Spin torques in spin valves and domain walls

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Outline

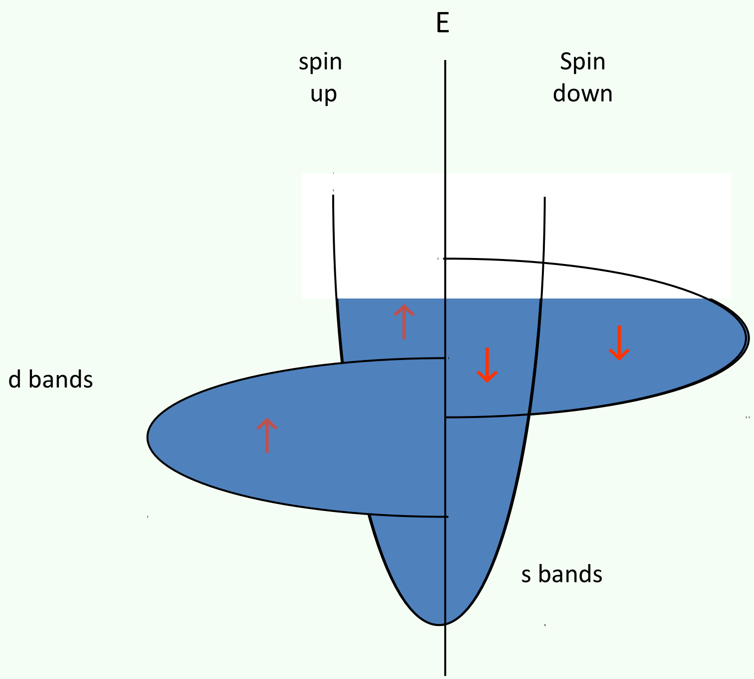
- Short Introduction: Spintronics
- LLG equation
- Spin Momentum Transfer in trilayers
- Magnetization dynamics in trilayers
- Domain Walls
- Pushing Domain Walls with Currents
- Spin Transfer in insulators

Thanks to several inspirational presentations:
Tom Silva (NIST), Ursula Ebels (SPINTEC), André Thiaville + Alexandra Mougin (IEF Orsay), Gerrit Bauer (Delft University)

Spintronics

Spin dependent transport in ferromagnetic metals

Different DOS for up and down spins :



s electrons : low density of states + high mobility

d electrons : large density of states + low mobility

Transport is dominated by s electrons scattered into d bands

d bands split by the exchange energy

→ diffusion is spin dependent

→ **Two current model** :

Two conduction channels in parallel with $\rho\uparrow \neq \rho\downarrow$

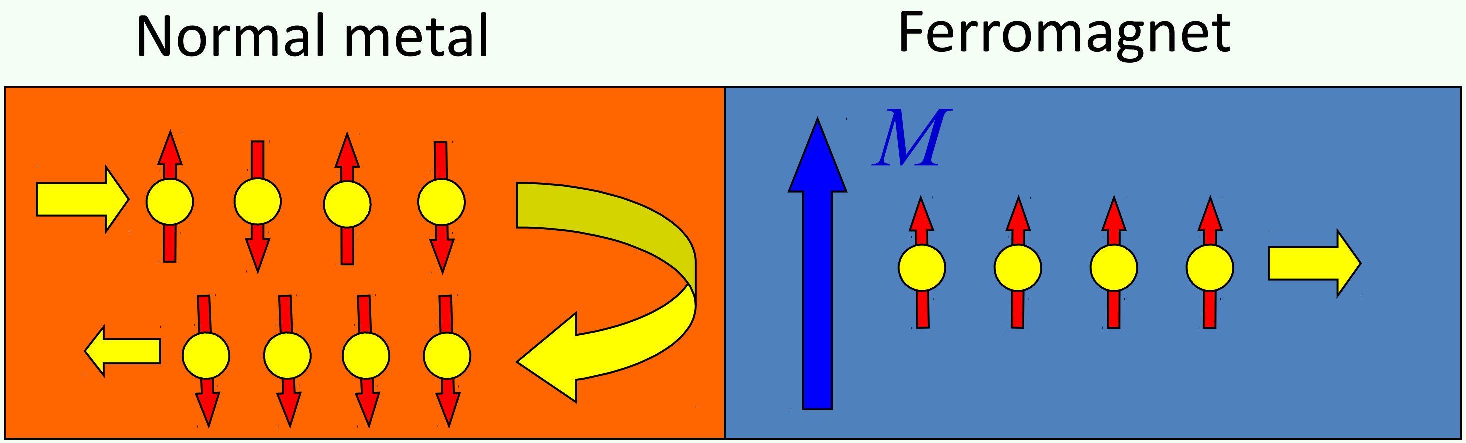
Resistivity :

$$\rho = \frac{\rho_{\uparrow}\rho_{\downarrow}}{\rho_{\uparrow}+\rho_{\downarrow}}$$

or (with spin-flip) :

$$\rho = \frac{\rho_{\uparrow}\rho_{\downarrow}+\rho_{\uparrow\downarrow}(\rho_{\uparrow}+\rho_{\downarrow})}{\rho_{\uparrow}+\rho_{\downarrow}+4\rho_{\uparrow\downarrow}}$$

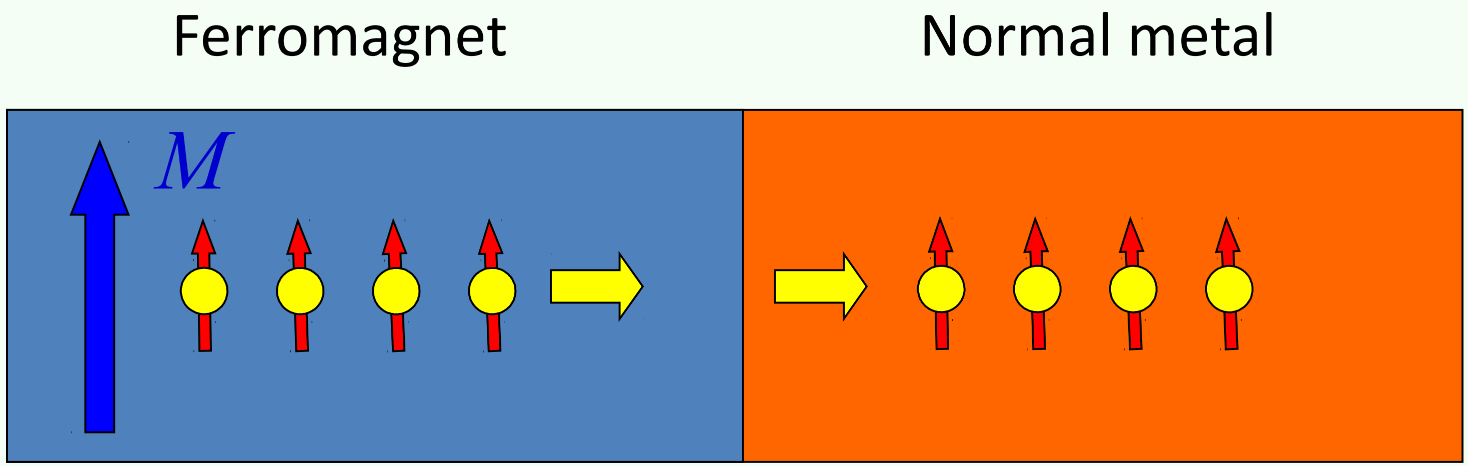
interfacial spin-dependent scattering



➔“Majority” spins are preferentially transmitted.

➔”Minority” spins are preferentially reflected.

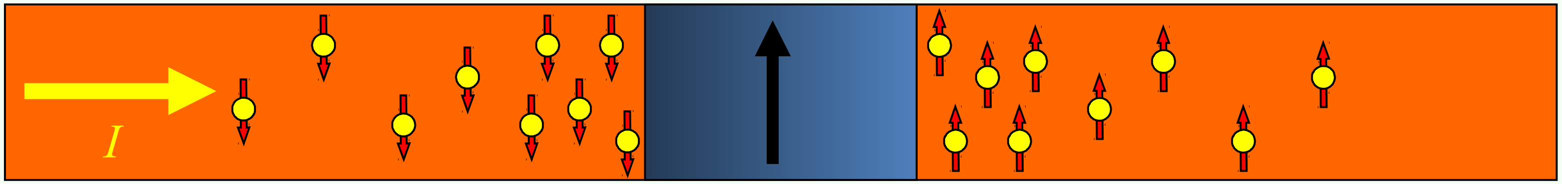
ferromagnets as spin polarizers



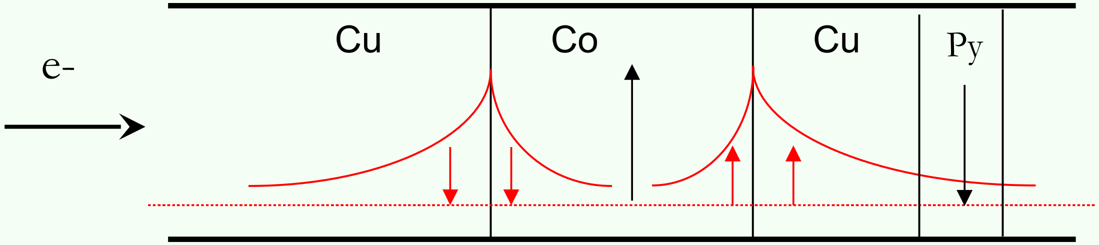
➔"Majority" spins are preferentially transmitted.

Ferromagnetic conductors are more permeable for majority spins than for minority spins.

spin accumulation

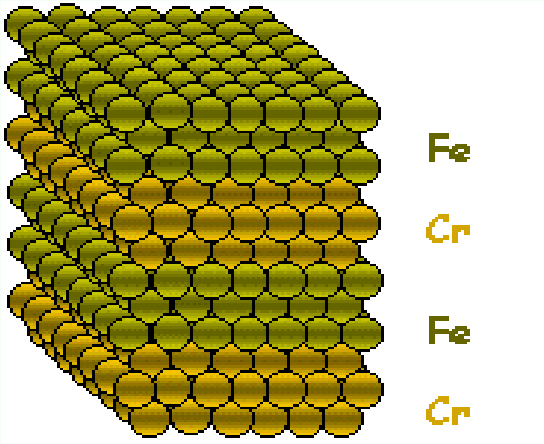


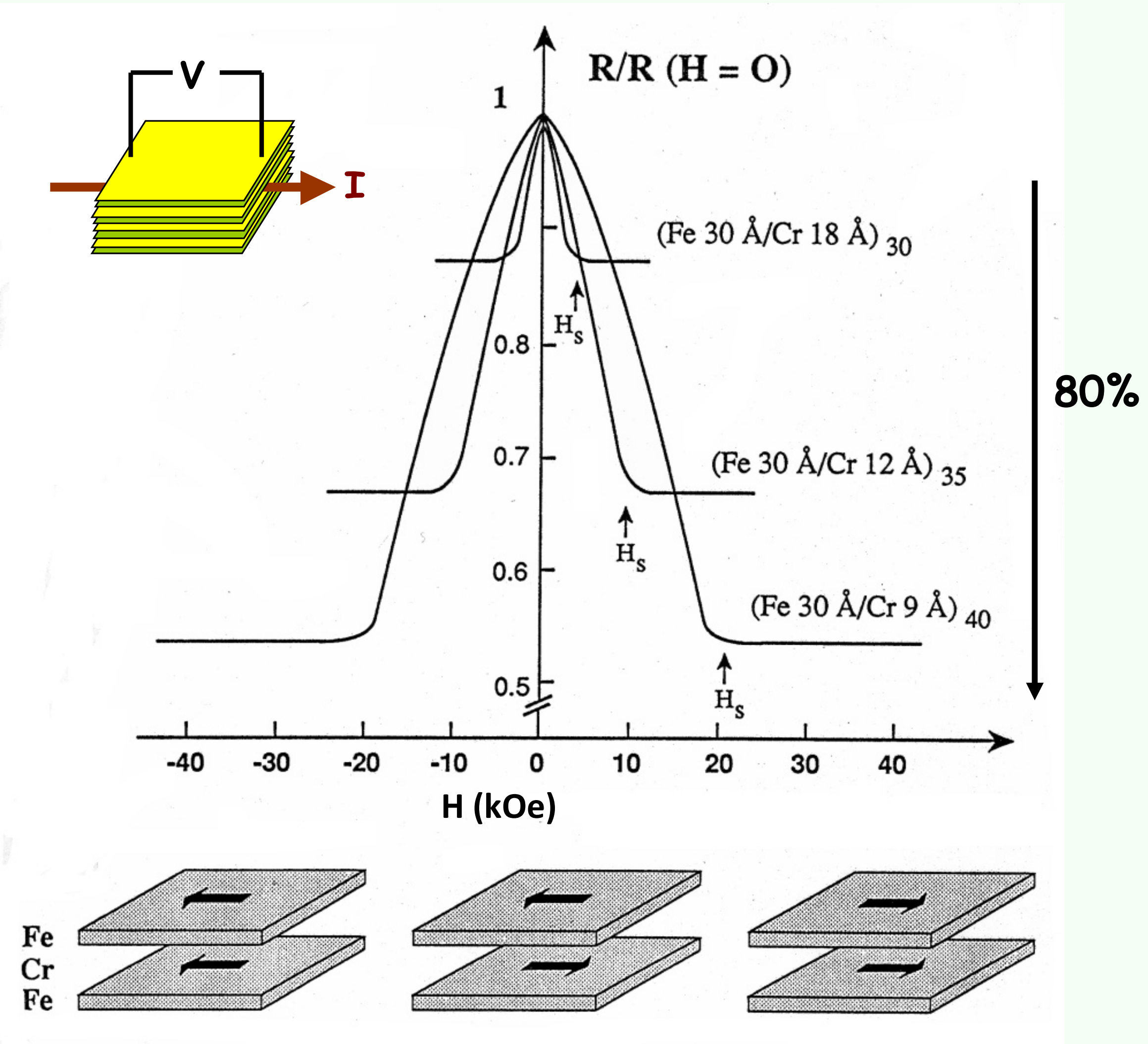
The Spin Valve:



→ Magneto-resistance in multilayers

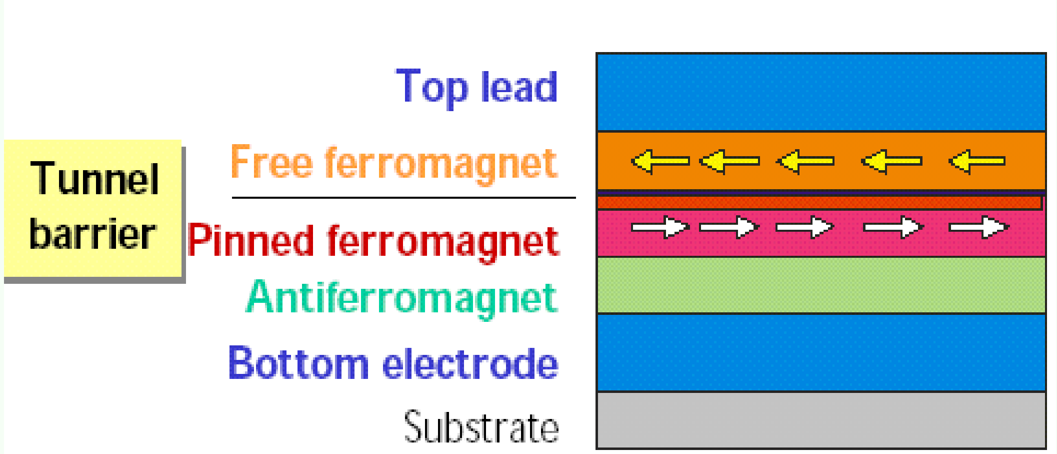
Multilayers
F metal / NM metal
(ex : Fe / Cr, Co / Cu, etc)

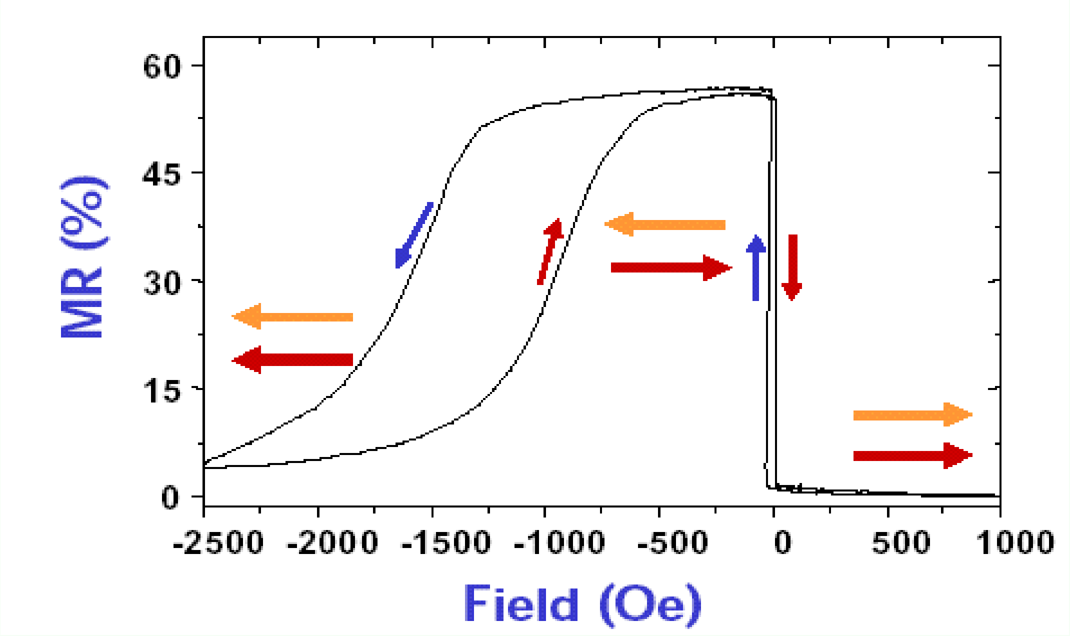




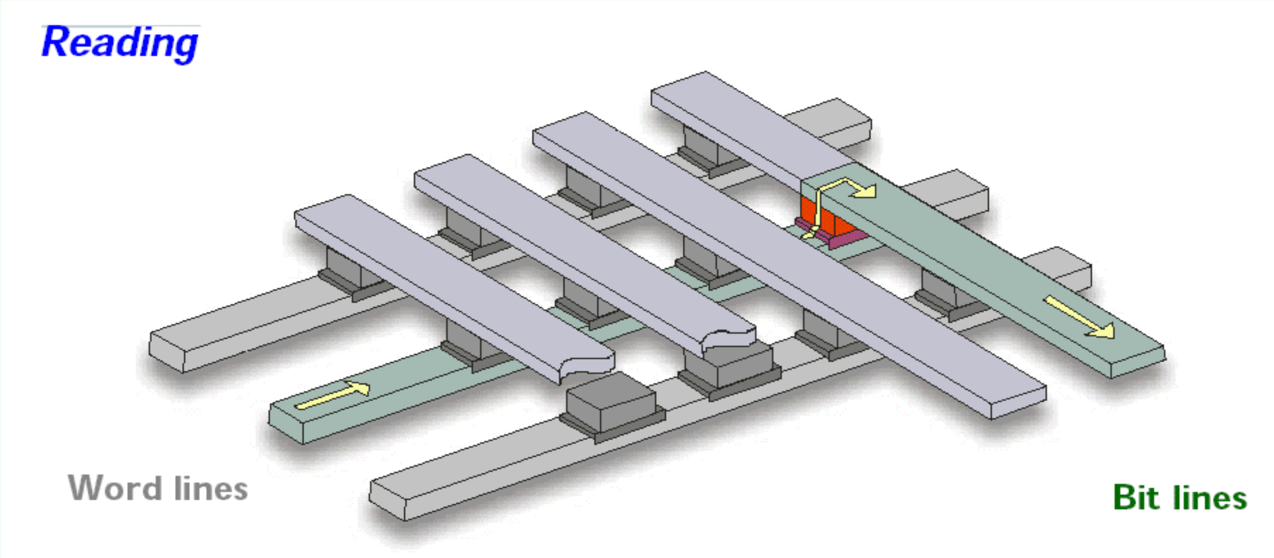
Industrial Applications

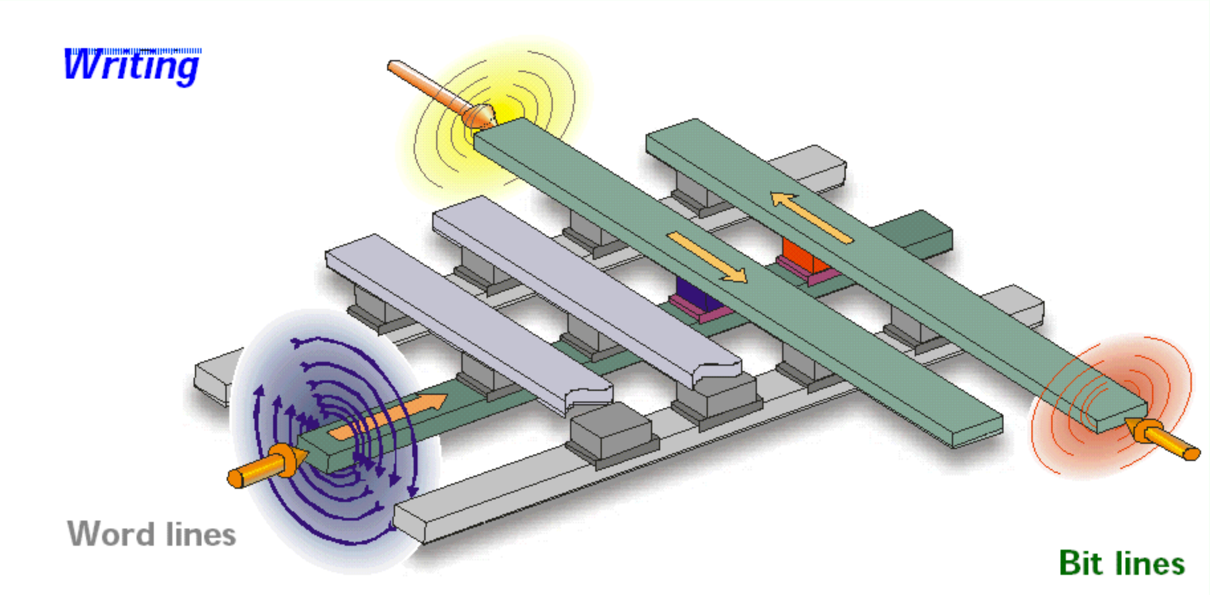
Computer read head:





MRAM :

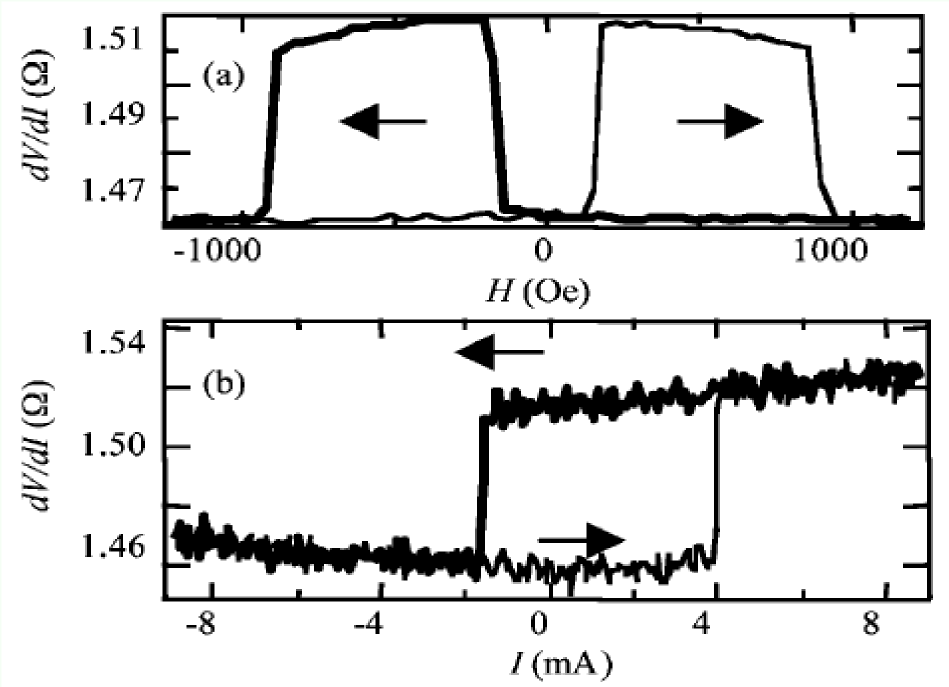




Latest developments: spin transfer

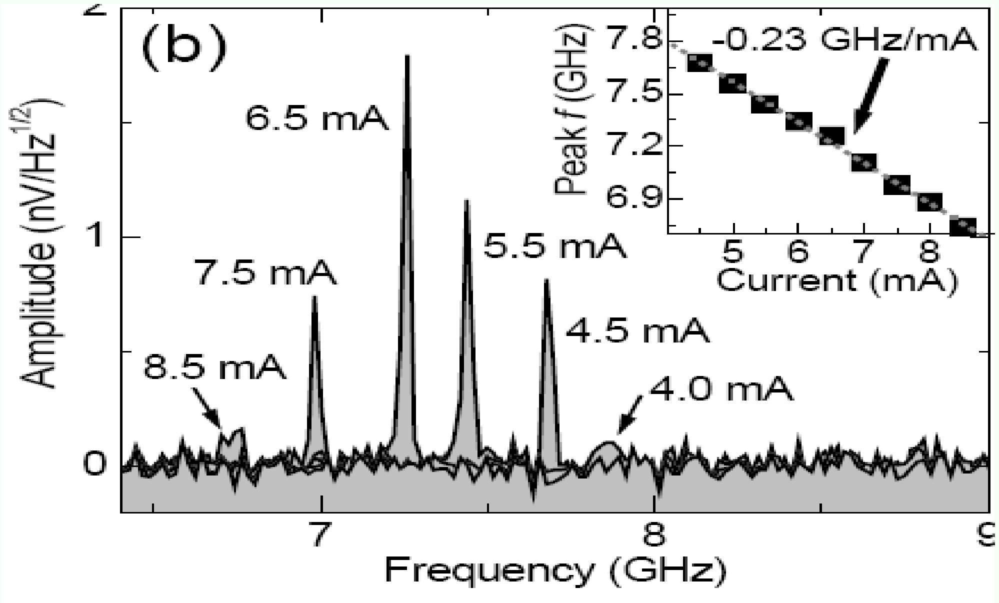
Switching:

F. J. Albert et al. PRL89, 226802 (2002)



Spin precession induced by a current:

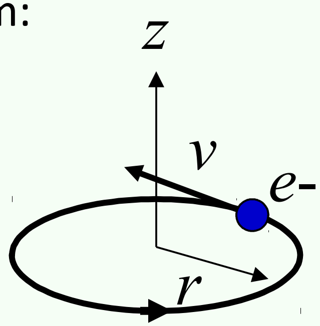
NIST, 2004



Magnetization dynamics

Magnets are Gyroscopes!

Classical model for an atom:



magnetic moment for atomic orbit:

$$\vec{\mu}_L = I\vec{A}$$

$$= -\left(\frac{ev}{2\pi r}\right)\left(\pi r^2\right)\hat{z}$$

$$= -\frac{evr}{2}\hat{z}$$

angular momentum for atomic orbit:

$$\vec{L} = \vec{r} \times \vec{p}$$

$$= rmv\hat{z}$$

$$\gamma_L = \frac{\mu_z}{L_z}$$

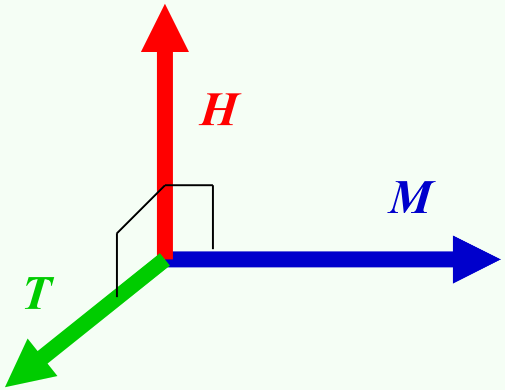
$$= -\frac{evr/2}{rm_e v}$$

$$\boxed{\gamma_L = -\frac{e}{2m_e} = -\frac{\mu_B}{\hbar}} \longrightarrow \gamma_s = -\frac{2\mu_B}{\hbar}$$

For spin angular momentum, extra factor of 2 required.

"The gyromagnetic ratio"

Larmor Equation



$$\vec{T} = \mu_0 \vec{M} \times \vec{H}$$

Magnetic field exerts torque on magnetization.

(definition of torque) $$\frac{d\vec{L}}{dt} = \vec{T}$$

$$\gamma \equiv \frac{\mu}{L}$$ (gyromagnetic ratio)

$$\frac{d\vec{M}}{dt} = \gamma \vec{T}$$

$$= \gamma \mu_0 \left(\vec{M} \times \vec{H} \right)$$

Gyromagnetic precession with energy loss: The Landau-Lifshitz equation

<u>Landau & Lifshitz (1935):</u>

$\vec{T}_p =$ precession torque

$$= \mu_0 \vec{M} \times \vec{H}$$

$\vec{T}_d =$ damping torque

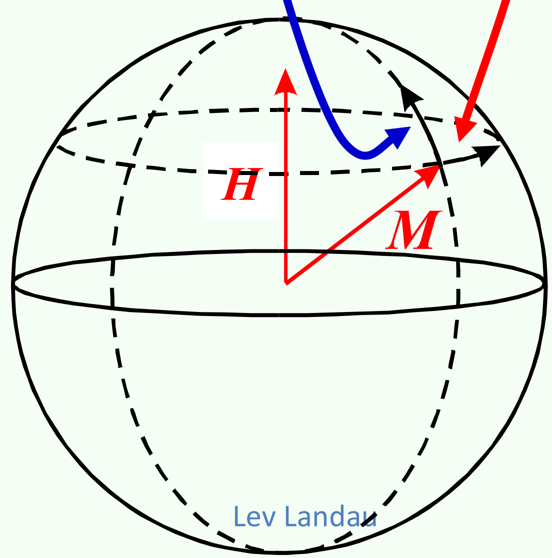
$$= \frac{\alpha \mu_0}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H} \right)$$

$\alpha =$ dimensionless Landau-Lifshitz damping parameter

$$\frac{d\vec{M}}{dt} = -|\gamma| \vec{T} = -|\gamma| \left(\vec{T}_p + \vec{T}_d \right)$$

$$= -|\gamma| \mu_0 \vec{M} \times \vec{H}$$

$$- \frac{\alpha |\gamma| \mu_0}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H} \right)$$

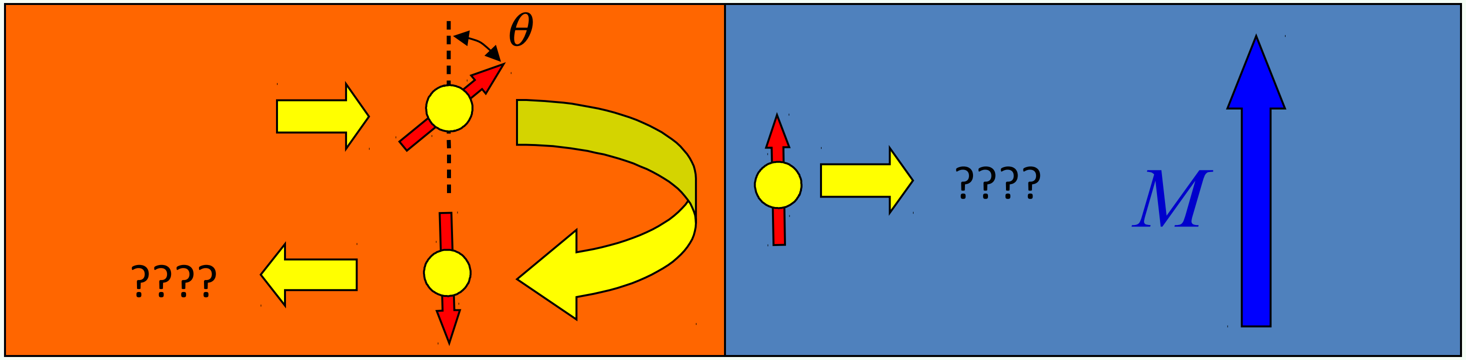


L. Landau and E. Lifshitz, Physik. Z. Sowjetunion **8**, 153-169 (1935).

Spin momentum transfer

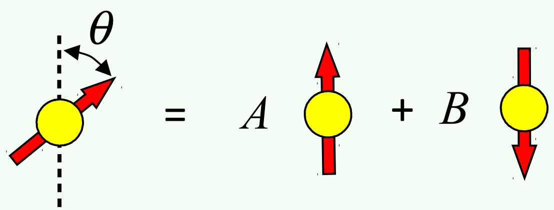
Non-collinear spin transmission

What if the spin is neither in the majority band nor the minority band???



Is the spin reflected or is it transmitted?

Quantum mechanics of spin:



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

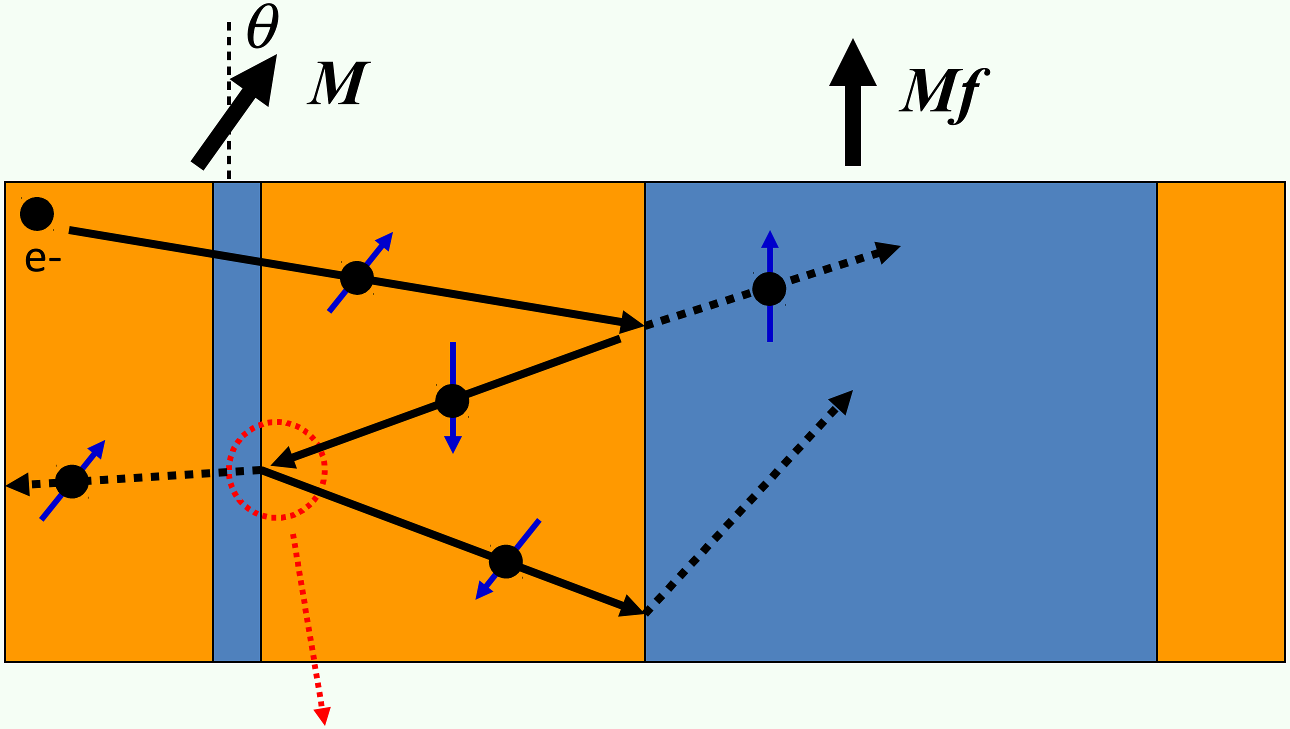
An arbitrary spin state is a coherent superposition of “up” and “down” spins.

