8

Dynamics of magnetization reversal

Magnetization reversal in thin films and some relevant experimental methods

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IFM PAN 2012

Today's plan

- Domain wall motion
- Micromagnetism
- Magnetostatic interactions in thin films

Domain wall in external magnetic field – Walker limit

- The velocities of domain walls are highly unlinear functions of the applied magnetic field.
- In “small fields”, up to the so called **Walker field** H_w, the velocity of the wall is approximately a linear function of the applied field.
- Above the critical field the velocity of the wall may fluctuate
- In samples of limited dimensions (wires, patterned media, etc.) the orientation of easy axes with respect to sample surfaces influences the character of velocity-field dependence [1].

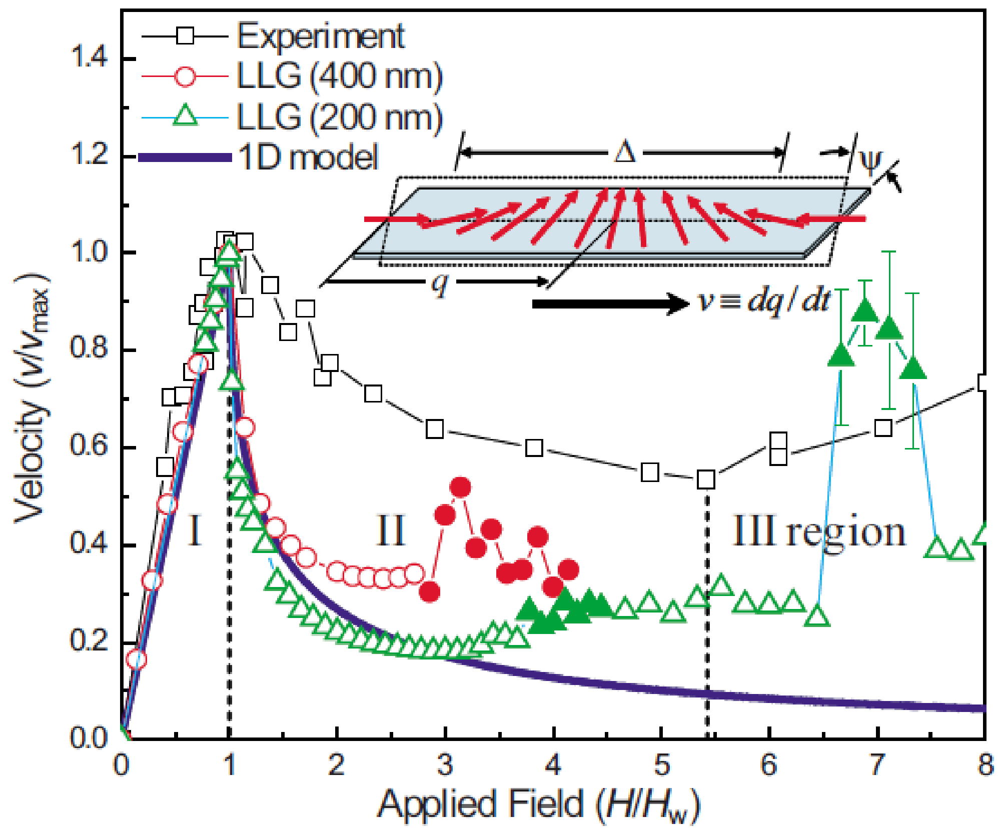


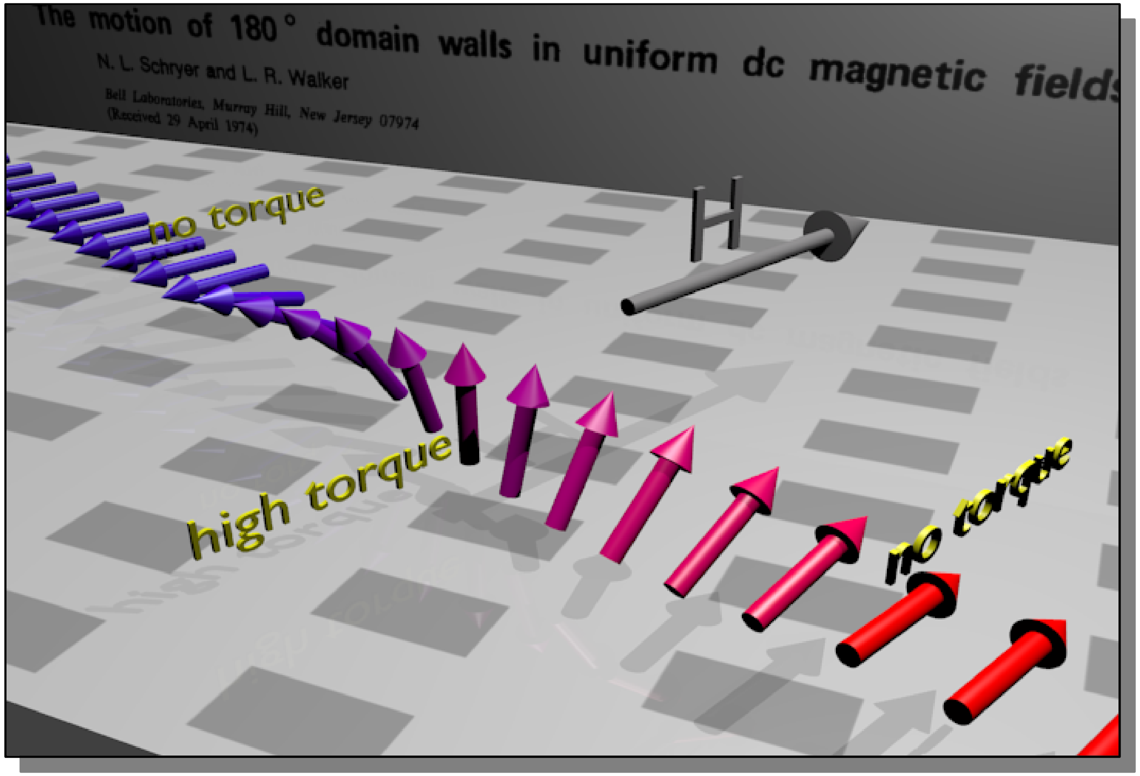
FIG. 1. (Color online) Measured and simulated DW velocity [normalized to $v_{max} \equiv v(H_W)$] as a function of applied field (normalized to the Walker field H_W). Walker breakdown occurs at $H = H_W$ corresponding to $\psi = \pi/4$. (Inset) Schematic description of the spin distribution within a propagating transverse DW showing tilt angle ψ and wall width Δ. Solid symbols for LLG simulations designate onset of noise in simulated velocity described later in text.

Jusang Yang, Corneliu Nistor, G. S. D. Beach, and J. L. Erskine, Phys. Rev. B **77**, 014413 (2008)

Domain wall in external magnetic field – Walker limit

- If the external field is applied parallelly to the straight Bloch wall the torque is exerted only on the spins within the wall (neglecting the infinite extent of the wall - see lecture 6).
- The torque forces precession of moments (see LLG equation – lecture 7) giving demagnetizing field component perpendicular to the wall [17].

- "*From the above qualitative picture it becomes clear that a wall has a finite maximum velocity. The reason is that the demagnetisation field H_S is necessarily finite (H_x<M_x), implying a finite precession frequency and thus a finite maximum velocity.*"
  F.H de Leeuw [17].



Domain wall mobility

•In relatively broad range of magnetic field the domain wall velocity is approximatelly linear function of the applied field [7].
•The velocity can be expressed as:

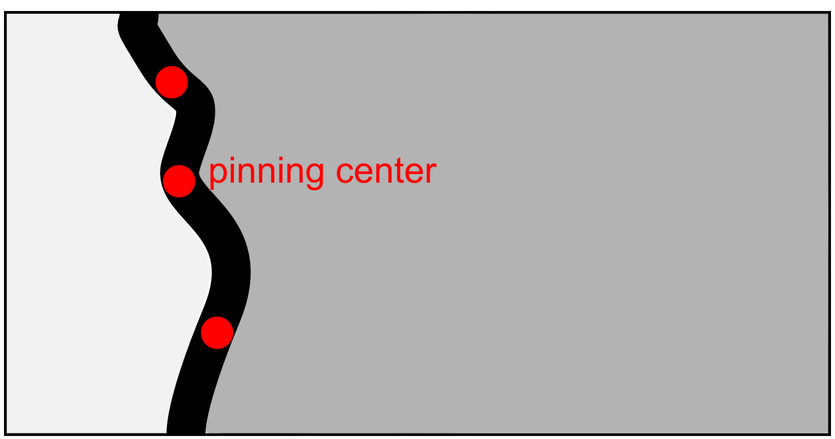
$$v(H)=\begin{cases} 0 & H<H_{dp} \\ \mu(|H|-H_{dp}) & H\geq H_{dp} \end{cases}$$

•Above depinning field H_{dp} the wall moves with velocity determined by mobility μ.
•Typical values of wall mobility are [7]:

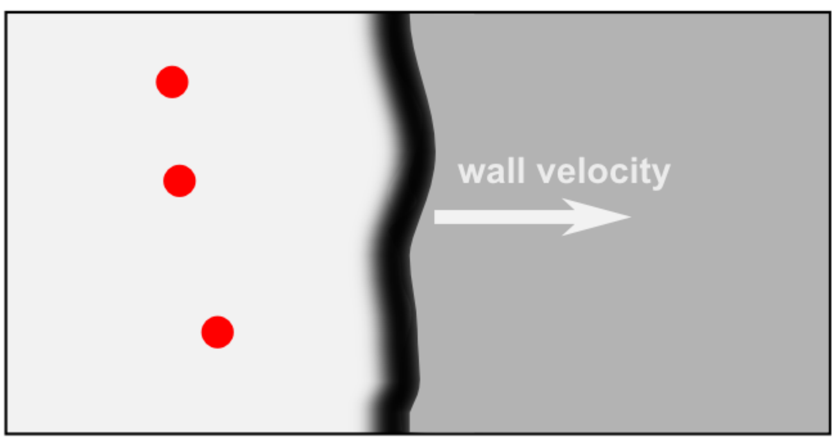
$\mu=1\text{-}1000\ ms^{-1}\ mT^{-1}$ $\approx 0.00125-1.25\ ms^{-1}\ (A/m)^{-1}$

•In thin films of permalloy the mobility is of the order of $\mu=100\ ms^{-1}\ mT^{-1}$[7].

