Spin transfer torque and thermally assisted FMR in magnetic tunnel junctions

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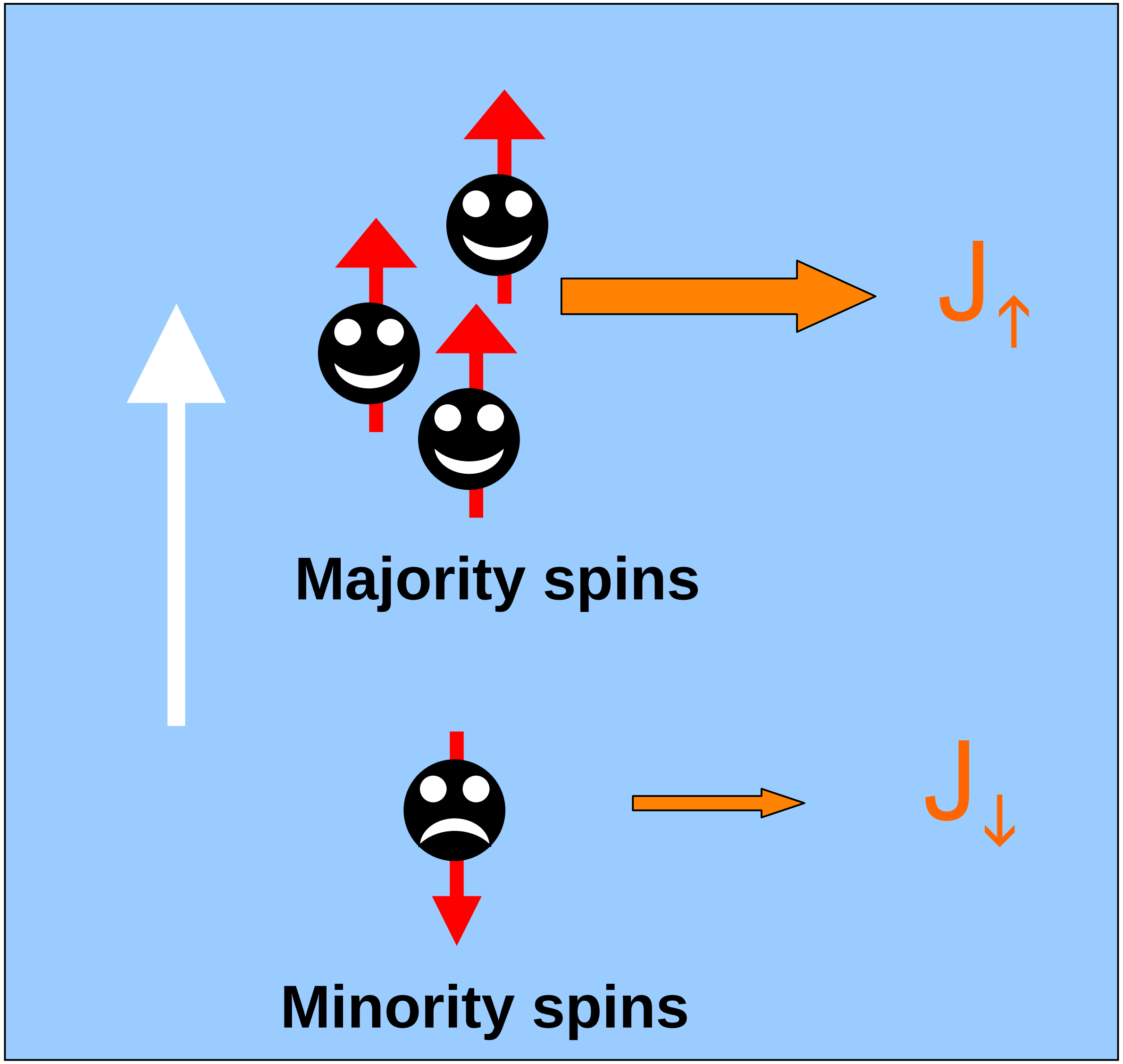
- Introduction to spin transfer torque (STT)
  - longitudinal (in-plane) torque
  - transverse (out-of-plane) torque
  - phase diagram
- Influence of STT on magnetic fluctuations
  - Model
  - Experimental result

