A simple vision of spin torques in domain walls

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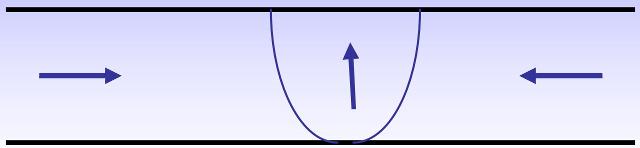
Micromagnetics of wall motion

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

Geometry :



(A. Thiaville)

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

(Velocity $u = JgP\mu_B/2eMs$)

only H : $\rightarrow$ 1: $\odot$, 3: $\rightarrow$, Demag $\otimes$, 2: $\rightarrow$, 3: $\otimes$ $\Rightarrow$ steady state motion

J only: 4: $\rightarrow$, 1: $\rightarrow$, 3: $\otimes$, Demag $\odot$, 2: $\leftarrow$, 3: $\odot$ $\Rightarrow$ no steady state motion

To obtain a steady state motion, one needs to introduce the beta term…
But what is its microscopic origin?

Spin transfer from the conduction electrons to the DW

Theory

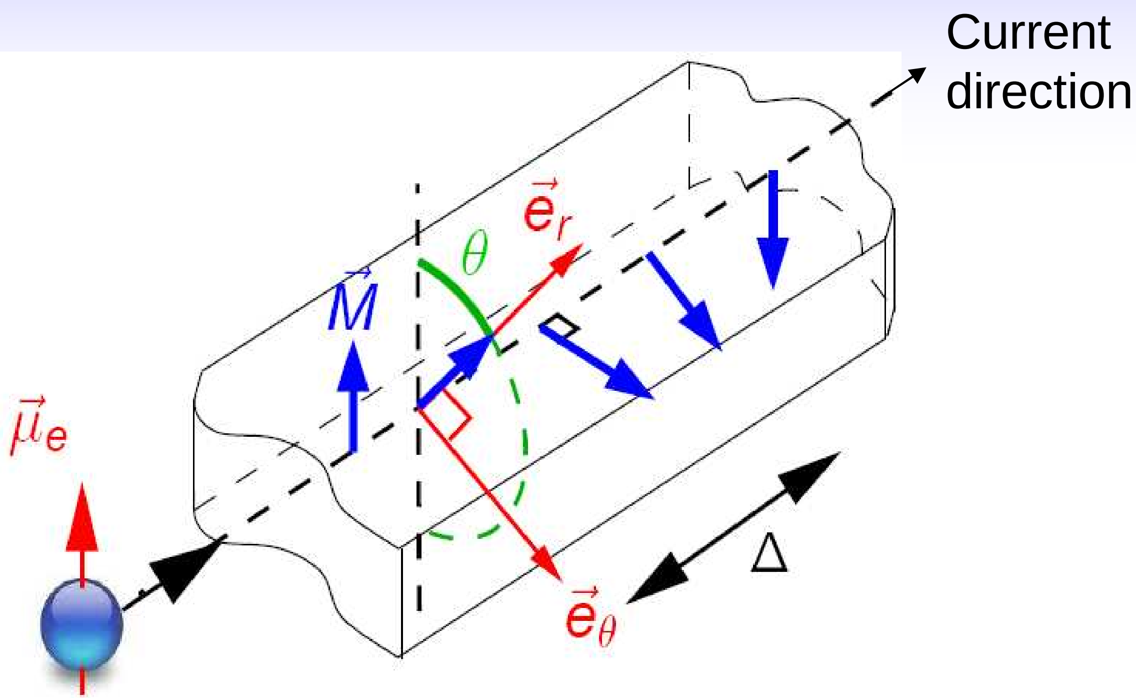
Two kinds of electrons:

- Localised d electrons
- Conduction electrons

→ s-d Hamiltonian

Action of a current:

Globally, the conduction electrons transfer $g\mu_B$ to the DW



Spin evolution in the wall

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

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

Ballistic quantum calculation (Waintal+Viret, EuroPhys. Lett. 65, 427 (2004))

Spinor: $\begin{pmatrix} \Phi_{\uparrow}(x) \\ \Phi_{\downarrow}(x) \end{pmatrix}$ Eigenstates: $\Psi(x)=R_{\theta(x)}\Phi(x)$

Hamiltonian: $H = -\dfrac{\hbar^2}{2m^*}\Delta - \dfrac{J_{\mathrm{exc}}}{2}\hat{m}(x)\cdot\vec{\sigma}$

Solution for linear walls: first order in $(1/Q_k\lambda_{\mathrm{w}})$, where $Q_k = \sqrt{k_\uparrow^{\|}k_\downarrow^{\|}}$)

$$\begin{cases} \Phi_\uparrow(x) = \dfrac{e^{ik_\uparrow^{\|}x}}{\sqrt{k_\uparrow^{\|}}} \\ \Phi_\downarrow(x) = \dfrac{i\pi}{4Q_k\lambda_{\mathrm{w}}\sqrt{k_\downarrow^{\|}}} \times \left(\dfrac{1}{P_k}\left[e^{ik_\uparrow^{\|}x} - e^{ik_\downarrow^{\|}x}\right] + P_k\left[-e^{ik_\uparrow^{\|}x} + \xi e^{-ik_\downarrow^{\|}x}\right]\right) \end{cases}$$

with $P_k=(k_\uparrow-k_\downarrow)/(k_\uparrow+k_\downarrow)$ and $\xi=e^{i(k_\uparrow+k_\downarrow)\lambda w}$

Precession

Simple (classical) calculation

s-d Hamiltonian :