$H<H_{dp}$



$H_{dp}\leq H$



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- Typical values of wall mobility are [7]:

μ=1-1000 ms^{-1} mT^{-1}

- Velocity of domain walls in typical fields used in experiments can exceed **10 km/s**

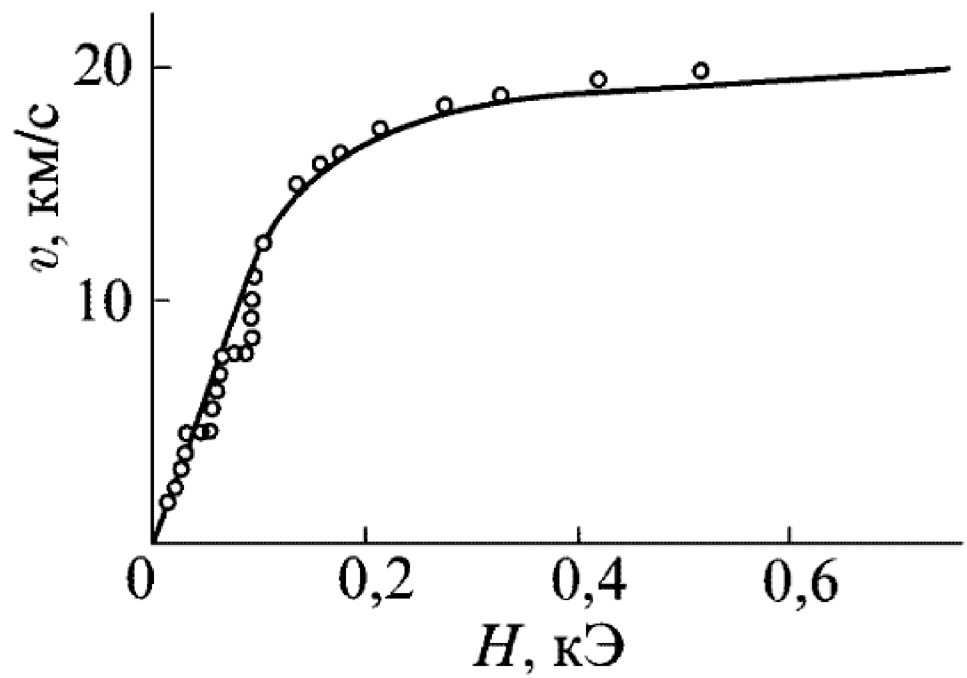


Рис. 26.3. Зависимость $v(H)$ для слабого ферромагнетика; точками показаны экспериментальные данные для иттриевого ортоферрита ($YFeO_3$)

image from: Боровик Е. С, Еременко В. В., Мильнер А. С. Лекции по магнетизму. , М.: ФИЗМАТЛИТ, 2005.

Domain wall in external magnetic field – thermally activated motion

- **Magnetic viscosity** - the delayed response of magnetic domains to changes in external field [2].
- The effect, called also *magnetic aftereffect*, is easily observable in ultrathin magnetic films.

- Cu(100)/Fe(7 ML) grown at RT
- Domain images were taken in-situ with the help of a *long-distance microscope* (the distance between the front of the microscope and the sample was 32 cm, the resolution was better than 10μm)

20s after field is switched on

5s after field is switched on

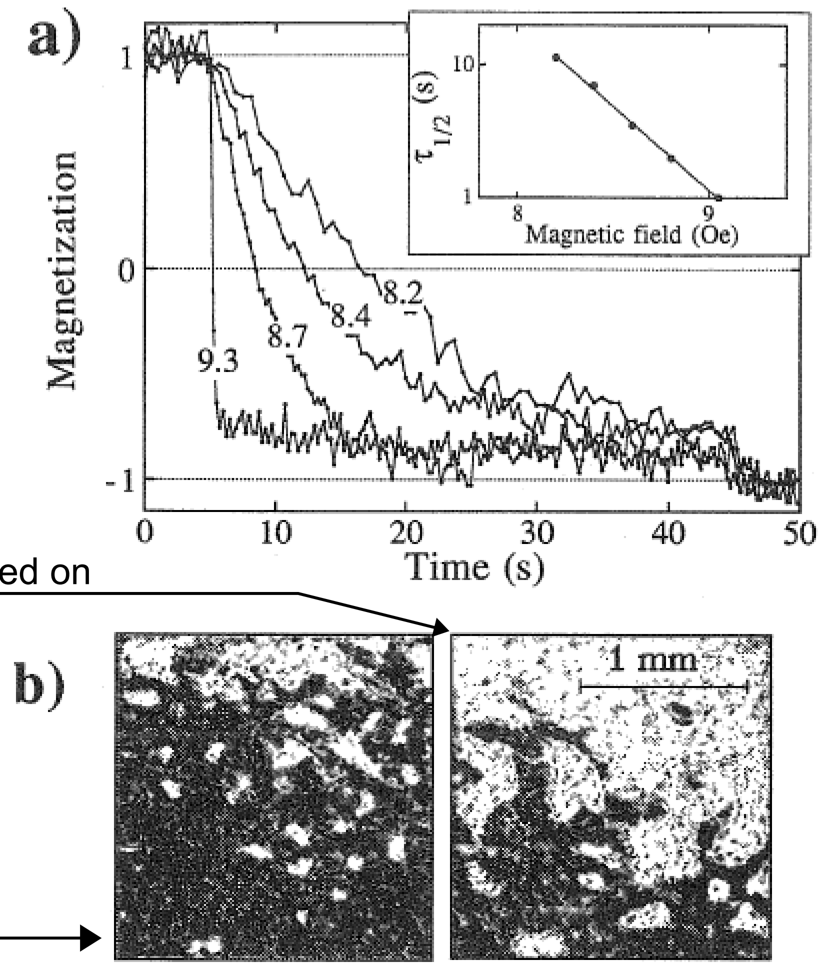


Fig. 5. (a) Magnetization relaxation curves for the sample III at different field values (indicated in the figure in Oe). (b) Domain images of the same location on the sample measured at constant magnetic field (8.2 Oe), but applied over different time (left panel – 5 s, right panel – 20 s).

A. Kirilyuk, J. Giergiel, J. Shen, J. Kirschner, Journal of Magnetism and Magnetic Materials **159**, L27 (1996)

Domain wall in external magnetic field – thermally activated motion

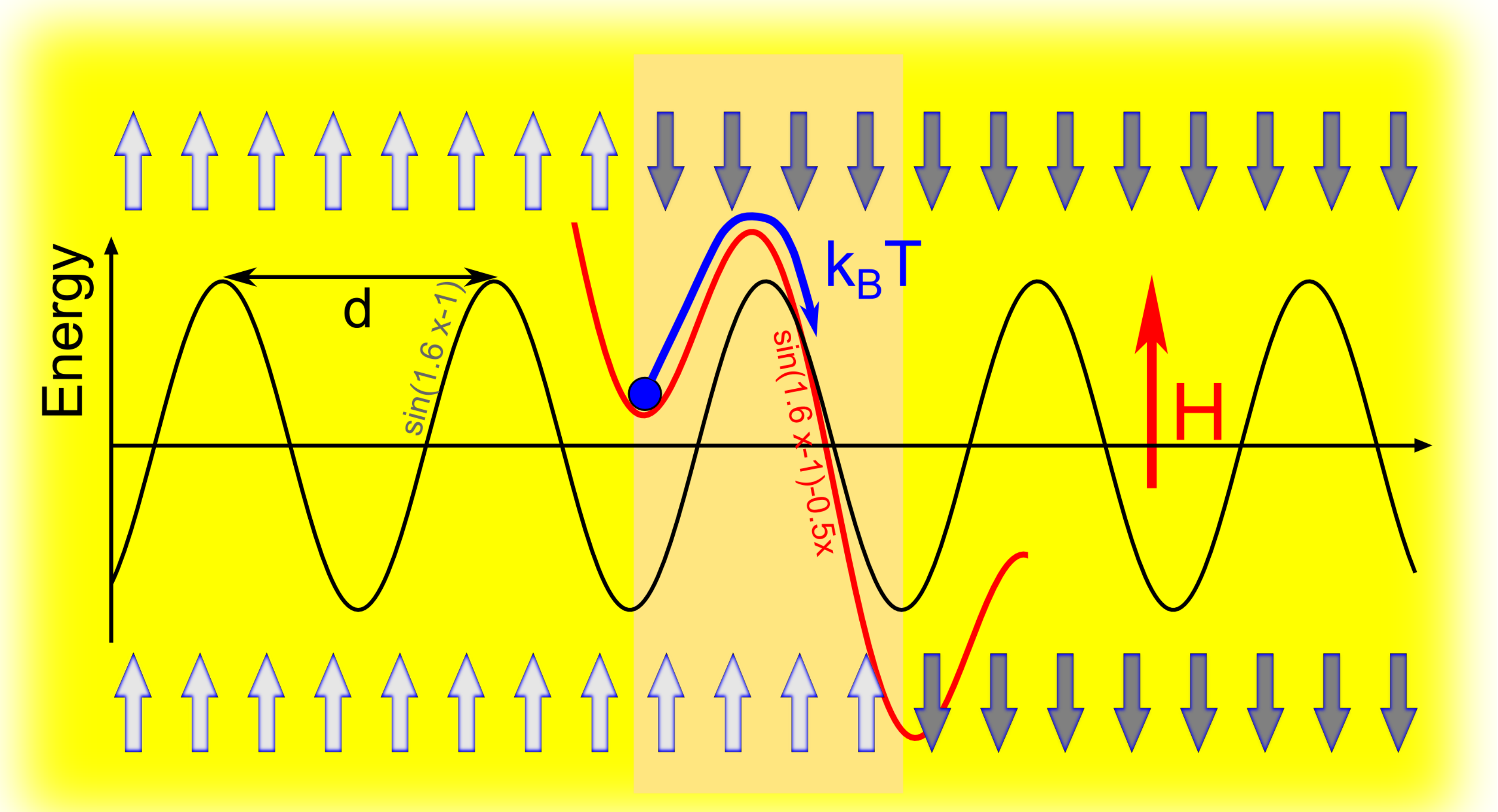
•Consider a domain wall crossing a sequence of potential barriers of equal* height E_0 [2].
•The energy that must be supplied to wall in the presence of field H in the direction of expanding domain is:

$$E = E_0 - \alpha H$$

, where α*H* is the energy supplied by the field during penetration of or the "climbing up" the barrier

•Number of occasions per second on which the wall acquires thermal energy *E* high enough to cross the barrier is:

$$N = C e^{(-E_0 - \alpha H)/kT}$$



*for simplicity

Domain wall in external magnetic field – thermally activated motion

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- The energy that must be supplied to wall in the presence of field H in the direction of expanding domain is:

$E = E_0 - \alpha H$, where αH is the energy supplied by the field during penetration of or the “climbing up” the barrier

- Number of occasions per second on which the wall acquires thermal energy E high enough to cross the barrier is:

$N = C e^{(-E_0 - \alpha H)/kT}$, where C* is a constant of the order 10^9 to 10^{10} Hz [2,3,5]

- If the average separation of energy minima is d and the delay of the wall at each energy barrier is much greater than time to move from barrier to barrier then the wall velocity is**:

$$v = N d = d C e^{-(E_0 - \alpha H)/kT} \propto e^{H/kT}$$

$$v \propto e^{H/kT}$$

- In many cases the reversal takes place in limited volume V_B (Barkhausen or activation volume [4]) and the energy associated with the reversal can be expressed as:

$$\alpha H \rightarrow 2 \mu_0 M V_B H$$

, which comes from the Zeeman energy of reversing volume (fragment of the wall etc.)

