Current-driven domain wall switching in multilayer exchange spring nanopillars

M. Franchin[1], T. Fischbacher[1], A. Knittel[1], P.A.J. de Groot[2], and H. Fangohr[1]

[1] School of Engineering Sciences, University of Southampton (UK)

[2] School of Physics and Astronomy, University of Southampton (UK)

e-mail: `franchin@soton.ac.uk`

CMMP09, 16-12-2009

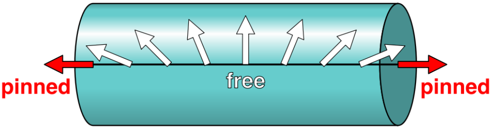
Outline of the talk

Idea: a domain wall responds "better"
to the application of a current
if it can rotate around its axis

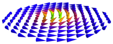
- a novel domain wall (DW) structure: **rotating DW**
- **the physics** of a rotating DW
- **analytical** considerations
- **pushing** the DW through a potential barrier

The system: rotating DW

In this talk we call **rotating domain wall** a Néel domain wall which is *constrained* in space, but *free to rotate* around its axis.



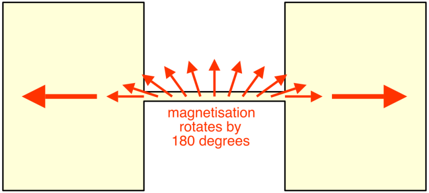
- ferromagnetic cylindrical nanopillar;
- magnetisation pinned along opposite directions at opposite faces of the cylinder;
- energy degeneracy: magnetisation free to rotate;
- inducing rotation does not "cost" any energy!



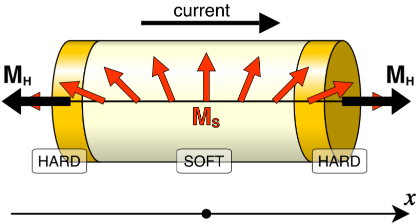
Possible realisations

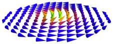
Possible ways of constraining a domain wall:

(a) geometrically

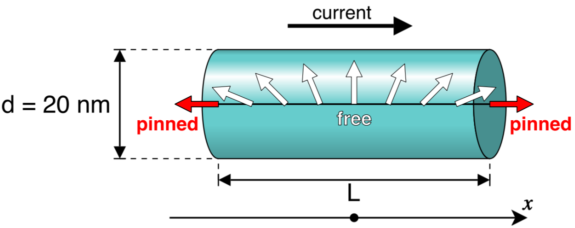


(b) exchange spring





Micromagnetic simulations



- Finite Element discretisation (Nmag, `http://nmag.soton.ac.uk`)
- Rigid pinning at opposite faces of cylinder ($\frac{\mathrm{d}\vec{M}}{\mathrm{d}t} = 0$)
- Applying current $j_\mathrm{P} = Pj = 10^{11}\ \mathrm{A/m^2}$ along the axis (positive x direction)
- zero applied field, $\vec{H}_\mathrm{app} = 0$
- Neglecting Oersted field and heating

Spin-currents in simulations

Zhang-Li correction to the LL equation (PRL 98, 187202 (2007)):

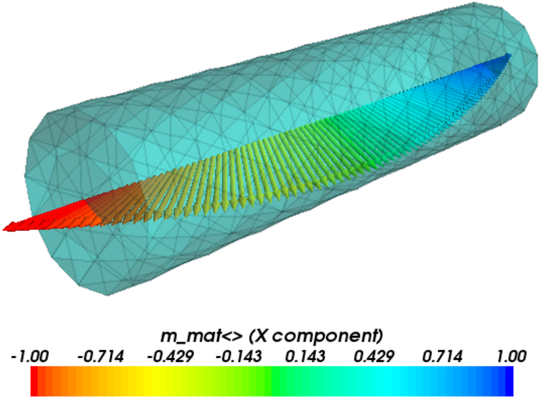
$$
\begin{aligned}
\frac{\mathrm{d}\vec{M}}{\mathrm{d}t} &= -\gamma\,\vec{M}\times\vec{H} + \frac{\alpha}{M_\mathrm{s}}\,\vec{M}\times\frac{\mathrm{d}\vec{M}}{\mathrm{d}t} \\
&\quad -\frac{v}{M_\mathrm{s}^2}\,\vec{M}\times\left(\vec{M}\times\frac{\mathrm{d}\vec{M}}{\mathrm{d}x}\right) - \frac{\xi v}{M_\mathrm{s}}\,\vec{M}\times\frac{\mathrm{d}\vec{M}}{\mathrm{d}x}
\end{aligned}
$$

