Magnetization Processes I (and II)

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Tentative Title:
Magnetization processes in bulk materials and films, and control: H and E, current, strain, photons

Overarching Question:

How can we manipulate (switch) the magnetization ?

- Magnetic field
- Electric field (magneto-electricity, voltage control)
- Stress/strain (magneto-striction, phonons)
- Spin polarized current (spin transfer torque)
- Light

- Simple magnetization reversal prozesses (Stoner-Wohlfarth-model, buckling, curling) and hysteresis
- Effects of thermal agitation
- Magnetization reversal by domain wall motion
- Precessional magnetization reversal
- Magnetization reversal by spin polarized currents
- Electric field induced magnetization reversal
- Light induced magnetization reversal

mostly Blundell !

Technological Aspects

Short Introduction to Micromagnetics

Stoner Wohlfarth model

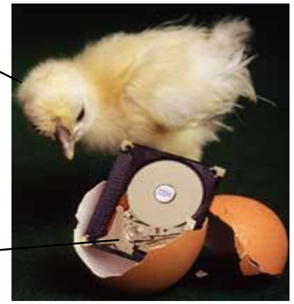
Temperature effects

Scaling

5 Mbyte

Microdrive 2000
15.2 Gbits/in^2
1 x 1” dia disk

1 Gbyte



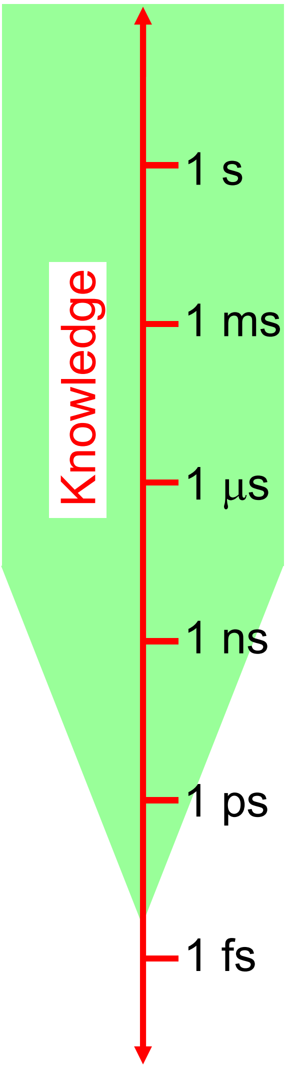
70 kbits/s

>100 Mbits/s

RAMAC 1956
2 kbits/in^2
50x 24 inch diameter disks

Source: Hitachi Global Storage

Time Scales for Magnetization Processes



Stability

Thermally activated magnetization processes (viscous regime, domain nucleation, domain growth)

Precessional Regime

(Precessional Switching)

Landau-Lifshitz-Gilbert equation:

$$\dot{\mathbf{M}} = -\gamma\, \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{\mathrm{M}} (\mathbf{M} \times \dot{\mathbf{M}})$$

Ultrafast demagnetization processes (optical excitation)

Technological Aspects

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Stoner Wohlfarth model

Temperature effects

The Energy Landscape / The Total Effective Field

Precessional Motion of a Single Spin (Quantum Mechanics)

The Landau-Lifshitz Equation

The Total Effective Field

- Zeeman-Energy E_z :

$$E_z = -\mu_0 M_s \int \vec{H}_{ext}(\vec{r}) \cdot \vec{m}(\vec{r})\, dV$$

where $\underline{M}(\underline{r},t) = M_s\, \underline{m}(r,t)$ ($|\underline{m}| = 1$)

- Exchange-Energy E_{ex} :

$$E_{ex} = A \int (grad\ \vec{m}(\vec{r}))^2\, dV$$

Attention:
Not the divergence
of a vector field !

(A: exchange constant)

Side note

Dzyaloshinskii-Moriya Interaction (DMI)

Isotropic exchange

$$E_{\text{exchange}} = -\frac{1}{2}\sum_{i\neq j} J_{ij}\vec{S}_i \cdot \vec{S}_j$$

General exchange

$$E_{\text{exchange}} = -\frac{1}{2}\sum_{i\neq j} \vec{S}_i^{\dagger} W_{ij} \vec{S}_j = -\frac{1}{2}\sum_{i\neq j}\left(\overbrace{J_{ij}\vec{S}_i \cdot \vec{S}_j}^{\text{isotropic}} + \overbrace{\vec{S}_i^{\dagger} W_{ij}^{\text{ani,s}} \vec{S}_j}^{\text{anisotropic symmetric}} + \overbrace{\vec{S}_i^{\dagger} W_{ij}^{\text{ani,as}} \vec{S}_j}^{\text{anisotropic antisymmetric}}\right)$$

$$W^{\text{ani,as}} = \begin{pmatrix} 0 & -D_z & D_y \\ D_z & 0 & -D_x \\ -D_y & D_x & 0 \end{pmatrix}, \quad \vec{D} = \begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix}$$

Usual DMI form

rewrite →

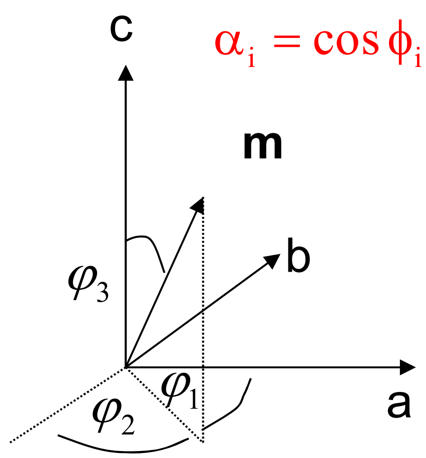
$$\vec{S}_i^{\dagger} W_{ij}^{\text{ani,as}} \vec{S}_j = \vec{D}_{ij} \cdot \left(\vec{S}_i \times \vec{S}_j\right)$$

Prerequisites:
- Broken inversion symmetry
- Spin-Orbit coupling

- Anisotropy-Energy E_{an} :

$$E_{an} = \int \varepsilon_{an}(\vec{m})\, dV \qquad E_{an}\left(\vec{m}\right) = K_0 + f(\alpha_1, \alpha_2, \alpha_2)$$

with the anisotropy energy density ε_{an}



cubic crystals:

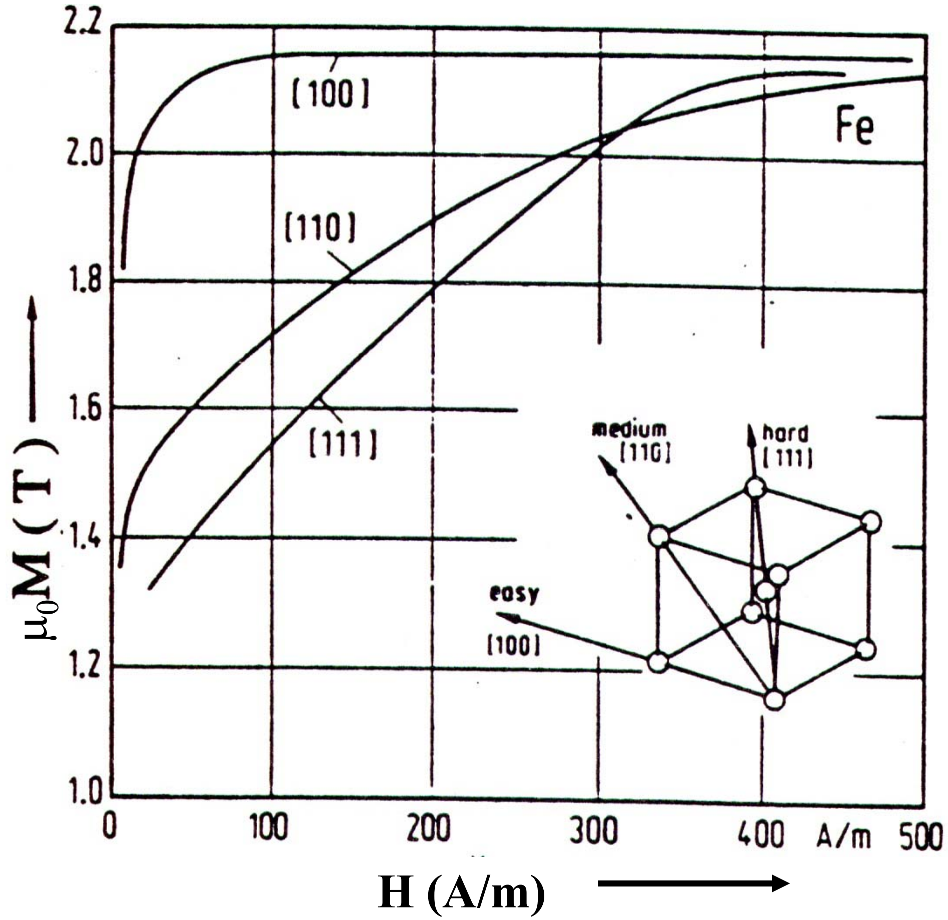
$$\varepsilon_{an} = K_1(m_x^2 m_y^2 + m_x^2 m_z^2 + m_y^2 m_z^2) + K_2(m_x^2 m_y^2 m_z^2)$$

uniaxial anisotropy (x-Axis = easy-Axis):

$$\varepsilon_{an} = - K_u m_x^2$$

(K_0, K_1 , K_2 , K_u : anisotropy constants)

Example: magneto-crystalline anisotropy of bulk Fe (bcc)



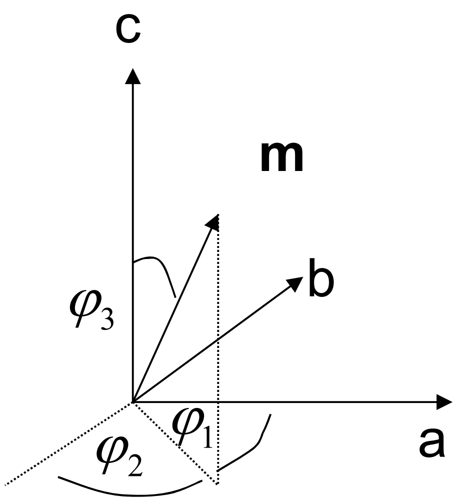
Bozorth

Magneto-crystalline anisotropies

For cubic crystals:

For symmetry reasons only terms containing $\alpha_i^{\;2}\left(\alpha_i^{\;4},....\right)$ can appear, since $\alpha_i \rightarrow -\alpha_i$

this means that terms with $\alpha_i\alpha_j\left(i \neq j\right)$ are not allowed



$$\alpha_i = \cos\varphi_i$$

$$E(\mathbf{m}) = K_0 + f(\alpha_1, \alpha_2, \alpha_2)$$

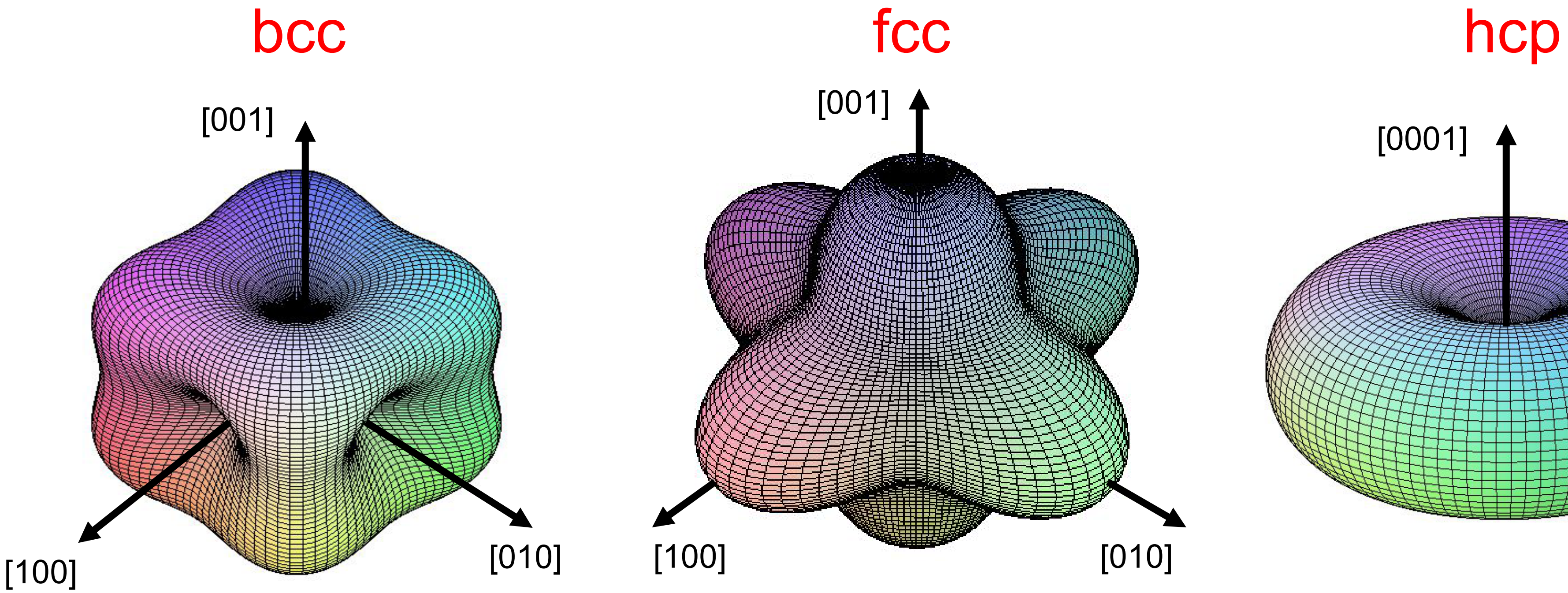
For cubic crystals no axis is special, thus

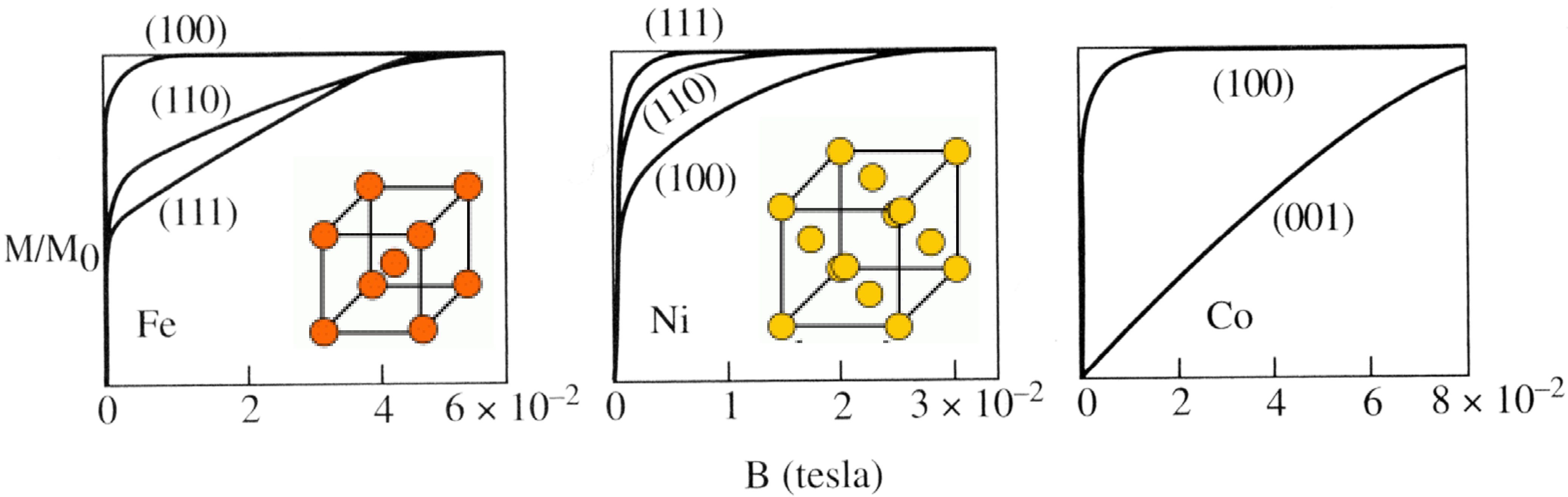
$$\alpha_1^{\;2}\alpha_2^{\;2} + \alpha_2^{\;2}\alpha_3^{\;2} + \alpha_1^{\;2}\alpha_3^{\;2}$$

It follows that:

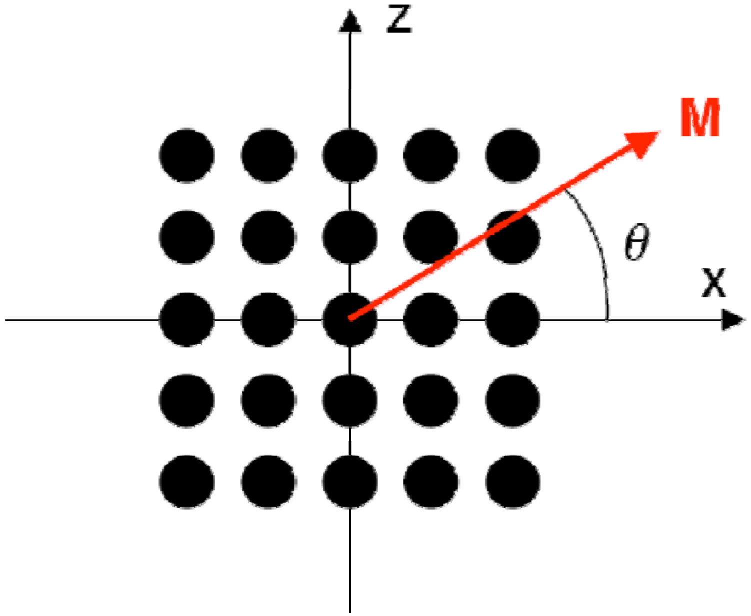
$$E(\mathbf{m}) = K_0 + K_1\left(\alpha_1^{\;2}\alpha_2^{\;2} + \alpha_2^{\;2}\alpha_3^{\;2} + \alpha_1^{\;2}\alpha_3^{\;2}\right) + K_2\alpha_1^{\;2}\alpha_2^{\;2}\alpha_3^{\;2}$$
$$+ K_3\left(\alpha_1^{\;2}\alpha_2^{\;2} + \alpha_2^{\;2}\alpha_3^{\;2} + \alpha_1^{\;2}\alpha_3^{\;2}\right)^2 + ...$$

Magneto-crystalline anisotropies in Fe, Ni und Co



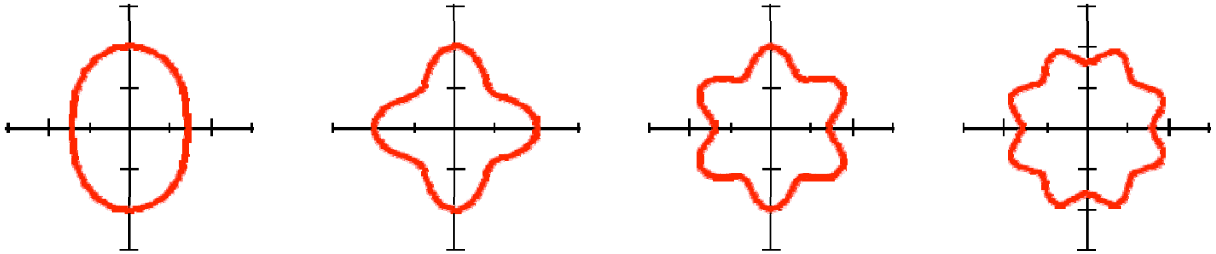


Magneto-crystalline anisotropies



Expand the angular dependence of the energy:

$$E(\theta) = K_0 \cos^2\theta + K_1 \cos^2 2\theta + K_2 \cos^2 3\theta + K_3 \cos^2 4\theta + \ldots$$

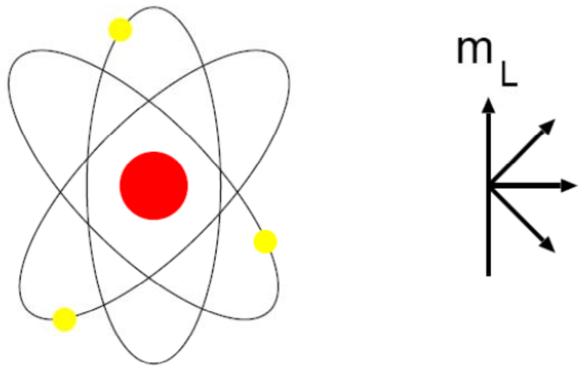


$K_0 = K_2 = 0$ for cubic symmetry ($x = z$)

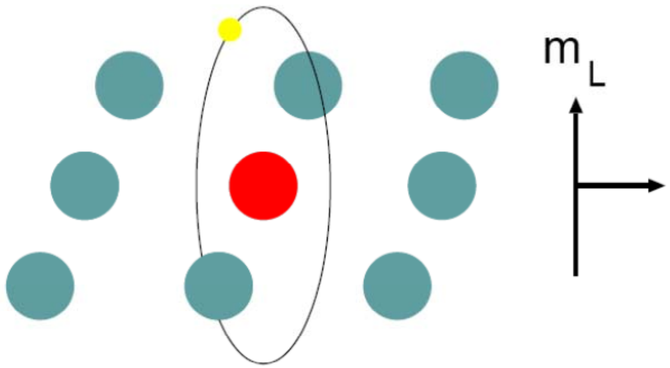
Origin of the magneto-crystalline anisotropy

- In a crystal the electron orbits are „tied“ to the lattice due to the crystal field.
  → L is quenched but not completely

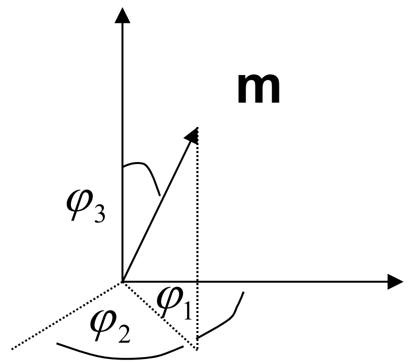
- Spin-orbit coupling mediates the energetic anisotropy with respect to the orientation of the magnetic moment



free atom



crystal



$$E(\mathbf{m}) = K_0 + f(\alpha_1, \alpha_2, \alpha_2)$$

$$\alpha_i = \cos \varphi_i$$

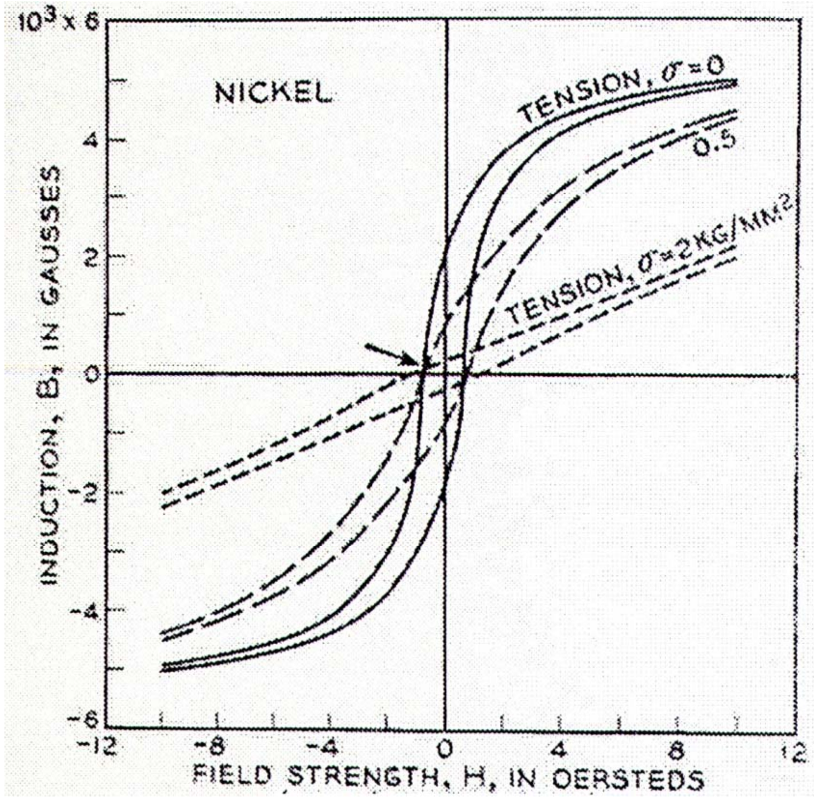
Energy functional and angles. The functional dependence results from the symmetry, the strength from the SOC

For simplicity we almost always assume only the uniaxial anisotropy in the following

$$\varepsilon_{an} = -K_u m_x^2$$

Magneto-striction and magneto-elastic coupling

Mechanical strain/stress breaks the crystal symmetry and an additional contribution to the energy density results:



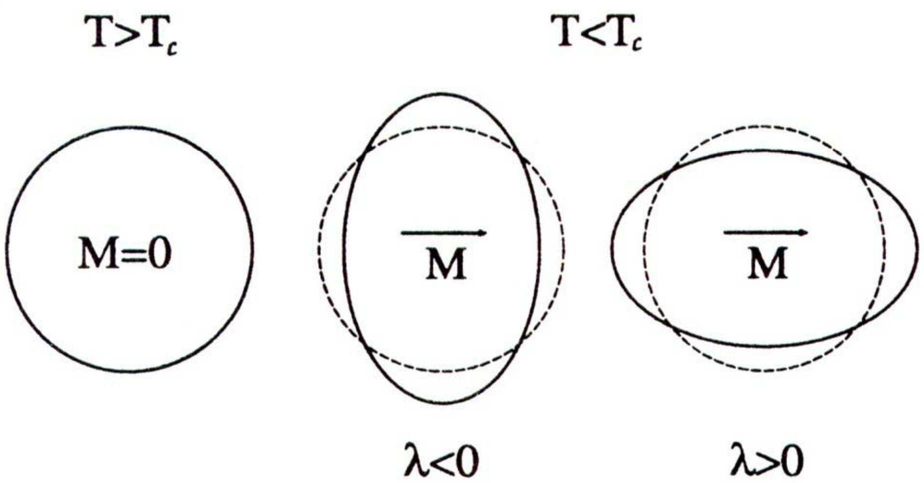
$$E = \varepsilon K \sin^2\theta \qquad \sigma = C\varepsilon$$

$\varepsilon\ldots$ tension in % $\qquad \sigma\ldots$ stress

Inverse effect: The magnetization leads to a slight deformation of the sample.

$$E = \varepsilon K \sin^2\theta + \frac{1}{2}C\varepsilon^2 \qquad \frac{\partial E}{\partial \varepsilon} = 0$$

$$\lambda = -\frac{K}{C}\sin\theta$$



Length change:

$$\Delta l / l \approx 10^{-5}$$

experimental verification and measurement by cantilever method!

