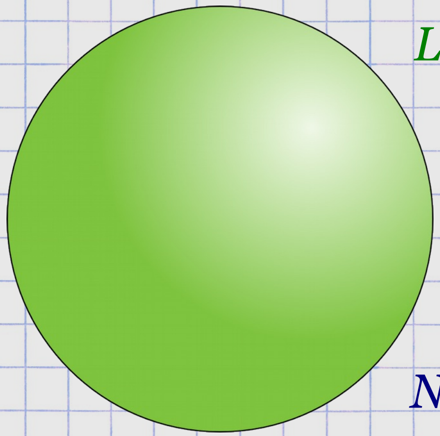
$L_x = L_y = D$

$L_z = \infty$

$N_x = N_y = \frac{1}{2}$

$N_z = 0$

Spheres



$L_x = L_y = L_z = D$

$N_x = N_y = N_z = \frac{1}{3}$

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,b,c)

$$N_x=\frac{\alpha^2}{1-\alpha^2}\left[\frac{1}{\sqrt{1-\alpha^2}}\operatorname{arsinh}\left(\frac{\sqrt{1-\alpha^2}}{\alpha}\right)-1\right]$$

For prolate revolution ellipsoid: (a,c,c) with $\alpha=c/a<1$

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

For oblate revolution ellipsoid: (a,c,c) with $\alpha=c/a>1$

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

Cylinders

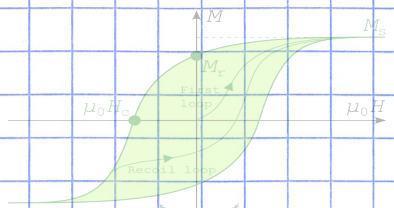
$$N_x=0 \qquad N_y=\frac{c}{b+c} \qquad N_z=\frac{b}{b+c}$$

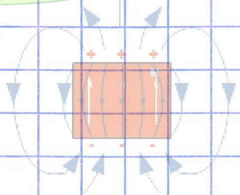
For a cylinder with axis along *x*

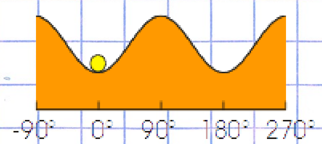
J. A. Osborn, Phys. Rev. 67, 351 (1945).

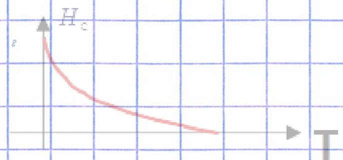
For prisms, see: **A. Aharoni, J. Appl. Phys. 83, 3432 (1998)**

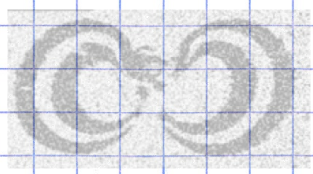
More general forms, FFT approach: **M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)**

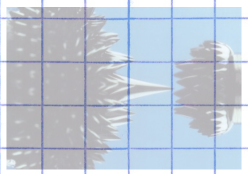

M
M_s
M_r
$\mu_0 H_c$
$\mu_0 H$




-90°
0°
90°
180°
270°


H_c
T



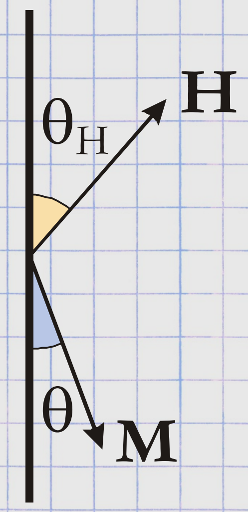


Framework

Approximation: $\partial_{\mathbf{r}} \mathbf{m} = \mathbf{0}$ (uniform magnetization)
(strong!)

$$\mathcal{E} = EV = V\left[K_{\text{eff}} \sin^2\theta - \mu_0 M_S H \cos(\theta - \theta_H)\right]$$

$$K_{\text{eff}} = K_{\text{mc}} + (\Delta N) K_d$$



Dimensionless units:

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

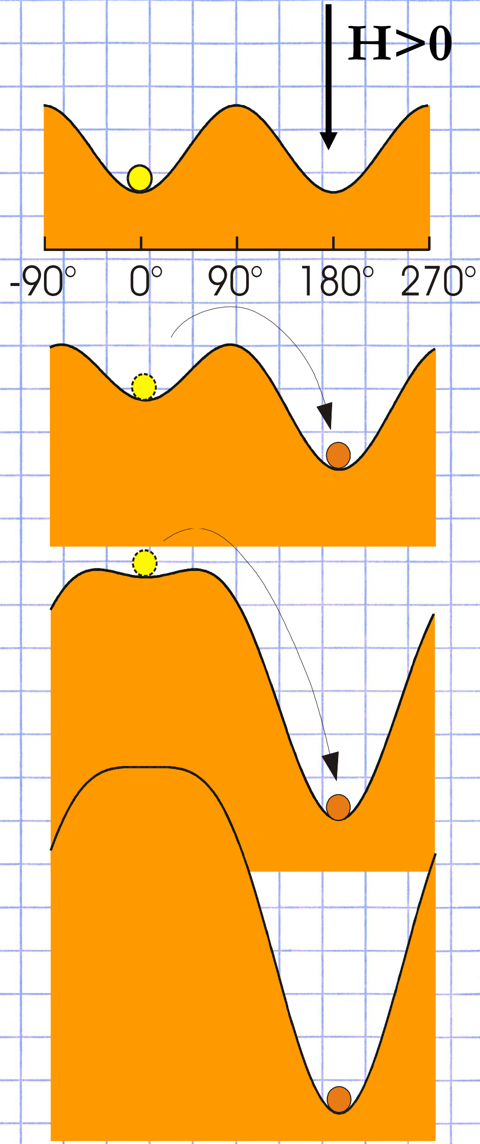
$$e = \mathcal{E}/KV$$
$$h = H/H_a$$
$$H_a = 2K/\mu_0 M_S$$

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.

Example for $\theta_H = 180°$ ► $e = \sin^2\theta + 2h\cos\theta$



Equilibrium states

$$\partial_\theta e = 2\sin\theta(\cos\theta - h) \qquad \partial_\theta e = 0 \Rightarrow \begin{cases} \cos\theta_m = h \\ \theta \equiv 0[\pi] \end{cases}$$

Stability

$$\partial_{\theta\theta} e = 2\cos 2\theta - 2h\cos\theta = 4\cos^2\theta - 2 - 2h\cos\theta$$

$$\partial_{\theta\theta} e(0) = 2(1-h)$$
$$\partial_{\theta\theta} e(\theta_m) = 2(h^2-1)$$
$$\partial_{\theta\theta} e(\pi) = 2(1+h)$$