*called attempt frequency [5] **note that, in this formulation, th velocity is different from zero in the absence of field → ,,Brownian motion”

Sweep rate dependence of coercivity

- Dependence of coercivity on magnetic field sweep rate is common to superparamagnetic particles [5].
- In particulate magnetic media the deciding factor in defining magnetic properties is not the volume of a single particle but the so called switching (activation) volume [5].
- If theses volumes are close to each other it means that the particles switch almost independently.

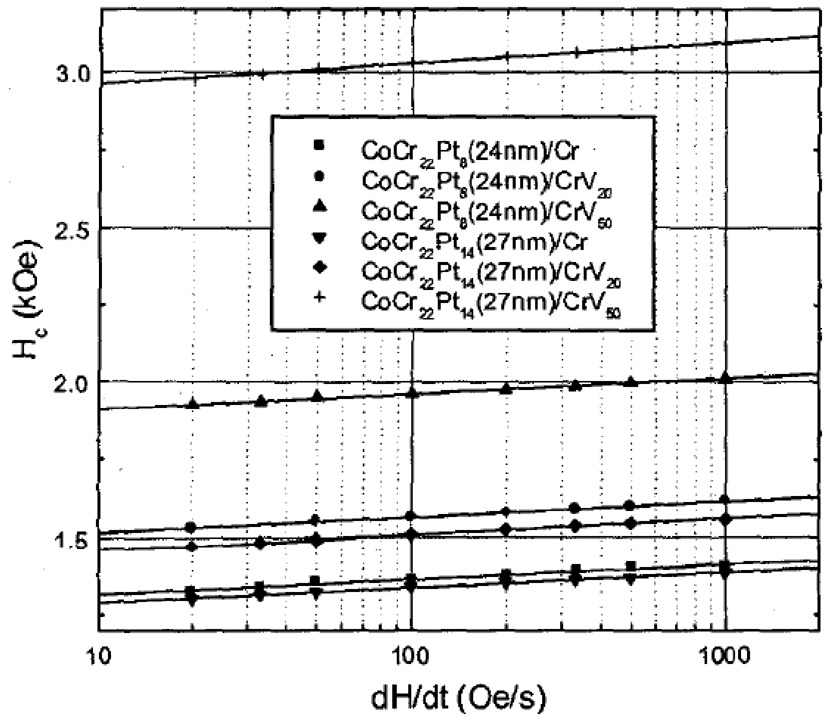


Fig. 1. Field sweep-rate (dH/dt) dependence of coercivity (H_c) of $CoCr_{22}Pt_8$(24nm)/CrV_x and $CoCr_{22}Pt_{14}$(27nm)/CrV_x films.

Mingjun Yu, M. F. Doerner, D. J. Sellmyer, IEEE Trans. Magn. **34**, 1534 (1998)

Sweep rate dependence of coercivity

- In some thin film systems the sweep rate dependence of coercivity can be used to distinguish between reversal by wall movement or domain nucleation [6].
- In the low dynamic regime ($\ln_{10}(\Delta H/\Delta t)<0$) usually the dynamic coercive field *H** is:

$$\log_{10}(H_C)\propto\ln_{10}(\Delta H/\Delta t)$$

- GaAs(100)/Fe
- The wall velocity is proportional to the applied field:

$$v(H)=\begin{cases}0 & H<H_{dp}\\ \mu(|H|-H_{dp}) & H\geq H_{dp}\end{cases}$$

with H_{dp} – depinning field and μ- wall mobility

- The reversal time of the sample's magnetization determines the frontier between low and high dynamic regime [6].

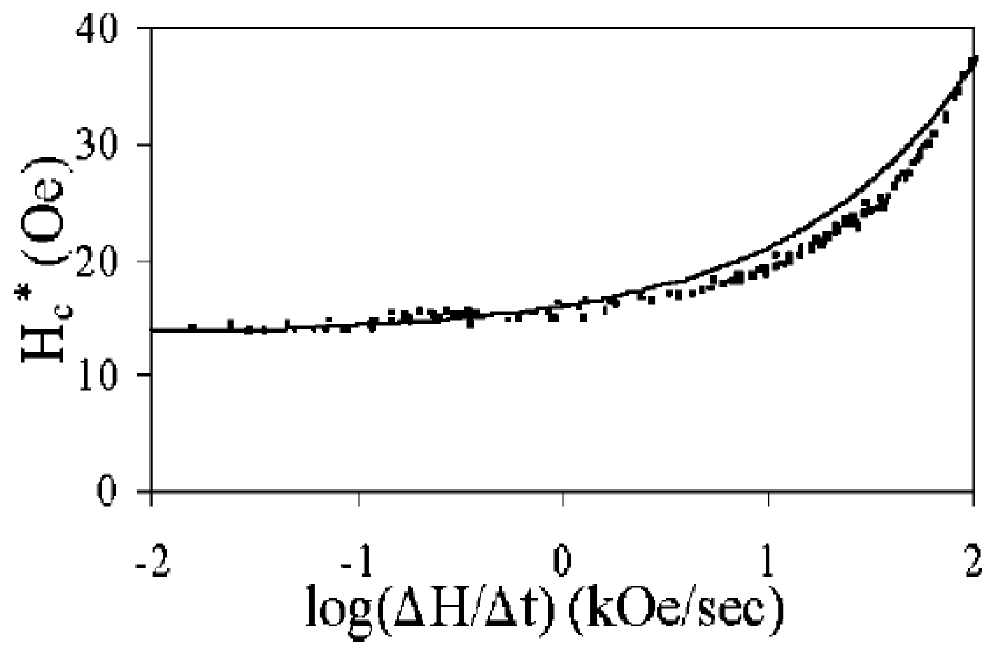


FIG. 5. Dots: experimental data (Ref. 3). Line: computational results, using model 1, of H_c^* vs $\ln(\Delta H/\Delta t)$ (kOe/sec), for $H_0=120$ Oe, $h_{dp}=14$ Oe, $\mu=0.9$ (m/s)/Oe; and $\rho=10^5$ m^{-2}.

I. Ruiz-Feal, T. A. Moore, L. Lopez-Diaz, and J. A. C. Bland, Phys. Rev. B **65**, 054409 (2002)

Eddy-current damping

- Eddy-currents (EC) - electric currents induced in a electrical *conductor* exposed to changing magnetic field.
- In magnetic materials the domain walls movement may produce changing field which create eddy currents.
- Eddy-currents are governed by Faraday's law
- In magnetic specimens the EC damping is more pronounced in the middle of the crystal which may lead, depending on the field value, to curving of the domain.
- In bulk materials the field penetrates the inner regions of the sample with a delay [15].
- The time required for the EC effect to disappear depends on resistivity and permeability of the material and the shape of the specimen.
- If the field applied to the rod is alternating then the maximum induction at the center of the specimen can be always less than the maximum field at its surface.

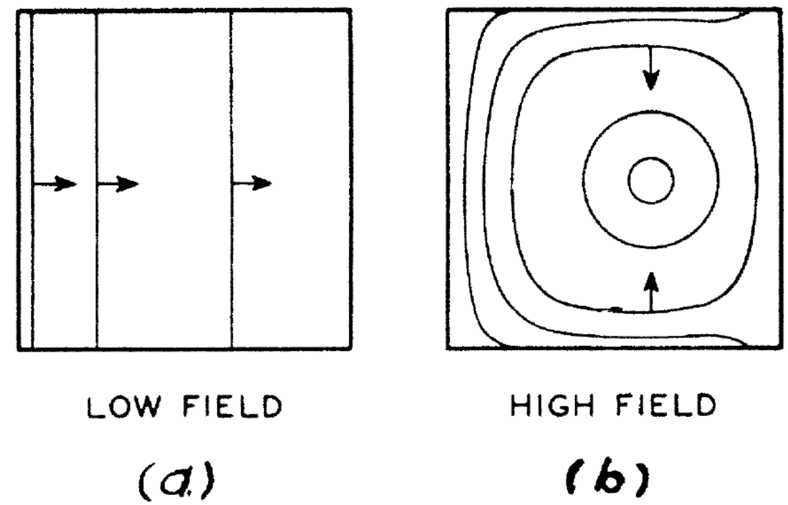
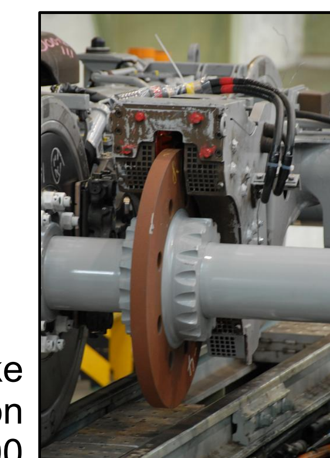


FIG. 2. Boundary motion in low and high fields.

magnetization normal to the image

H. J. Williams, W. Shockley, and C. Kittel, Phys. Rev. 80, 1090 (1950)



Eddy current brake equipment on Shinkansen series 700

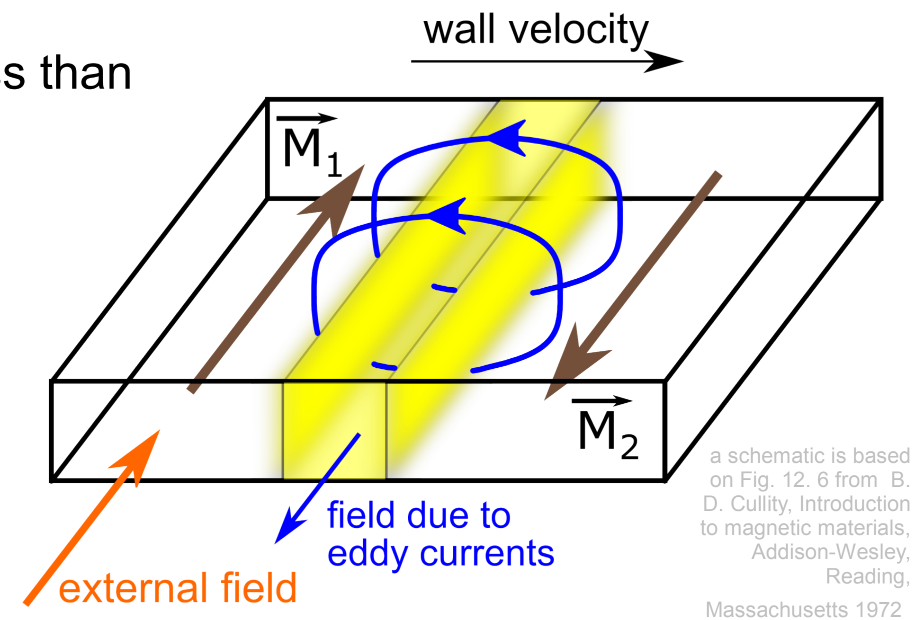
from Wikimedia Commons; author: Take-y at ja.wikipedia