- Strayfield-Energy E_d :

$$E_d = -\frac{1}{2}\mu_0 \int \vec{H}_d(\vec{r}) \cdot \vec{M}(\vec{r})\, dV$$

the strayfield $\underline{H}_d$ is given by

$$\text{div}\, \vec{H}_d(\vec{r}) = -\, \text{div}\, (\vec{M})$$

(from Maxwell's equations)

because *rot* $\underline{H}_d = 0$ we can express $\underline{H}_d$ via a skalar potential Φ_d :

$$\vec{H}_d(\vec{r}) = -\, grad\, \Phi_d(\vec{r})$$

where

$$\Phi_d(\vec{r}) = \frac{M_s}{4\pi}\left[\int \frac{-\text{div}\, \vec{m}(\vec{r}')}{|\vec{r}-\vec{r}'|}\, dV' + \int \frac{\vec{m}(\vec{r}') \cdot \vec{n}(\vec{r}')}{|\vec{r}-\vec{r}'|}\, dS'\right]$$

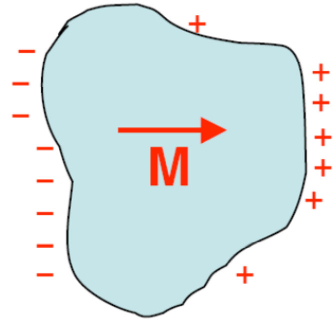
Simplification:

We consider only the demagnetizing field of an ellipsoid

Shape anisotropy

Demagnetizing field for sphere, wire and thin film

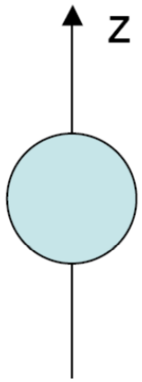
Energy (density): $E_{demag} = -\frac{1}{2}\mu_0 \mathbf{M}\cdot\mathbf{H}_{demag}$



In general: $\mathbf{H}_{demag} = -\mathcal{D}\mathbf{M}$

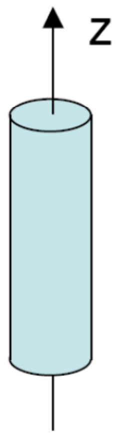
Demagnetizing tensor D: $(\mathrm{tr}\,\mathcal{D} = 1)$

Sphere



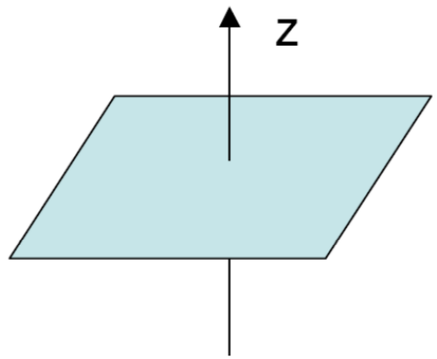
$$\mathcal{D} = \begin{pmatrix} \frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{3} \end{pmatrix}$$

Infinitely long wire



$$\mathcal{D} = \begin{pmatrix} \frac{1}{2} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Infinite thin film

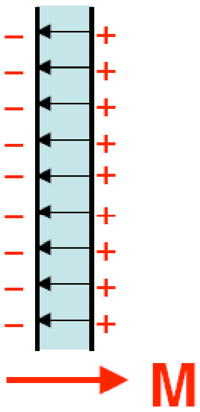


$$\mathcal{D} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

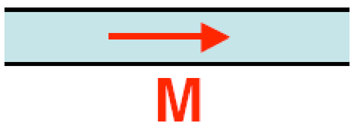
shape anisotropy

Thin film

$$\mathbf{H}_{demag} = -\mathbf{M}$$

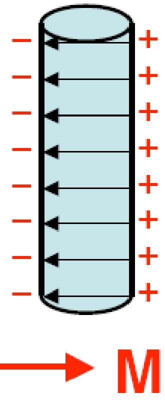


$$\mathbf{H}_{demag} = 0$$

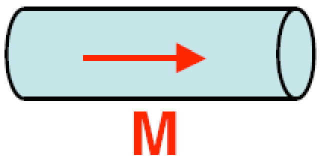


Thin wire

$$\mathbf{H}_{demag} = -\tfrac{1}{2}\mathbf{M}$$

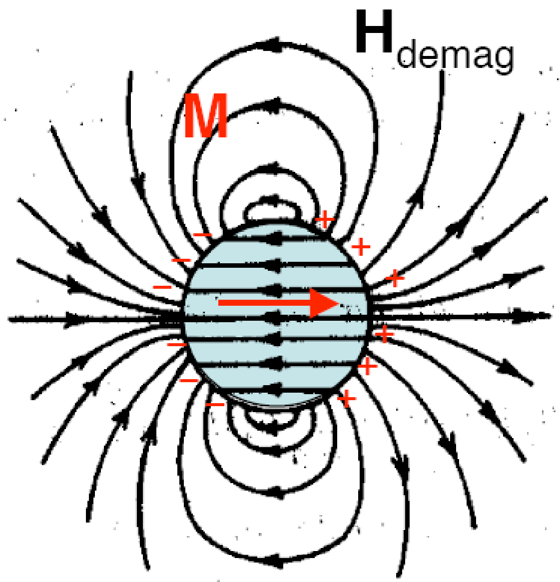


$$\mathbf{H}_{demag} = 0$$

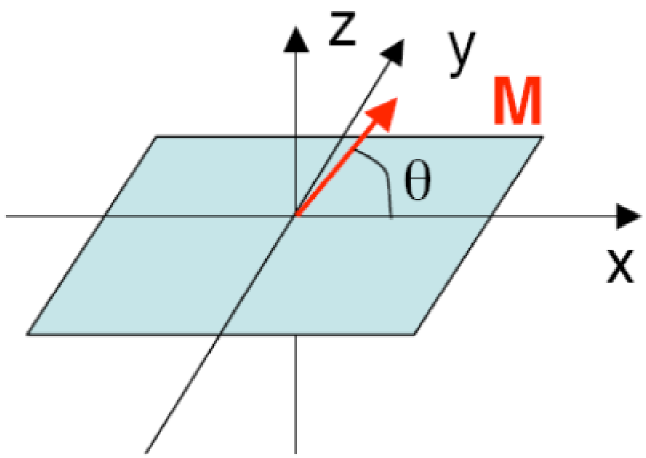


Sphere

$$\mathbf{H}_{demag} = -\tfrac{1}{3}\mathbf{M}$$



Demagnetizing field for an infinite thin film



$$\mathbf{M} = M\begin{pmatrix}\cos\Theta \\ 0 \\ \sin\Theta\end{pmatrix} \qquad \mathcal{D} = \begin{pmatrix}0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1\end{pmatrix}$$

$$\boxed{E_{demag}} = \frac{1}{2}\mu_0 \mathbf{M}\mathcal{D}\mathbf{M} = \frac{1}{2}\mu_0 M^2 \begin{pmatrix}\cos\Theta \\ 0 \\ \sin\Theta\end{pmatrix}\begin{pmatrix}0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\Theta \\ 0 \\ \sin\Theta\end{pmatrix} =$$

$$= \frac{1}{2}\mu_0 M^2 \begin{pmatrix}\cos\Theta \\ 0 \\ \sin\Theta\end{pmatrix}\begin{pmatrix}0 \\ 0 \\ \sin\Theta\end{pmatrix} = \boxed{\frac{1}{2}\mu_0 M^2 \sin^2\Theta}$$

Technological Aspects

Short Introduction to Micromagnetics

Stoner Wohlfarth model

Temperature effects

Equilibrium of the magnetization in an applied field

Consider only shape anisotropy and Zeeman energy

Energy minimization with respect to the angle:

$$\frac{\partial E}{V\partial\theta} = 0 = -M_s^{\ 2}\sin\theta\cos\theta + M_s H\sin\theta$$

$$0 = -M_s\cos\theta + H$$

$$\cos\theta = \frac{H}{M_s}$$

Magnetization component M(H)

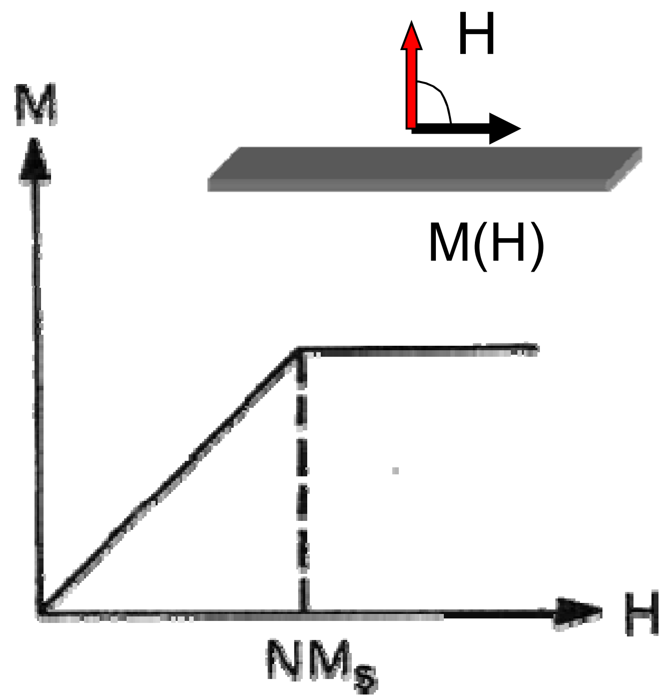
$$M(H) = M_S\cos\theta = H$$

M increases linearly until the value

$$H = M_S$$

Is reached. In general we obtain:

$$H = NM_S$$

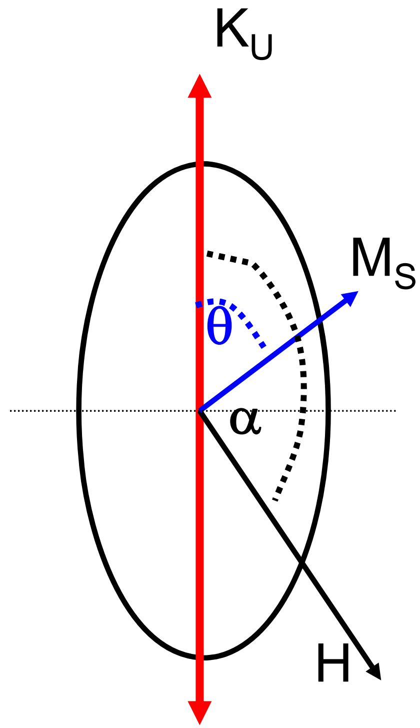


Uniform rotation: Stoner-Wohlfarth model (1949)

Calculation of hysteresis loops:

Ideal magnetizion loop of a magnetic particle with uniaxial anisotropy (e.g. ellipsoid with short axes a=b, and long axis c)

For K_U>0 the c-axis is the easy axis of the magnetization.



Total energy for the determination of the minimum energy and thus the angle θ (α,H,M,K_U):

Anisotropy energy: $E_{Aniso} = K_0 + K_U \sin^2\theta$

Zeeman energy: $E_{Zeeman} = -\mu_0 HM\cos(\alpha-\theta)$

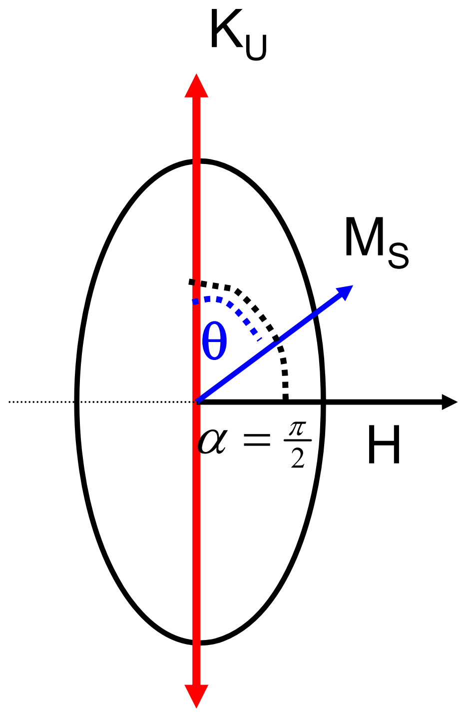
Energy minimum $\frac{\partial E}{\partial\theta} = 0 \quad \frac{\partial^2 E}{\partial\theta^2} > 0$

$$\frac{\partial E}{\partial\theta} = 2K_U \sin\theta\cos\theta - \mu_0 HM_S \sin(\alpha-\theta) = 0$$

Stoner-Wohlfarth model $\alpha=\pi/2$

Calculation of Hysteresis loops for $\alpha = \frac{\pi}{2}$

We search for the magnetization along the direction of H



$$\frac{\partial E}{\partial \theta} = 2K_U \sin\theta\cos\theta - \mu_0 H M_S \sin(\tfrac{\pi}{2} - \theta)$$

$$0 = 2K_U \sin\theta\cos\theta - \mu_0 H M_S \cos\theta$$

$$\Rightarrow \cos\theta = 0 \Rightarrow \theta = \frac{\pi}{2}, \frac{3\pi}{2}$$

or

$$2K_U \sin\theta = \mu_0 M_S H$$

$$\sin\theta = \frac{M_S}{2K_U}\mu_0 H$$

With the magnetization component M in the direction of H

$$M(H) = M_S \sin\theta \Rightarrow \frac{M(H)}{M_S} = \frac{M_S}{2K_U}\mu_0 H$$

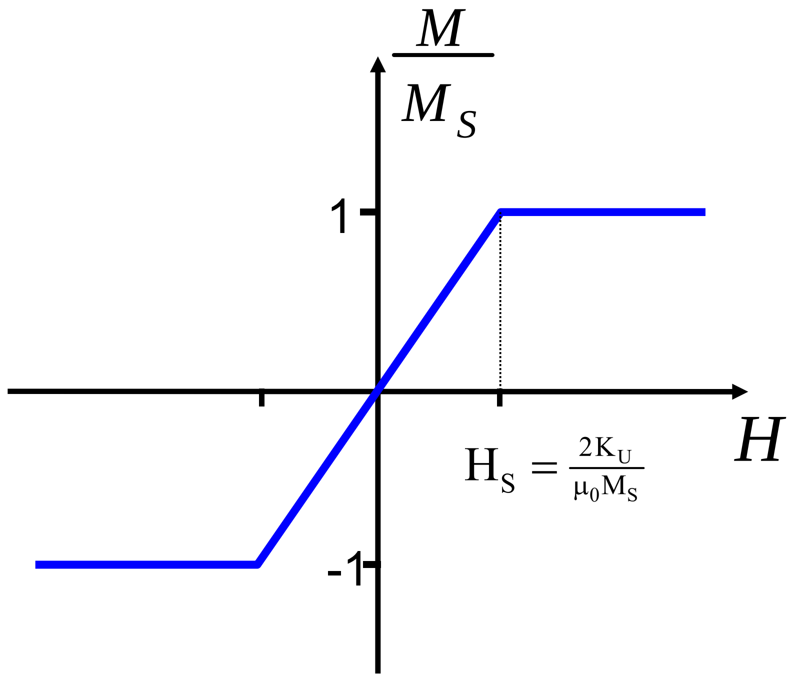
Saturation is reached for:

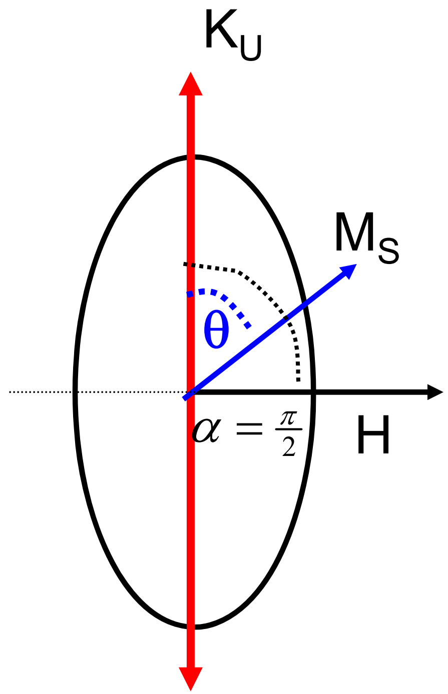
$$1 = \frac{M_S}{2K_U}\mu_0 H$$

$$H_S = \frac{2K_U}{\mu_0 M_S}$$

Stoner-Wohlfarth model $\alpha=\pi/2$

Calculation of magnetization „loop" for $\alpha = \frac{\pi}{2}$





For H perpendicular to the easy axis
M grows linearly with H

$$H_S = \frac{2K_U}{\mu_0 M_S}$$

$$\frac{M(H)}{M_S} = \frac{M_S}{2K_U}\mu_0 H$$

Stoner-Wohlfarth model $\alpha=0,\pi$

Calculation of magnetization loop for $\alpha = 0, \pi$

$$\frac{\partial E}{\partial \theta} = 2K_U \sin\theta \cos\theta + \mu_0 H M_S \sin\theta = 0$$

$$\sin\theta = 0 \quad \Rightarrow \quad \theta = 0, \pi$$

or

$$2K_U \cos(\theta) = -\mu_0 M_S H$$

$$\cos(\theta) = -\frac{M_S}{2K_U}\mu_0 H$$

No minimum since $\frac{\partial^2 E}{\partial \theta^2} \leq 0$

This means that the magnetization jumps between the two values

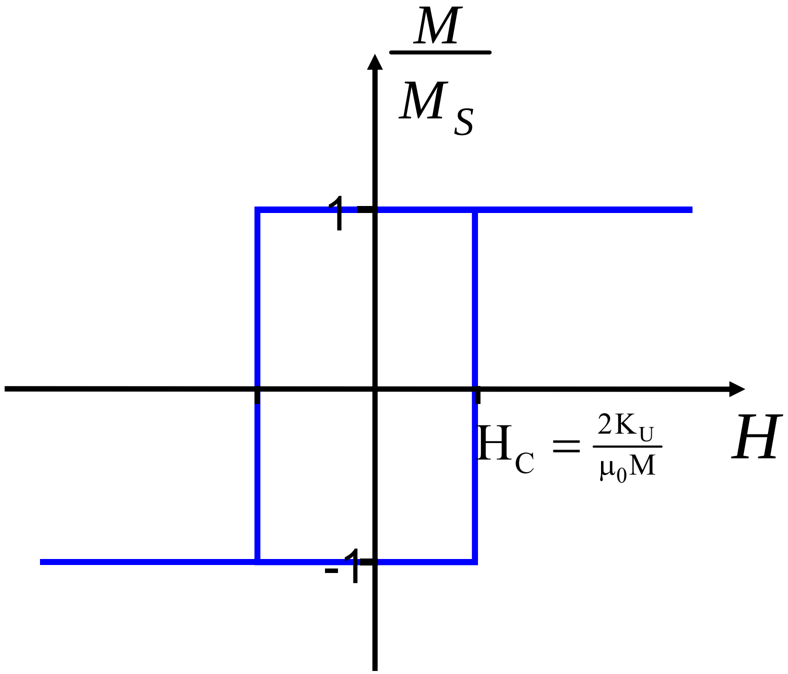
$$\theta = 0, \pi \qquad \frac{M(H)}{M_S} = -1, 1$$

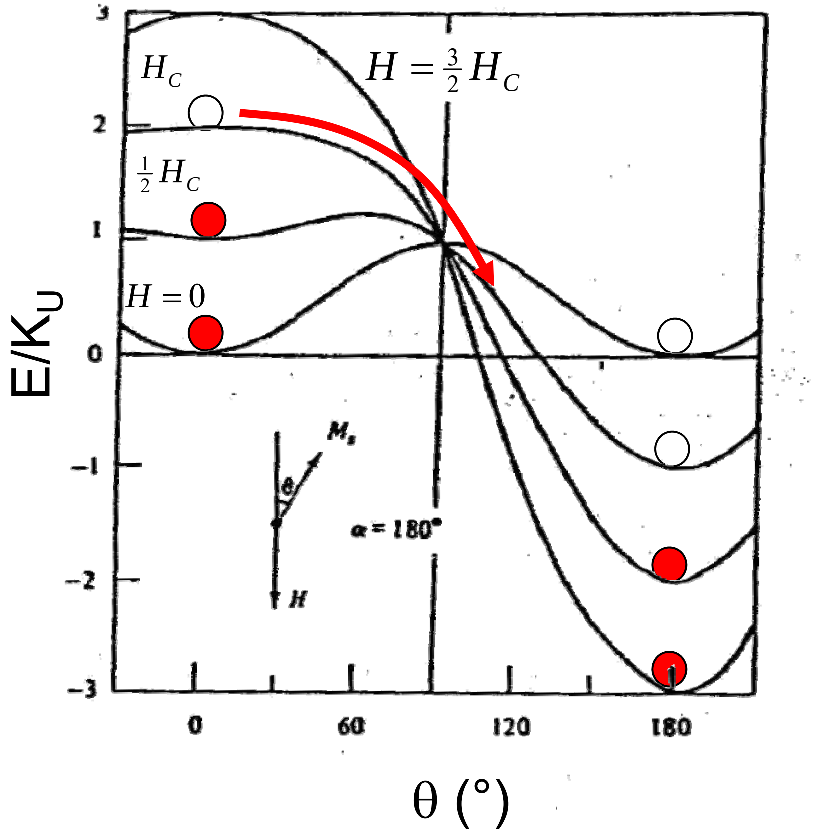
The magnetic field at which M jumps is

$$1 = \frac{M_S}{2K_U}\mu_0 H \quad \Rightarrow \quad H_C = \frac{2K_U}{\mu_0 M_S}$$

Stoner-Wohlfarth model $\alpha=0,\pi$

Calculation of hysteresis loops: $\alpha = 0, \pi$





Solutions are only $\theta = 0, \pi$

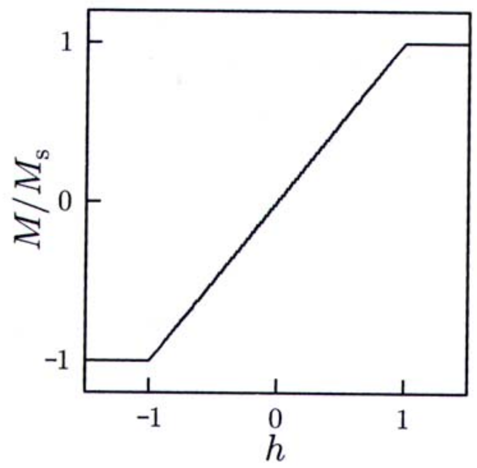
The magnetization jumps between $\frac{M(H)}{M_S} =$ -1 and 1

The coercive field is $H_C = \frac{2K_U}{\mu_0 M_S}$

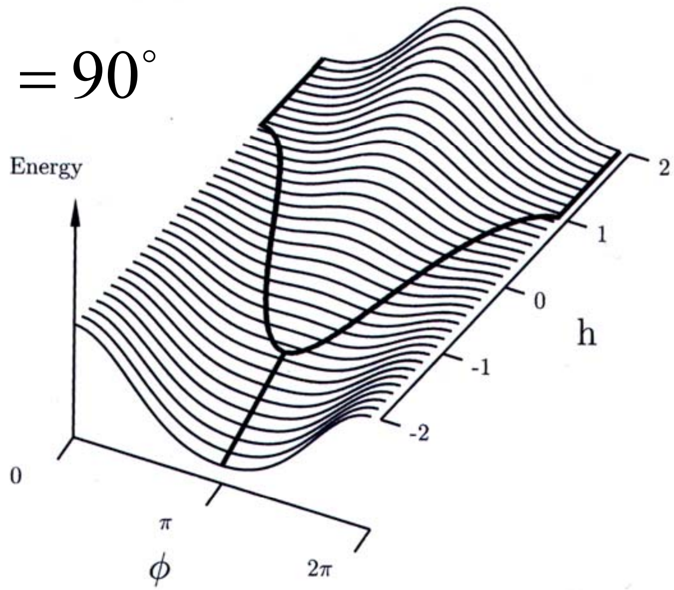
Stoner-Wohlfarth model: energy landscape

Energy landscape for both extremes:

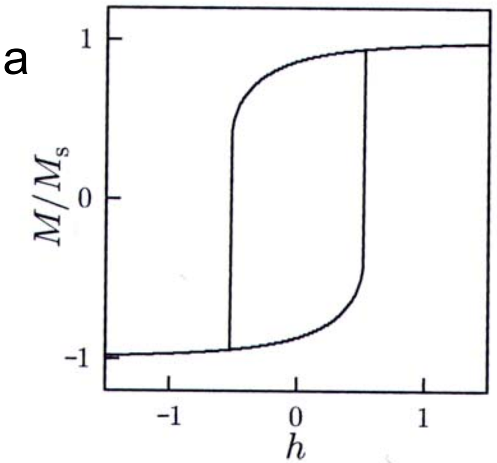
#1
Steady rotation from 90° to -90°



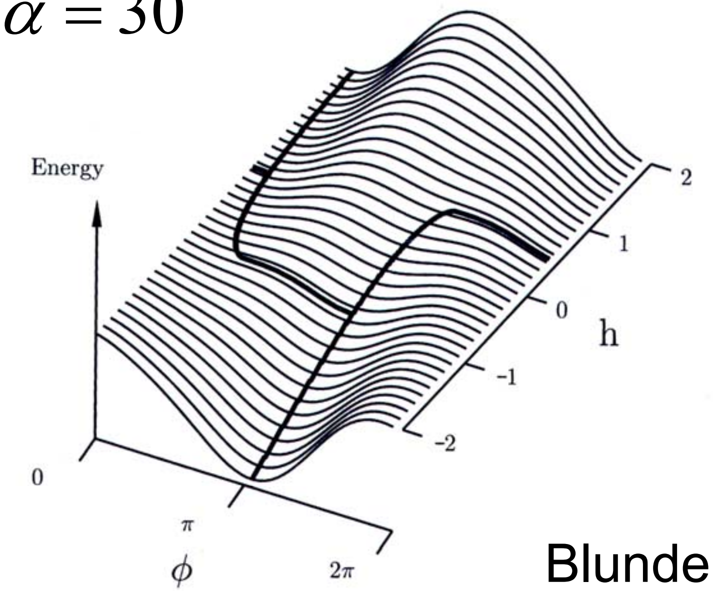
$\alpha = 90^\circ$



#2
Jump into the second minimum via a saddle point



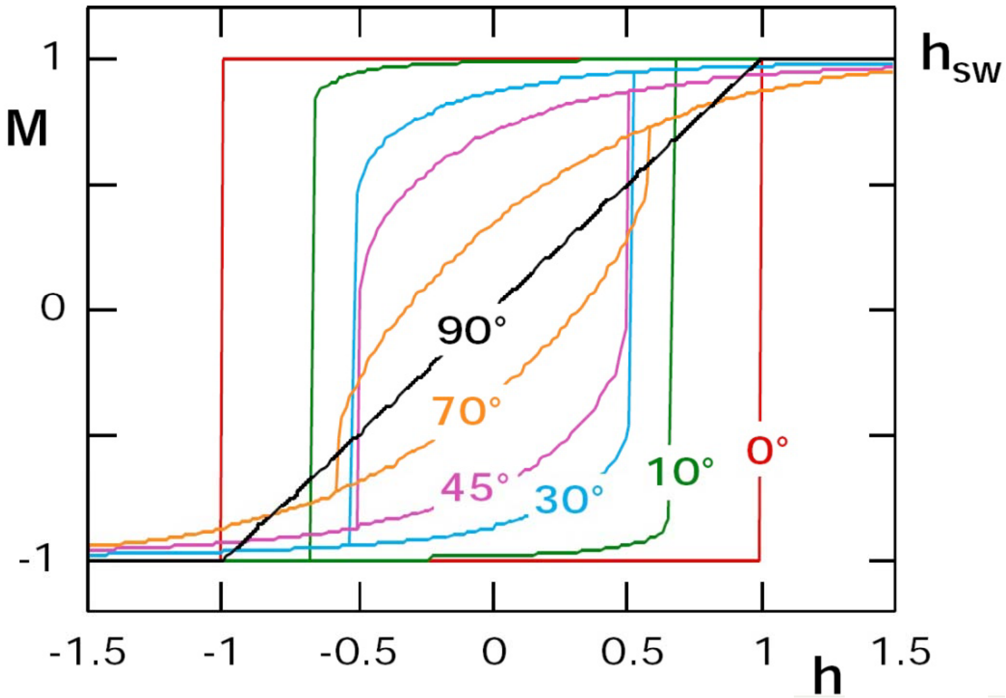
$\alpha = 30^\circ$



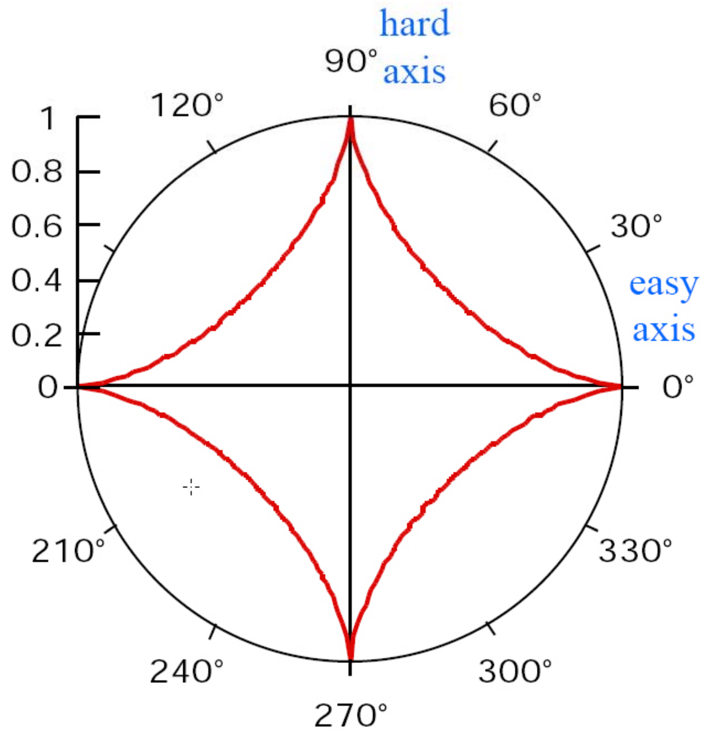
Blundell

Stoner-Wohlfarth Astroid

Hysteresis loops for various angles α



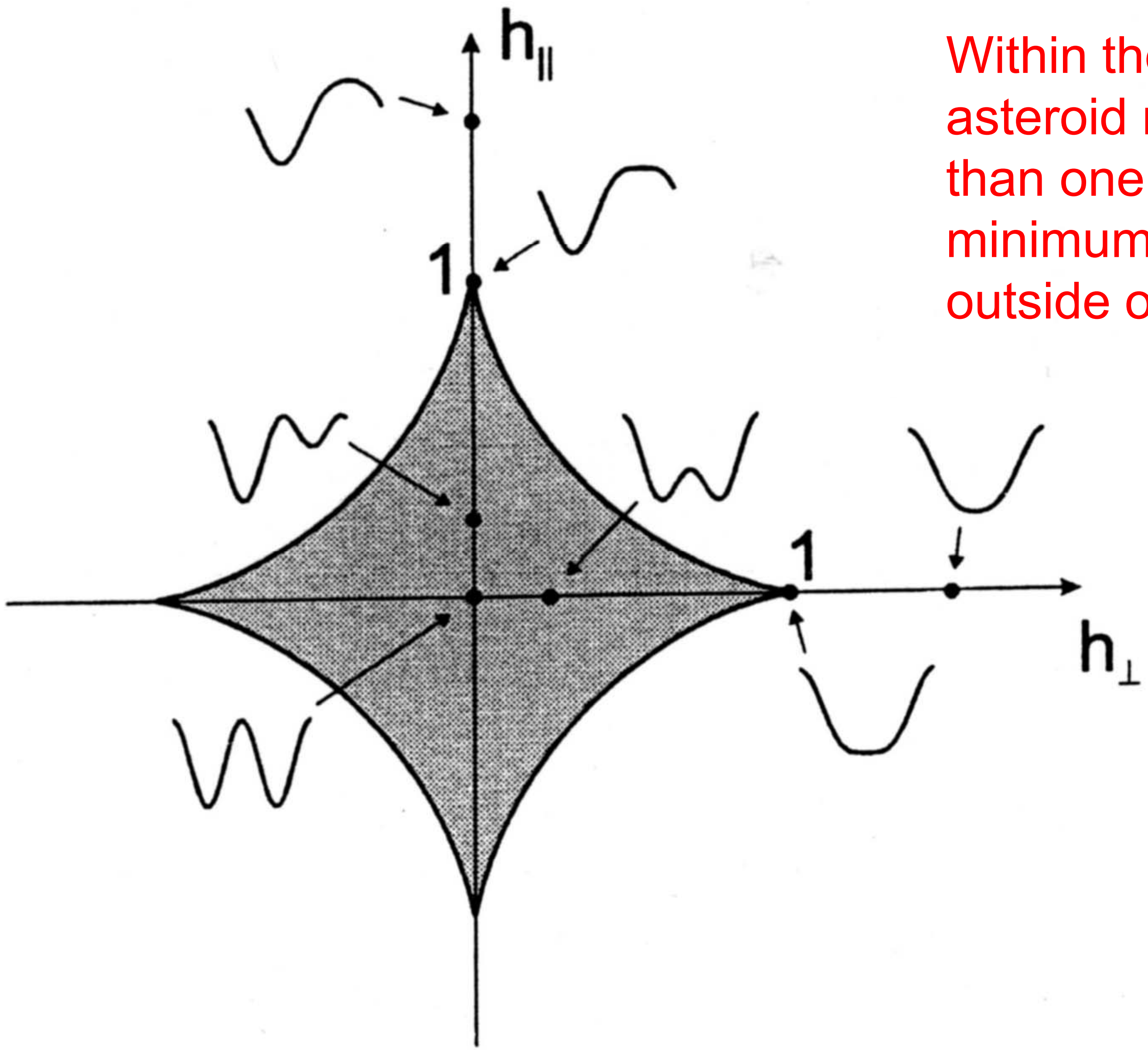
Switching behavior



Stoner - Wohlfarth astroid

For arbitrary angles one obtains a mixture of both cases. The coercive fields (H_C) for switching into the stable minimum for arbitrary directions show a minimum. The switching fields for coherent rotation can be summarized in the switching asteroid.

