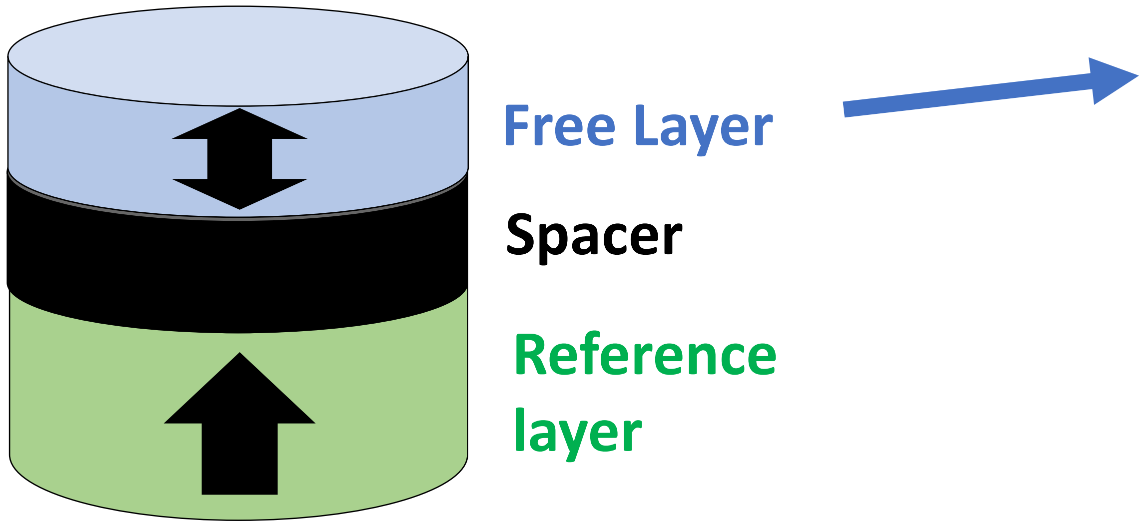
The switching paths of spin transfer torque magnetic random access memories

Café scientifique : ***Paul BOUQUIN***
28/10/2021

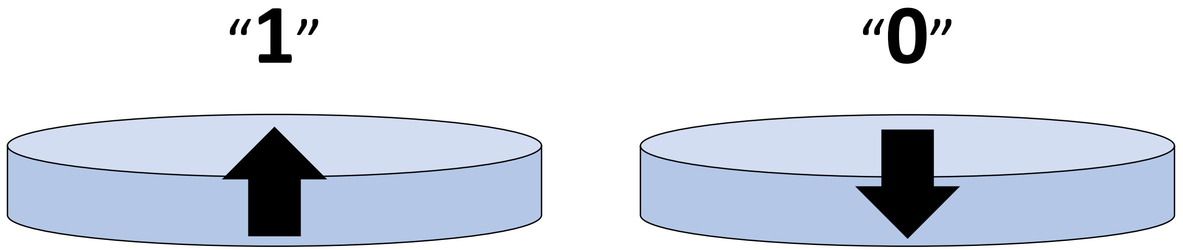
STTMRAM: storing

Spin transfer torque magnetic random access memories (STTMRAM)

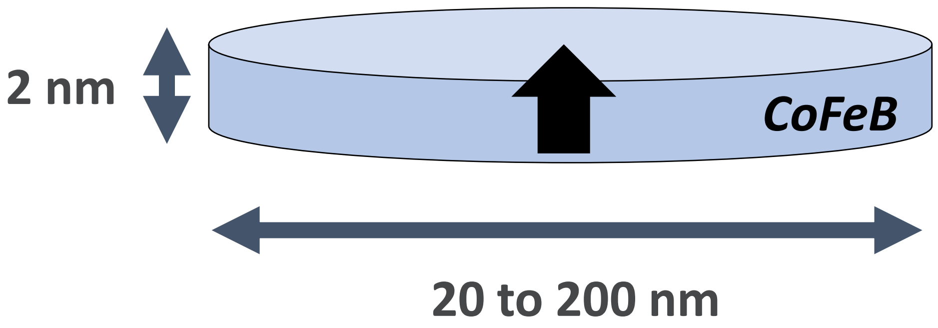


Task 1: storing

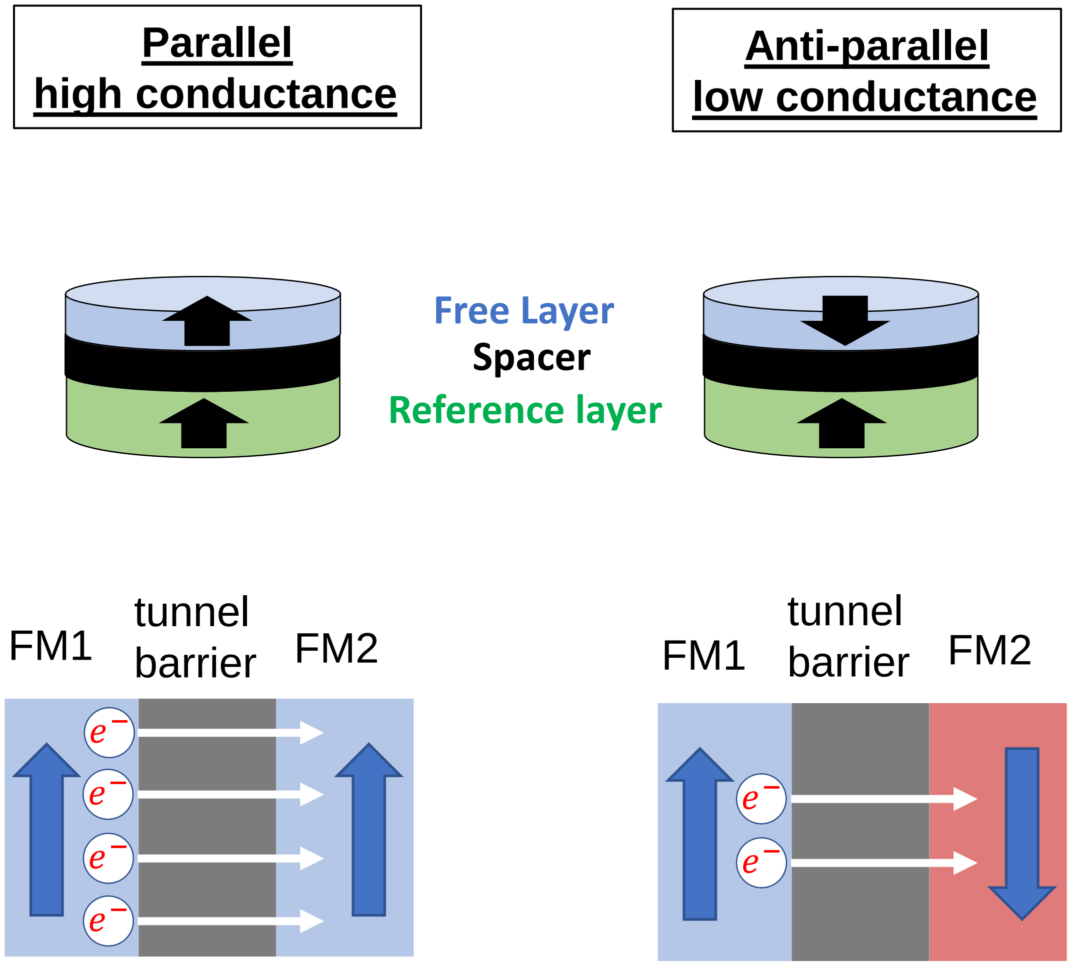
The free layer carry information.



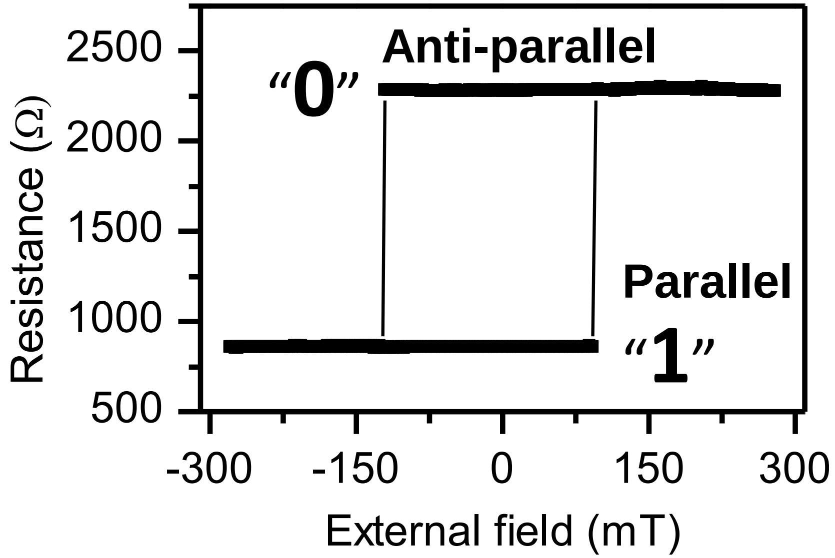
This is our system:



STTMRAM: reading

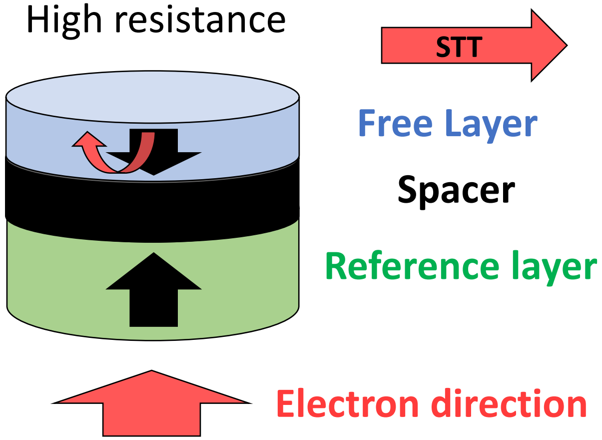


The tunnel magnetoresistance in a magnetic tunnel junction.