Spin polarized current



Charge current

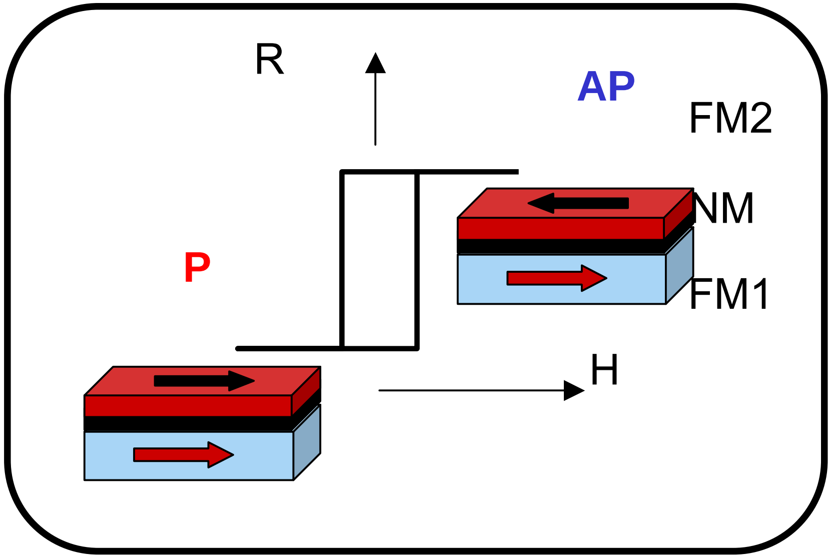
$$J = e\,(J_\uparrow + J_\downarrow)$$

Spin current

$$J_p = J_\uparrow - J_\downarrow$$

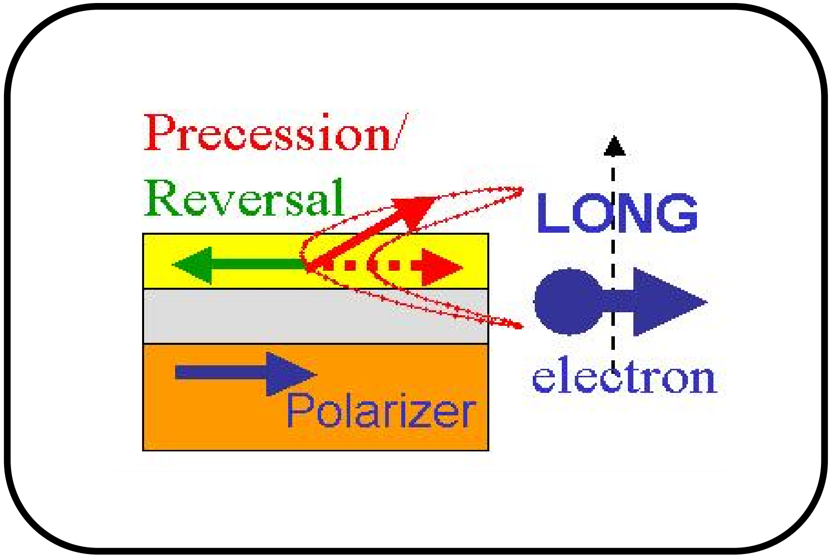
Interaction magnetization-current

Spin filtering



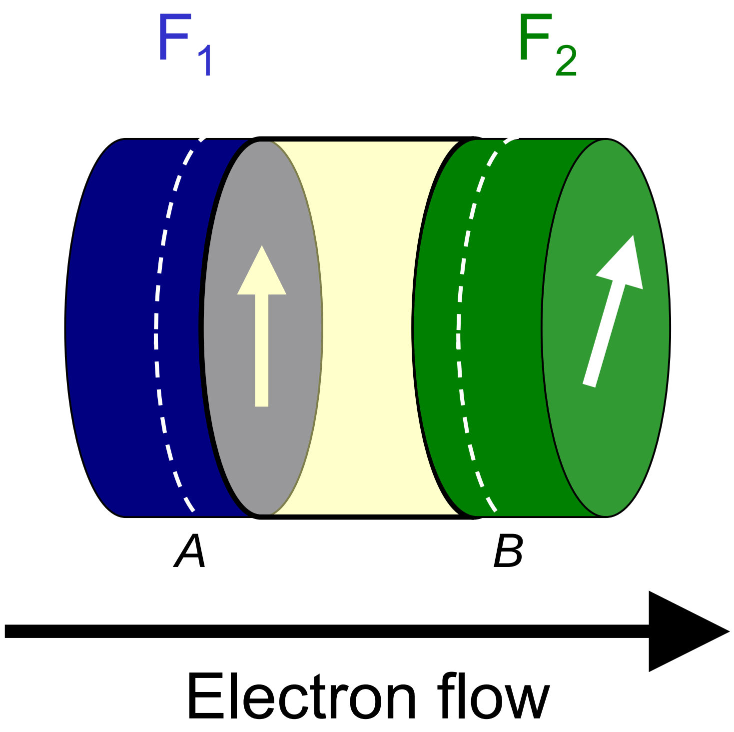
Magnetization controls current

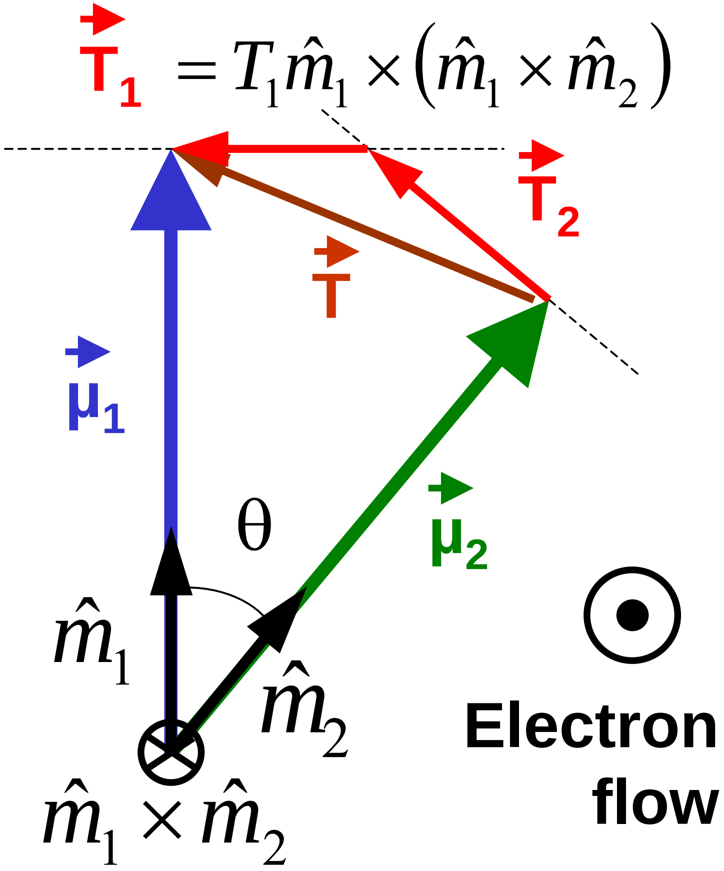
Spin transfer torque



Current controls magnetization

Longitudinal (in-plane) spin transfer torque





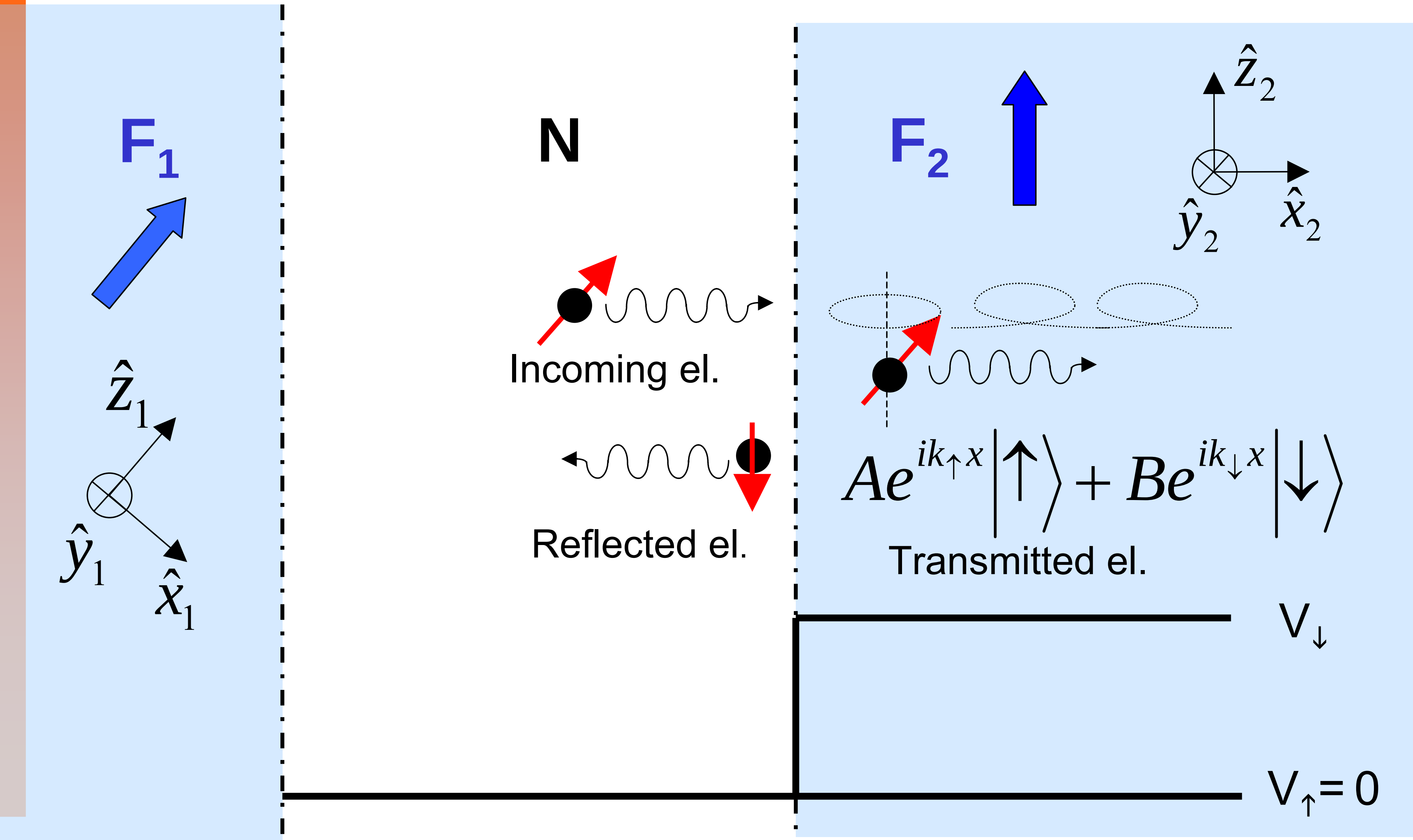
$$\vec{T}_1 = T_1 \hat{m}_1 \times \left(\hat{m}_1 \times \hat{m}_2\right)$$