Stoner-Wohlfarth astroid



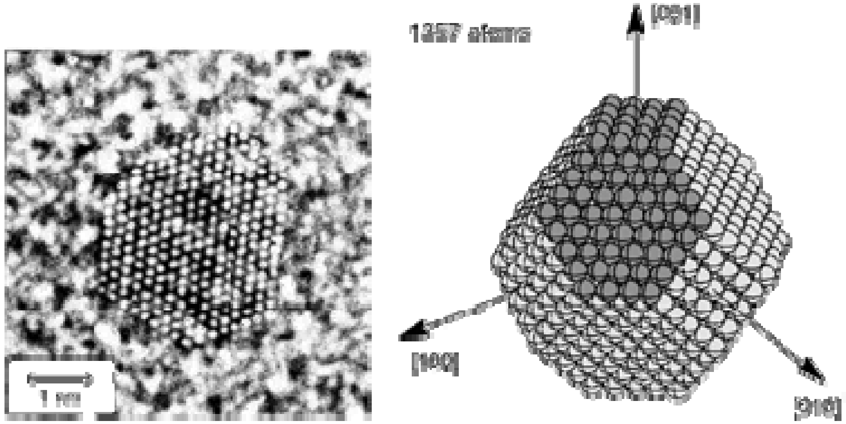
Within the asteroid more than one minimum exists, outside only one!

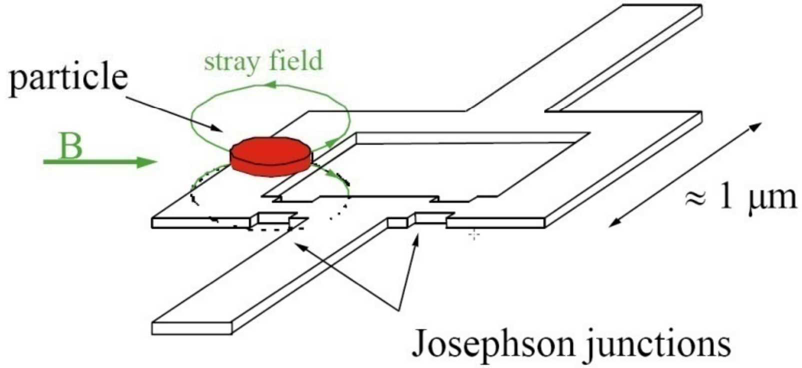
Stoner-Wohlfarth model: experiment

SQUID: Superconducting Quantum Interference Device

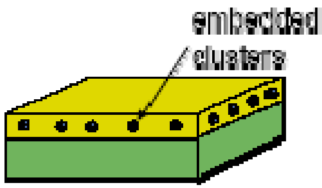
Sensitive method for the measurement of single clusters (2 nm Diameter, corresponding to 10^2-10^3 atoms)

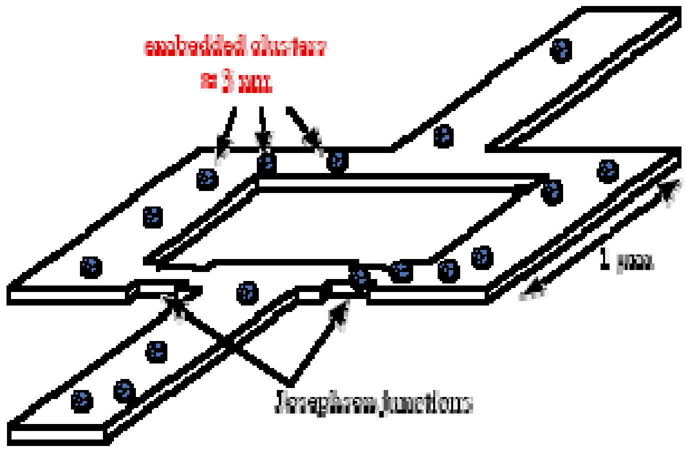
Micro-SQUID magnetometry





3 nm Co Cluster, embedded in a Niobium film.





Wernsdofer et al. PRL 2002
Jamet et al. PRL 2001

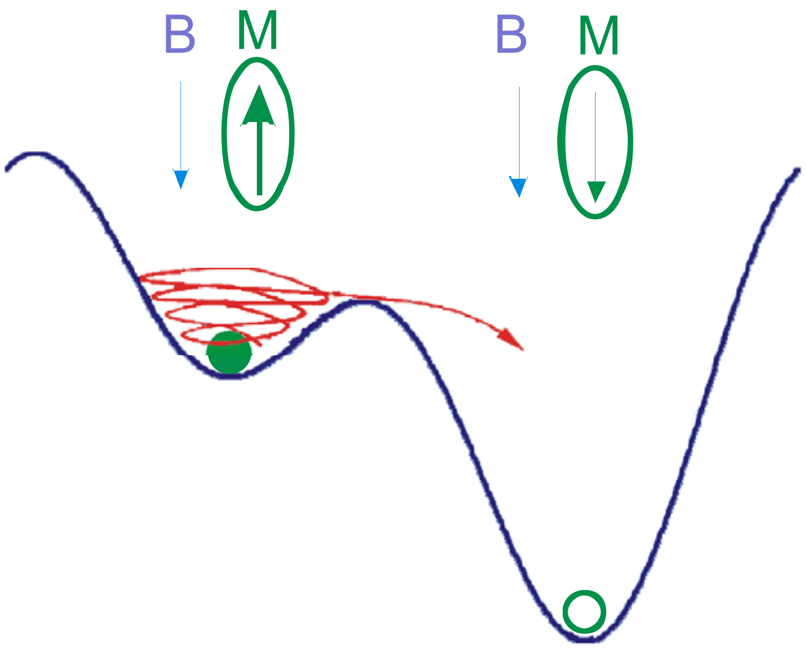
Technological Aspects

Short Introduction to Micromagnetics

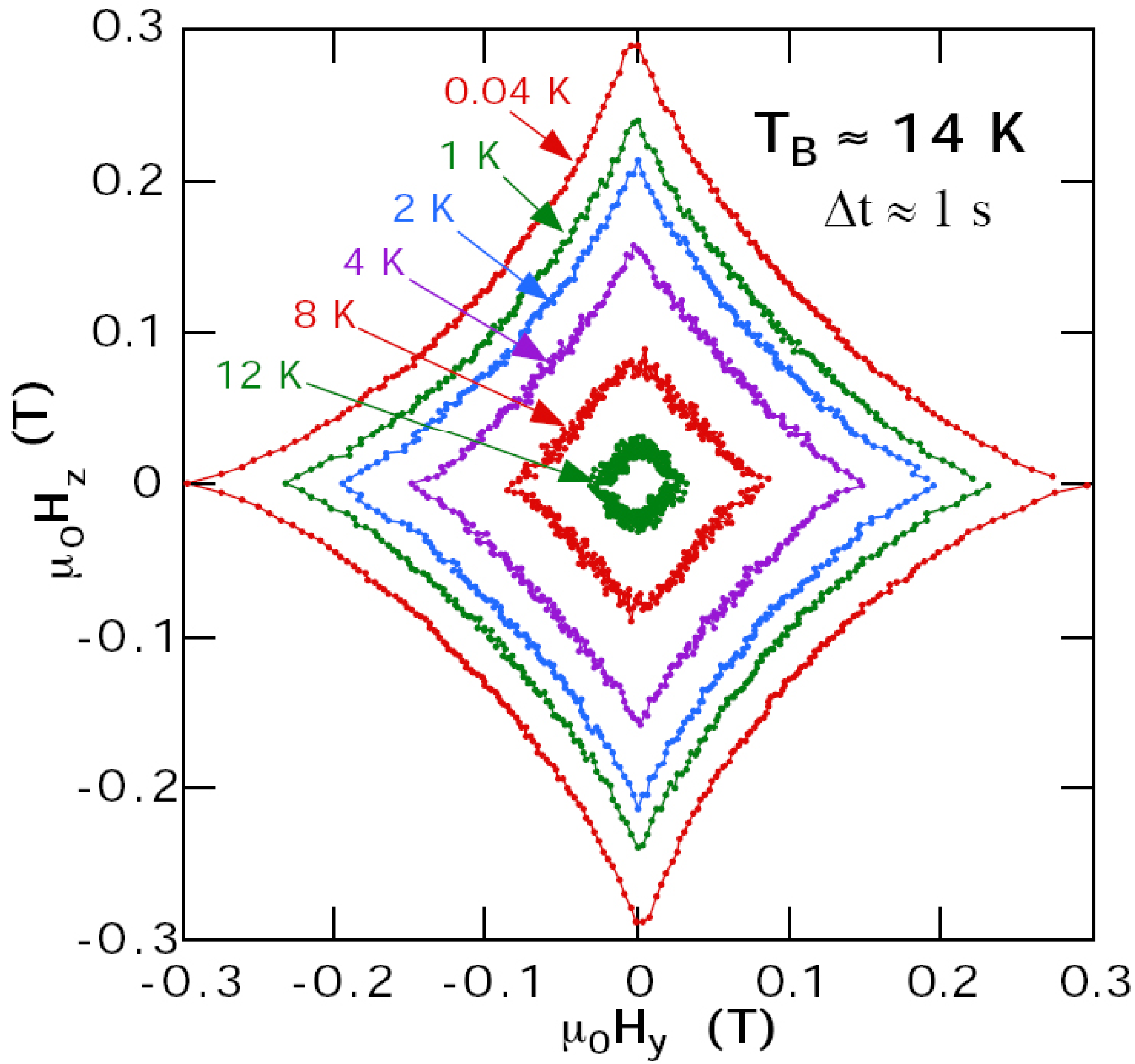
Stoner Wohlfarth model

Temperature effects (very briefly)

Stoner-Wohlfarth Astroid at various temperatures



Thermal agitation effectivly reduces the energy barrier! Exponentially!



3 nm Co Cluster, Micro-SQUID Experiment
Wernsdofer et al. PRL 2002

Beyond S-W-Model: e.g. Curling Mode

Curling Reversal Mode

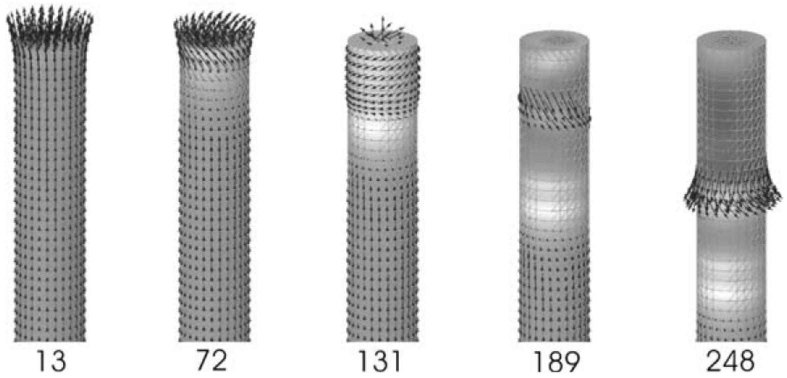


Fig. 3. Snapshots of the beginning of a localized curling mode reversal in a Ni wire of 60 nm thickness. The numbers are picoseconds after application of the reversed field. A vortex nucleates at the wire's end and propagates along the wire axis.

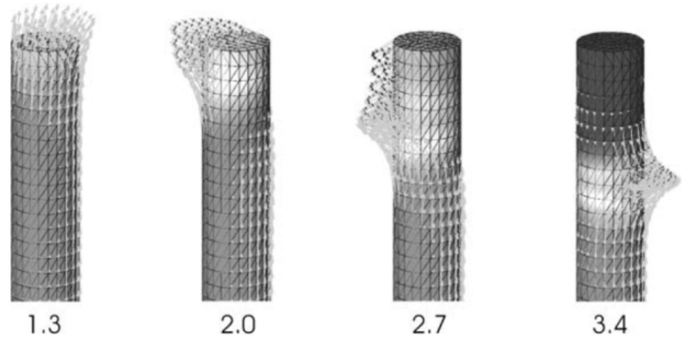


Fig. 1. Snapshots of the initial stages of the "corkscrew" reversal mode in a Ni wire with a diameter of 40 nm; the numbers indicate time in nanoseconds. The wire is exposed to a reversed field of 200 mT. A head-to-head domain wall is nucleated at the end of the wire. It propagates along the wire axis on a characteristic spiralling orbit.

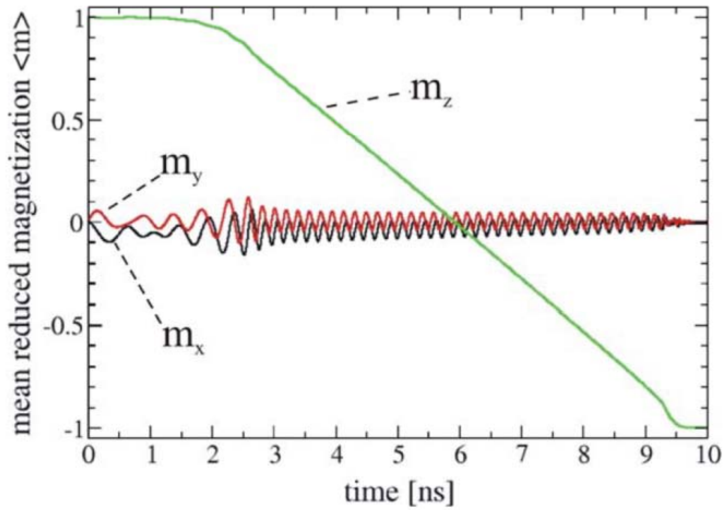
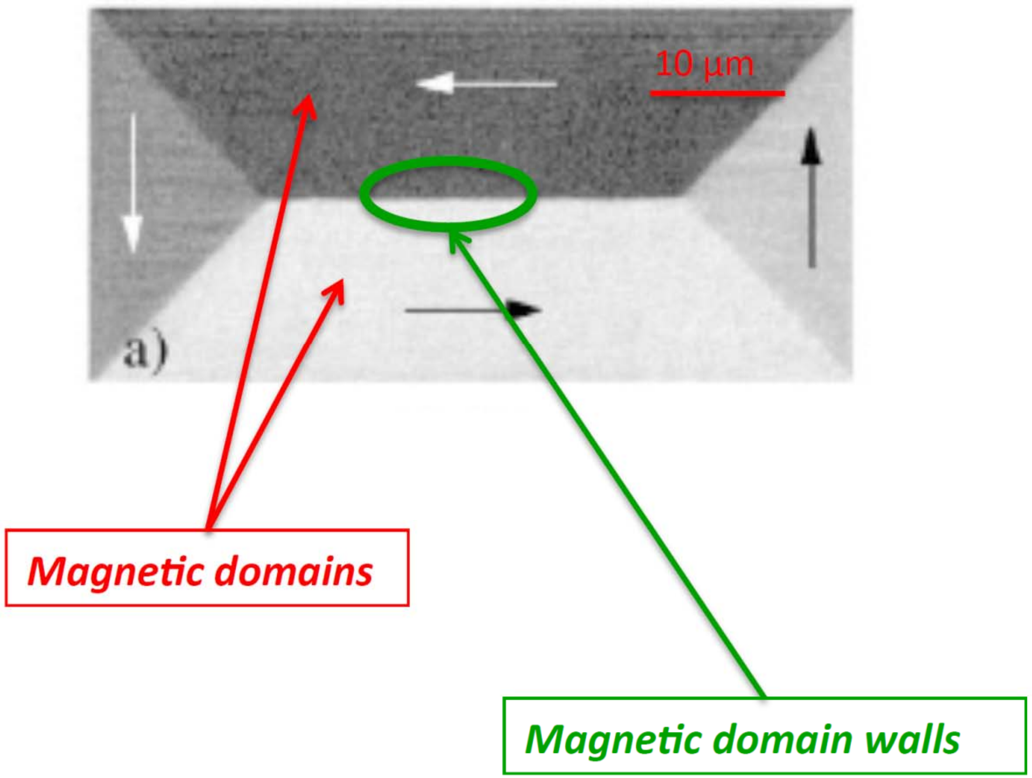


Fig. 2. Spatially averaged magnetization components as a function of time in the case of the corkscrew reversal mode in a Ni nanowire of 40 nm thickness and 1 μm length. The change in the axial magnetization component m_z indicates the propagation of the domain wall. The gyrating motion of the domain wall around the axis reflects in the oscillations of the perpendicular components m_x, m_y.

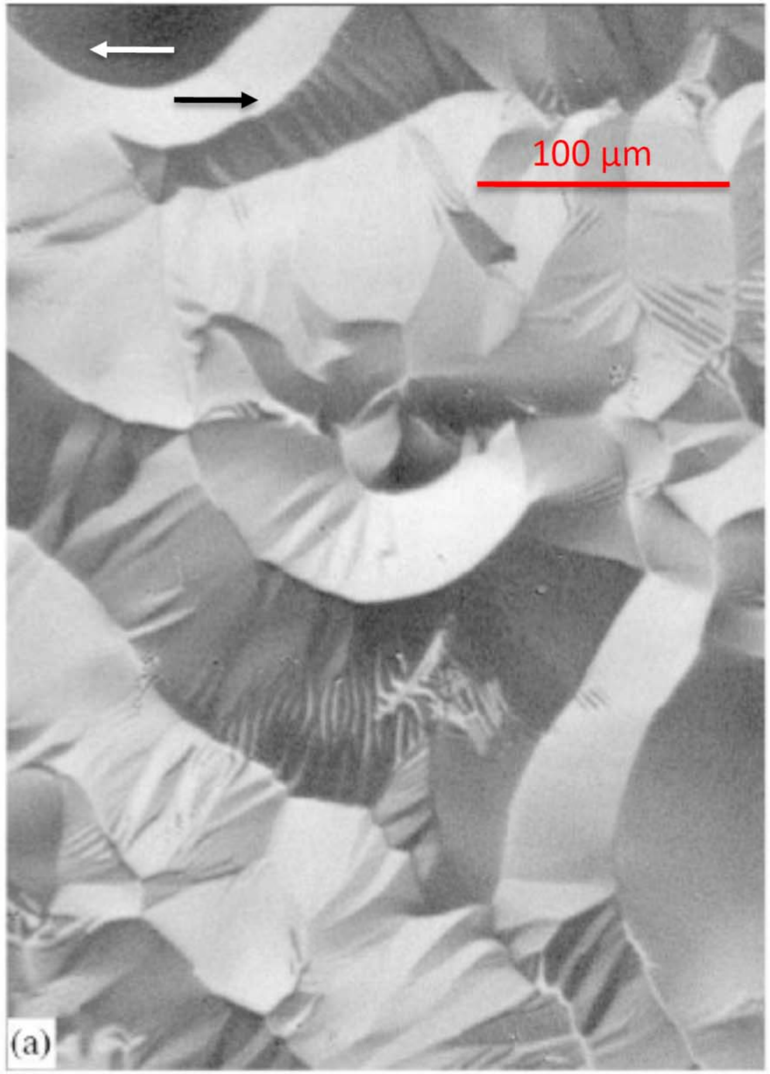
Hertel, Kirschner, Physica B (2004)

Real magnetic materials

Py : $Ni_{80}Fe_{20}$ (thickness : 240 nm)



R. Schäfer, JMMM, 215-216 (2000) 652-663

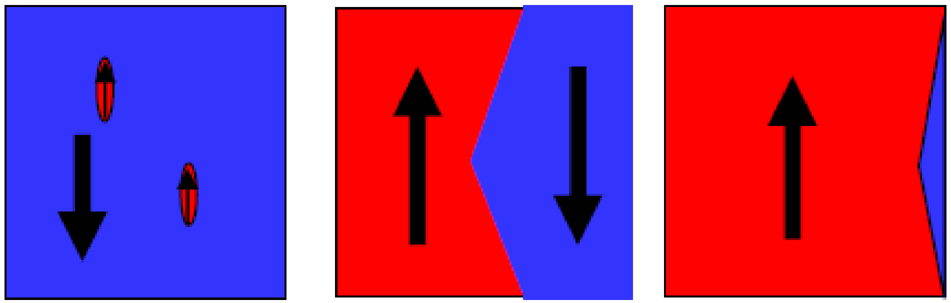


$(FeCo)_{83}(Si,B)_{17}$ [VC7600]

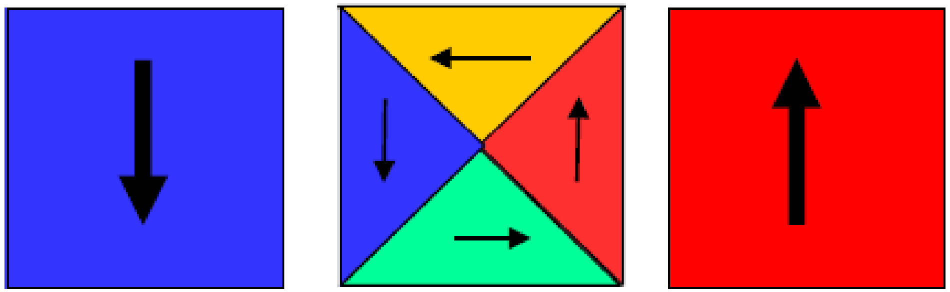
10

Mechanisms for magnetization reversal

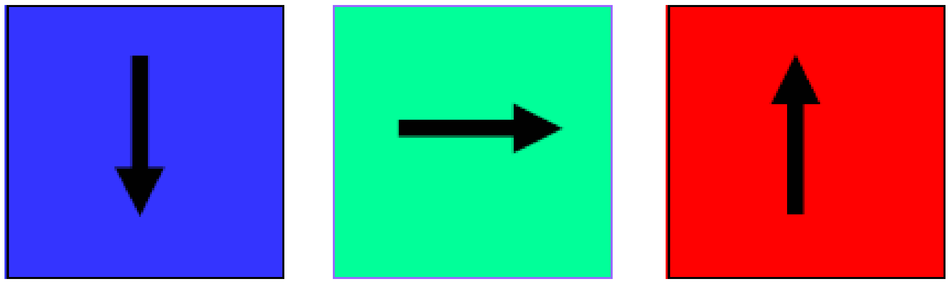
Nucleation and domain wall motion



Domain creation (smaller particle size)



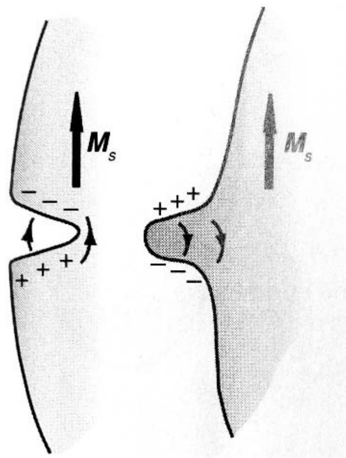
Coherent rotation (see Stoner Wohlfarth)



Why is it easier to nucleate a domain wall from an edge of the sample?

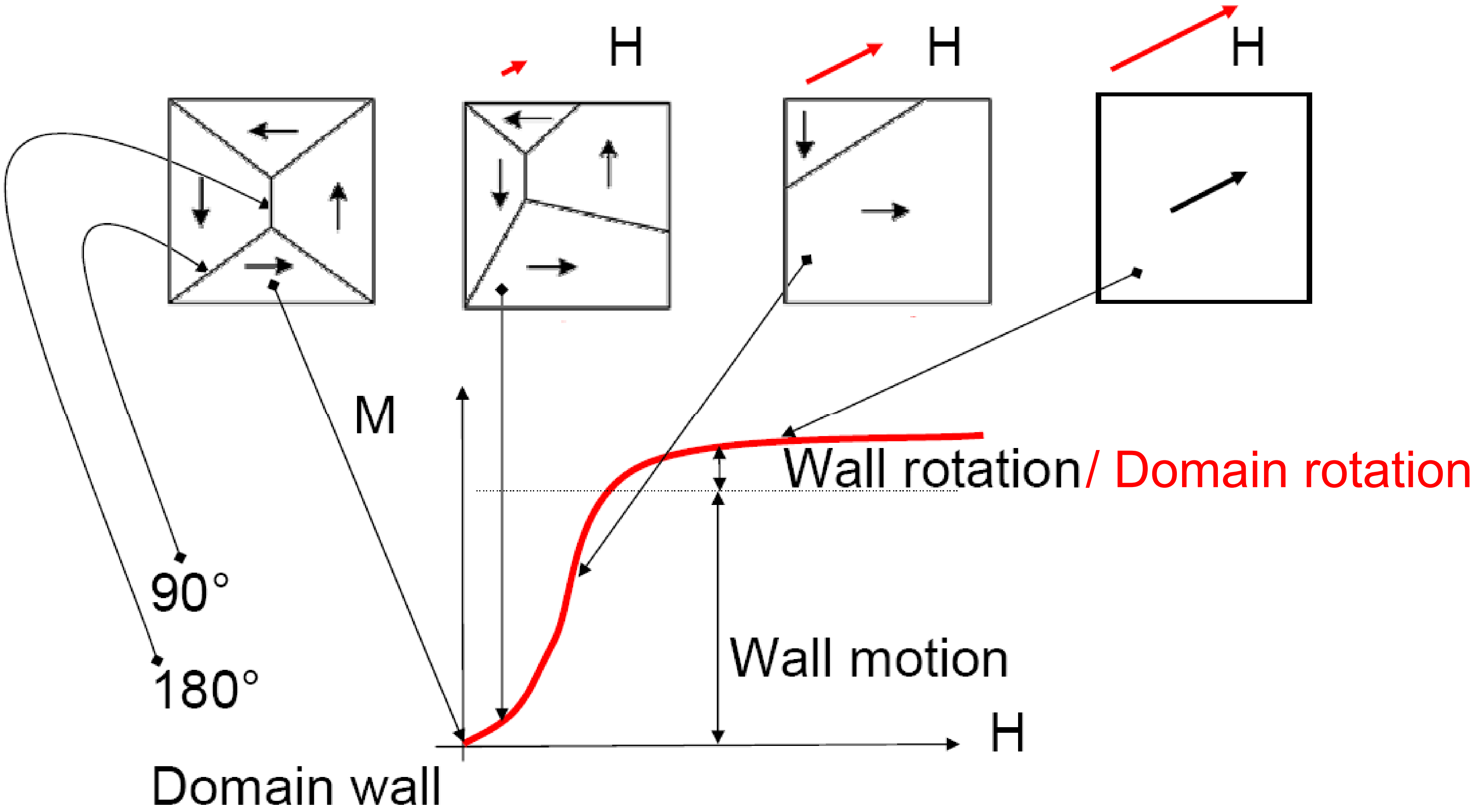
Increase of the local demagnetizing field by surface roughness (asperities) → reversal of the magnetization becomes more easy

(a similar process occurs at defects inside a sample!)