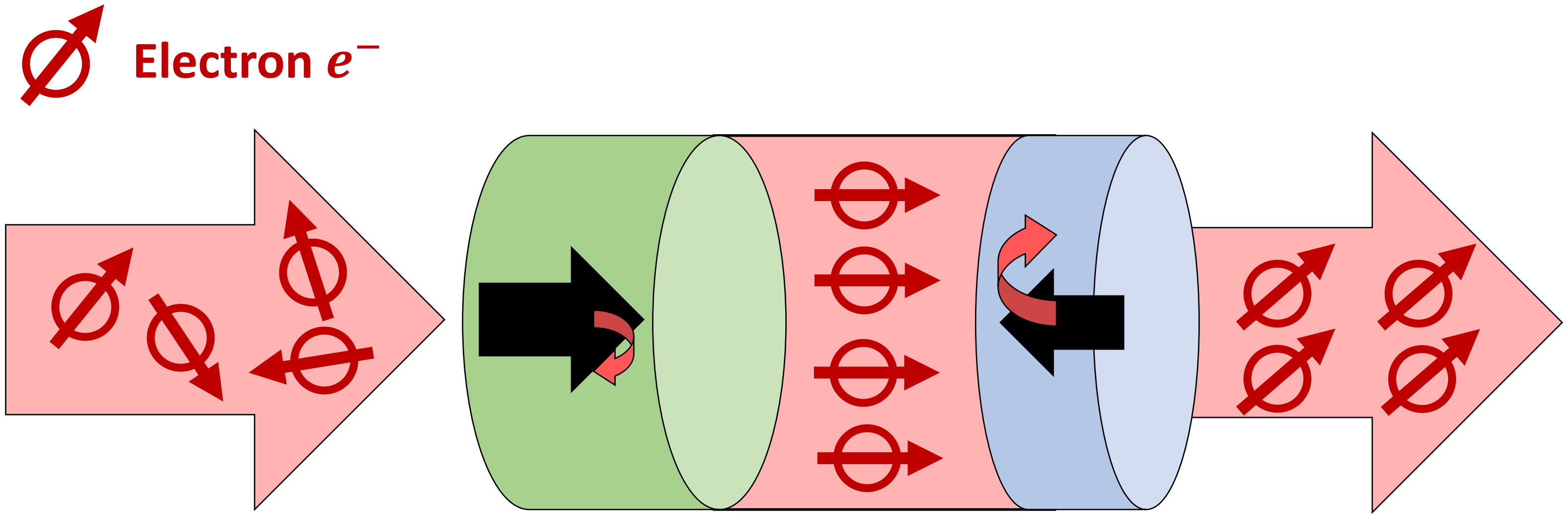
Due to spin-dependent density of states in a ferromagnet.

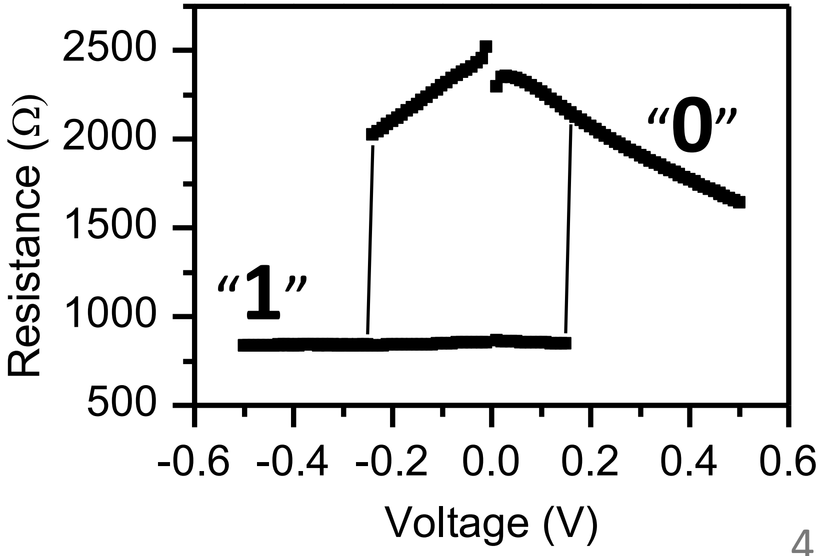
STTMRAM: writing



The spin transfer torque (STT):

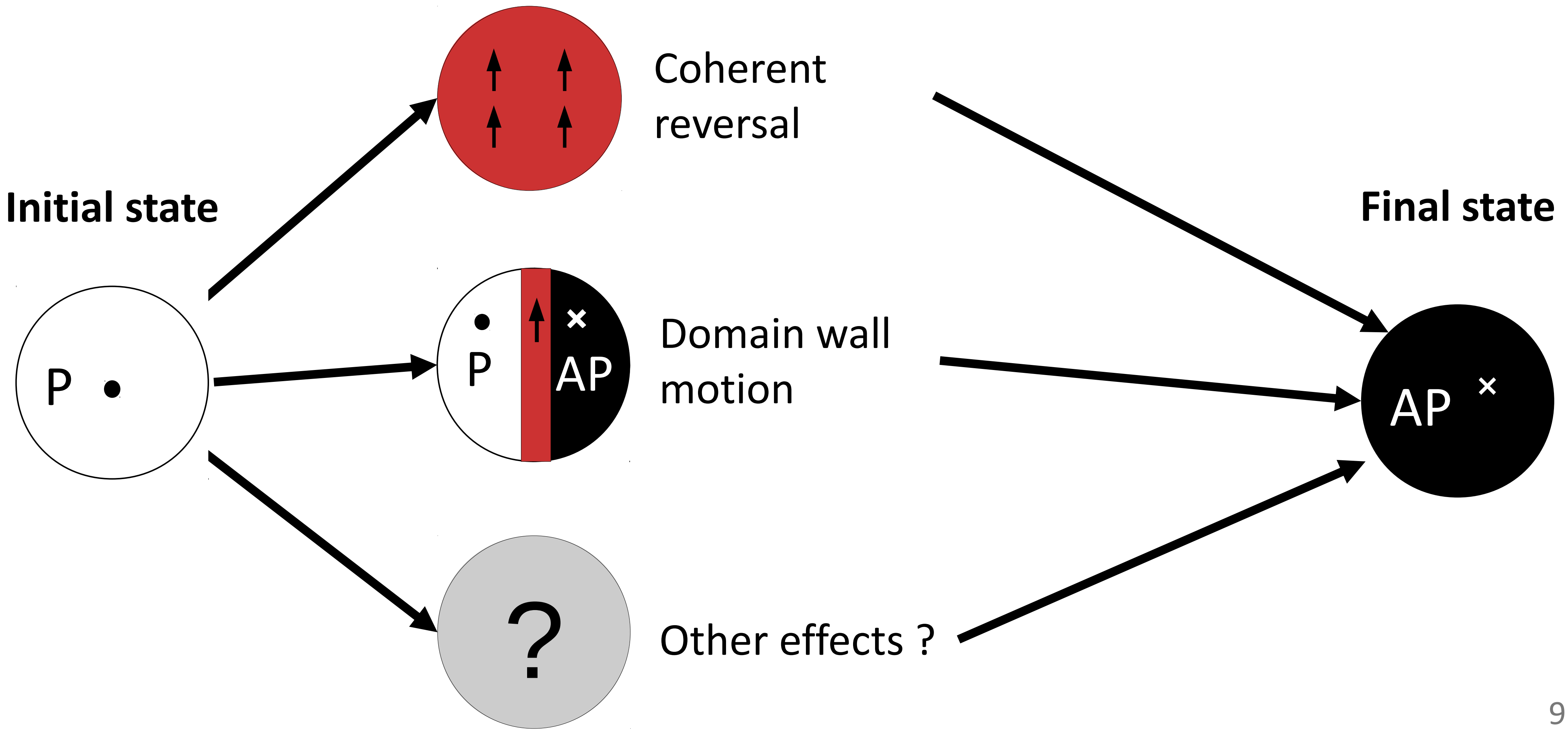
1) Exchange of angular momentum between the e^- of the current and the ones of the reference layer.
2) The spin-polarized current flows through the free layer, same effect.
3) By conservation of angular momentum, torque on the free layer.





The switching path

The switching path is all the configurations taken between the initial state and the final state during the switching.



The problematic

What is the switching path in spin transfer torque random access memories?

Important for applications it determines the models for**:**

- Speed of reversal.
- Thermal stability of the memory.
- Write error rate.

Outline of this talk

What is the switching path in spin transfer torque random access memories?

I. Micromagnetic simulations of the reversal

- Critical size for non-uniformity.
- Identifying the expected switching path in our samples.

II. Modeling the domain wall motion within a disk

- Understanding the complex domain wall motion observed in the simulations.
- Predicting how to measure these effects.

III. Time-resolved electrical measurements of the switching

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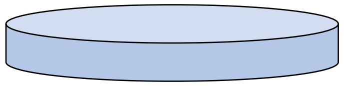
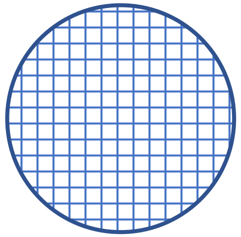
- Looking for the complex domain wall effects.