Energy barrier

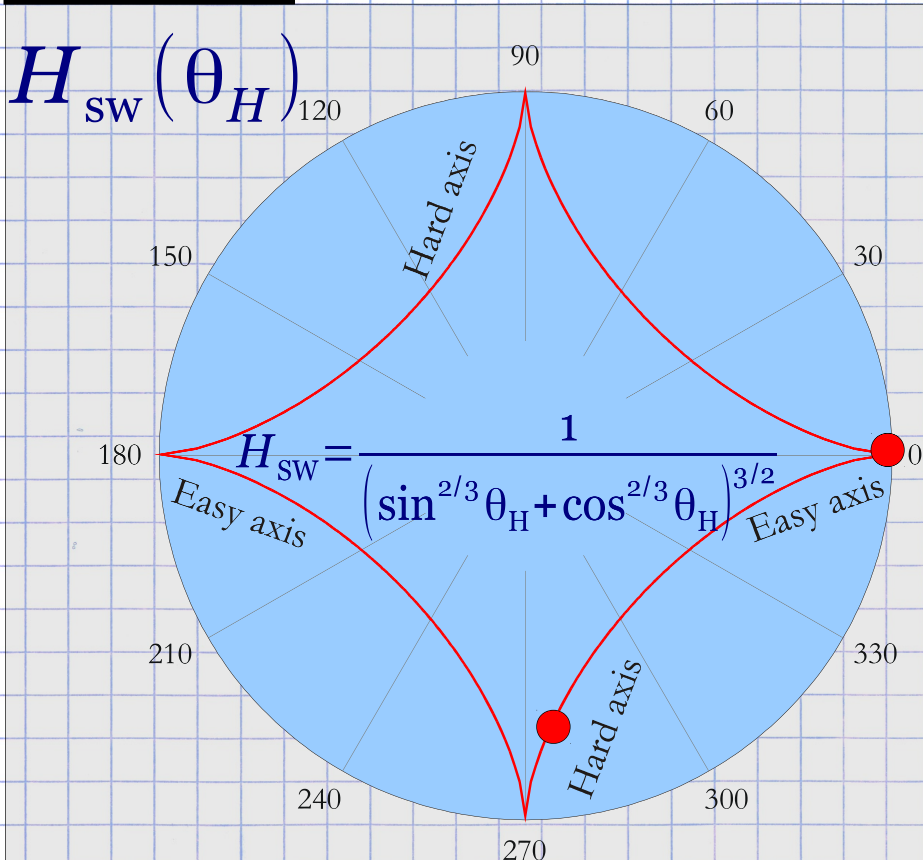
$$\Delta e = e(\theta_{max}) - e(0) = 1 - h^2 + 2h^2 - 2h = (1-h)^2$$

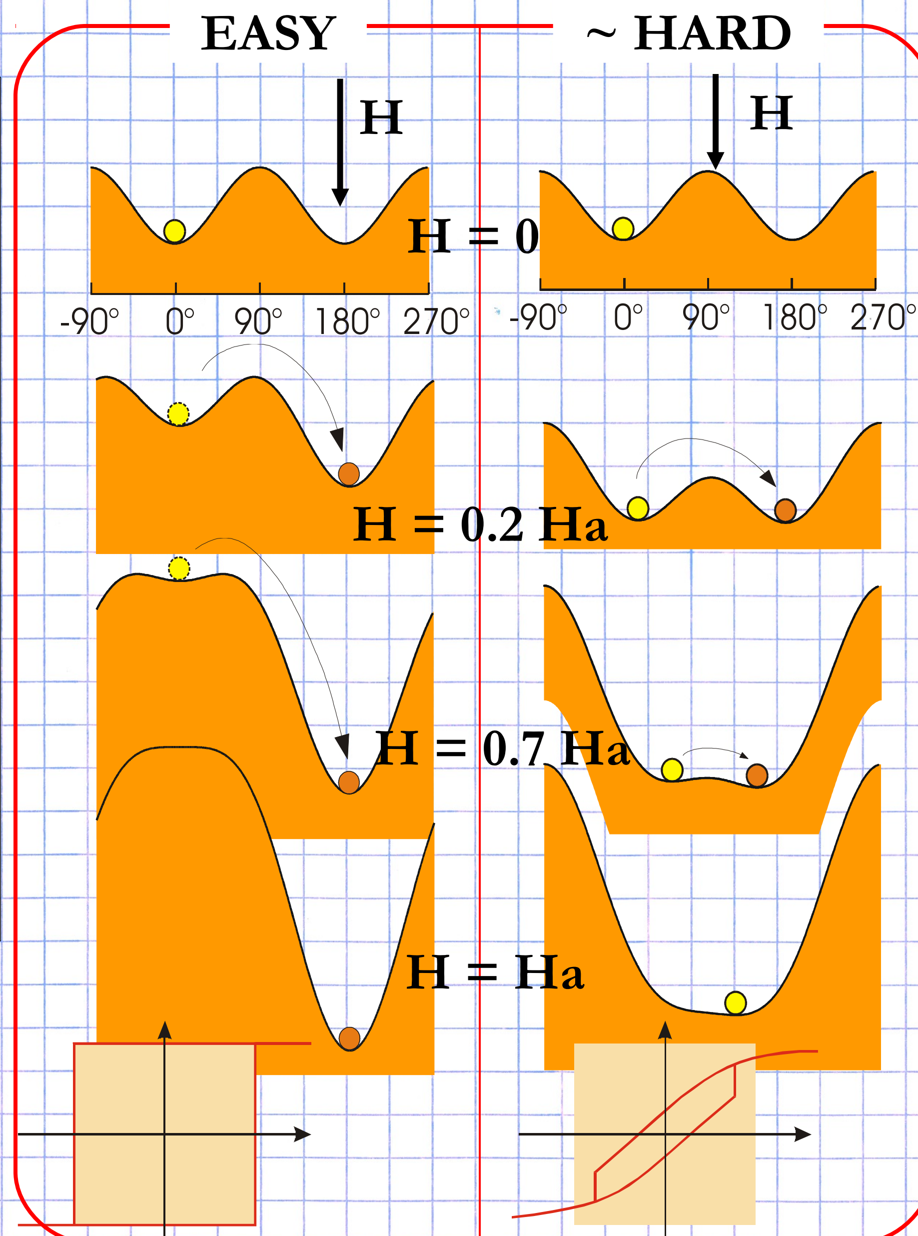
Switching

$$h = 1$$
$$H = H_a = 2K/\mu_0 M_s$$

$(1-h)^\alpha$ with exponent 1.5 in general

'Astroid' curve





- $H_{sw}(\theta)$ is only <u>one</u> signature of reversal modes

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.

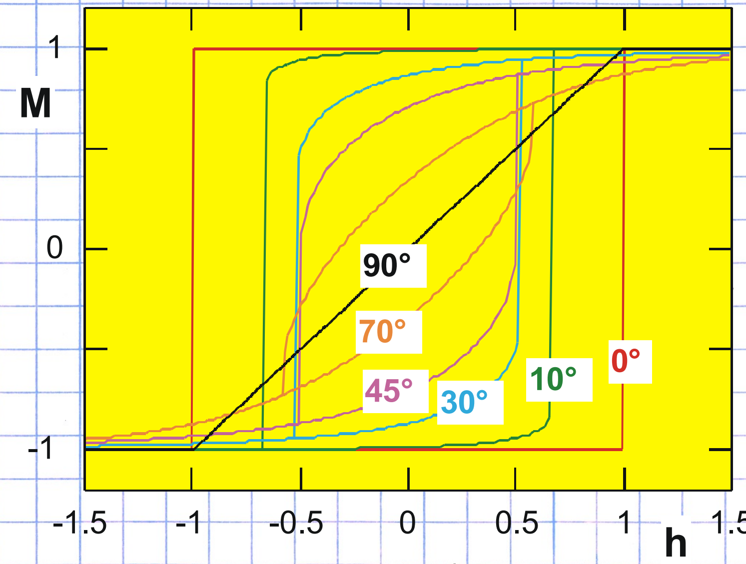
Can be measured only in single particles.