Conservation of length

$$\frac{dM^2}{dt} = 2\vec{M}\cdot\frac{d\vec{M}}{dt} = 0$$

$$\boxed{\vec{T}_{//} = \gamma_0 \frac{a_j}{M_s} \vec{M}\times\left(\vec{M}\times\vec{p}\right)}$$

Microscopic picture



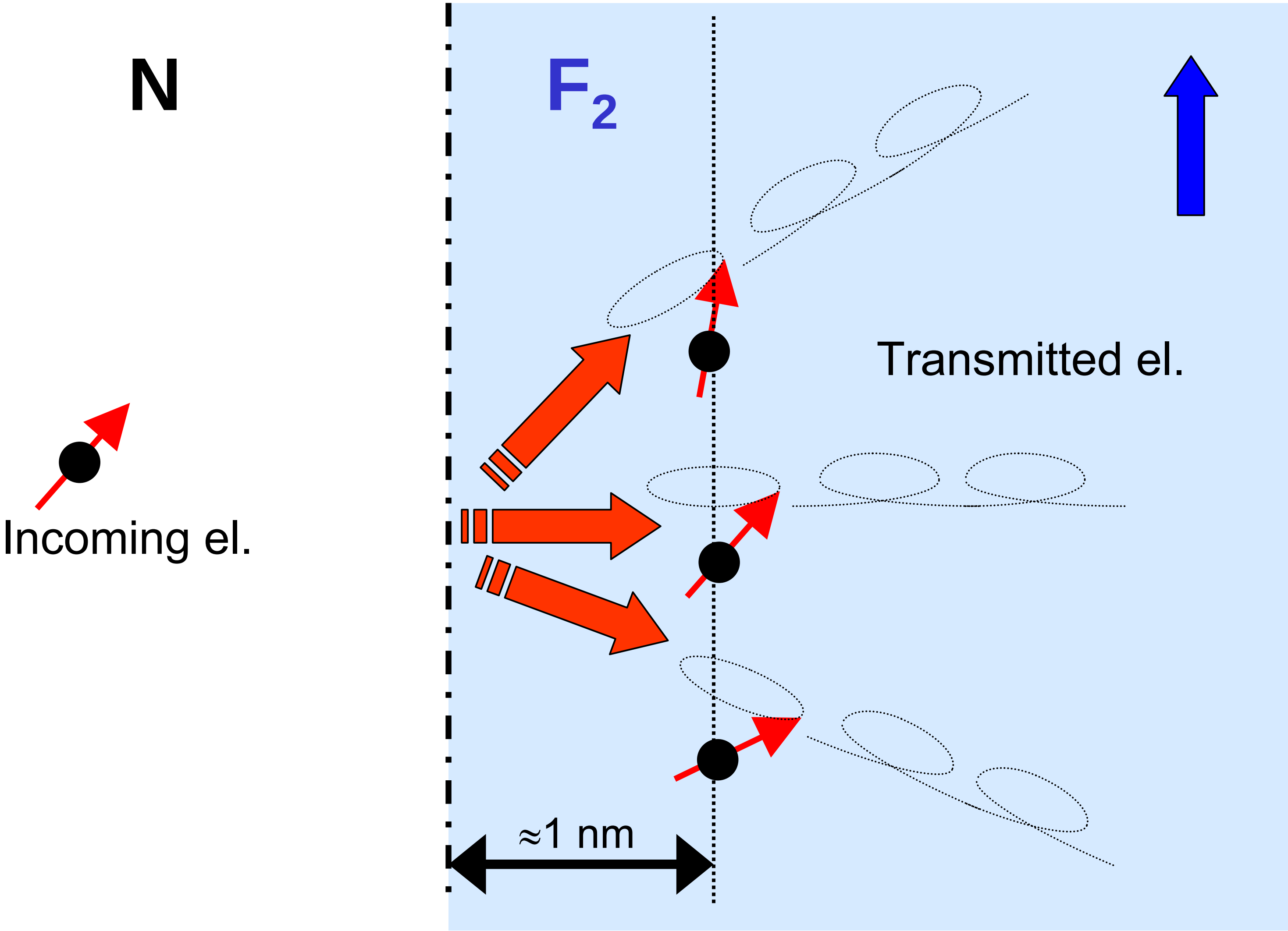
Incoming el.

Reflected el.

$$Ae^{ik_\uparrow x}\left|\uparrow\right\rangle + Be^{ik_\downarrow x}\left|\downarrow\right\rangle$$

Transmitted el.

Microscopic picture (2)