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

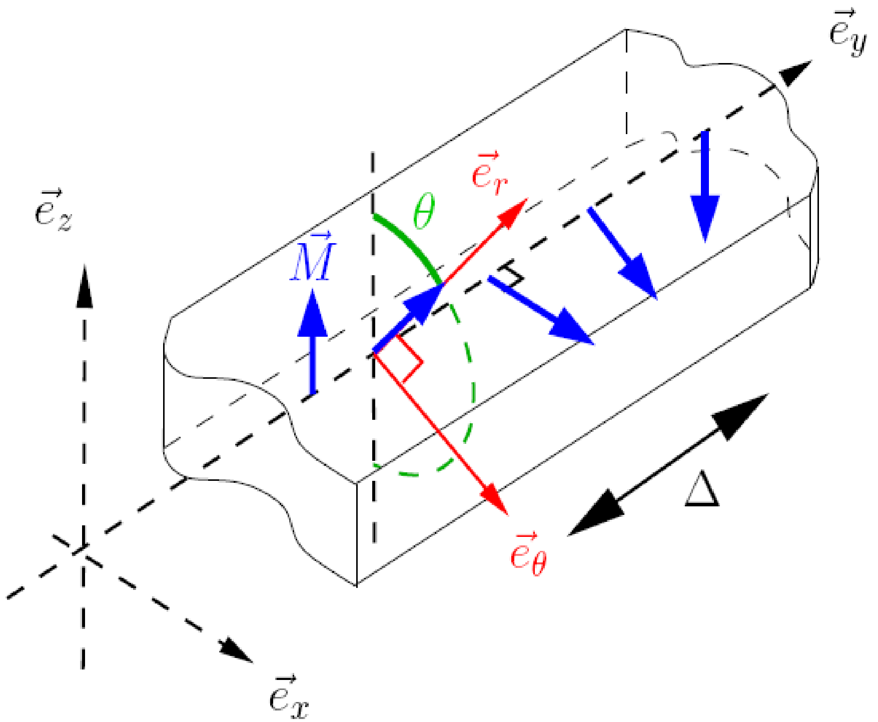
$\Rightarrow$

Precession equation :

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

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

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

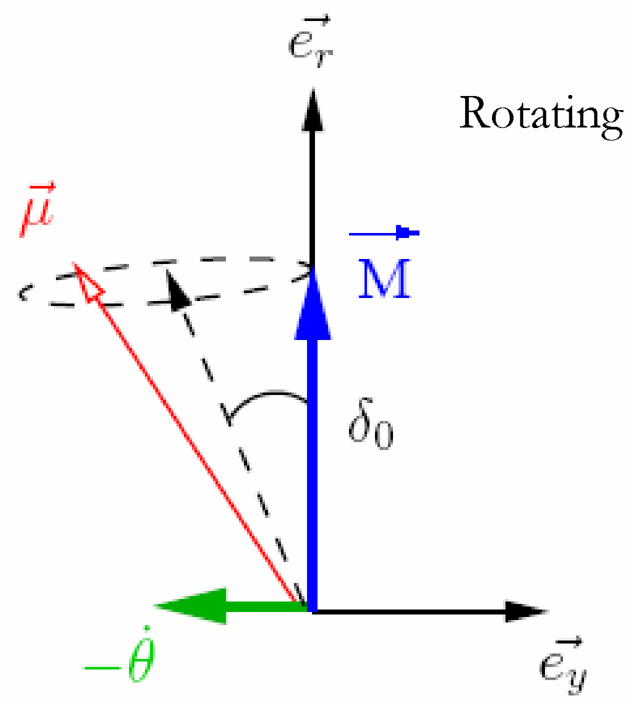
For a long wall and $\ddot{\theta} = 0$

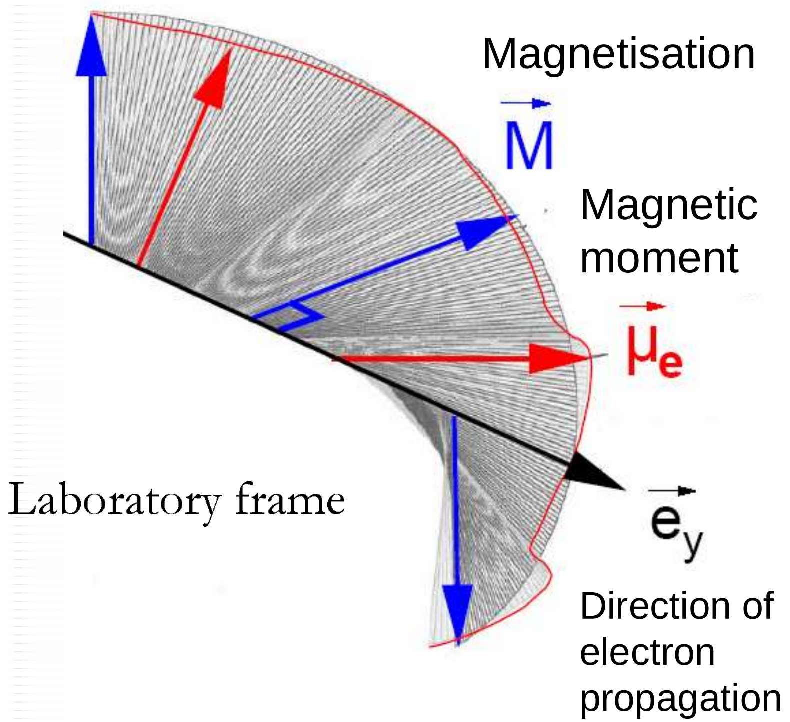
$$\ddot{\mu_\theta} + \frac{1}{\tau_{ex}^2}\mu_\theta = 0$$

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

Precession around the effective field :