Eddy-current damping

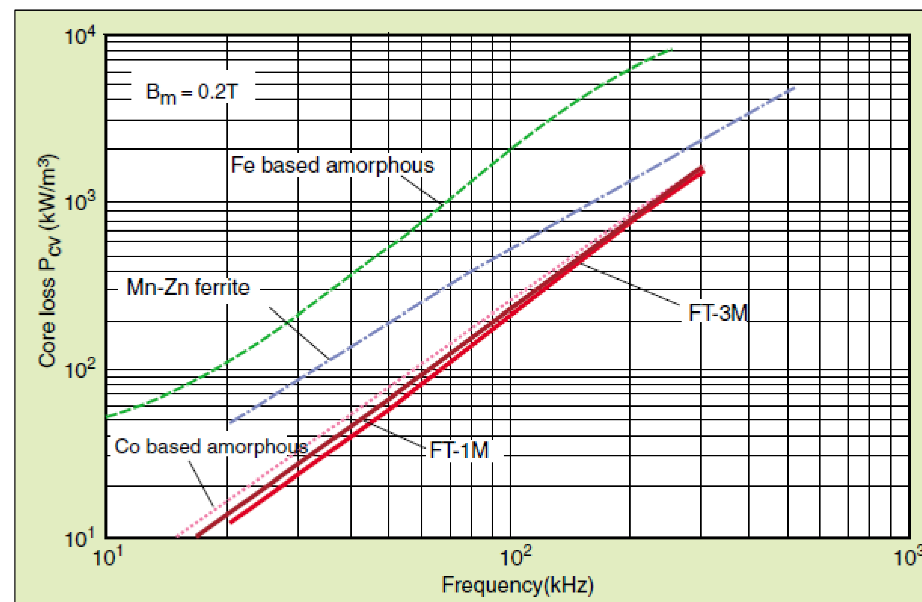
- Domain wall movement creates the eddy-currents which in turn (Lenz's rule) create the field opposing the applied field.
- The wall moves now in a effective field which is less than the applied field – the wall velocity diminishes.
- For the special case of the straight wall moving in a rod of square cross section expression for the velocity is [15]:

$$v(H) \approx 8 \times 10^9 \frac{\pi \rho}{M_s d},$$

d -edge length



- To note is that the low resistivity materials are characterized high eddy-current damping and consequently low wall mobilities.
- Eddy-current damping depends on the geometry of the specimen



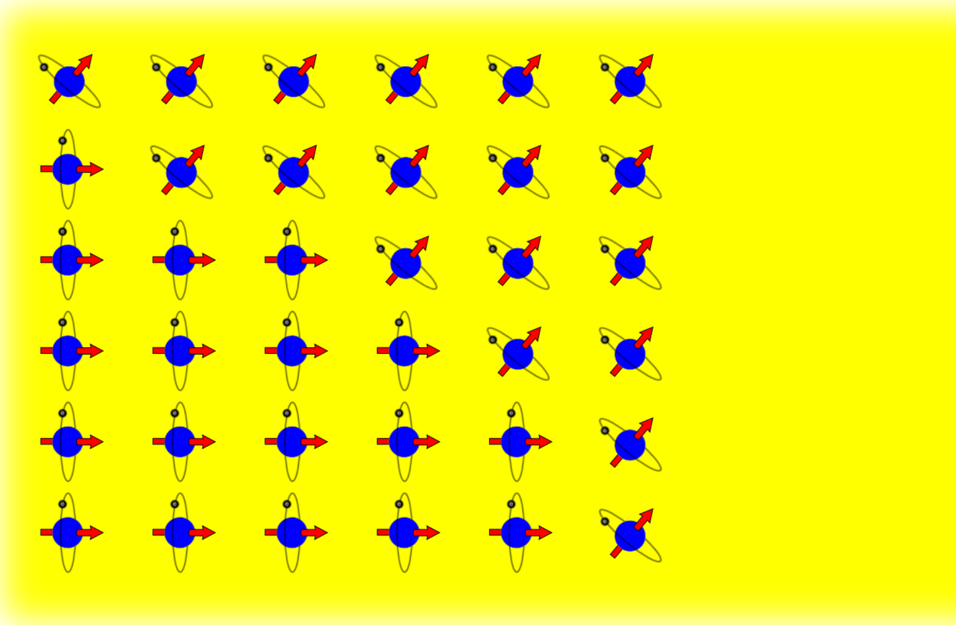
exemplary values of core losses in modern FINEMET® soft magnetic materials

image source HITACHI, www.hilltech.com/pdf/hl-fm10-cFinemetIntro.pdf.pdf

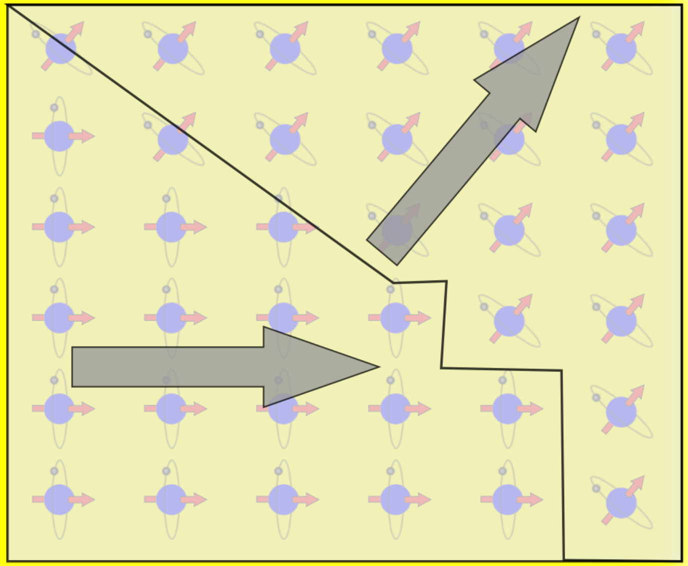
Micromagnetism

- Micromagnetism*, as a refinement of *domain theory*, begins in 1930-ies (Landau, Lifshitz) [8].
- In most cases of interest the use of atomistic description is too computationally demanding.
- In micromagnetism microscopic details of the atomic structure are ignored and the material is considered from the macroscopic point of view as **continuous** [8].
- Spins are replaced by classical vectors motion of which is described by LLG equation (see lecture 7).

atomistic description



micromagnetic description



*the term micromagnetism was coined by William Fuller Brown

Continuous form of exchange energy

- The exchange energy among spins*, assuming that coupling is non-zero between nearest neighbors only, can be written as [8]:

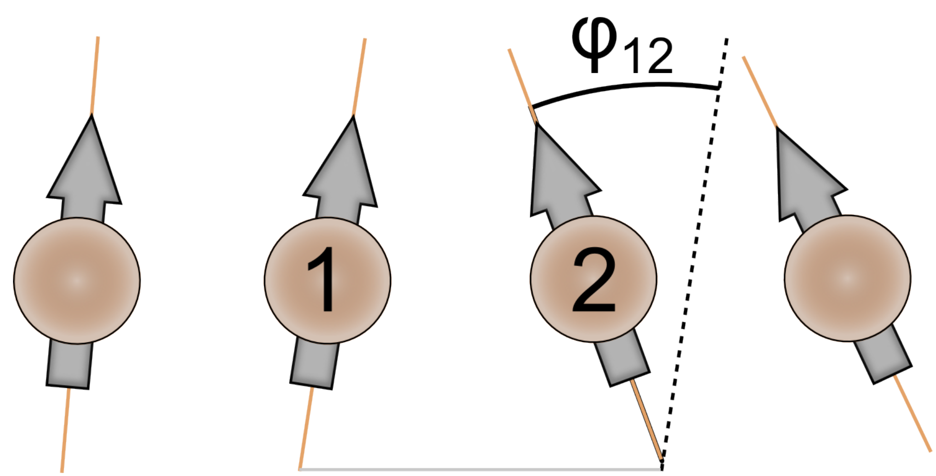
$$E_{ex} = -JS^2 \sum_{neighbours} \cos\phi_{i,j}$$

- The angles between the magnetic moments of neighboring spins are always small due to high strength of exchange coupling [8]. The angle between spins can be expanded in series coefficients**. In one dimensional case we have:

$$E_{ex} = -JS^2 \sum_{neighbours} \cos\phi_{i,j} = -JS^2 \sum_{neighbours} \left(1 - \frac{1}{2}\phi_{i,j}^2 + \ldots\right) \approx -JS^2 \sum_{neighbours} 1 + JS^2 \sum_{neighbours} \frac{1}{2}\phi_{i,j}^2$$

- If we use the state with all spins aligned ($\varphi_{ij}=0$) as a reference state we get:

$$E_{ex} \approx \frac{1}{2} JS^2 \sum_{neighbours} \phi_{i,j}^2$$



*this section is taken mainly from A. Aharoni, Introduction to the Theory of Ferromagnetism, Clarendon Press, Oxford 1996
**compare Bloch wall profile calculation in lecture 6

Continuous form of exchange energy

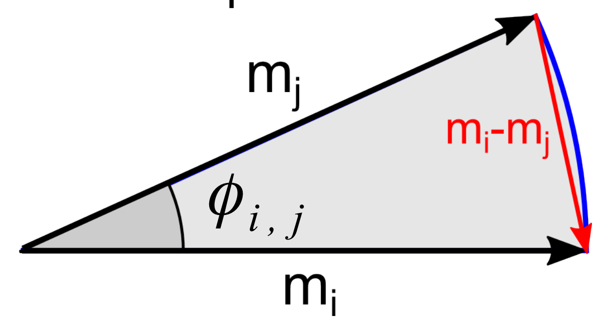
- If the angle between neighboring magnetic moments is small it can be expressed as:

$$|\phi_{i,j}| \approx |\vec{m}_i - \vec{m}_j|$$

$$\vec{m} := \frac{\vec{M}}{|\vec{M}|}$$

- If ***M*** (magnetization vector) is a continuous variable we can use first-order expansion in Taylor series [8]:

$$|\vec{m}_i - \vec{m}_j| = \left| \left(dr_x \frac{\partial}{\partial x} + dr_y \frac{\partial}{\partial y} + dr_z \frac{\partial}{\partial z} \right) \vec{m} \right| = |(\vec{dr} \cdot \nabla) \vec{m}|$$



If φ_{ij} is small the vector $\mathbf{m_i}$-$\mathbf{m_j}$ is approximately of the same length as arc.