Classical dephasing → transverse component is transferred

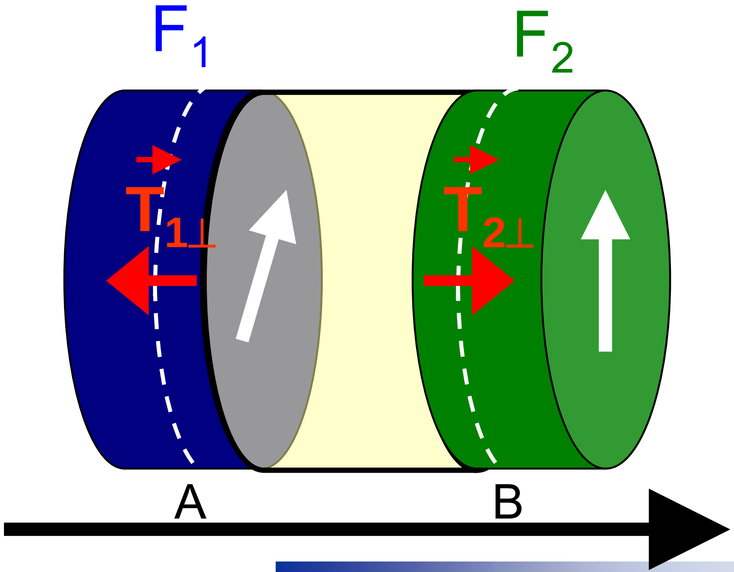
Transverse (out of plane) torque

Inter-layer coupling energy $E = J_{ex} \vec{M}_1 \cdot \vec{M}_2$

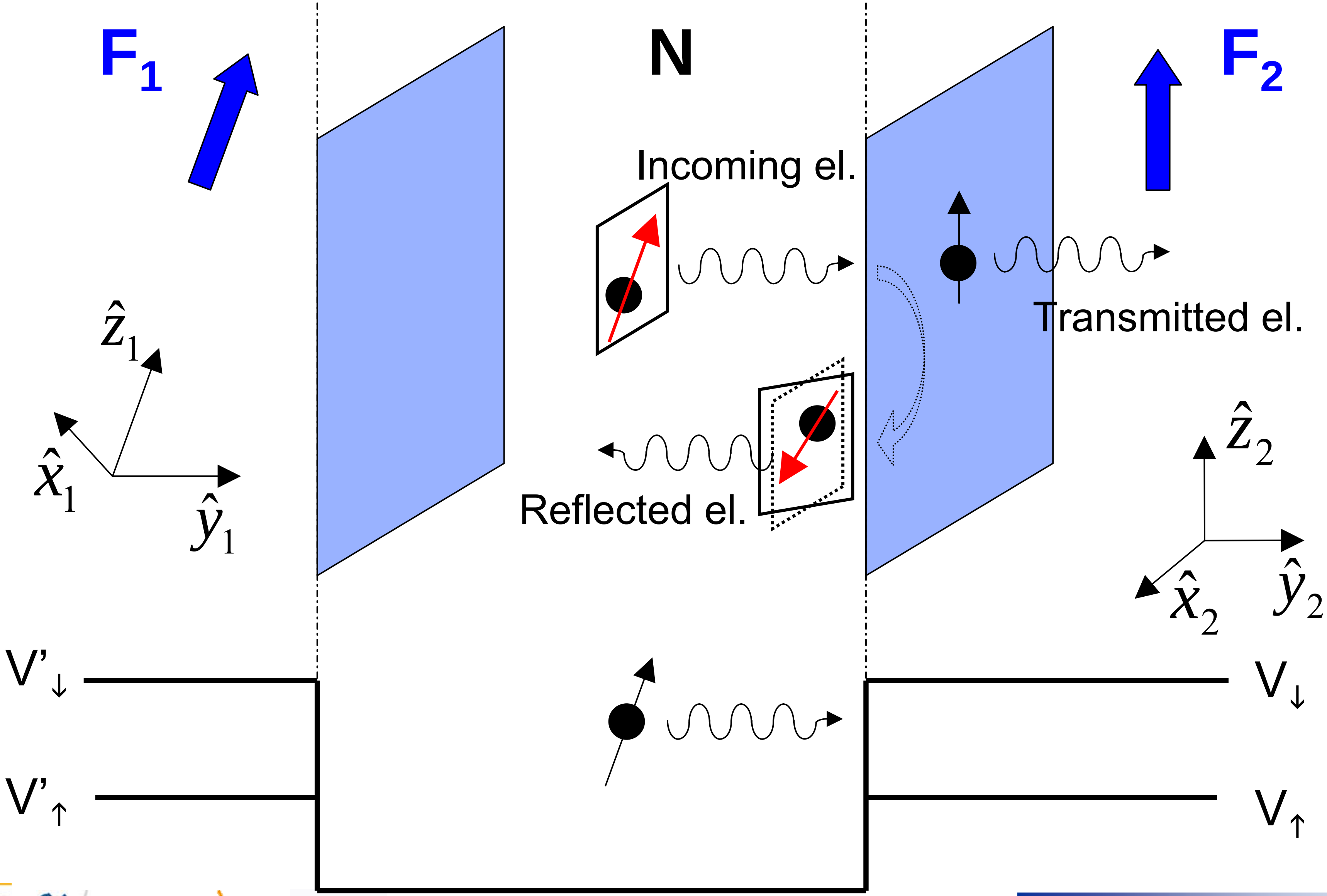
Equivalent to a **field** in the direction of the magnetization of the other layer $\vec{H}_1 = -\partial E / \partial \vec{M}_1 \propto \vec{M}_2$

Equivalent to a torque $\vec{T}_\perp \propto \vec{M}_1 \times \vec{M}_2$

$$\boxed{\vec{T}_\perp = \gamma_0 b_j \vec{M} \times \vec{p}}$$



Microscopic picture



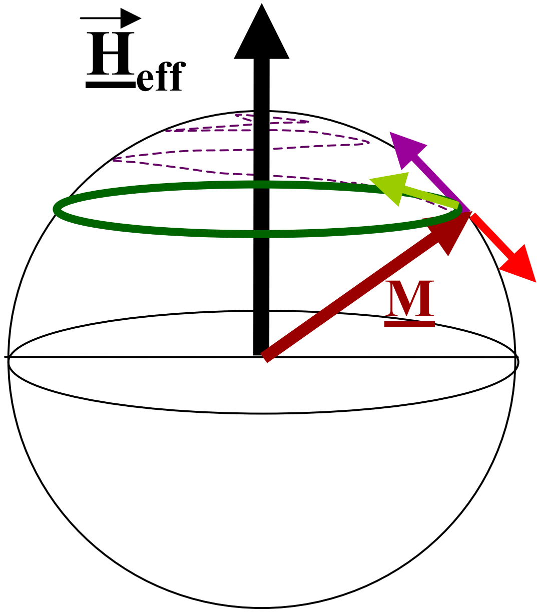
Magnetization dynamics

$$\frac{d\vec{M}}{dt} = -\gamma_0 \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{\mathrm{M_s}} \vec{M} \times \frac{d\vec{M}}{dt} + \frac{\gamma_0 a_j}{\mathrm{M_s}} \vec{M} \times \left(\vec{M} \times \vec{P} \right)$$

Larmor precession

Damping (Gilbert)

Longitudinal spin torque (Slonczewski)