Coercive field

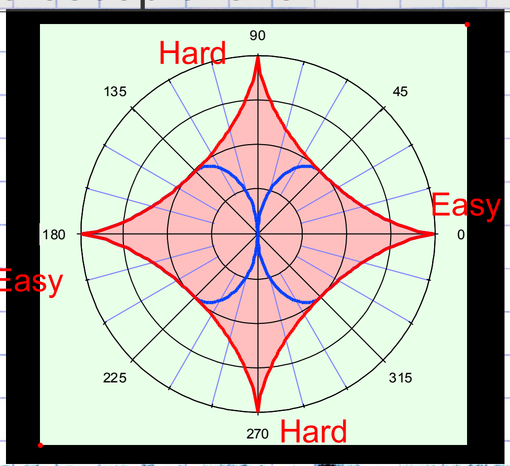
The value of field at which **M.H=0** $(\theta=\theta_H \pm \pi/2)$

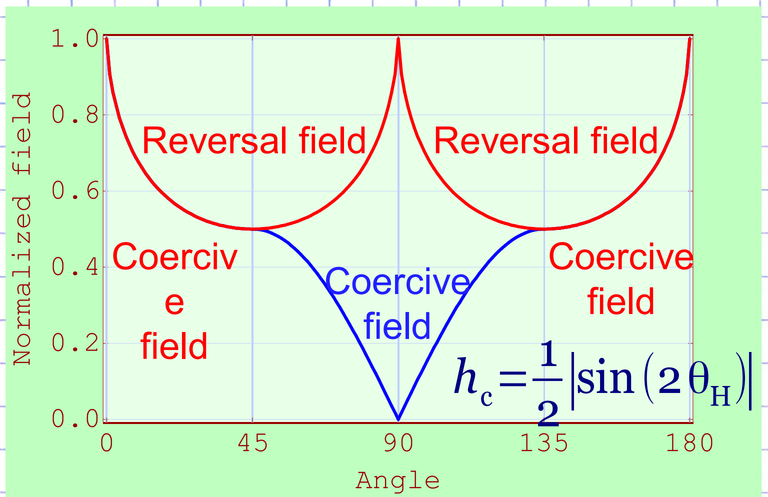
A quantity that can be measured in real materials (large number of 'particles').

May be or may not be a measure of the mean switching field at the microscopic level

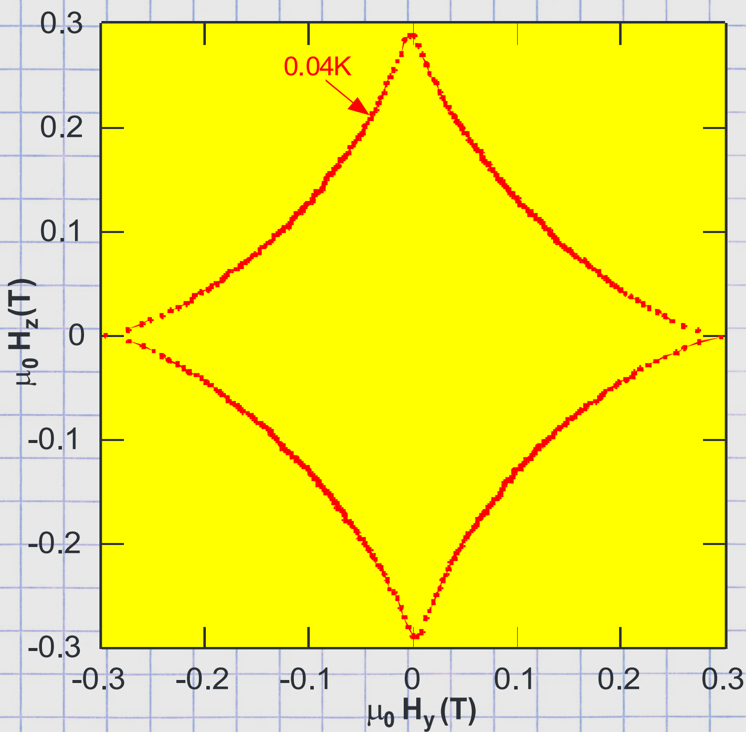


$$h_{Sw} = \frac{1}{\left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{3/2}}$$

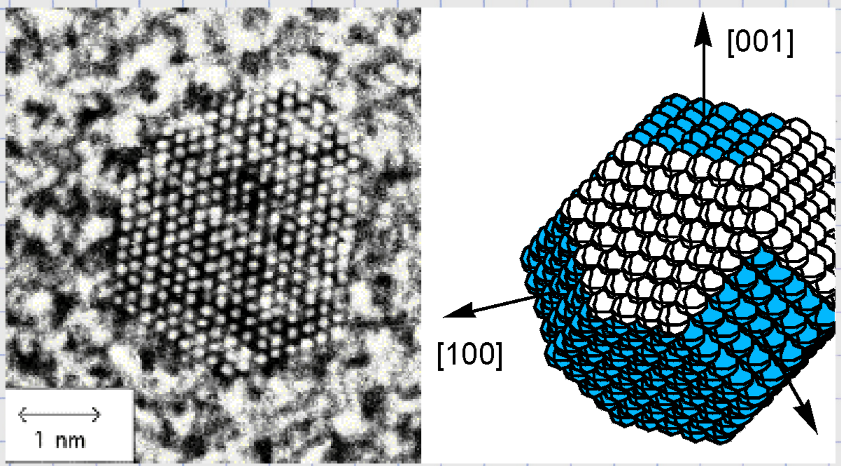




Experimental evidence



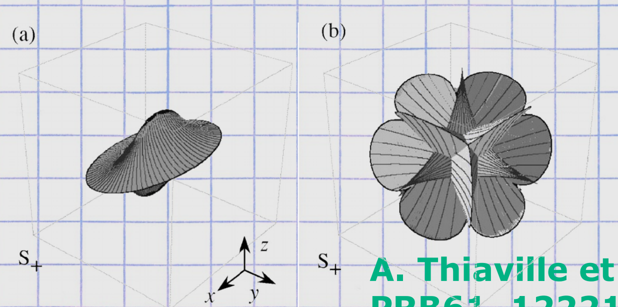
First evidence: W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)



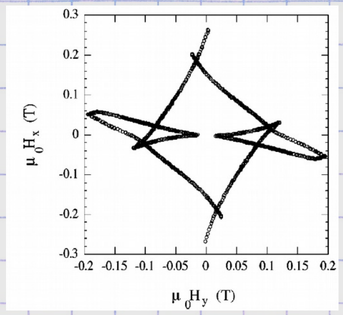
Co cluster

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

Extensions: 3D, arbitrary anisotropy etc.