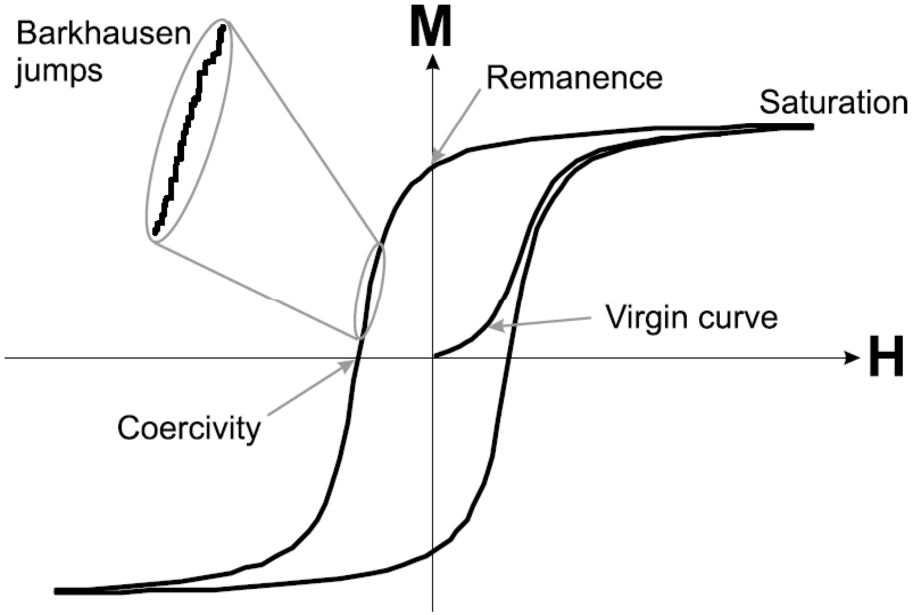


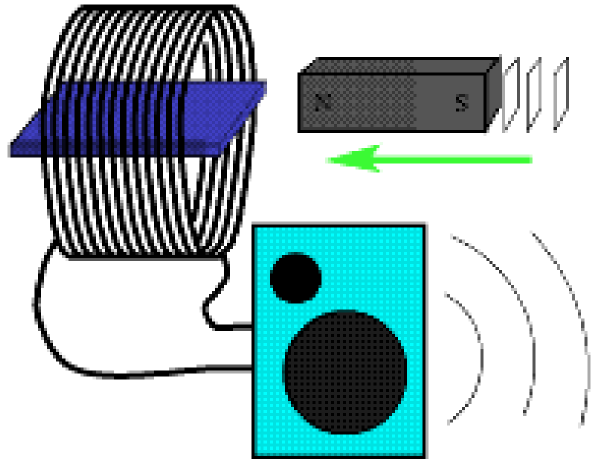
Local stray fields near a surface pit or bump. The region prone to reversal is shaded.

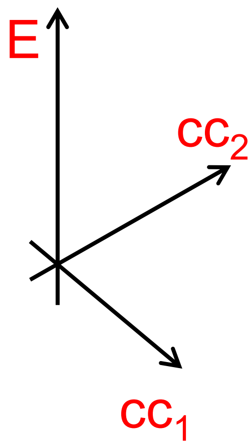
Magnetic Hysteresis (micron sized element)



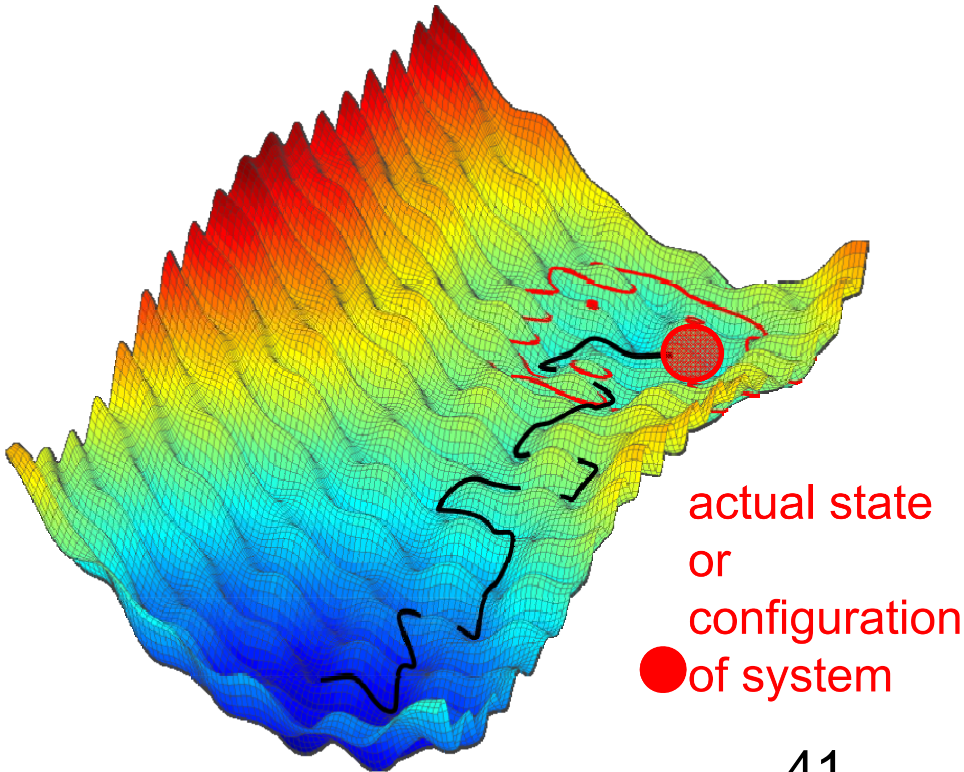
Barkhausen jumps



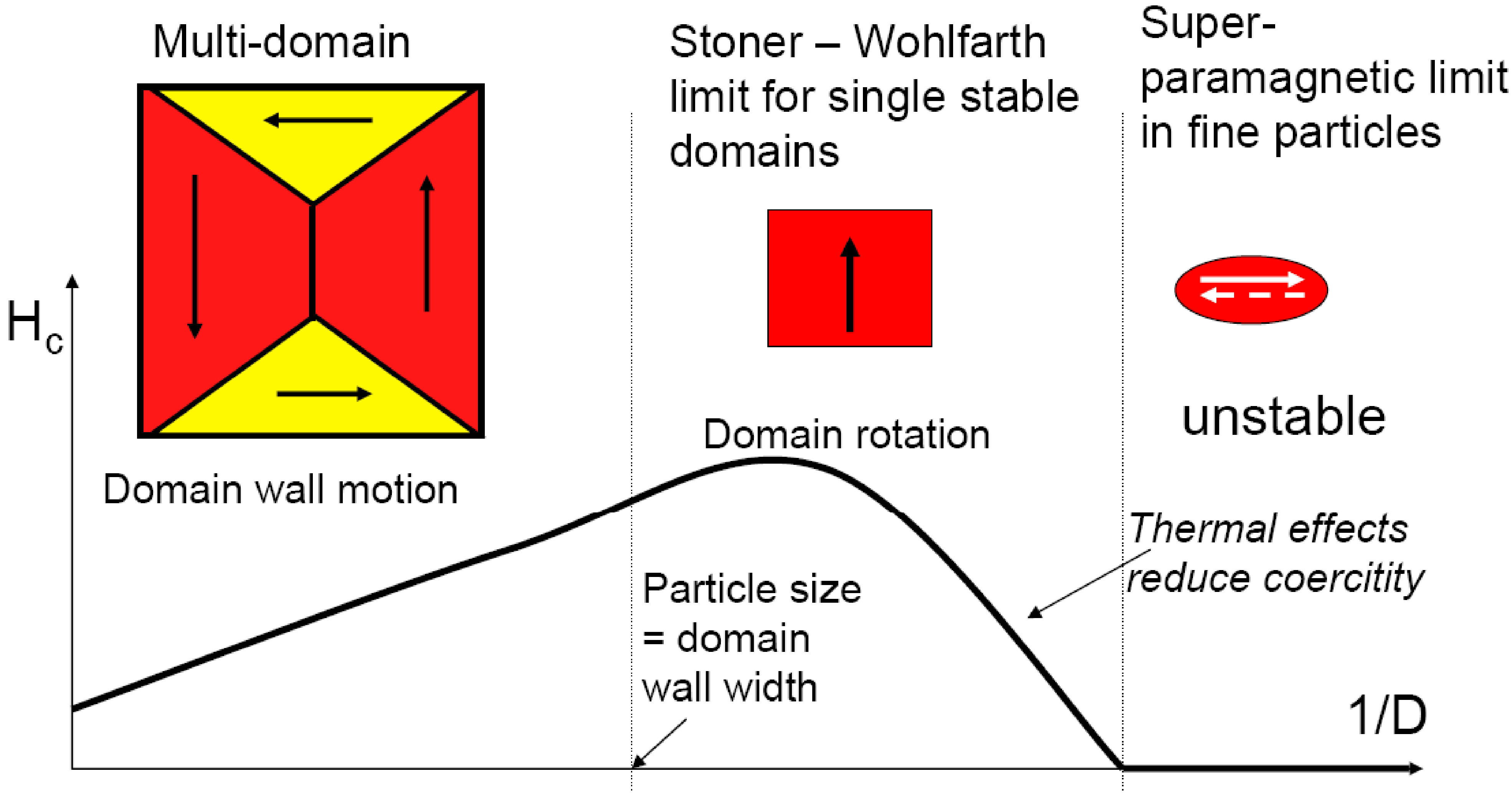


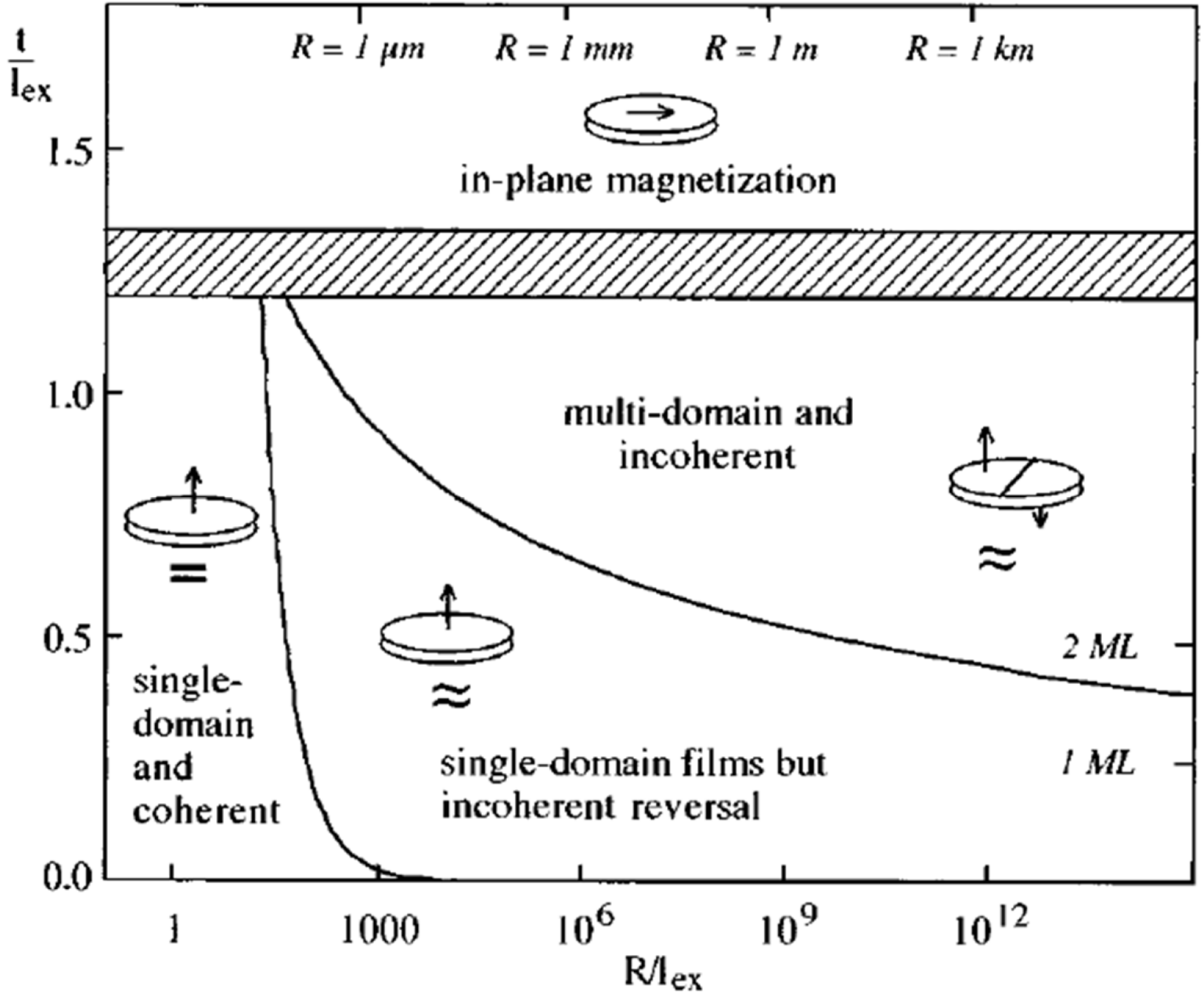


cc: Configuration Coordinate



magnetization reversal as a function of size





Skomski et al. PRB 58, 3223 (1998)

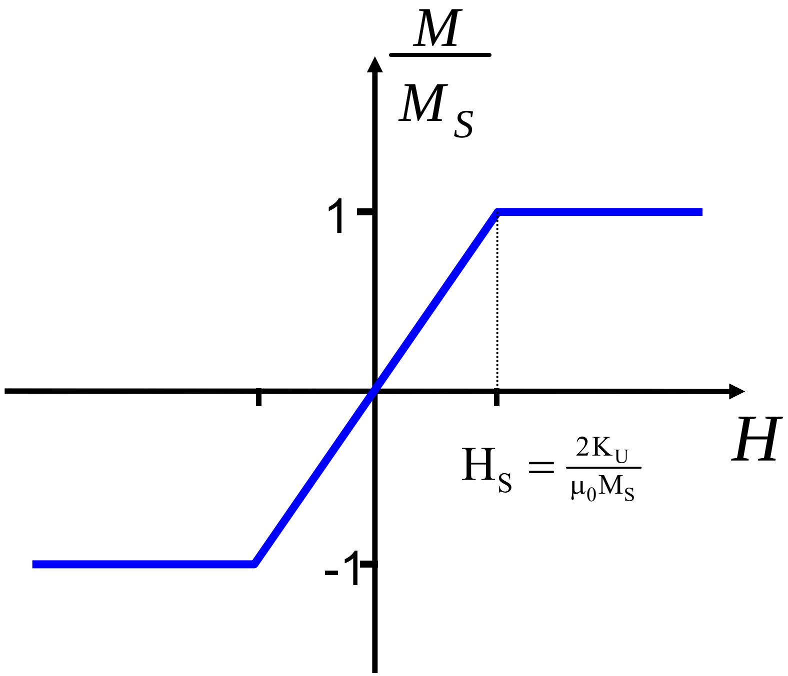
Magnetization Processes II

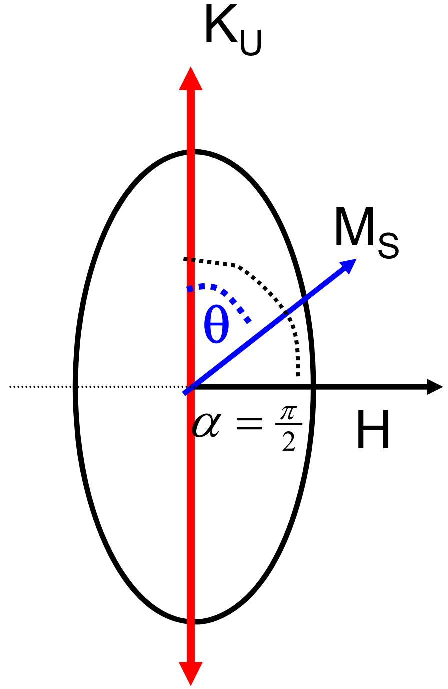
C.H. Back

Universität Regensburg

Stoner-Wohlfarth model $\alpha=\pi/2$

What happens if a short magnetic field pulse is applied (let's say < 1 ns)





Precessional magnetization reversal

Precessional motion of a single electron spin (Quantum Mechanics)

The time evolution of an observable is given by its commutator with the Hamilton operator. For the spin operator this means:

$$i\hbar \frac{d}{dt} < \vec{S} > = < [\vec{S}, \mathcal{H}] >$$

The Hamilton operator consists only of the Zeeman term

$$\mathcal{H} = -\frac{g\mu_B}{\hbar} \vec{S} \cdot \vec{H}$$

z-component:

$$\begin{aligned}
[S_z, \mathcal{H}] &= -\frac{g\mu_B}{\hbar}[S_z, S_x H_x + S_y H_y + S_z H_z] \\
&= -\frac{g\mu_B}{\hbar}(H_x[S_z, S_x] + H_y[S_z, S_y]) \\
&= \frac{g\mu_B}{\hbar} i\hbar (S_y H_x - S_x H_y)
\end{aligned}$$

whereby the last step makes use of the commutation rules for the spin operator:

$$[S_i, S_j] = i\hbar \epsilon_{ijk} S_k$$

Thus, one obtains:

$$\frac{d}{dt} < S_z >= \frac{1}{i\hbar}[S_z, \mathcal{H}] = \frac{g\mu_B}{\hbar}(\vec{S} \times \vec{H})_z$$

The same holds for the other components of **S**:

$$\frac{d}{dt} < \vec{S} >= \frac{g\mu_B}{\hbar}(\vec{S} \times \vec{H})$$

We now want to extend this equation to the magnetization. In the macrospin model the magnetization is considered uniform and is given as the average of the spin magnetic moments (we ignore a contribution from the orbital momentum) :

$$\vec{M} = -\mu_B g < \vec{S} >$$

From here we arrive at the analog relation for the magnetization:

$$\frac{d}{dt}\vec{M} = -\gamma \vec{M} \times \vec{H} \quad \text{with} \quad \gamma = \frac{g\mu_B}{\hbar}$$

the gyromagnetic ratio and g = 2.0023 the gyromagnetic splitting factor for a free electron.

This is the first part of the Landau-Lifshitz equation.

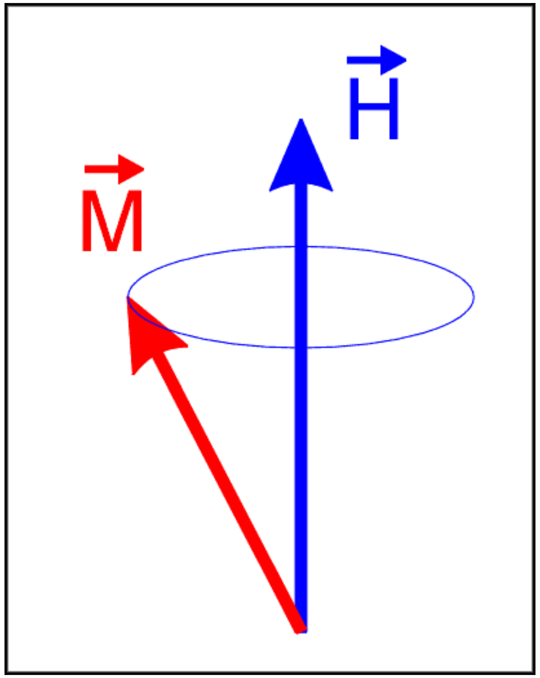
Landau- Lifshitz- Equation:

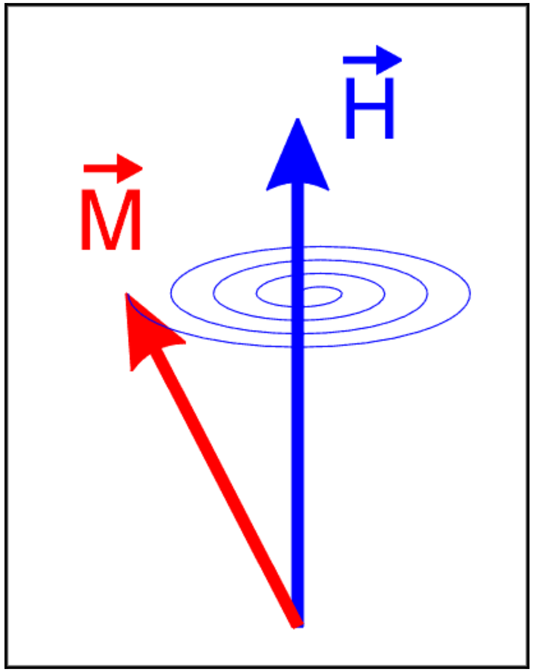
$$\frac{d\vec{M}}{dt} = -\gamma(\vec{M} \times \vec{H}_{eff}) - \alpha \frac{\gamma}{M}\left[\vec{M} \times (\vec{M} \times \vec{H}_{eff})\right]$$

$$\vec{H}_{eff} = -\frac{\partial \varepsilon_{tot}}{\partial \vec{M}}$$

γ_0: gyromagnetic ratio

sets the time scale





The total energy E_{tot} :

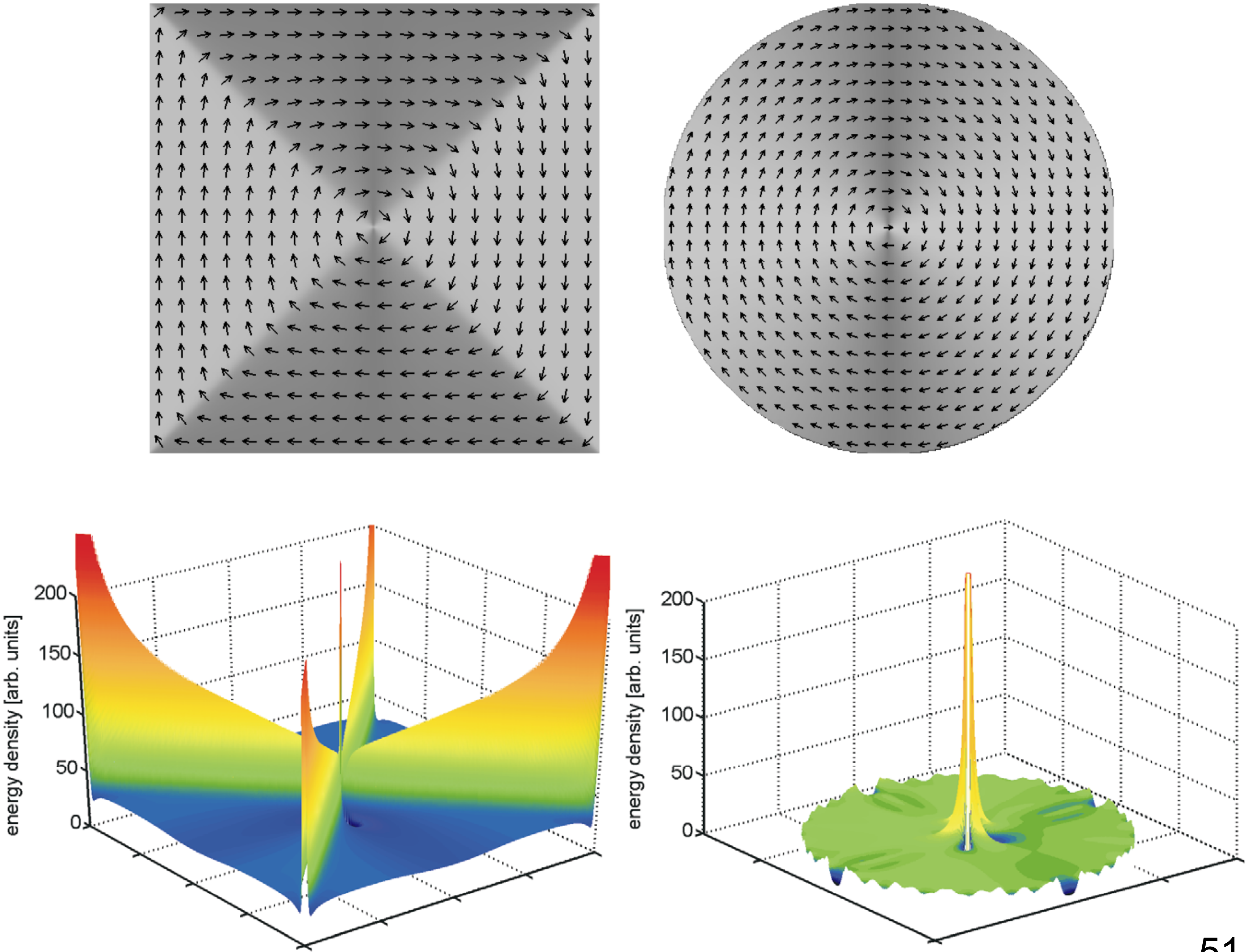
$$E_{tot} = E_z + E_{ex} + E_{an} + E_d =$$

$$= \underbrace{\int \left[A\,(\mathrm{grad}\,\vec{m})^2 + \varepsilon_{an}(\vec{m}) - \mu_0 M_s\,\vec{H}_{ext}\cdot\vec{m} - \frac{1}{2}\,\mu_0 M_s\,\vec{H}_d\cdot\vec{m} \right] dV}_{\varepsilon_{tot}(\vec{m})}$$

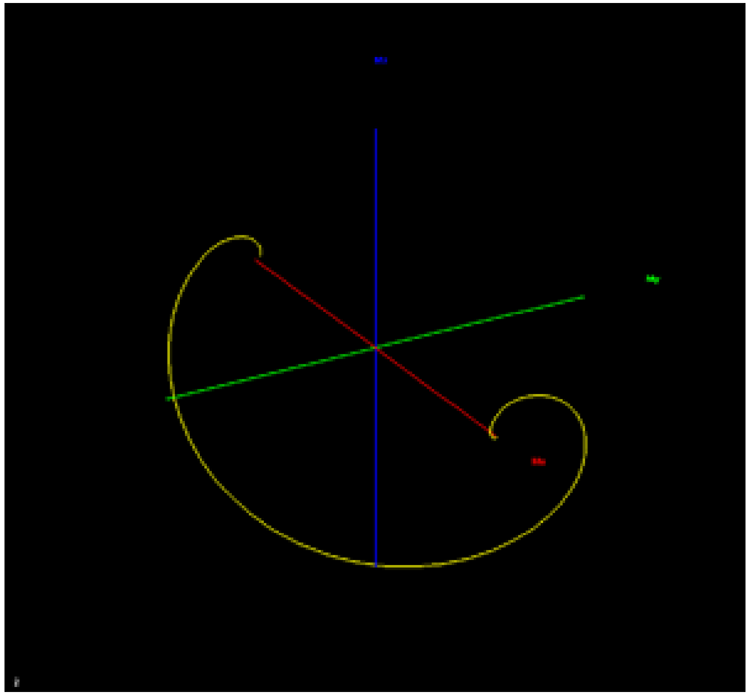
The variation of $\varepsilon_{tot}(\underline{m})$ with respect to $\underline{m}$ will result in the effective field $\underline{H}_{eff}$ that will excert a torque on the magnetization $\underline{M}$:

$$\vec{H}_{eff} = -\frac{1}{M_s}\frac{\delta\,\varepsilon_{tot}}{\delta\,\vec{m}} = \left[\underbrace{\frac{2A}{M_s}\nabla^2\vec{m}}_{\text{Exchange field } \vec{H}_{ex}} - \underbrace{\frac{1}{M_s}\,\mathrm{grad}_{\vec{m}}\,\varepsilon_{an}(\vec{m})}_{\text{Anisotropy field } \vec{H}_{an}} \right] + \vec{H}_{ext} + \vec{H}_d$$