Quantum mechanical probabilities:

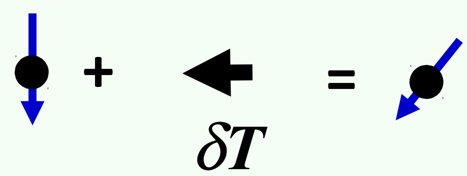
$$\Pr[\uparrow] = |A|^2 = \frac{1}{2}\left(1 + \cos(\theta)\right)$$

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

Spin Momentum Transfer: Small Current Limit

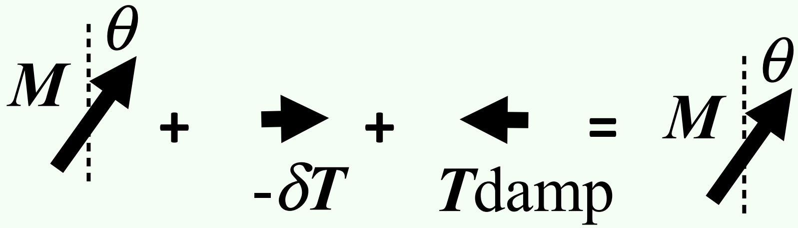


Electrons:



$$\delta \vec{T} \mu \;\; \theta ; \theta < 1$$

Polarizer:

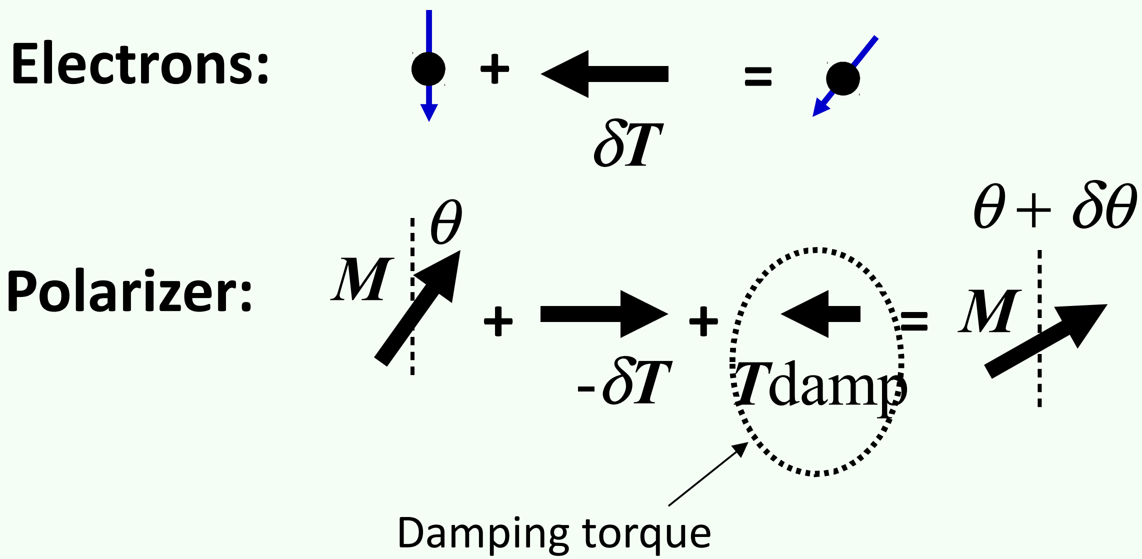


At low electron flux, damping torque compensates spin torque: Magnetization is stable.

Spin Momentum Transfer: Large Current Limit

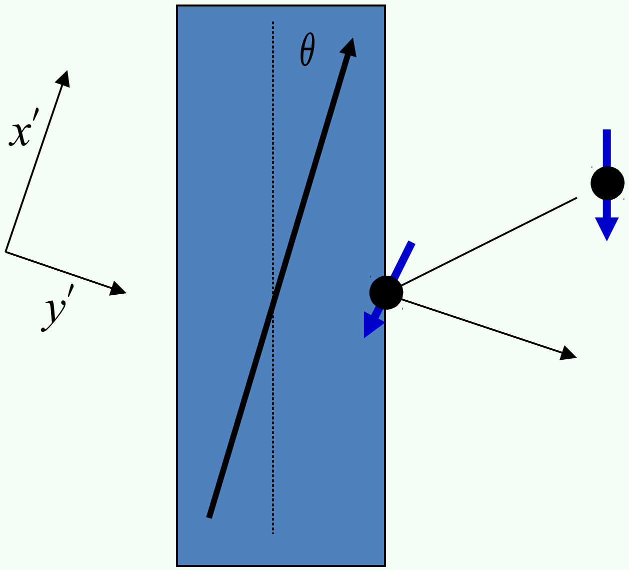
δT is driven by spin accumulation in the Cu spacer.

Spin accumulation is proportional to current flowing through the structure.



Spin torque exceeds damping torque: Polarizer reacts with changing M. Torque proportional to angle θ: Unstable!

Transverse torque via spin reorientation/reflection

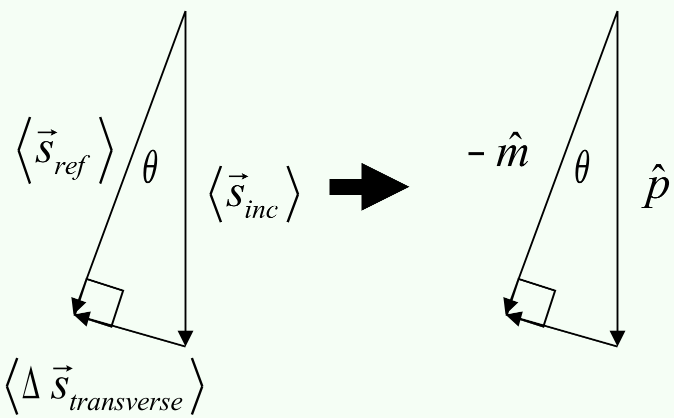


Consider only reflection events...

AND

Consider only change in angular momentum **transverse** to magnetization axis. (Equivalent to assuming magnitude of $\boldsymbol{M}$ does not change.)

For the electron:



$$\langle \Delta \vec{s}_{transverse} \rangle = -\left|\langle \vec{s}_{inc} \rangle\right| \frac{\left|\langle \Delta \vec{s}_{transverse} \rangle\right|}{\left|\langle \vec{s}_{inc} \rangle\right|} \hat{y}'$$

$$= -\frac{\hbar}{2}\sin(\theta)\,\hat{y}'$$

$$= -\frac{\hbar}{2}\hat{m}\times(\hat{m}\times\hat{p}) \quad \text{where} \quad \hat{p} = \frac{2}{\hbar}\langle \vec{s}_{inc} \rangle$$

$$= \frac{\hbar}{2}\hat{m}\times(\hat{m}\times\hat{m}_f)$$

If…

$$\left\langle \Delta \vec{s}_{trans} \right\rangle = \frac{\hbar}{2} \hat{m} \times \left(\hat{m} \times \hat{m}_f \right)$$

…then…

Total moment of "free" magnetic layer

$$\left(\Delta \vec{M} \right) V = |\gamma| \frac{\hbar}{2} \hat{m} \times \left(\hat{m} \times \hat{m}_f \right)$$

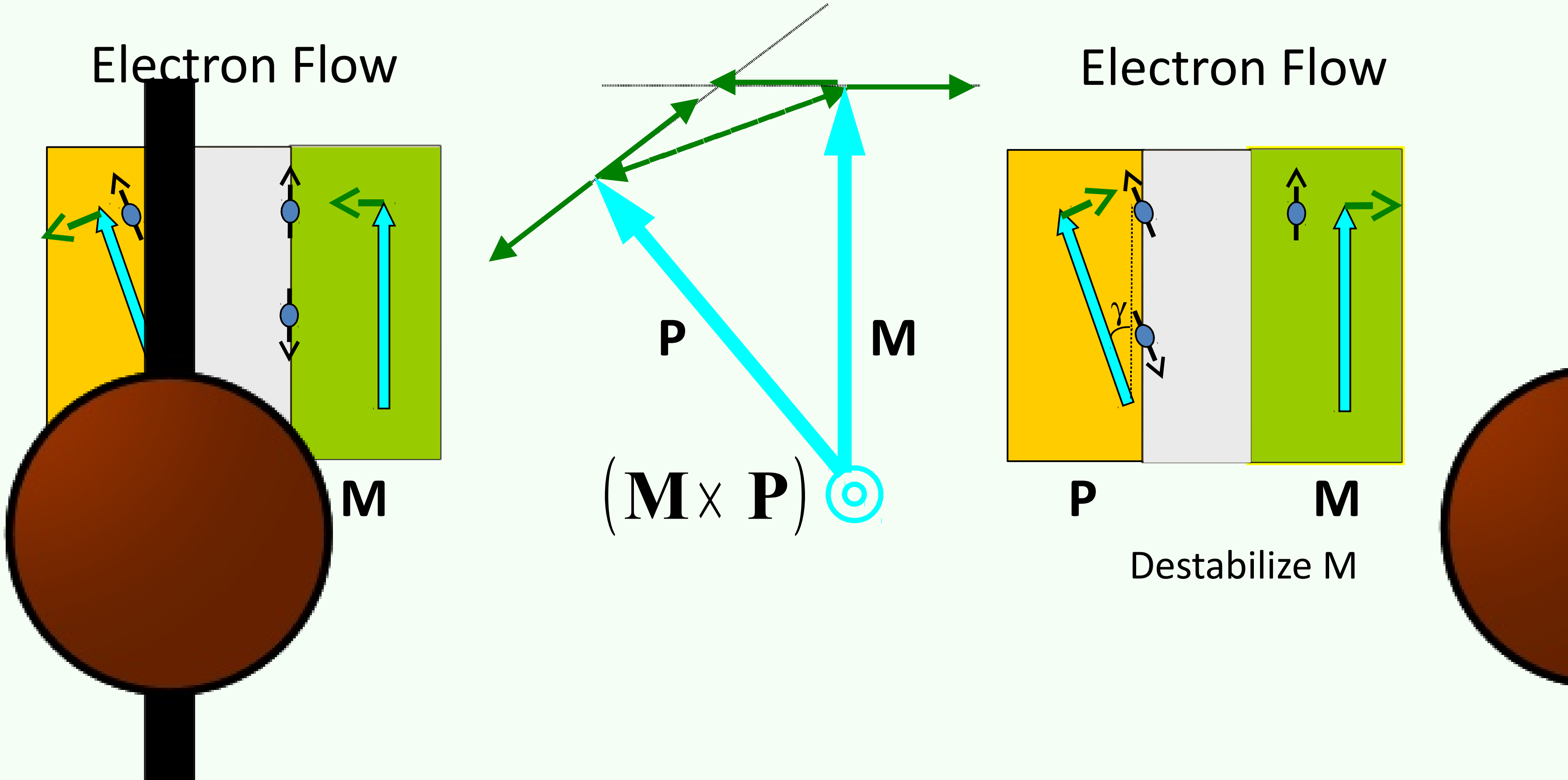
…per electron.

For a flowing stream of electrons:

Rate of electron impingement on "free" layer

$$\left(\frac{d\vec{M}}{dt} \right) = \frac{|\gamma| \frac{\hbar}{2} \hat{m} \times \left(\hat{m} \times \hat{m}_f \right)}{V} \left(\frac{I}{e} \right)$$

$$= \left(\frac{I |\gamma| \hbar}{2eM_s^2 V} \right) \left(\vec{M} \times \left(\vec{M} \times \hat{m}_f \right) \right)$$

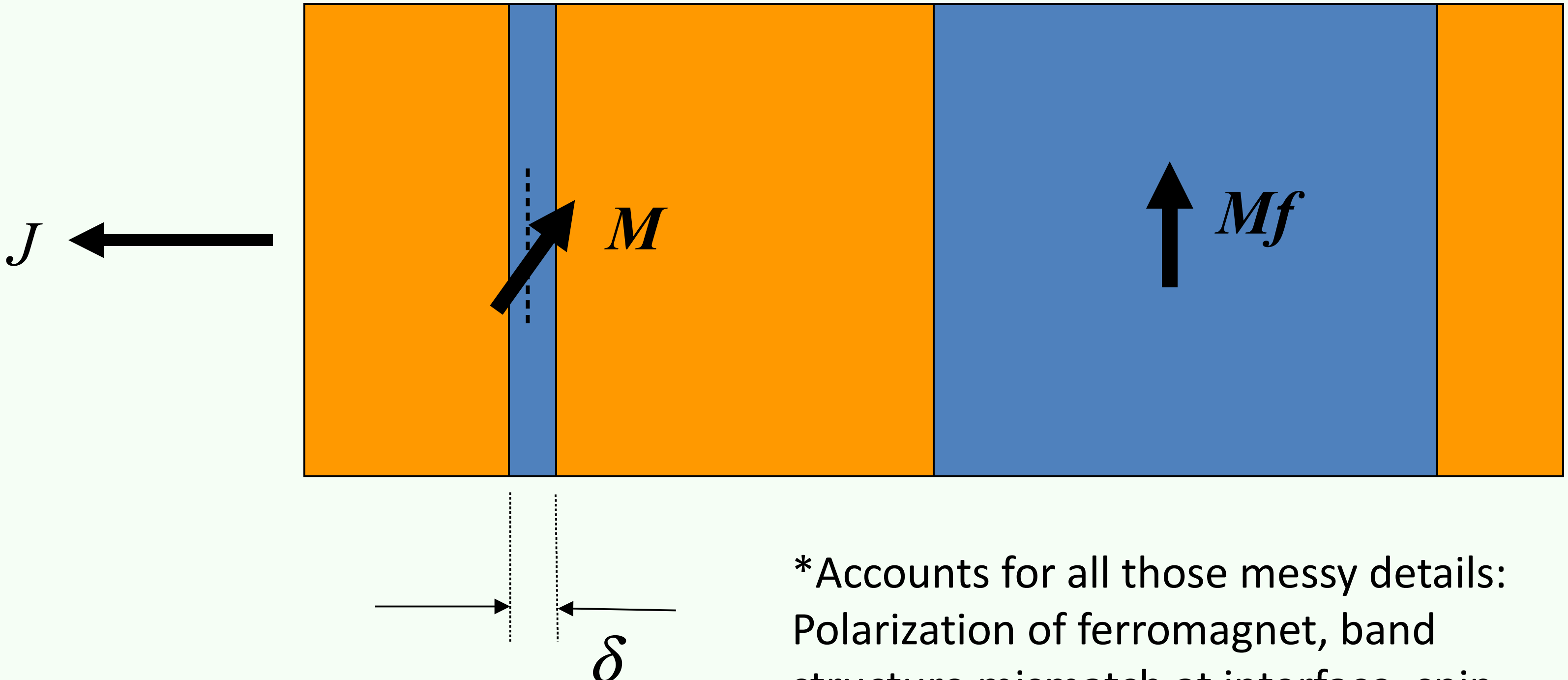


The torque is applied on both layers but if one is pinned, the ‘free’ layer rotates on its own

The Slonczewski Torque Term

efficiency* ~ 0.2 - 0.3

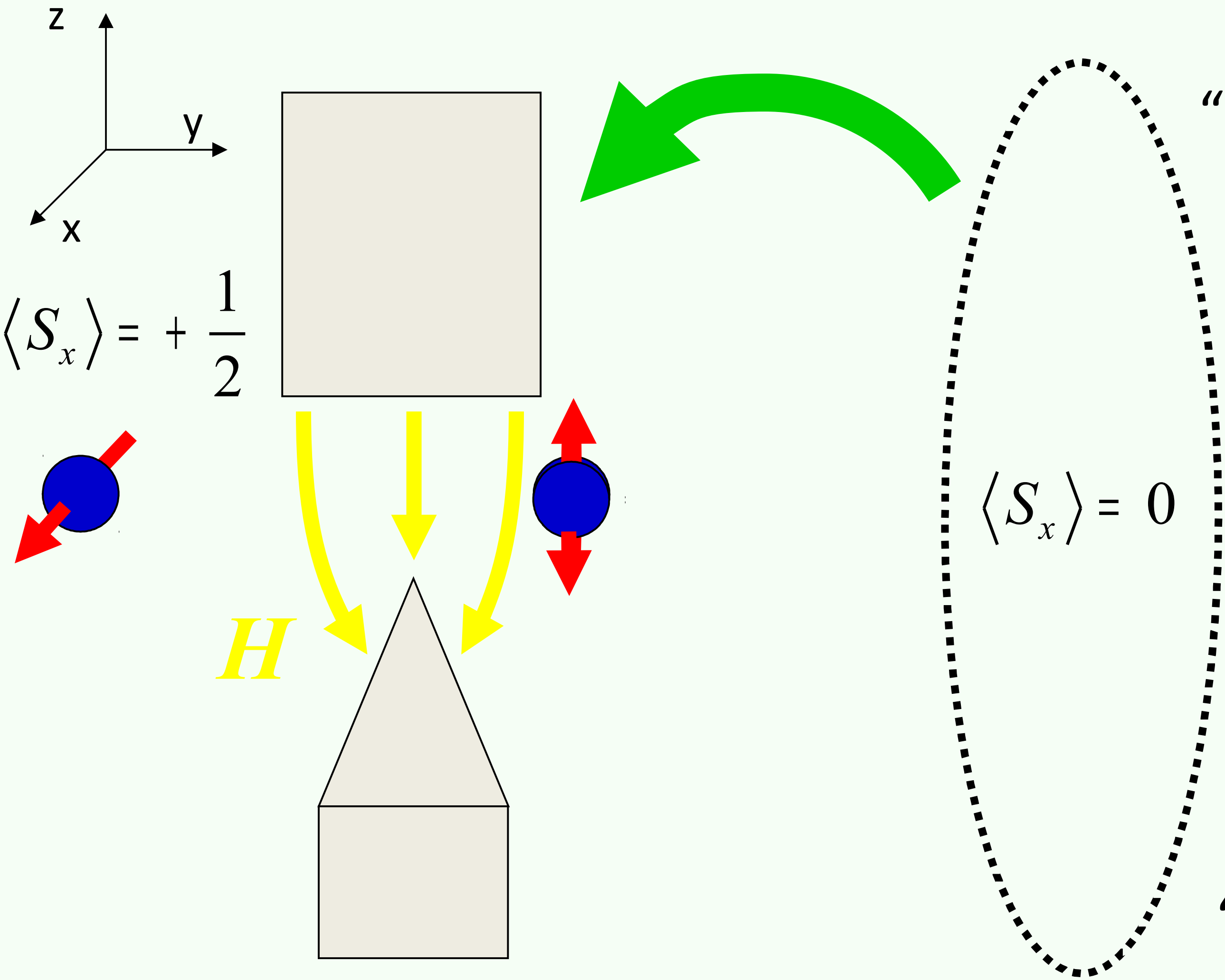
$$\vec{T}_{Sloncewski} = \frac{J\hbar\varepsilon}{2e\delta M_s^2}\vec{M} \times (\vec{M} \times \hat{m}_f)$$



*Accounts for all those messy details: Polarization of ferromagnet, band structure mismatch at interface, spin decoherence, etc…

J. Slonczewski, Journal of Magnetism and Magnetic Materials, vol. 159, page L1 (1996)

Remark on the "Stern-Gerlach" experiment



"Up" spin current

Once the linear momentum for the two spin components is split, the transverse angular momentum is "released" to do work on the magnet system.

"Down" spin current

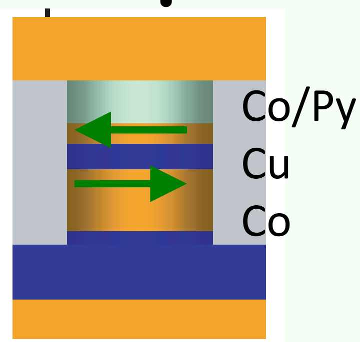
Nanostructures required!

Torque ∝ to current **density**: must have high current *densities* to produce large torques

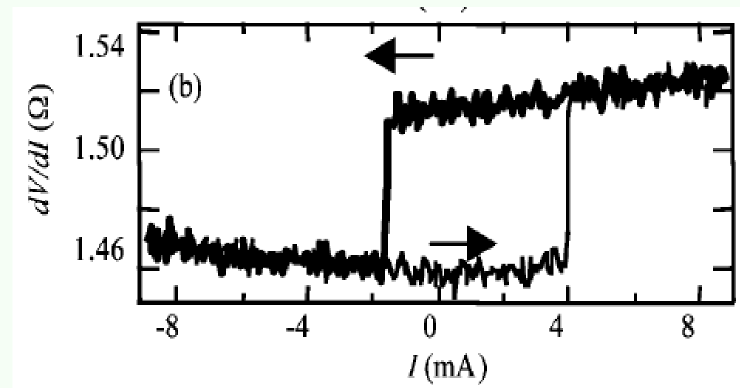
	Required Idc	Possible
Typical wire 1 mm	I ≈ 0.1 MA	X
Size of a human hair 10 μm	I ≈ 10 A	X
≈ 500 atoms across 100 nm	I ≈ 1 mA	✓

We will use ***nanopillar*** and ***nanocontact*** structures

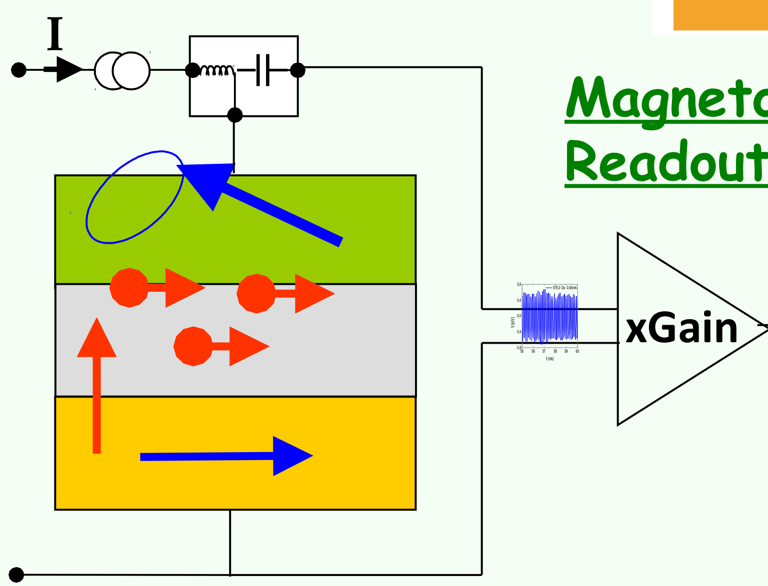
Measurements in spin valves



Zero field: current induced reversal of the free layer:



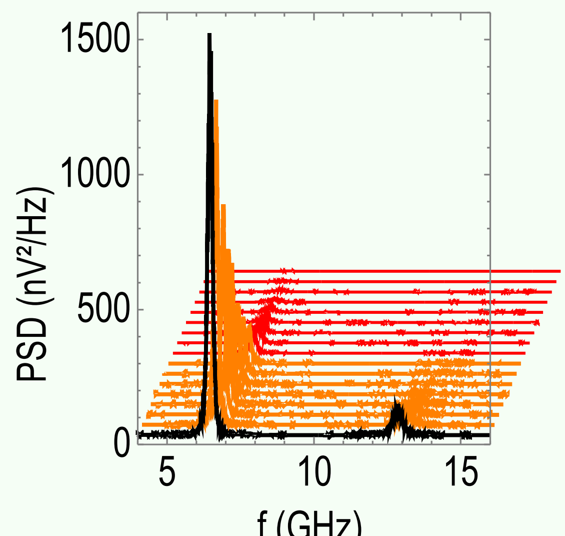
Current + field



Magnetoresistive Readout

Output Voltage U~

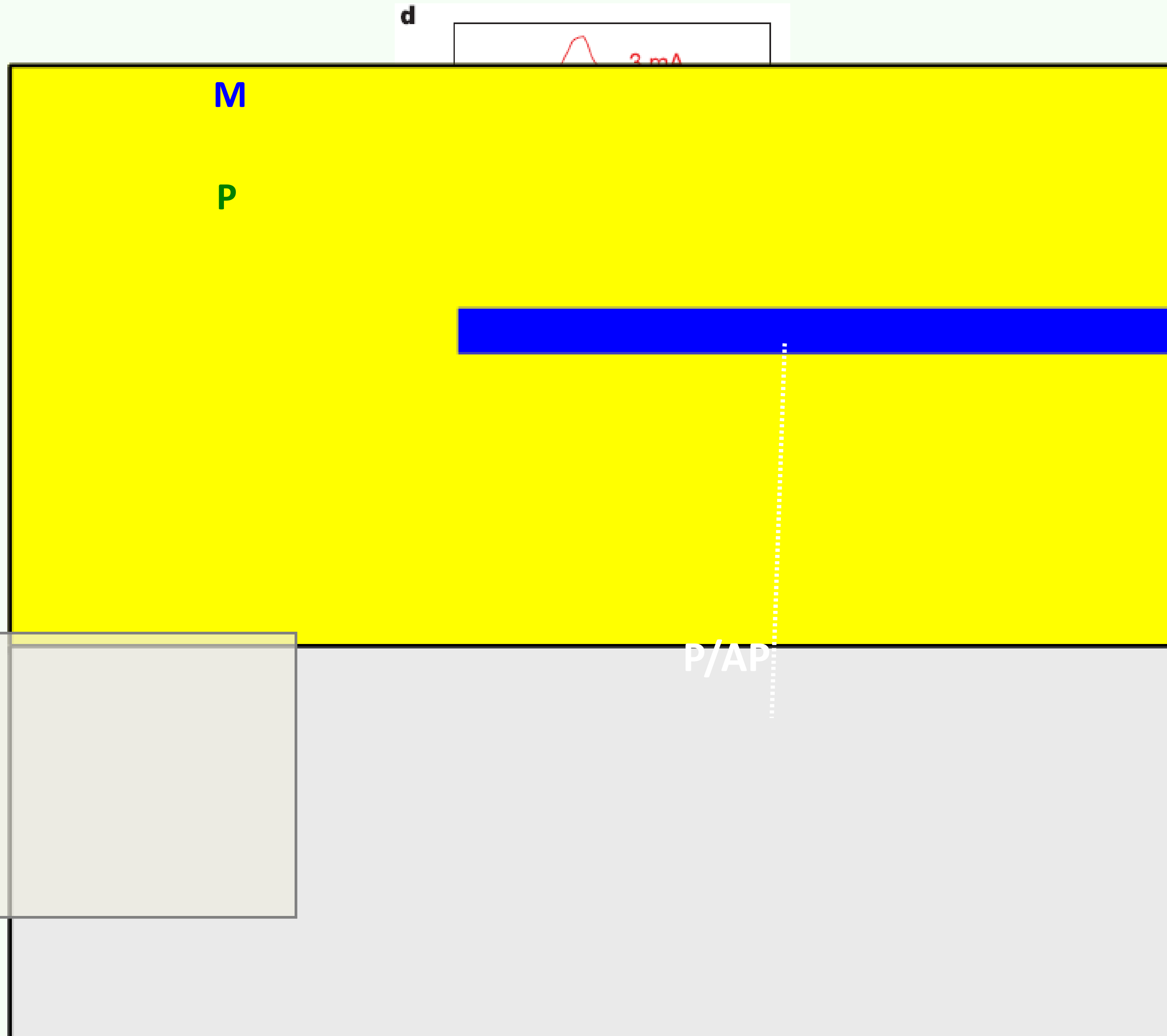
Field + current: auto-oscillations of M



Spin Transfer Nano-Oscillator STNO

Spin momentum transfer – State Diagram

Spin valve
Co40/Cu10/Co3



Magnetization dynamics in thin films

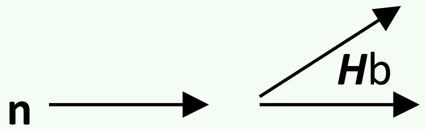
Conservative Dynamics in thin films (no damping)

Energy of an in-plane uniaxial system

$$E = K_u\left[1 - (\mathbf{mn})^2\right] - M_s\mathbf{mH}_b + 2\pi M_s^2\left[\mathbf{m}\left(\overleftrightarrow{\mathbf{N}}\mathbf{m}\right)\right]$$

Anisotropy Zeeman Demagnetization

$$\mathbf{m} = \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix} = \begin{pmatrix} \sin\theta\ \cos\varphi \\ \sin\theta\ \sin\varphi \\ \cos\theta \end{pmatrix}; \quad \overleftrightarrow{N} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}; \quad \mathbf{n} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$



$$\mathbf{H}_b = \begin{pmatrix} H_b \\ 0 \\ 0 \end{pmatrix}; \quad or \quad \mathbf{H}_b = \begin{pmatrix} 0 \\ H_b \\ 0 \end{pmatrix}$$

bias field **H**b

Easy axis Hard axis

n unit vector of easy axis
N demagnetization tensor
M = **m** Ms
Uniaxial anisotropy field *H*u

Effective Field

$$\mathbf{H}_{eff} = -\frac{\partial E}{\partial \mathbf{M}} = H_u(\mathbf{nm})\mathbf{n} + \mathbf{H}_b - H_d\overleftrightarrow{\mathbf{N}}\mathbf{m}$$

$$H_u = \frac{2K_u}{M_s}$$

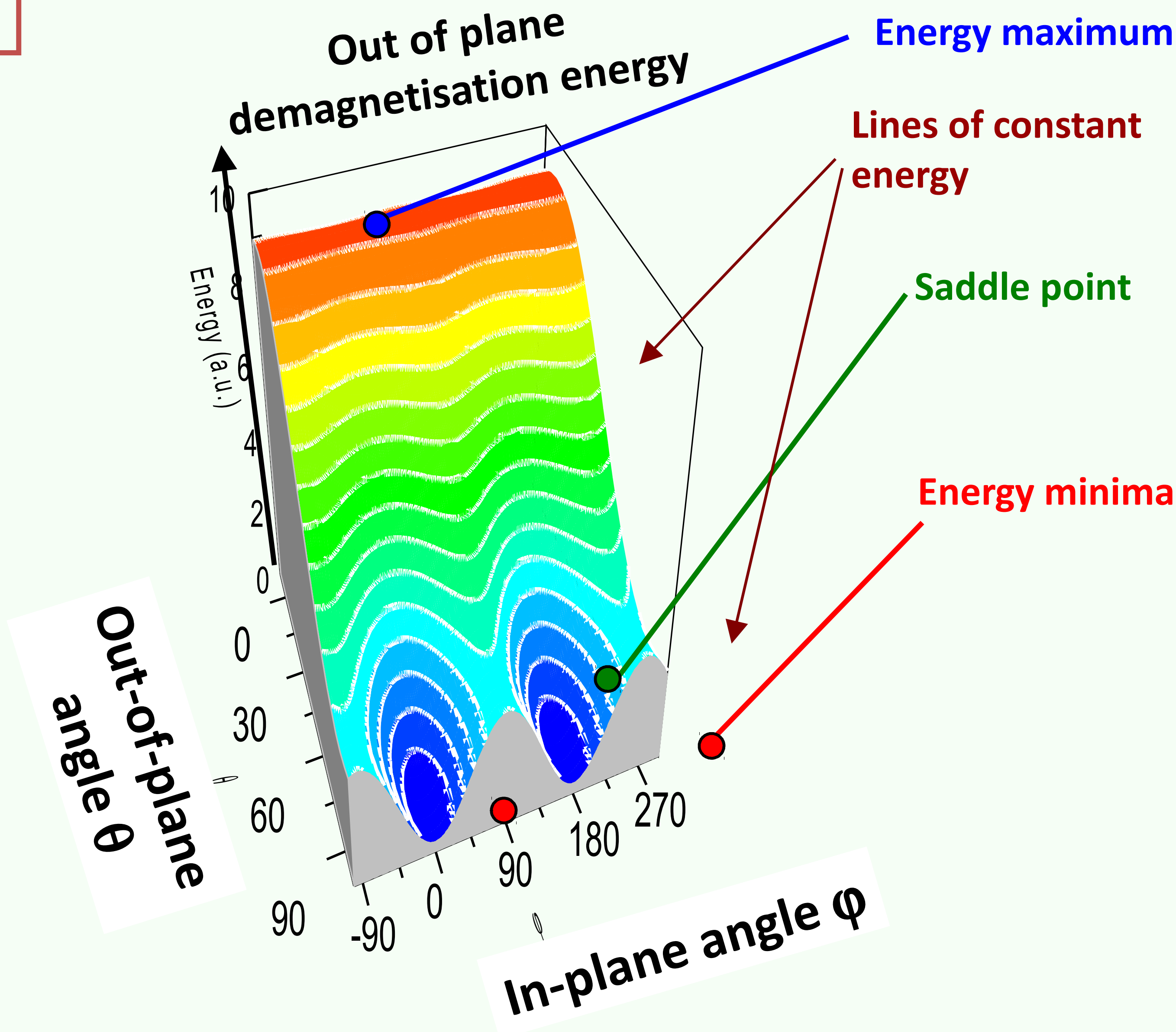
$$H_d = 4\pi M_s$$

Energy landscape (H=0)