- The exchange energy then becomes:

$$E_{ex} \approx \frac{1}{2} J S^2 \sum_{neighbours} \phi_{i,j}^2 \approx \frac{1}{2} J S^2 \sum_i \sum_{\vec{dr}_i} \left((\vec{dr} \cdot \nabla) \vec{m} \right)^2$$

summation from lattice point to all its neighbors

Continuous form of exchange energy

•As an example consider a simple cubic lattice with following six vectors to the nearest neighbors:

$$\vec{dr}:(1,0,0),\ (0,1,0),\ (-1,0,0),\ (0,-1,0),\ (0,0,1),\ (0,0,-1)$$

•We substitute the above vectors into the sum from previous page. We have:

$$\sum_{\vec{dr}_i}\left((\vec{dr}\cdot\nabla)\vec{m}\right)^2 = 2\left(\frac{\partial}{\partial x}m_x\right)^2 + 2\left(\frac{\partial}{\partial y}m_x\right)^2 + 2\left(\frac{\partial}{\partial z}m_x\right)^2 + 2\left(\frac{\partial}{\partial x}m_y\right)^2 + 2\left(\frac{\partial}{\partial y}m_y\right)^2 + 2\left(\frac{\partial}{\partial z}m_y\right)^2 +$$

$$2\left(\frac{\partial}{\partial x}m_z\right)^2 + 2\left(\frac{\partial}{\partial y}m_z\right)^2 + 2\left(\frac{\partial}{\partial z}m_z\right)^2$$

$$\left(\frac{\partial}{\partial x}m_y\right)^2 + 2\left(\frac{\partial}{\partial y}m_y\right)^2 + 2\left(\frac{\partial}{\partial z}m_y\right)^2 = (\nabla m_y)\cdot(\nabla m_y)$$

$$\frac{1}{2}\sum_{\vec{dr}_i}\left((\vec{dr}\cdot\nabla)\vec{m}\right)^2 = (\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2$$

•Changing the summation to integration over the ferromagnetic body we obtain for cubic systems [8,11 p. 134]:

$$E_{ex} = \frac{1}{2}C\int\left[(\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2\right]dV$$

C - constant

•For lower symmetries of crystal lattice the expression for exchange energy density has slightly different forms . *“But for most cases of any practical interest this equation can be taken as a good approximation for the exchange energy, in as much as the assumption of the continuous material is a good approximation to the physical reality.”*-A. Aharoni [8]

Continuous form of exchange energy

•Constant C depends on lattice type [8]:

$$E_{ex}=\frac{1}{2}C\int\left[(\nabla m_x)^2+(\nabla m_y)^2+(\nabla m_z)^2\right]dV$$

$$C=\frac{2JS^2}{a}c$$

J- exchange integral, S – spin, a-lattice constant, c- constant

lattice	c
sc	1
bcc	2
fcc	4

•For hexagonal crystal, such as cobalt, one obtains the same form of expression but the value of constant C is different:

$$C=\frac{4\sqrt{2}JS^2}{a}$$, where **a** is nearest neighbors' distance

•It is common ([9] for example) to write the expression for exchange energy density without the factor ½; a different constant A= ½ C is defined then.

•Both A and C are referred to as "**exchange constant of the material**" [8] or *exchange stiffness constant* (A) [9].

•Constant A is of the order of 10×10^{-12} Jm^{-1} in ferromagnetic materials.

•The exchange constant is roughly proportional to Curie temperature [7]:

$$A\approx\frac{k_B T_C}{2a_0},$$ a_0 -lattice parameter in a simple structure

	$A[pJ\ m^{-1}]$*
α-Fe	21
Co	31
Ni	7
$Ni_{80}Fe_{20}$ [7]	11

*from H. Kronmüller, M. Fähnle, Micromagnetism... [9]

Equilibrium condition

Effective field is an extension of magnetostatic energy terms of different origin:

$$E_{magn} = -\vec{M} \cdot \vec{B}$$

$$\vec{H}_{eff} = -\frac{1}{\mu_0 M_S} \frac{\partial}{\partial \vec{m}} E_{total}$$

•From lecture 7 we have the expression for the effective field [8,10]:

$$\vec{H}_{eff} = \frac{2A}{M^2}\left[(\nabla M_x)^2 + (\nabla M_y)^2 + (\nabla M_z)^2\right] + \vec{H}_{app} + \vec{H}_d + \frac{\partial}{\partial \vec{m}} E_{anisotropy}$$

•If one is interested in magnetization distribution static equilibrium the only condition that must be satisfied is [10,11]:

$$\vec{m} \times \vec{H}_{eff} = 0$$

M must point at each point along the direction of the effective field

•Symmetry breaking of exchange interactions at outer surfaces brings additional so called *free boundary conditions* [10,11 p.135]:

$$\frac{\partial \vec{m}}{\partial \vec{n}} = 0$$

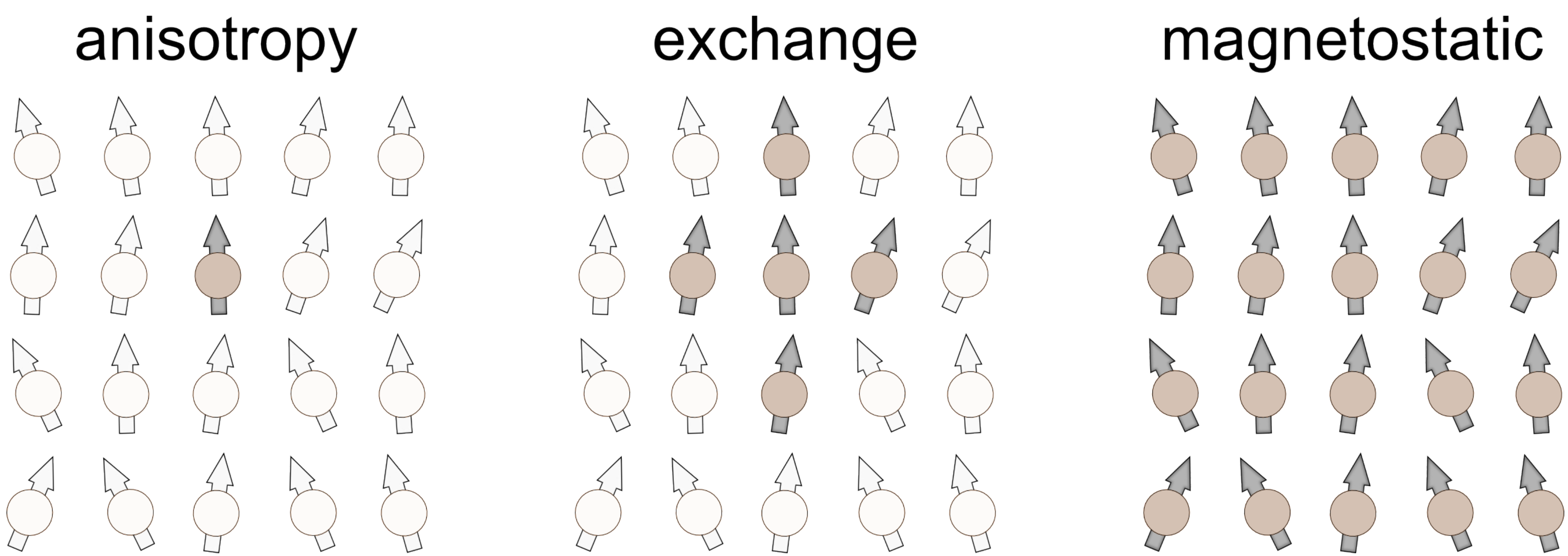
to be read as $\frac{\partial}{\partial \vec{m}} f = \hat{x} \frac{\partial}{\partial m_x} f + \hat{y} \frac{\partial}{\partial m_y} f + \hat{z} \frac{\partial}{\partial m_z} f$ ([8, p.178], [11, p. 126])

Finite difference micromagnetism

•In the so called *field based approach* [10] one is seeking a numerical solution to LLG equation by first calculating the effective field and then inserting it into LLG equation.

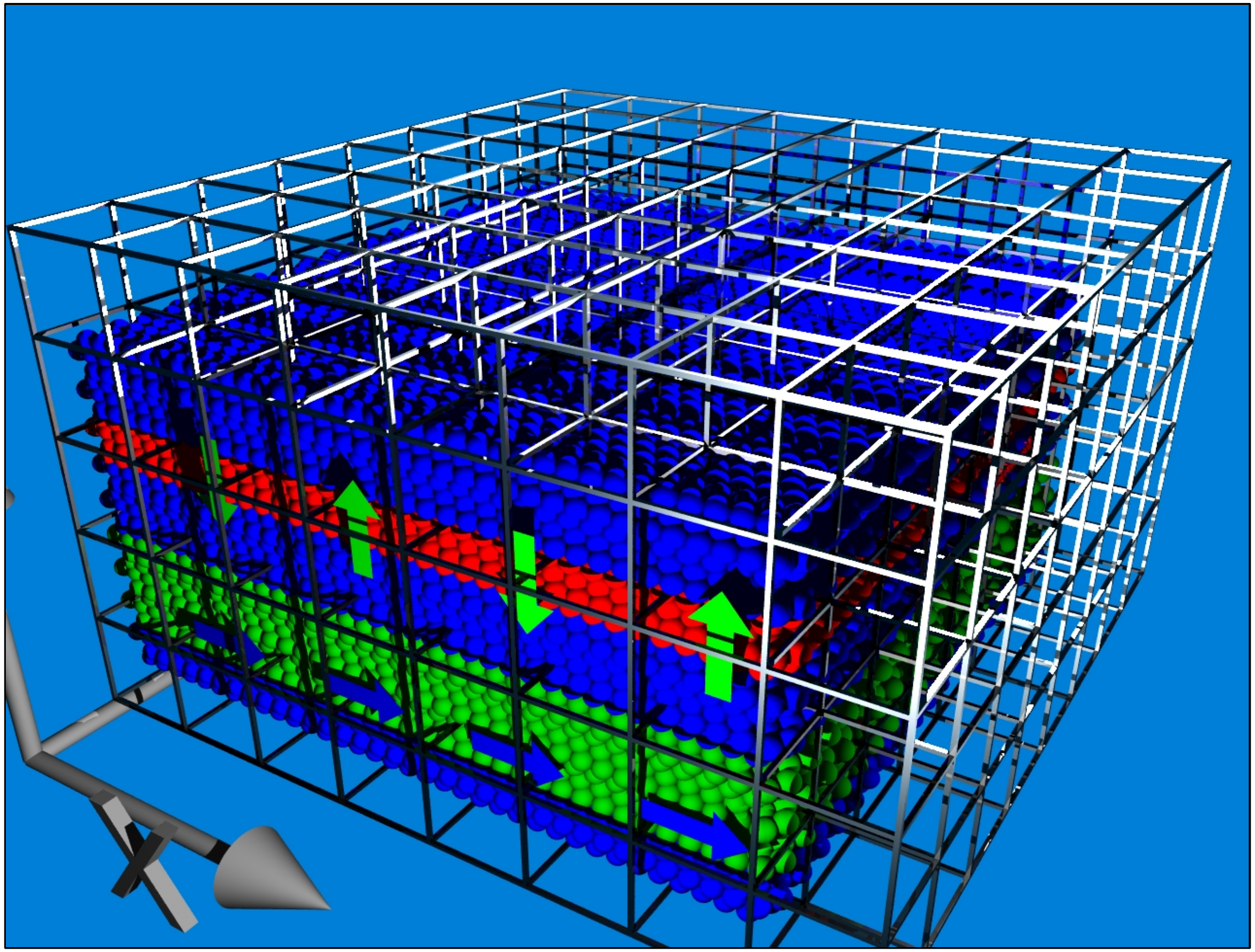
$$\vec{H}_{eff} = -\frac{1}{\mu_0 M_S} \frac{\partial}{\partial \vec{m}} E_{total}$$

•The most difficult task is the calculation of long range magnetostatic interactions
• Exchange interactions and magnetocrystalline anisotropy are calculated locally:
- exchange energy depends on the magnetic moment orientation of nearest neighbors (nn) (6-neighbor exchange in simple cubic crystals) or nnn
- magnetocrystalline energy depends only on the orientation of the moment itself



Finite difference micromagnetism – demagnetizing field evaluation

- Demagnetizing field evaluation can be calculated in formalism of volume and surface charges (lecture 2).
- **The volume of magnetic body is divided into a number of discretization cells.**
- It can be assumed that each cell has *constant* magnetization divergence within its volume and surface tiles with magnetic charge density [11].
- The demagnetizing field in a given cell is averaged across its volume for integrating LLG equation.
- It can be assumed to that the magnetization within each cell is homogeneous [9].
- The discretization cell must not necessarily be a cube [12].