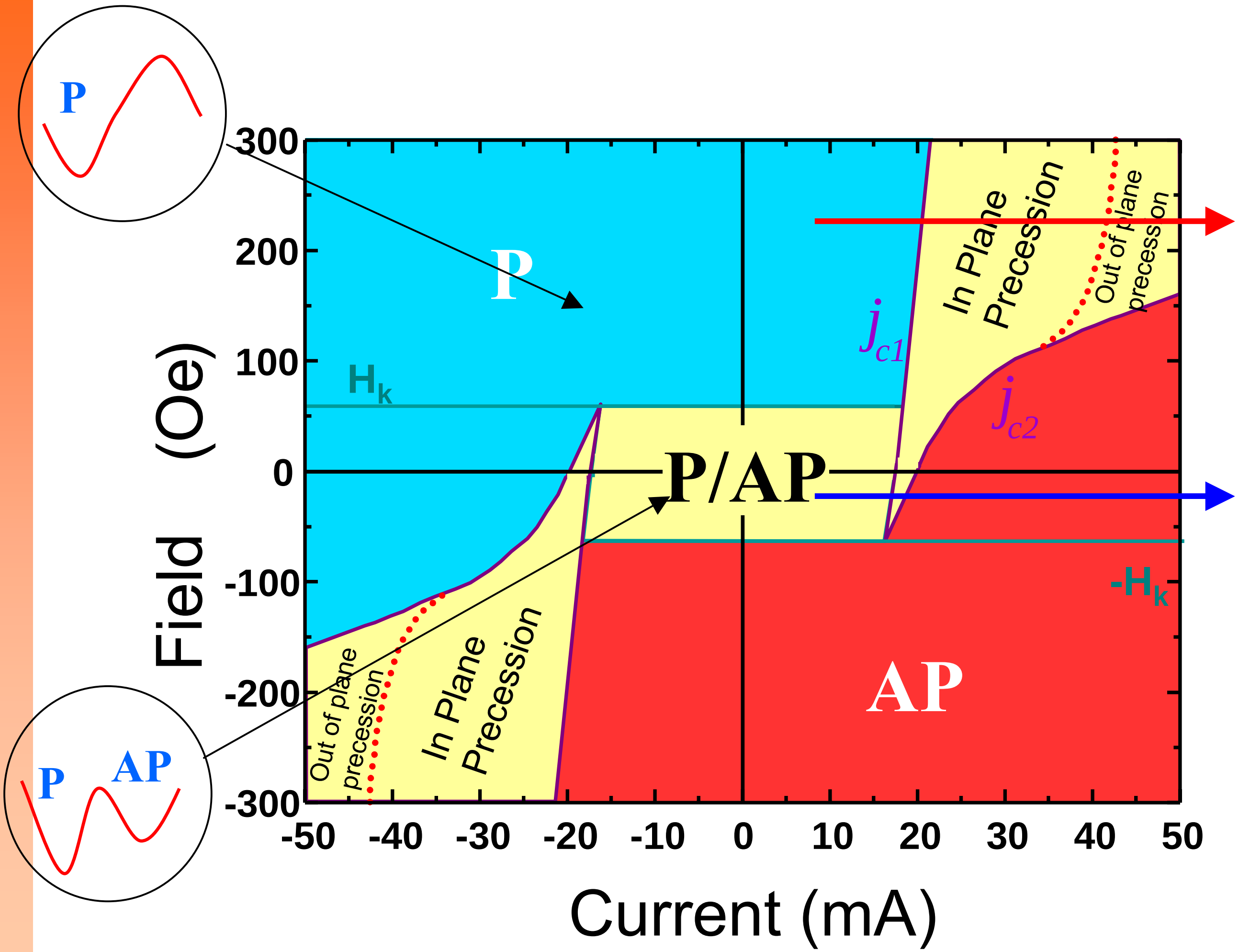
Low current → damped motion

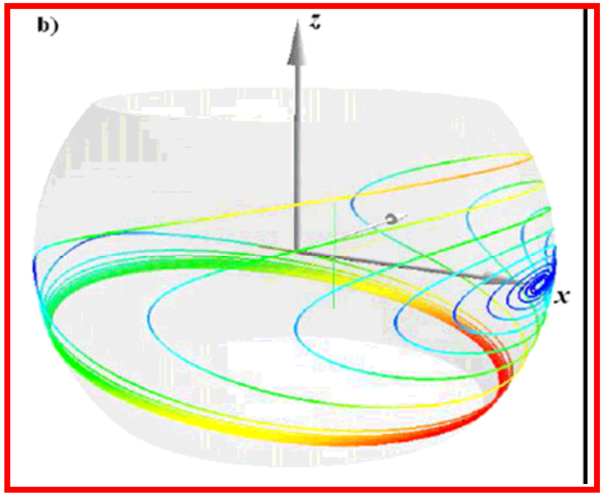
High current → precession

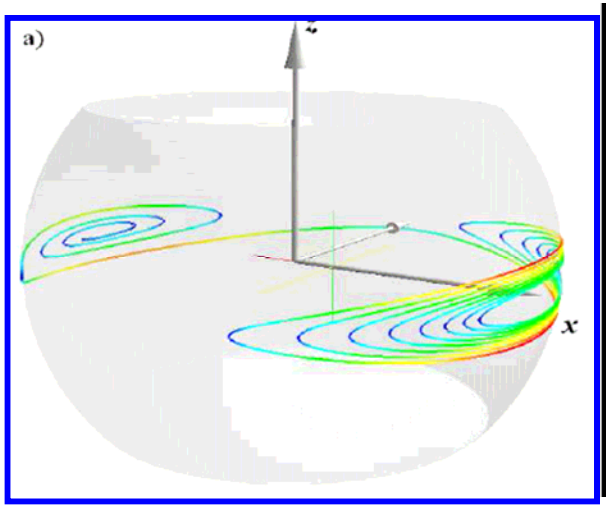
High current → switching

Ralph and Stiles, JMMM(2008)

Phase diagram







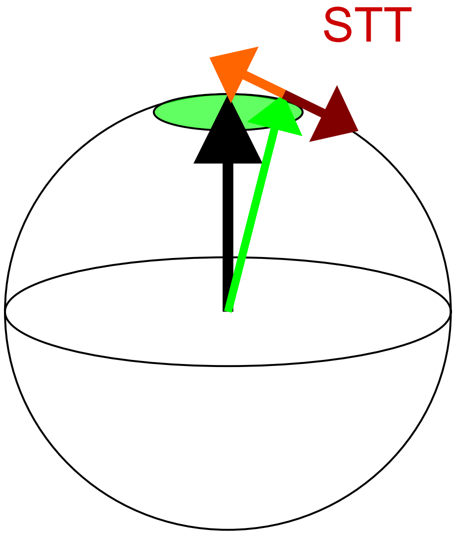
Stiles and Miltat, *Spin Dynamics in Confined Magnetic Structures III*, 225-308, (2006)

STT at equilibrium

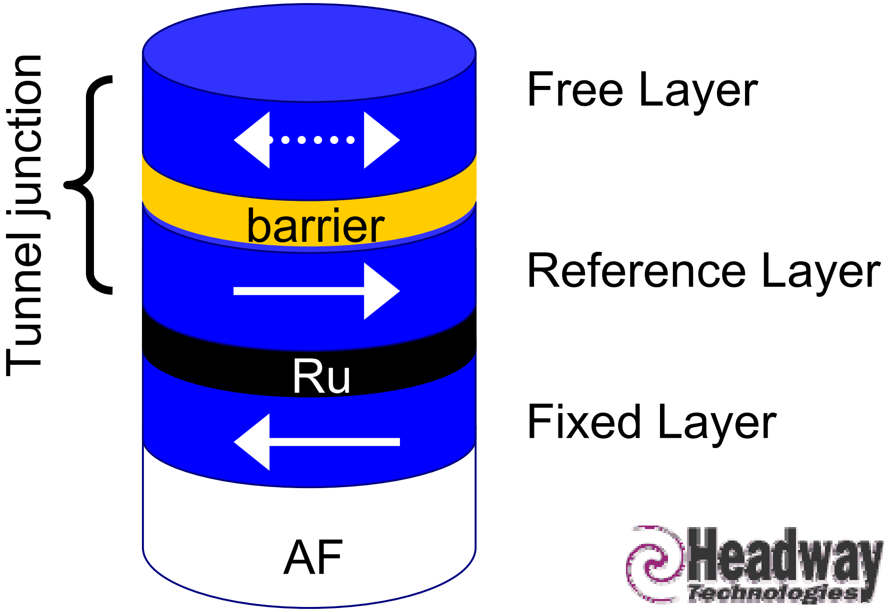
Influence of STT on mag. fluctuations

-Linear regime

-Stabilizing/Destabilizing torque

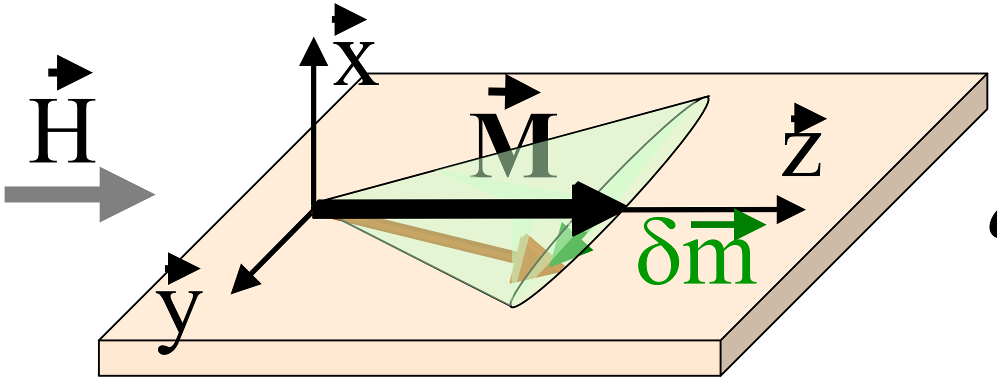


TMR Read-heads:



Ø=300 nm RA=3 Ω.µm²

Magnetization fluctuations of the free layer



$$\delta\vec{m}(\omega) = \underline{\chi}(\omega)\boxed{\delta\vec{h}_T(\omega)}$$

$$\frac{d\vec{M}}{dt} = -\gamma_0\ \vec{M}\times\left(\vec{H}_{eff} + \boxed{\delta\vec{h}_T}\right) + \frac{\alpha}{Ms}\vec{M}\times\frac{d\vec{M}}{dt}$$

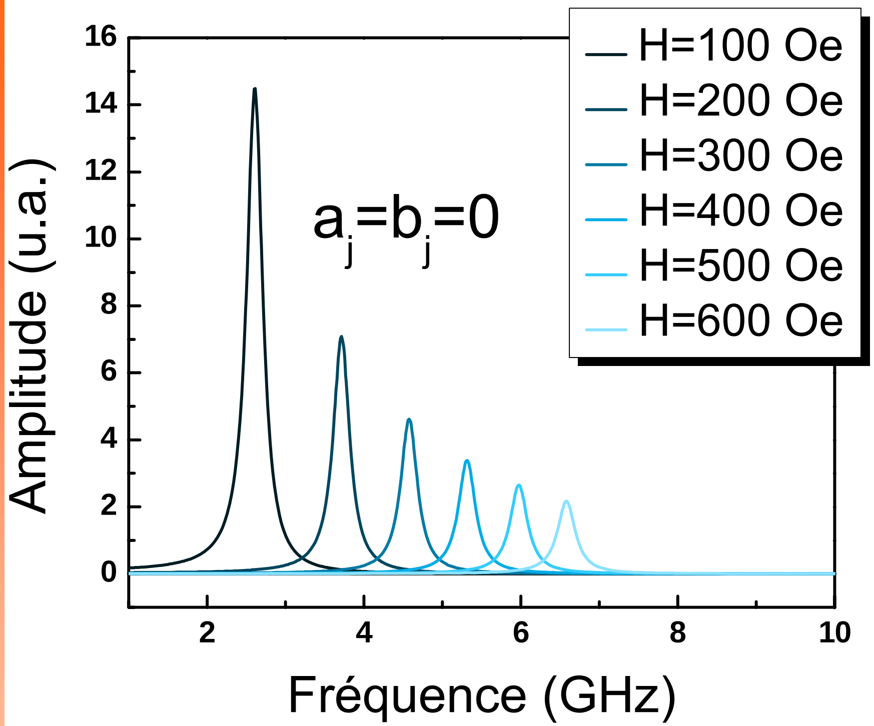
$$+\frac{\gamma_0\ a_J}{Ms}\vec{M}\times(\vec{M}\times\hat{p}) + \gamma_0\ b_J\vec{M}\times\hat{p}$$

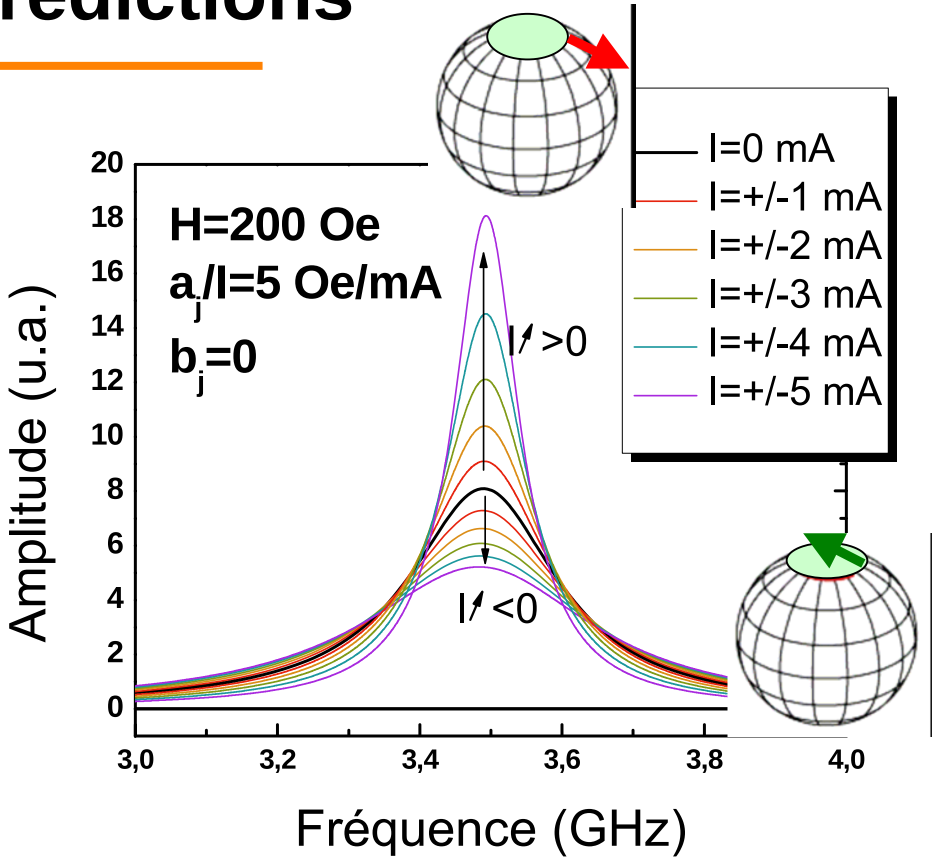
Spin torque T// **T⊥**

Fluctuation-dissipation theorem gives the magnetization Power Spectral Density (PSD) :

$$S_{M_y} = \frac{4kT}{\mu_0 V}\frac{\chi''_{yy}}{\omega}$$

Model predictions





$$\omega_0^2 \approx \gamma_0^2\left[H(4\pi Ms+H)-(4\pi Ms+2H)b_j\varepsilon\right]$$

$$\Lambda = \gamma_0\alpha(2H+4\pi M_s)-\gamma_0 2a_j\varepsilon$$

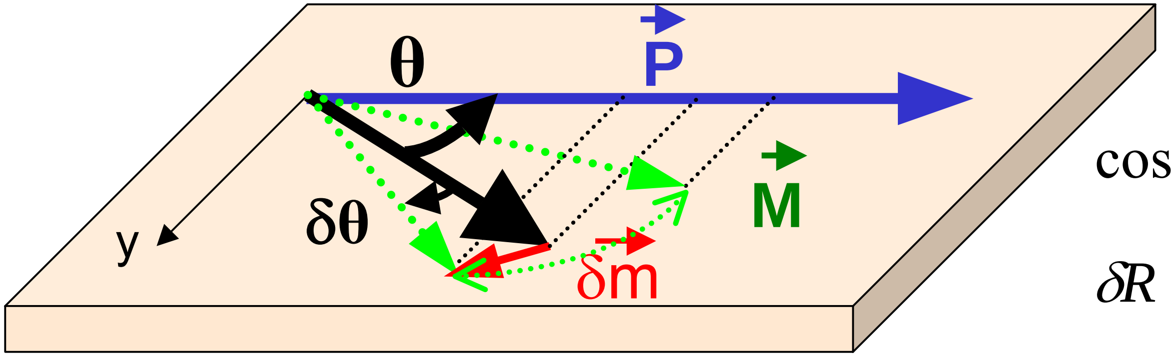
$\varepsilon = 1$ (P)