Uniaxial thin film

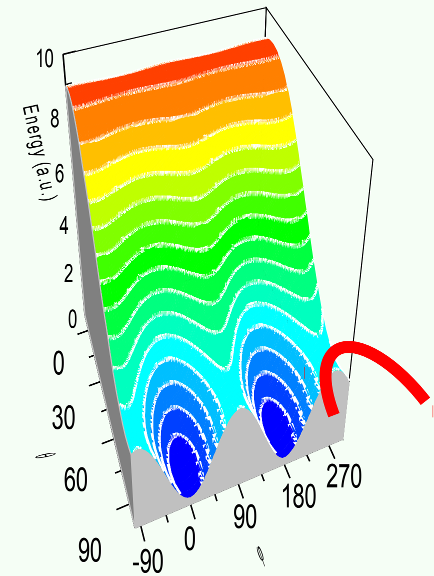
→ **Hu**

*H*b =0

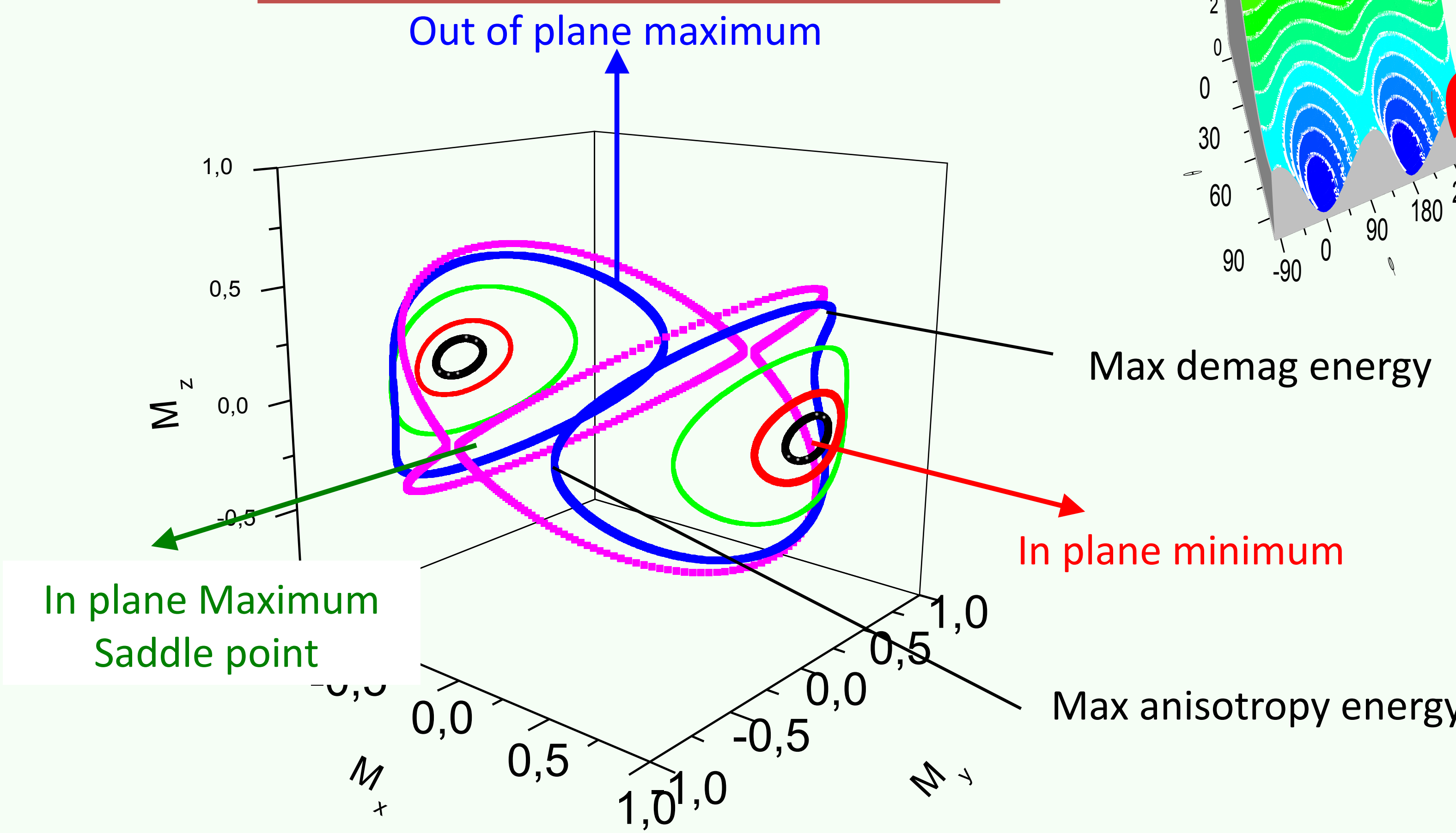


Conservative Dynamics - Trajectories

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



In-plane precession IPP orbit

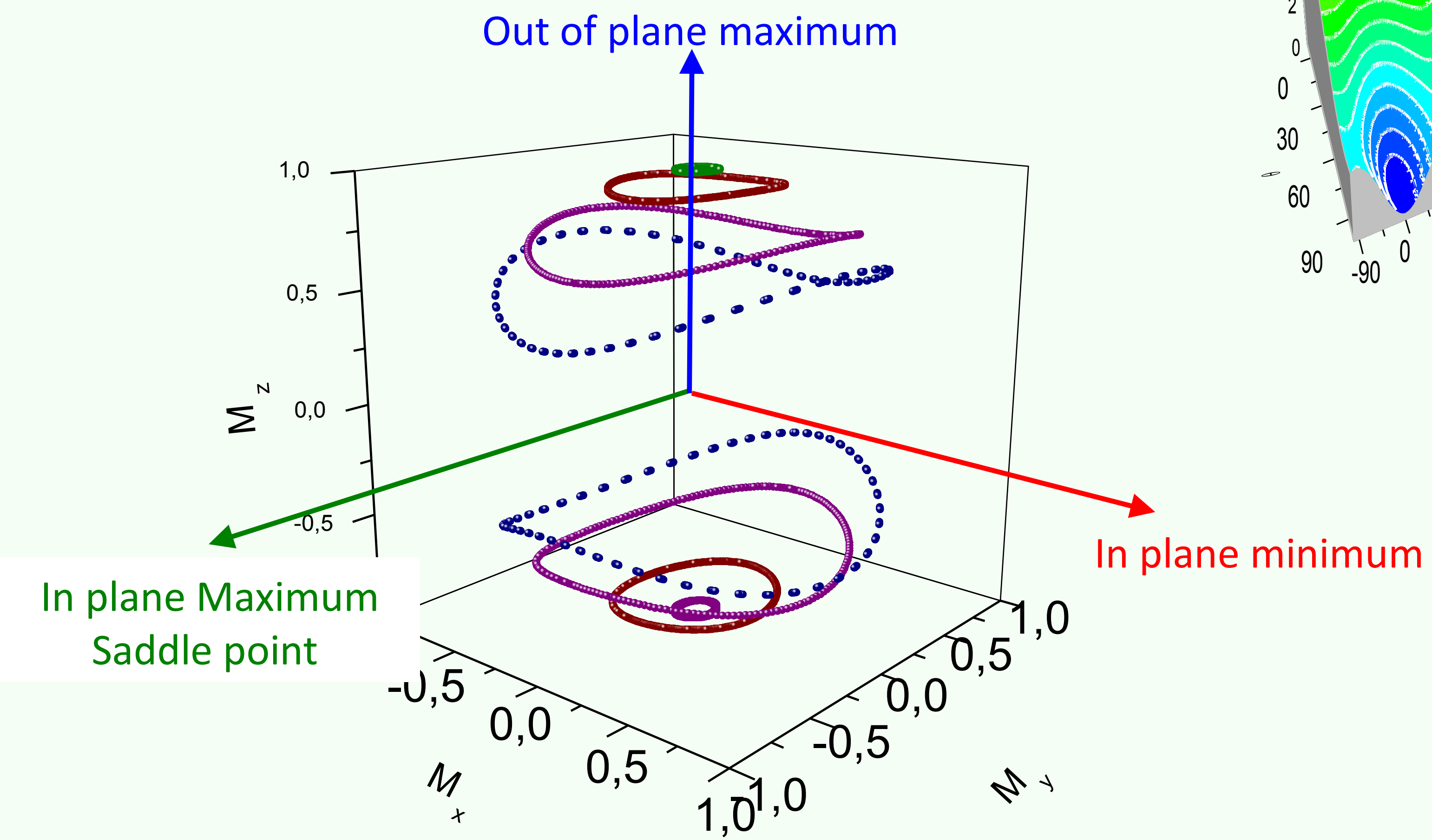


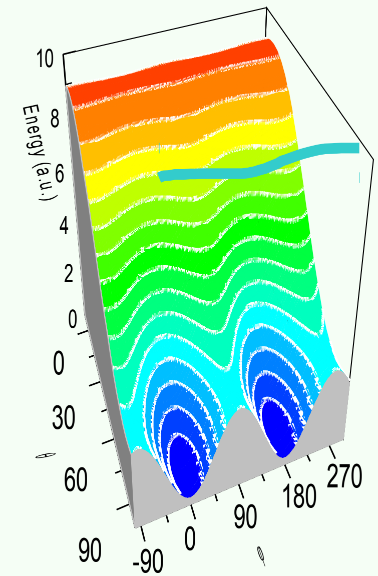
- Energy below saddle point,
- Oscillation around energy minimum

Conservative Dynamics - Trajectories

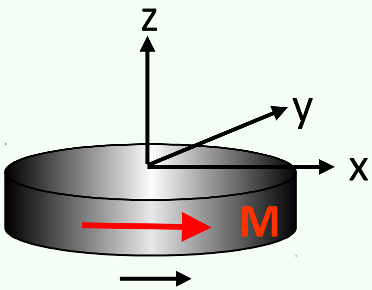
Out-of-plane precession OPP orbit

- Energy above saddle point,
- Oscillation around energy maximum





Conservative Dynamics - Frequency

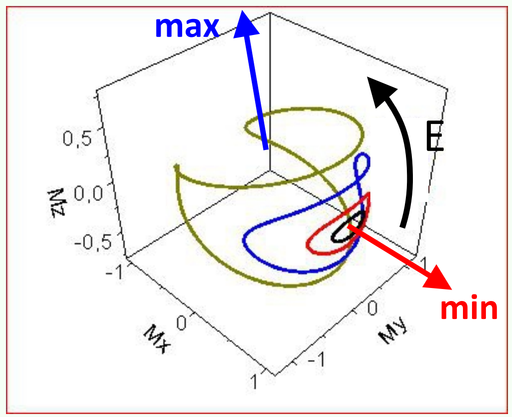


Hu, Hb

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

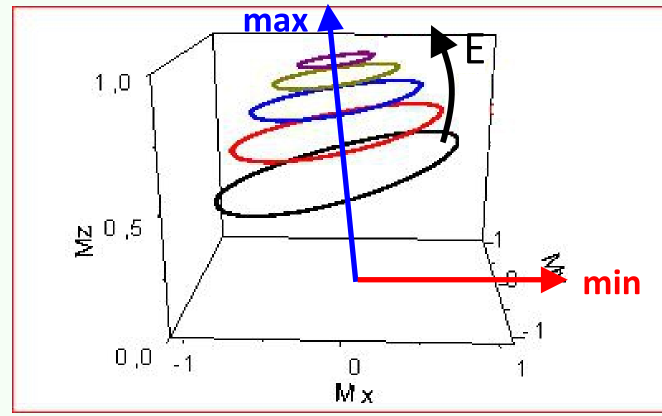
Precession

In-Plane Precession IPP



Oscillation around energy minimum

Out of Plane Precession OPP

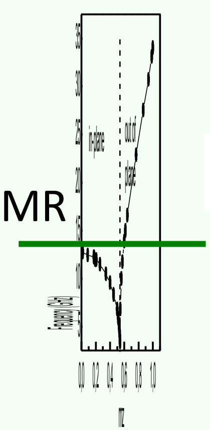


Oscillation around energy maximum

Non-linear **H**eff (**M**)

Frequency depends on amplitude!

FMR



IPP

$\omega^2=\gamma^2 Hb(Hb+HdMx)$

« redshift »

OPP

$\omega=\gamma H\sim Hd\sim Mz$

« blueshift »

Non Conservative Dynamics - LLG

Landau-Lifshitz-Gilbert Equation (LLG)

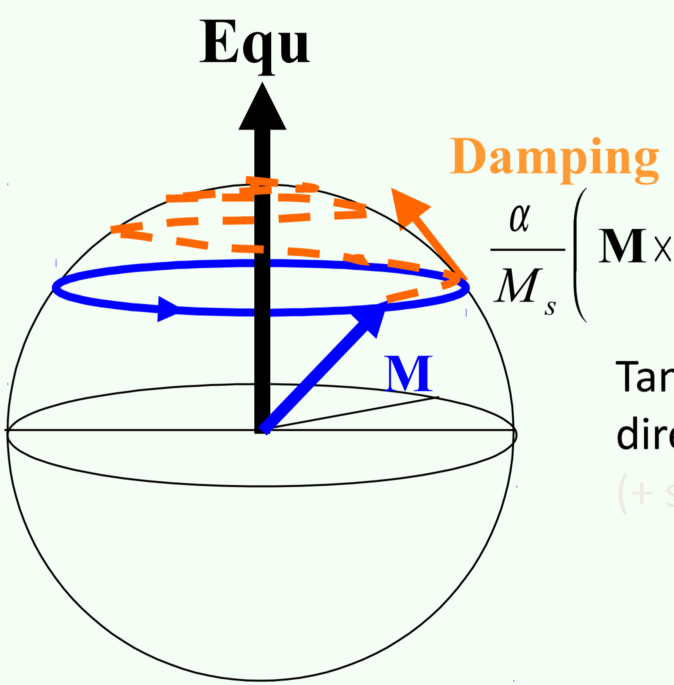
$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{H}_{eff}\right) + \frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

Precession | **Damping**

α = damping constant
typically 0.01 for metals

Time scales

Precession : order or below ns
Damping : few ns



$$\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

Tangential,
directed towards equilibrium
(+ small component antiparallel to precession torque)

Non Conservative Dynamics - LLG

Landau-Lifshitz-Gilbert Equation (LLG)

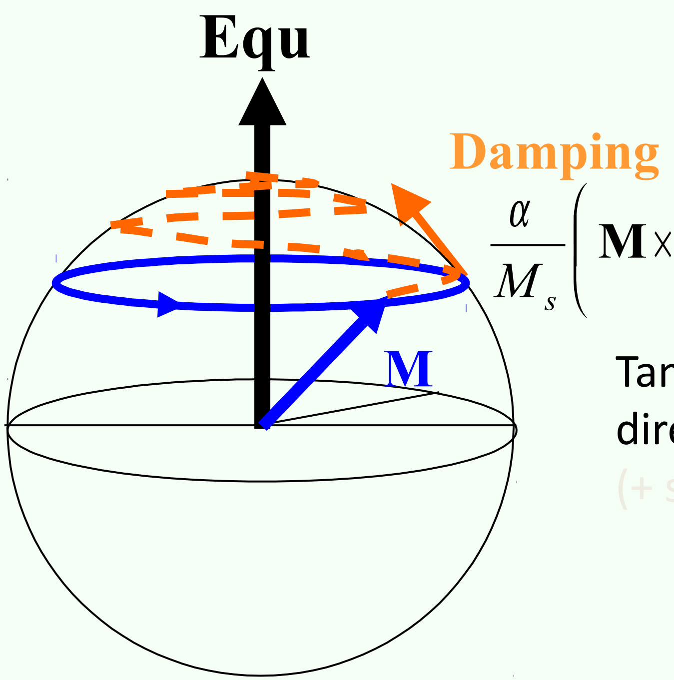
$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{H}_{eff}\right) + \frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

Precession **Damping**

→ Non-Linear dynamical system

Norm of **M**
Conserved since

$$\mathbf{M}\frac{d\mathbf{M}}{dt} = 0$$



$$\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

Tangential,
directed towards equilibrium
(+ small component antiparallel to precession torque)

Non Conservative Dynamics – Energy Dissipation

Energy change

$$\frac{dE}{dt} = \frac{dE}{d\mathbf{M}}\frac{d\mathbf{M}}{dt} = -\mathbf{H}_{eff}\frac{d\mathbf{M}}{dt}$$

$$\frac{dE}{dt} = \gamma\mathbf{H}_{eff}(\mathbf{M}\times\mathbf{H}_{eff}) - \frac{\alpha}{M_s}\mathbf{H}_{eff}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right) = -\frac{\gamma\alpha}{M_s}\left(\frac{d\mathbf{M}}{dt}\right)^2 < 0$$

$$\frac{dE}{dt} < 0$$

since $\alpha > 0$

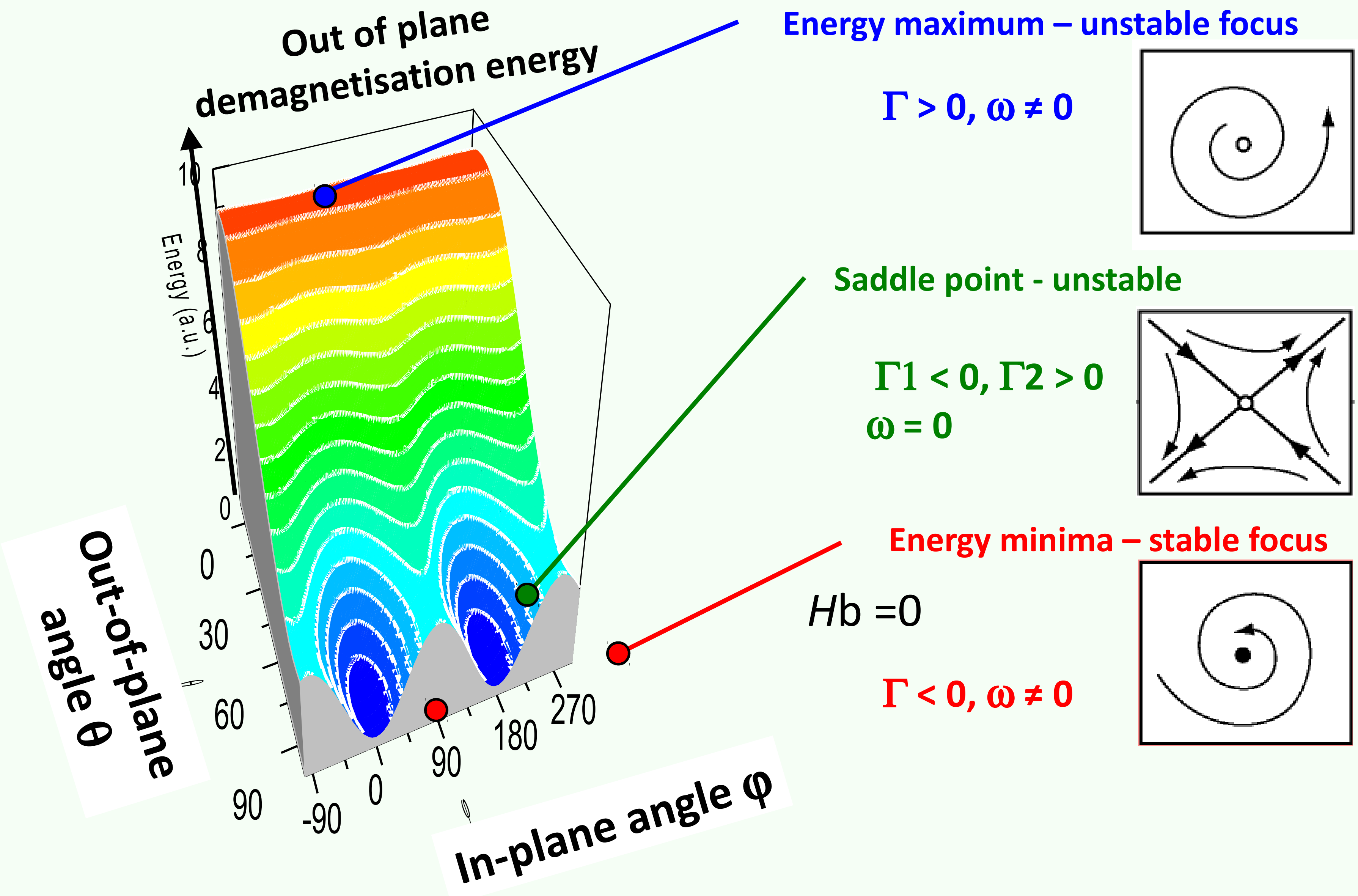
Damping decreases the energy

Equilibria **Mo** $\quad \frac{d\mathbf{M}}{dt} = 0 \Rightarrow \mathbf{M}_o \Leftrightarrow (\theta_o, \varphi_o)$

Same as for conservative dynamics since (d**M**/dt=0)

→ The system relaxes towards the nearest (local) energy minimum

Non Conservative Dynamics Stability of Equilibria



ST Precession - LLG + STT

$$\frac{d\mathbf{M}}{dt} = \underbrace{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})}_{\text{Precession}} + \underbrace{\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}}_{\text{Damping}} + \underbrace{\frac{\gamma\, a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}_{\text{Spin torque (ST)}}$$

Norm of **M**
Conserved since

$$\mathbf{M}\frac{d\mathbf{M}}{dt} = 0$$

→ STT has « dissipative » action on trajectory

Spin torque cannot be derived from a generalized energy

→ **ST does not change the energy surface**
→ **ST does not change conservative part of LLG**

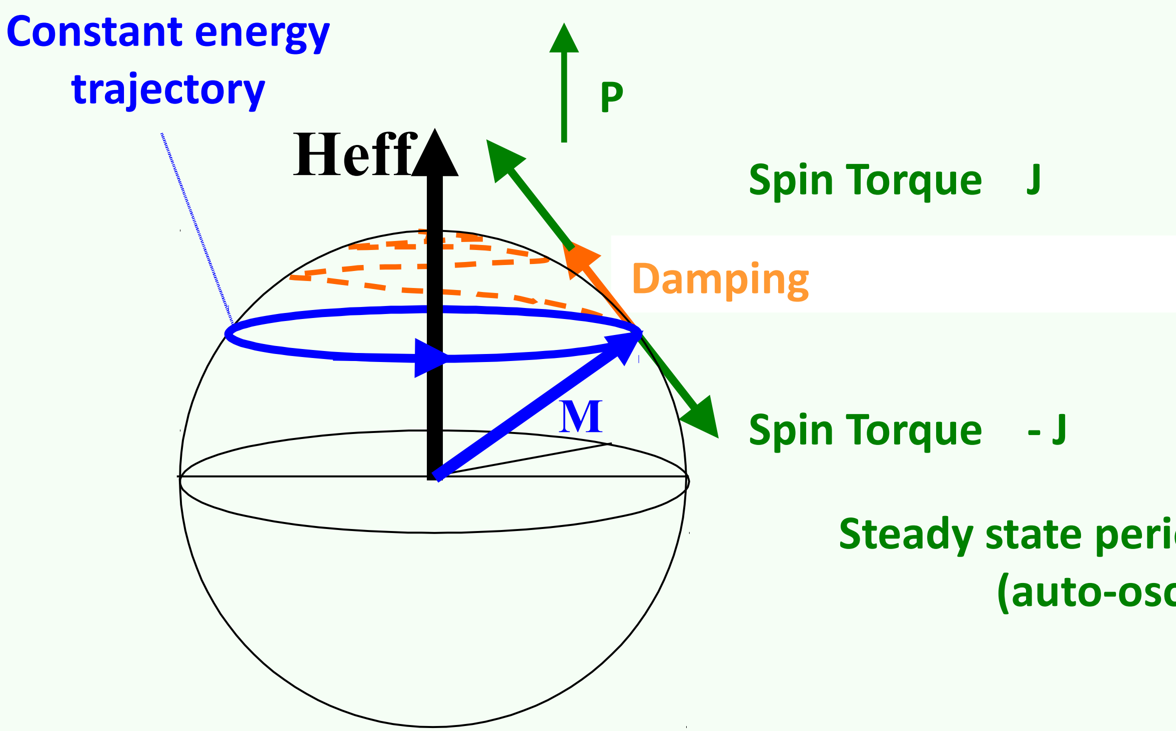
ST Precession

$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma\,(\mathbf{M}\times\mathbf{H}_{eff})} + \boxed{\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}} + \boxed{\frac{\gamma\, a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}$$

Precession   **Damping**   **Spin torque (ST)**

aJ ~current J

P = spin polarization vector



Stabilizing Initial state

Destabilizing Initial state

Steady state periodic oscillations (auto-oscillations)

ST Precession - Limit Cycles

$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma\left(\mathbf{M}\times\mathbf{H}_{eff}\right)} + \boxed{\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)} + \boxed{\gamma\frac{a_j}{M_s}\left(\mathbf{M}\times\left(\mathbf{M}\times\mathbf{P}\right)\right)}$$

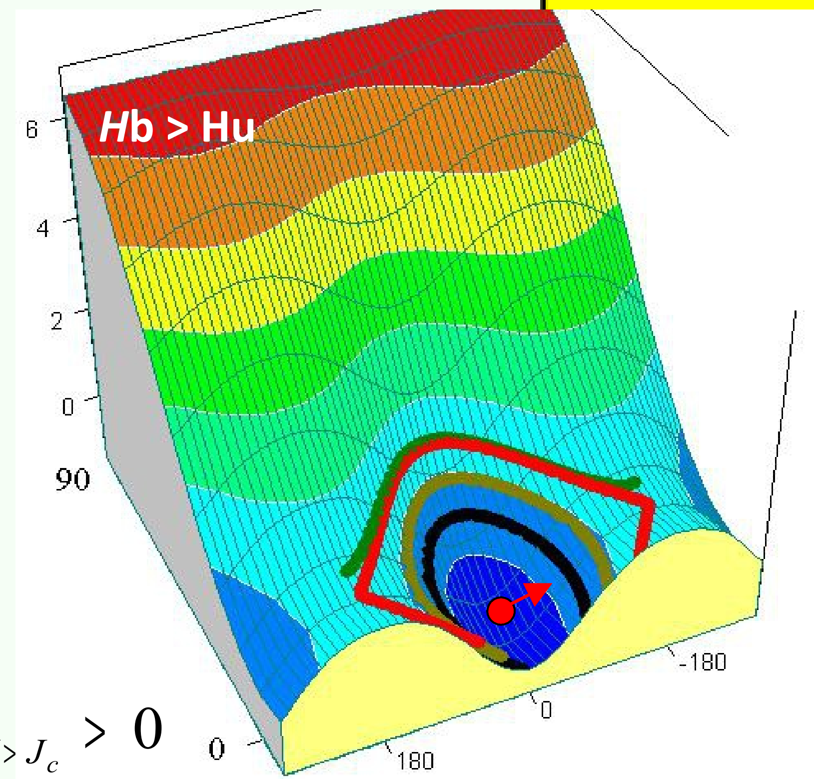
Precession — Damping — Spin torque

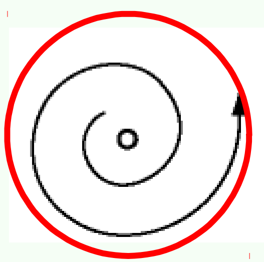
M

P

- Depending on the control parameter *J* (current amplitude) the energy minimum can change from a stable to an unstable focus

- When *J*>*J*c STT moves **M** along the energy surface until **M** stabilizes on a limit cycle





$$\delta\mathbf{M} \sim e^{\Gamma t} e^{i\omega_o t}$$

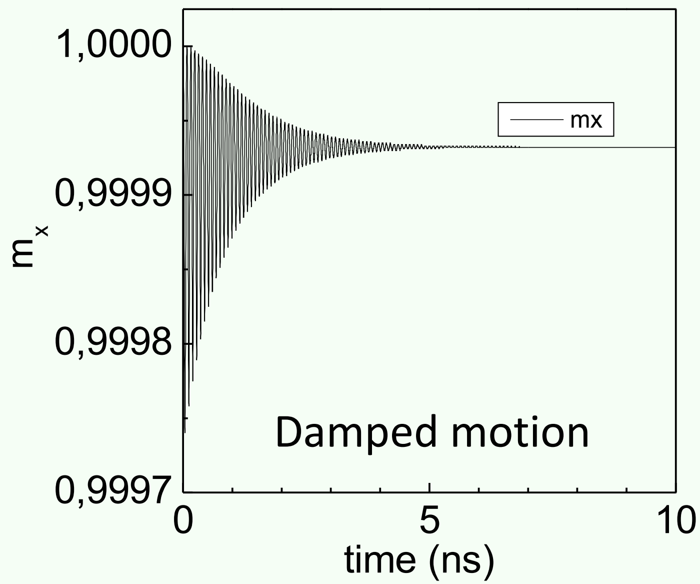
$$\Gamma_{J<J_c} < 0 \Rightarrow \Gamma_{J>J_c} > 0$$

Note: energy surface is not changed by STT

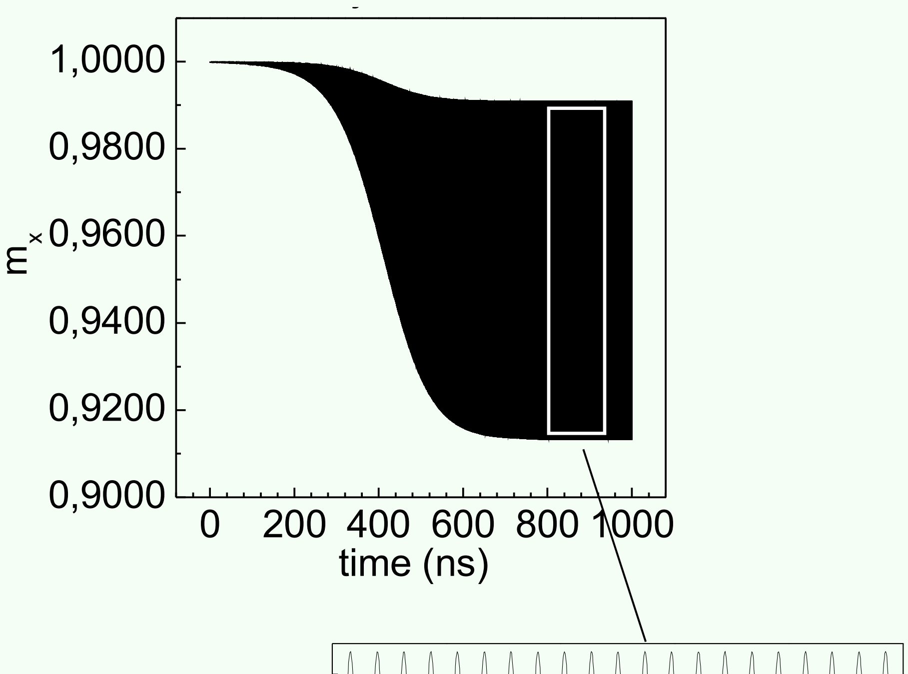
ST Precession – Limit Cycles

Apply current so as to destabilize the initial stable state

Low current amplitude



High current amplitude



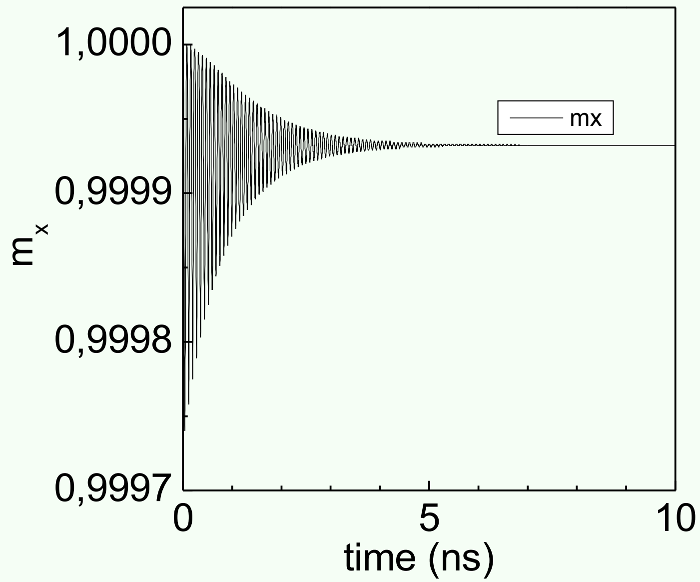
M

P

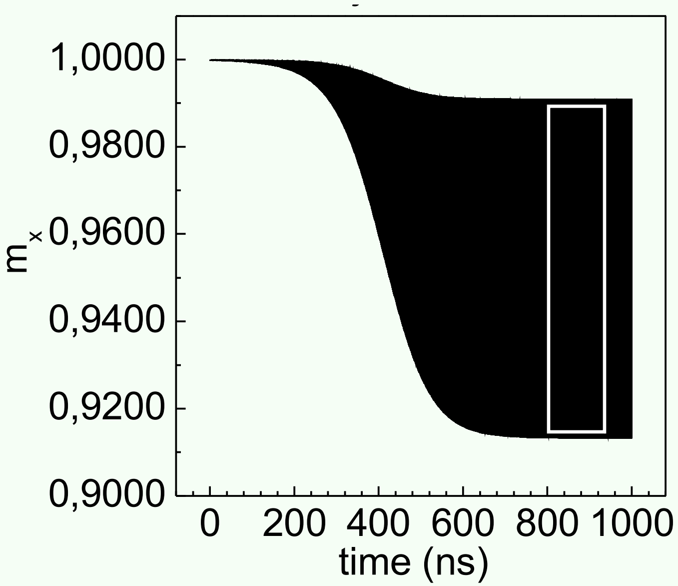
ST Precession – Limit Cycles

Apply current so as to destabilize the initial stable state

Low current amplitude

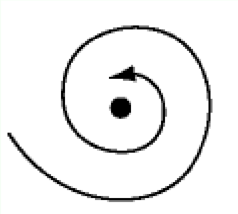


High current amplitude

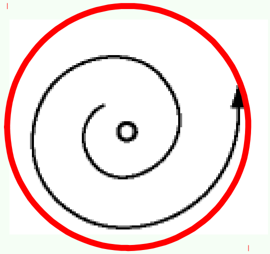


Depending on the amplitude of the current

Damped oscillation around stable focus



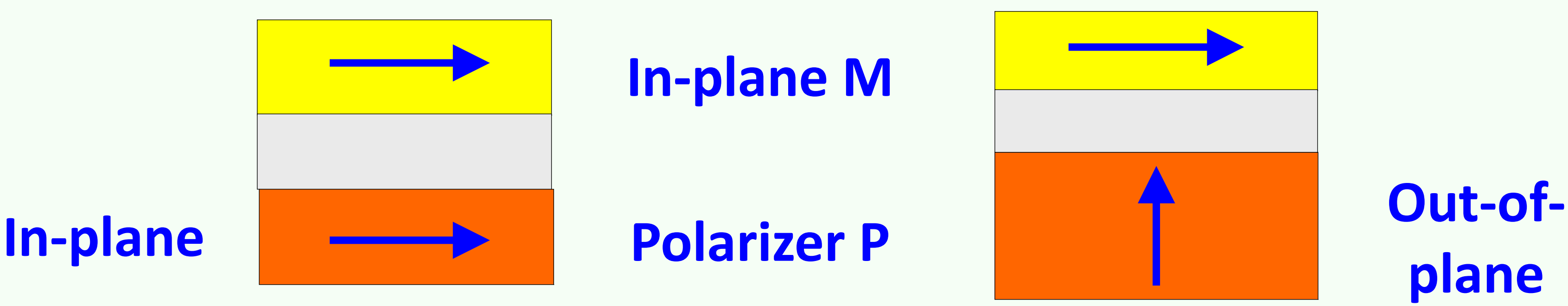
Oscillation away from unstable focus towards a Limit Cycle



ST Precession – Polarizer Geometries

Consider two geometries

Planar polarizer | **Perpendicular Polarizer**



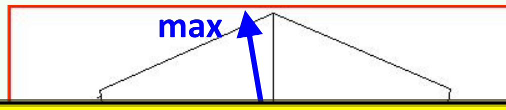
M and P collinear

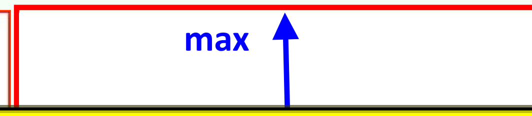
Control parameters:
H changes energy surface,
J, **P** change « dissipation »