Micromagnetic simulations principle

Free layer → 2D grid



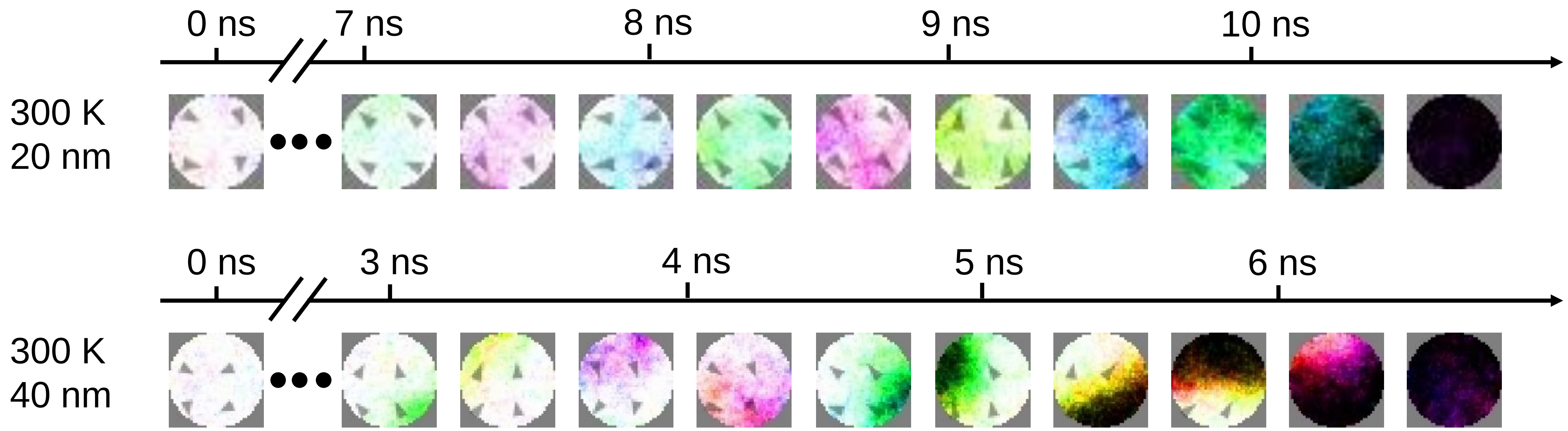


- Magnetization assumed uniform in each cell.
- Possible because of exchange. 2x2 nm^2 cell.
- In each cell the basic equation of magnetization dynamics under STT is solved: Landeau-Lifshitz-Gilbert-Slonczewski equation (LLGS).

- This is done numerically using mumax3 software [1].
- We extract the expected switching path in a perfect, isolated free layer.
- We vary the size of the disk.

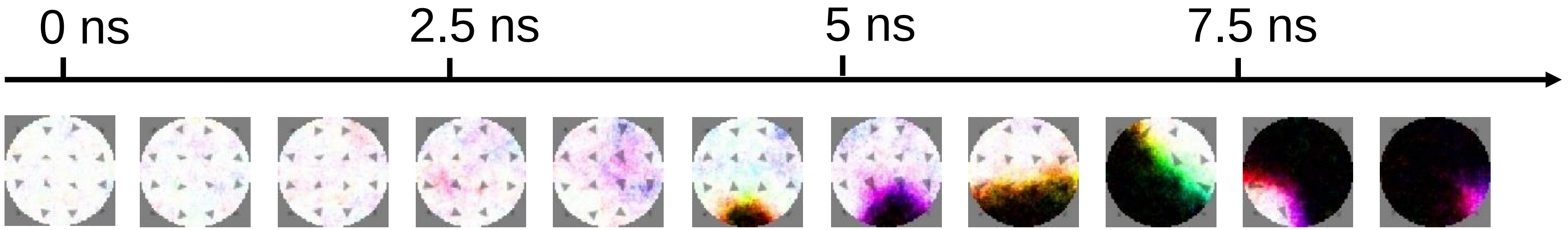
1. *Vansteenkiste et al., AIP Adv.* ***4.10*** *(2014)*

Switching for 20 nm and 300 K

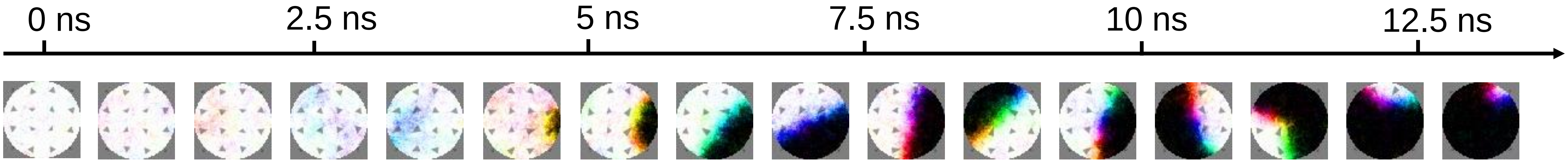


- For disks of 20 nm or less the reversal is coherent.
- For larger disks, there is a coherent phased followed by a domain wall motion.

Switching for 80 nm and 300 K



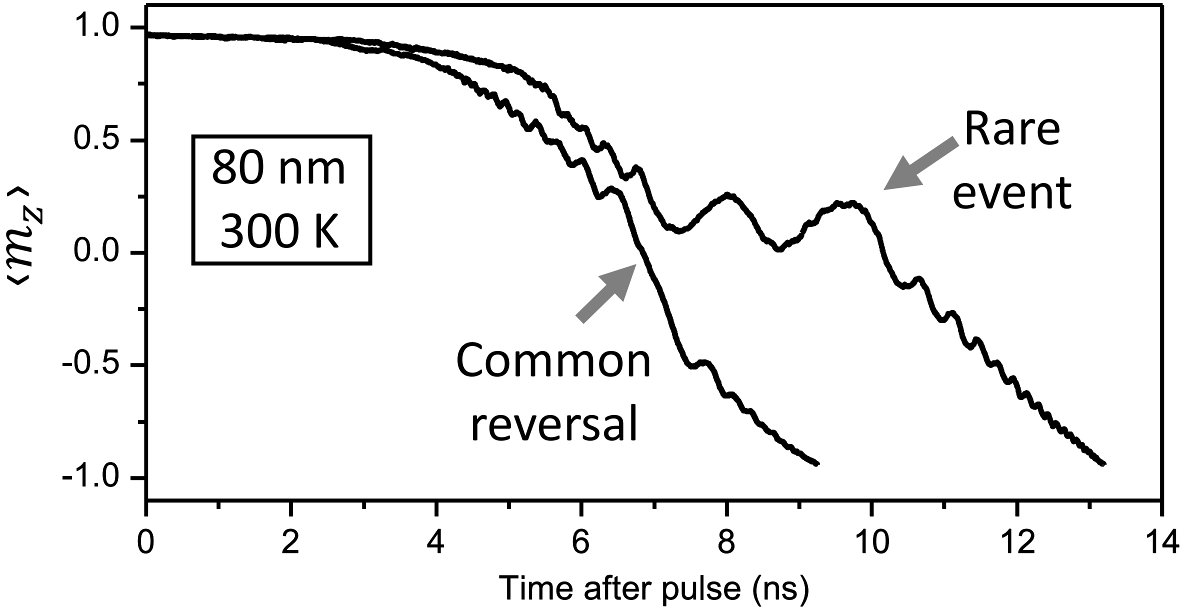
80 nm
300 K
common
reversal



80 nm
300 K
rare event

<u>80 nm 300K:</u>

- The switching depends on initial conditions
- Rare event with complex domain wall motion that slows the reversal.



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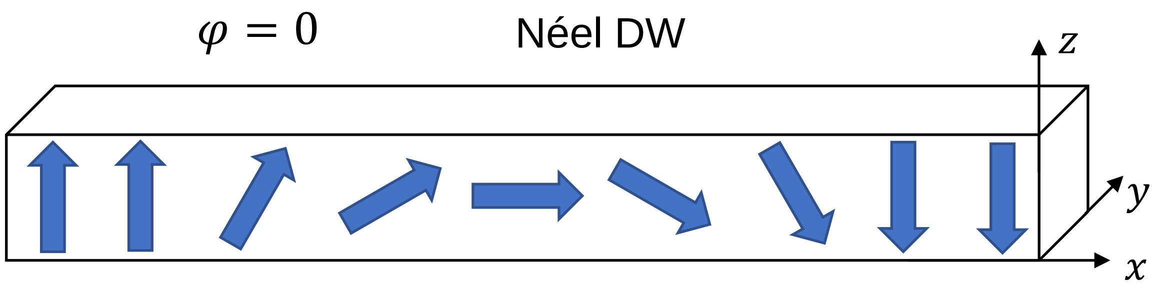
The collective coordinates

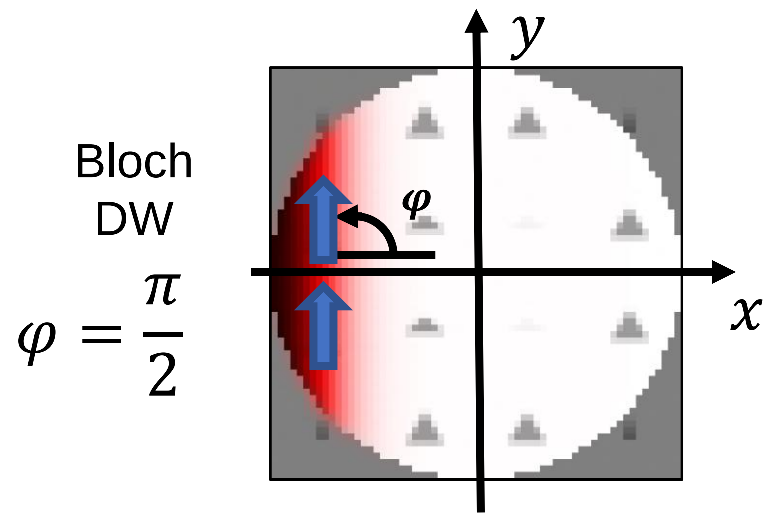
<u>Domain wall:</u>

Collective state of the magnetization.