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

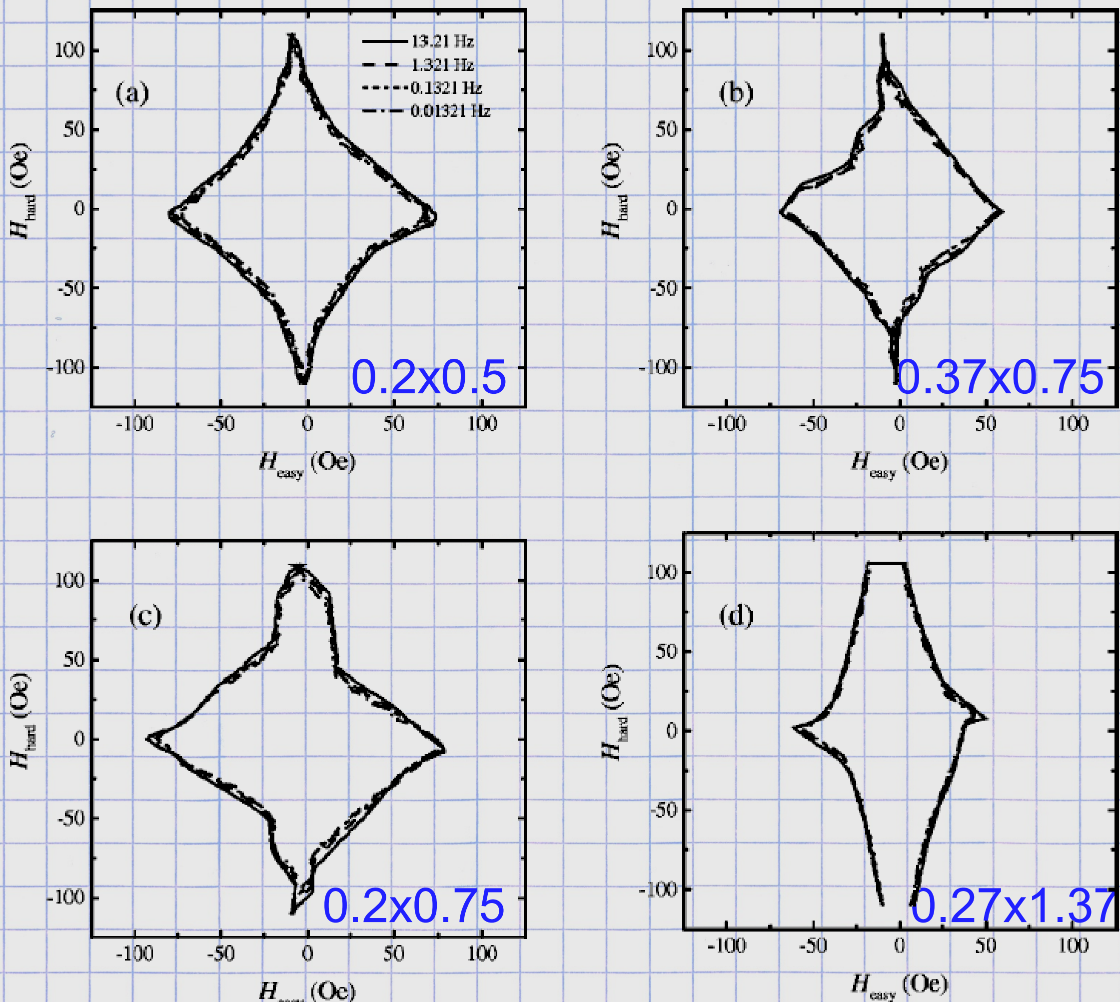


M. Jamet et al., PRB69, 024401 (2004)

Size-dependent magnetization reversal

Size in micrometers

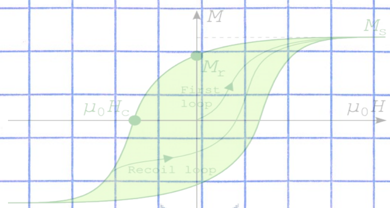
Astroids of flat magnetic elements with increasing size

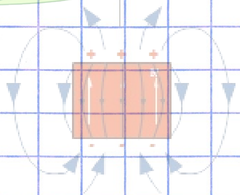


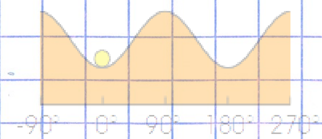
J. Z. Sun et al., Appl. Phys. Lett. 78 (25), 4004 (2001)

Conclusion over coherent rotation

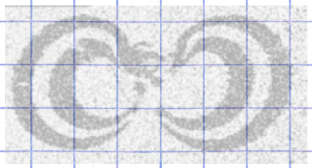
- The simplest model
- Fails for most systems because they are too large: **apply model with great care!..**
- Hc<<Ha for most large systems (thin films, bulk): **do not use Hc to estimate K!** Early known as **Brown's paradox**

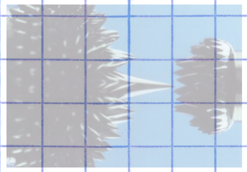

M
Ms
Mr
μ0Hc
μ0H




-90° 0° 90° 180° 270°


Hc
T

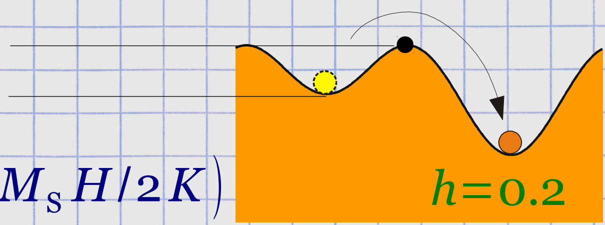




Barrier height

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

Δe



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

Thermal activation

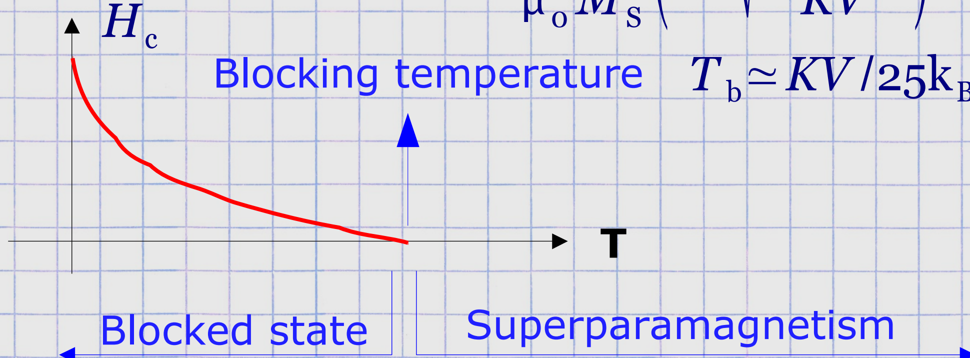
Brown, Phys.Rev.130, 1677 (1963)