ST Precession – Limit Cycles

In-Plane
Precession IPP

Out of Plane
Precession OPP





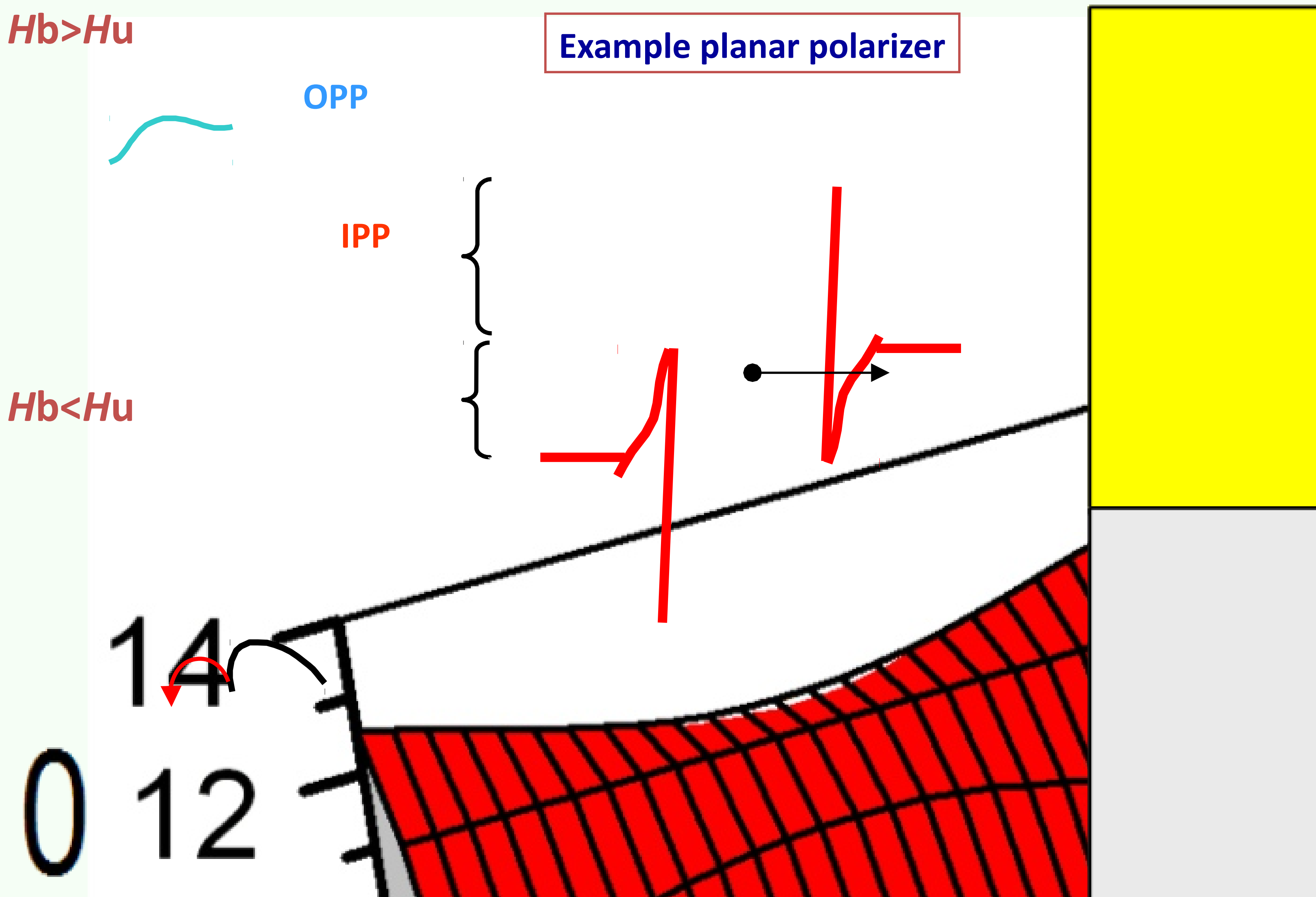
M

P

M

P

Spin momentum transfer – State Diagram



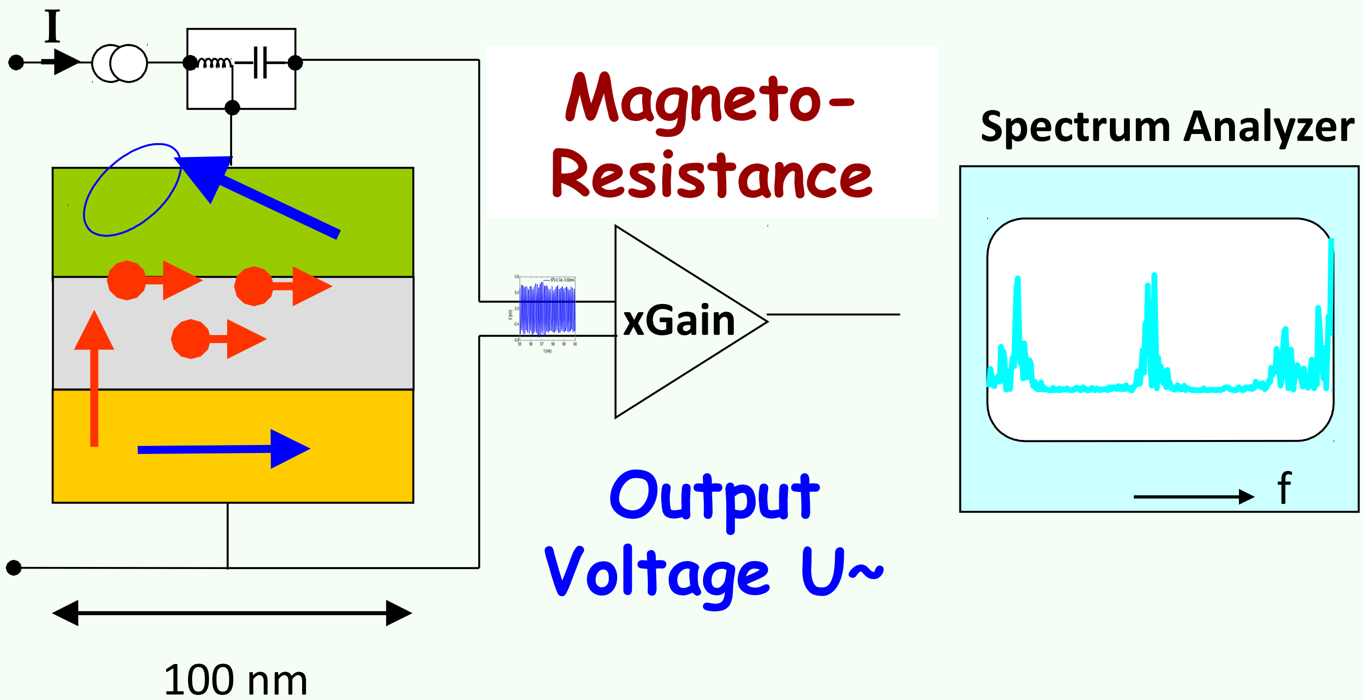
ST Precession – Experiments

Excitation | **Readout**

Spin momentum transfer

↓

Auto-oscillations of M



Nanoscale Tuneable Microwave Oscillator

Spin Transfer Nano-Oscillator STNO

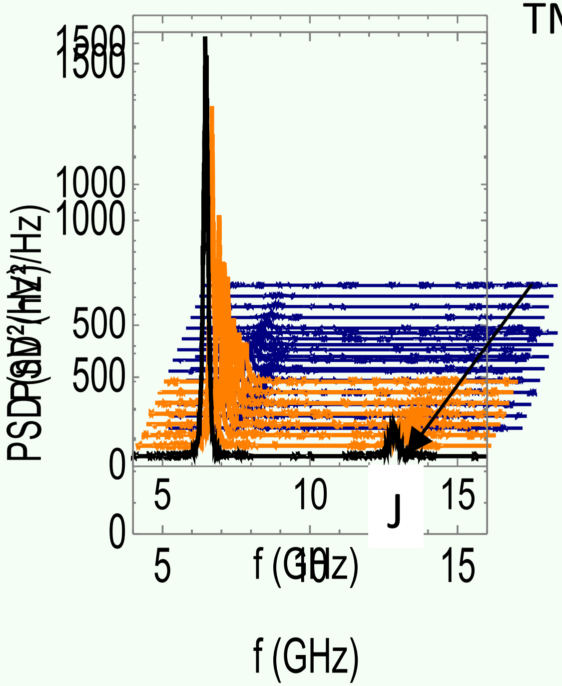
Spin momentum transfer – Transition

$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma\left(\mathbf{M}\times\mathbf{H}_{eff}\right)} + \boxed{\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)}$$

Precession **Damping**

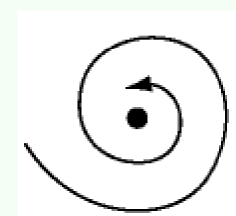
Tunnel Junction

MTJ Device
TMR = 80%



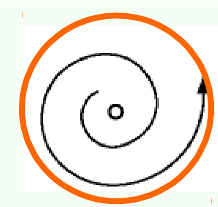
$$\int \frac{dE}{dt} < 0$$

Damped



J<Jc **Γ(*J*)<0**

J>Jc **Γ(*J*) > 0**

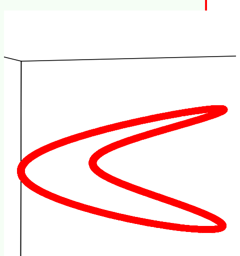


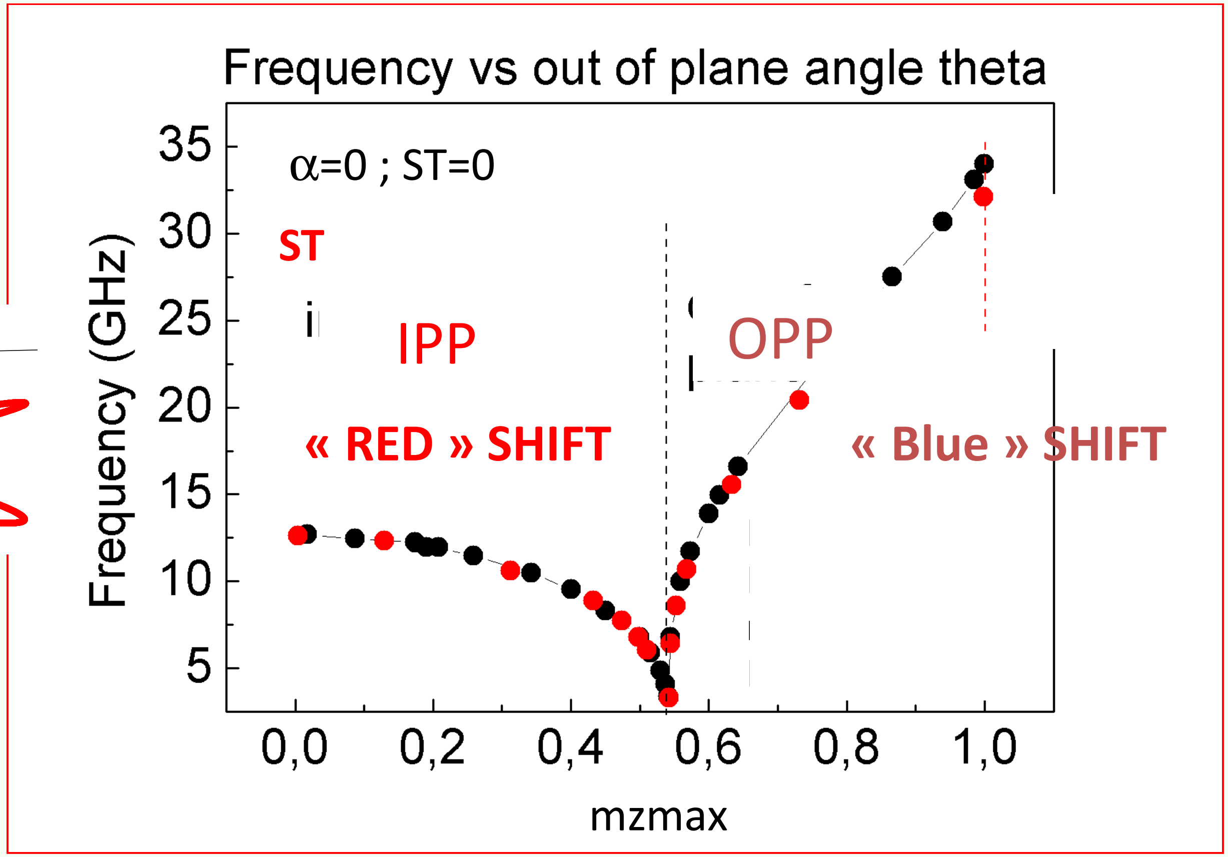
Stable Limit cycle

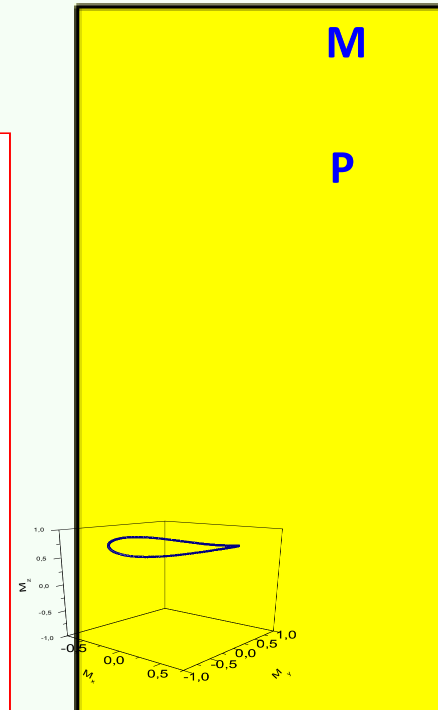
$$\int \frac{dE}{dt} = 0$$

Limit Cycle – Frequency Shift

Example Frequencies of Planar Polarizer







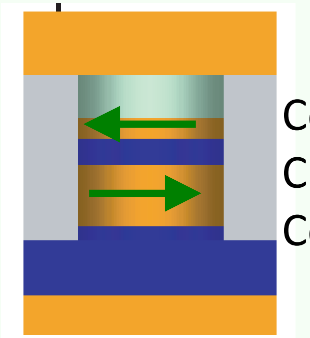
Frequencies of conservative and STT trajectories are the same

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

Non-linear **H**eff (**M**)

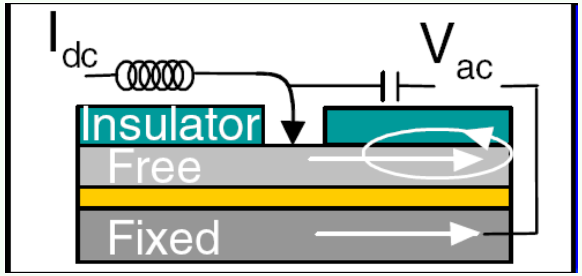
Microwave Oscillators

Nanopillars NP



Cornell

Nanocontacts NC

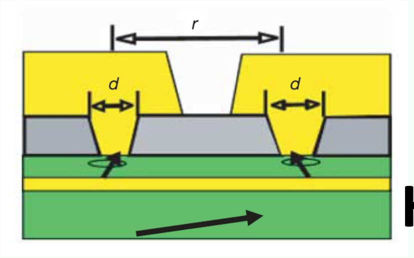


NIST

H//

H⊥

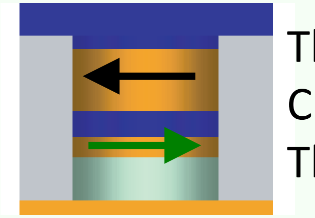
NC Coupling



H⊥

NIST

« Wavy » NP



CNRS/Thales

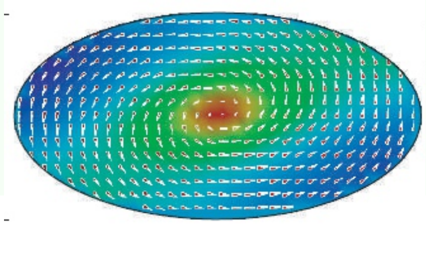
FL Oscillation → IEF

Perpendicular Pol

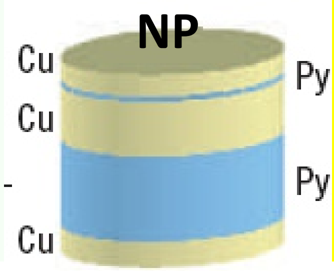
Spintec/LETI

H//

Vortex

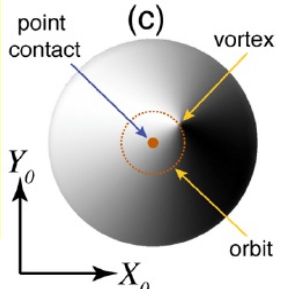


NP

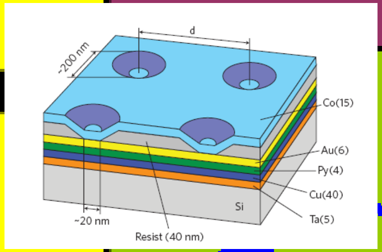


Cornell/CEA

NC



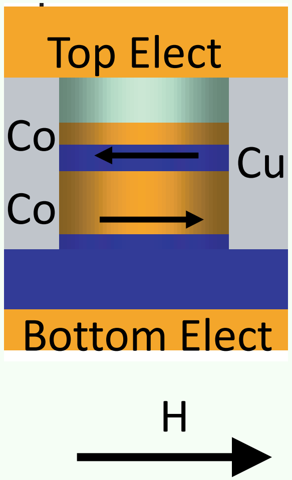
IEF/IMEC
CNRS/Thales



CNRS/Thales

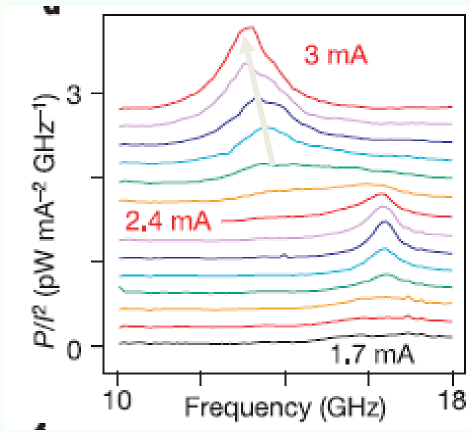
Experiment – Frequency Shift

Cornell



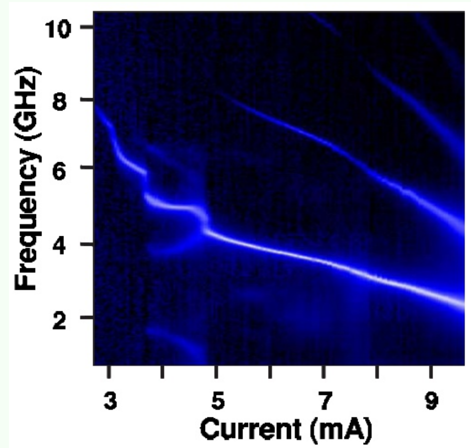
1 GHz/mA @ 2-4 GHz

2.5 GHz/mA



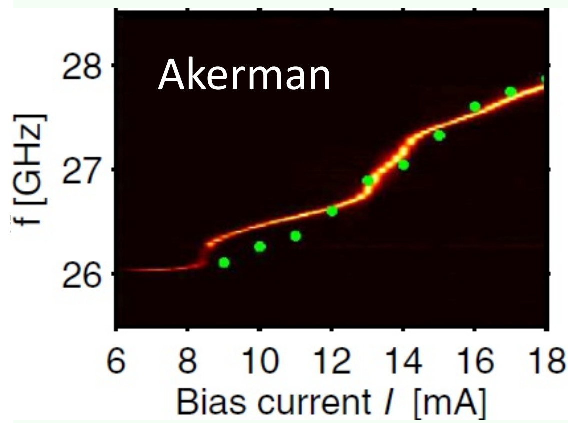
@ 12-14 GHz

0.5 GHz/mA



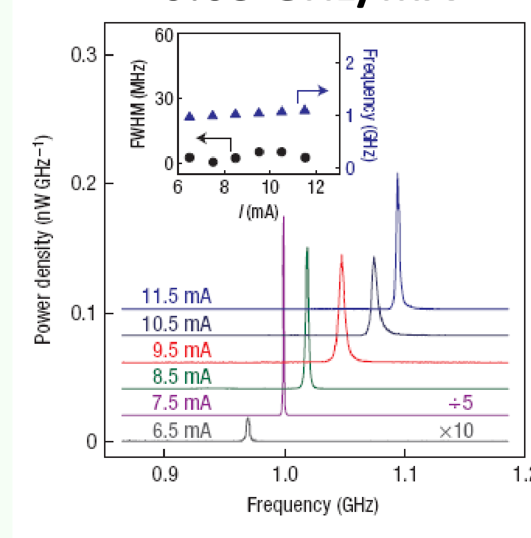
@ 5-9 GHz

0.3 GHz/mA

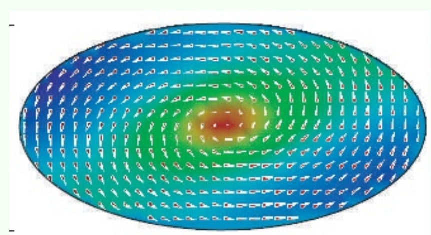


@ 27 GHz

0.03 GHz/mA



Cornell

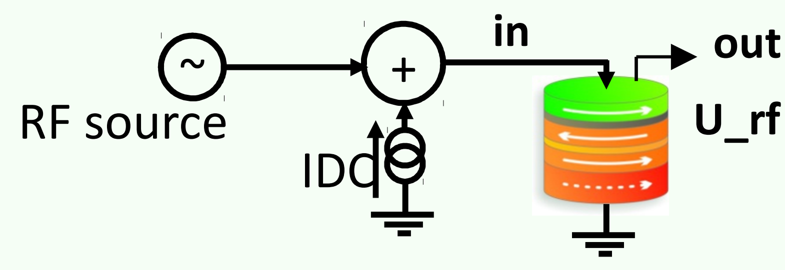


Spintec/LETI

Applications

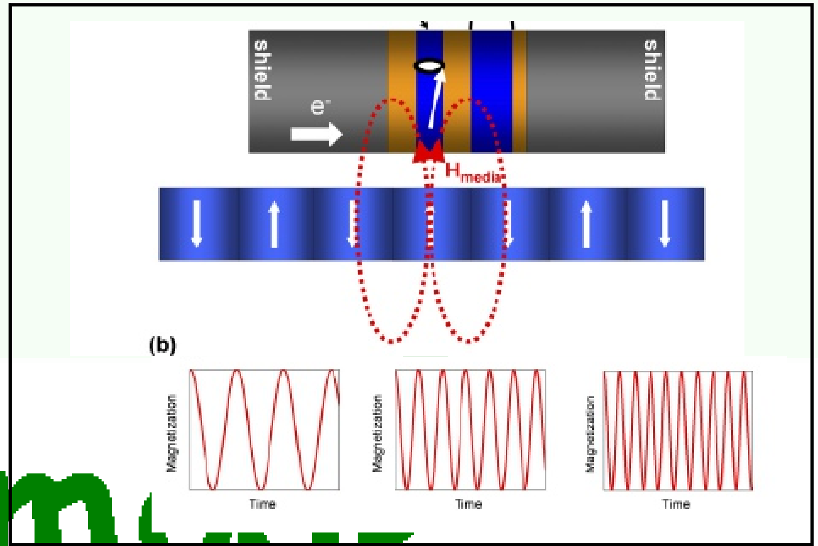
Frequency Generation

Frequency Mixing / Synchronisation



Signal treatment

Field Sensor in Read Heads



Frequency Detection

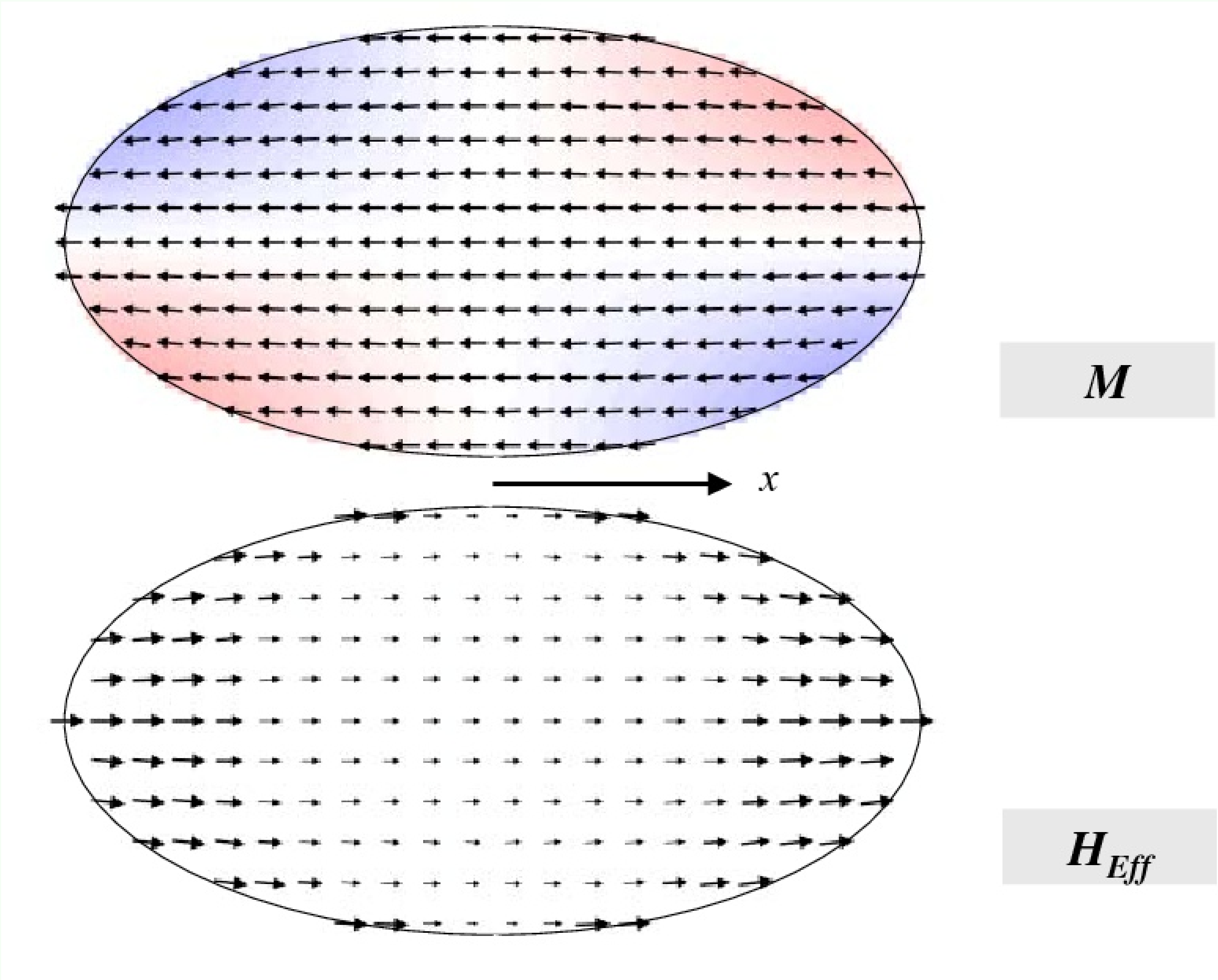
Tulapurkar et al 2005
Cornell PRL 2006

I_RF in

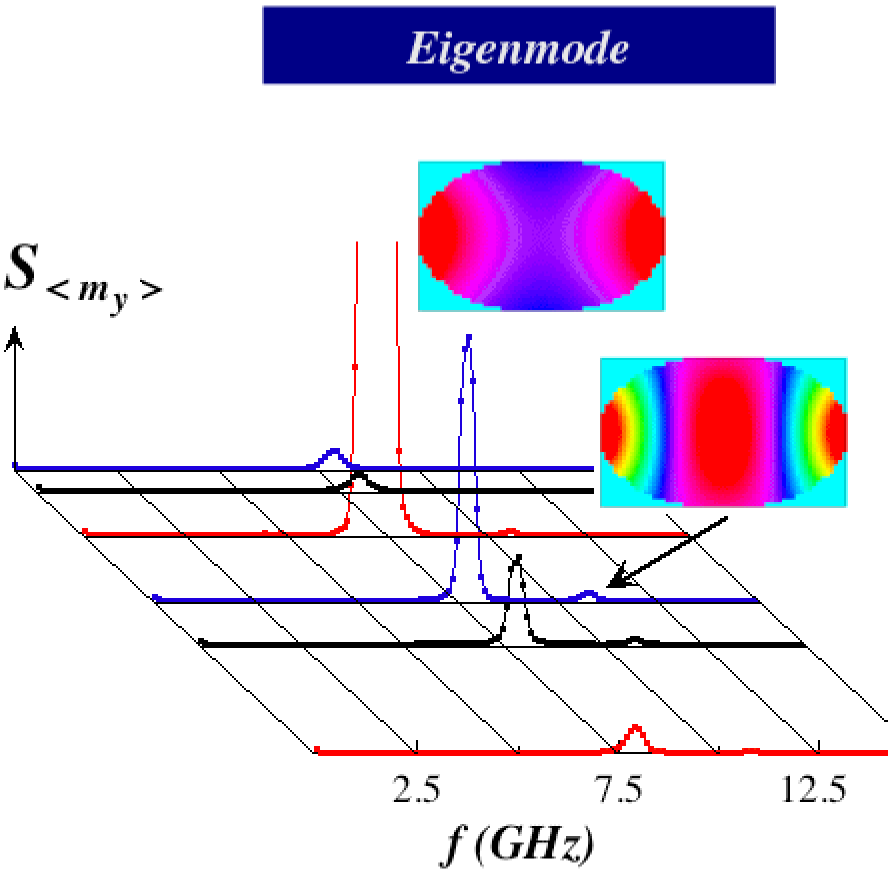
U_DC out

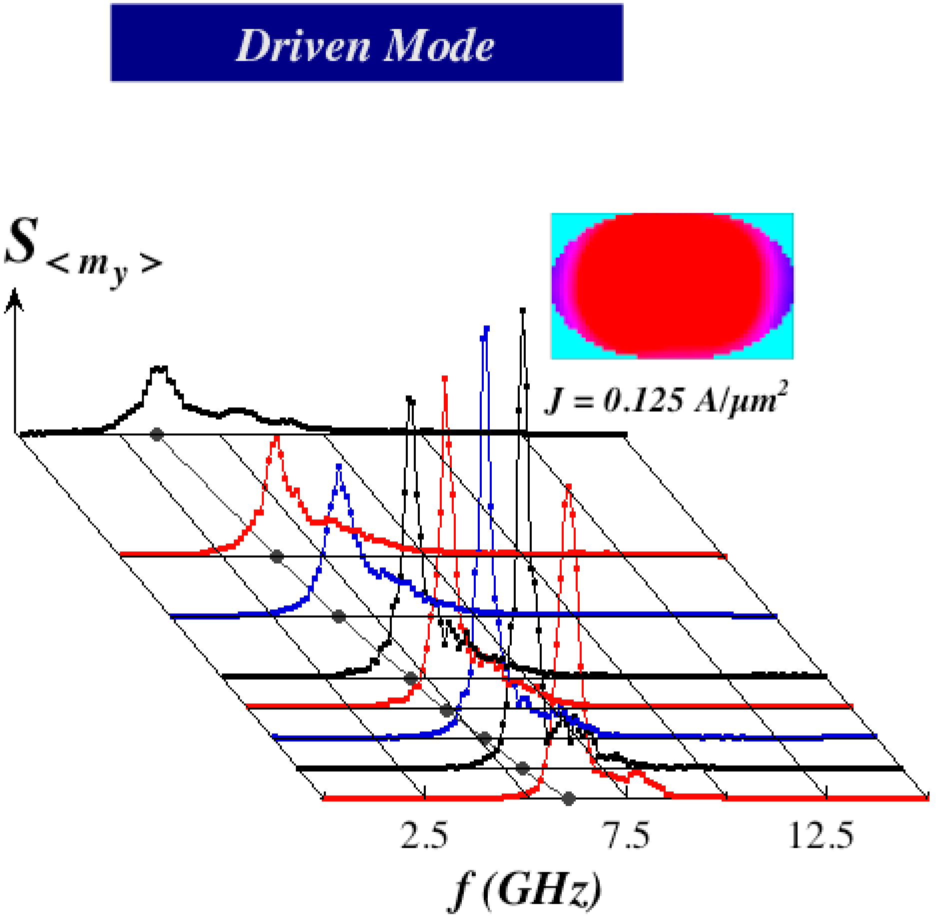
$I_{rf}(f_{mod}$

Micromagnetics…



Precessional states



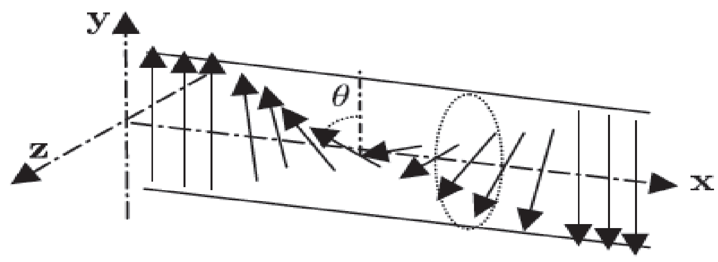


B. Montigny & J. Miltat, J. Appl. Phys. 97, 10C708 (2005)

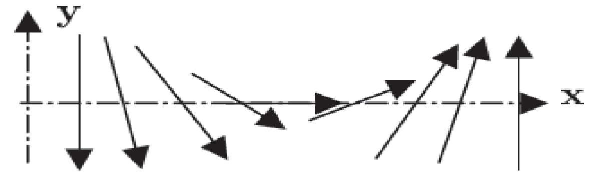
Domain walls

Domain walls

Thin films:

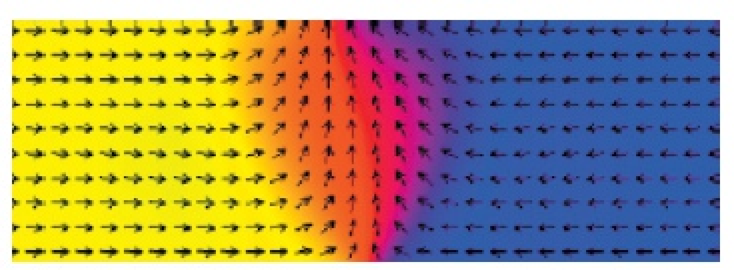


Bloch wall $$\delta = \pi\sqrt{\frac{A}{K}}$$

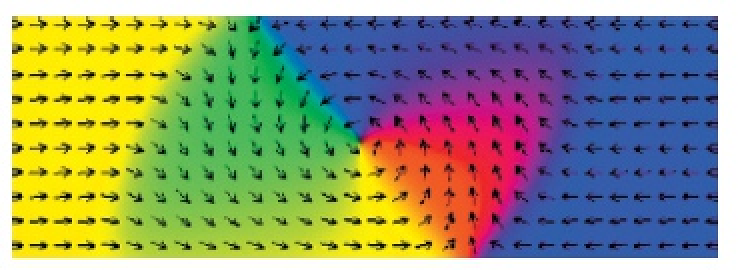


Néel wall

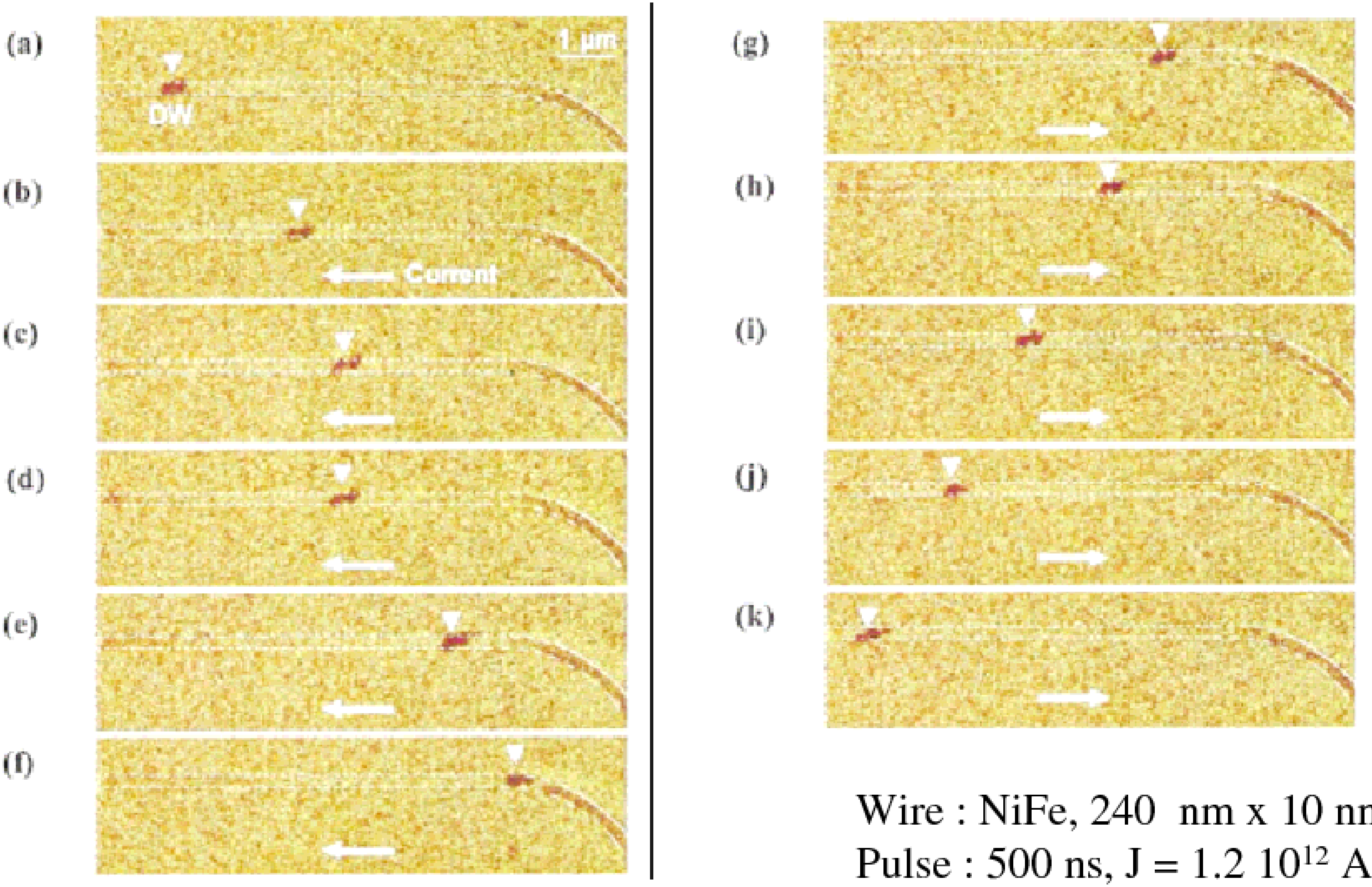
Nanostripes) :



Transverse wall



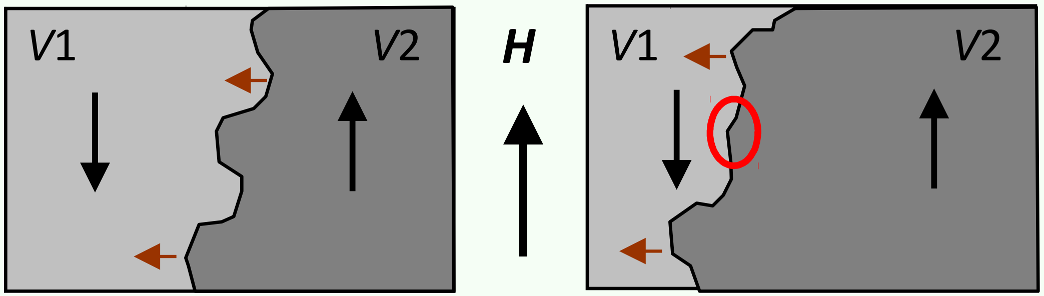
Vortex wall



Wire : NiFe, 240 nm x 10 nm
Pulse : 500 ns, J = 1.2 10^{12} A/m^2
(revised J = 0.7 10^{12} A/m^2)

A. Yamaguchi et al., Phys. Rev. Lett. **92**, 077205 (2004)

Domain wall Dynamics under an applied field



Time *t*1

Time *t*2

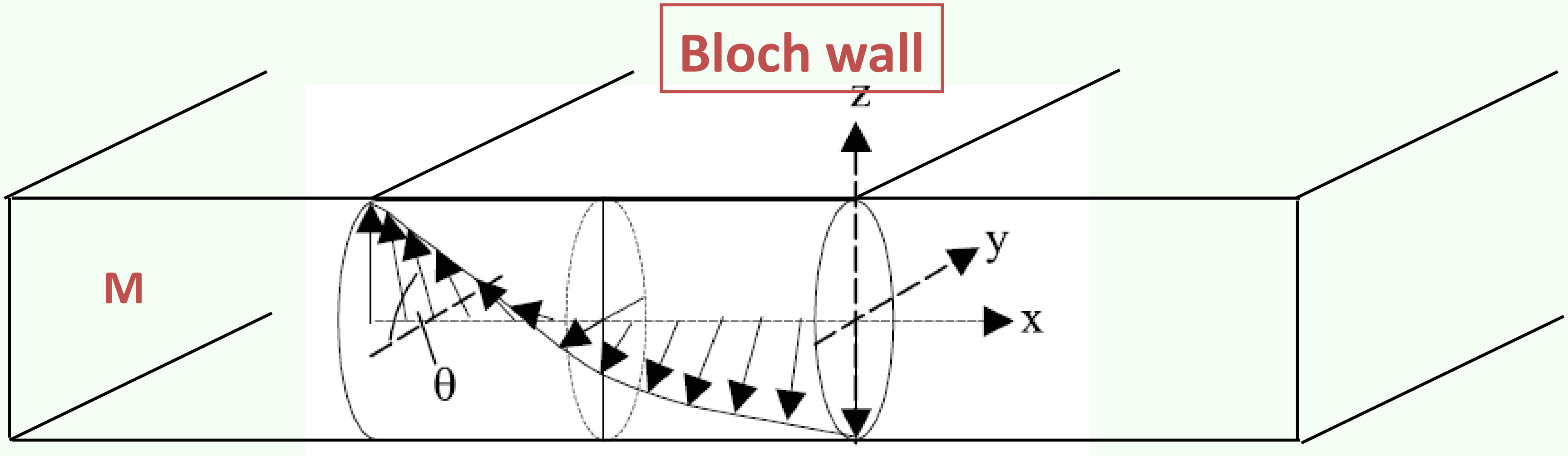
- Wall displaces perpendicularly to field
- Domain parallel to bias field increases in size, to minimize Zeeman energy

$$E = M_1 H V_1 - M_2 H V_2$$

All changes of the magnetization state pass via a precessional motion of the magnetization

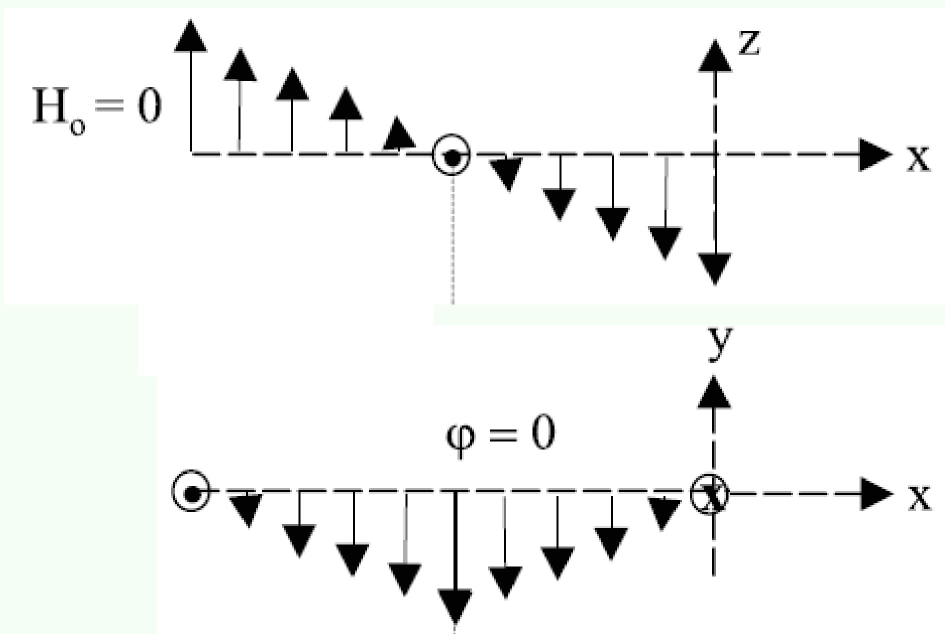
What is underlying process?