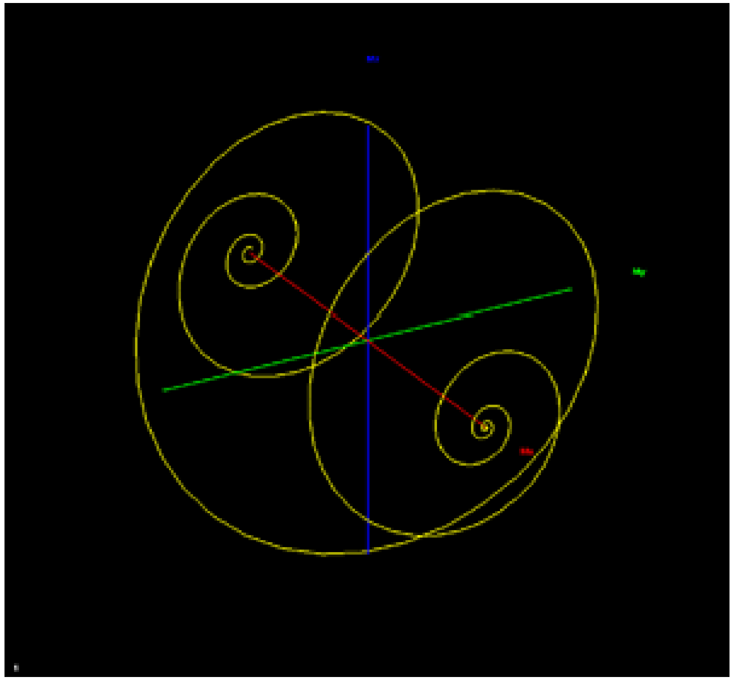
The energy landscape of confined magnetic systems (4 micron objects)



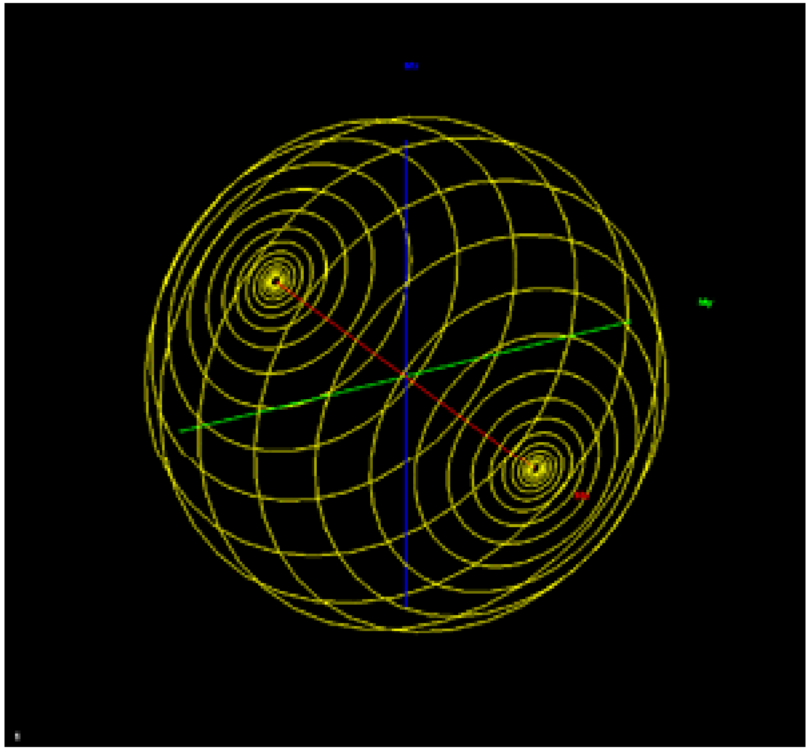
Response of a single magnetic moment to a static DC-field



$\alpha = 1.0$



$\alpha = 0.2$



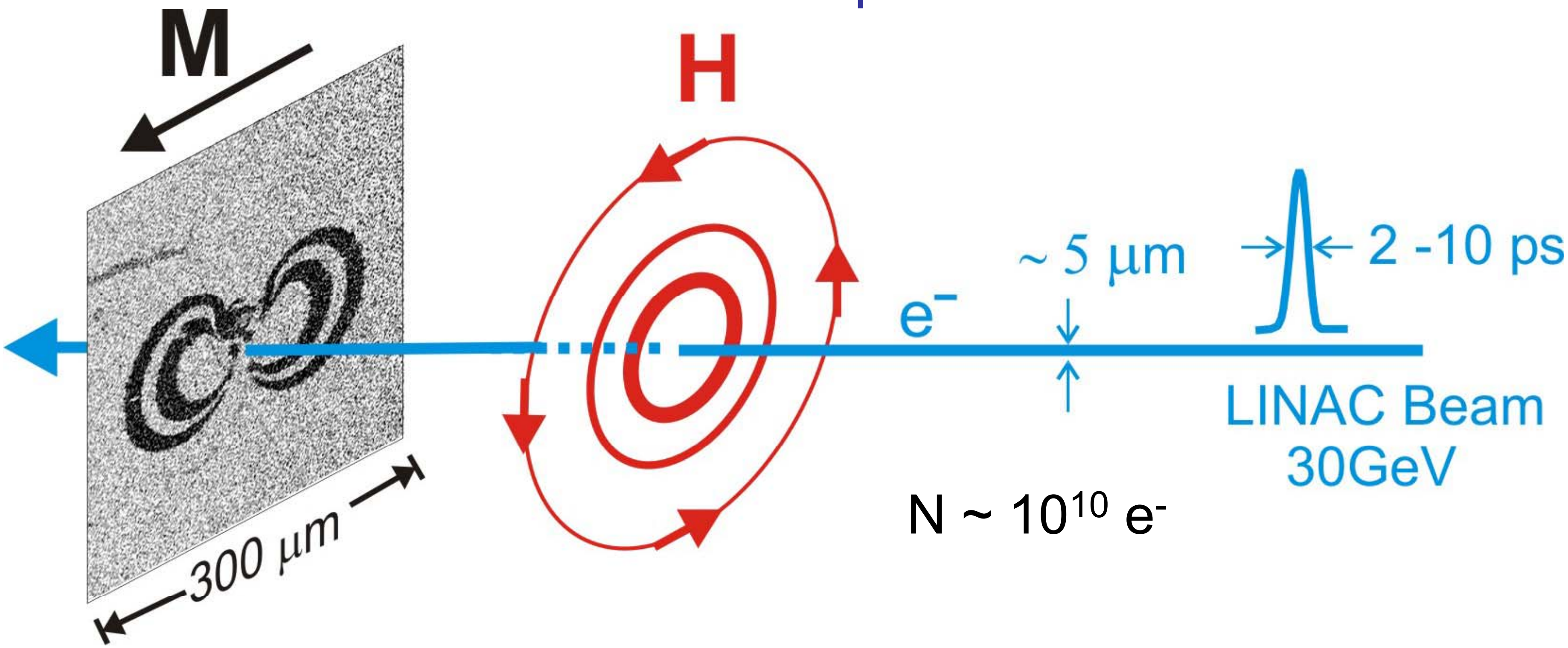
$\alpha = 0.05$

The damping parameter α governs how quickly the moments relax to the effective field direction, and in nature $\alpha \sim 0.01$ for Fe for example.

$$\frac{d\vec{M}}{dt} = -\gamma(\vec{M} \times \vec{H}_{eff})$$

Example for a precessional switching experiment „explained“ by the macrospin model

The SLAC experiment



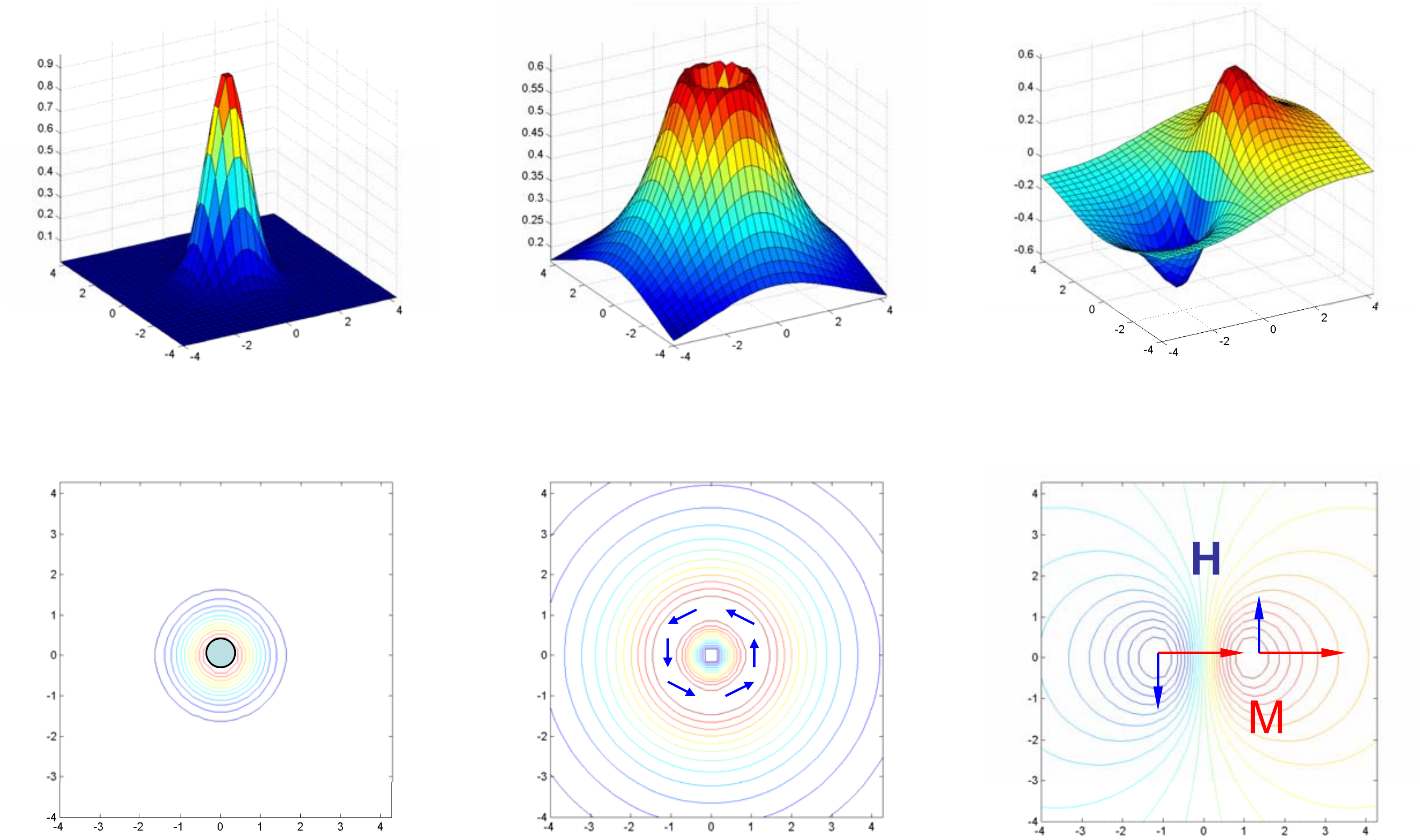
$N \sim 10^{10}\ e^-$

Parameters: 2-5 ps pulse duration

up to 20 T amplitude

In-plane and perpendicular magnetized Films

Current Density | Magnetic Field Profile | Torque **M** x **H**



micron | micron | micron

special case for dipolar stray field (shape anisotropy):
homogeneously magnetized ellipsoid:

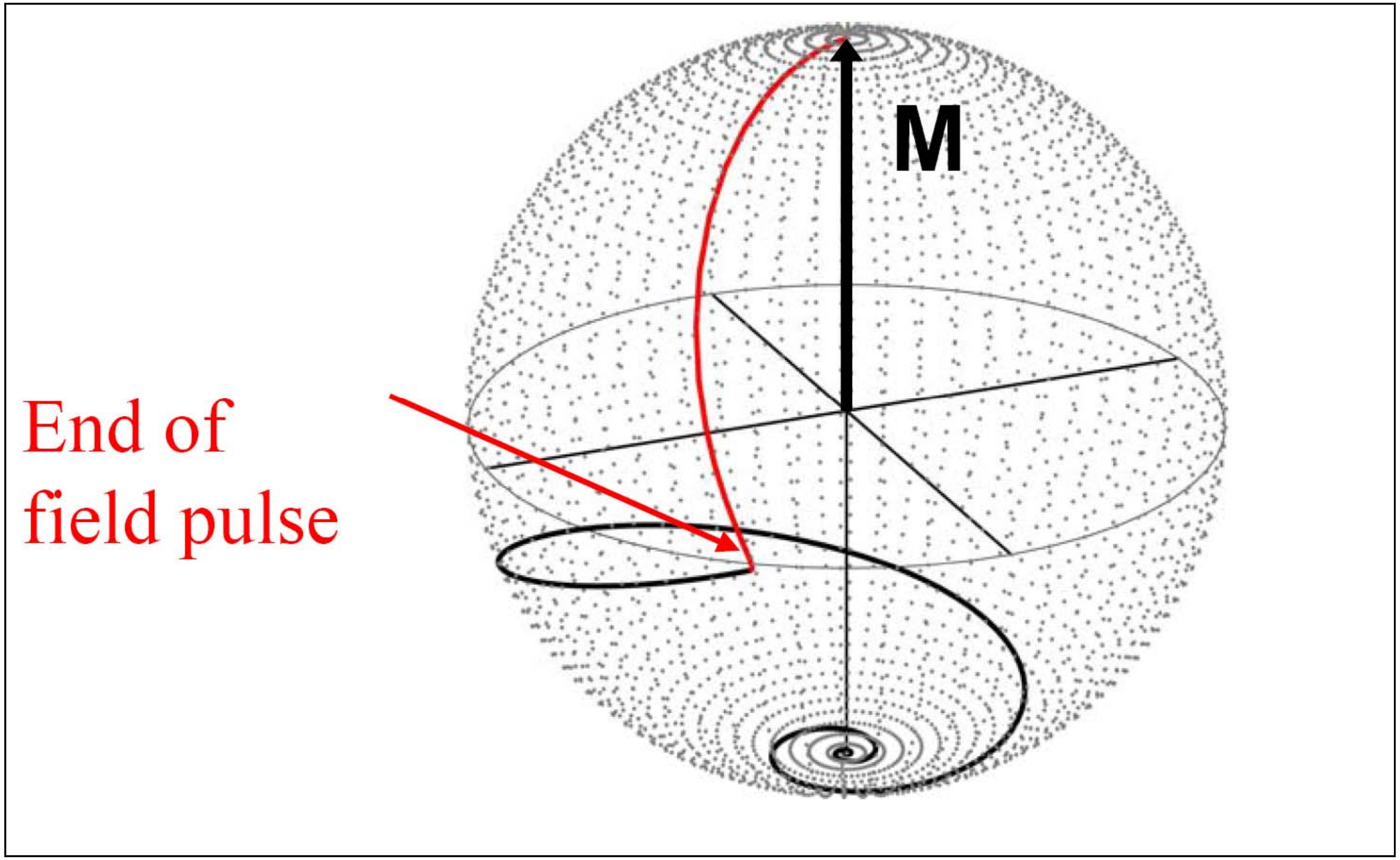
$$\vec{H}_D = -\mu_0 (N_{xx} M_x \vec{e}_x + N_{yy} M_y \vec{e}_y + N_{zz} M_z \vec{e}_z)$$

with N_{ii} being the diagonal elements of the demagnetizing tensor:

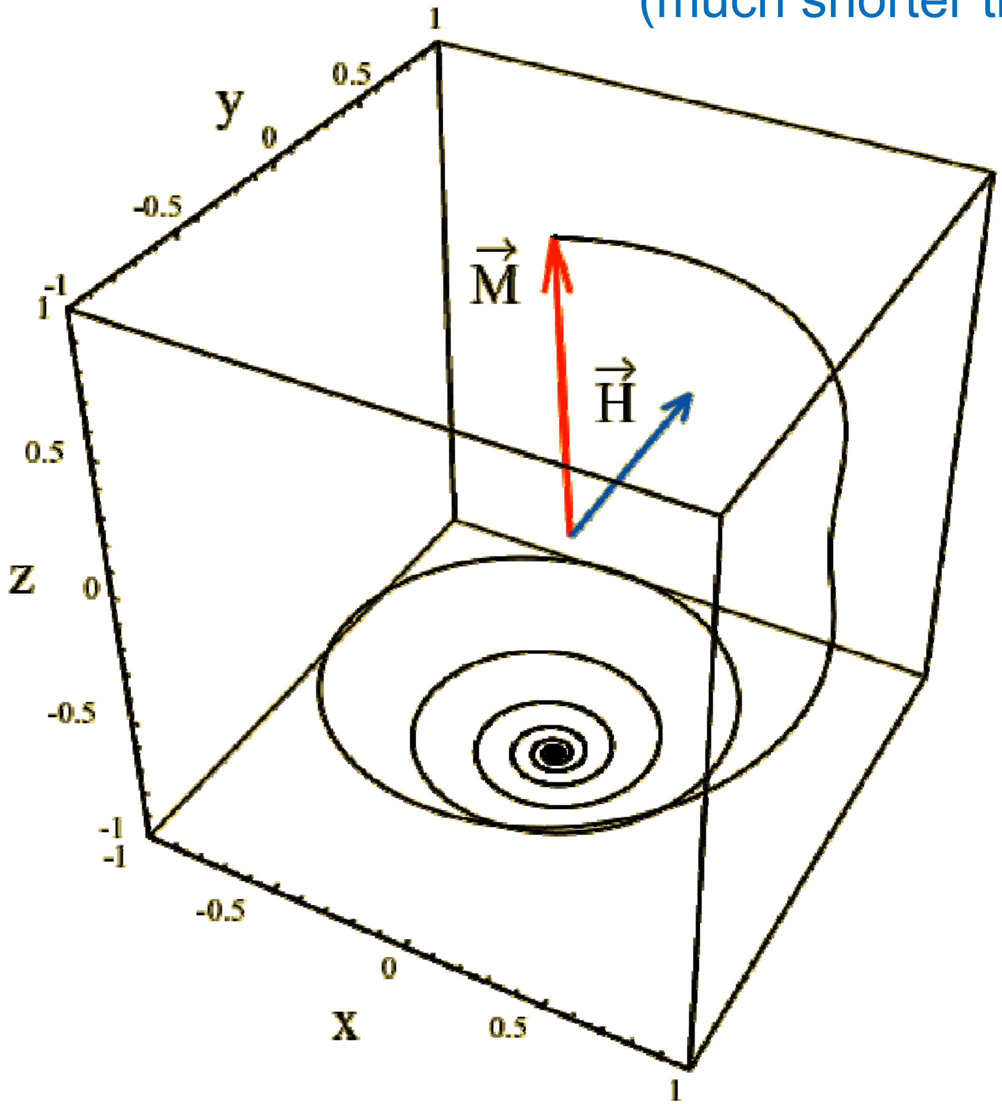
In this example: thin film: $N_{xx} = N_{yy} = 0, N_{zz} = 1$

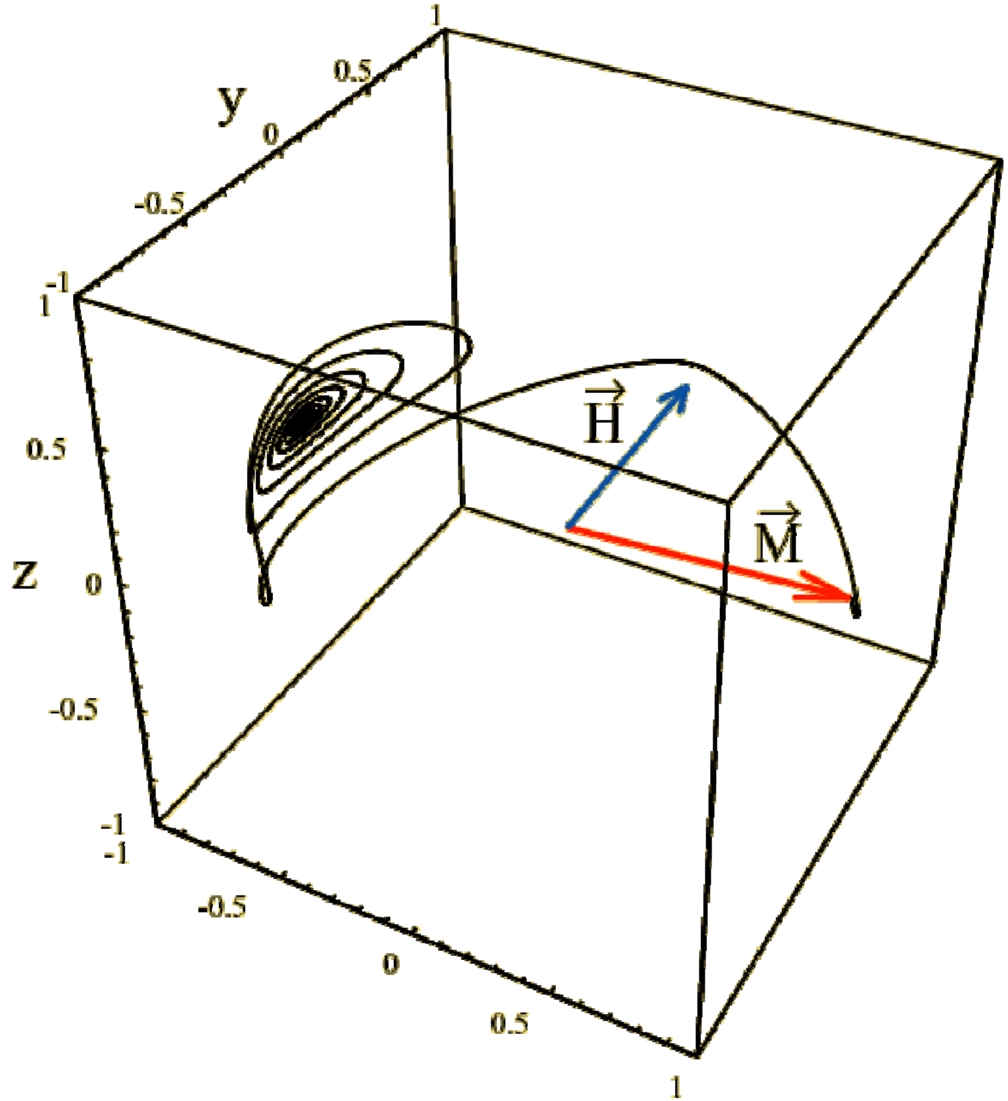
$$\vec{H}_D = -\mu_0 M_z \vec{e}_z$$

Response of a single magnetic moment (with perpendicular crystalline anisotropy, and shape anisotropy) to a short pulsed field (in the x-y plane) for precessional switching



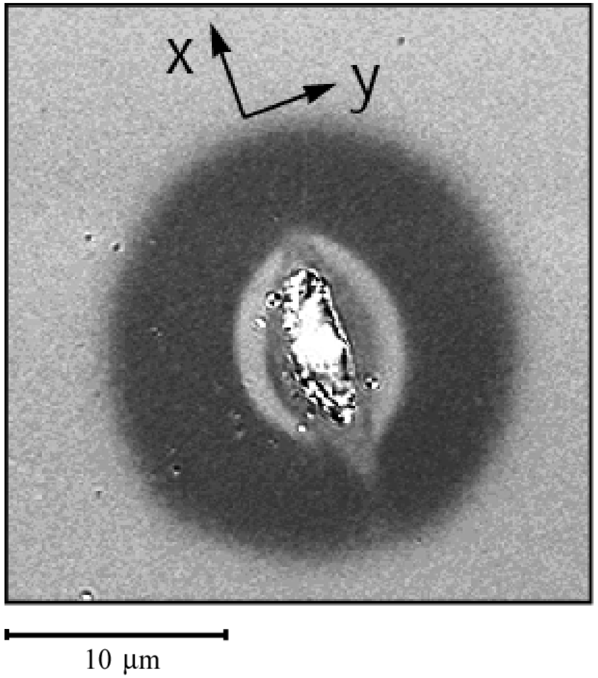
Short field pulse (some picosecond)
(much shorter than relaxation time)





Perpendicularly Magnetized Co/Pt Multilayer

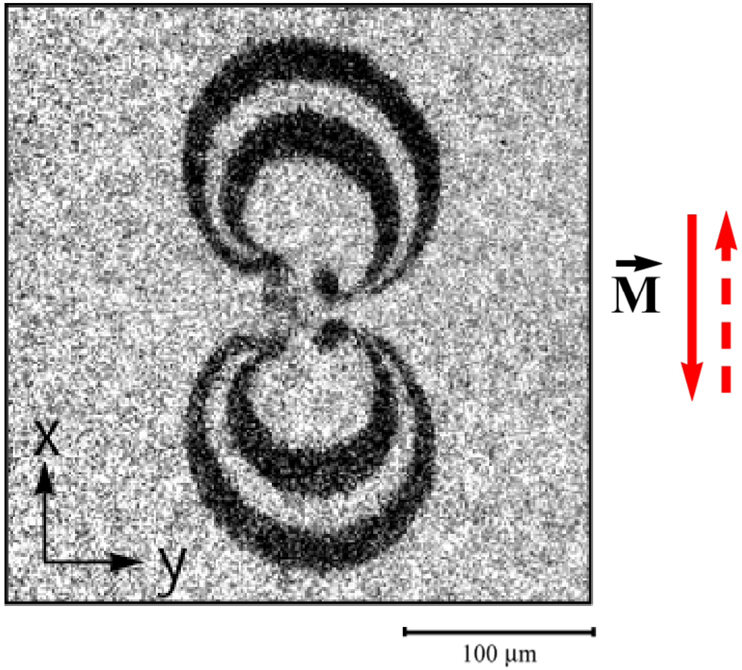
$\mu_0 M_{s,eff} = 1.6$ T

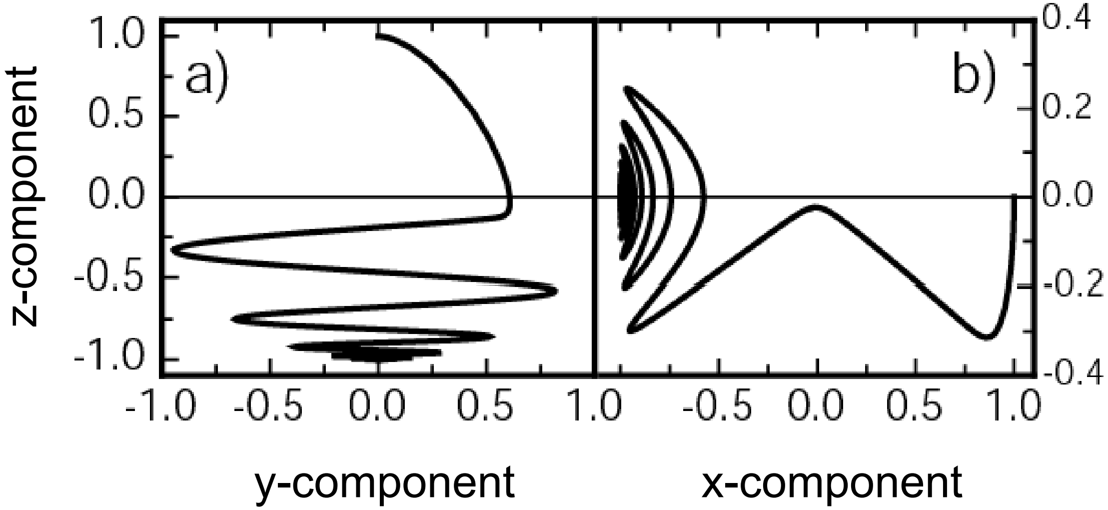


$\sigma_t = 2$ ps

In-plane magnetized 20 nm Co Film

$H_k = 168$ kA/m, $\mu_0 M_s = 1.7$ T

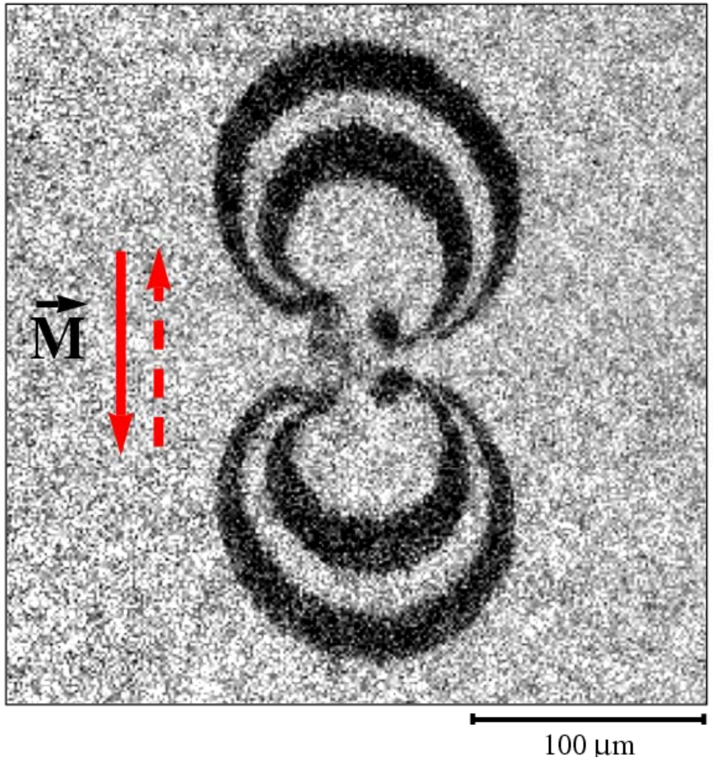




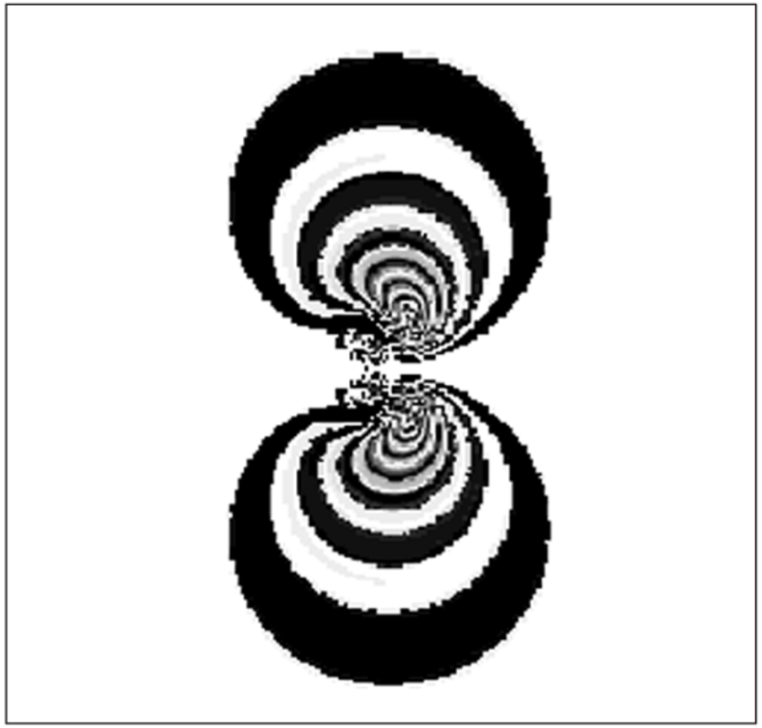
Phys. Rev. Lett. **81**, 3251 (1998)

Science **285**, 864 (1999)

Experiment



Macrospin Calculation



Fairly good agreement !