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





The total moment is conserved $\rightarrow$

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

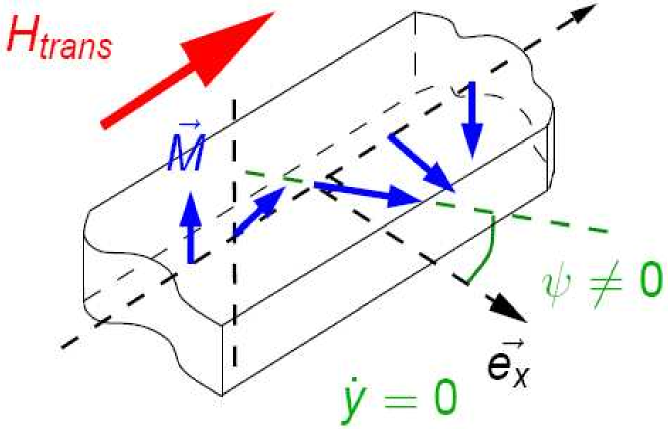
The torque can be decomposed into a constant and periodic part

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 $\rightarrow$

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

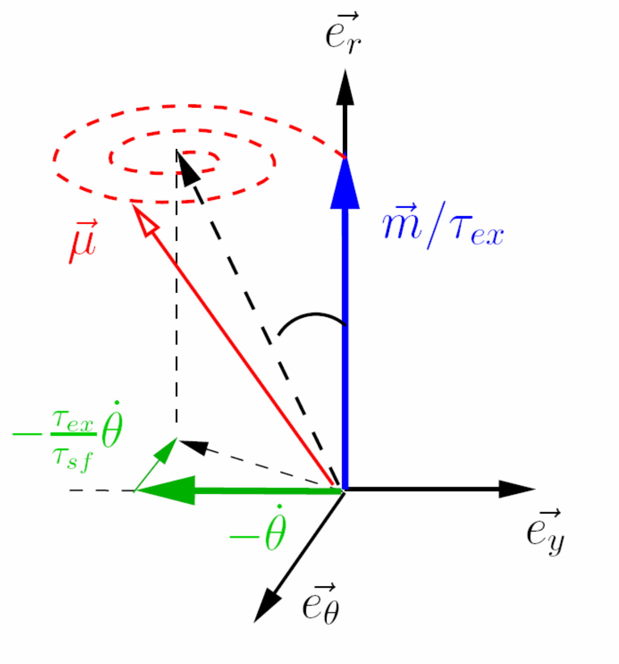
with $\vec{\mu}_{eq} = g\mu_B/2\vec{e}_r$

$\rightarrow$

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

$\rightarrow$ 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 of the new component on the local magnetisation:

$$\left.\frac{\delta \vec{M}}{\delta t}\right|_{sf} = \frac{1}{\tau_{ex}} < \mu_\theta > \vec{e_\theta} \times \vec{m} = \frac{g\mu_B}{2}\dot{\theta}\frac{\tau_{ex}}{\tau_{sf}}\vec{e_y}$$

= Li + Zhang term

However: if the total magnetisation is preserved, then dM/dt = -dμ/dt and a second term appears:

$$\left.\frac{\delta \vec{M}}{\delta t}\right|_{sf} = \frac{1}{\tau_{sf}} < \mu_y > \vec{e_y} = -\frac{g\mu_B}{2}\dot{\theta}\frac{\tau_{ex}}{\tau_{sf}}\vec{e_y}$$

Which leads to the full cancellation of the 'beta' term!

→ Conceptual problem of spin flip events: do they conserve the total M or not?

→ Fundamental difference in scattering events: magnons/phonons ?

For **non M conserving events**, we get for the two constant torques :