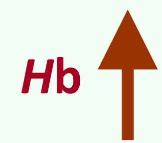
Domain wall Dynamics – Static Wall



Side view

Top view





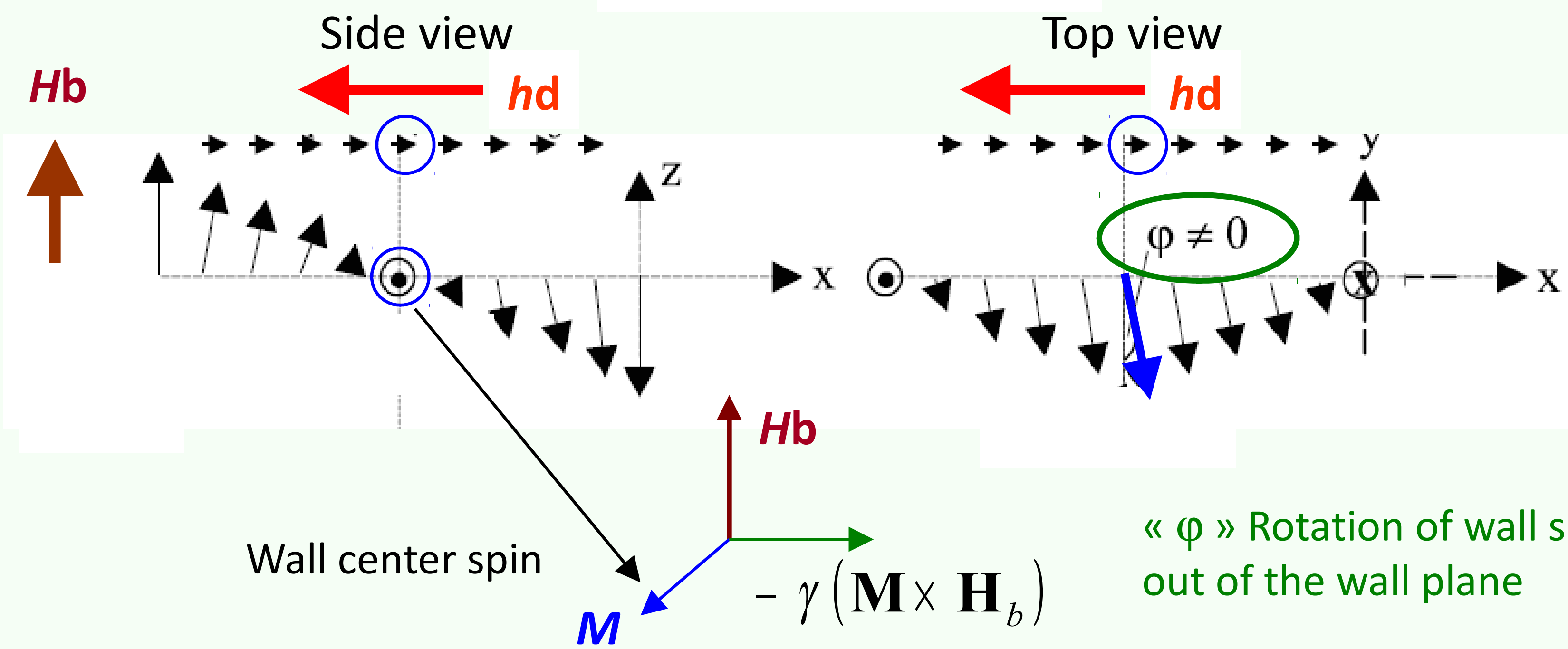
Upon application of an upward field, the wall displaces to the right

Domain wall Dynamics – Dynamic Wall

Two step reversal of magnetization inside the wall

1) Rotation of wall spins around the external field *H*b

$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{H}_b\right)$$



« φ » Rotation of wall spins out of the wall plane

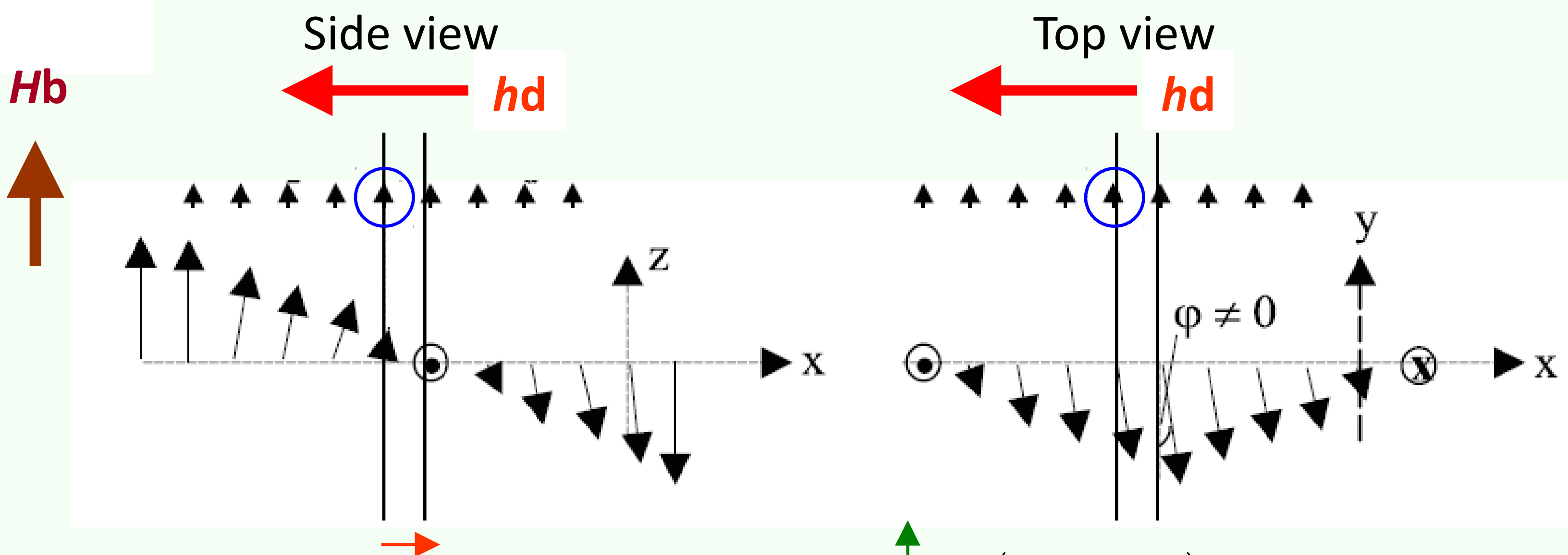
This rotation leads to an internal dipolar field *h*d

Domain wall Dynamics – Dynamic Wall

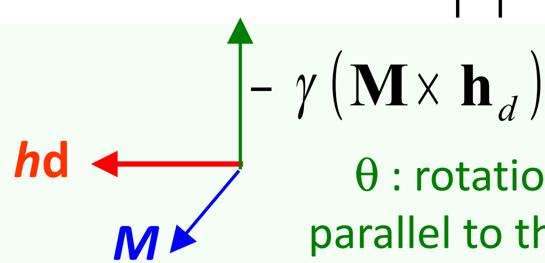
Two step reversal of magnetization inside the wall

2) Rotation of wall spins around the dipolar field *hd*

$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{h}_d\right)$$

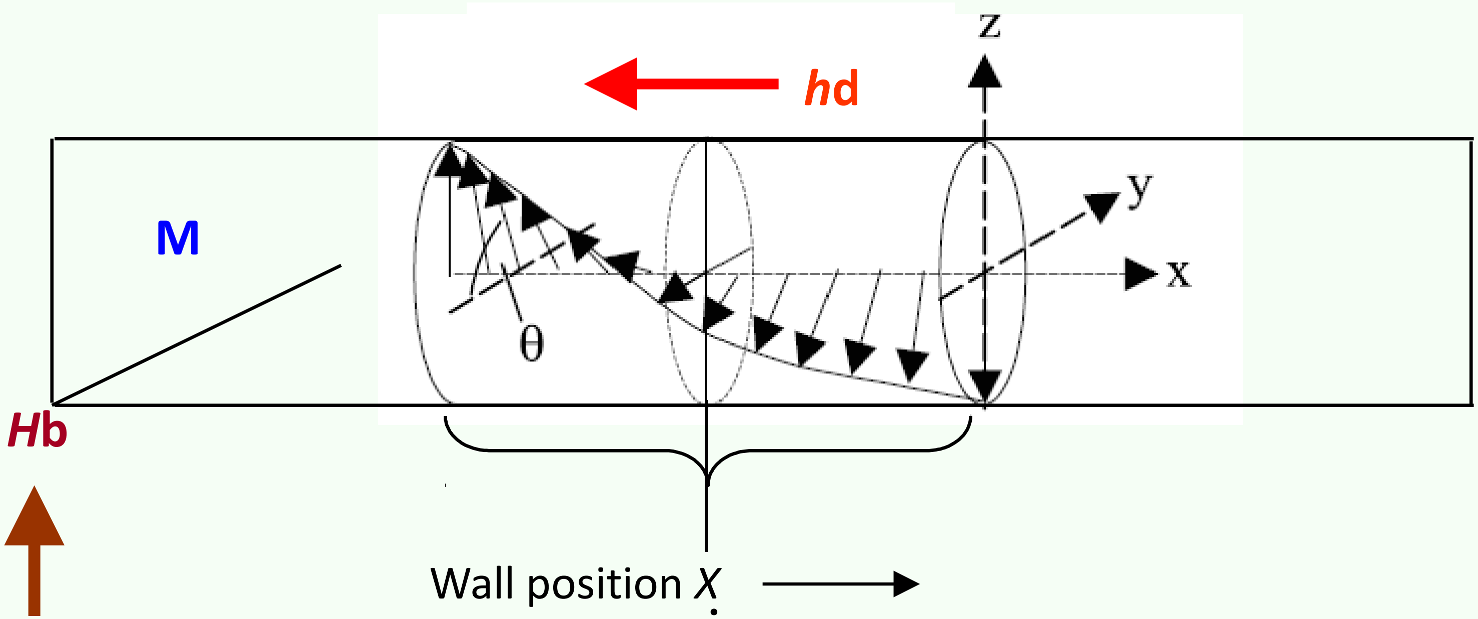


Rigid displacement of wall profile due to *θ* rotation



θ : rotation of spins parallel to the wall plane

Domain wall Dynamics – Dynamic Wall



Wall speed $\dot{X} = v \sim \varphi \sim H_b$

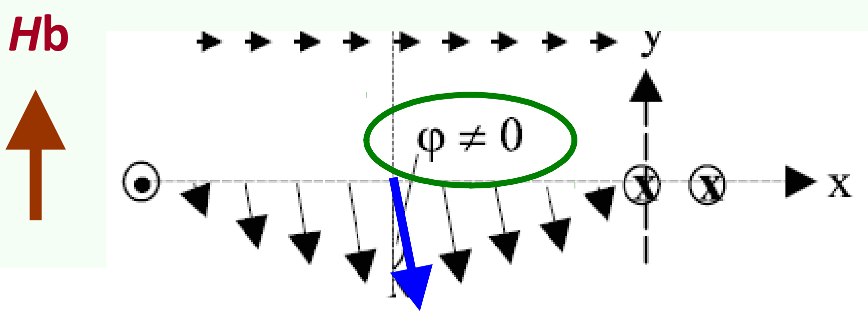
- The larger the bias field *H*b, the larger the angle φ
- The larger φ, the stronger *h*d and in consequence the faster the « θ » rotation
- The faster the « θ » rotation, the faster the wall displaces
- For constant φ, constant wall velocity *v*

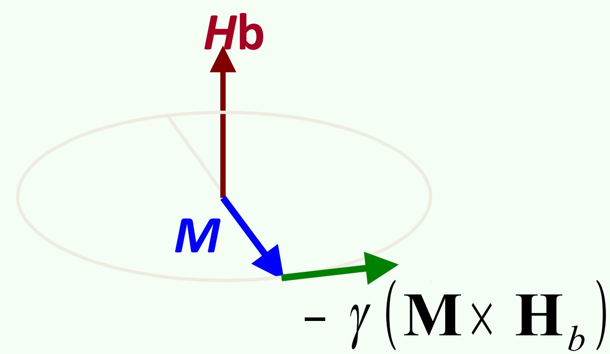
Domain wall Dynamics –Wall Displacement

- **Why is φ constant?**
- **For constant *H*b, the wall spins should precess around *H*b**

« φ » Rotation of spins out of the wall plane

Top view





$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{H}_{eff}\right) + \boxed{\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)}$$

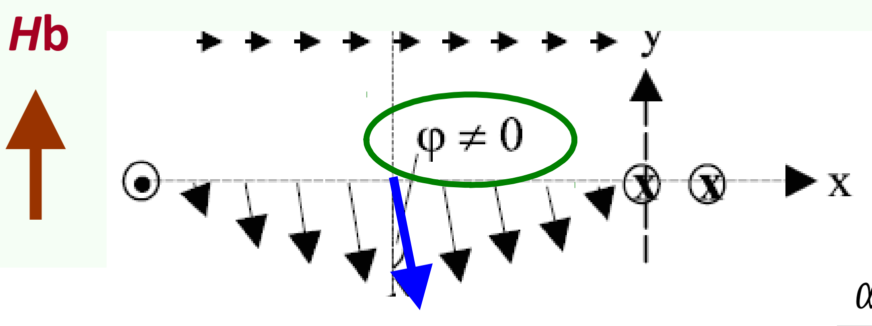
Due to damping, φ remains constant

The fast θ rotation due to *hd* provides a strong damping torque that counteracts the precession torque around *H*b

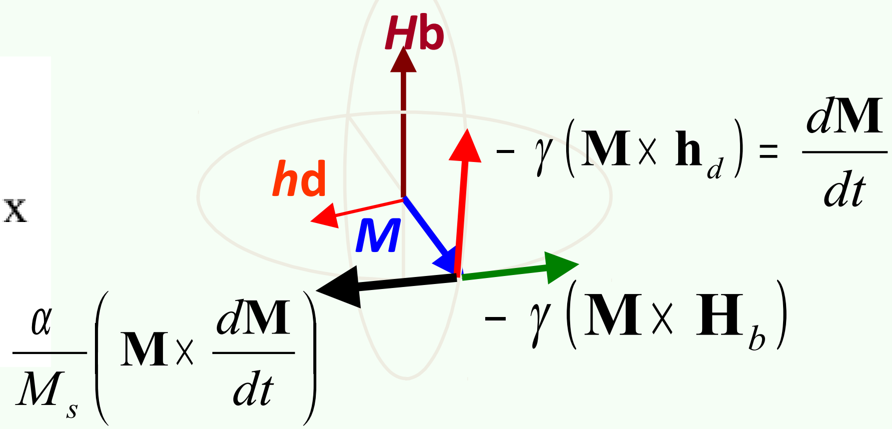
Domain wall Dynamics –Wall Displacement

- **Why is φ constant?**
- **For constant *H*b, the wall spins should precess around *H*b**

Top view



« φ » Rotation of spins out of the wall plane



$$\frac{d\mathbf{M}}{dt}=-\gamma(\mathbf{M}\times\mathbf{h}_d)+\boxed{\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)}$$

Due to damping, φ remains constant

Upon field application, φ increases until damping torque due to θ rotation is strong enough to counterbalance φ rotation

Domain wall Dynamics –Wall Displacement

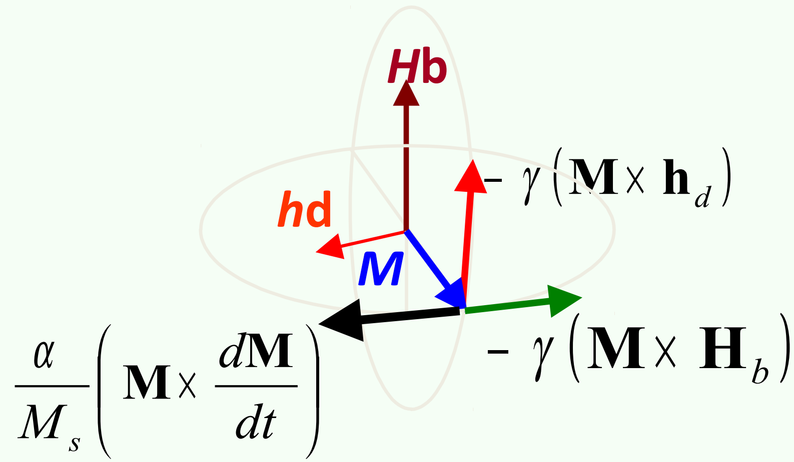
Two step reversal of magnetization inside the wall

1) Balance between precession and damping

$$\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)=\frac{-\gamma\alpha}{M_s}\left(\mathbf{M}\times\left(\mathbf{M}\times\mathbf{h}_d\right)\right)$$

$$\frac{-\gamma\alpha}{M_s}\left(\mathbf{M}\times\left(\mathbf{M}\times\mathbf{h}_d\right)\right)=-\gamma\left(\mathbf{M}\times\mathbf{H}_b\right)$$

$$\alpha\, h_d \cos\varphi = H_b$$



2) Precession around **hd**

$$\frac{d\mathbf{M}}{dt}=-\gamma\left(\mathbf{M}\times\mathbf{h}_d\right)$$

$$\left|\frac{d\mathbf{M}}{dt}\right|=\gamma M_s h_d\cos\varphi \qquad \left|\frac{d\mathbf{M}}{dt}\right|=M_s\dot{\theta}$$

$$\left|\frac{d\mathbf{M}}{dt}\right|=\gamma M_s\frac{H_b}{\alpha} \qquad \left|\frac{d\mathbf{M}}{dt}\right|=M_s\frac{\partial\theta}{\partial x}\frac{\partial x}{\partial t}=M_s\frac{\partial\theta}{\partial x}v=M_s\frac{\pi}{\Delta}v$$

$$v=\frac{\gamma\Delta}{\alpha\,\pi}H_b$$

$$v=\mu H_b$$

μ wall mobility

Domain wall Dynamics –Wall Displacement

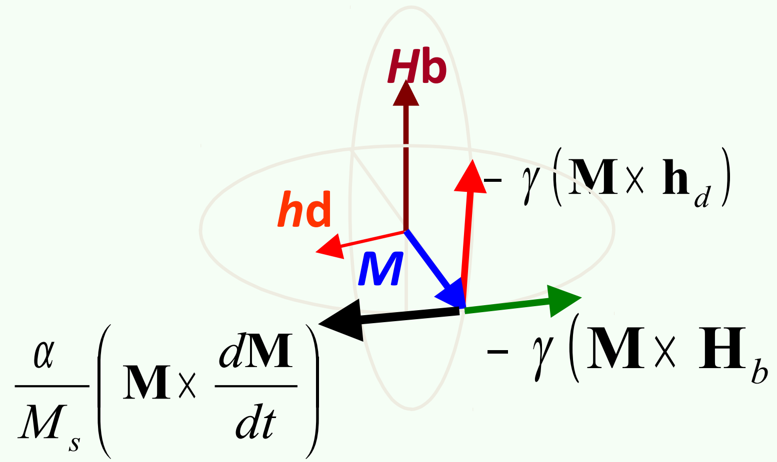
Two step reversal of magnetization inside the wall

1) Balance between precession and damping

$$\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right) = \frac{-\gamma\alpha}{M_s}\left(\mathbf{M}\times\left(\mathbf{M}\times\mathbf{h}_d\right)\right)$$

$$\frac{-\gamma\alpha}{M_s}\left(\mathbf{M}\times\left(\mathbf{M}\times\mathbf{h}_d\right)\right) = -\gamma\left(\mathbf{M}\times\mathbf{H}_b\right)$$

$$\alpha\, h_d \cos\varphi = H_b$$



V

$$v = \frac{\gamma\Delta}{\alpha\,\pi}H_b$$

$$v = \mu H_b$$

µ wall mobility

Domain wall Dynamics –Wall Displacement

Maximum dipolar field when static rotation of φ = 45°

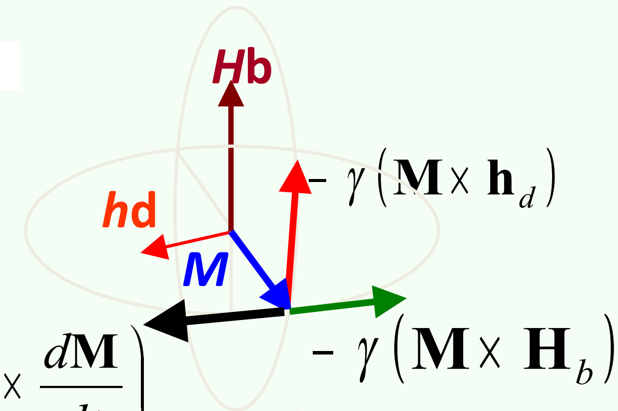
1) Balance between precession and damping

$$\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)=\frac{-\gamma\alpha}{M_s}\left(\mathbf{M}\times\left(\mathbf{M}\times\mathbf{h}_d\right)\right)$$

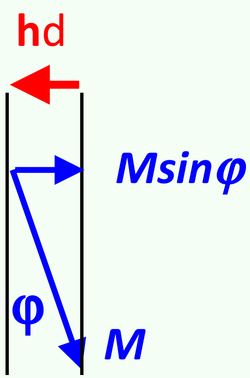
$$\alpha\, h_d \cos\varphi = H_b$$

$$h_d = 4\pi M_s \sin\varphi$$

$$\alpha\, 4\pi M_s \sin\varphi\, \cos\varphi = H_b$$



$$\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

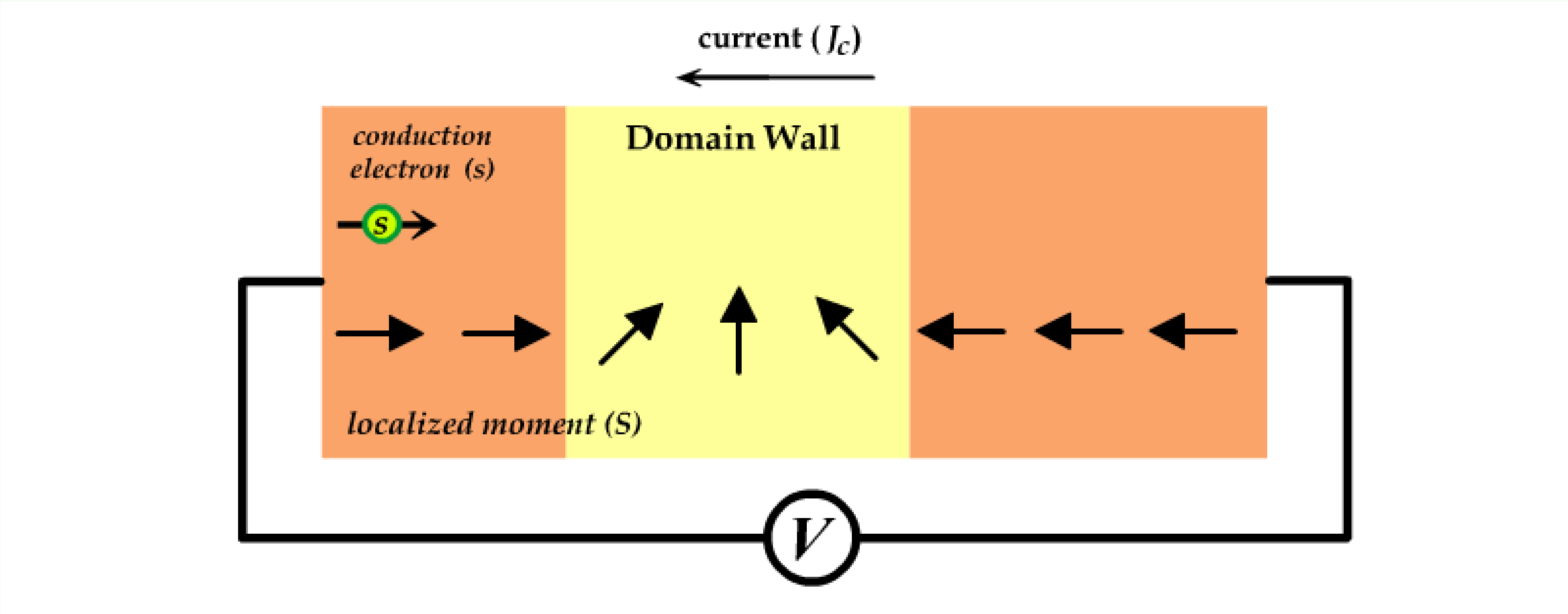


Walker breakdown

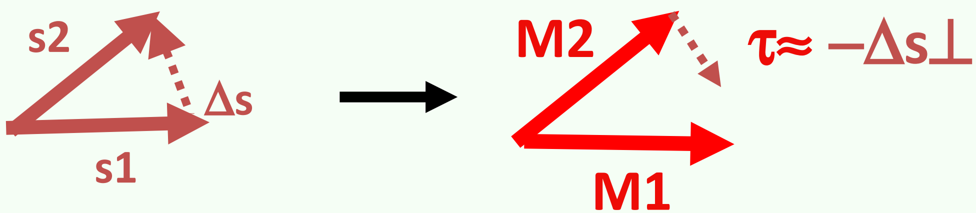
- Maximum damping torque at φ=45°.
- For larger φ, precession torque from **H**b is no more compensated
- Wall spin precess continously

$$H_W = \alpha\, 2\pi M_s$$

Domain wall motion under spin torque: concept



ourtesy of
. Maekawa



● The spin of the conduction electron adiabatically follow the direction of the local magnetization (large DW)

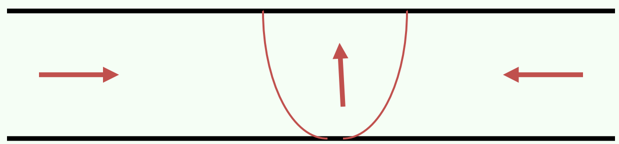
● Conservation of angular momentum → Spin transfered to the local magnetization **Torque** on magnetization

● **DW motion** in the direction of the e- flow

Domain wall displacement: H vs I

What happens to a transverse DW under application of a field or a current?

Geometry :



(A. Thiaville)

LLG :

$$\overbrace{\frac{\partial \vec{m}}{\partial t}}^{1} = \overbrace{\gamma \cdot \vec{H} \times \vec{m}}^{2} + \overbrace{\alpha \cdot \vec{m} \times \frac{\partial \vec{m}}{\partial t}}^{3} - \overbrace{u.\vec{\nabla}\, \vec{m}}^{4} + \beta u(\vec{m} \times \vec{\nabla}\, \vec{m})$$

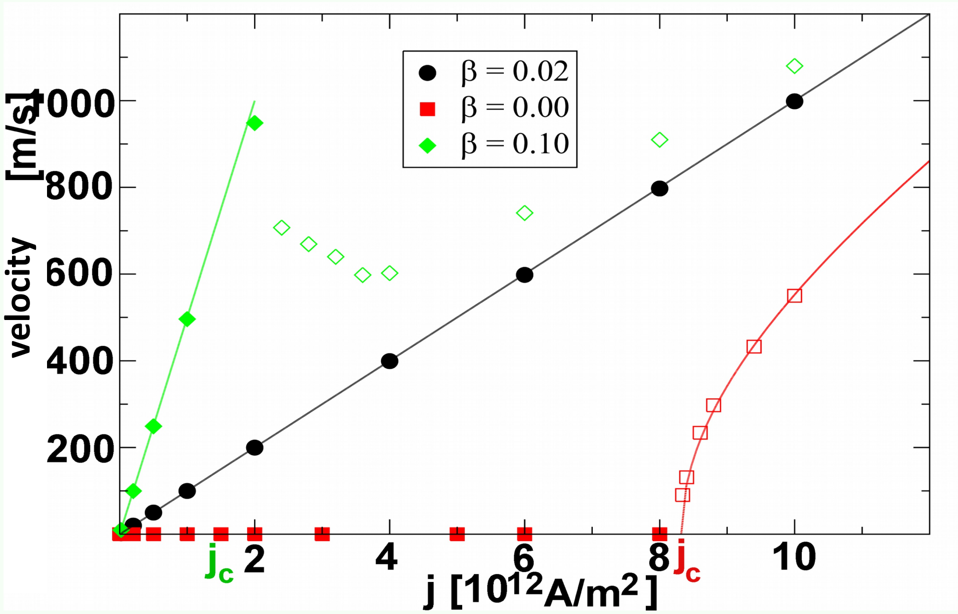
(Velocity u=JgPμB/2eMs)

only H(→): 2: ⊙ , 1: ⊙ ,Demag ⊗ , 2: → , 3: ⊗ ⇒ steady state motion

J only: 4: → , 1: → , 3: ⊗ , Demag ⊙ , 2: ← , 3: ⊙ ⇒ no steady state motion

To obtain a steady state motion, one needs to introduce the beta term…

β term and DW dynamics



Perfect wire with no edge roughness

- **β =0**, **only adiabatic term**
  - **No motion for J<Jc**
  - **Jc « intrinsic »** (depends on the magnetic properties of the DW)
  - **Turbulent motion** above Jc with complex **DW transformation**

- **β≠0**
  - v **≠0** for perfect wire with **v∝ jβ/α**
  - Jc **« extrinsic »** due to pinning (roughness, defect in the material,…)
  - « Field like » torque

⇨ **β is a key parameter in the DW dynamics, but its value and microscopic origin still controversial.**

A. Thiaville et al., J. Appl. Phys. 95, 7049 (2004) G. Tatara et al., Phys. Rev. Lett. 92, 86601 (2004), S. Zhang and Z. Li, PRL **93**, 127204 (2004)

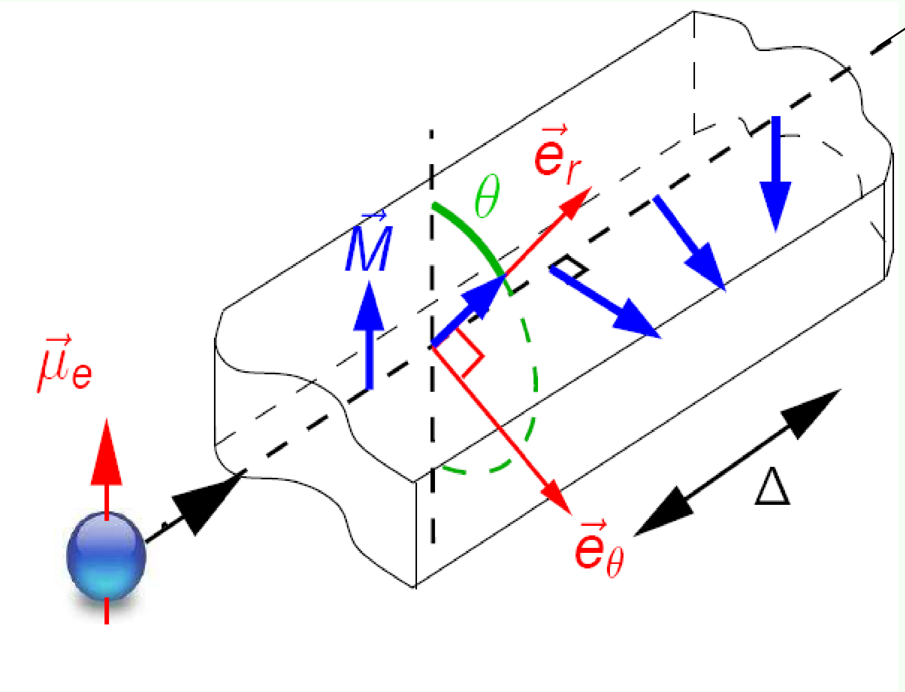
Spin transfer from the conduction electrons to the DW (my vision)

Theory

Two kinds of electrons:

- Localised d electrons
- Conduction electrons

→ s-d Hamiltonian



Action of a current:

Globally, the conduction electrons transfer gμB to the DW

Simple model : the particle approach

s-d Hamiltonian :

$$H_{s-d} = -J_{ex}\vec{s}\cdot\vec{S}$$

$$\Rightarrow$$

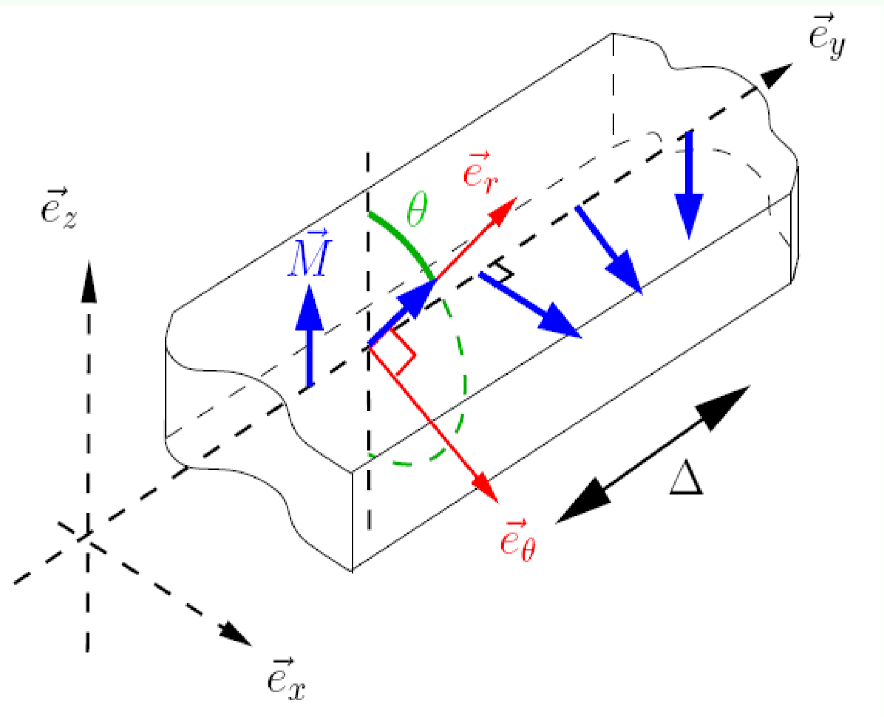
Precession equation :

$$\frac{d\vec{\mu}}{dt} = \frac{J_{ex}S}{\hbar}\,\vec{m}\times\vec{\mu} \qquad (\vec{\mu} = -g\mu_B\vec{s})$$

$< \vec{S} > /S = -\vec{M}/M_s$: localised spins

s : conduction electrons

In the rotating frame:

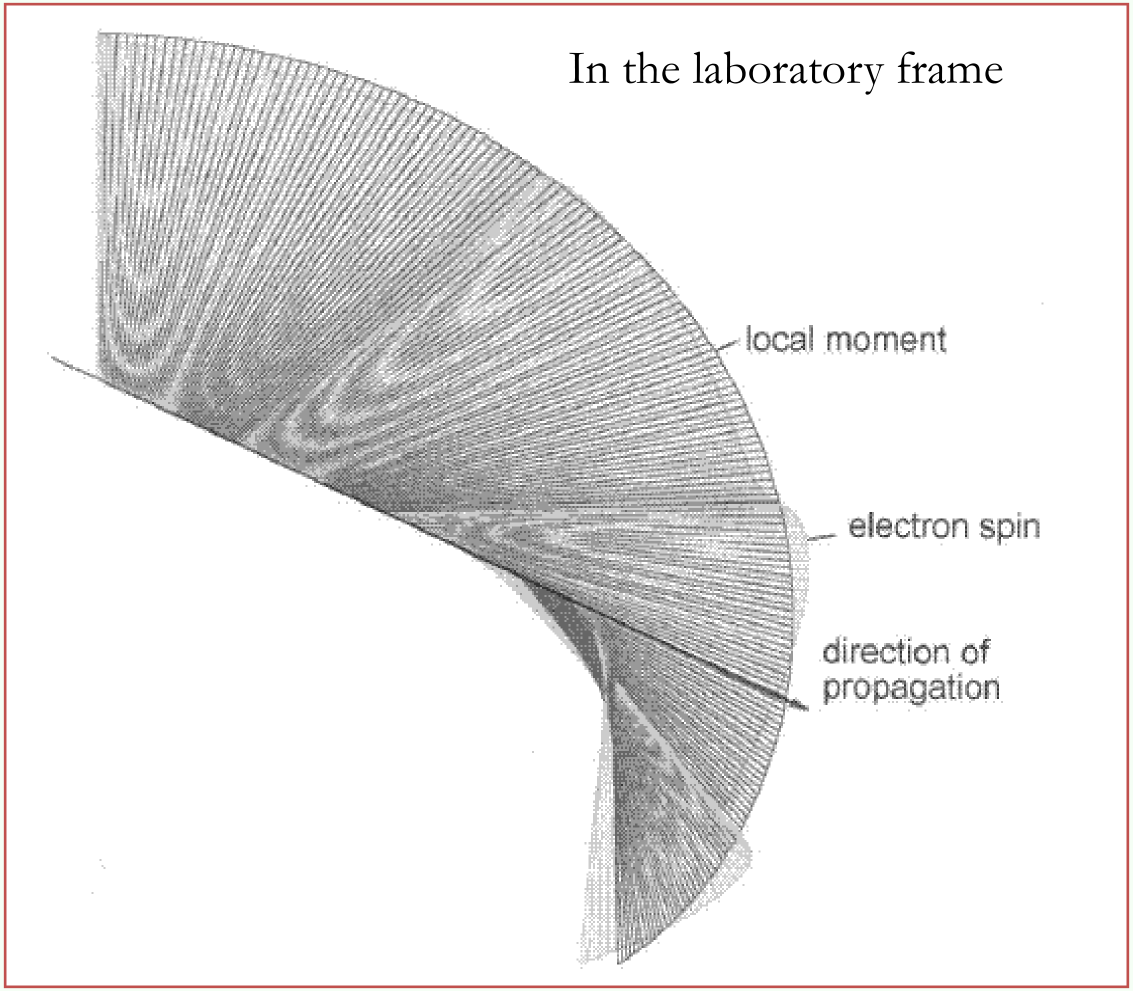


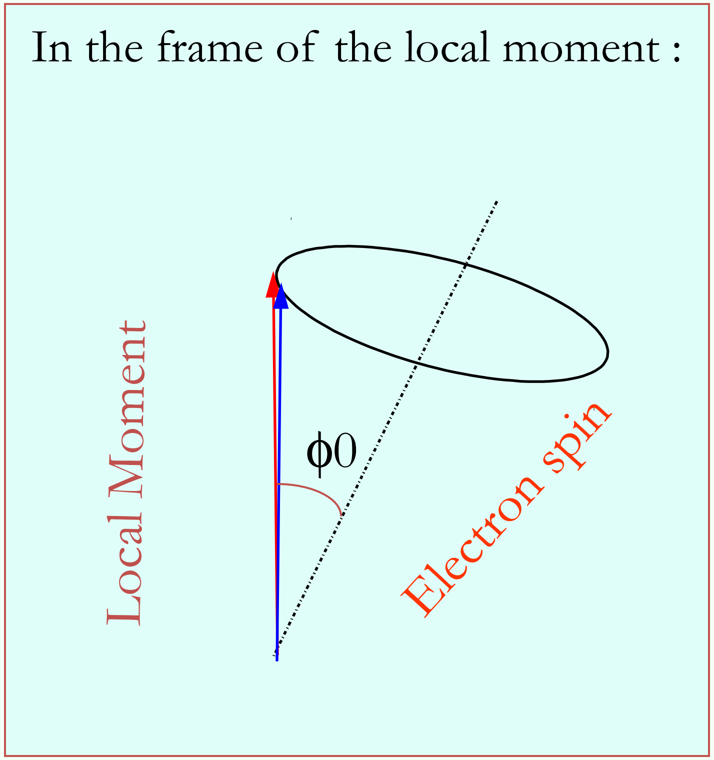
$$\Rightarrow \frac{d\vec{\mu}}{dt} = \begin{pmatrix} \dot{\mu}_r - \dot{\theta}\mu_\theta \\ \dot{\mu}_\theta + \dot{\theta}\mu_r \\ \dot{\mu}_y \end{pmatrix} = \frac{SJ_{ex}}{\hbar}\begin{pmatrix}1\\0\\0\end{pmatrix}\times\begin{pmatrix}\mu_r\\ \mu_\theta \\ \mu_y\end{pmatrix}$$

Defining $\tau_{ex} = \hbar/SJ_{ex}$ we get:

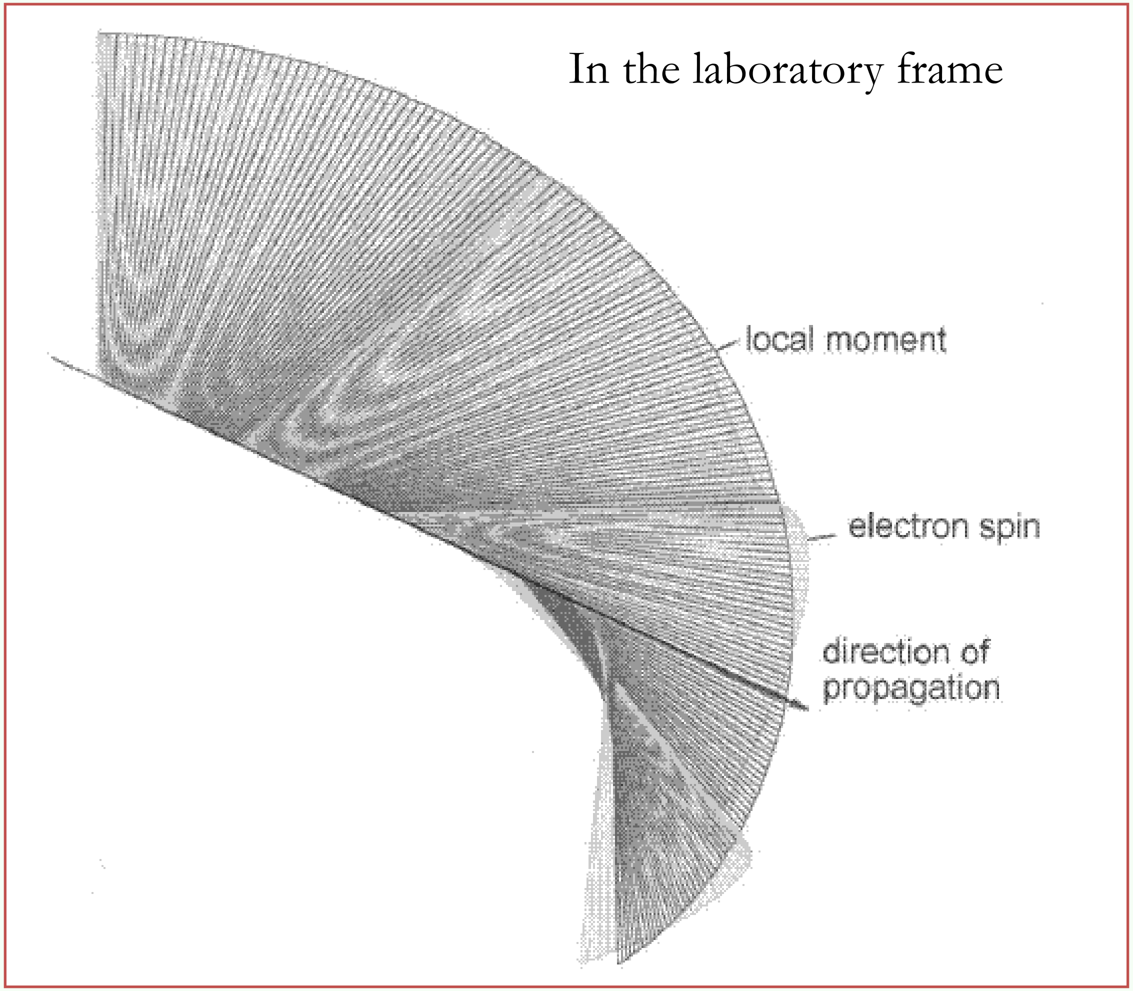
$$\begin{cases} \dot{\mu}_r - \dot{\theta}\mu_\theta = 0 \\ \dot{\mu}_\theta + \dot{\theta}\mu_r = -\frac{\mu_y}{\tau_{ex}} \\ \dot{\mu}_y = \frac{\mu_\theta}{\tau_{ex}} \end{cases}$$