But: the effective damping α is much too large: α=0.02

and the inner structure cannot be explained

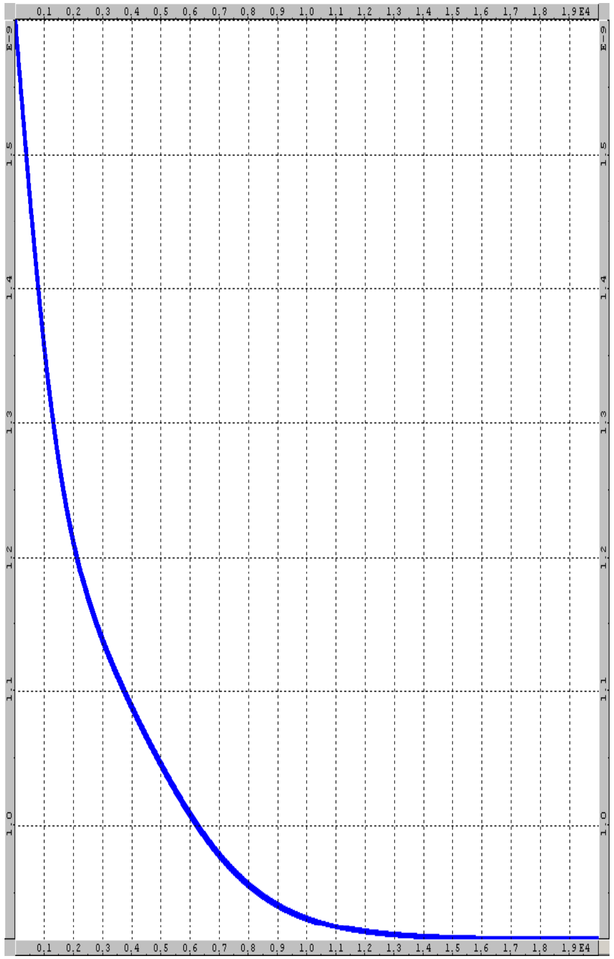
Total internal field oversimplified? Non uniform excitation field! Excitations?

Simple example: two dipoles coupled by their own stray fields

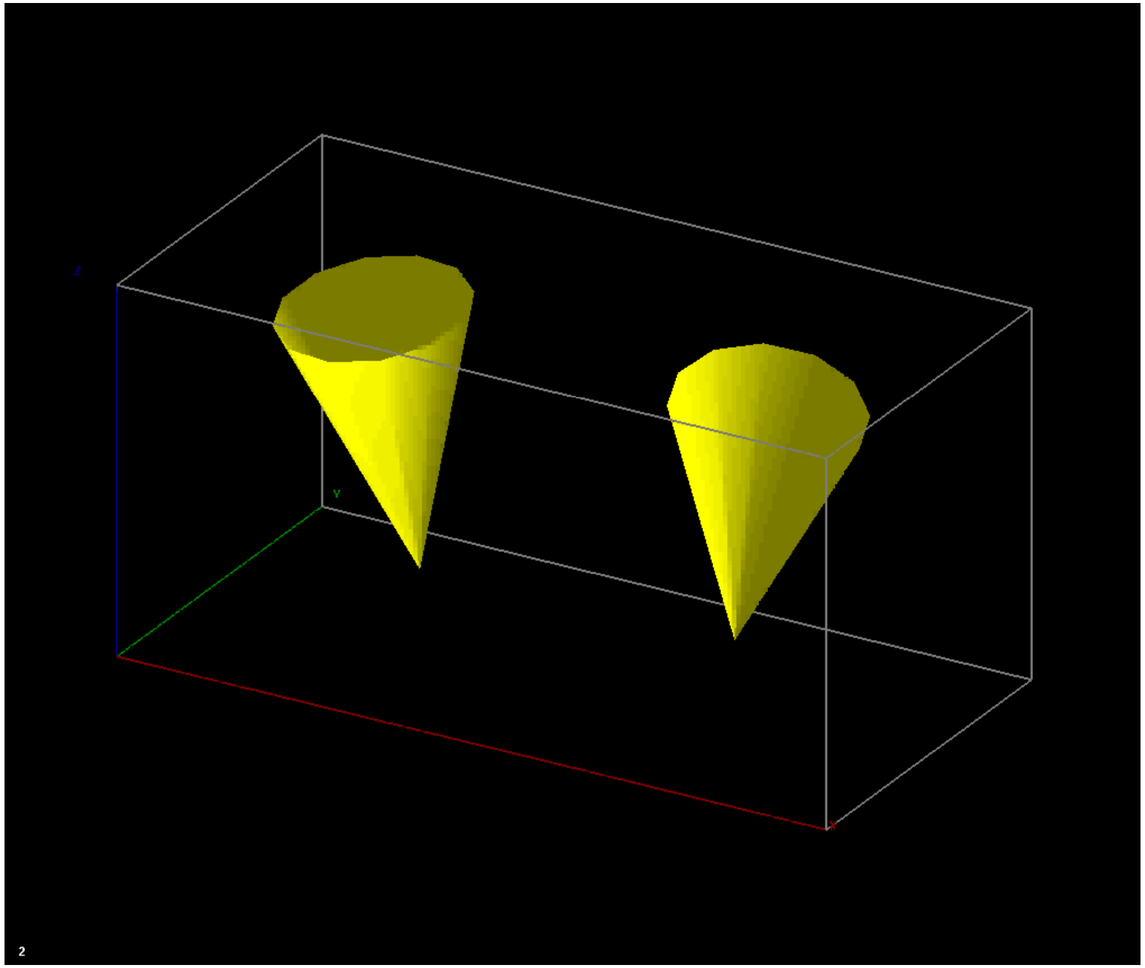
(Micromagnetic Simulations using M.Scheinfein's LLG code)

$0 \rightarrow 10$ns γ=17.6 MHz/Oe α=0.01 M_s=1714 emu/cc

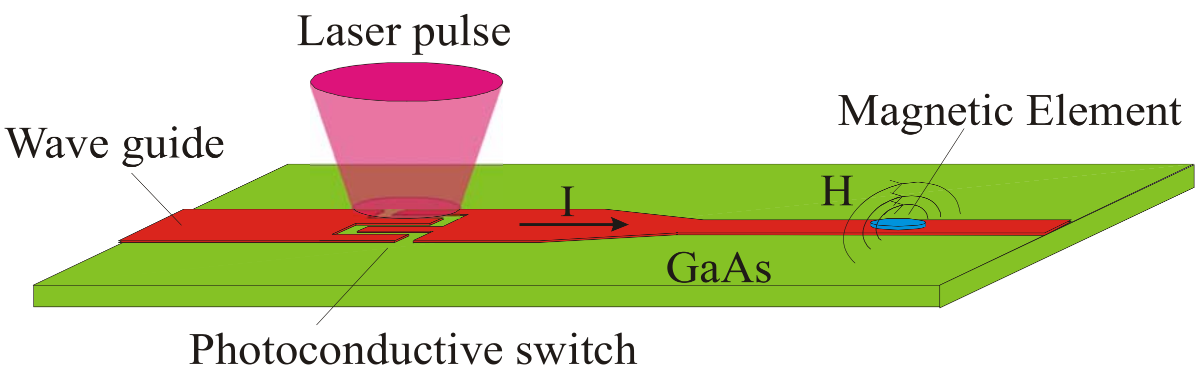
E



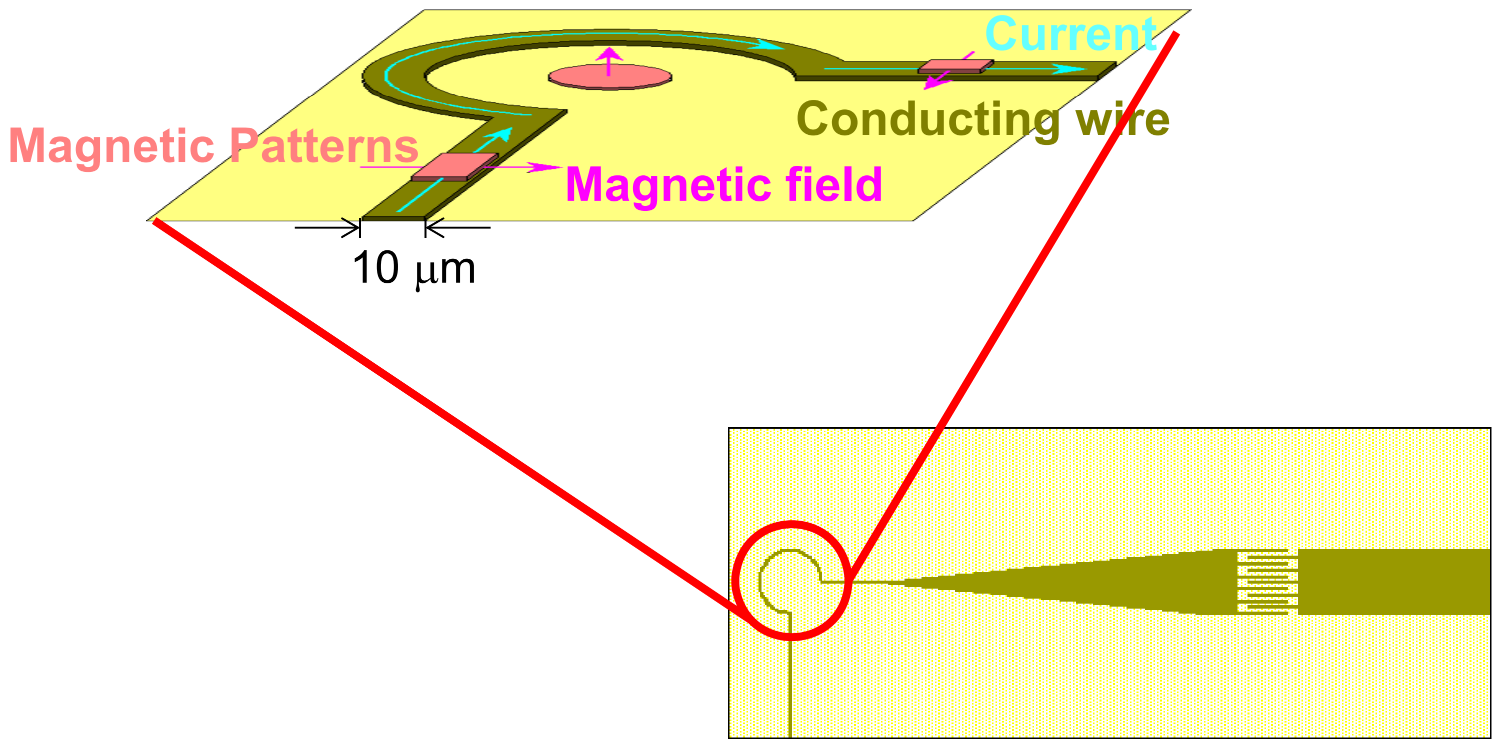
0 time 20ns



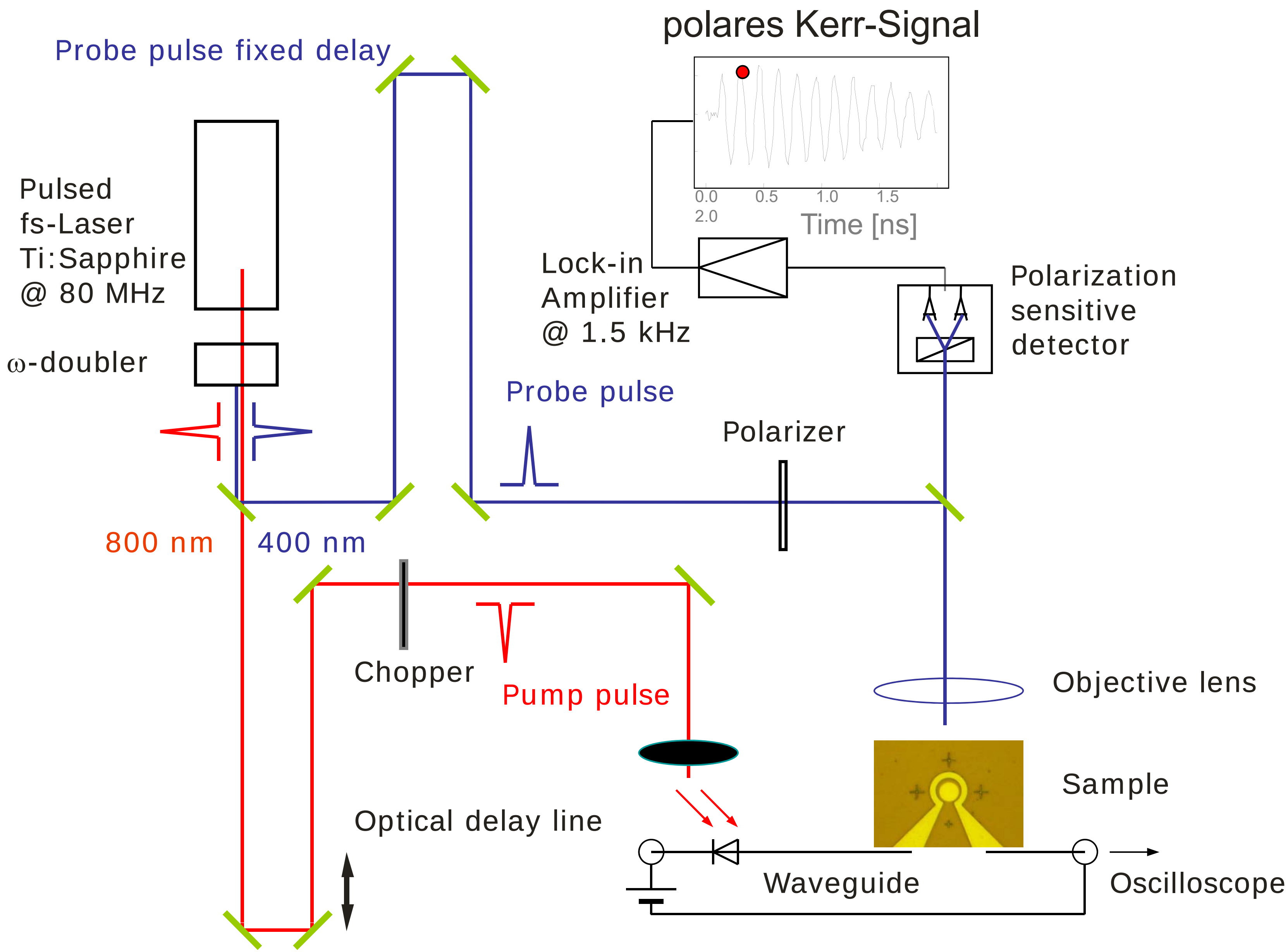
Spatially and time resolved experiments



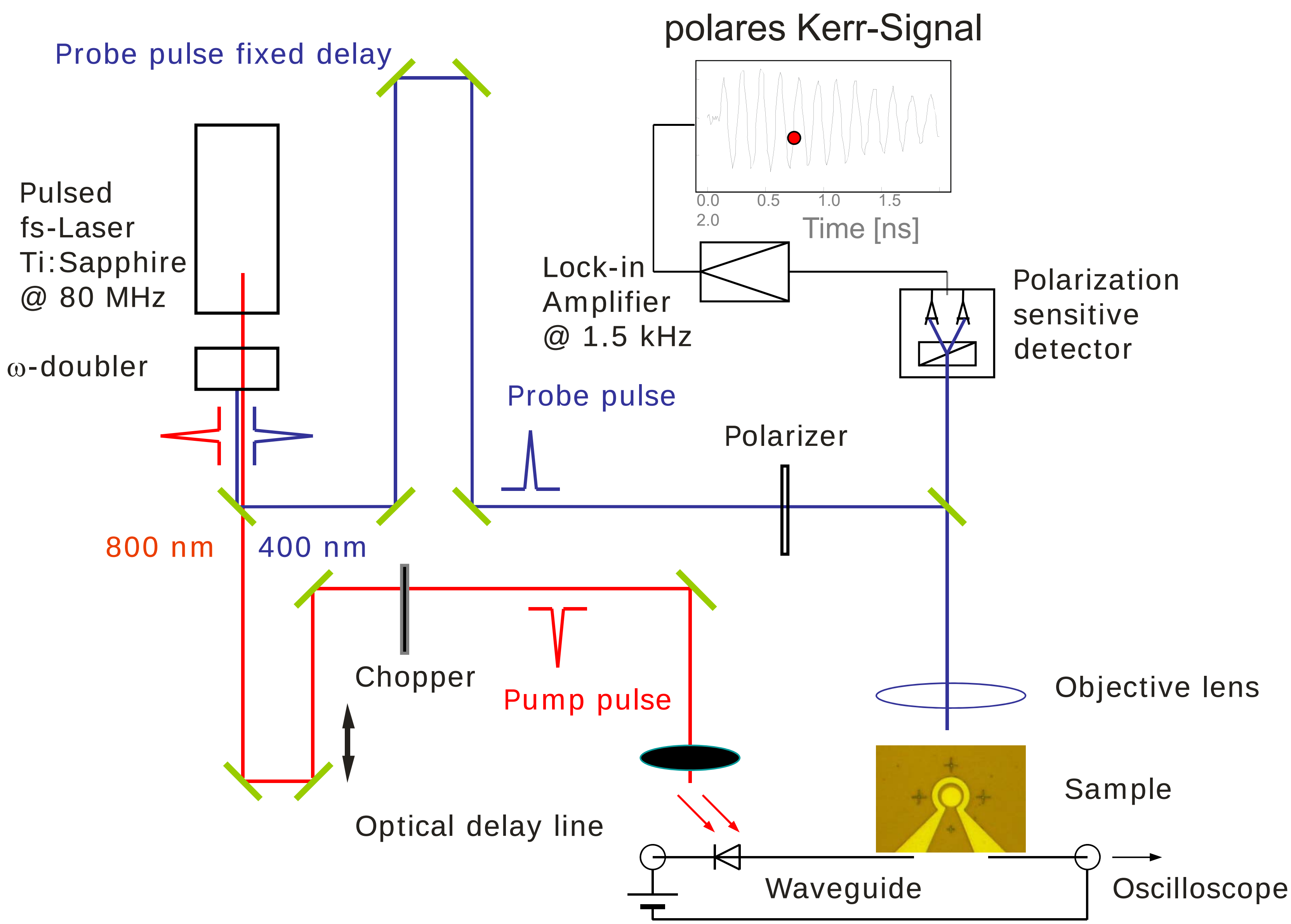
S.-B. Choe et al Science **304**, 420 (2004)



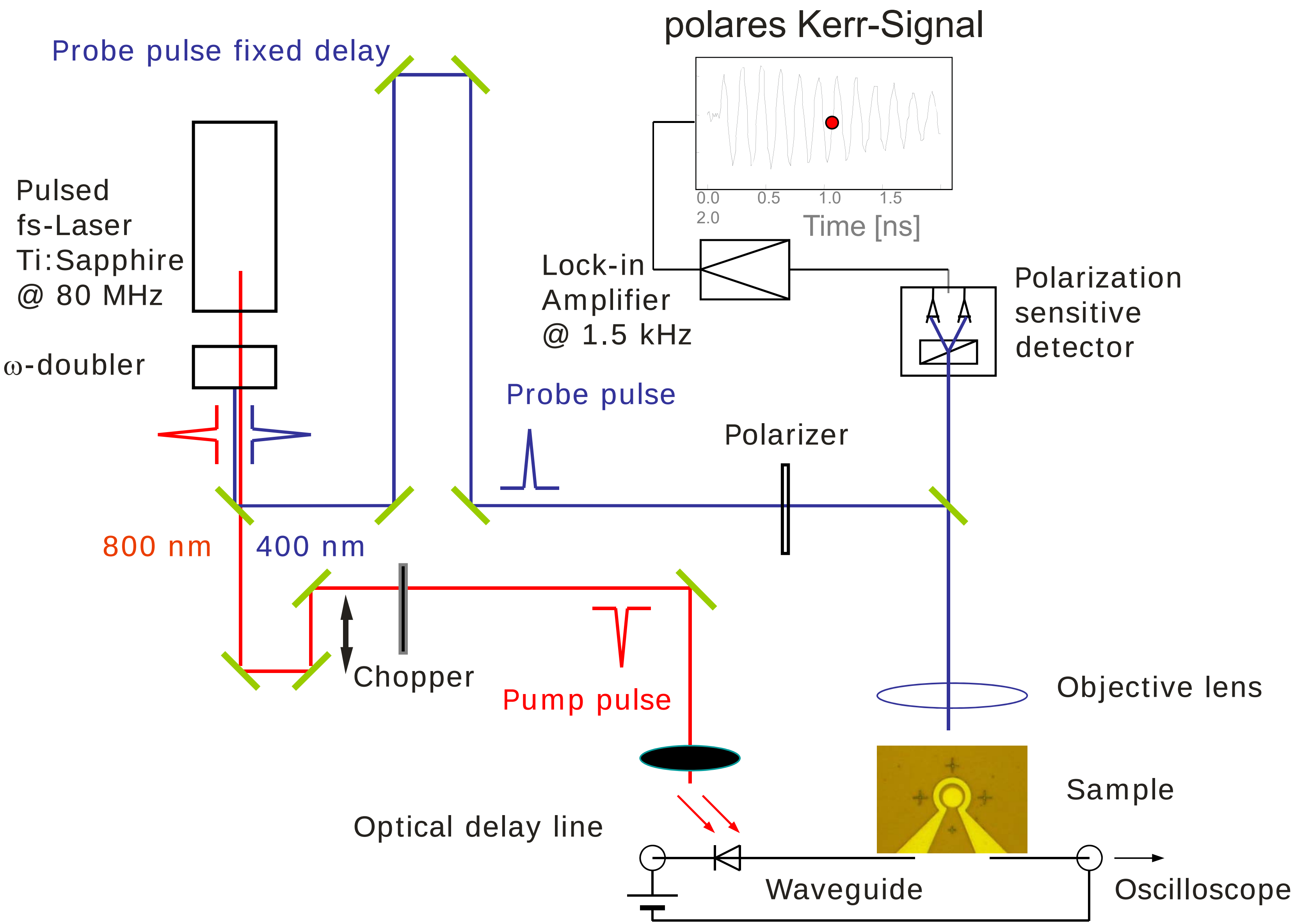
Time resolved (~1 ps resolution) scanning (~300nm resolution) Kerr microscopy
polar Kerr geometry



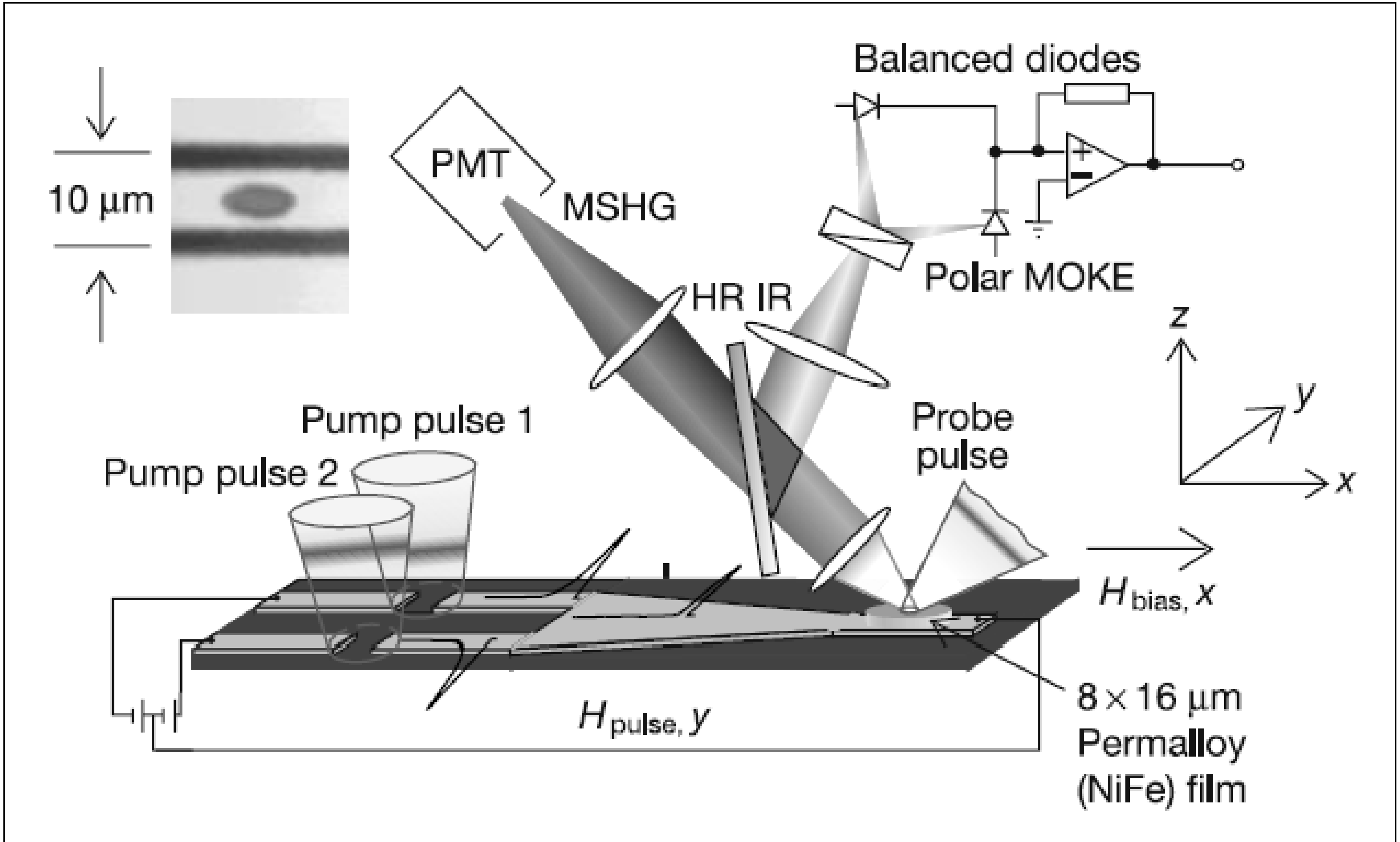
Time resolved (~1 ps resolution) scanning (~300nm resolution) Kerr microscopy
polar Kerr geometry