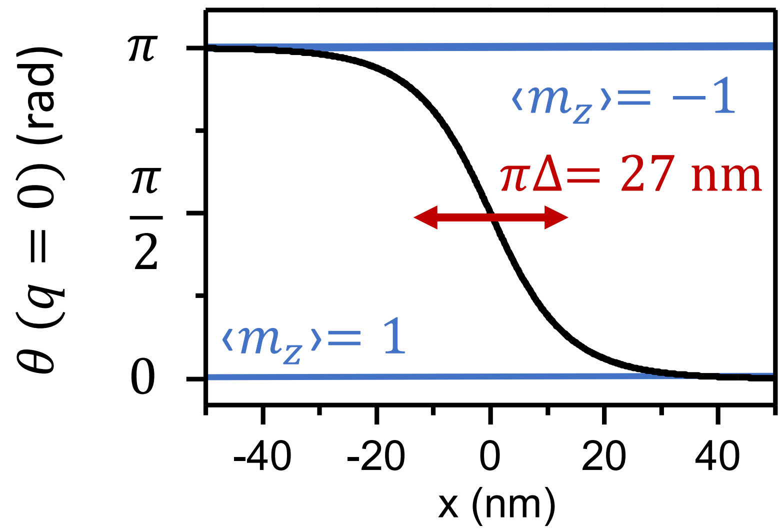
Tradeoff between anisotropy and exchange.

1D assumption → described with *q* and *φ*.

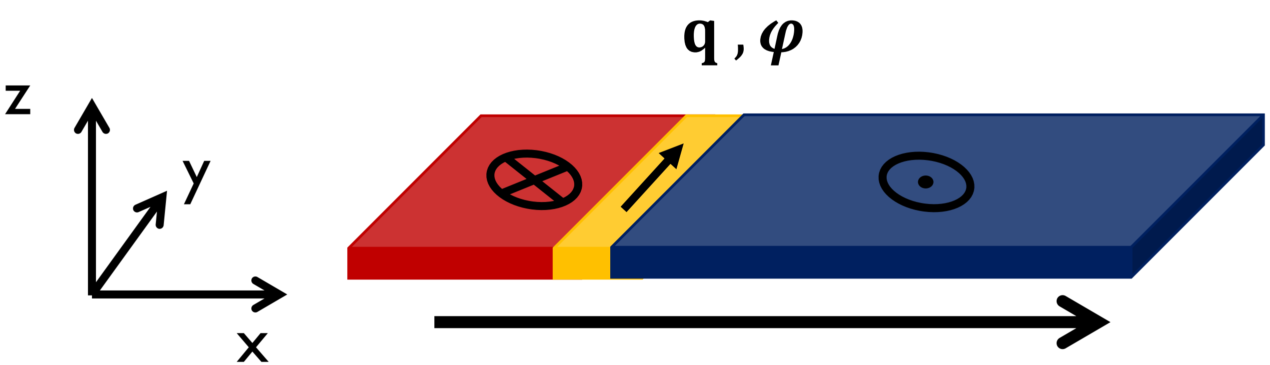




Domain wall profile:



Equations within a stripe (state of the art)



Domain wall motion

Existing DW models.

Infinite stripe.

Lagrange-Euler equation on **q** and ***φ***

Coupled equations on φ and q.

$$\begin{cases} -\dot{\varphi} + \alpha \dfrac{\dot{q}}{\Delta} = -\gamma_0 H_z \\ \dfrac{\dot{q}}{\Delta} + \alpha\dot{\varphi} = \gamma_0 \dfrac{H_{DW}}{2} \sin(2\varphi) + \sigma j \end{cases}$$

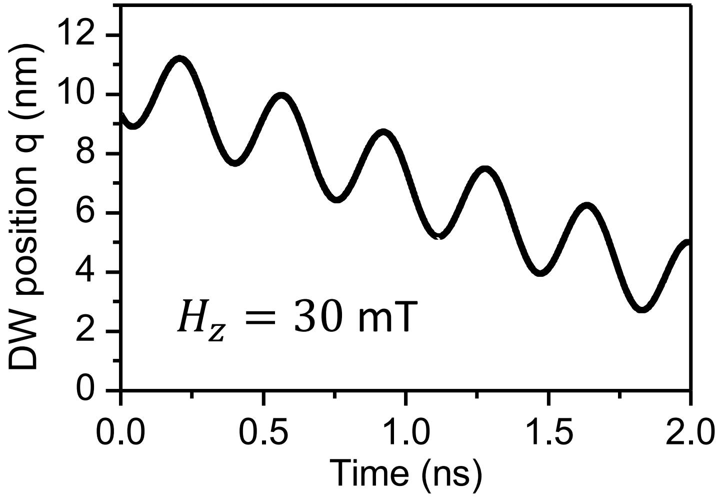
H_z: total out-of-plane field.
H_{DW}: in-plane demag.
α: damping.
σj : STT.

We know *q*(t) and *φ*(t).

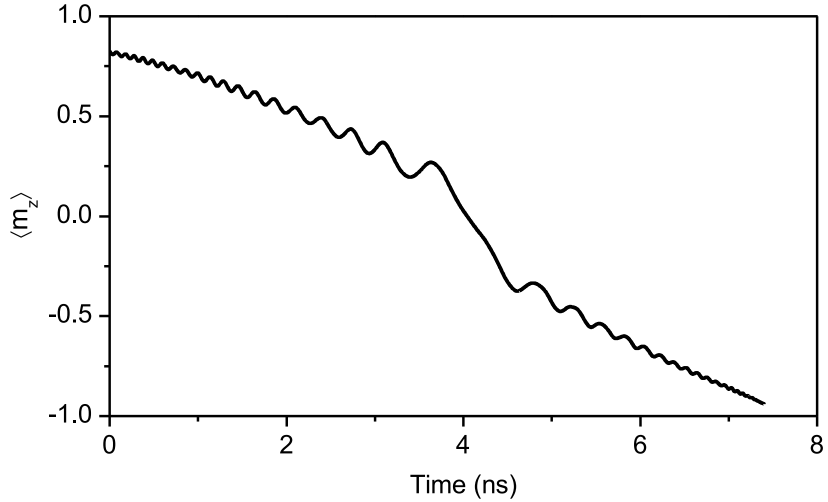
Stripe versus micromagnetics

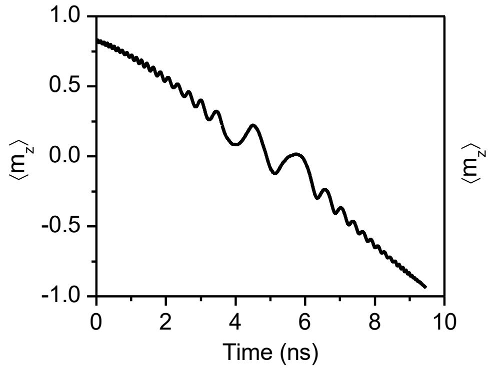
Stripe 1D model:

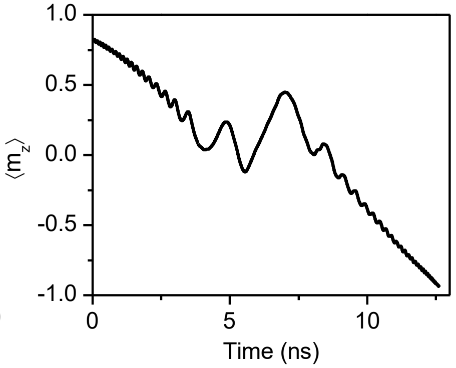
$$\|\dot{q}\| = \Delta(\sigma j - \alpha\, \gamma_0 H_z)$$
$$\omega_q = 2\omega_\varphi \approx \gamma_0 H_z$$
$$D_{osc} \approx \Delta \frac{H_{DW}}{H_z}$$

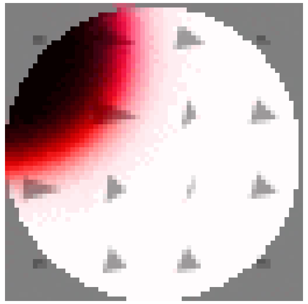


DW micromagnetics 80 nm:







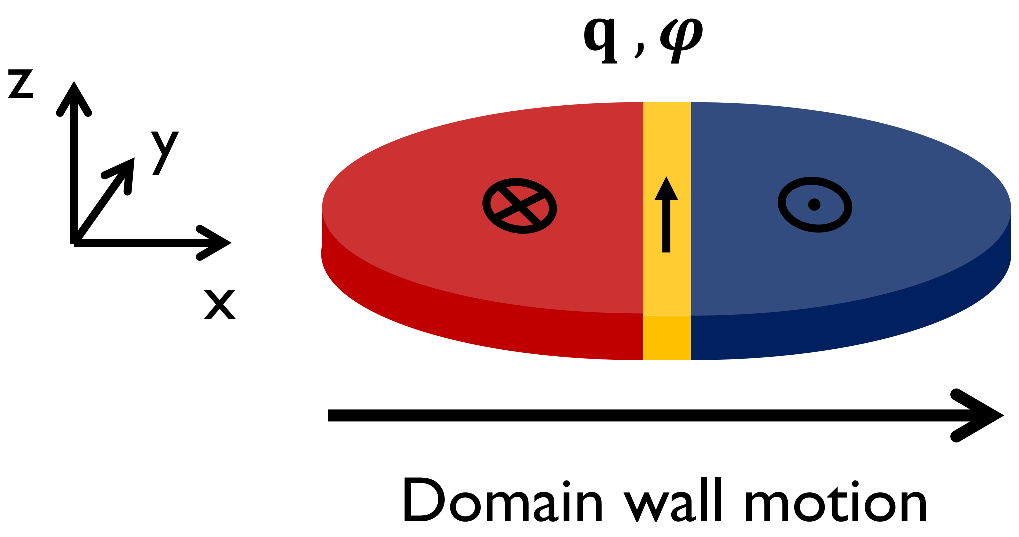


- Drift + coupled oscillations ok.

Deficiencies:

- No change in frequency and amplitude.
- No rare events.
- We need a new model.