Finite difference micromagnetism – exchange lengths

- The required resolution of discretization (the maximum sizes of cells) is determined by the smallest features which may appear in the solution of micromagnetic problem [13].
- In micromagnetism there are three typical length scales [9,10]:

-magnetocrystalline exchange length – related to the width of the Bloch wall ($\pi\, l_k$)

$$l_k = \sqrt{A / K_1}$$

-magnetostatic exchange length* [10] – related to the width of the Néel wall ($\pi\, l_s$)

$$l_k = \sqrt{\frac{2A}{\mu_0 M_s^2}}$$

-thermal exchange length [13]

$$l_k = \sqrt{\frac{A}{\mu_0 M_s H_{th}}}, \qquad H_{th} = \sqrt{\frac{2 \alpha k_b T}{\Delta \gamma \mu_0 M_s l^3}}$$

- The discretization cell should be smaller than the smaller than the minimum of three lengths defined above [13].
- The magnetostatic exchange length rarely exceeds a few nanometers in 3d ferromagnetic metals or alloys; it imposes a severe constraint on the mesh size in numerical simulations [10].

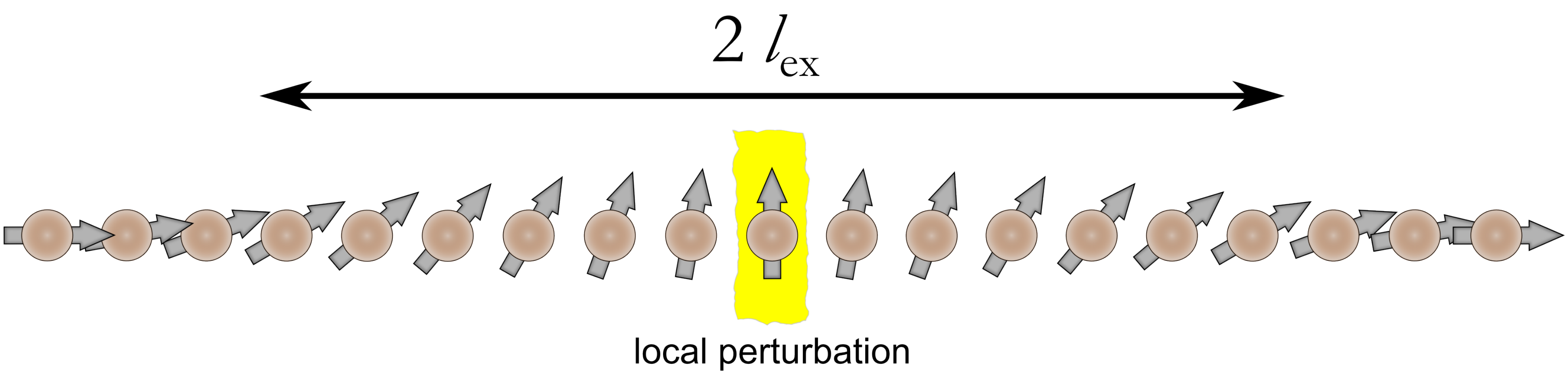
*that length is sometimes defined without ,,2” under square root [7].

Finite difference micromagnetism – exchange lengths

•The magnetostatic exchange length rarely exceeds a few nanometers in 3d ferromagnetic metals or alloys; it imposes a severe constraint on the mesh size in numerical simulations [10].

	l_k[nm]	l_s[nm]
α-Fe	21	3.3
Co	8.3	4.9
Ni	7	8.7
$SmCo_5$	0.84	5.3

table data from:
H. Kronmüller, M. Fähnle, Micromagnetism and the Microstructure of Ferromagnetic Solids, Cambridge University Press, 2003



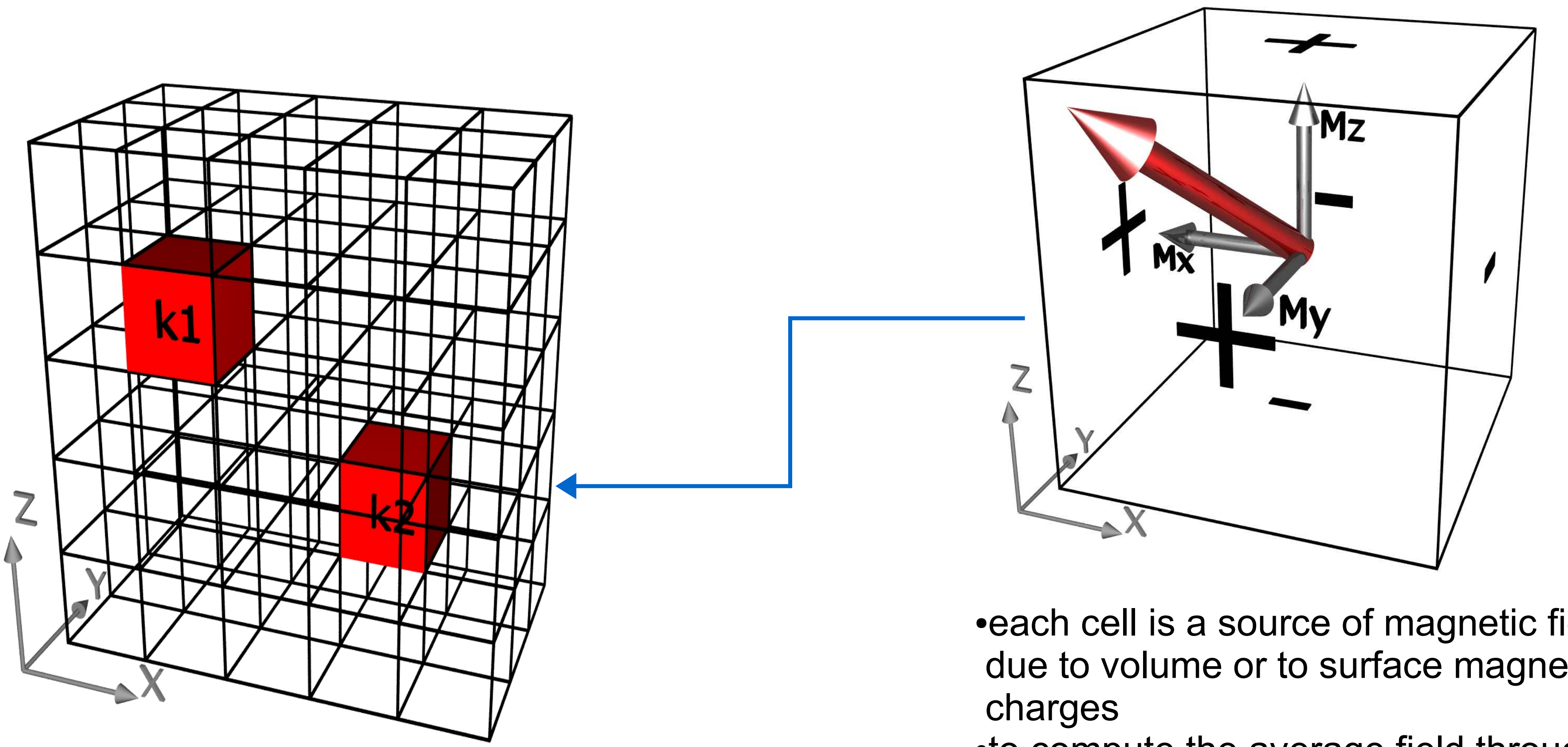
•At a distance roughly equal to the appropriate exchange length the spin configuration is that of unperturbed state:

- the local perturbation can be a grain with high magnetocrystalline anisotropy with easy direction perpendicular to the applied field (here, on the drawing, directed to the right)

-it can be laser-heated region of the sample in which magnetocrystalline anisotropy vanishes and the spin is directed along the external field (this time directed upward), etc.

Finite difference micromagnetism – exchange lengths

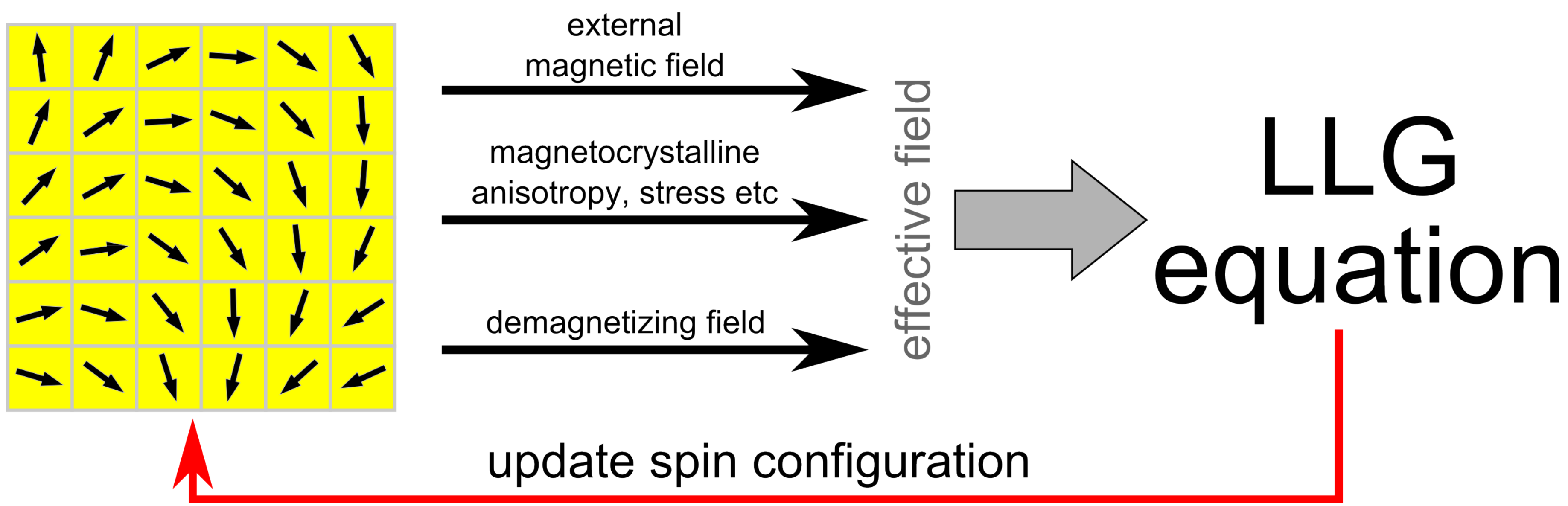
- In micromagnetic simulation every discretization cell interacts with every other cell by magnetostatic interactions .
- The shortest exchange length determines which energy term contributes the largest amount to the total energy [9].
- In soft magnetic materials the spin arrangements are more or less divergence free – **pole avoidance principle** [8].