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

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

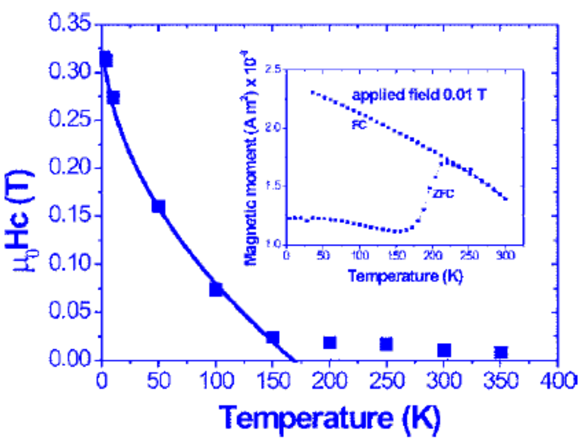
Lab measurement: $\tau \approx 1\ \mathrm{s} \Rightarrow \Delta \mathcal{E} \approx 25 k_B T$

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



Blocking temperature $T_b \simeq KV/25k_B$

J. Appl. Phys. **99**, 08Q514 (2006)



E. F. Kneller, J. Wijn (ed.) Handbuch der Physik XIII/2: Ferromagnetismus, Springer, 438 (1966)

M. P. Sharrock, J. Appl. Phys. 76, 6413-6418 (1994)

Notice, for magnetic recording : $\tau \approx 10^9\ \mathrm{s}$ $\quad KV_b \approx 40-60 k_B T$

Formalism

C. P. Bean & J. D. Livingston, J. Appl. Phys. 30, S120 (1959)

Energy

$$E = KV\, f(\theta,\varphi) - \mu_0 \mu H$$

Partition function

$$Z = \sum \exp(-\beta E)$$

Average moment

$$\langle \mu \rangle = \frac{1}{\beta \mu_0 Z} \frac{\partial Z}{\partial H}$$

Isotropic case

$$Z = \int_{-\mathcal{M}}^{\mathcal{M}} \exp(-\beta E)\, d\mu$$

Note: equivalent to integration over solid angle

$$\langle \mu \rangle = \mathcal{M} \left[\coth(x) - \frac{1}{x} \right]$$

Langevin function

Note:
Use the moment M of the particule, not spin ½ .

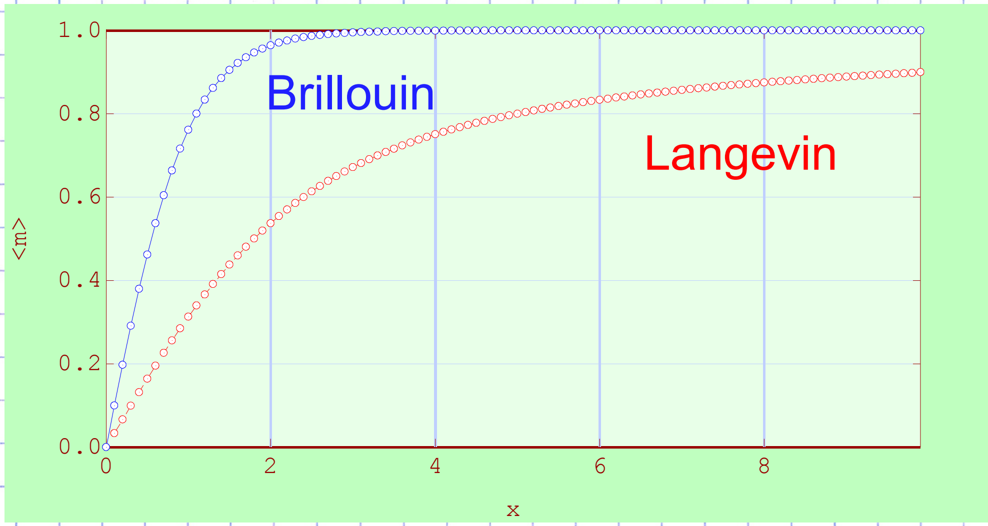
$$x = \beta \mu_0 \mathcal{M} H$$

Infinite anisotropy

$$Z = \exp(\beta \mu_0 \mathcal{M} H) + \exp(-\beta \mu_0 \mathcal{M} H)$$

$$\langle \mu \rangle = \mathcal{M} \tanh(x)$$

Brillouin ½ function



REVIEW : S. Bedanta & W. Kleemann, Supermagnetism, J. Phys. D: Appl. Phys., 013001 (2009)

Properties (including thermal) of usual magnetic materials

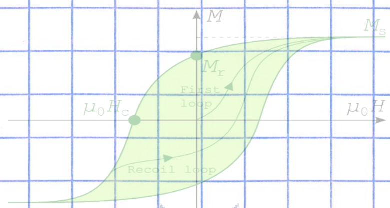
Material	T_C (K)	M_s (kA/m)	$\mu_0 M_s$ (T)	K (kJ/m^3)	$D_{300\,K}$ (nm)
Fe	1043	1730	2.174	48	16
Co	1394	1420	1.784	530	7.2
Ni	631	490	0.616	-4.5	35
$Fe_{20}Ni_{80}$ (Permalloy)	850	835	1.050	≈ 0	–
Fe_3O_4	858	480	0.603	-13	25
$BaFe_{12}O_{19}$	723	382	0.480	250	9.2
$Nd_2Fe_{14}B$	585	1280	1.608	4900	3.4
$SmCo_5$	995	907	1.140	17000	2.3
Sm_2Co_{17}	1190	995	1.250	3300	3.9
FePt $L1_0$	750	1140	1.433	6600	3.1
CoPt $L1_0$	840	796	1.000	4900	3.4
Co_3Pt	1100	1100	1.382	2000	4.6

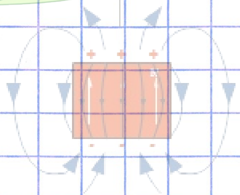
T_c Curie ordering temperature

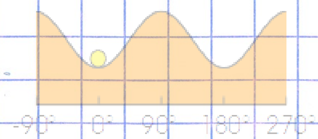
M_S Spontaneous magnetization at 300K

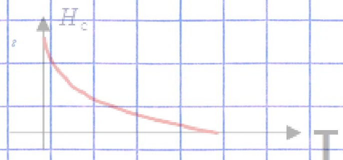
K First magnetocrystalline anisotropy coefficient at 300K

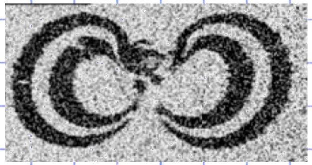
$D_{300\,K}$ Diameter for superparamagnetic limit at 300K and time constant 1s

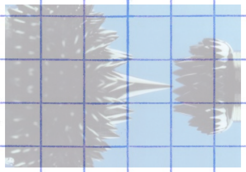





-90°
0°
90°
180°
270°


T





Basics of precessional switching

Demonstration: 1999

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

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

γ_0 Gyromagnetic factor

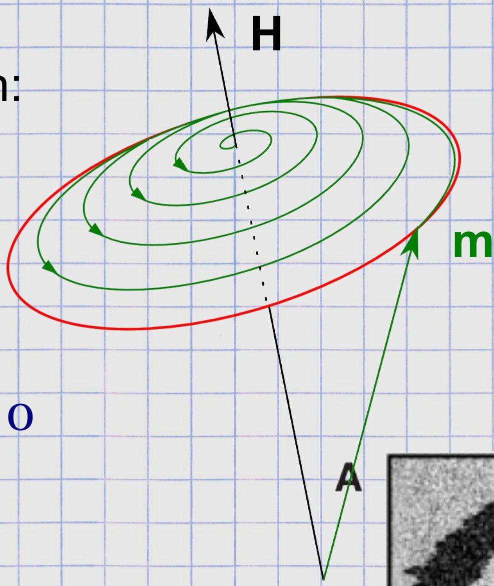
$$\gamma_0 = \mu_0\gamma \qquad \gamma = -g_J\frac{e}{2m_e} < 0$$