where,

$$
v = \frac{Pj\mu_B}{eM_\mathrm{s}(1+\xi^2)},
$$

P is the spin-polarisation and ξ a dimensionless number, expressing the “degree” of non-adiabaticity.

Animation



Precession frequency as a function of time

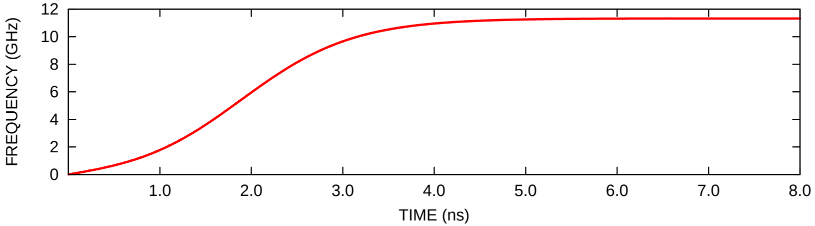
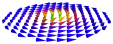


Figure: Time-evolution of the precession frequency.

The frequency of rotation of $\langle \vec{M} \rangle$ around the nanopillar axis increases monotonically toward an **asymptotic value**.



Asymptotic frequency as function of j and L

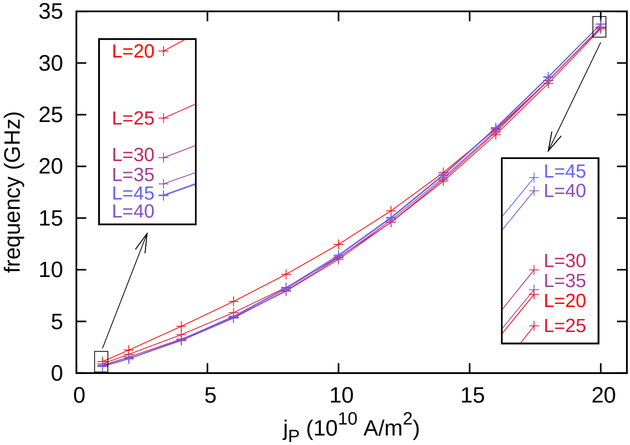
Result:

- Direct current (DC) gives rise to stationary precession!
- Nano-oscillator which requires no applied field!
- Could be used as a microwave generator!

How does the asymptotic frequency depend on the current density, j, and the nanopillar length, L?

Asymptotic frequency as function of j and L

We carry out several simulations for different values of j and L:



Analytical results

One dimensional analytical model [PRB 78, 054447 (2008)]: frequency ν as a function of current density j and damping α.

A critical current j_c can be identified, $j_\mathrm{c} = \frac{2e\gamma}{\mu_0 \mu_B} \frac{\alpha A}{L}$, and,

- LINEAR REGIME: $\boxed{\nu \propto \frac{j}{\alpha L} \text{ for } j \ll j_\mathrm{c}}$
  - **no deformation** of DW
  - precession frequency increases **linearly** with the current

- QUADRATIC REGIME: $\boxed{\nu \propto \left(\frac{j}{\alpha}\right)^2 \text{ for } j \gg j_\mathrm{c}}$
  - **DW deformed** by current (gets compressed)
  - precession frequency increases **quadratically** with current