$\varepsilon = -1$ (AP)

From δm to δV

How to access experimentally to the magnetization fluctuations spectrum ?

$$\delta\vec{h}_T \longleftrightarrow \delta\vec{m} \longleftrightarrow \delta R \longleftrightarrow \delta V$$



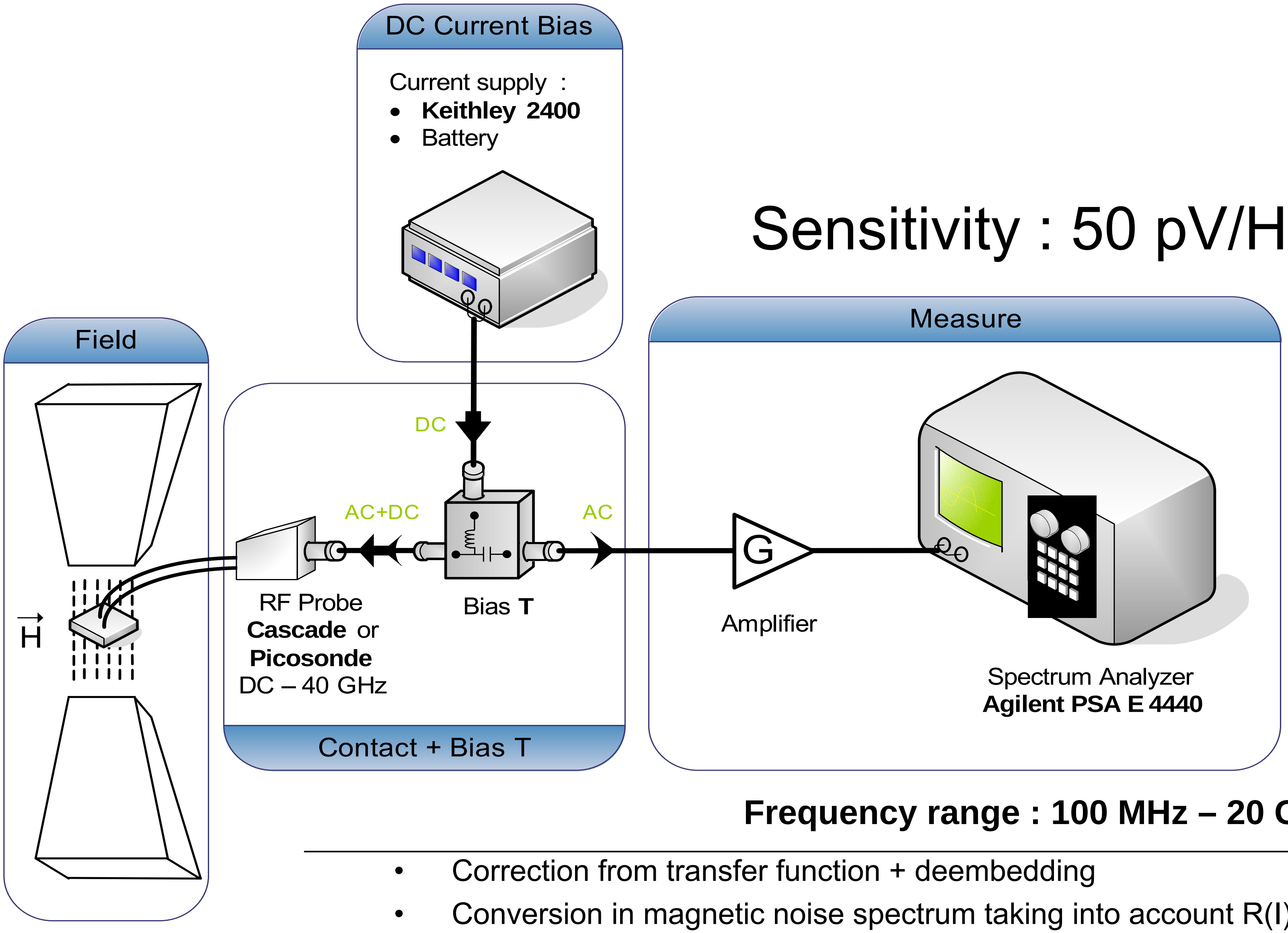
$$R = R_0 - \frac{\Delta R}{2}\cos\theta$$

$$\cos(\theta+\delta\theta) \approx \cos\theta - \sin\theta * \delta\theta$$

$$\delta R \approx \frac{\Delta R}{2}\sin\theta * \delta\theta$$

$$\boxed{\delta V = I * \delta R \approx I\,\frac{\Delta R}{2}\sin\theta\,\frac{\delta m}{M_s}}$$