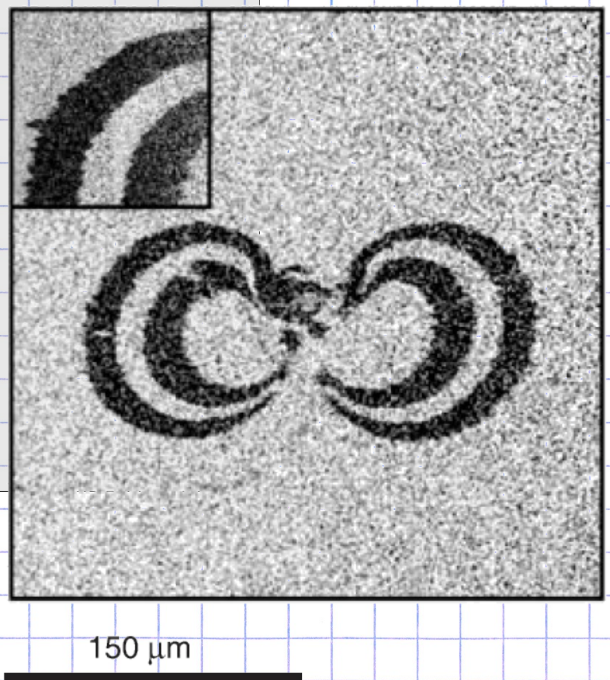
$$|\gamma_0|/2\pi \approx 28\ \mathrm{GHz/T}$$

H_{eff} Effective field (including applied)

$$H_{\mathrm{eff}} = -\frac{\partial E_{\mathrm{mag}}}{\mu_0\,\partial\mathbf{M}}$$

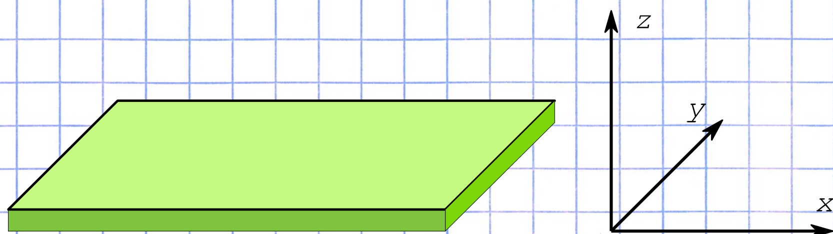
α Damping coefficient $\alpha = 10^{-1} - 10^{-3}$

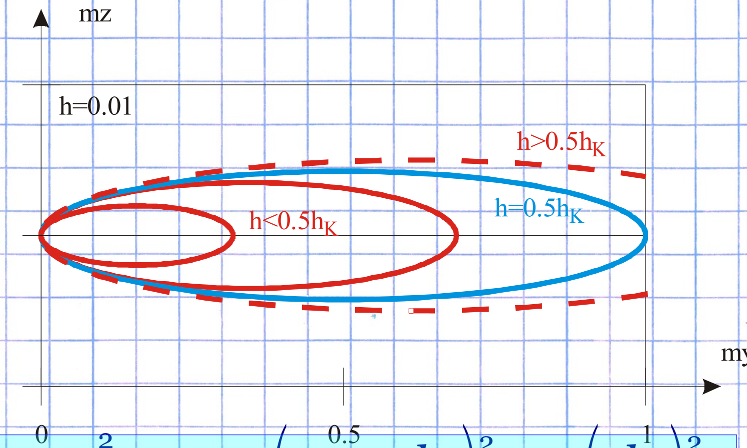




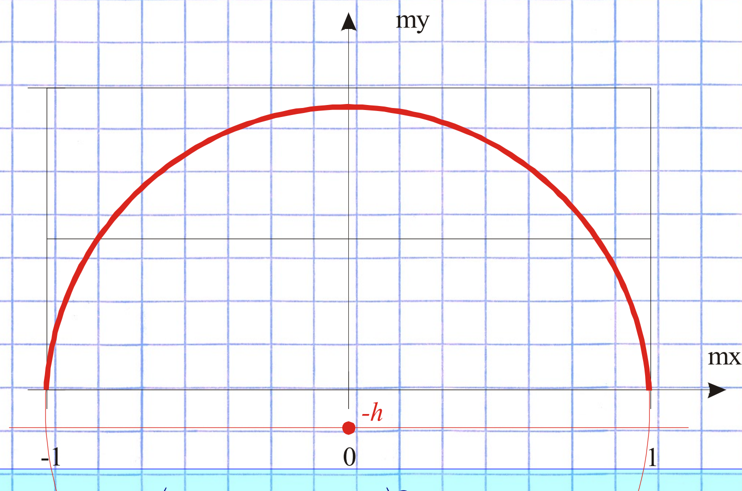
C. Back et al., Science 285, 864 (1999)

Magnetization trajectories

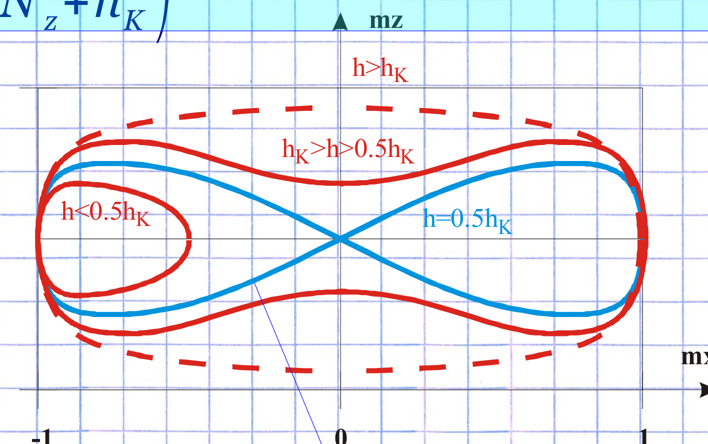




$$\frac{m_z^2}{\left(\dfrac{h_K}{N_z+h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$$



$$m_x^2 + \frac{\left(m_y + h/N_z\right)^2}{1+h_K/N_z} = 1 + \frac{h^2}{N_z\left(N_z+h_K\right)}$$