Validation of the analytical model

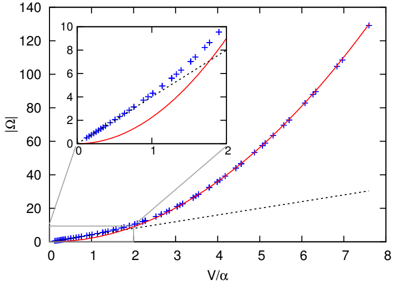


Figure: Analytical model (solid and dashed lines) and 1D micromagnetic simulations (blue crosses).

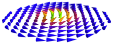
We obtained formulas for frequency as function of applied current j and nanopillar length L:

$$\nu = \begin{cases} \frac{2}{\pi^2} \frac{v}{\alpha L} & \text{for } j \ll j_c \\ \frac{1}{2\pi\,\gamma C} \left(\frac{3}{2} \frac{v}{\alpha} \right)^2 & \text{for } j \gg j_c \end{cases}$$

Recall that:

$$v = \frac{\mu_B P j}{e M_s (1 + \xi^2)} \propto j.$$

NOTE: j always appears as j/α



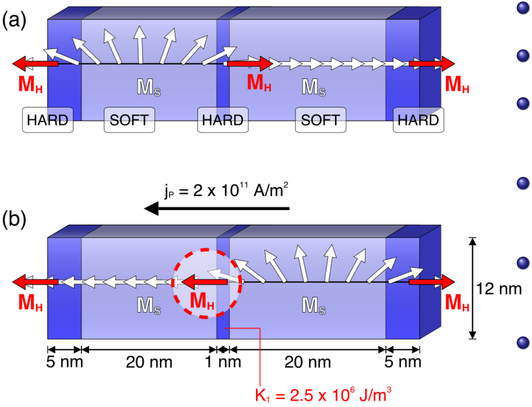
Energy pumping in the quadratic regime

In the **quadratic regime**, the DW is compressed
$\Rightarrow$ **energy is pumped** into the DW!

IDEA:

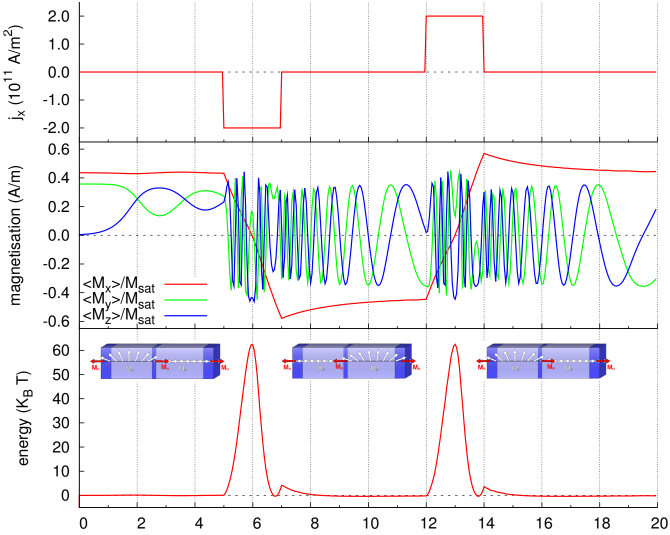
Use such energy to overcome an energy barrier: push the domain wall through a hard layer!

Current-driven switching of DW



- five-layer nanopillar
- square cross section (12 nm)
- "rigid" pinning in external layers
- "weak" pinning in central layer
- two stable states: DW on the left, DW on the right
- current to switch between the two states

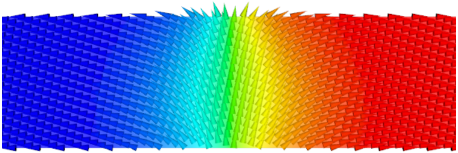
Current-driven switching of DW

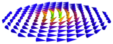


(energy in $K_B T$, for $T = 300$ K)

Doubt:

Is this the usual current-driven domain wall motion?