Equations within a disk



$$\begin{cases} -\dot{\varphi} + \alpha \dfrac{\dot{q}}{\Delta} = -\gamma_0 (H_z + \boldsymbol{H}_{\boldsymbol{stretch}}(q)) \\ \dfrac{\dot{q}}{\Delta} + \alpha \dot{\varphi} = \gamma_0 \dfrac{H_{DW}}{2} \sin(2\varphi) + \sigma j \end{cases}$$

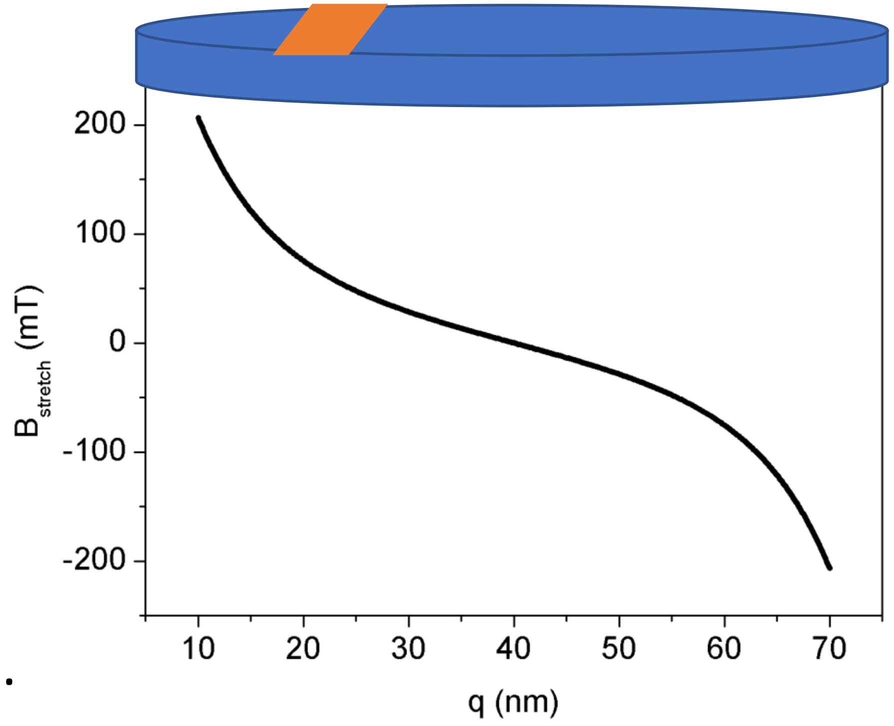
- Same energies, integrated over a disk this time.
- Result is the same equations with one main additional term and new stray field.
- This stretch field comes from exchange and anisotropy energies.

Stretch field: qualitative

Stretch field

$$H_{sretch} = \frac{1}{\mu_0 M_s} \frac{1}{S_{DW}(q)} \frac{\partial S_{DW}(q)}{\partial q} 2\sqrt{A_{ex}K_{eff}})$$

$S_{DW}(q)$: Effective wall surface



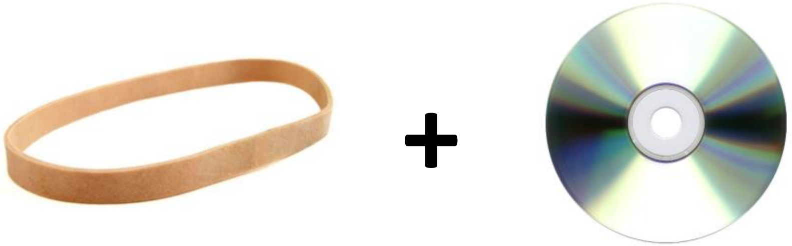
Qualitative understanding

The longer is a DW, the more it cost energy to the system.

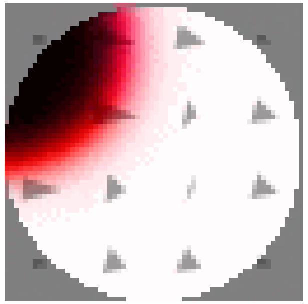
Elasticity of the DW: minimum of energy when small.

This pushes the DW towards the edges of the disk.

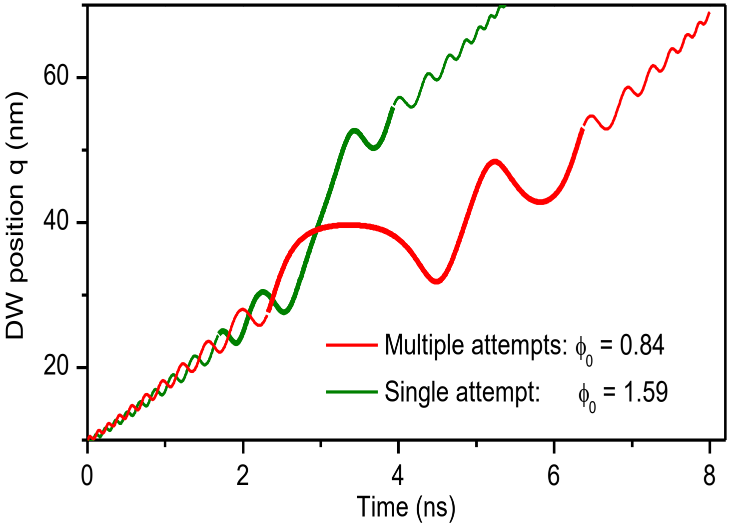
This torque can be expressed as a simple out-of-plane field.



Disk model versus micromagnetics

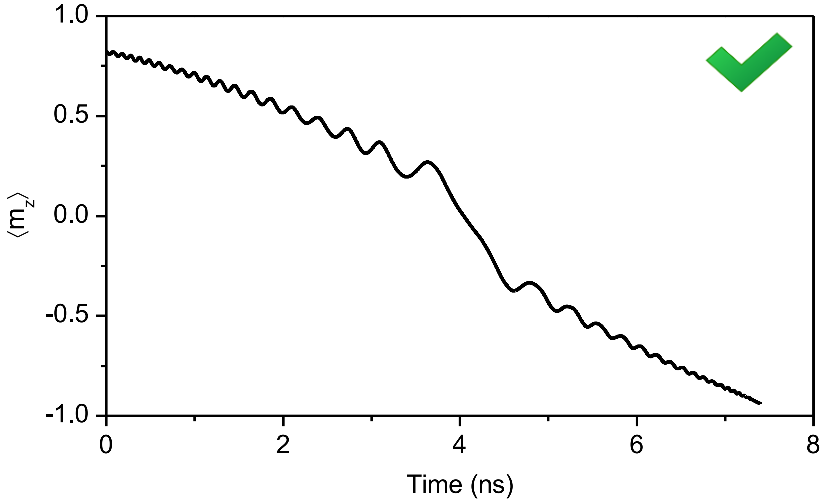


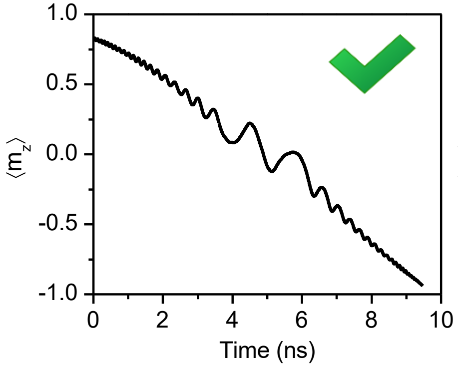
Disk 1D model:

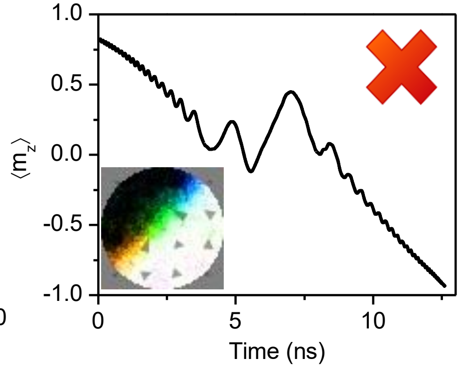


$$\omega_q = 2\omega_\varphi \approx \gamma_0 H_{stretch}$$
$$\|\dot{q}\| = \sigma j - \alpha\, \gamma_0 H_{stretch}$$
$$D_{osc} \approx \Delta \frac{H_{DW}}{H_{stretch}}$$

DW micromagnetics:







- Drift + coupled oscillations ok.
- Change of frequency ok.
- Rare events first type ok.
- Need more than 1D to explain strong move backs.