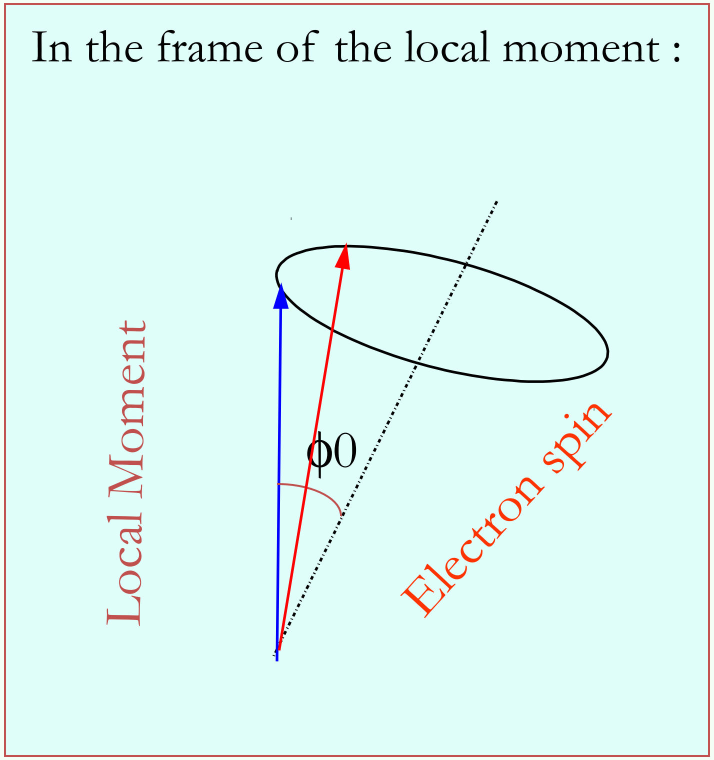
Spin evolution during DW crossing



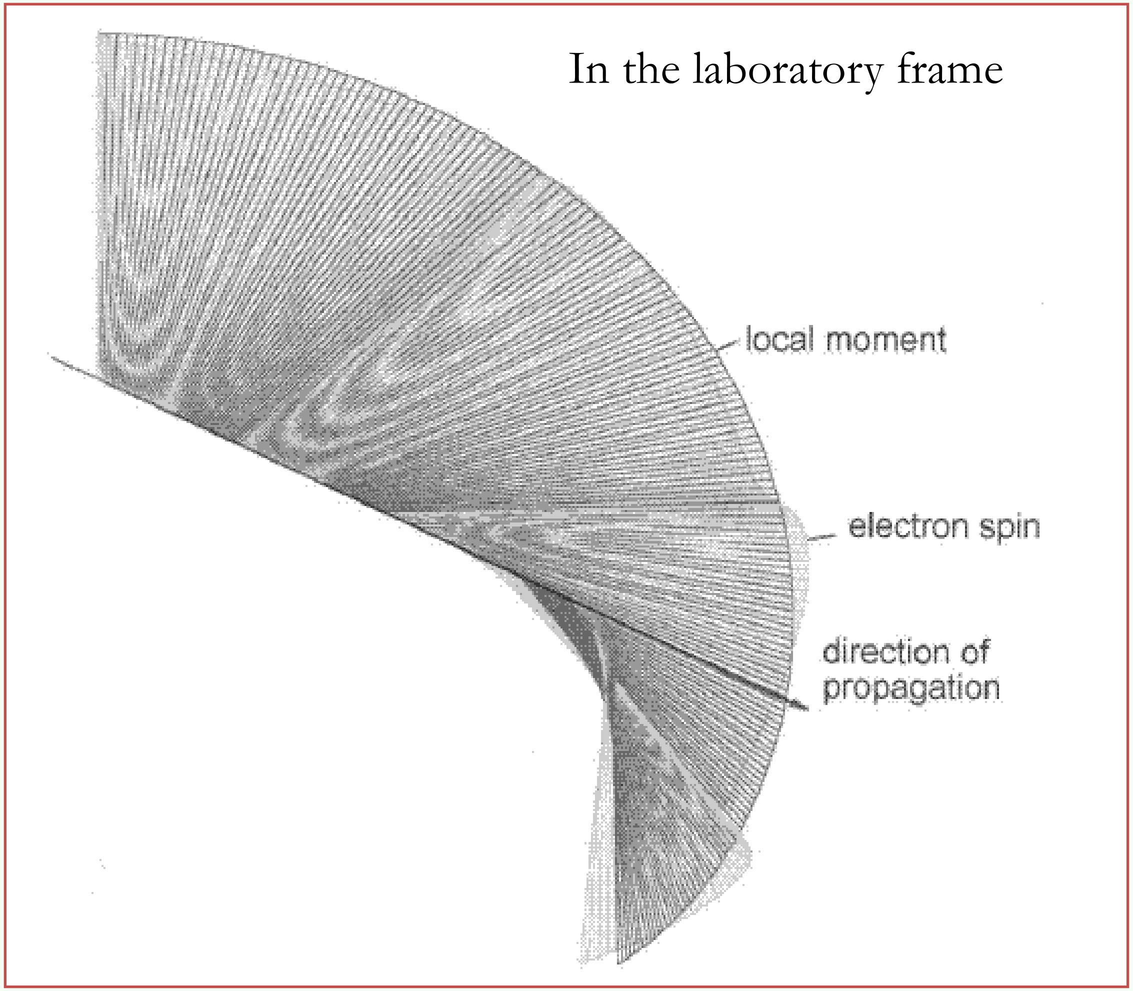


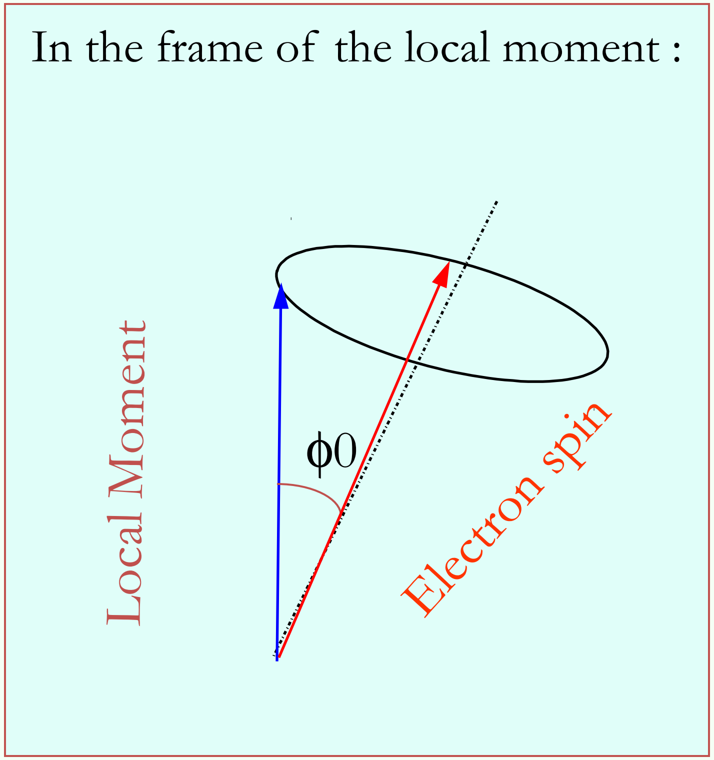
Spin evolution during DW crossing



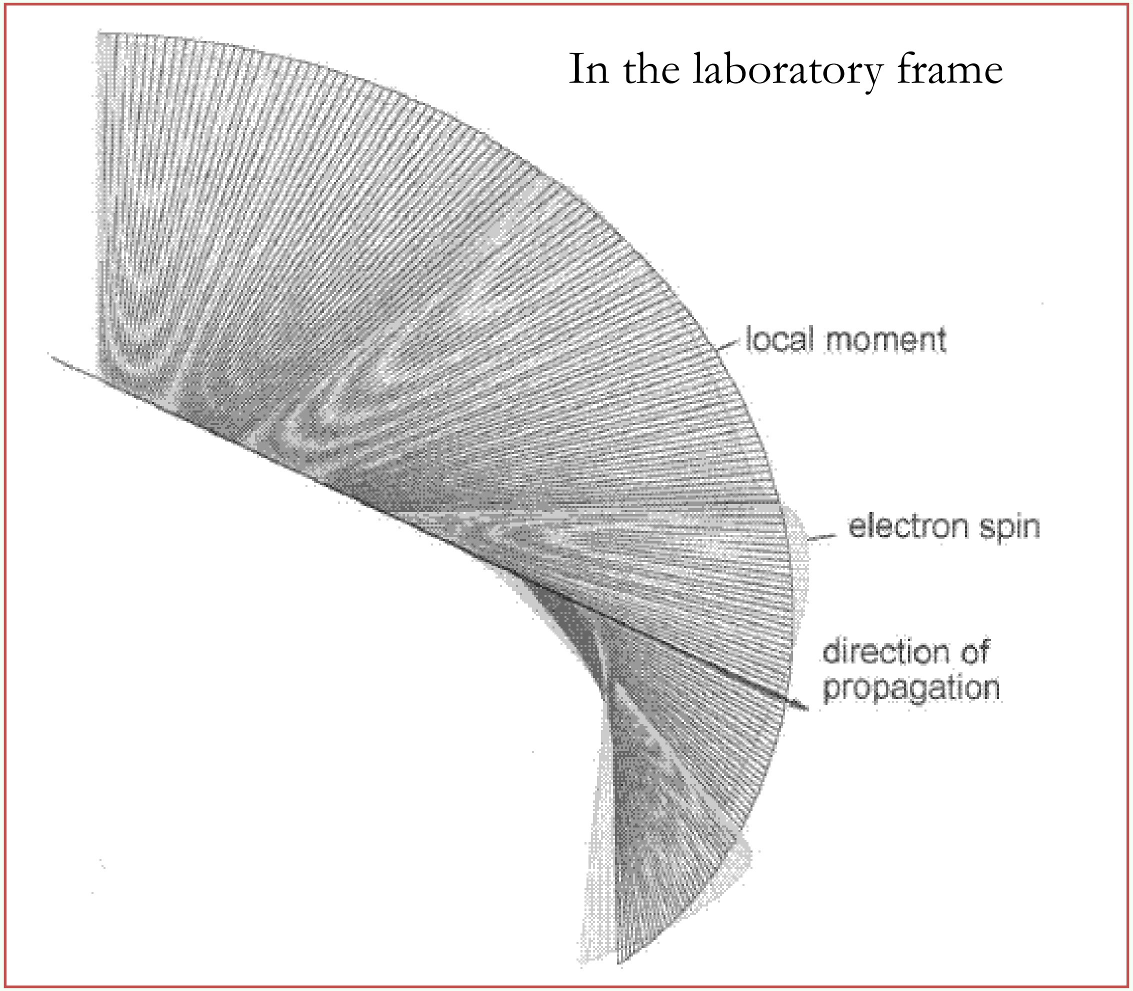


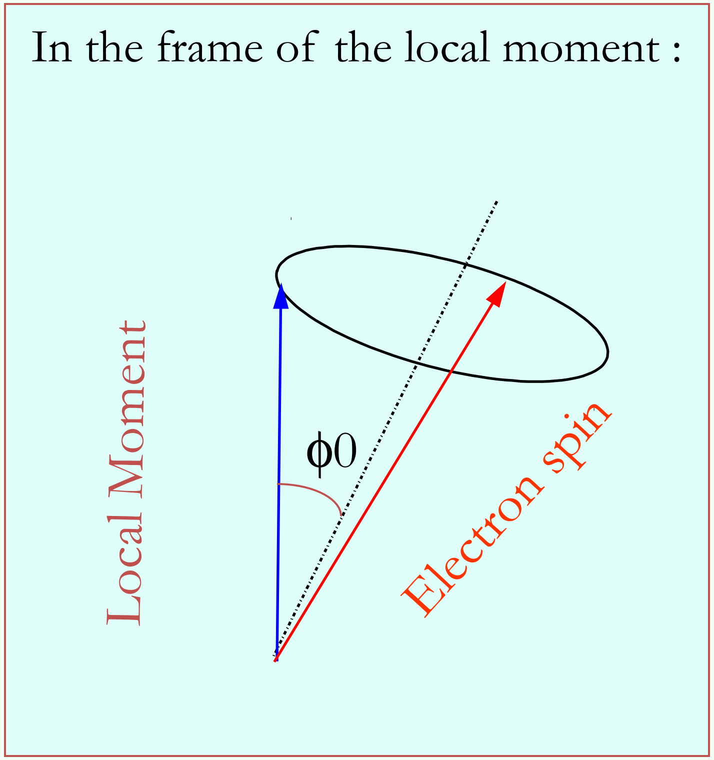
Spin evolution during DW crossing



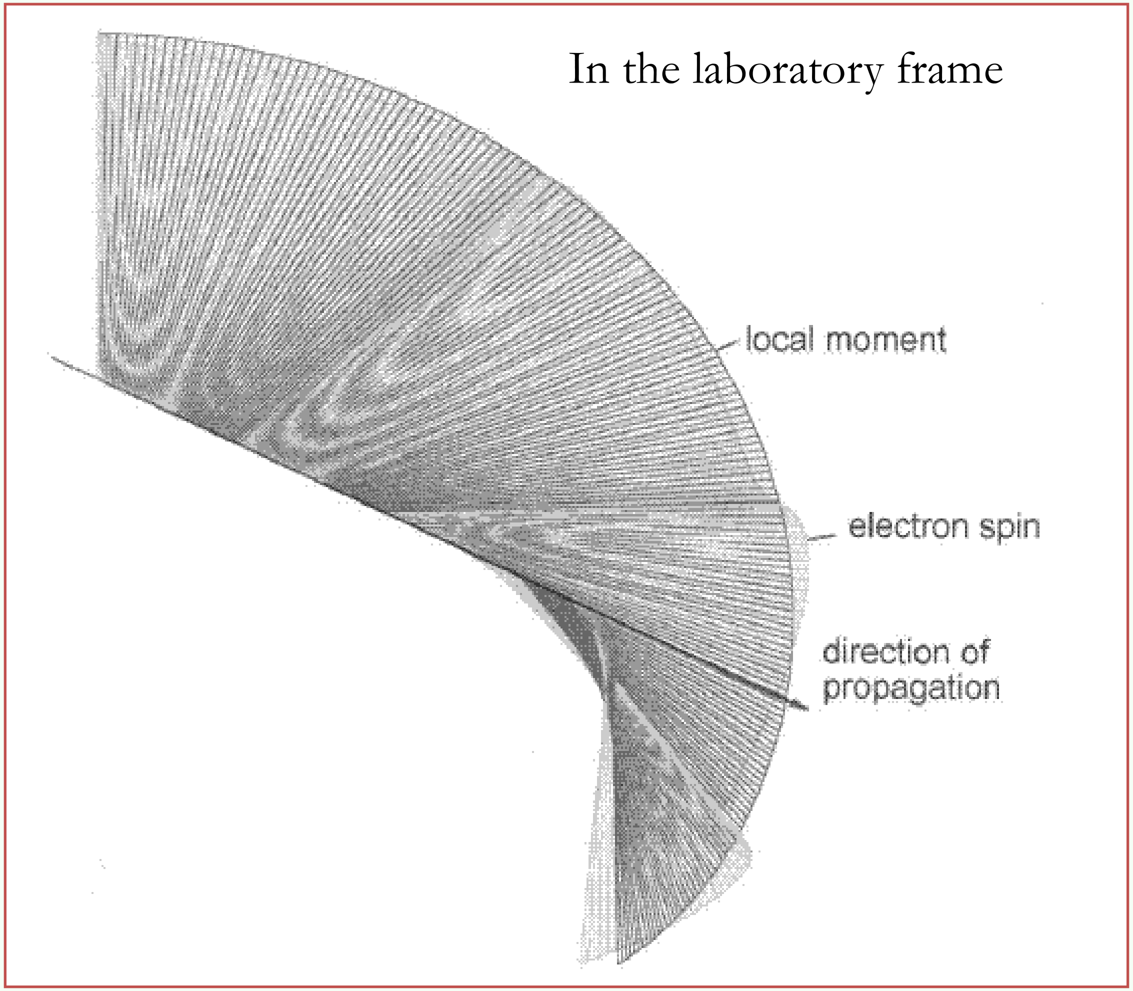


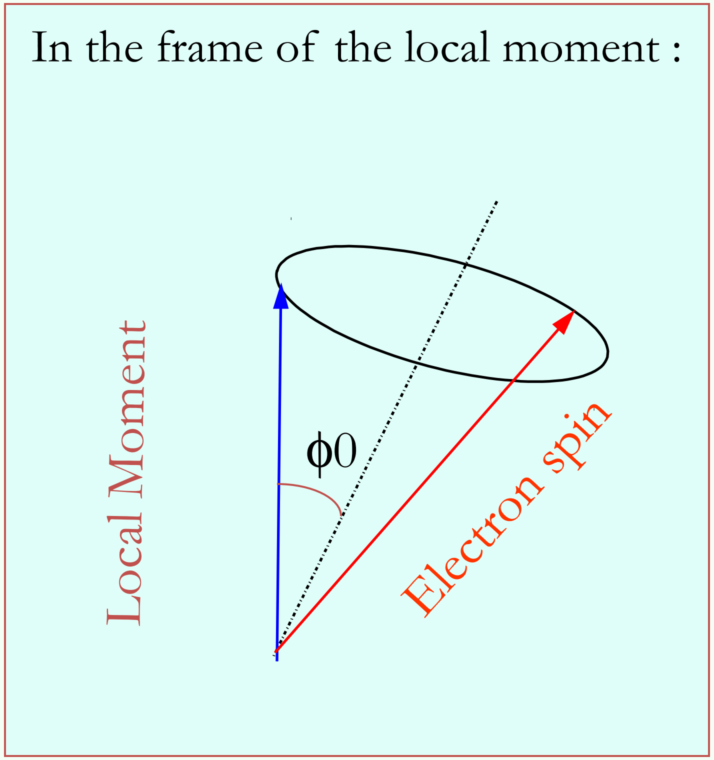
Spin evolution during DW crossing



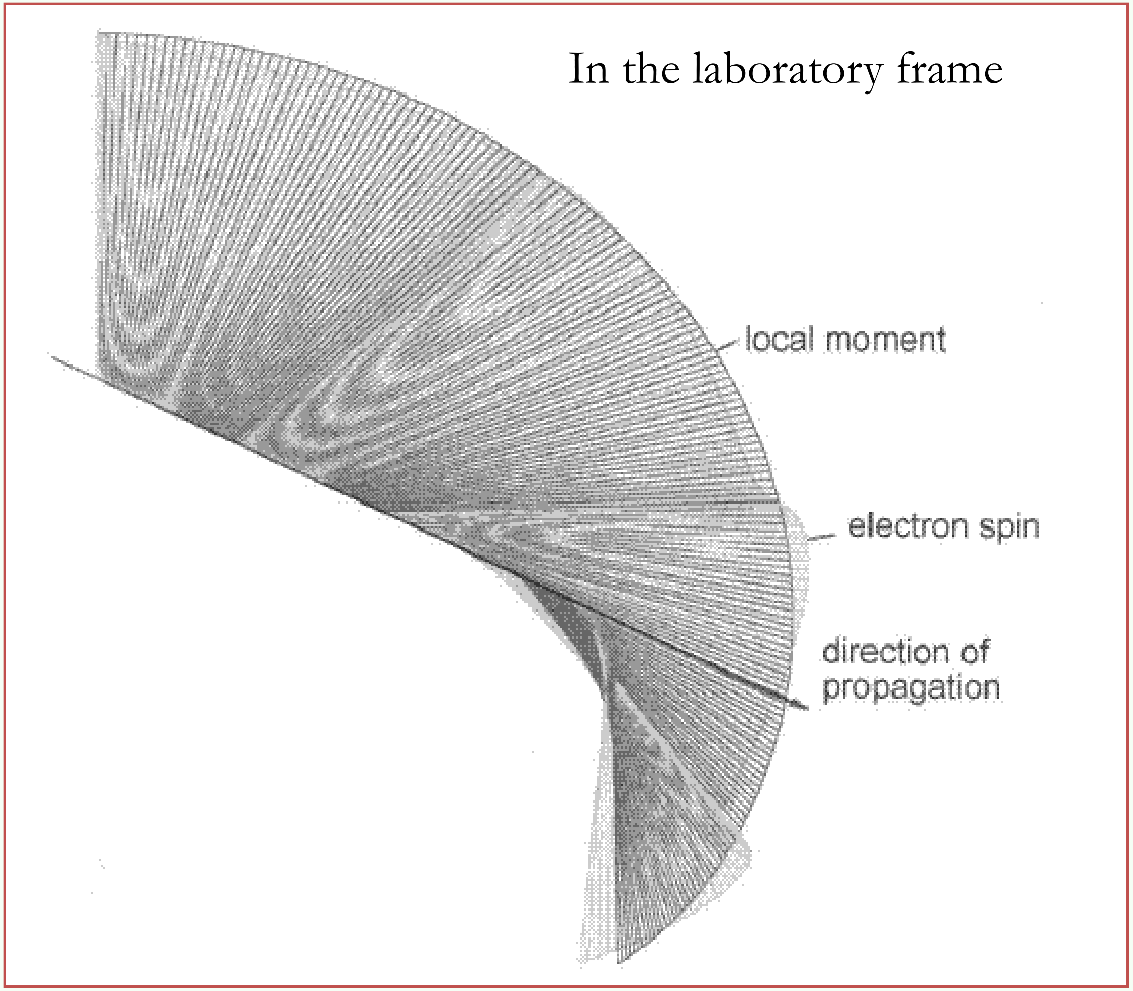


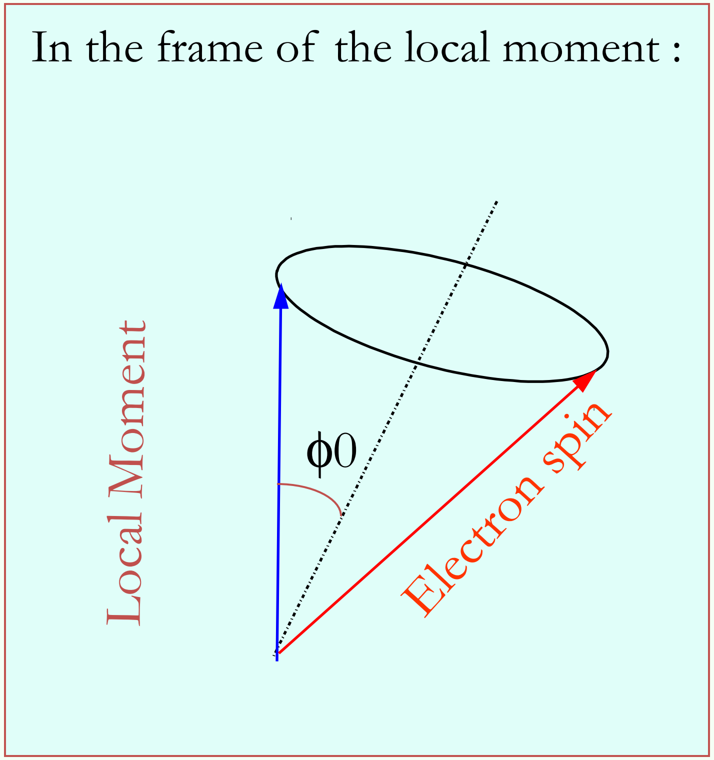
Spin evolution during DW crossing



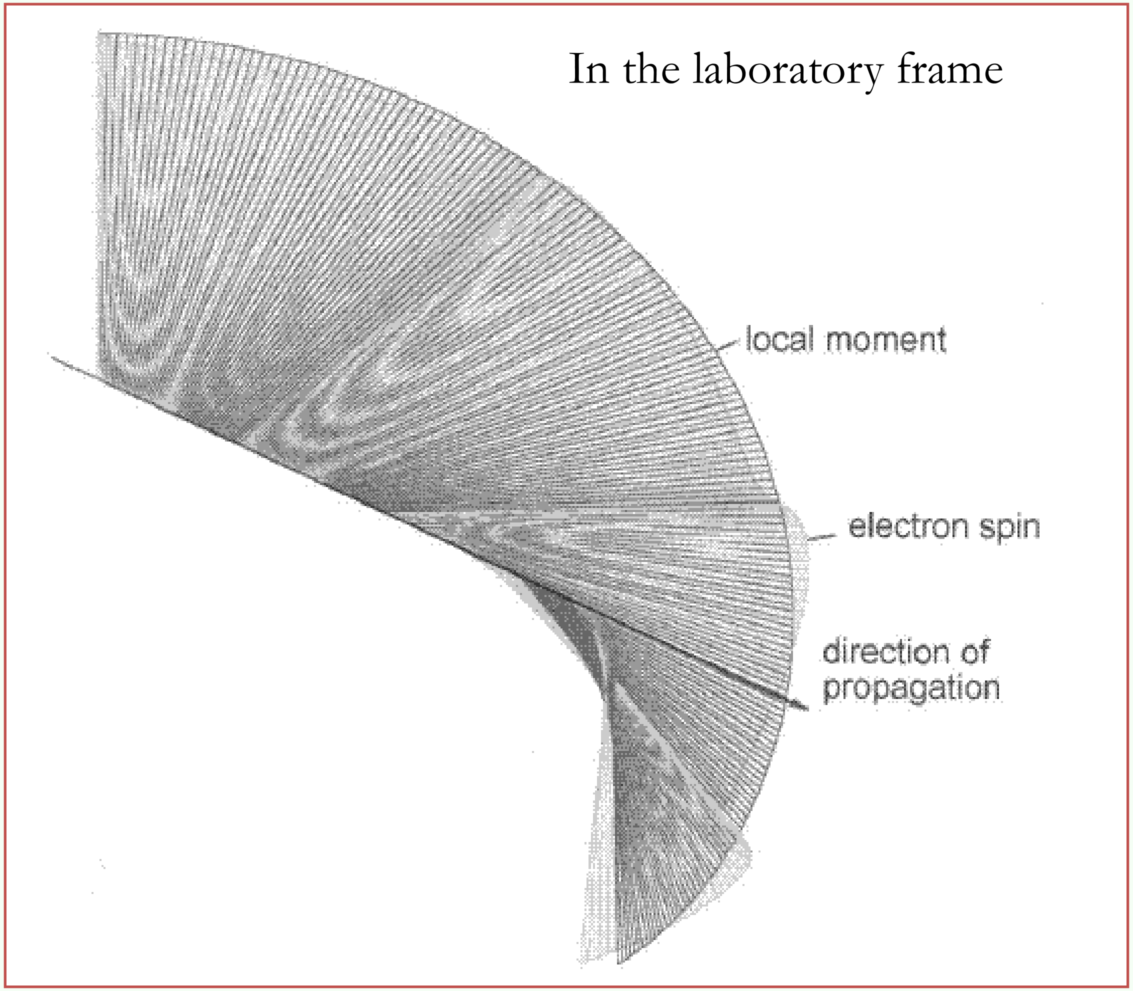


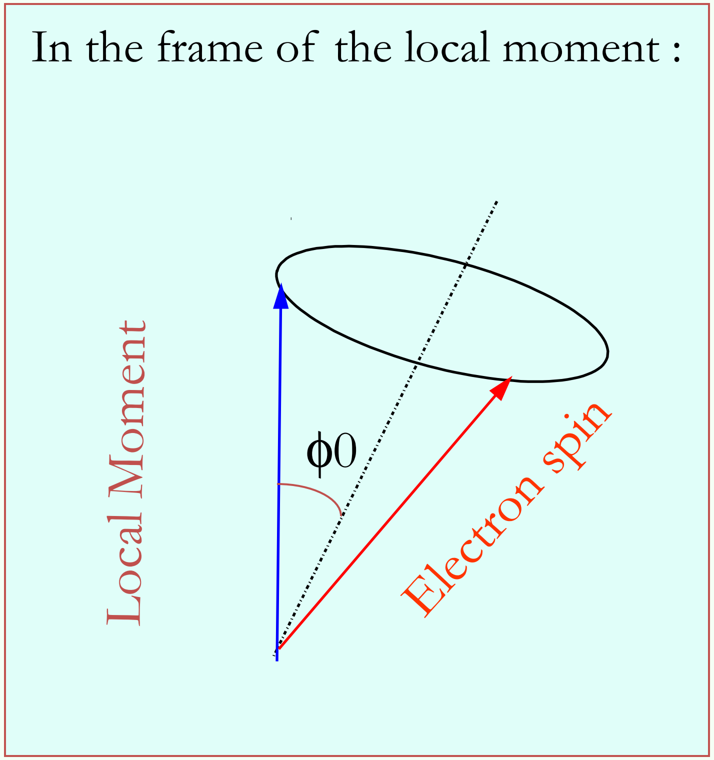
Spin evolution during DW crossing



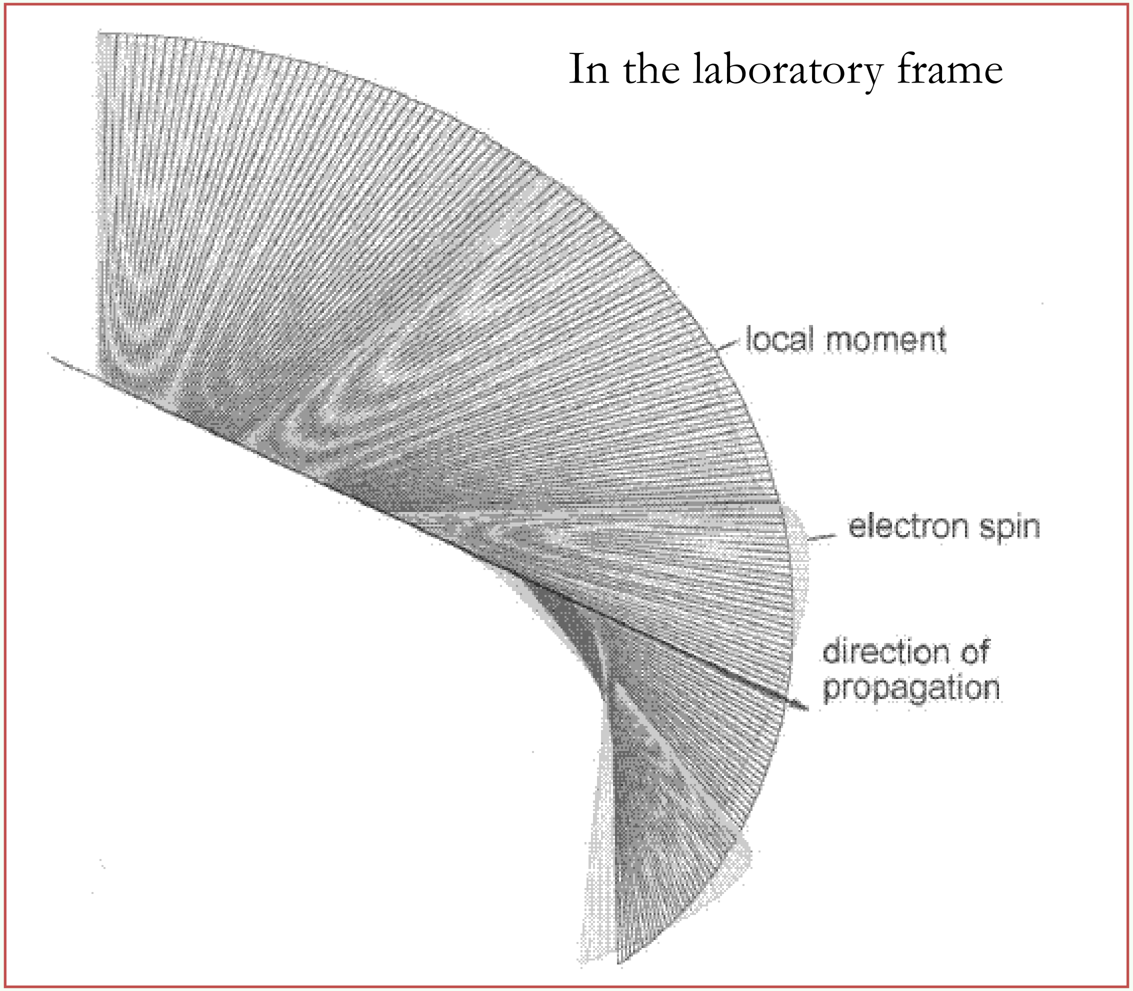


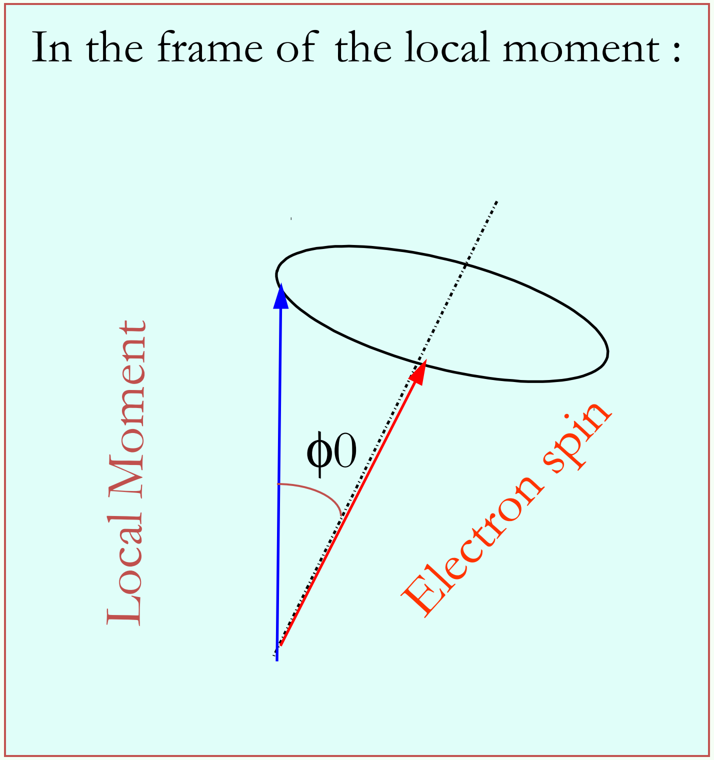
Spin evolution during DW crossing



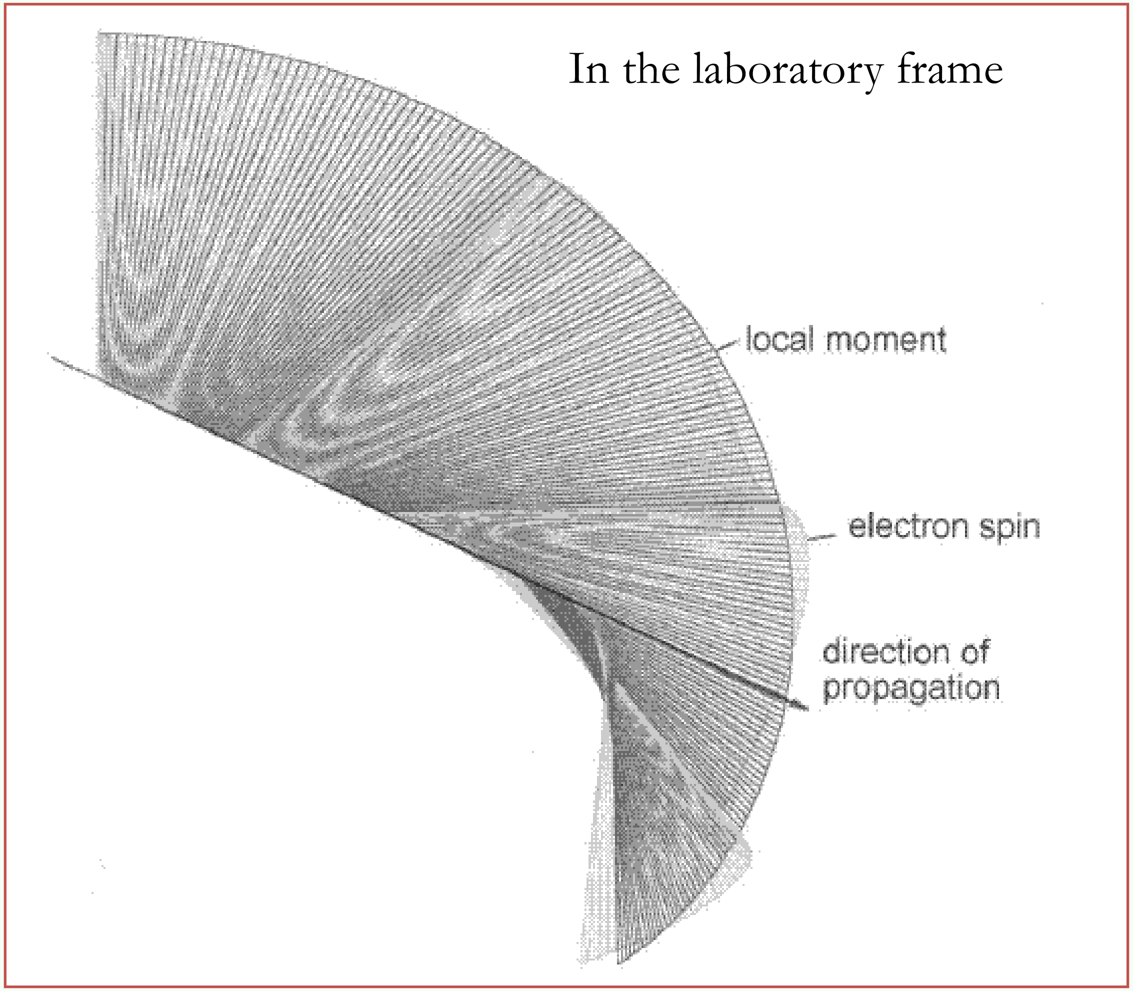


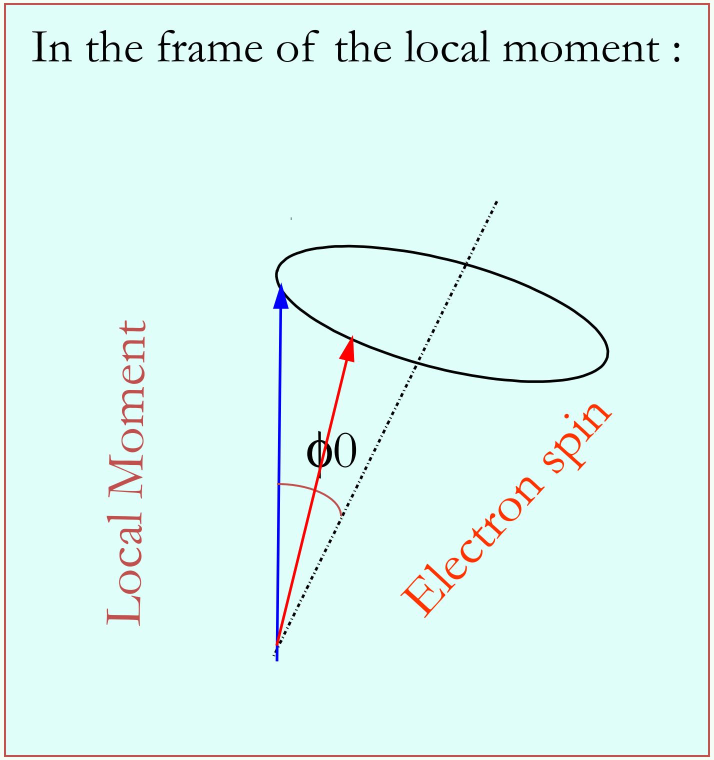
Spin evolution during DW crossing



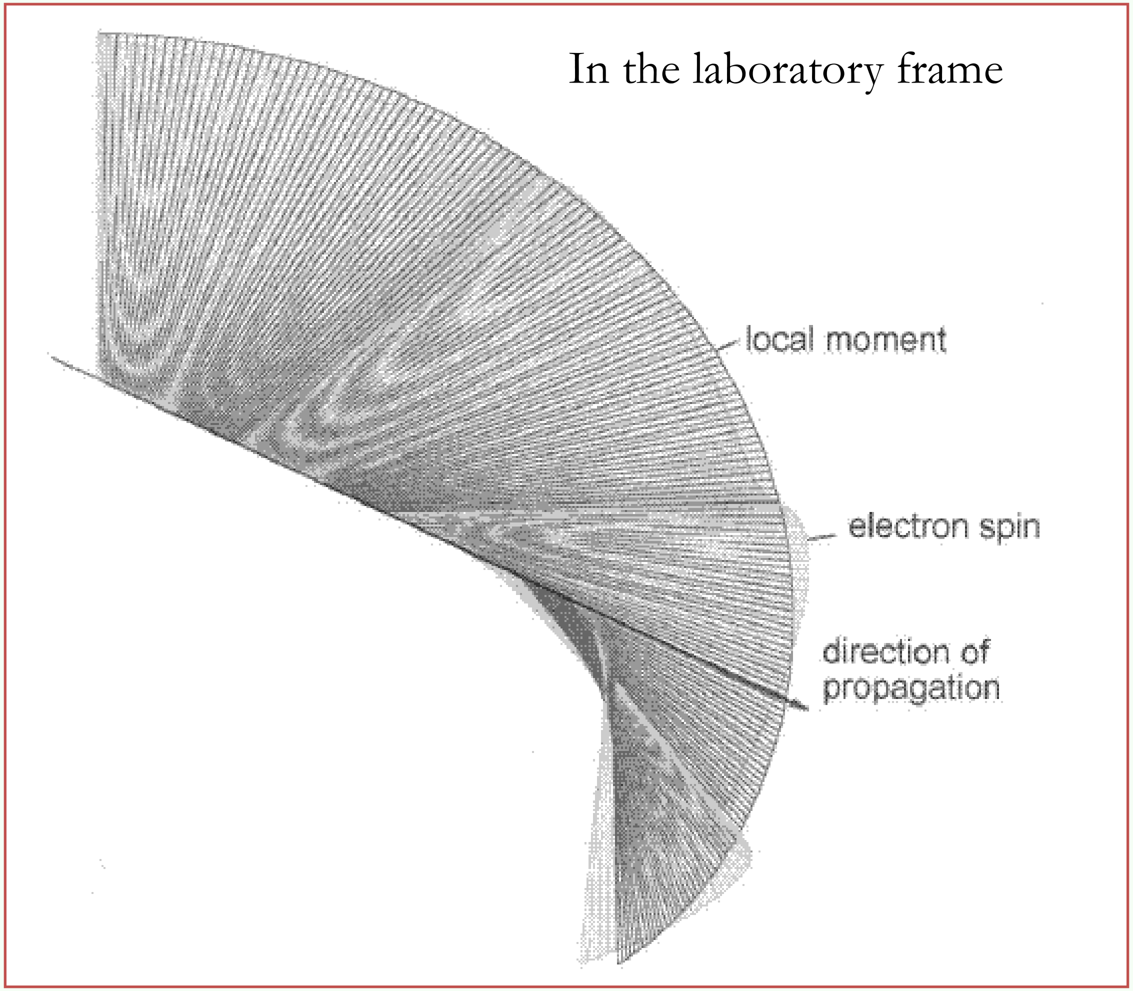


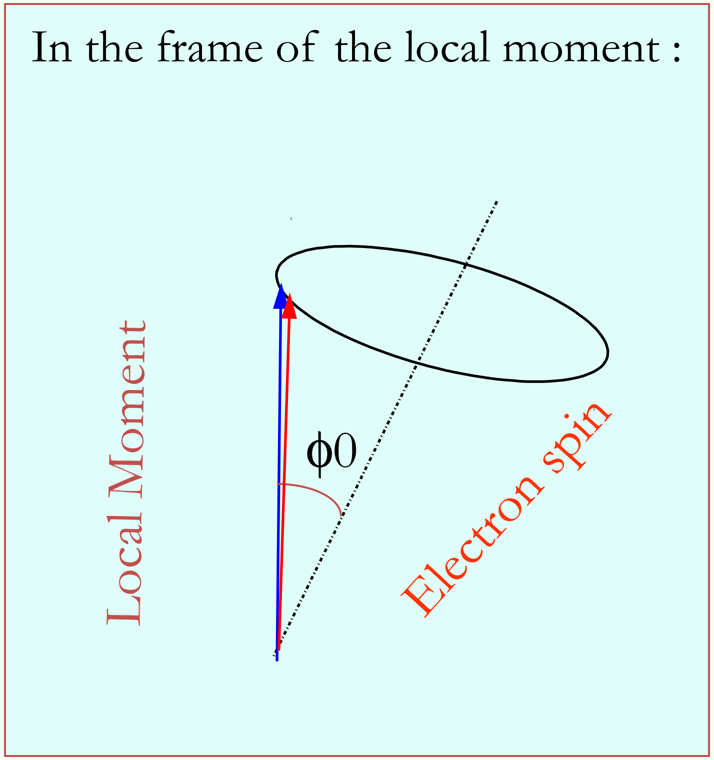
Spin evolution during DW crossing





Spin evolution during DW crossing



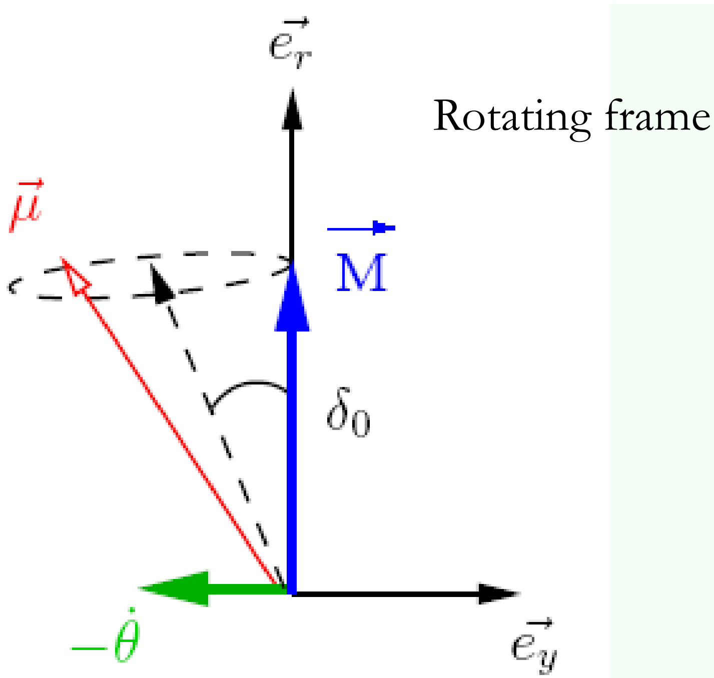


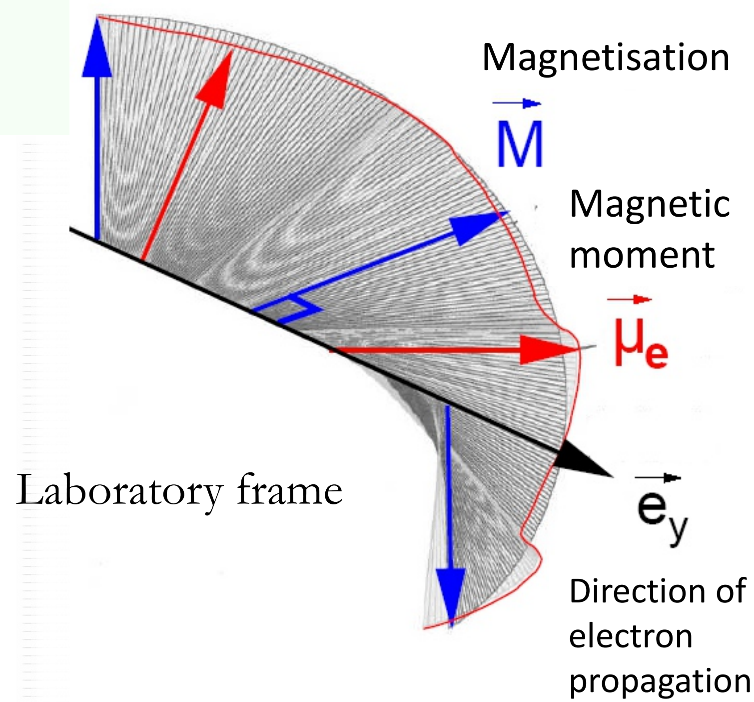
For a long wall and $\ddot{\theta} = 0$

$$\begin{aligned} \ddot{\mu_\theta} + \frac{1}{\tau_{ex}^2}\mu_\theta &= 0 \\ \ddot{\mu_y} + \frac{1}{\tau_{ex}^2}\mu_y &= -\frac{\dot{\theta}}{\tau_{ex}}\frac{g\mu_B}{2} \end{aligned}$$

Precession around the effective field :

$$<\vec{\mu}>= \frac{g\mu_B}{2}\begin{pmatrix} 1 \\ 0 \\ -\dot{\theta}\tau_{ex} \end{pmatrix}$$





→ The mistracking angle is small (a few degrees) and the induced spin scattering is weak

The total moment is conserved $\rightarrow$

$$\frac{\delta \vec{M}}{\delta t} = \frac{1}{\tau_{ex}} \vec{\mu} \times \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

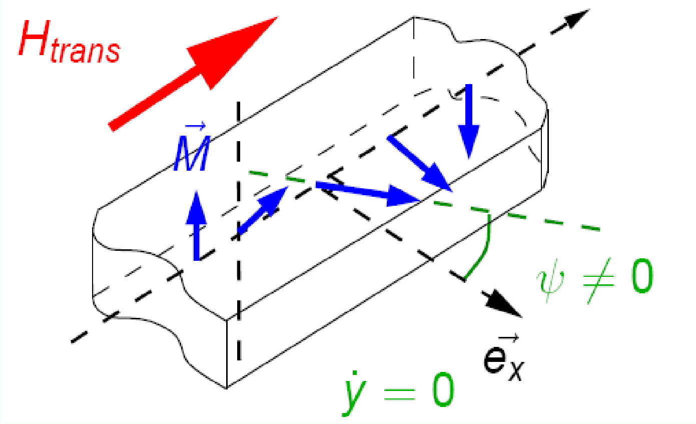
The torque can be decomposed into a constant and periodic part

For long walls, the periodic part averages to zero and the constant part reads:

$$\left.\frac{\delta \vec{M}}{\delta t}\right|_{st} = \frac{1}{\tau_{ex}} \begin{pmatrix} \frac{g\mu_B}{2} \\ 0 \\ < \mu_y > \end{pmatrix} \times \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = -\frac{g\mu_B}{2} \dot{\theta} \vec{e_\theta}$$

This is in the wrong direction for pushing the wall (in steady state). But it distorts the DW.

Equivalent to a transverse field $\rightarrow$



Spin-flip terms included in Landau-Lifshitz →

$$\frac{d\vec{\mu}}{dt} = -\frac{1}{\tau_{ex}}\vec{m}\times\vec{\mu} - \frac{1}{\tau_{sf}}(\vec{\mu}-\vec{\mu}_{eq})$$

with $\vec{\mu}_{eq} = g\mu_B/2\vec{e}_r$

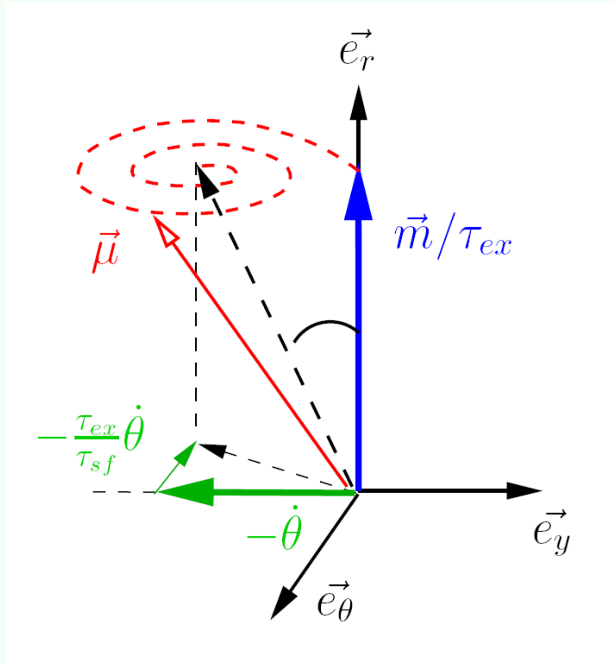
→

$$\ddot{\mu_\theta} + \frac{2}{\tau_{sf}}\dot{\mu_\theta} + \frac{1}{\tau_{ex}^2}\mu_\theta = -\frac{\dot{\theta}}{\tau_{sf}}\frac{g\mu_B}{2}$$

$$\ddot{\mu_y} + \frac{2}{\tau_{sf}}\dot{\mu_y} + \frac{1}{\tau_{ex}^2}\mu_y = -\frac{\dot{\theta}}{\tau_{ex}}\frac{g\mu_B}{2}$$

→ Precession around a tilted effective field:

$$<\vec{\mu}> = \frac{g\mu_B}{2}\begin{pmatrix}1\\ -\dot{\theta}\tau_{sf}\\ -\dot{\theta}\tau_{ex}\end{pmatrix}$$



Reaction on the wall

Effect of the current : Globally, the conduction electrons transfer $g\mu B$ to the DW
→ **Spin torque**

The total moment is conserved →

$$\frac{\delta \vec{M}}{\delta t} = \frac{1}{\tau_{ex}} \vec{\mu} \times \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

The torque can be decomposed into a constant and periodic part
For long walls, the periodic part averages to zero and the constant part reads:

$$\left.\frac{d\vec{M}}{dt}\right|_{st} = \frac{jP}{e} \frac{g\mu_B}{2} \frac{\partial \vec{m}}{\partial y}$$

← distortion (steady state)

$$\left.\frac{d\vec{M}}{dt}\right|_{sf} = \frac{jP}{e} \frac{g\mu_B}{2} \frac{\tau_{ex}}{\tau_{sf}} \left(\vec{m} \times \frac{\partial \vec{m}}{\partial y} \right)$$

← pressure

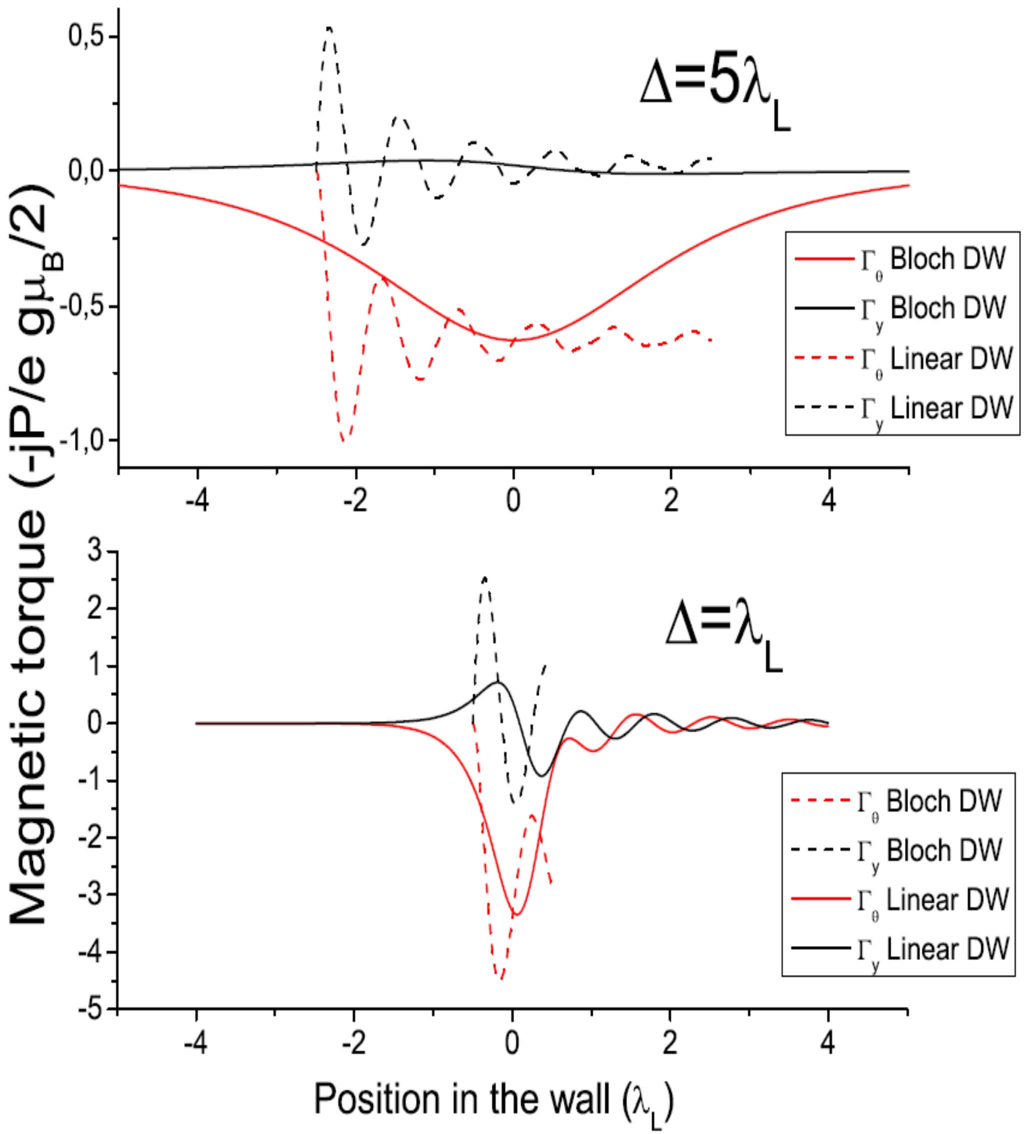
P = polarisation,
j = current density

Conclusions :

- Torques: non-homogeneous within the walls + small 'pressure' term
- Importance of the magnetic structure of the DW
- Very thin DWs: Enhanced pressure oscillating with thickness

'Not so thick walls': numerical simulations

Torques within the wall : (red: distortion, black: pressure)

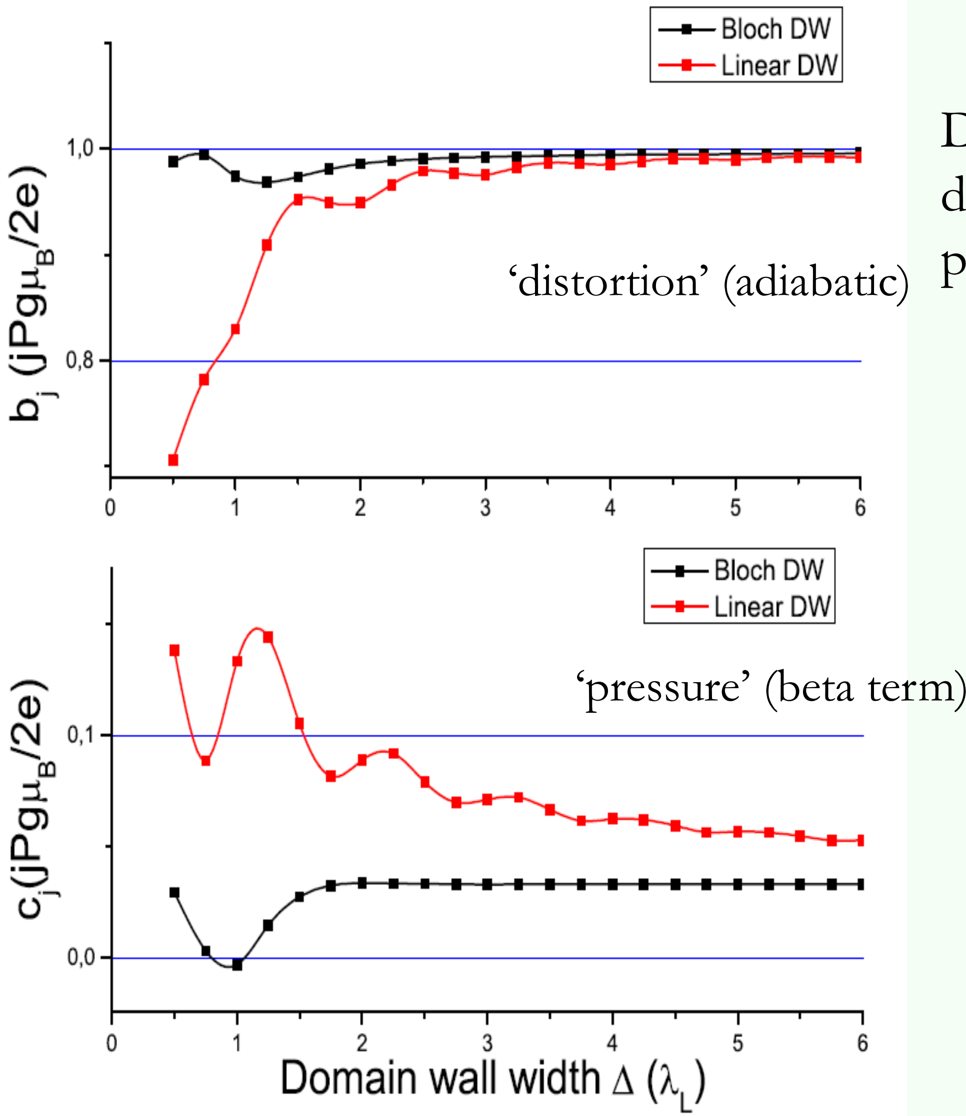


Influenced by the shape and width of the DW…

<u>Bloch wall</u>: smooth boundary conditions prevent the spin precession of conduction electrons

'Not so thick walls': numerical simulations

Averaged torques on the wall width :

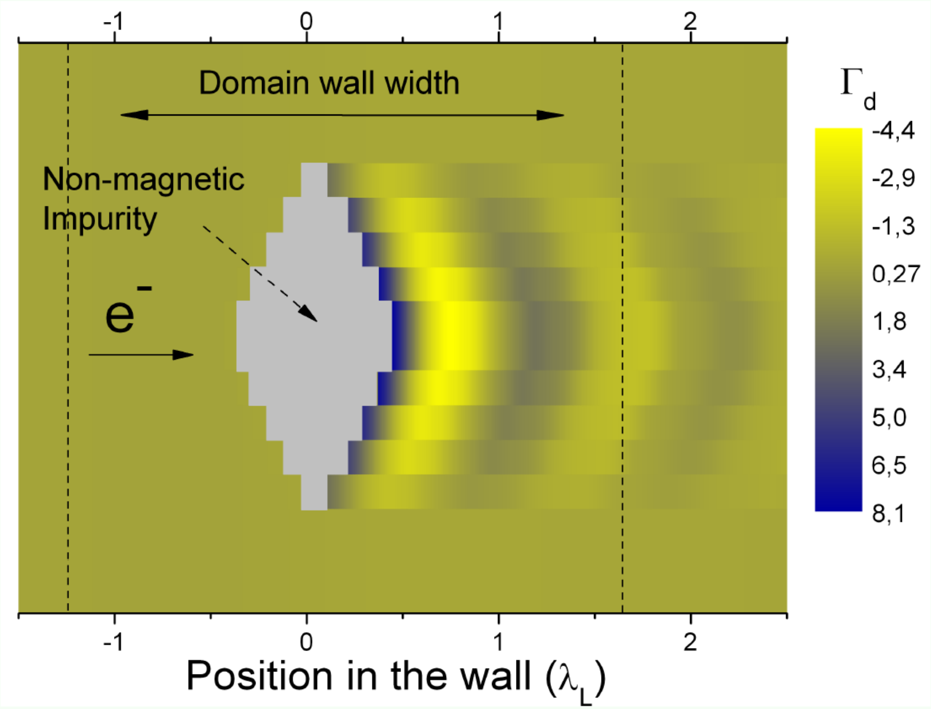


Differences for linear and Bloch walls due to the suppression of spin precession in Bloch walls.