- each cell is a source of magnetic field either due to volume or to surface magnetic charges
- to compute the average field through the cell the demagnetizing factors for rectangular ferromagnetic prisms are used.

Finite difference micromagnetism – calculation scheme

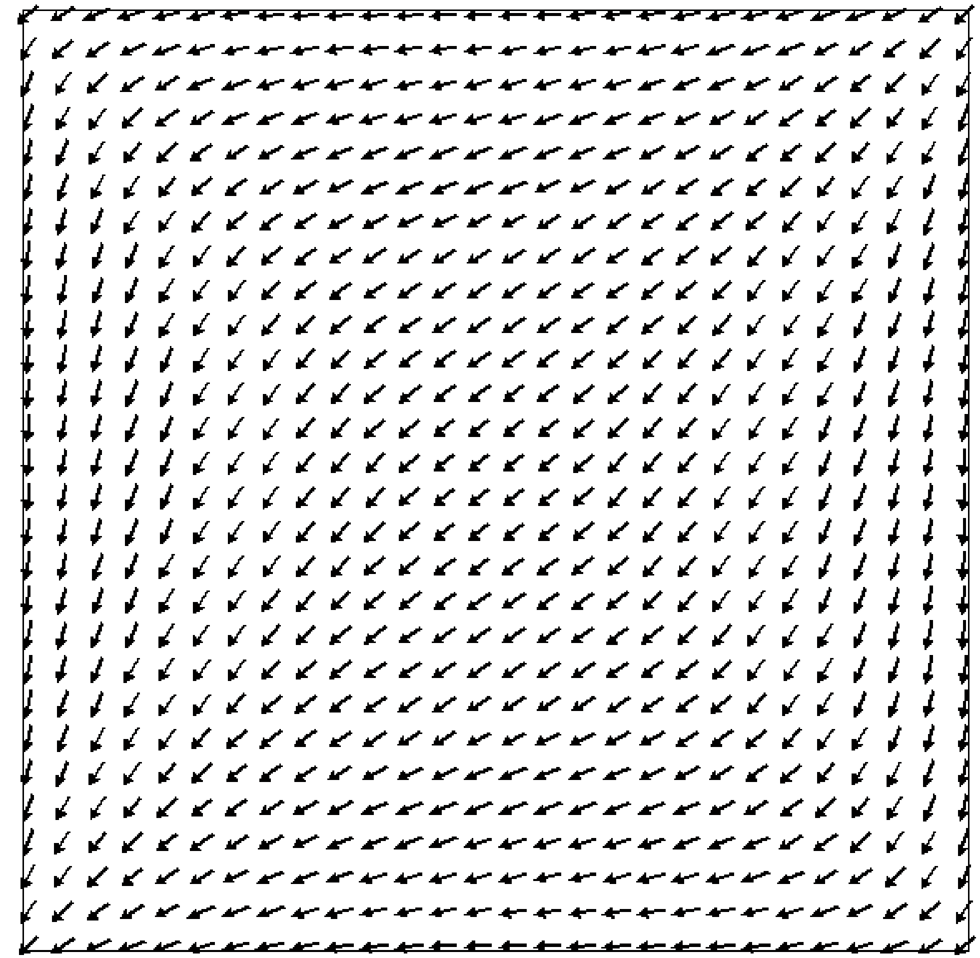
•In dynamic micromagnetic simulation the effective field is calculated as the input of LLG equation (for example OOMMF) [14].
•The magnetic moments of the cells are then updated according to angular velocities obtained from LLG equation.
•The time step is adjusted so that the "*the total energy of the system decreases, and the maximum error between the predicted and final M is smaller than a nominal value*" [14]



$$\frac{d\vec{m}}{dt} = \frac{\gamma}{(1+\alpha^2)}\vec{m}\times\vec{B} - \frac{\alpha}{(1+\alpha^2)}\frac{\gamma}{|\vec{m}|}\vec{m}\times\vec{m}\times\vec{B}$$

Finite difference micromagnetism – an example

- Remanent state of thin 900×900nm NiFe film; discretization cell 3×3×1nm
- Simulation time – 6ns (simulated with OOMMF [14])

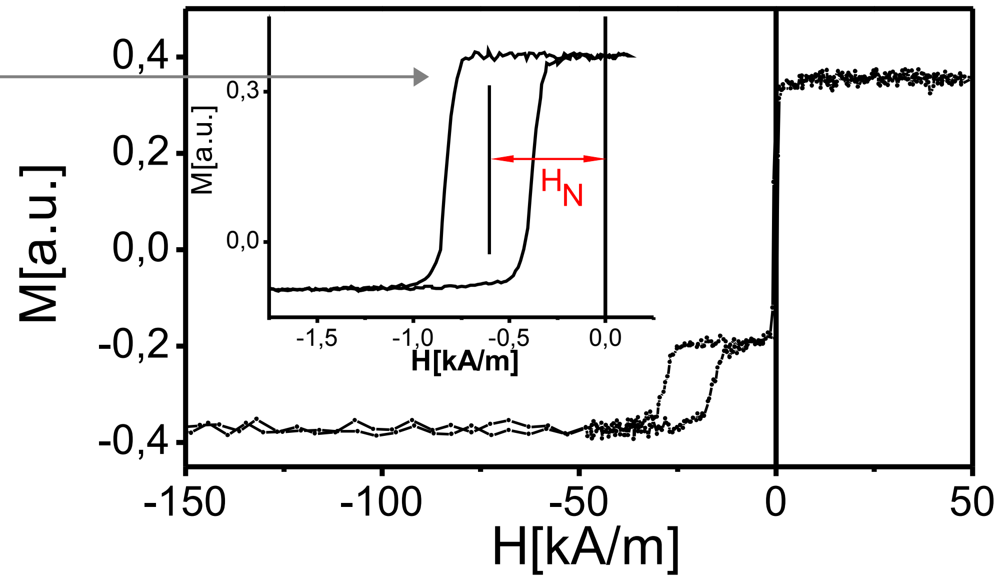


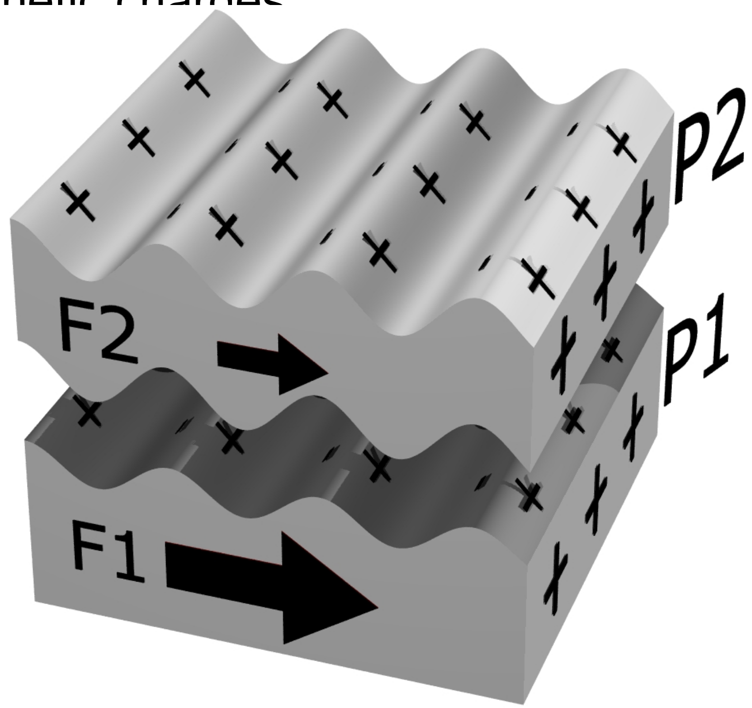
each arrow corresponds to 11×11 discretization cells

- Magnetization tends to be align along outer edges of the specimen – minimization of surface charges
- Exchange anisotropy forces moments to be parallel to each other – central part of the specimen

Orange peel coupling

- Orange peel (OP) coupling (Néel coupling) is due to the roughness of interfaces in thin magnetic films.
- The roughness results in the appearance of surface magnetic charges.
- The OP coupling leads to the relative shift of hystereses of neighboring ferromagnetic layers:





~~Si(100)/100nm~~ thermally oxidated Si/Cu(20nm)/ $Ni_{80}Fe_{20}$(10nm)/V(2.1nm)/$Ni_{80}Fe_{20}$(4nm)/$Mn_{83}Ir_{17}$(10nm)/Cu(3nm)

magnetically soft layer

exchange coupling

$$\vec{H} = -\nabla \varphi_m$$

$$\varphi_m(\vec{r}) = \oint_S \frac{\vec{M} \cdot \vec{ds}}{|\vec{r}|} - \int_V \frac{\nabla \cdot \vec{M}}{|\vec{r}|} d^3 r'$$

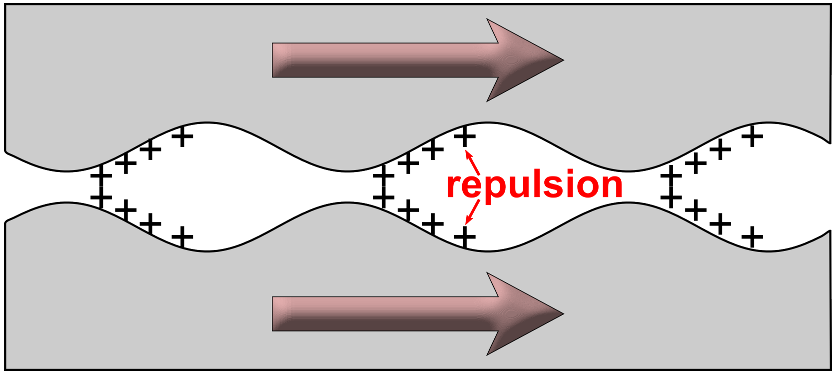
Orange peel coupling

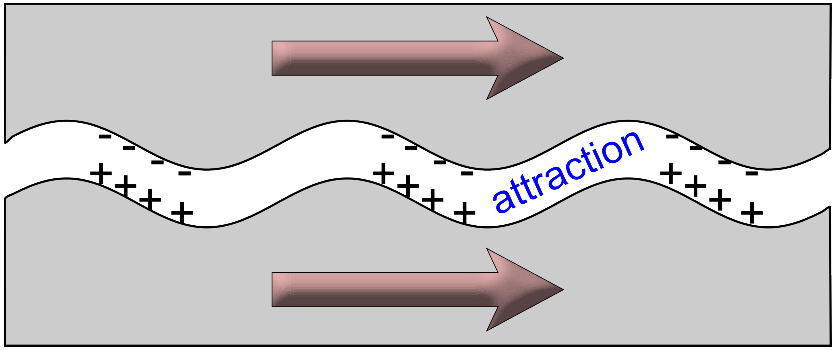
- Orange peel (OP) coupling is due to the roughnes of interfaces in thin magnetic films.
- The roughness results in the appearance of surface magnetic charges.
- The OP coupling leads to the relative shift of hystereses of neighboring ferromagnetic layers.
- If roughness profile on all interfaces is equal the shift field H_N can be shown to be given by (assuming that the hard layer is thick enough so that the influence of its second surface can be neglected):

$$H_N = \frac{\pi^2}{\sqrt{2}} \left(\frac{h^2}{\lambda t_f} \right) M_p e^{-2\pi \sqrt{2} t_s / \lambda}$$