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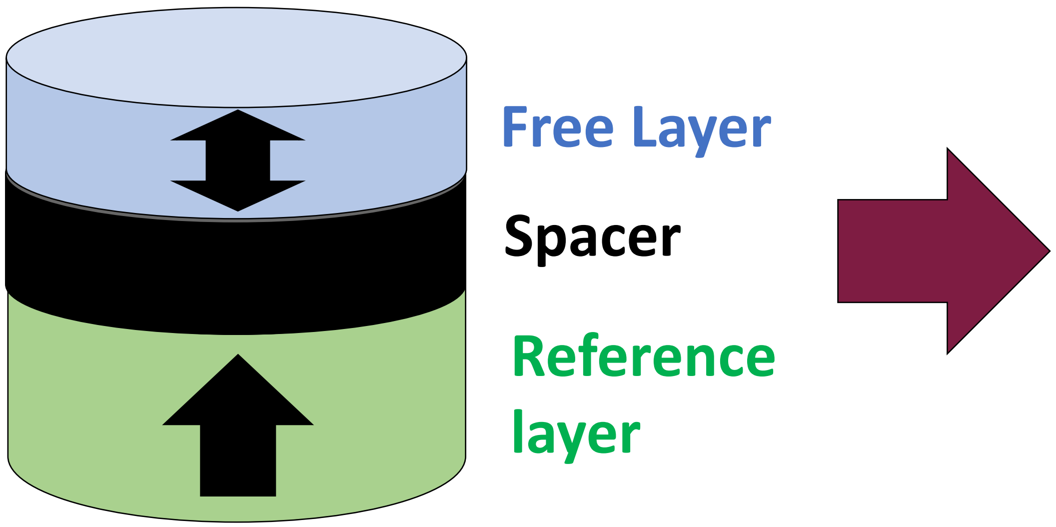
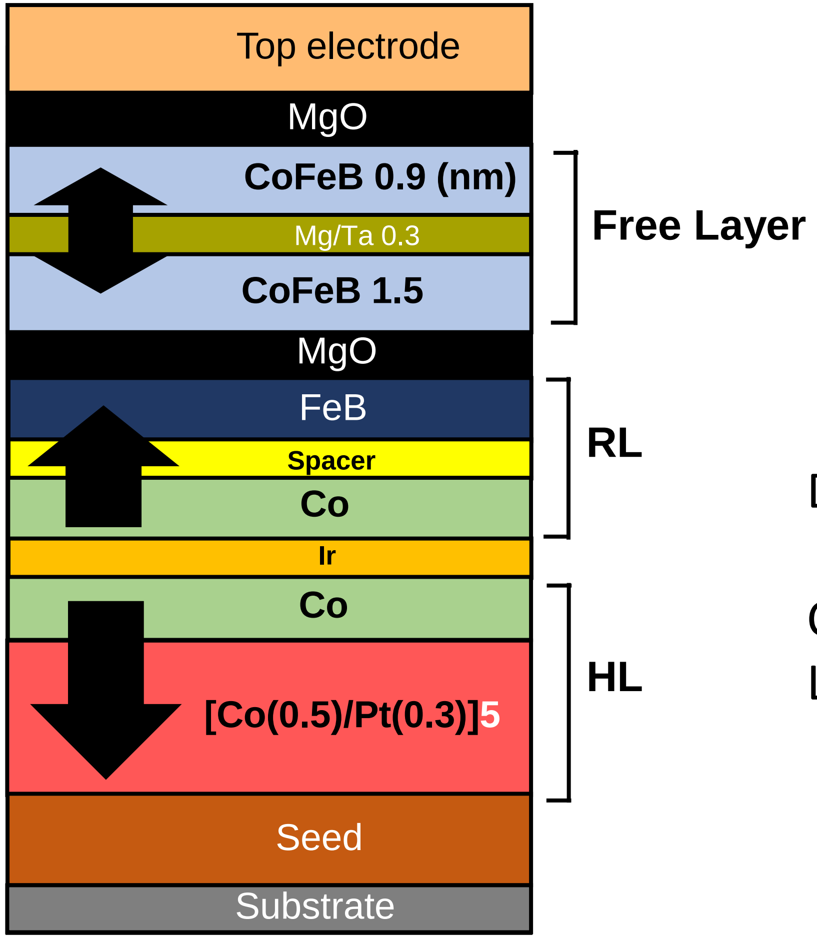
STTMRAM stack

Introduction:



Real stack:

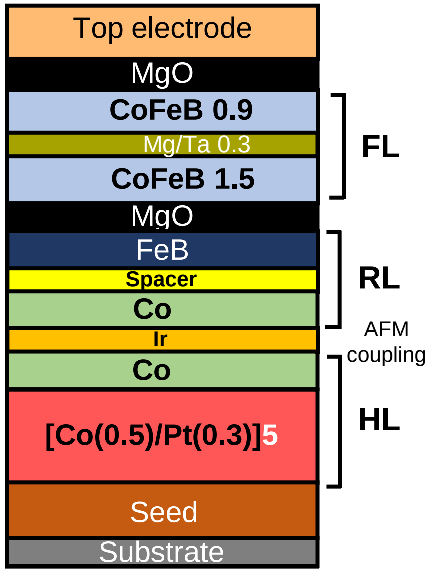


Dual MgO Free Layer.

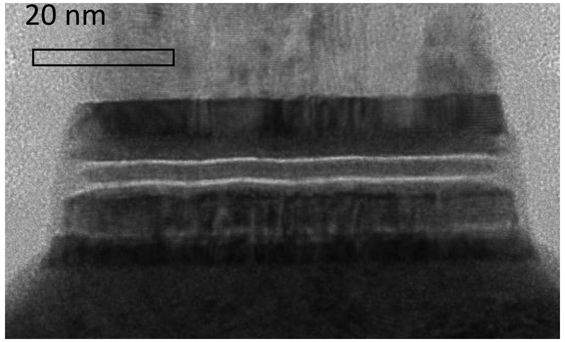
Compensated Reference Layer.

STTMRAM devices

Stack:



Pillar in TEM:



- Devices from IMEC optimized for applications.
- Patterned into pillars down to 26 nm electrical cd.
- Static properties:

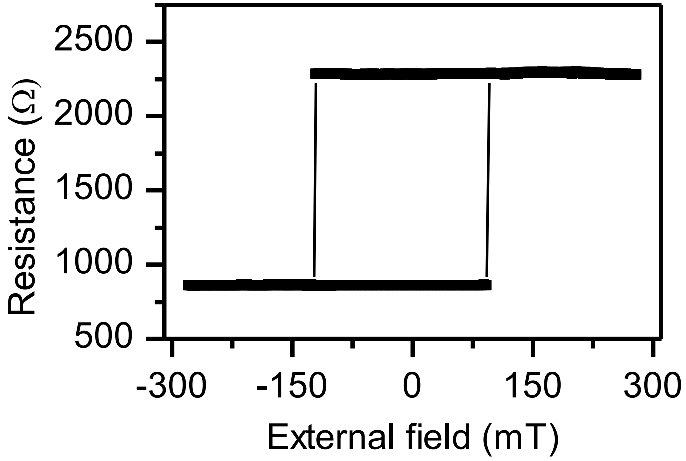
  Strong TMR.

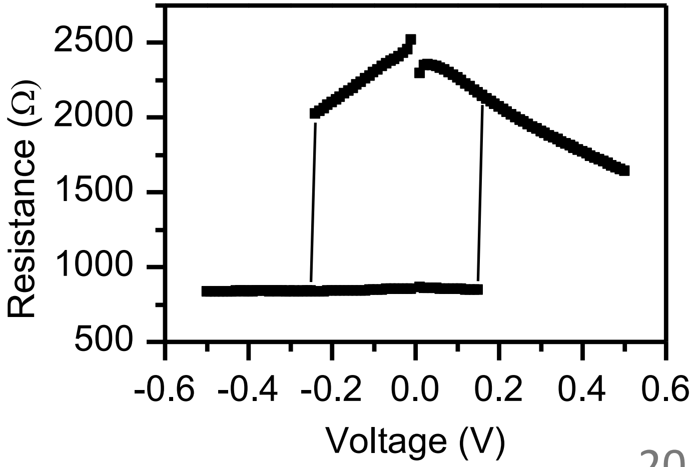
  Low offset field.

  Dc switching voltage about 0.2 V.

  Good memory devices.

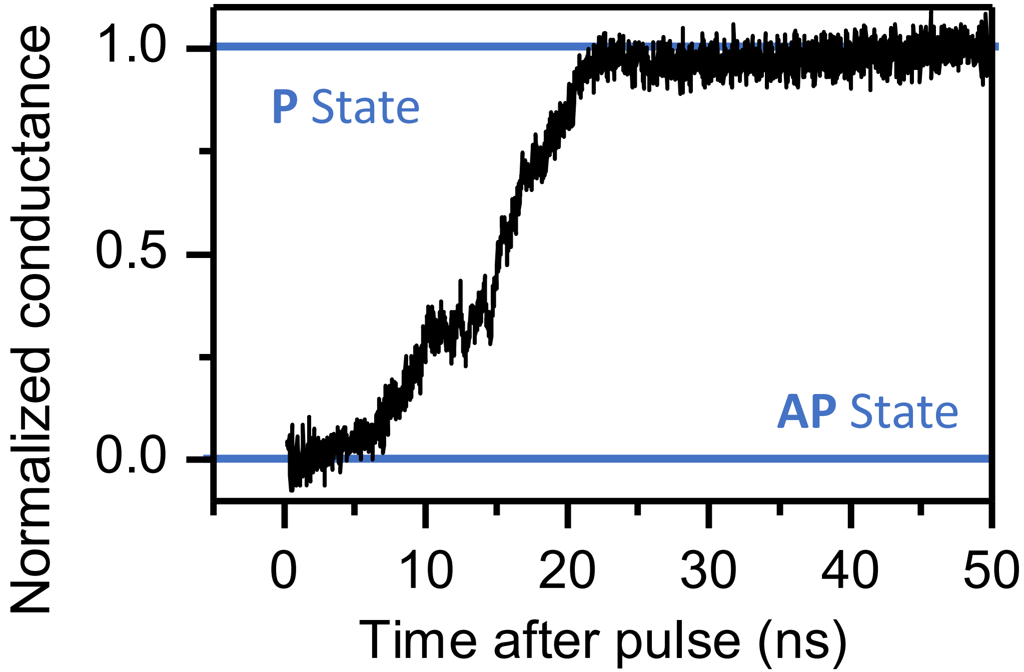
Static properties:





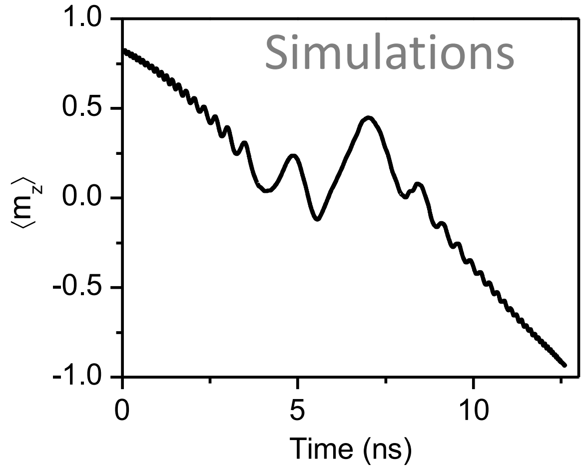
Time-resolved measurements

- We send a voltage pulse.
- We recover the conductance vs time with an oscilloscope.
- We remove experimental artifacts.