Experimental setup



DC Current Bias

Current supply :
- **Keithley 2400**
- Battery

Sensitivity : 50 pV/Hz

Field

Measure

RF Probe
Cascade or
Picosonde
DC – 40 GHz

Bias **T**

Amplifier

Spectrum Analyzer
Agilent PSA E 4440

Contact + Bias T

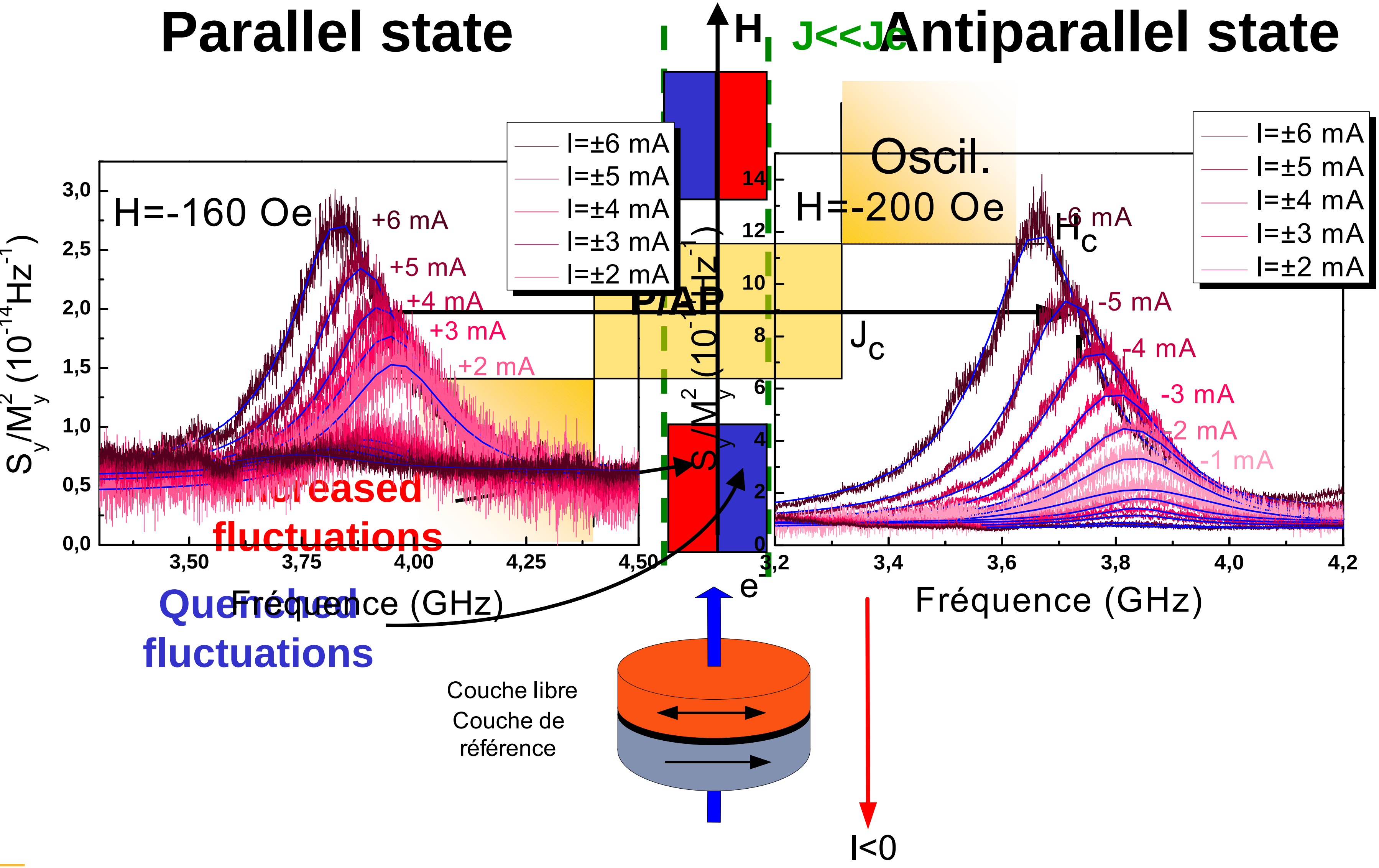
Frequency range : 100 MHz – 20 GHz

- Correction from transfer function + deembedding
- Conversion in magnetic noise spectrum taking into account R(I)

Influence of STT on noise

Parallel state

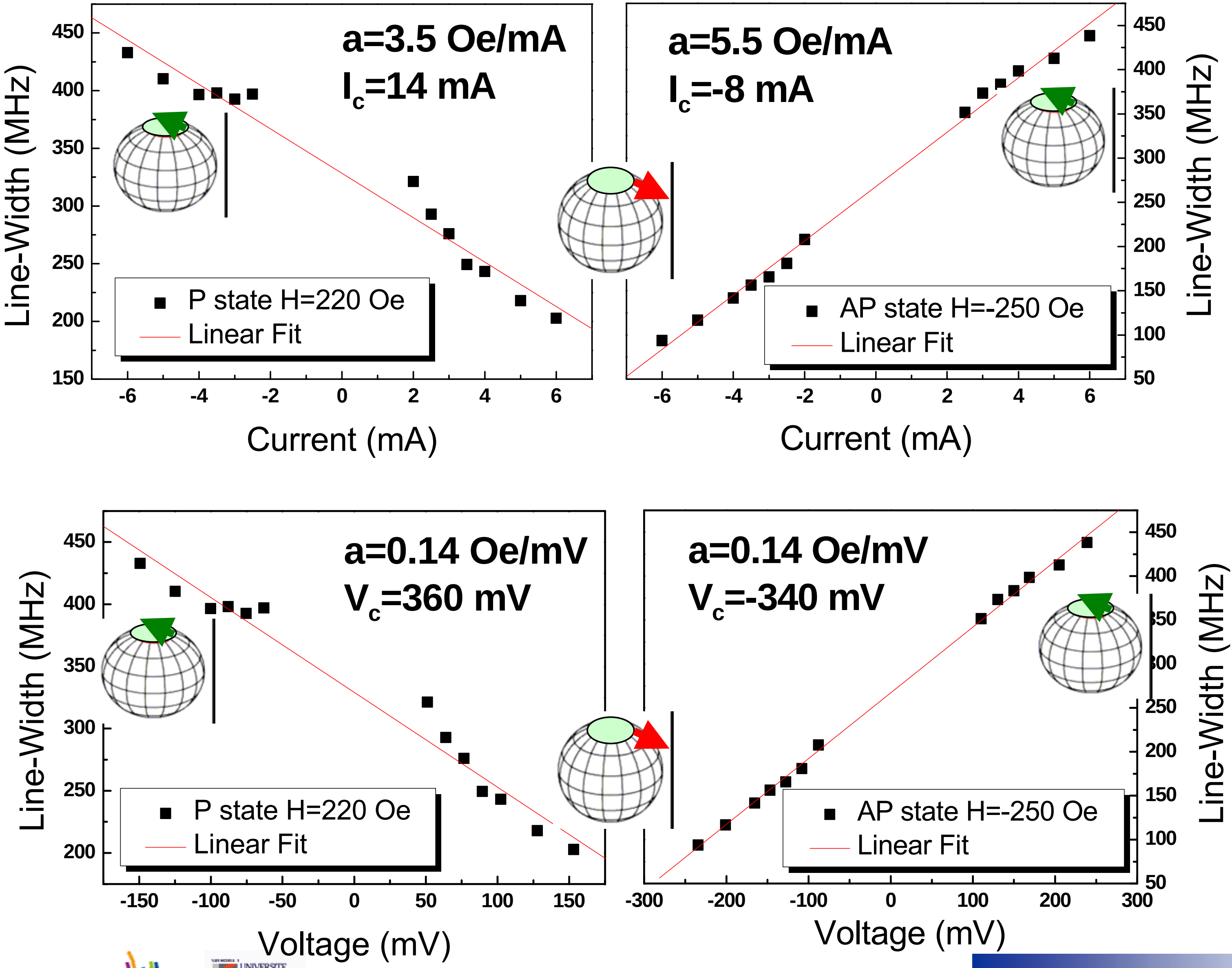
Antiparallel state



creased fluctuations

Quenched fluctuations

Peak Linewidth → longitudinal torque a_j



Summary

- **Longitudinal (in-plane) STT:**
  direct transfer of electron momentum → a_j
- **Transverse (out-of-plane) STT:**
  field-like term (exchange coupling) → b_j
- **STT at equilibrium:**
  effect on magnetization fluctuations (noise)
- Stabilizing and destabilizing torque can be measured:
  extract a_j and b_j
- Voltage more relevant than current for STT in magnetic tunnel junctions.
  Polarized current directly related to the voltage.

Petit et al., PRL **98,** 077203 (2007)