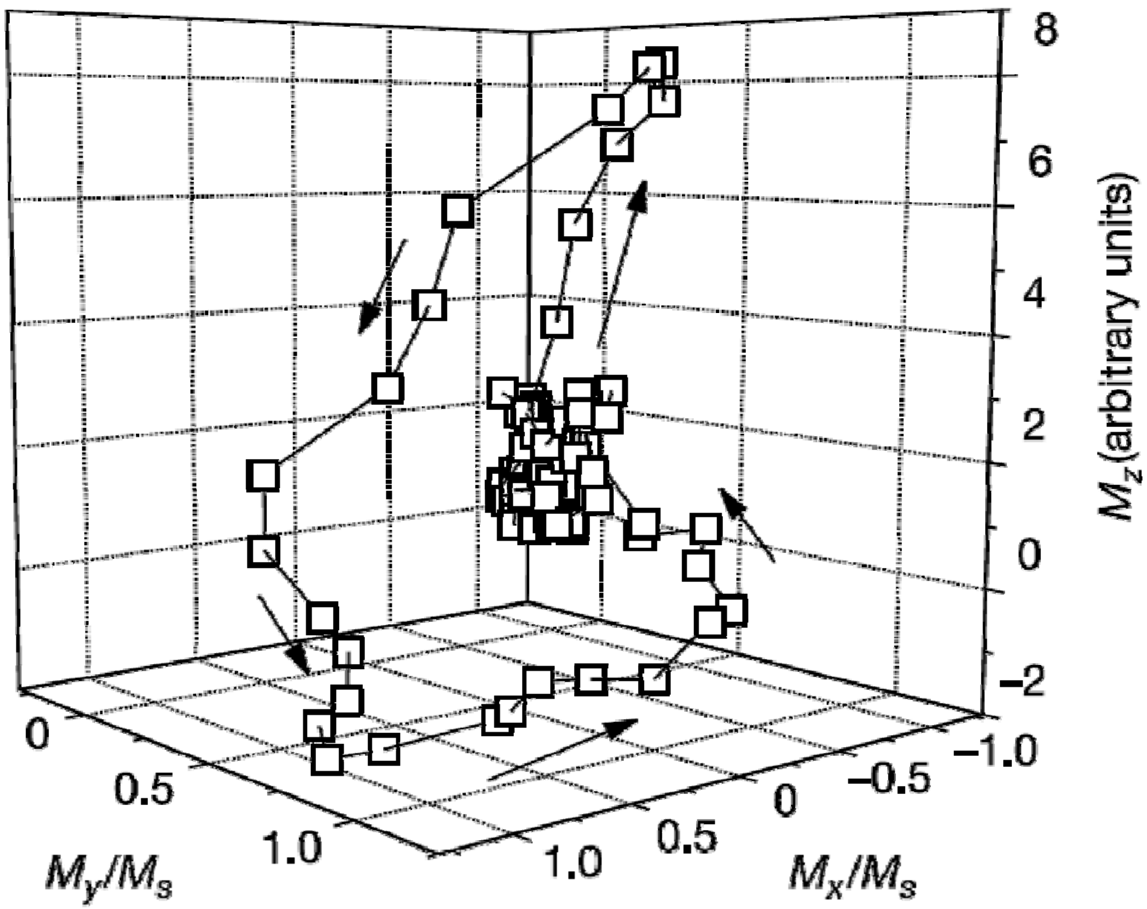
Time resolved (~1 ps resolution) scanning (~300nm resolution) Kerr microscopy polar Kerr geometry

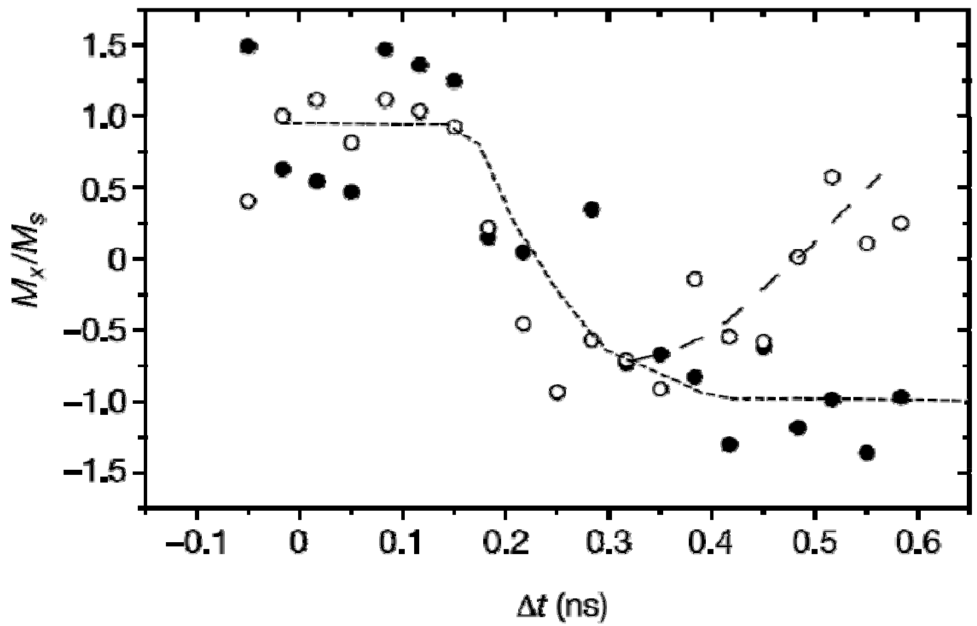


Time resolved switching experiment



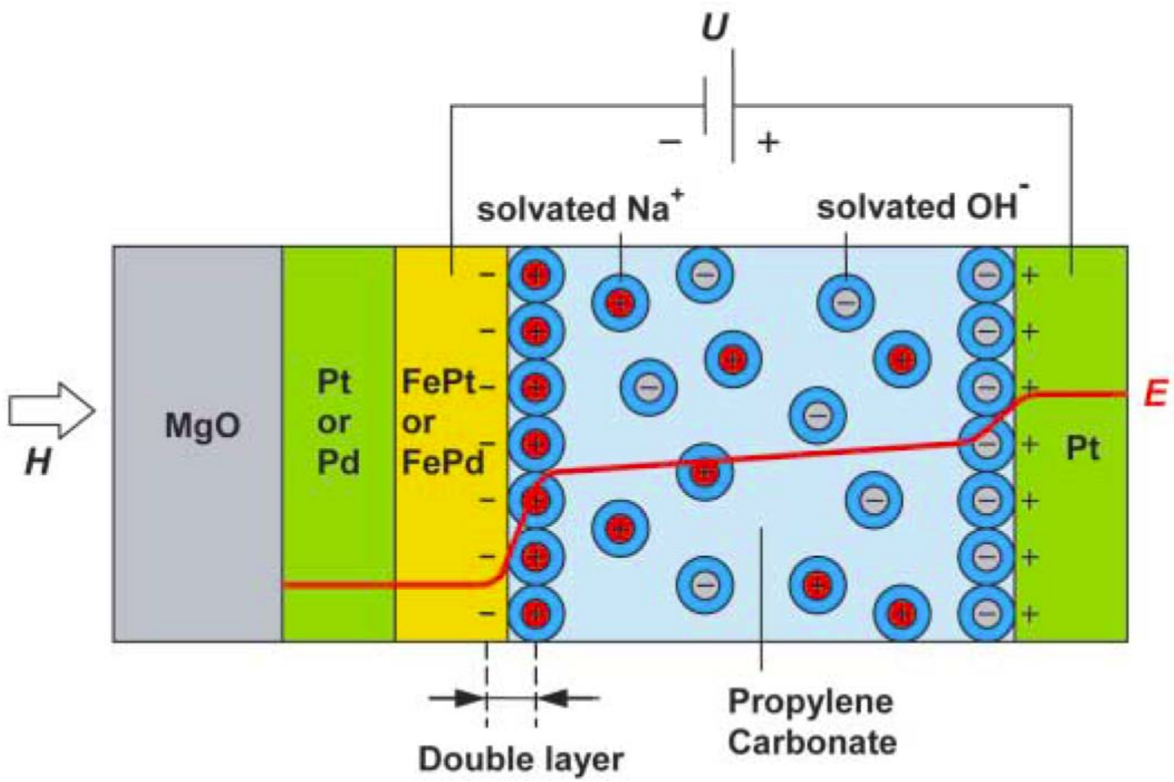
Nature **418**, 509 (2002)

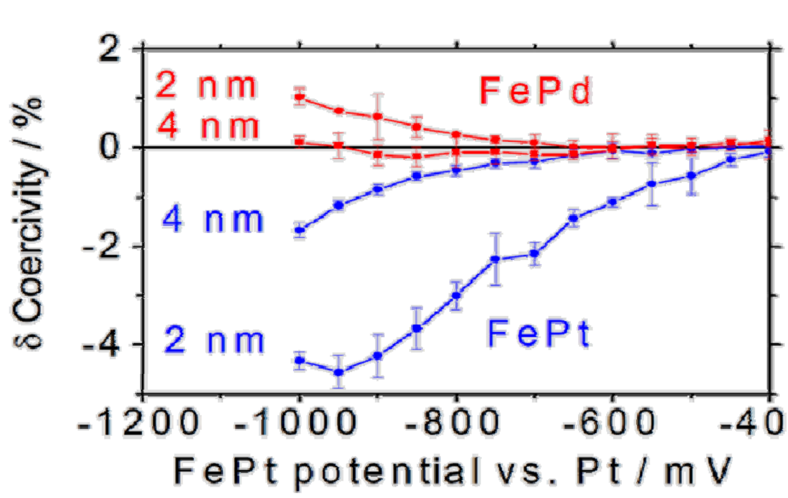




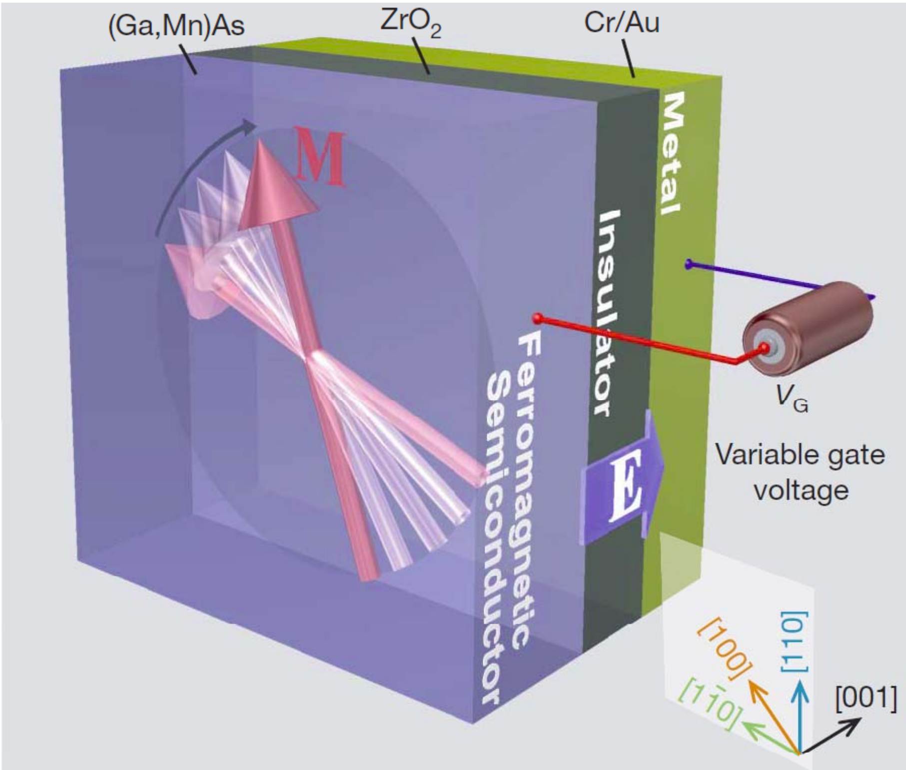
Nature **418**, 509 (2002)

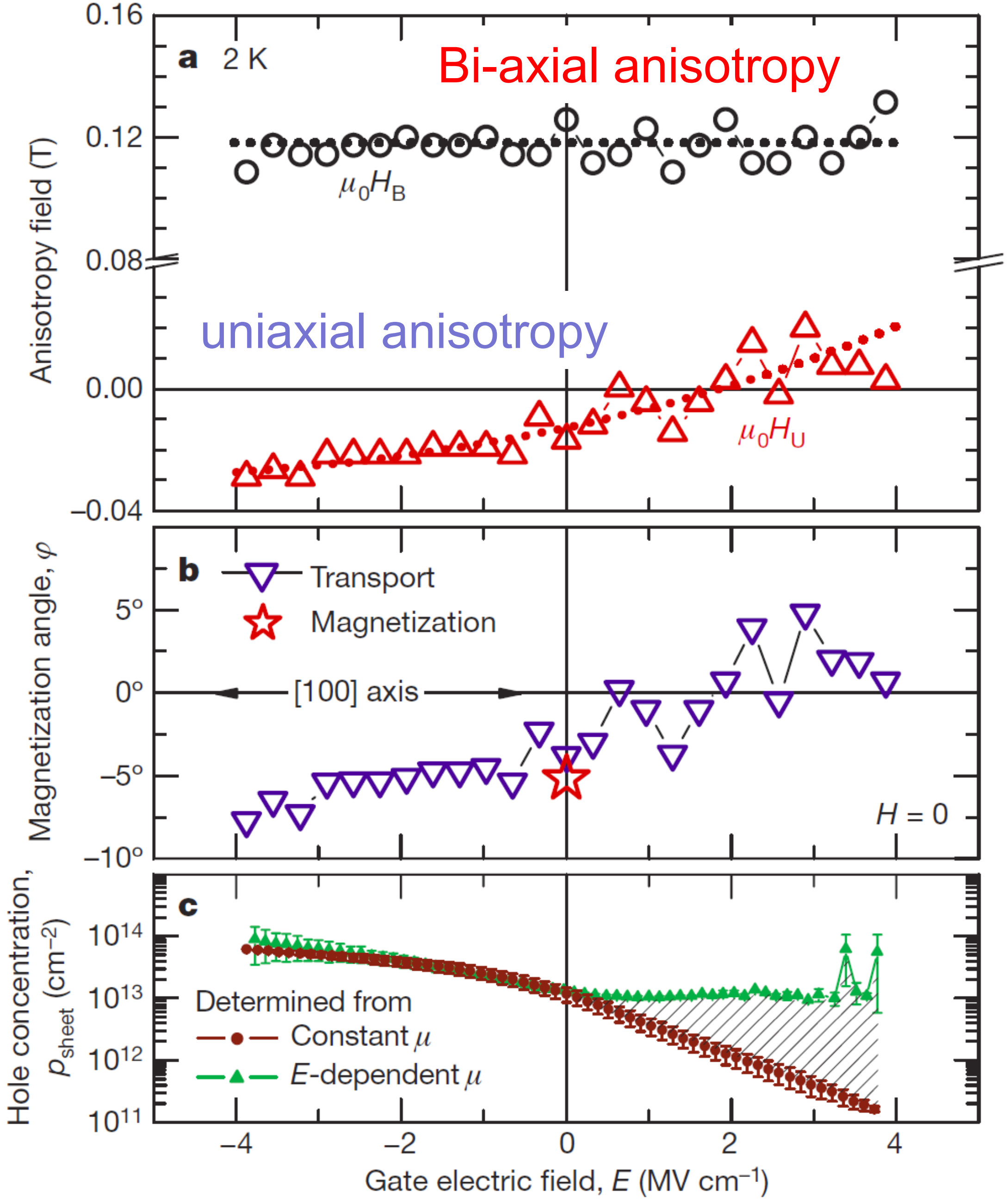
Electric field control ?



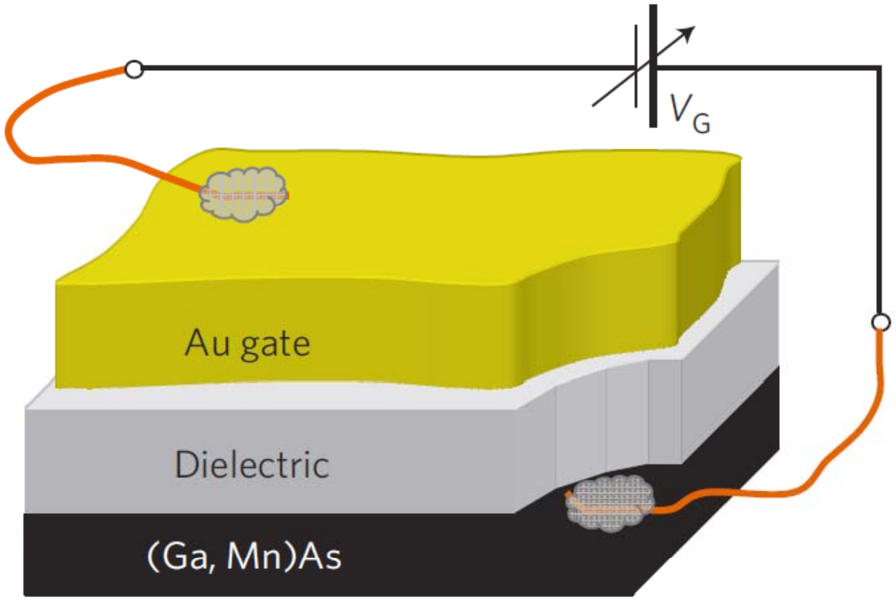


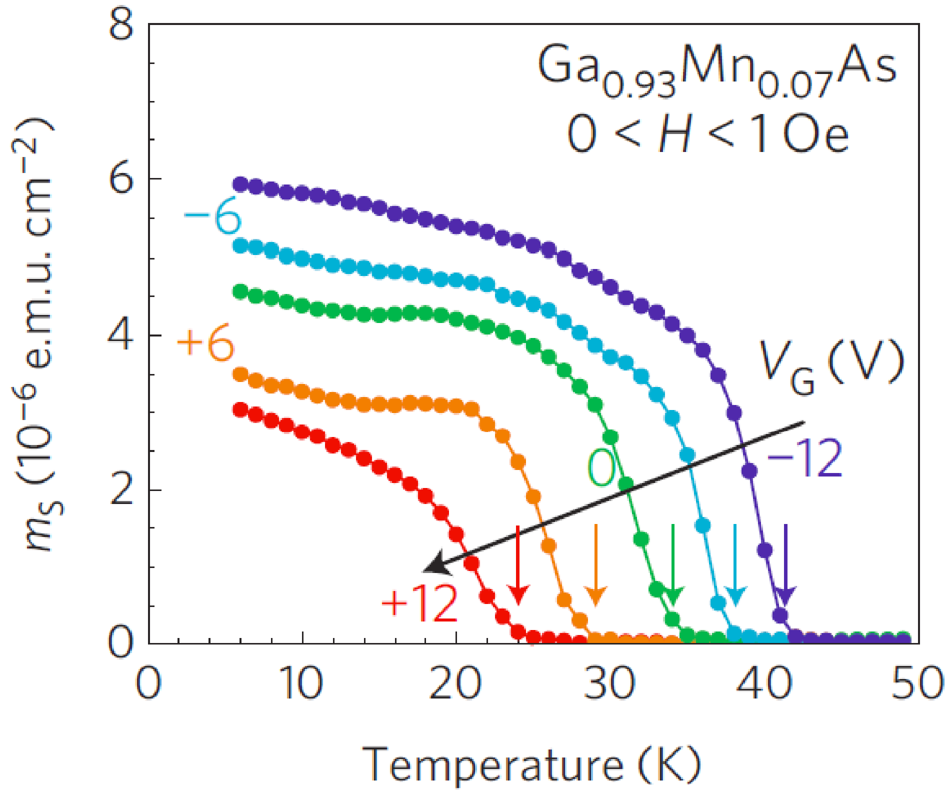
Weisheit et al., Science 315, 349 (2007)



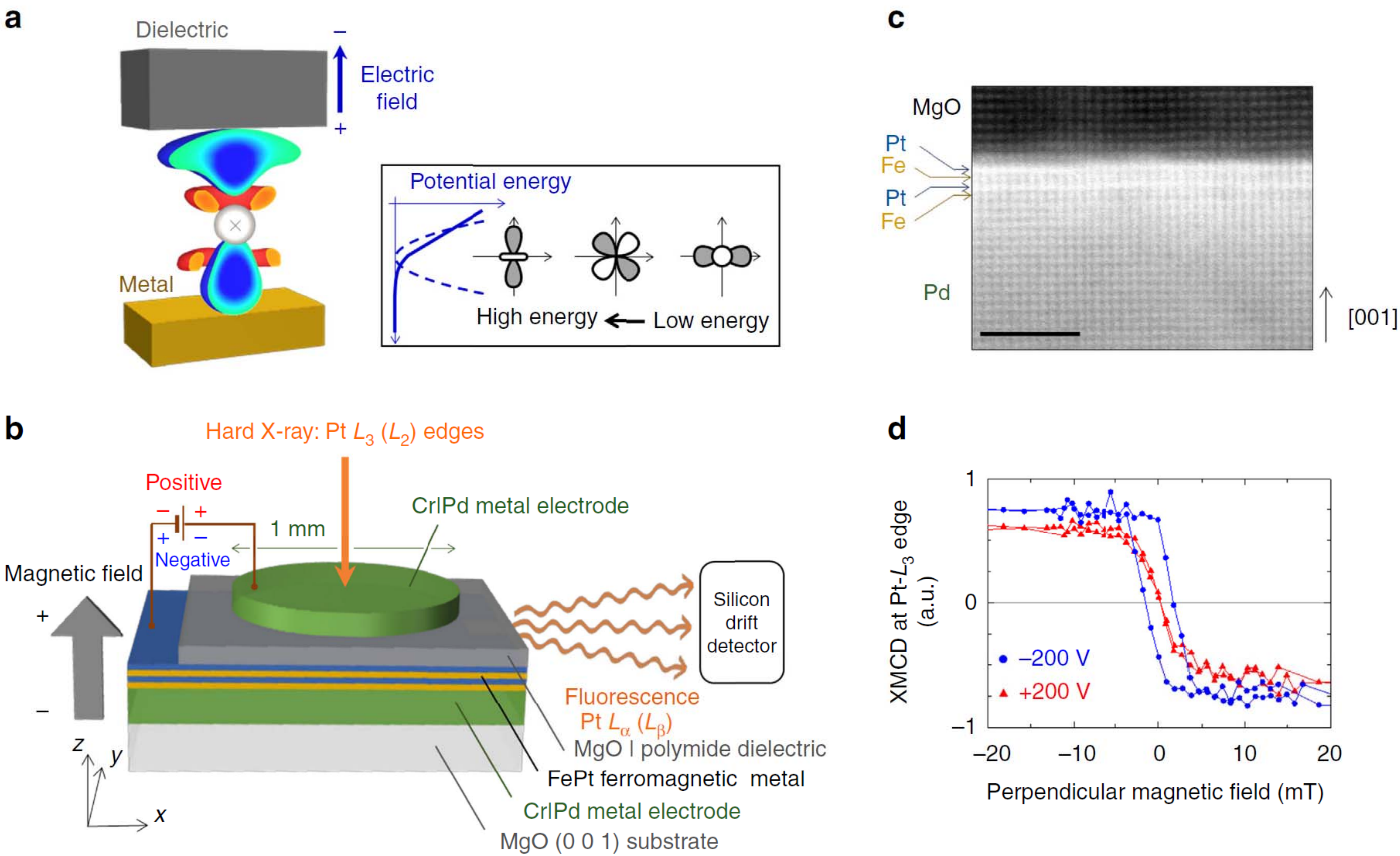


D. Chiba et al., Nature 455, 07318 (2008)





M. Sawicki et al., Nature Physics 2009 (DOI: 10.1038/NPHYS1455)



S. Miwa, Nature Communications (2017) (DOI: 10.1038/ncomms15848)

Spin-polarized currents ?

Reminder giant magneto resistance (GMR)

VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

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P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France

(Received 24 August 1988)

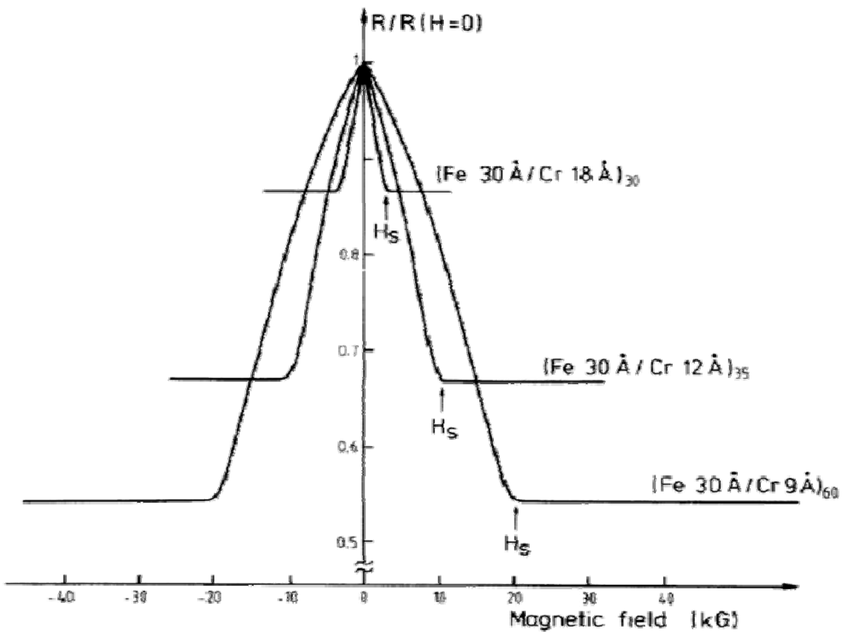
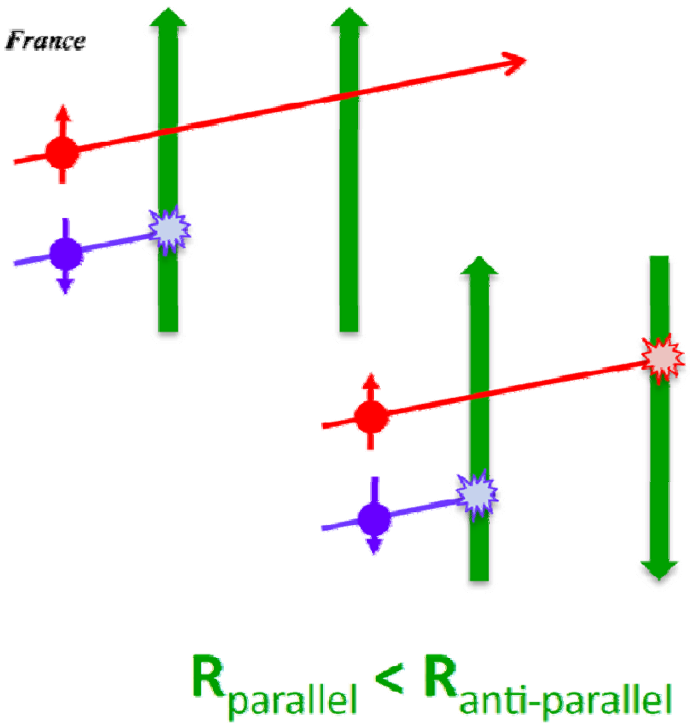


FIG. 3 Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.