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

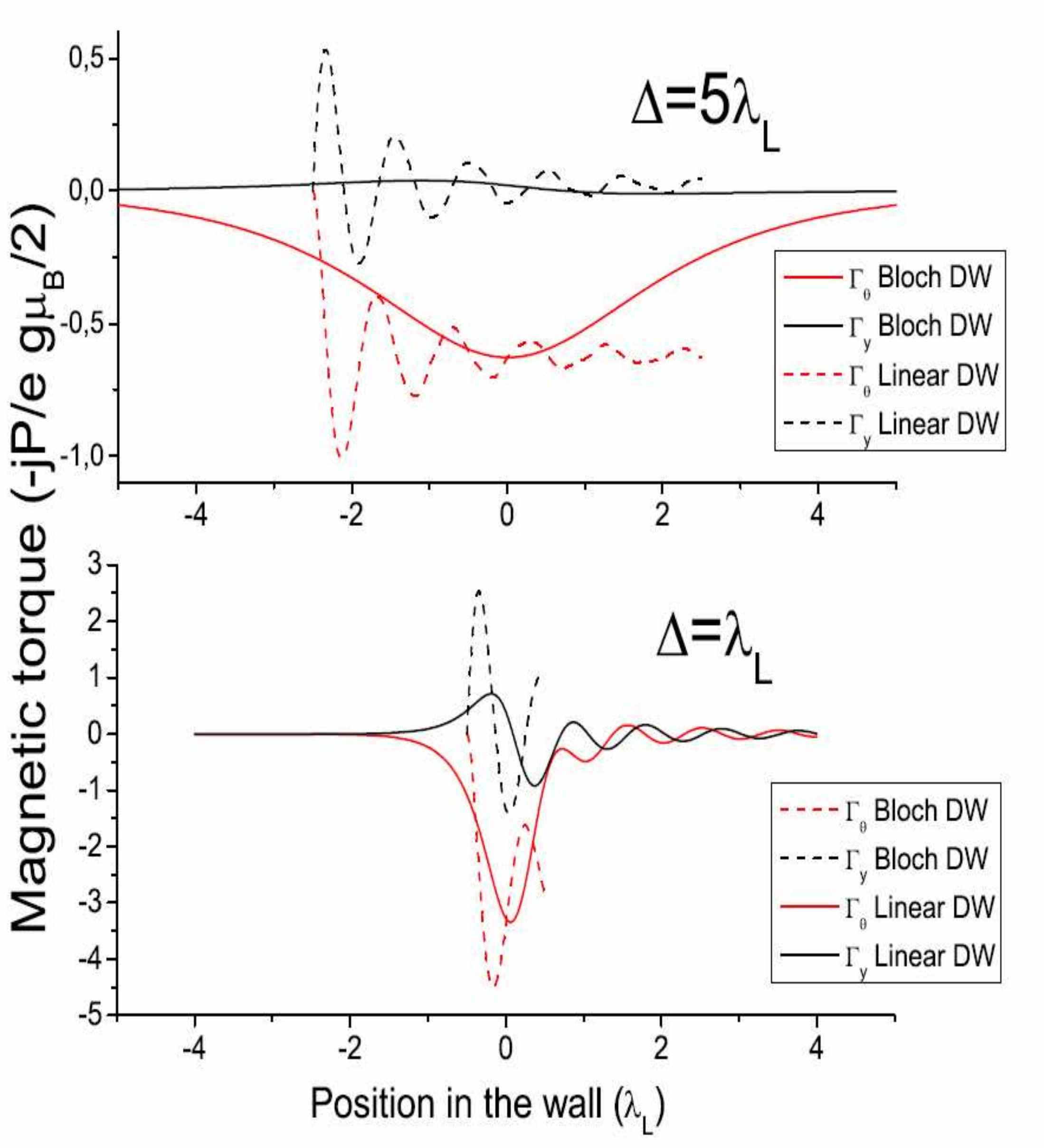
P = polarisation,
j = current density

Conclusion:

The beta term might depend on the nature of scattering processes.
It is at most $\beta = \tau_{ex}/\tau_{sf}$

'Not so thick walls': numerical simulations

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

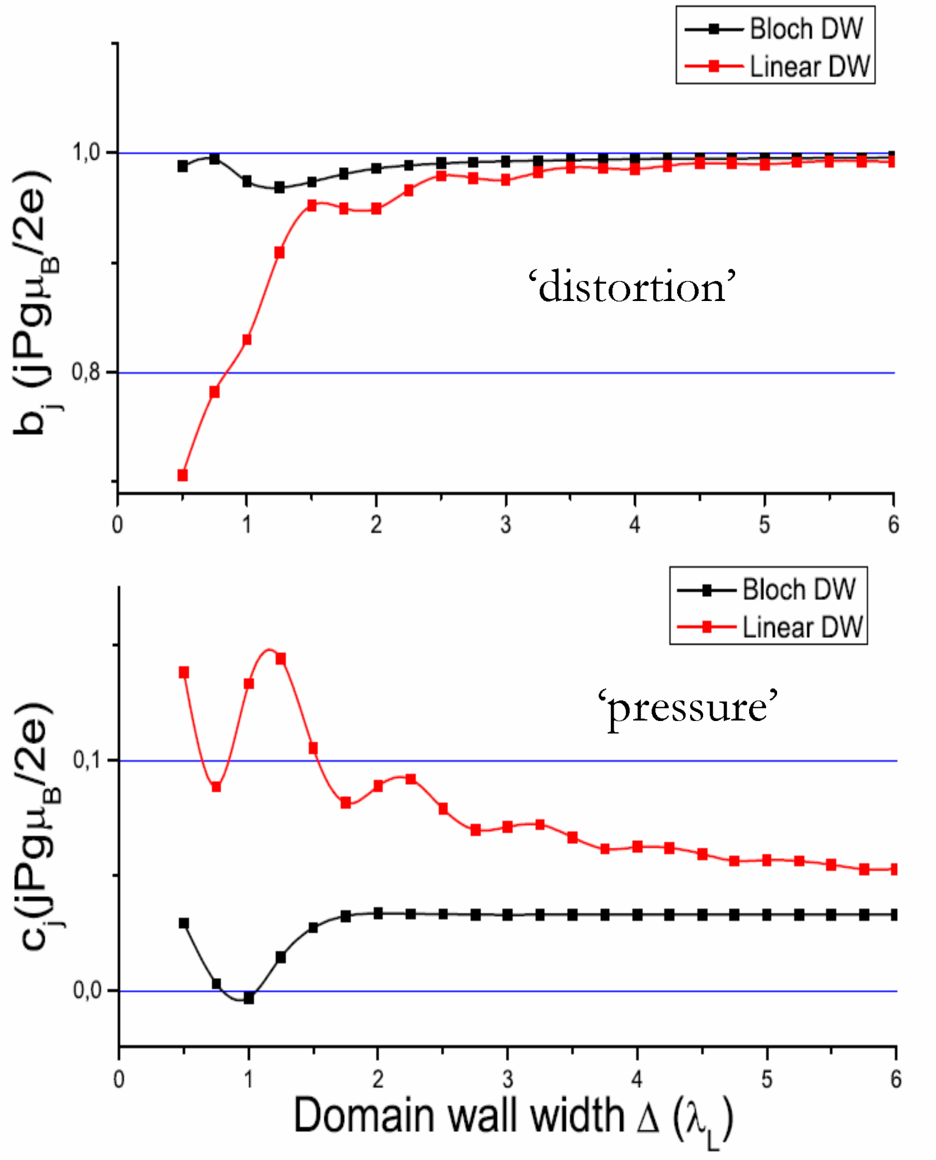


Influenced by the shape and width of the DW…

Bloch wall: smooth boundary conditions prevent the spin precession of conduction electrons

'Not so thick walls': numerical simulations

Averaged torques on the wall width :