Remark: constrained narrow DWs are likely to be linear walls (N. Kazantseva, R. Wieser, and U. Nowak, PRL94, 037206 (2005))

Real systems?

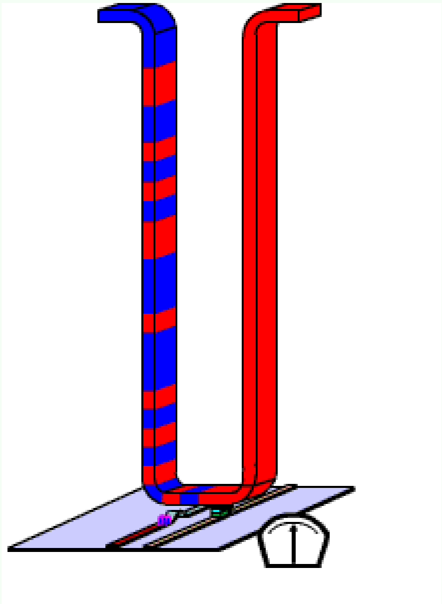
Non magnetic impurity pinning a Bloch DW:

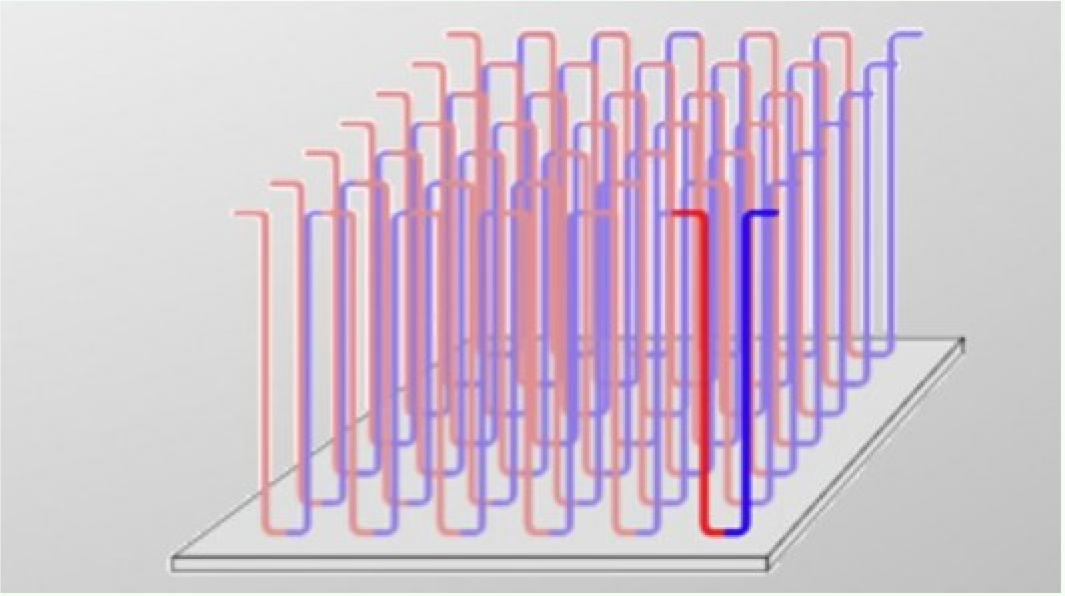


Spatially varying torques are very large near the impurity → de-pinning ?

Potential applications

Racetrack memory (IBM)





Spin transfer in insulators

Idea:

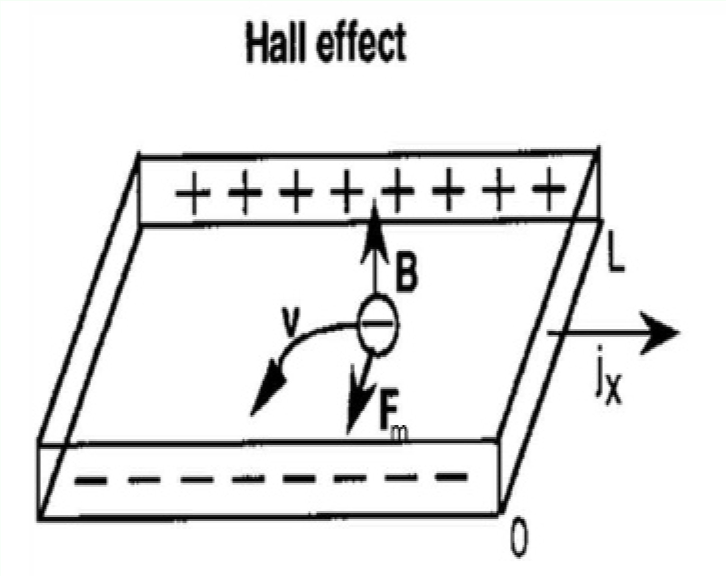
spin transfer does not have to be associated to a current!!

How can we generate pure spin currents?

Spin currents in normal metals

Normal Hall effect:

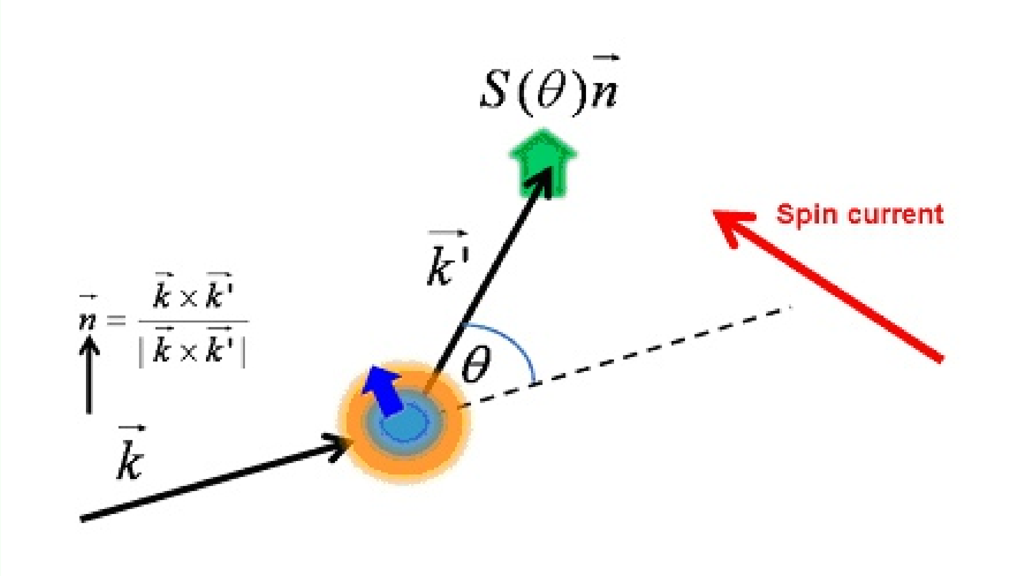
B affects electrons' trajectories because of Lorentz force



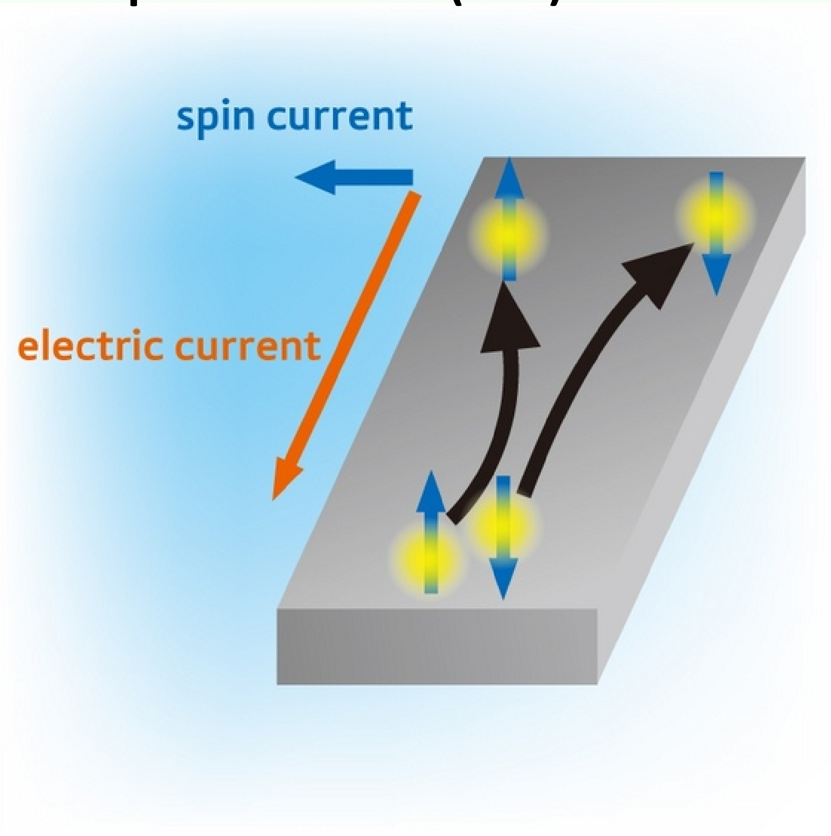
= Transverse charge current
$\rightarrow$ Charge accumulation
$\rightarrow$ Transverse potential difference

Spin currents in normal metals

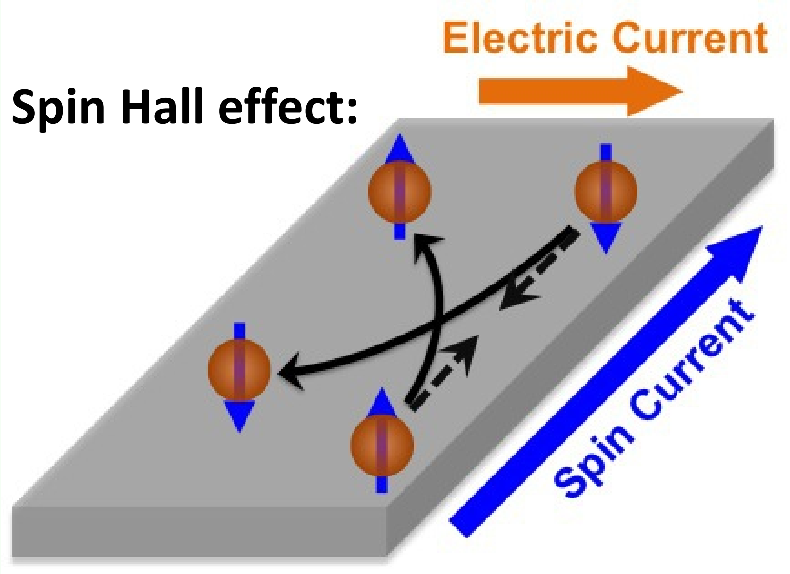
Spin orbit (skew) scattering:



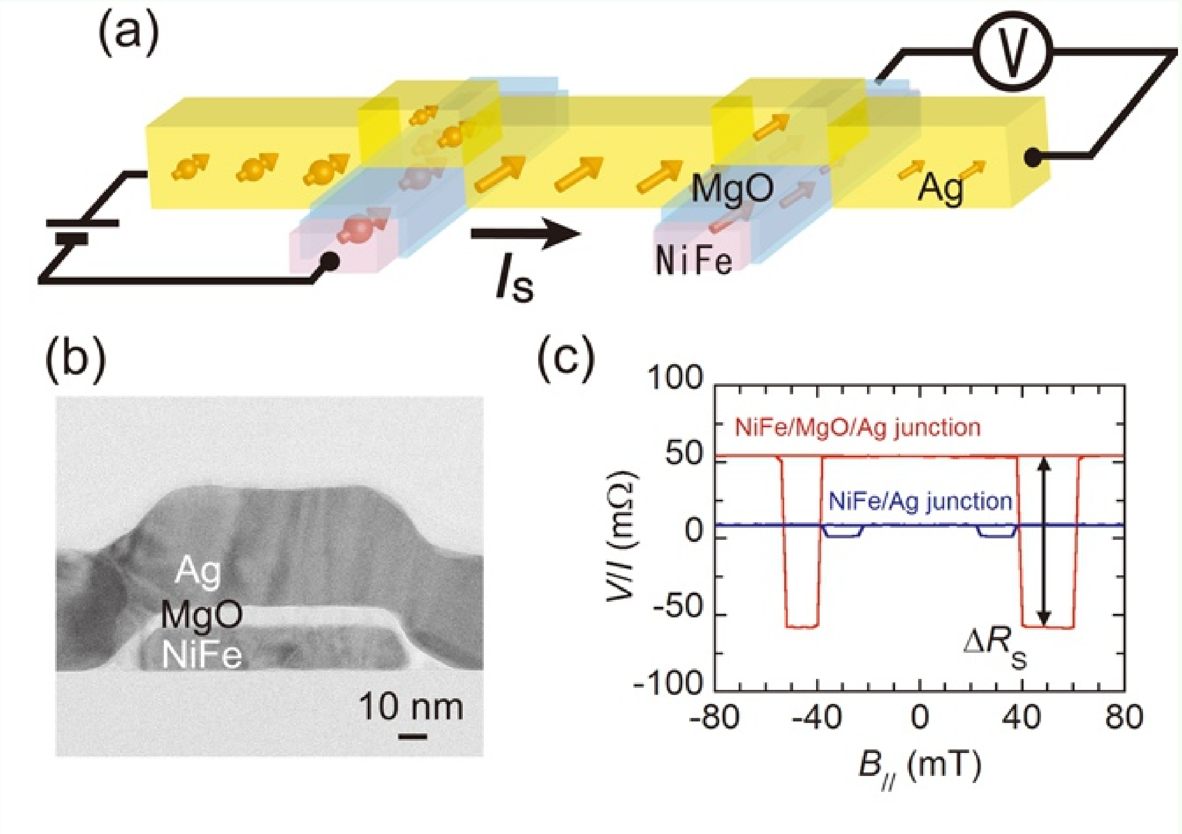
Spin Hall effect (B=0):



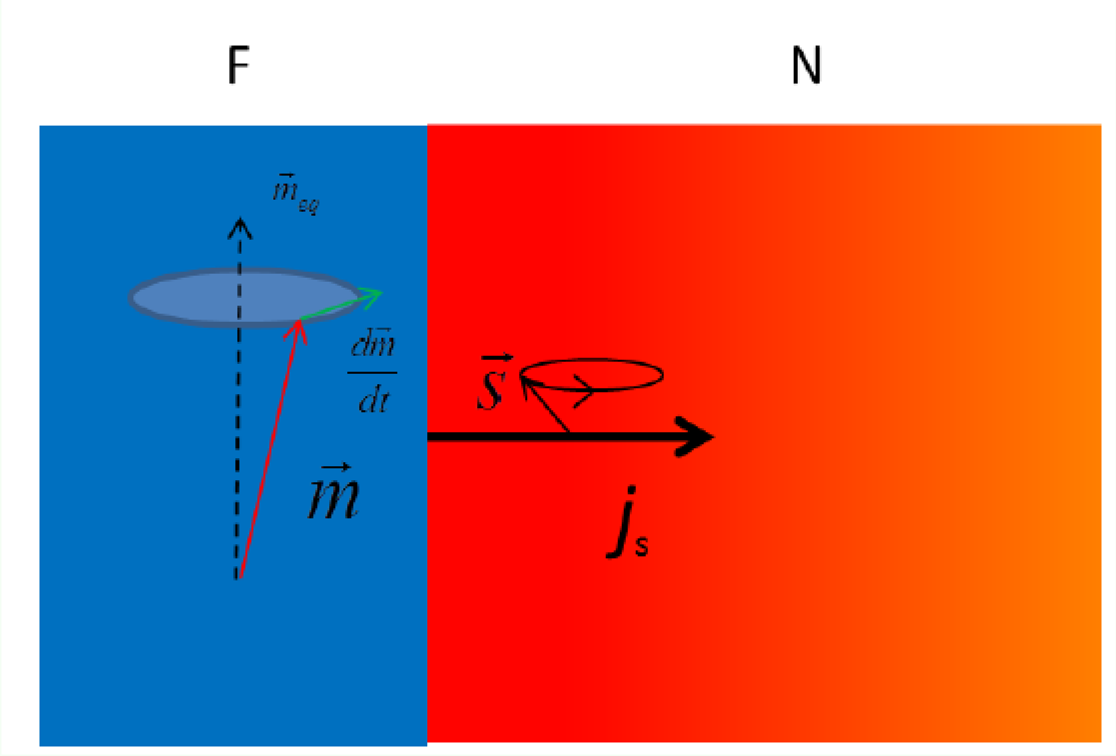
Inverse Spin Hall effect:



Non local generation of spin currents



Spin pumping by a dynamical magnetization



Spin current emitted from FMR:

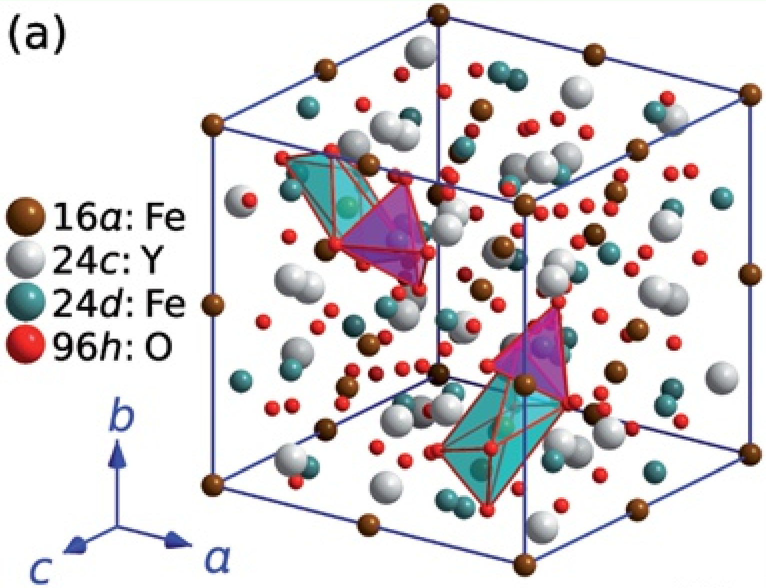
$$j_s^0\vec{s} = \frac{\hbar}{4\pi}g^{\uparrow\downarrow}\vec{m}\wedge\frac{d\vec{m}}{dt}$$

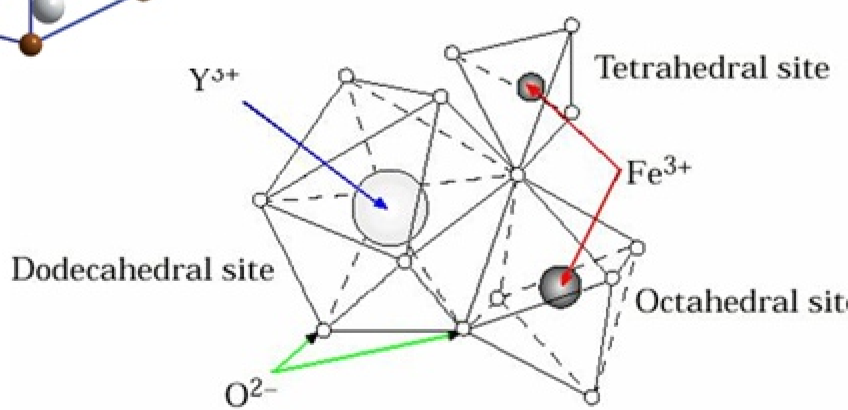
Conversion into a charge current by ISHE:

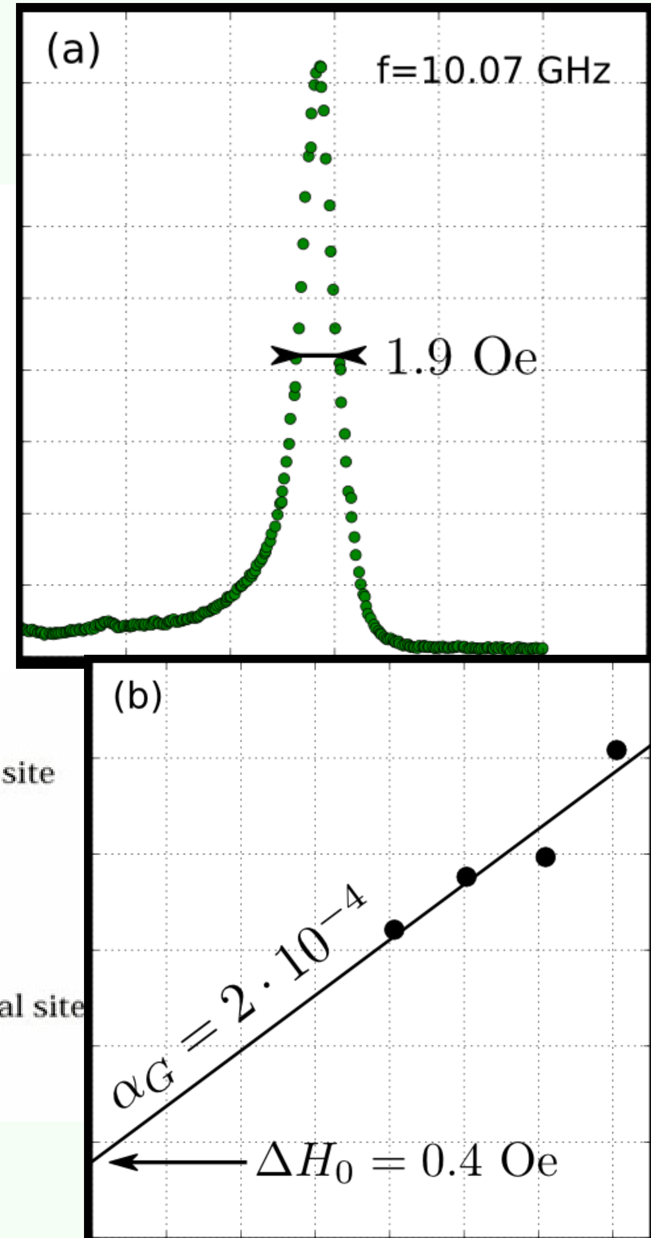
$$\vec{j}_c^{ISHE}(z) = \gamma(2e/\hbar)j_s^{eff}[\vec{n}\otimes\vec{s}]$$

Works also for ferromagnetic insulators!!

YIG, THE ferrimagnet for FMR

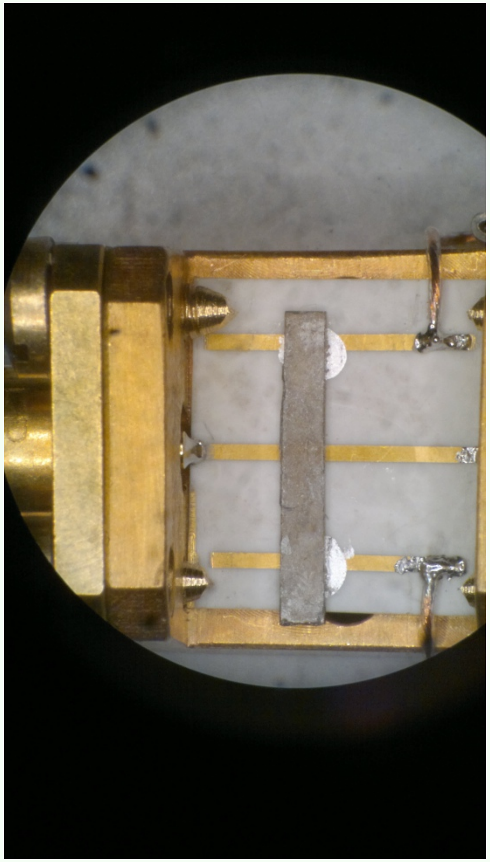






Measurement setup

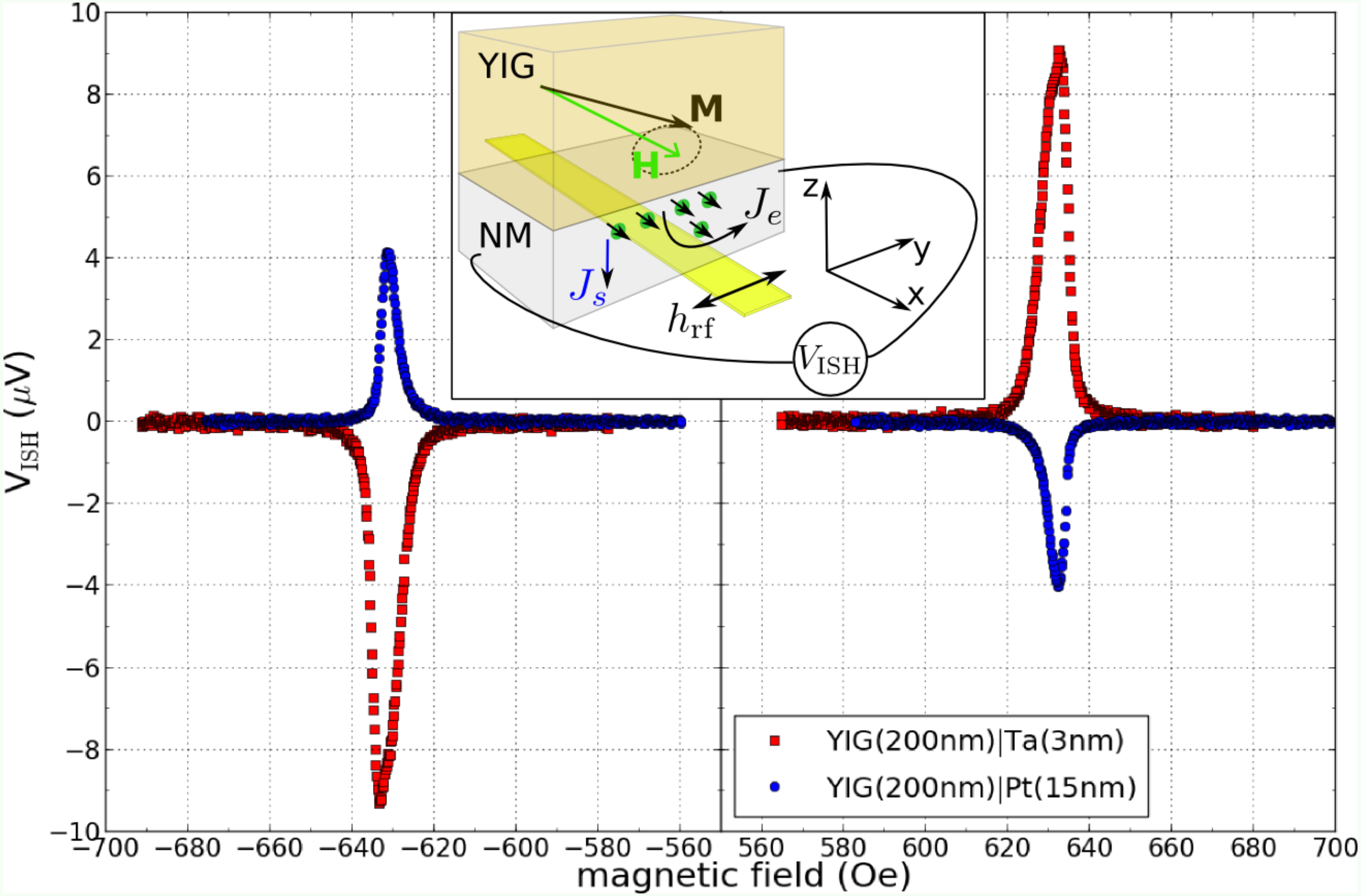
Broadband antena + ‘DC’ contacts
Can go down to 77K



Samples: bilayers FM/NM

Measurements by Christian Hahn + Gregoire de Loubens

Probing spin currents during ferromagnetic resonance in insulating YIG



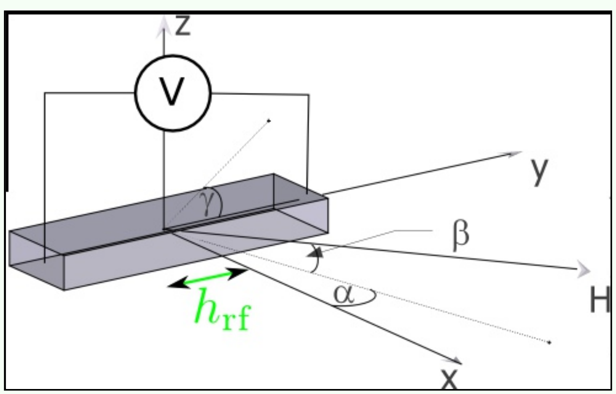
Spin Hall Magnetoresistance

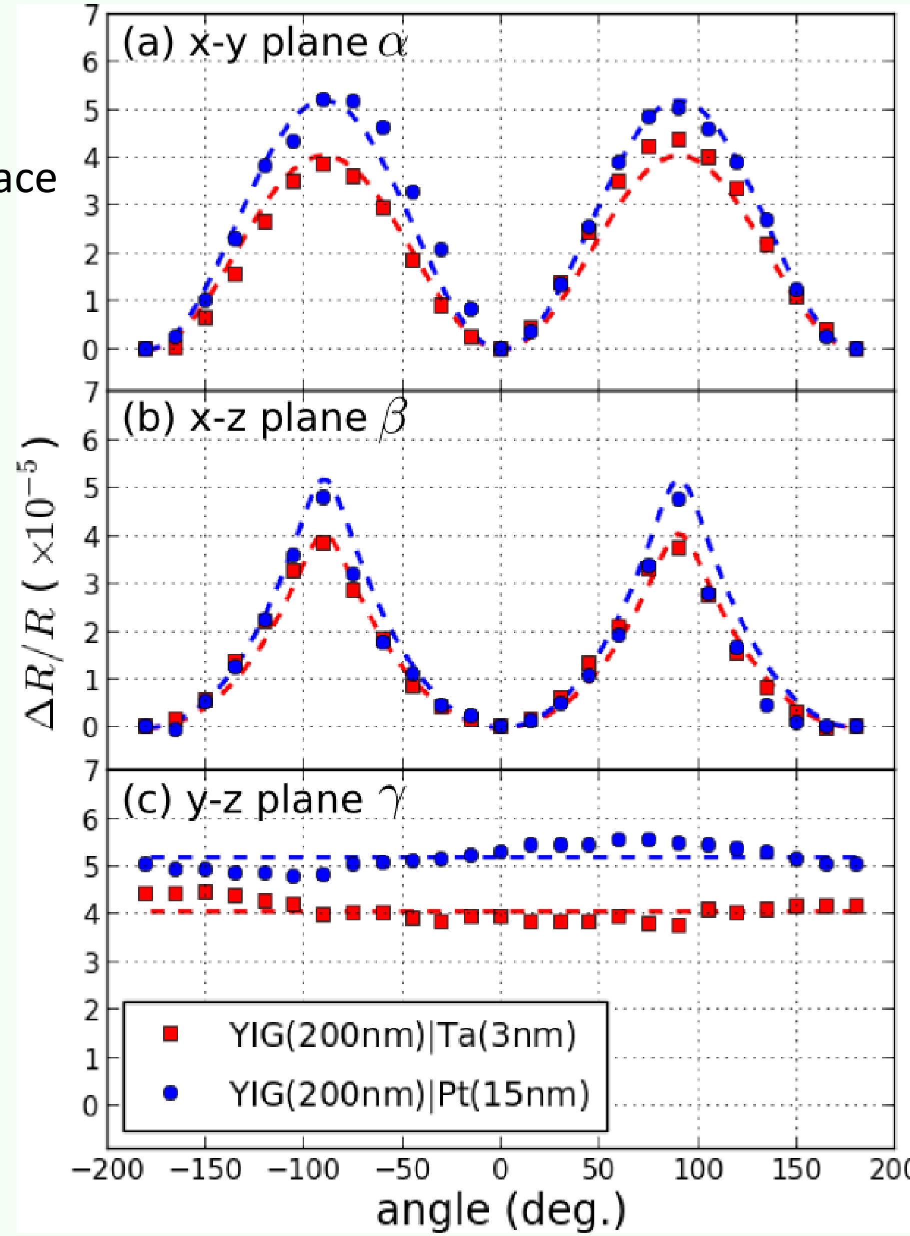
Mechanism:
SHE spin polarizes at the interface
Backscattered spins flipped at the FM interface deflected by ISHE oppose the initial
$\rightarrow$ R increases

$$R = R_0 + \Delta R_{\max} \sin^2(M, s)$$

M=ferromagnet mag., s=spin accumulation

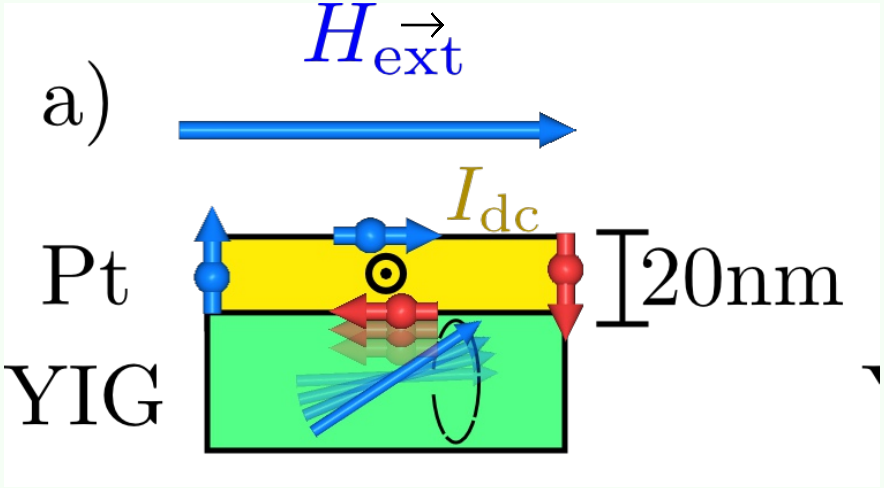
Rq: not the same symmetry as AMR because s is transverse…





Aim to integrate isolators: making a resonator with YIG

Goal:
spin Hall effect induced ferromagnetic resonance
with compensated damping!
Has it really been done?...



Conclusions / perspectives

- Spin transfer torque has led to the invention of new devices based on switching + oscillators

- Correlation transport/dynamics allows to imagine new devices including delay lines, agile GHz sources…

- Insulators are now a potentially important part of spintronics!