Normalized conductance: **0 to 1 for AP to P**.

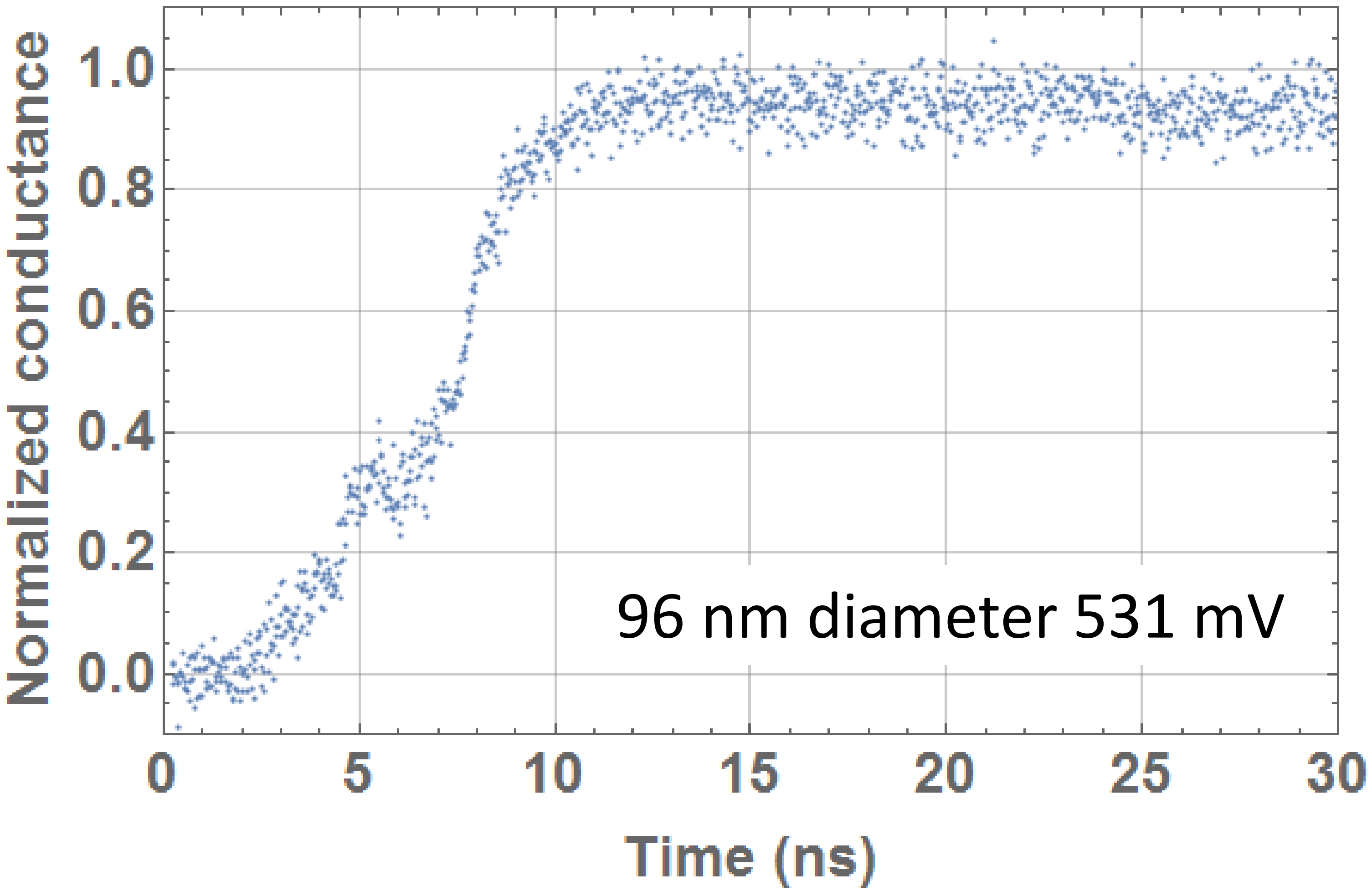
Average magnetization similar to $\langle m_z \rangle (t)$.



Stochasticity of the switching path

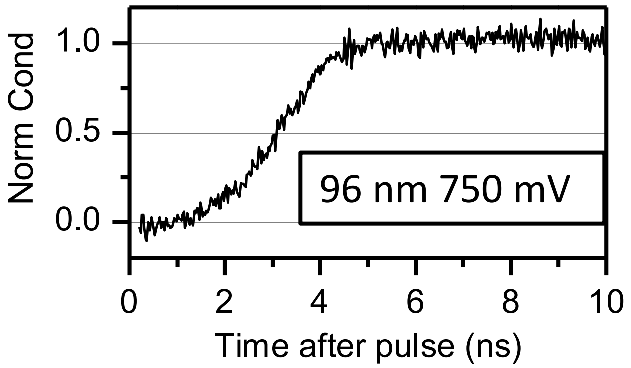
Stochasticity of the switching path

- Even at a single voltage and diameter.
- We vary voltage (0.3 to 1 V). And diameter (25 to 150 nm).

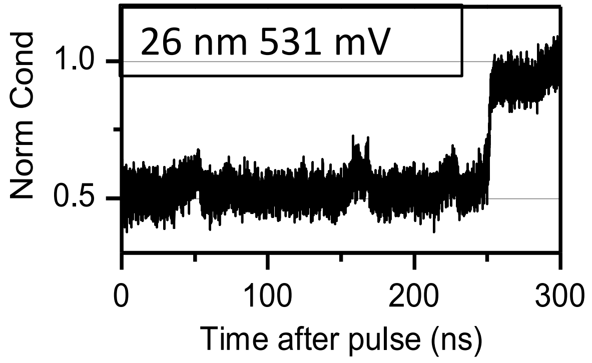


Zoology of the switching

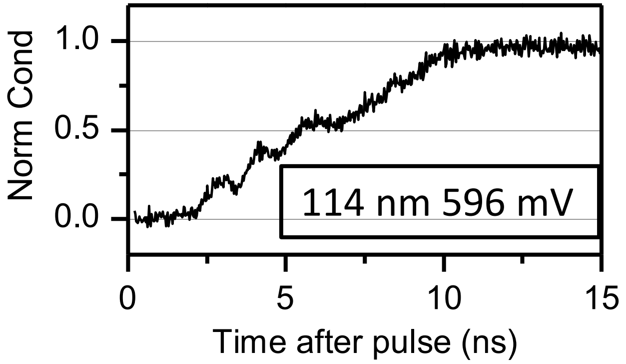
Most common: <u>ballistic</u>



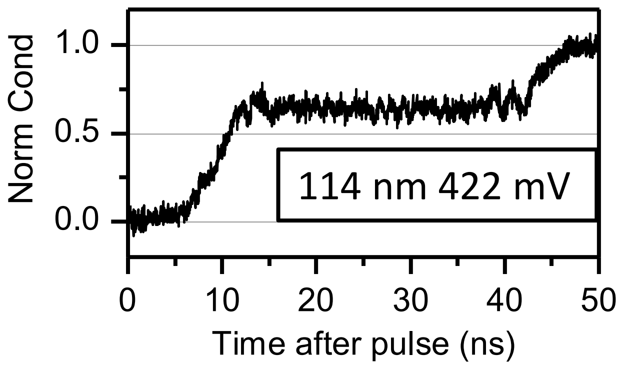
Common small size, low voltage: <u>failed trial</u>



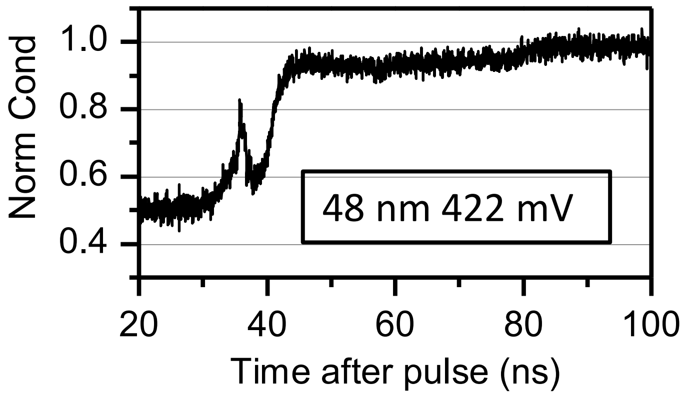
Rare event: <u>oscillations</u>



Common large size, Weak voltage: <u>pinning</u>



Rare event: <u>move-backs</u>

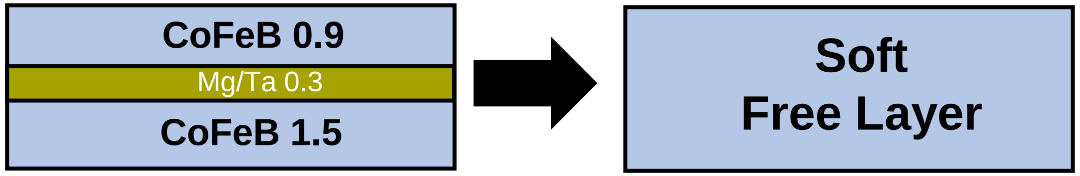


No clear cutoff size between 26 and 150 nm, save for the pinning.