GMR: Effect of the magnetization distribution on the electric conductivity

Spin Transfer Torque:
Action of the conduction electrons (for example 4s-like) on the local magnetization (for example 3d-like)

Independent proposals by L. Berger and J. Slonczewski

PHYSICAL REVIEW B VOLUME 54, NUMBER 13 1 OCTOBER 1996-I

Emission of spin waves by a magnetic multilayer traversed by a current

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(Received 31 January 1996)

ELSEVIER
Journal of Magnetism and Magnetic Materials 159 (1996) L1–L7
journal of magnetism and magnetic materials

Letter to the Editor

Current-driven excitation of magnetic multilayers

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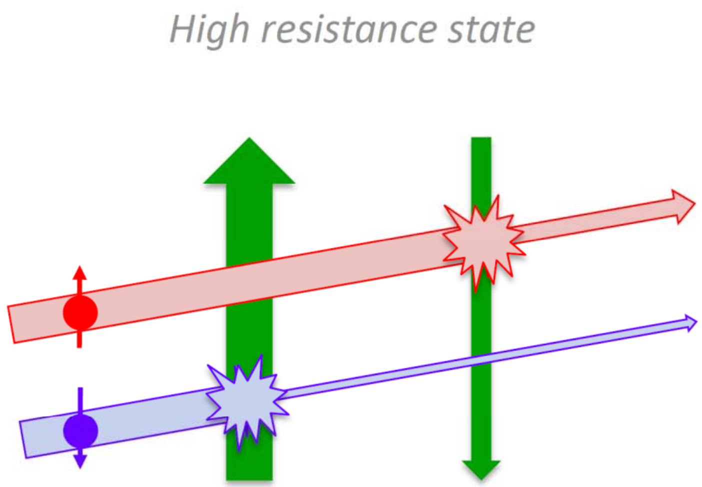
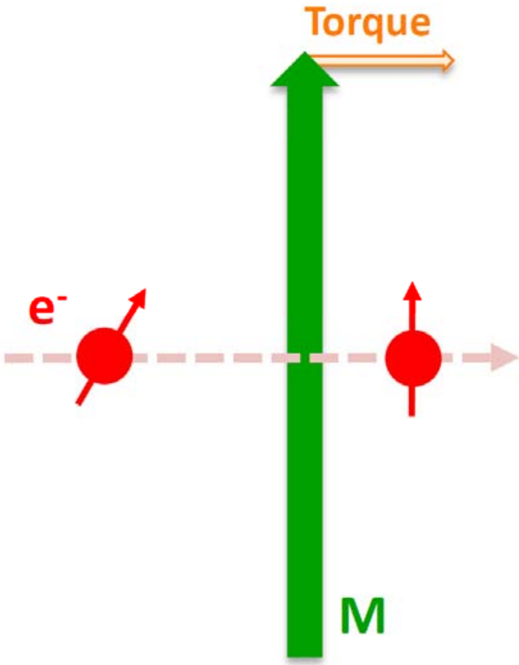
IBM Research Division, Thomas J. Watson Research Center, Box 216, Yorktown Heights, NY 10596, USA
Received 27 October 1995; revised 19 December 1995

A sufficiently large spin-polarized current crossing a ferromagnetic layer should exert a torque on the local magnetization : ***current-induced magnetization dynamics***





Transfer of angular momentum between conduction electrons and the electrons which make up the local magnetization results in a torque on the local magnetization

PHYSICAL REVIEW B **66**, 014407 (2002)

Anatomy of spin-transfer torque

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(Received 21 February 2002; published 24 June 2002)

First experimental demonstration

VOLUME 84, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 2000

Current-Driven Magnetization Reversal and Spin-Wave Excitations in Co/Cu/Co Pillars

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E. B. Myers and D. C. Ralph
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853

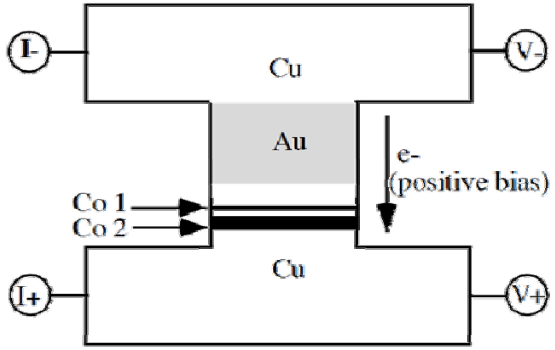
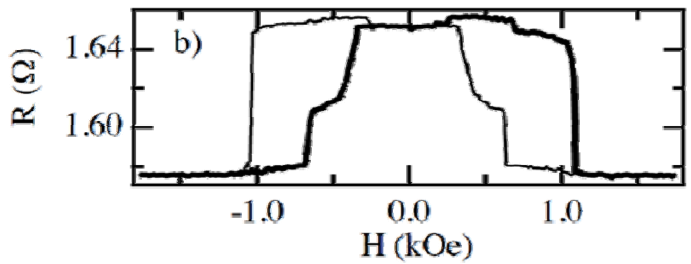


FIG. 1. Schematic of pillar device with Co (dark) layers separated by a 60 Å Cu (light) layer. At positive bias, electrons flow from the thin (1) to the thick (2) Co layer.



APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 23

Spin-polarized current induced switching in Co/Cu/Co pillars

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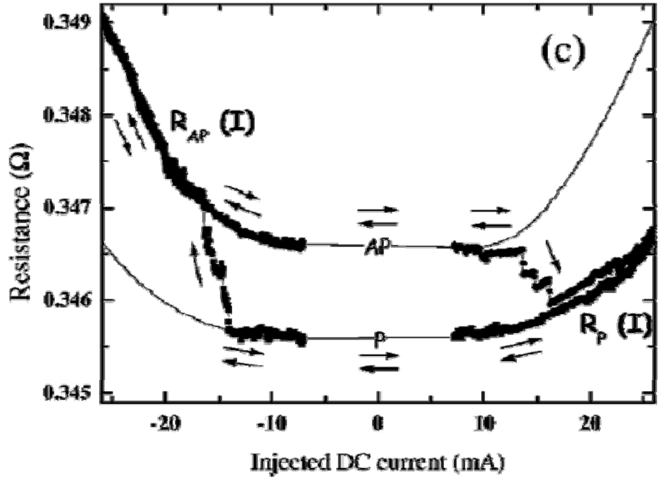
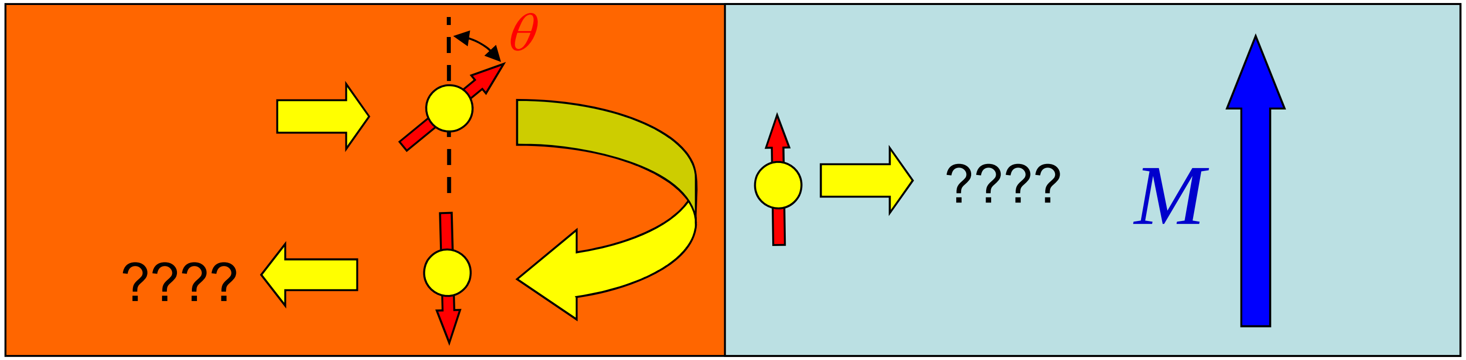
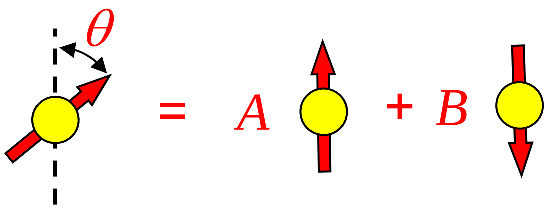




Quantum mechanics of spin:



$$\begin{cases} A = \cos\left(\frac{\theta}{2}\right) \\ B = \sin\left(\frac{\theta}{2}\right) \end{cases}$$

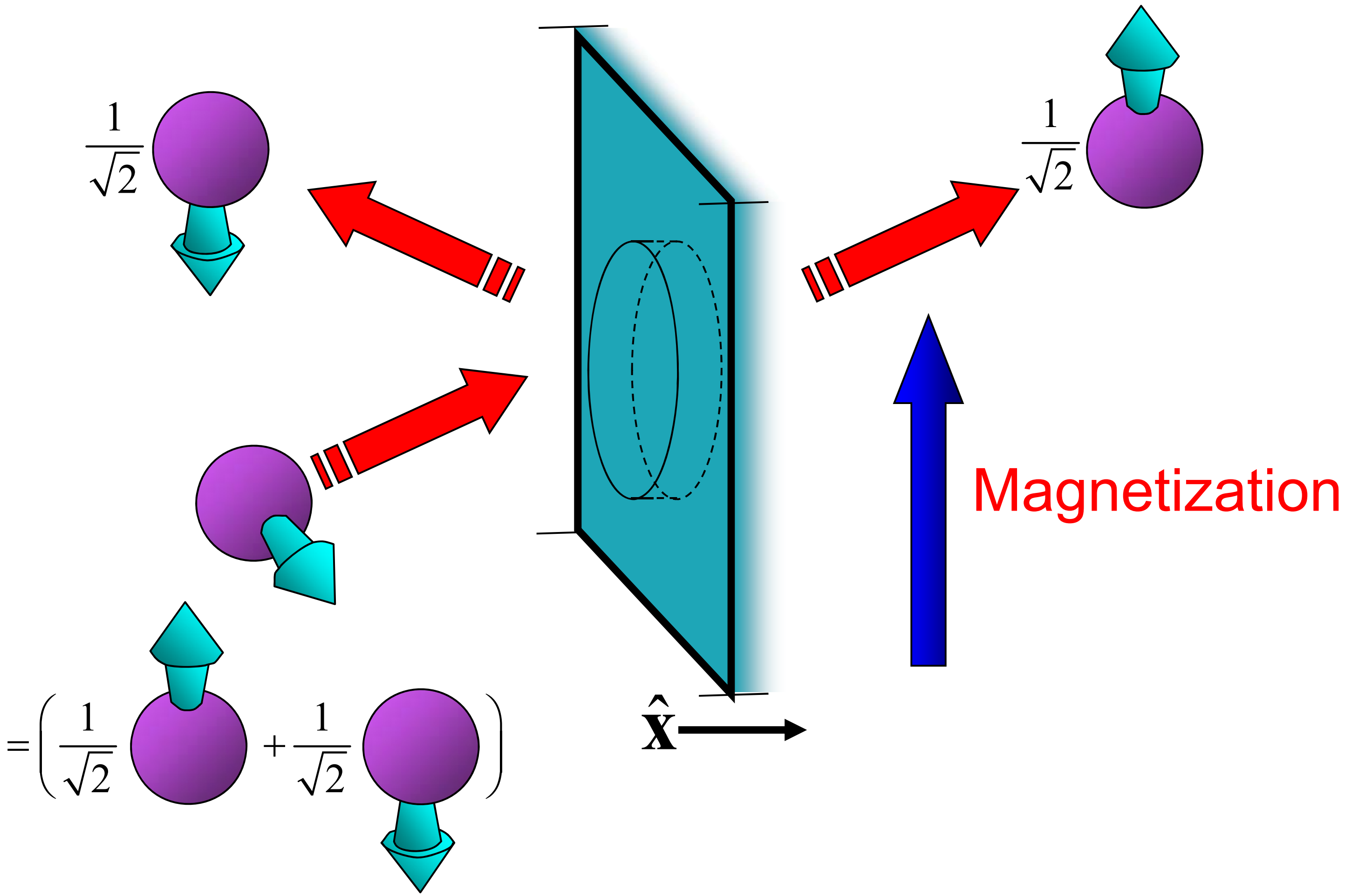
An arbitrary spin state is a coherent superposition of "up" and "down" spins.

Quantum mechanical probabilities:

$$\Pr\left[\uparrow\right] = |A|^2 = \frac{1}{2}\left(1+\cos(\theta)\right)$$

$$\Pr\left[\downarrow\right] = |B|^2 = \frac{1}{2}\left(1-\cos(\theta)\right)$$

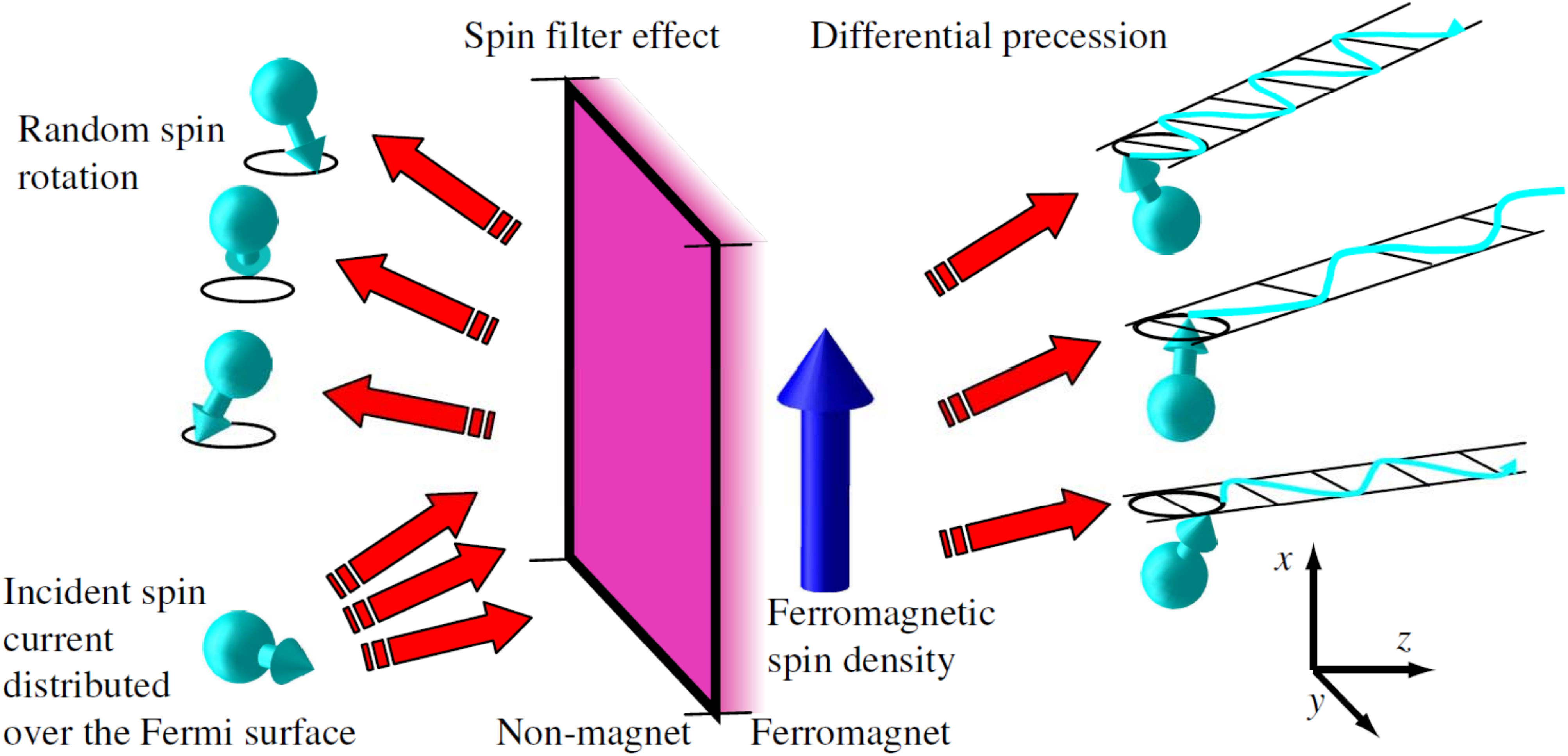
Absorption of transverse angular momentum



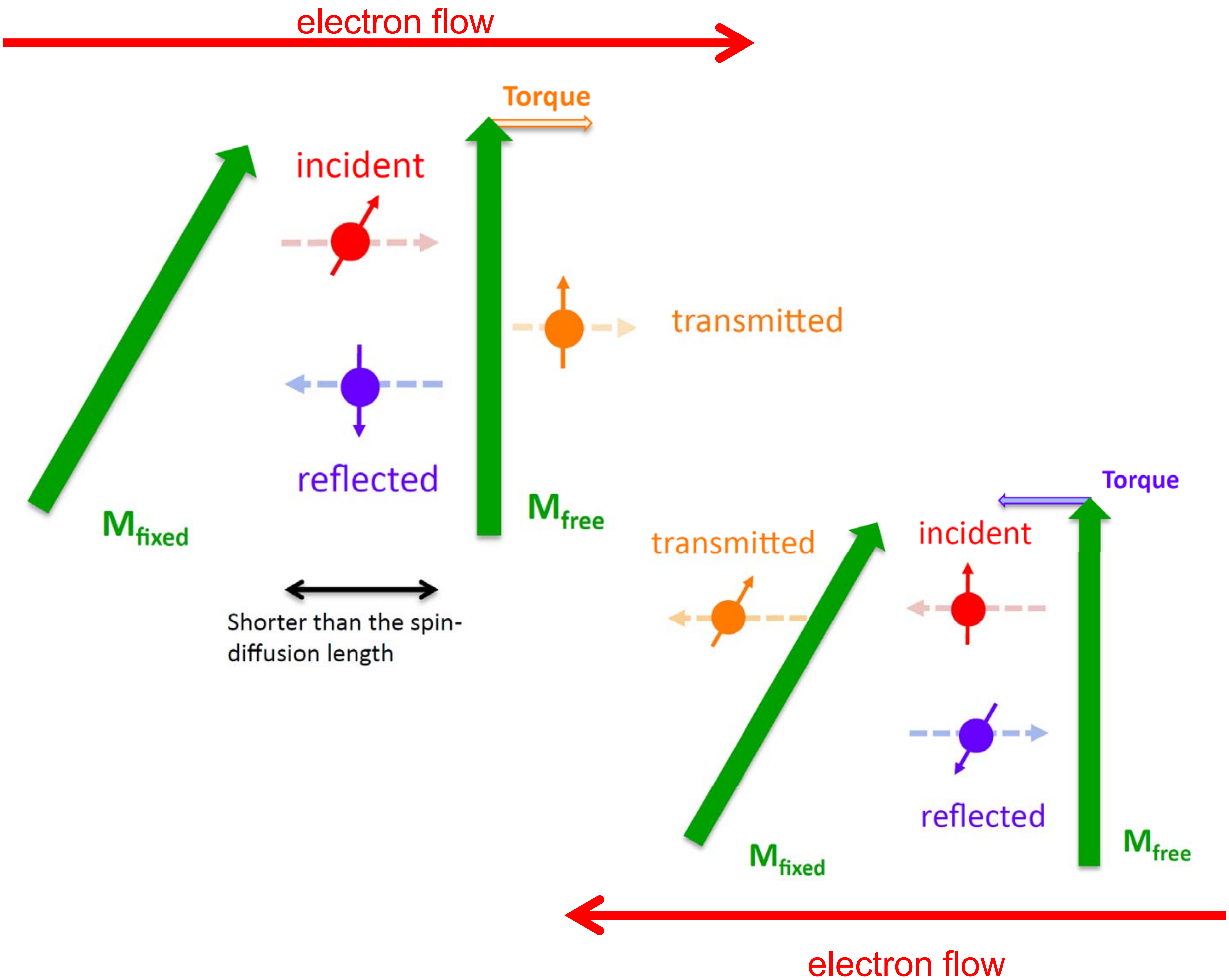
- Transverse component of reflected and transmitted spin current is zero
- Absorbed by the interface and acts as a current-induced torque on the magnetization

Stiles and Zangwill PRB 2002

- Reflection and transmisson coefficients are spin dependent
- Reflection and transmisson coefficients are complex leading to rotation (classical dephasing)
- Different wave vectors for spin up and spin down in FM lead to precession

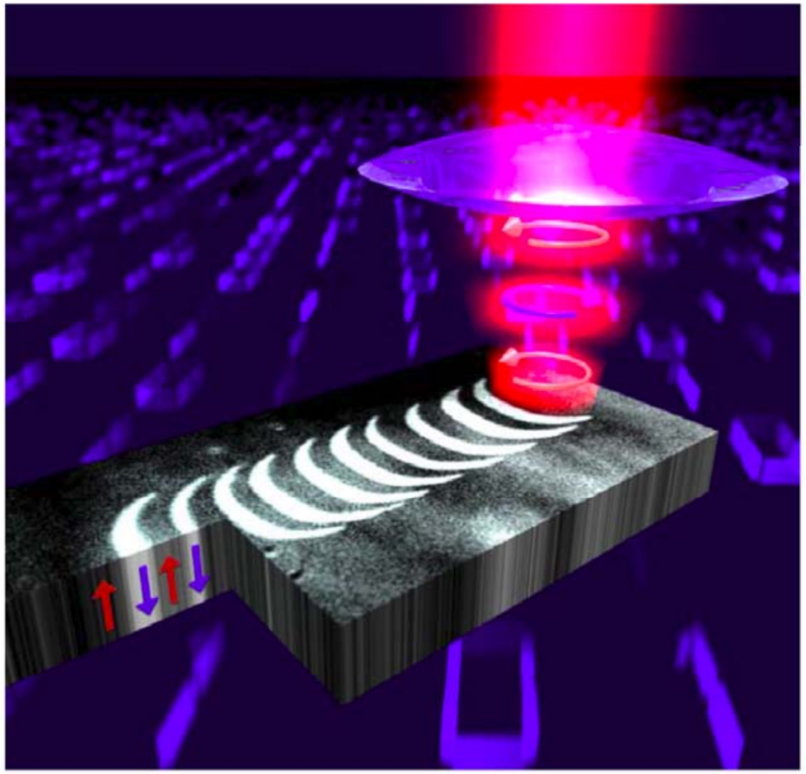


M. D. Stiles and J. Miltat, Topics in App. Phys. 101, 225 (2006).



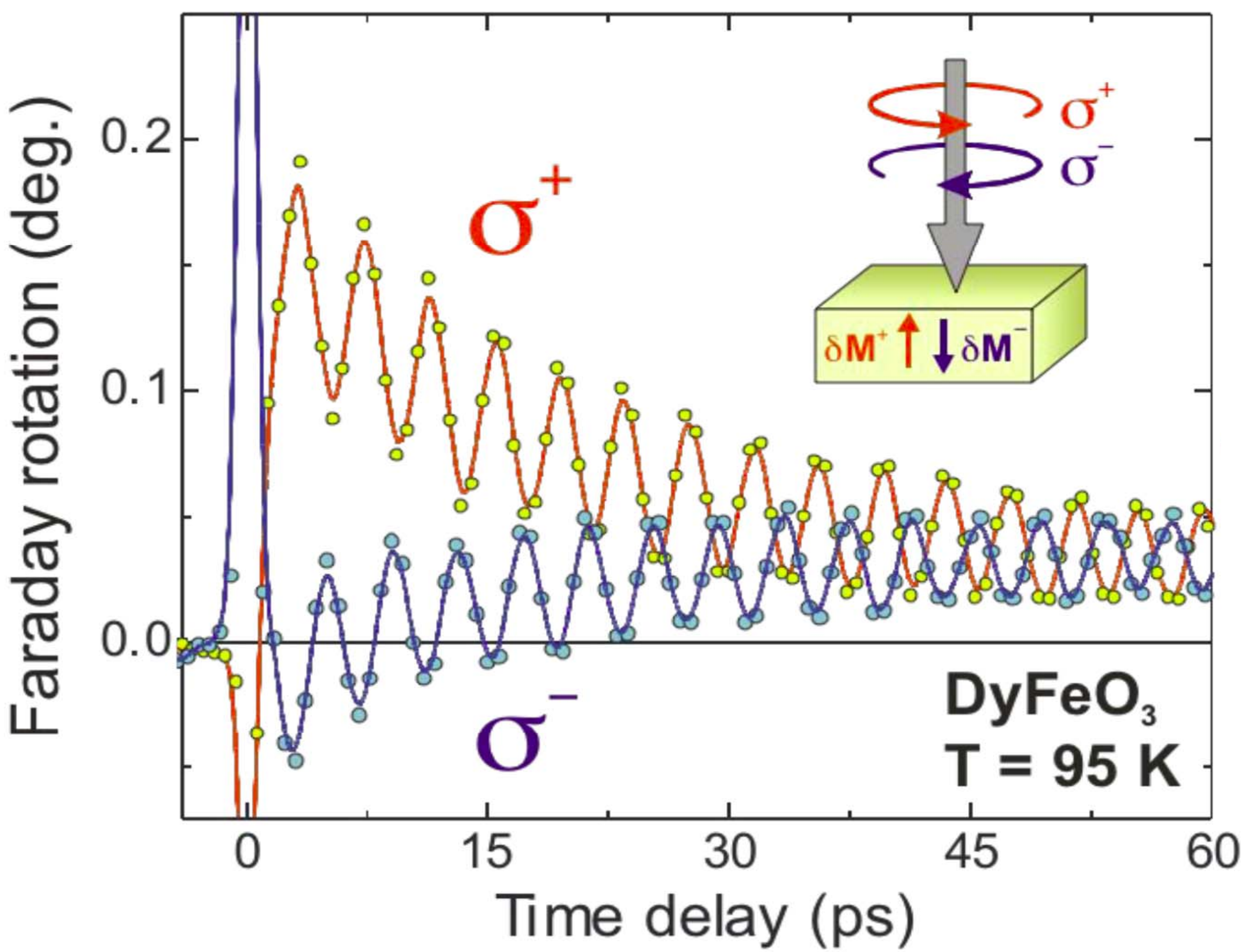
electron flow
Torque
incident
transmitted
reflected
M_{fixed}
M_{free}
Shorter than the spin-diffusion length
Torque
transmitted
incident
reflected
M_{fixed}
M_{free}
electron flow

Control of the magnetization by light?



Stanciu *et al*, PRL **99**, 047601 (2007)

Inverse Faraday effect:



Kimel *et al*, Nature **435**, 655 (2005)

Does it work in metallic systems ?

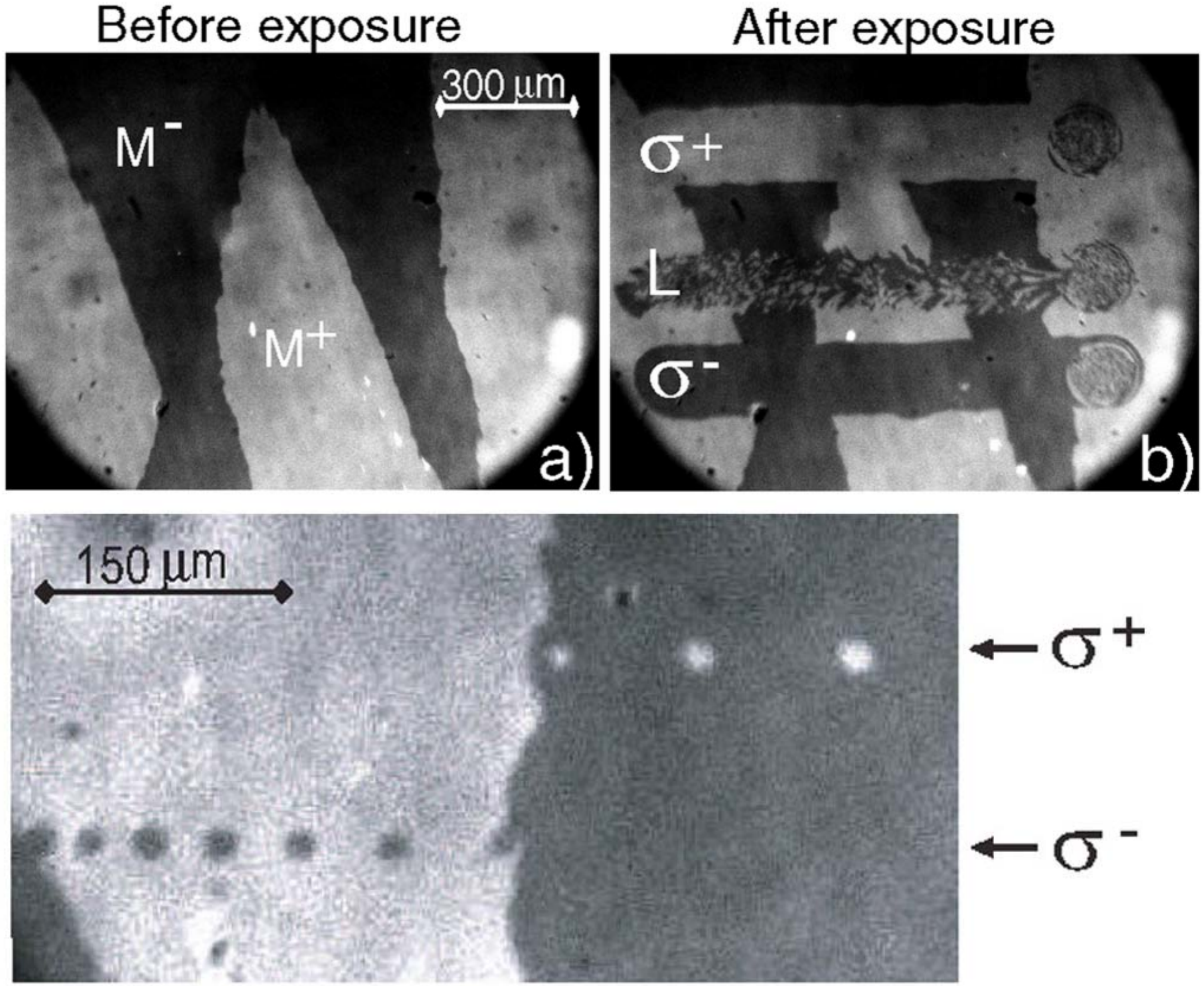
Here: ferrimagnet GdFeCo

Combined heating
+ inverse Faraday effect
+ dichroism ?

Magneto-optical material. Tc=500K

$Gd_{22}Fe_{74.6}Co_{3.4}$

Ti:S laser:
λ=800nm; $\Delta\tau$=40fs.



All-Optical Magnetic Recording with Circularly Polarized Light

Stanciu et al., Phys Rev Lett **99**, 047601 (2007)

Manipulation of magnetization is possibe by many different methods:

- Magnetic field control
- Electric field control
- Strain control
- Spin polarized currents
- Light