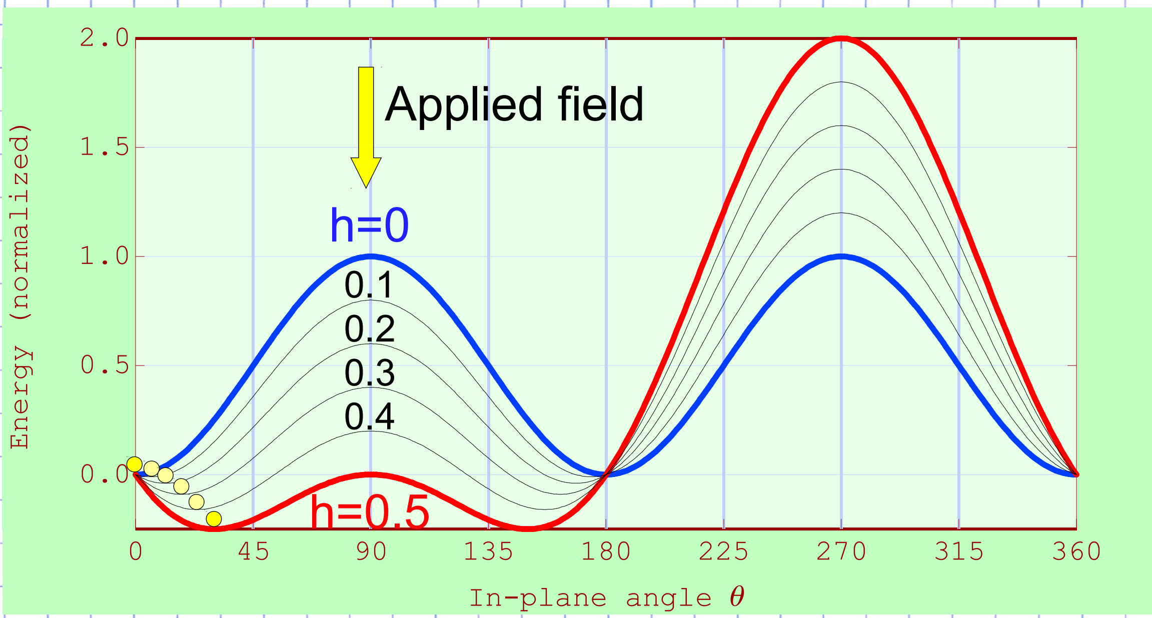


$$\omega \approx 0.847\left|\gamma_0\right|\sqrt{M_s\left(H-H_K\right)/2}$$

Stoner-Wohlfarth versus precessional switching

Stoner-Wohlfarth model: describes processes where the system follows quasistatically energy minima, e.g. with slow field variation

Precessional switching: occurs at short time scales, e.g. when the field is varied rapidly



Relevant time scales

Precession period

$2\pi/|\gamma| = 35$ ps.T

→ 25-500 ps

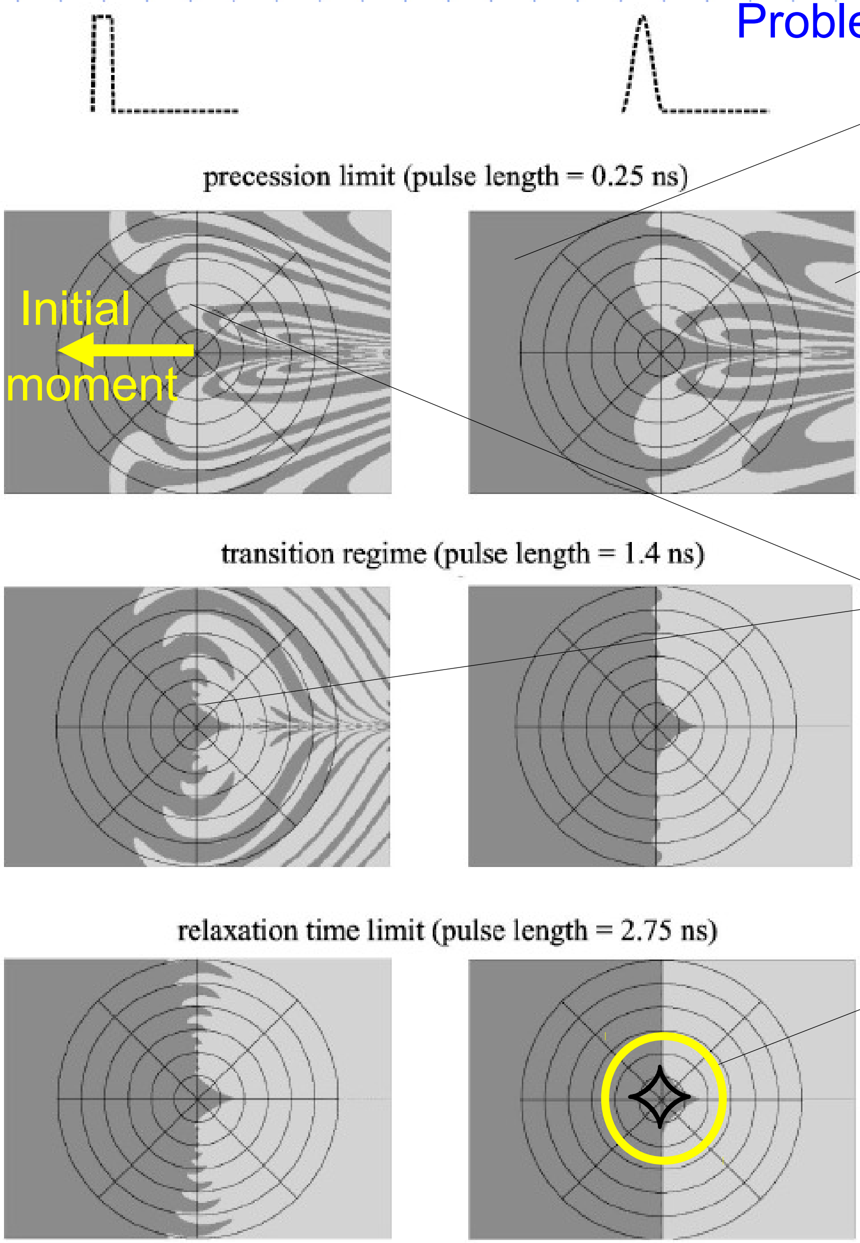
Precession damping

$1/(2\pi\alpha)$ per period

$\alpha = 0.01 - 0.5$

Notice Magnetization reversal allowed for $h > 0.5h_K$ (more efficient than classical reversal

Problems : multiple switching and ringing



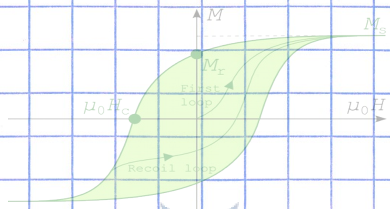
Non-switched

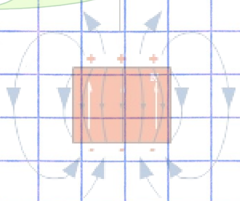
Switched

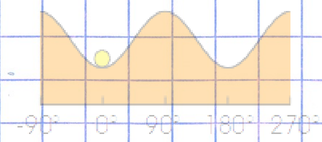
Reversal below the quasistatic value h=1 for hy, and even for m.h>0!