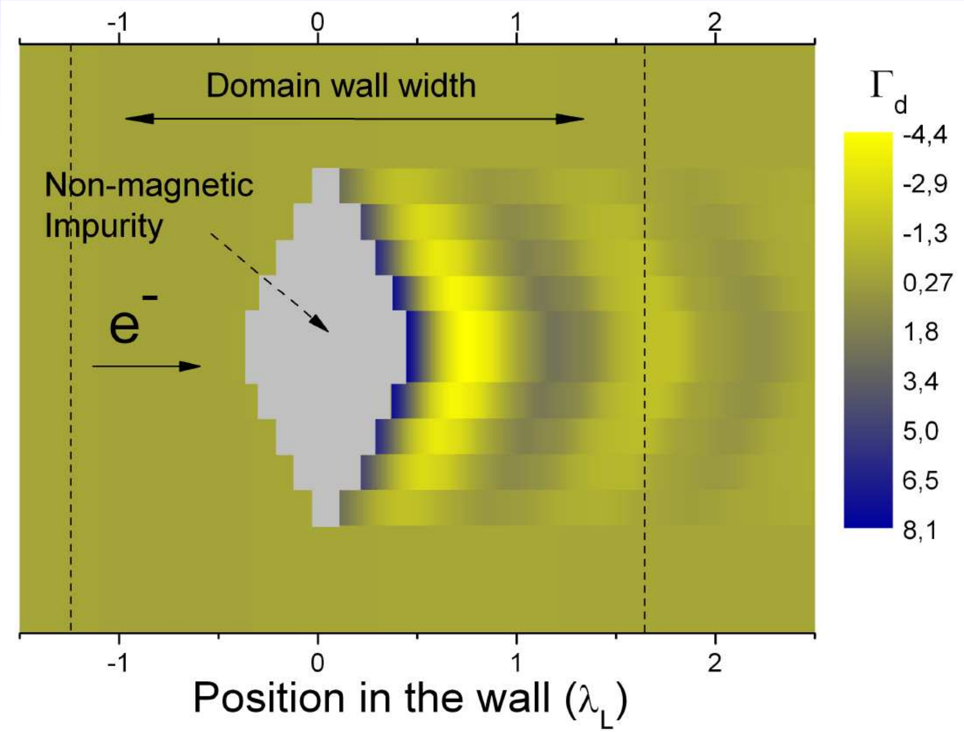


Differences for linear and Bloch walls due to the suppression of spin precession in Bloch walls.

Remark: constraint 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:



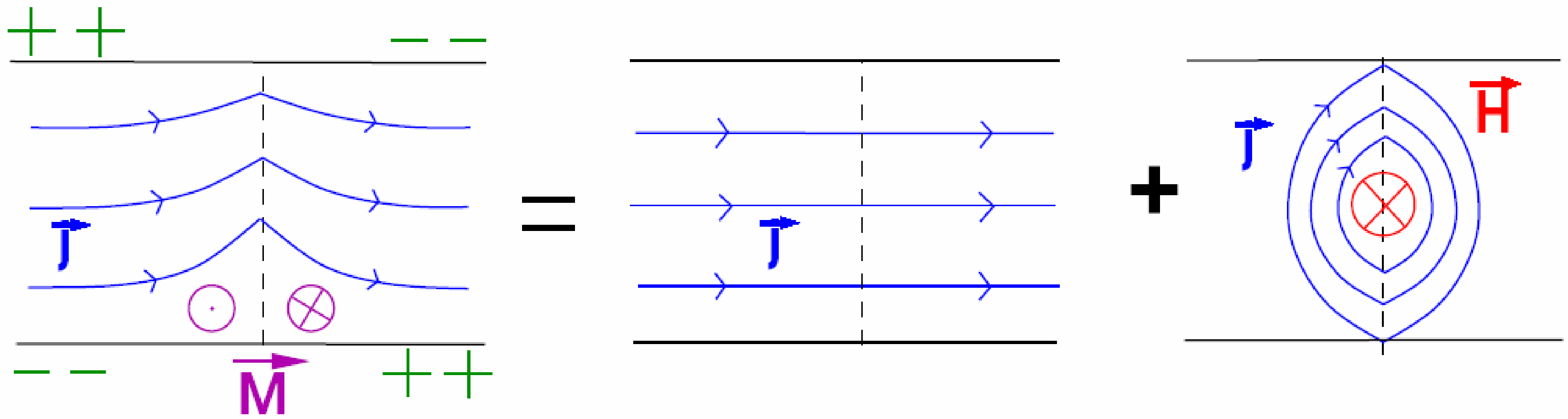
Spatially varying torques are very large near the impurity → de-pinning ?

Hall effect induced perturbation of current lines

The Hall effect polarity changes at the DW
→ Current lines are distorted

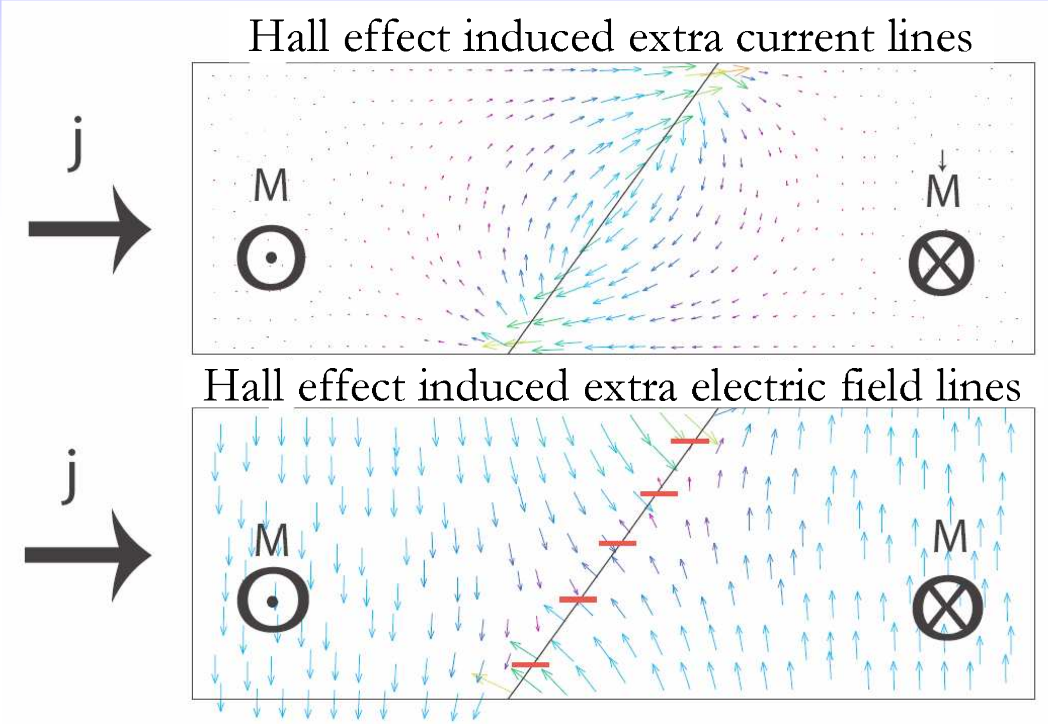
A perpendicular magnetic field is induced
→Pressure