λ -wavelength of roughness modulation, t_f-thickness of ,,free" ferromagnetic layer, *h*-roughness amplitude, M_P-saturation magnetization of hard (or pinned) magnetic layer

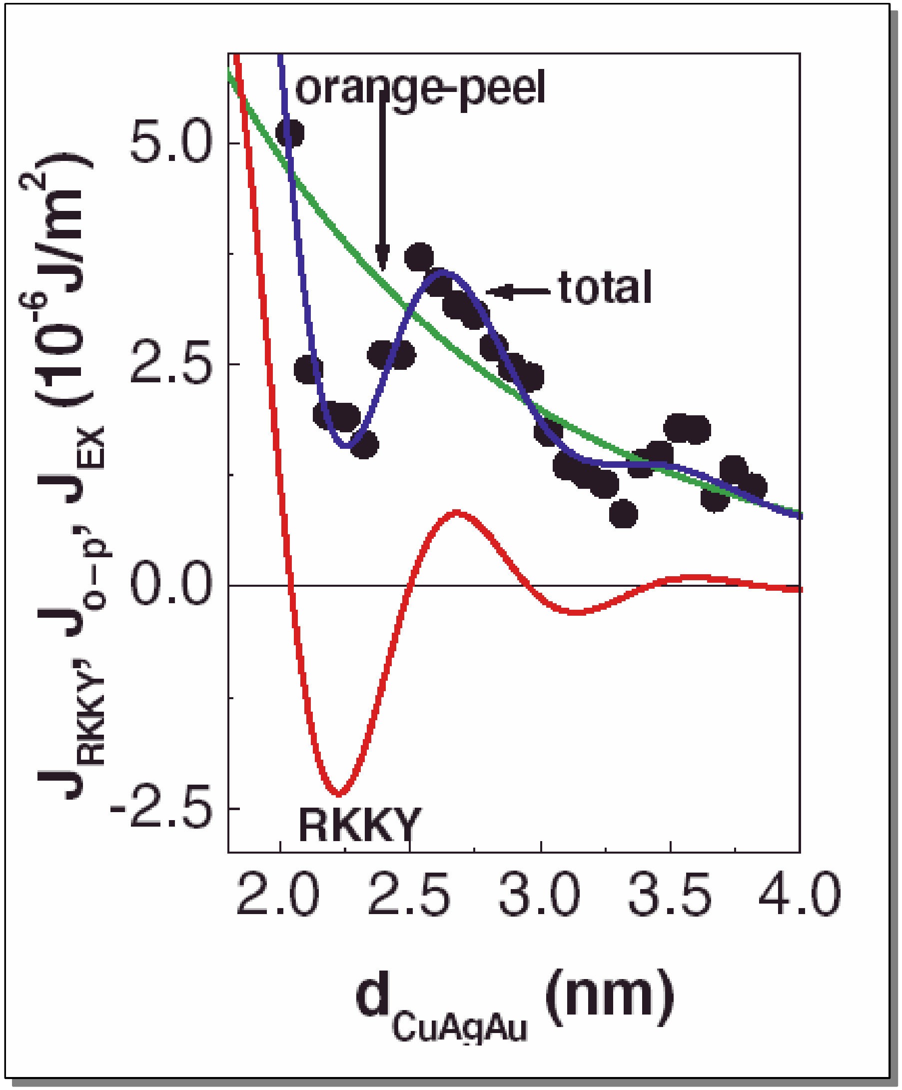
- The coupling may be ferromagnetic or antiferromagnetic depending on a phase difference between roughnesses of neighboring interfaces (with the same direction of magnetization in neighboring layers):





Orange peel coupling

•Orange peel coupling can be comparable in strength with RKKY oscillatory coupling



Py(2.5 nm)Co(2.5 nm)/CuAgAu(2,4 nm)/
Co(2.5 nm)

T. Luciński, A. Hütten, H. Brückl, T. Hempel, S. Heitmann, and G. Reiss
phys. stat. sol. (a) 196, No. 1, 97–100 (2003)

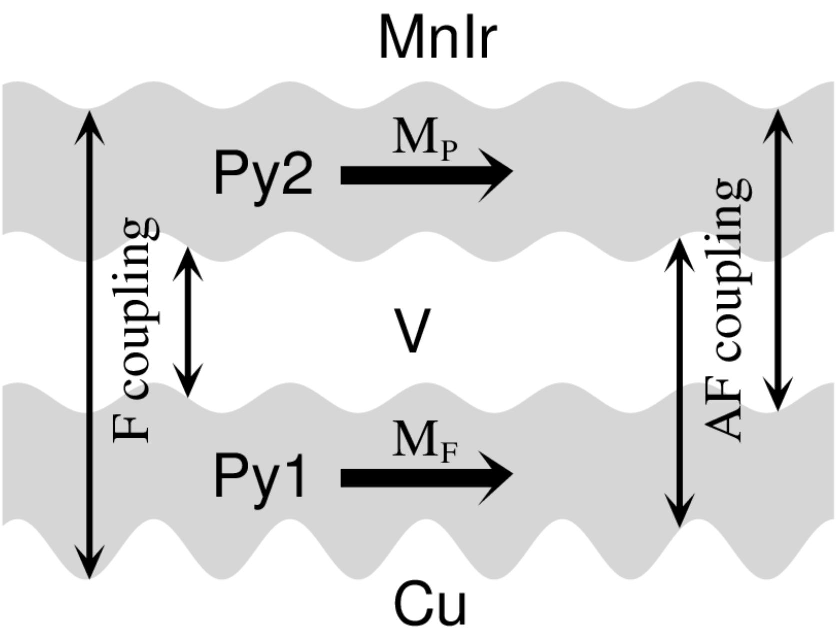
Orange peel coupling

- In his original paper Néel derived the coupling formula for the interaction between two semi-infinite magnetic layers
- The above description can be extended to the case of interacting thin films [16]:

\- in the case shown here there are four interactions to take into account

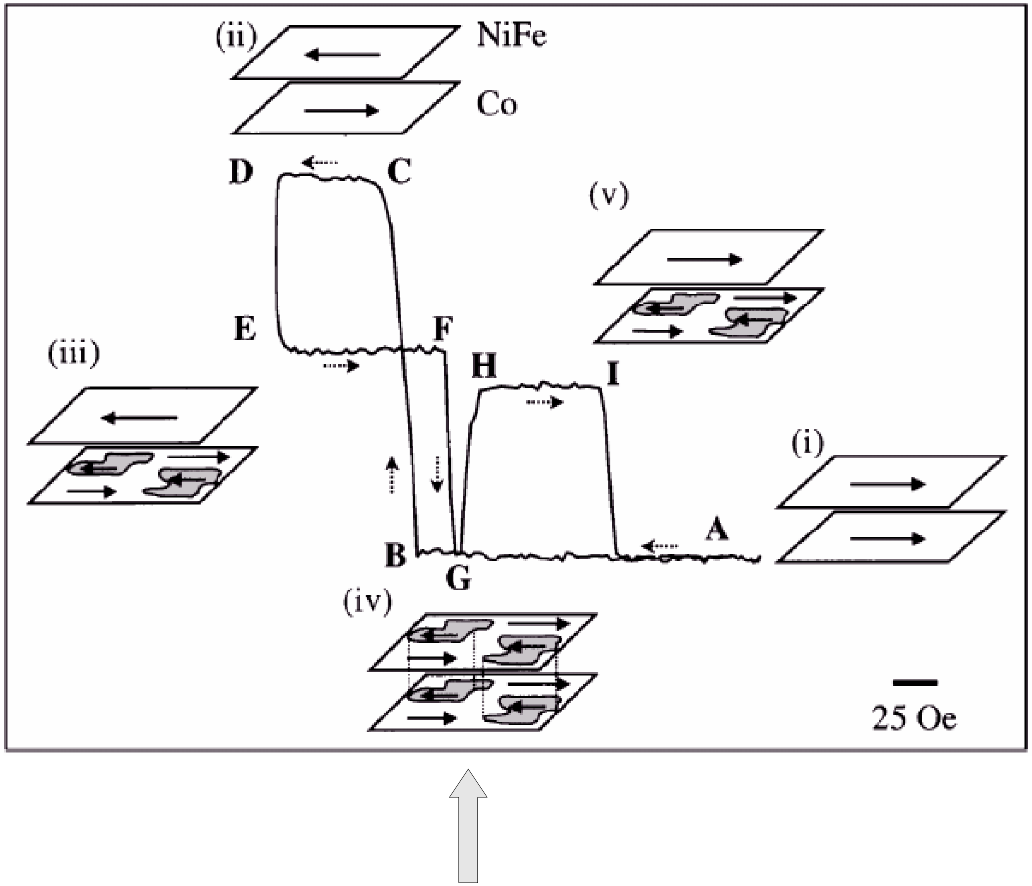
- The interaction between the bottom surface of Py1 layer and top surface of Py2 layer leads, for example, to the following contribution to shift field:

$$H_S = \frac{\pi^2}{\sqrt{2}} \left(\frac{h_1 h_2}{\lambda t_{Py1}} \right) M_p e^{-2\pi\sqrt{2}(t_{Py1}+t_V+t_{Py2})/\lambda}$$



Domain wall coupling

•Magnetic fields emanating from domain walls can influence magnetization reversal in neighboring layers

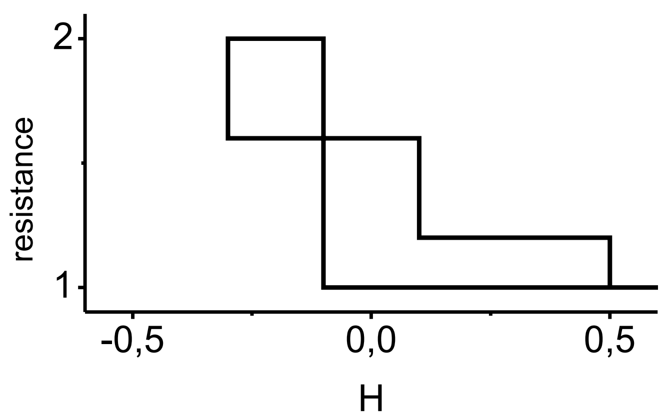


•GaAs(100)/Co(1.8nm)/Cu(**6nm**)/ **$Ni_{80}Fe_{20}$**(6nm)

•D→E: only part of Co layer reverses
•F→G: coupling

resistance decrease to absolute minimum- moments in neighboring layers parallel

Schematic of R(H) dependence without the coupling:



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- Blender www.blender.org
- Paint.Net www.getpaint.net

Special thanks are due to Google team as I used the searche engine but bought nothing from the ads.