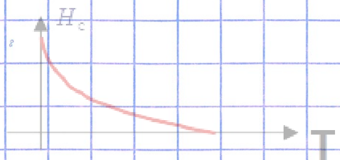
Stoner-Wohlfarth astroid (quasistatic limit)

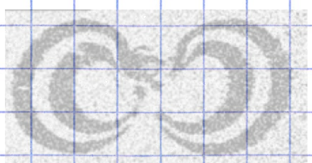
M. Bauer et al., PRB61, 3410 (2000)

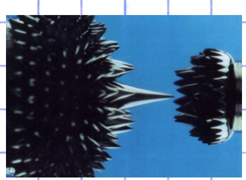

M
μ0H




-90° 0° 90° 180° 270°


T





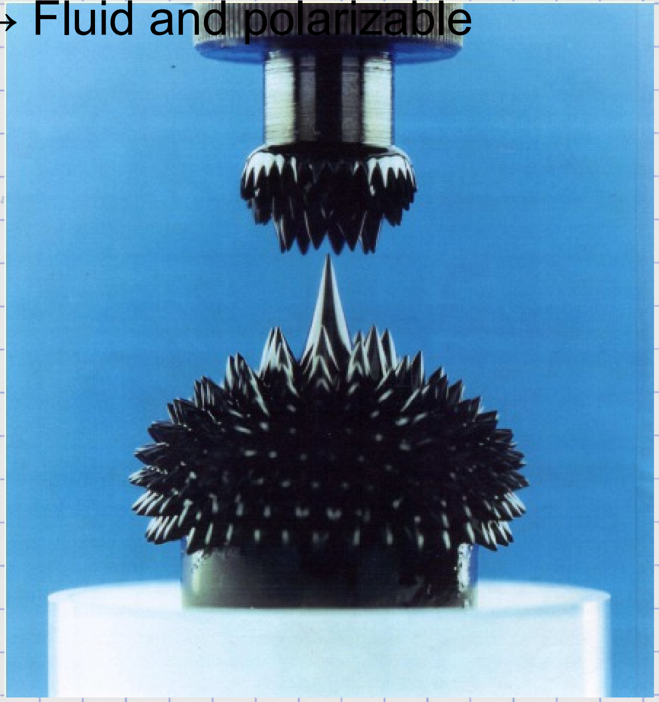
Ferrofluids

⇨ Principle

Surfactant-coated nanoparticles, preferably superparamagnetic

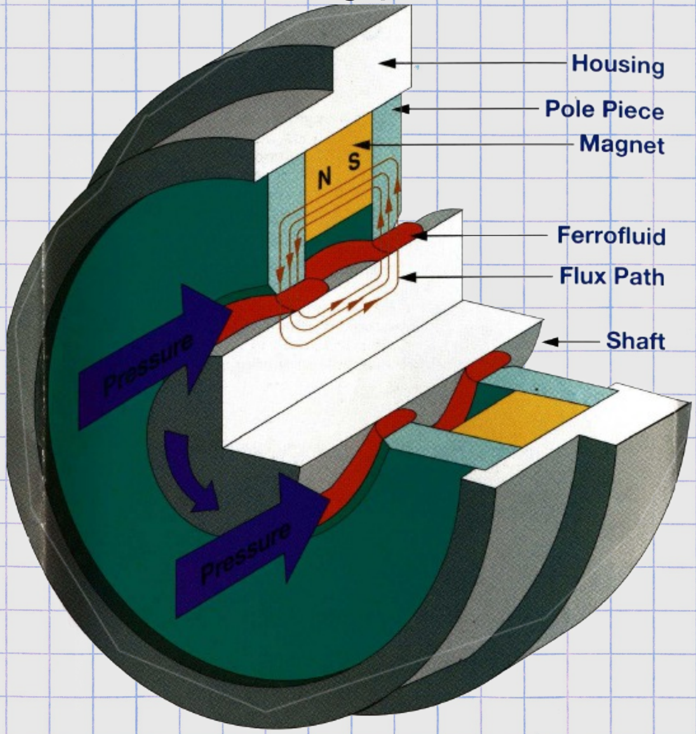
→ Avoid agglomeration of the particles

→ Fluid and polarizable



⇨ Example of use

Seals for rotating parts



R. E. Rosensweig, Magnetic fluid seals, US patent 3,260,584 (1971)

http://magnetism.eu/esm/2007-cluj/slides/vekas-slides.pdf

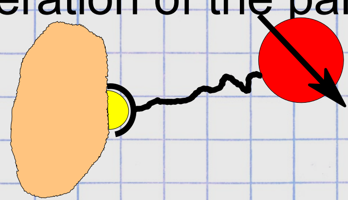
Health and biology

Beads = coated nanoparticles, preferably superparamagnetic

→ Avoid agglomeration of the particles

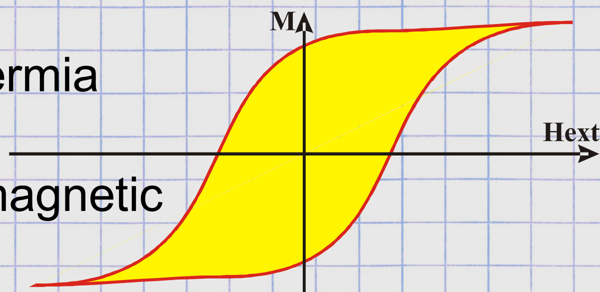
⇨ Cell sorting

$$\mathbf{F}=\nabla \boldsymbol{\mu}.\mathbf{B}$$

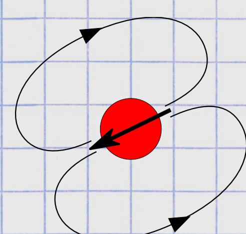


⇨ Hyperthermia

Use ac magnetic field



$$H_c = H_{c,0}\left(1-\sqrt{\frac{\ln(\tau/\tau_0)k_B T}{KV}}\right)$$



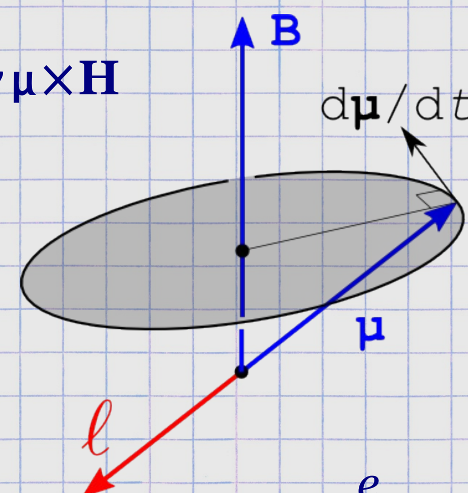
RAM (radar absorbing materials)

⇨ Principle

Absorbs energy at a well-defined frequency (ferromagnetic resonance)

$$\frac{d\boldsymbol{\ell}}{dt}=\boldsymbol{\Gamma}=\mu_0\boldsymbol{\mu}\times\mathbf{H}=\mu_0\gamma\boldsymbol{\ell}\times\mathbf{H}$$

$$\frac{d\boldsymbol{\mu}}{dt}=\mu_0\gamma\boldsymbol{\mu}\times\mathbf{H}$$



$$\gamma=-g_J\frac{e}{2m_e}<0$$

$$\gamma_s/2\pi \approx 28\ \mathrm{GHz/T}$$