L.BERGER, J. PHYS. CHEM. SOLIDS 1974



Tilted DWs

Other effect when the **wall is tilted**: the DW gets electrically charged



Electric pressure: $P = 2\epsilon_0 \beta \rho^2 j^2 \sin\alpha$

Weak for thin films in 3d elements, not so weak for semiconductors

See M. Viret, A. Vanhaverbeke, F. Ott, J.-F. Jacquinot, Phys. Rev. B 72 (14), 140403 (2005).

Conclusions for the theoretical part

• Relevance of classical model for for spin evolution in the DW

• 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

•'Hall charge Effect': Important for magnetic semi-conductors

Independent of current direction.

Experimental: Pt/Co/Pt

Very large perpendicular interface anisotropy (Co/Pt)

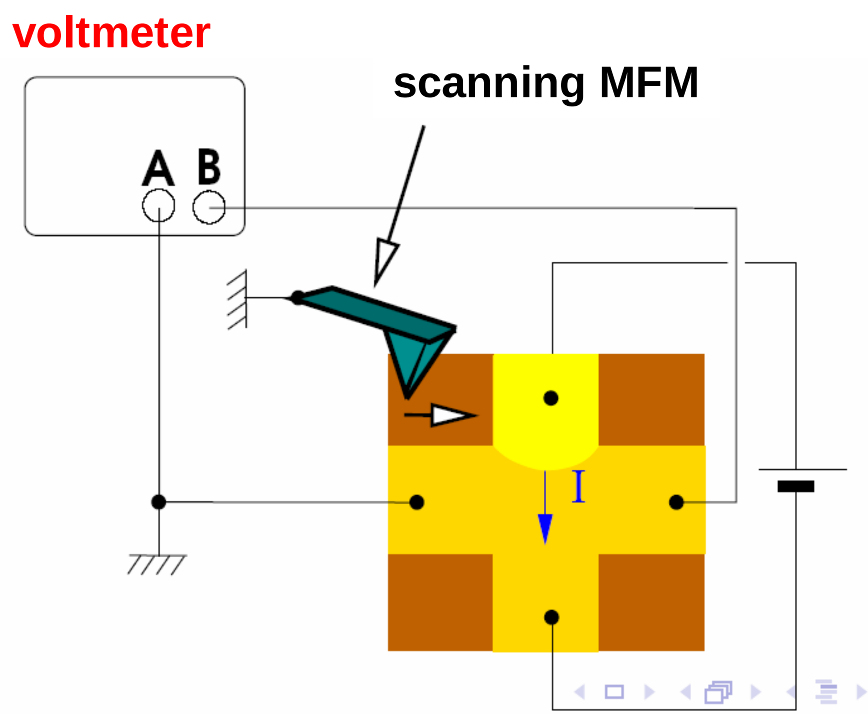
Very well defined DW structure: Bloch wall + very thin (= 5 nm)

Perpendicular magnetisation:

2D system

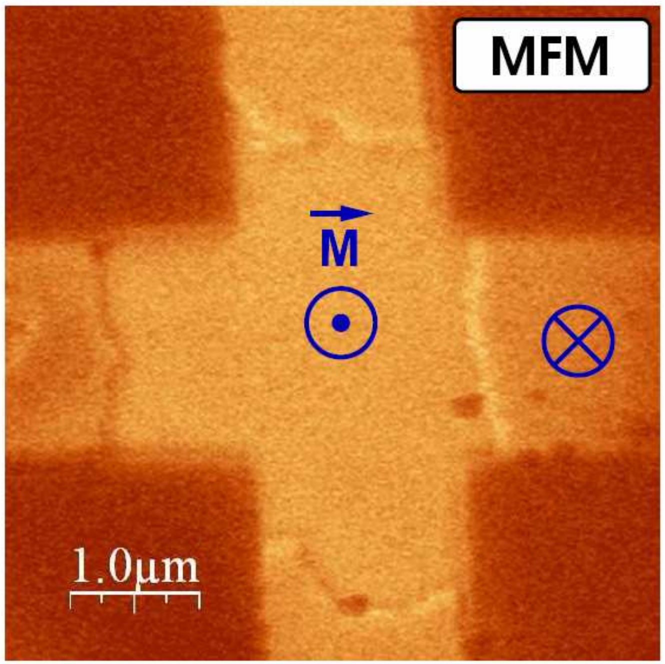
Extraordinary Hall Effect (measurement of DW position)