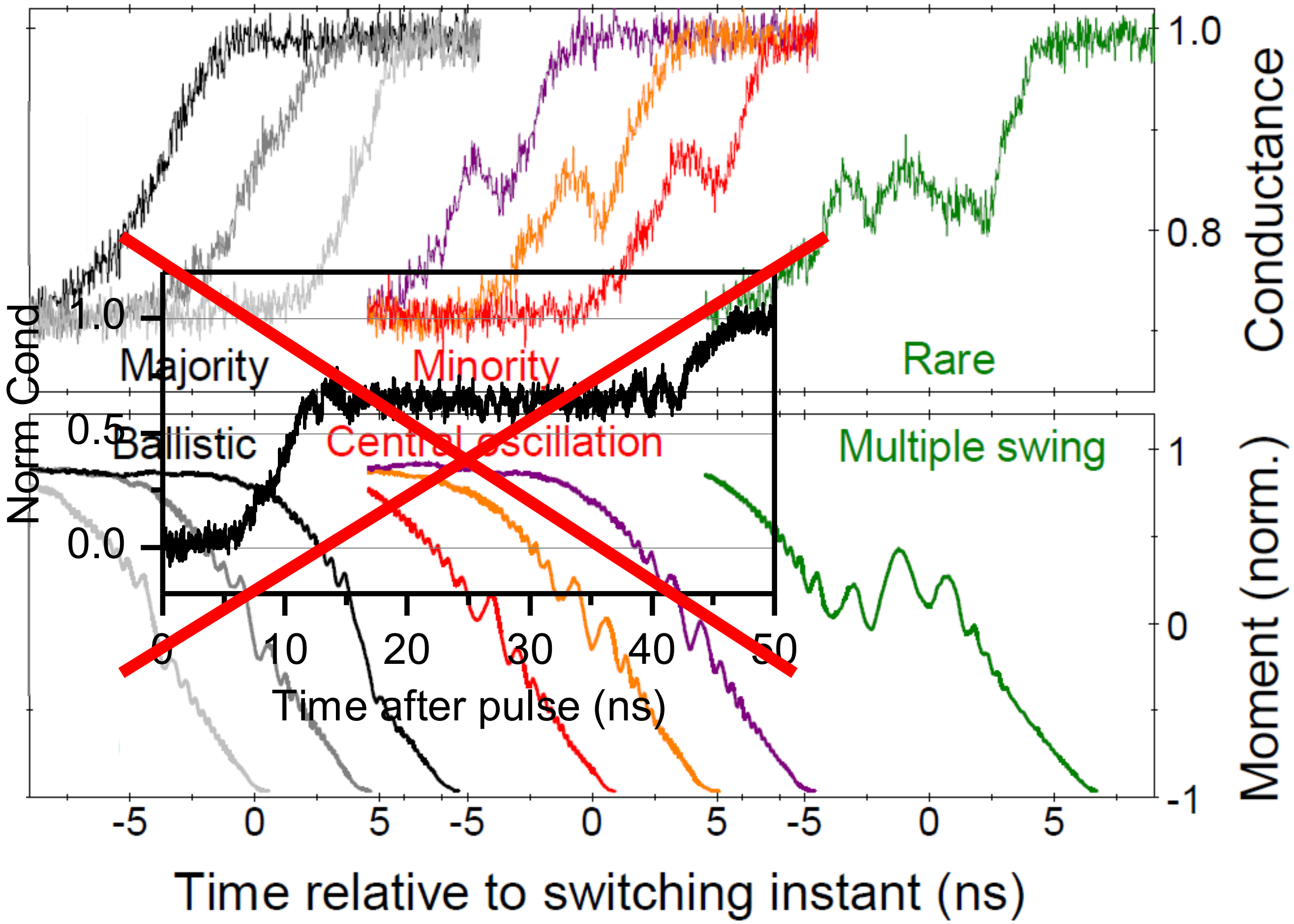
Complex effects. **Our models are not sufficient.**

Walker oscillations in smooth samples

Dual MgO Free Layer



Events measured in soft sample vs simulations



- Engineered free layer with no spacer and very well compensated offset field.
- Pinning is not observed.
- Walker oscillations predicted by our models are observed

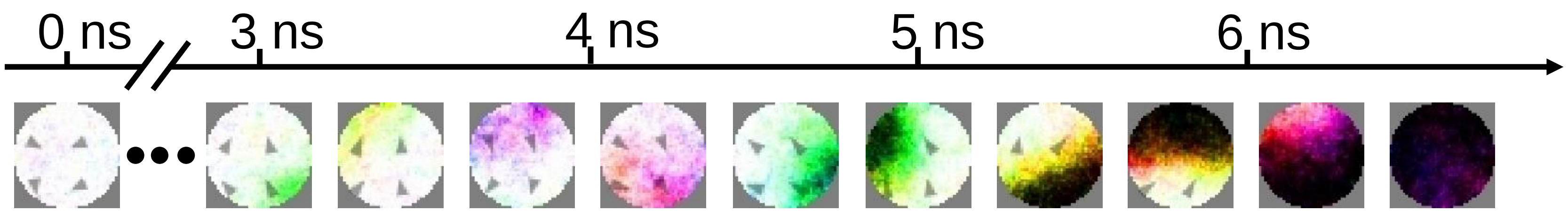
Intrinsic dynamics

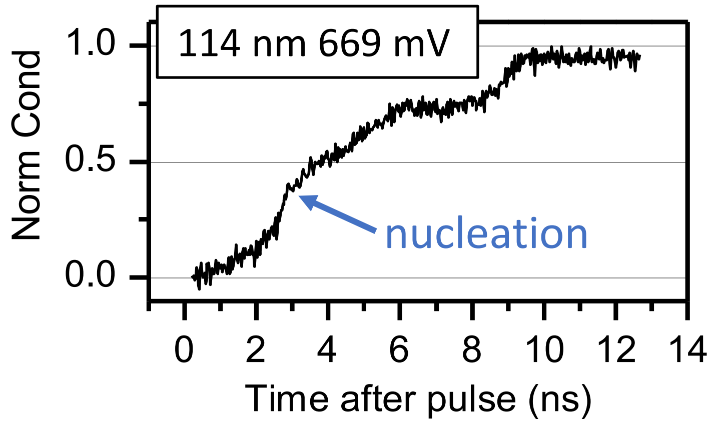
Conclusion 1/2

What is the switching path in spin transfer torque random access memories?

- We tried to answer this question by comparing micromagnetics of a perfect free layer with measurements.

- In devices between 26 to 150 nm, the initial stage of the switching is most likely the amplification of a coherent precession. Followed by a domain wall nucleation and motion.

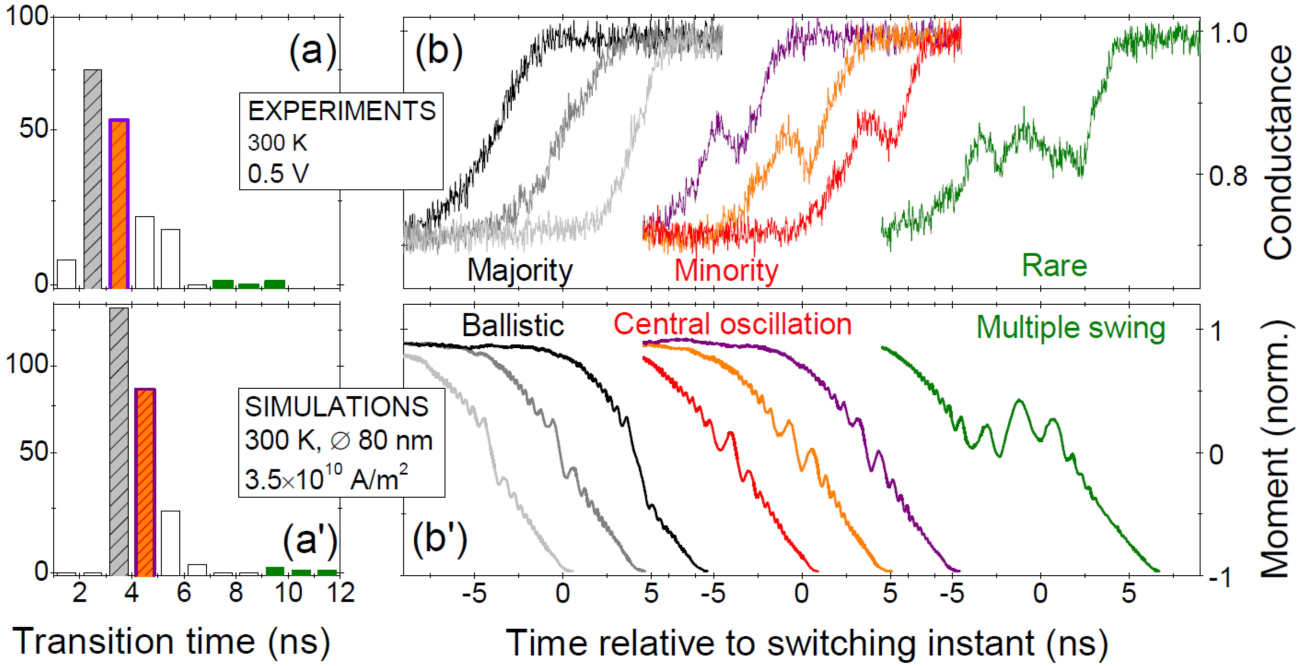


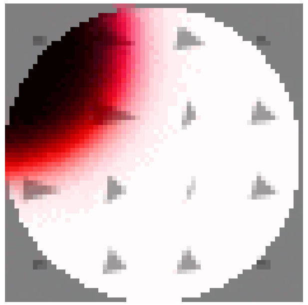


Conclusion 2/2

What is the switching path in spin transfer torque random access memories?

- The complex domain wall motion was studied with a good agreement between micromagnetics, analytical model and our measurement.
- The intrinsic dynamics are only observed in soft free layer devices.





Context of this work

Partnership

What is done:

- High frequency measurements.
- Micromagnetic simulations.
- Magnetization dynamics.

The NOMADE group:

Thibaut Devolder
Joo-Von Kim
Jean-Paul Adam
Claude Chappert

What is done:

- Stack design and deposition.
- Sample patterning.
- Funding.

The memory team:

Siddarth Rao
Sebastien Couet
Johann Swerts
Gouri Sankar
and others …