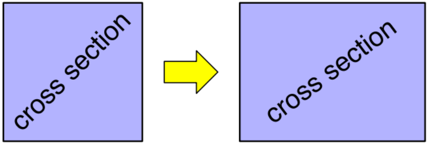


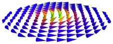
Doubt:

Is the rotation important at all?

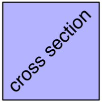
What happens if the DW is not free to rotate?

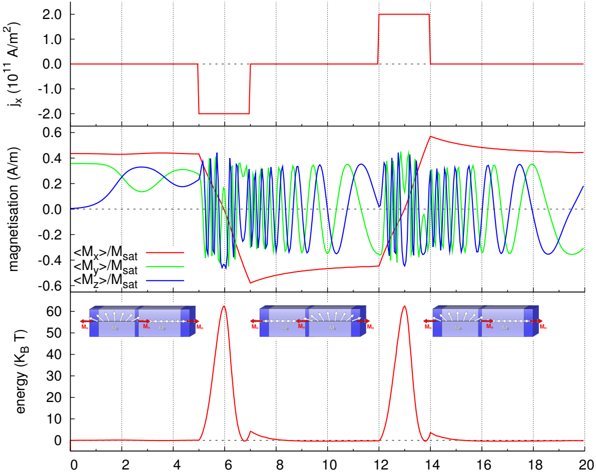
For example, let's choose a rectangular cross section...





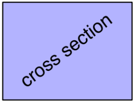
What happens with a rectangular cross section?

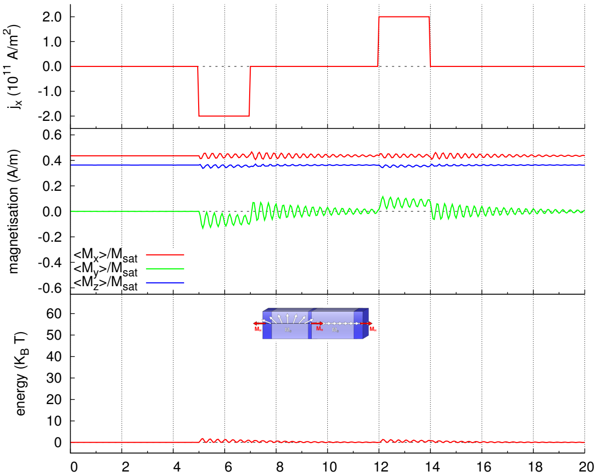




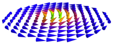
The DW is **not free to rotate**: nothing happens then!

What happens with a rectangular cross section?





The DW is **not free to rotate**: nothing happens then!



Conclusion:

A rotating DW can do things that a conventional DW can not!

It can:

- get in a **stationary precession** motion (microwave generation)
- **absorb** relevant quantities of **energy** (compression)

Summary

- A rotating domain wall can be used for **microwave generation** and
- Can be **pushed** effectively through a potential barrier
- New **switching** mechanism for MRAM?
- For more info, see:
  M. Franchin *et al.*, J. Appl. Phys. 103, 07A504 (2008)
  M. Franchin *et al.*, Phys. Rev. B 78, 054447 (2008)

Acknowledgement: The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n$^\circ$ 233552, and from EPSRC (EP/E040063/1)

Thank you!

Summary

- A rotating domain wall can be used for **microwave generation** and
- Can be **pushed** effectively through a potential barrier
- New **switching** mechanism for MRAM?
- For more info, see:
  M. Franchin *et al.*, J. Appl. Phys. 103, 07A504 (2008)
  M. Franchin *et al.*, Phys. Rev. B 78, 054447 (2008)

Acknowledgement: The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n° 233552, and from EPSRC (EP/E040063/1)

Thank you!