Tool: MFM under magnetic field with transport measurements

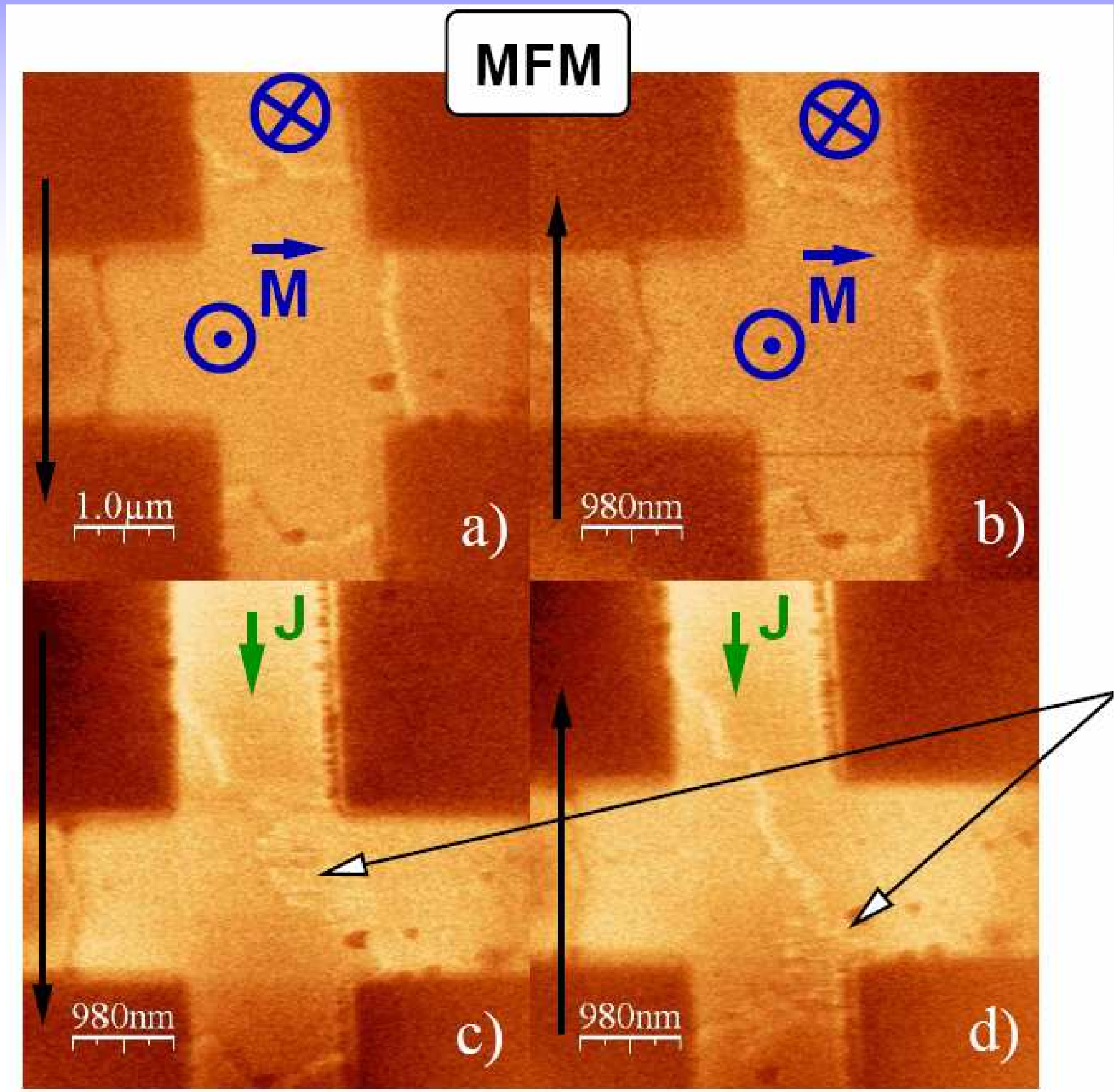


Domain drawing

"Domain drawing" : The tip magnetisation is reversed and its stray field can nucleate locally a minority domain.
Then the tip is demagnetised to minimise stray fields.



Domain Wall de-pinning



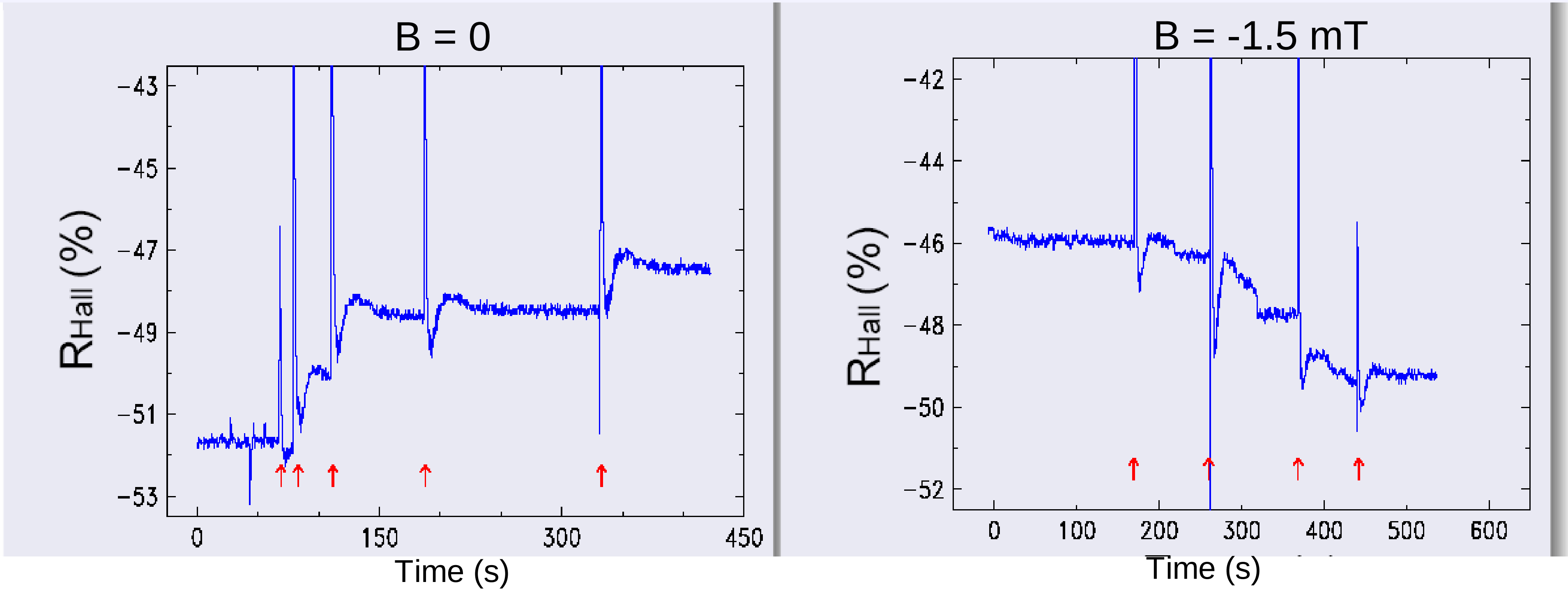
Tip induced de-pinning
assisted by the current *J*

$J = 7\ 10^{11}\ A/m^2$

Tip induced de-pinning of the DW

De-pinning wins over spin pressure

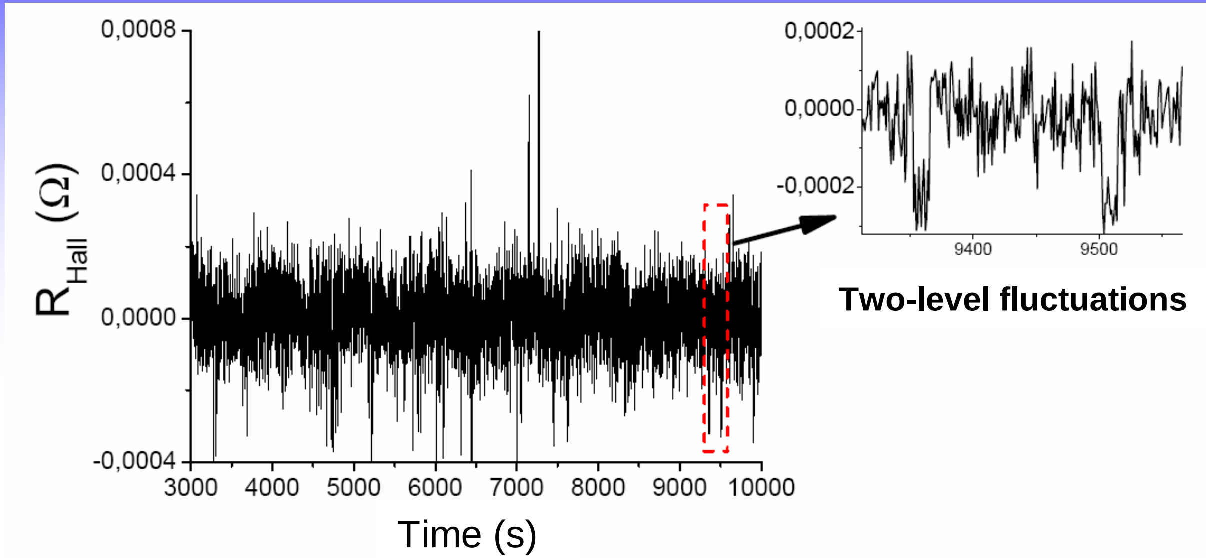
Measurement of Hall voltage in the cross during current pulses (several 10μs)



The DW moves in the direction of the field

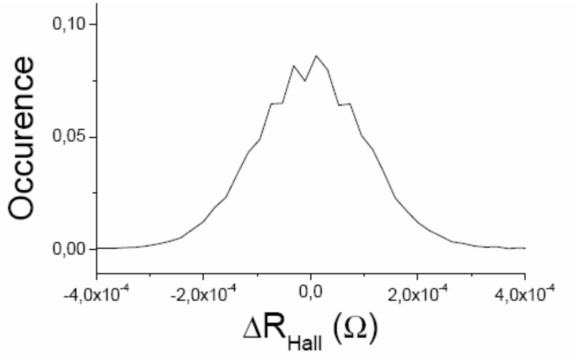
Current effect on noise in EHE

Two-level fluctuations :

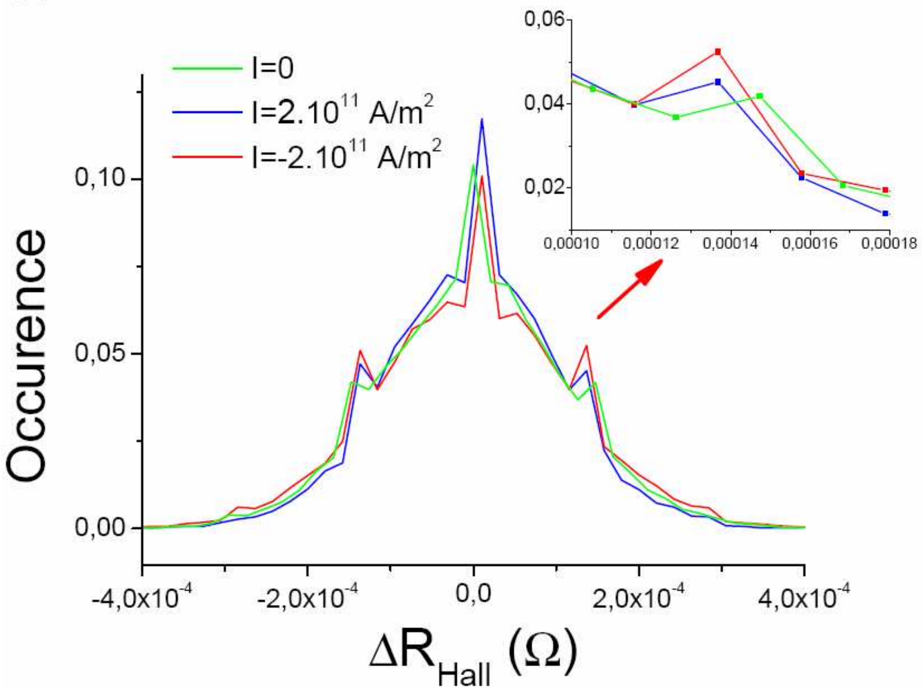


Histograms of (R(t)-R(t-1)) :

No DW:



DW + current:



Conclusion

DC Current effect on DW:

Mainly depinning + a little bit of pushing

Qualitative agreement with modelled torques