Pushing Domain Walls with Spin Polarized Currents in Cylindrical Nanowires

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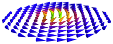
MMM 2010 - Atlanta, 16$^{\mathrm{th}}$ Nov 2010



Outline of the talk

- motion of DWs through potential barriers,
- cylindrical nanowires with small diameter,
- rotational symmetry deeply affects the DW properties,
- depending on how the barrier pins the magnetization the critical current density changes of a factor 130.

Introduction

DWs in cylindrical nanowires/nanopillars:

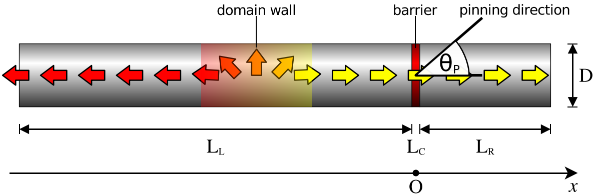
can be used as:

- **nano oscillators:** [PRB 78, 054447 (2008); Appl. Phys. Expr. 1, 061301 (2008)]
- **as better behaved DWs:** no walker breakdown, zero depinning current [PRL 104, 057201 (2010); PRB 82, 144430 (2010)]

Problem: need very small nanowires. (for Permalloy $\varnothing \lesssim 50$ nm) Experimental difficulties in building such systems!

Why? Transition Transverse DW $\Rightarrow$ Vortex DW

The idea



- Long cylindrical nanowire. Small diameter, $D \lesssim 50\,\mathrm{nm}$,
- Barrier: region with extra anisotropy which pins magnetisation
- DW sitting on the left, pushed using applied field/electric current
- Determine H_{crit}, j_{crit} as function of the pinning angle θ_{P}

The method

Dynamics from the Landau Lifshitz equation extended with STT effects [PRL 93, 127204 (2004)]

$$\frac{\mathrm{d}\vec{M}}{\mathrm{d}t} = -\gamma\,\vec{M}\times\vec{H} + \frac{\alpha}{M_\mathrm{s}}\,\vec{M}\times\frac{\mathrm{d}\vec{M}}{\mathrm{d}t} + v\,\frac{\mathrm{d}\vec{M}}{\mathrm{d}x} - \frac{\xi v}{M_\mathrm{s}}\,\vec{M}\times\frac{\mathrm{d}\vec{M}}{\mathrm{d}x}$$

Barrier modeled as localized uniaxial anisotropy which **pins the magnetization on the barrier**:

$$U_\mathrm{barrier} = -K_1\,(\vec{m}\cdot\vec{a})^2$$

$\vec{m} = \frac{\vec{M}}{M_\mathrm{s}}$, $\vec{a}$ is the pinning direction, K_1 the pinning strength.
Discretized using finite element method (unreleased version of Nmag, http://nmag.soton.ac.uk)

The method

Determine H_{crit} and j_{crit} in **two stages**:

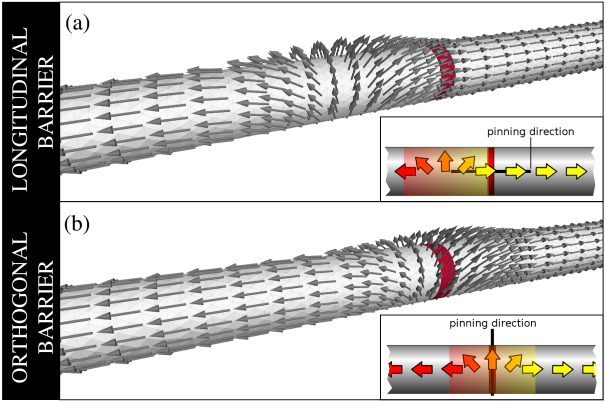
PREPARATION:
the DW is relaxed and pushed weakly towards the barrier using a field/current

MAIN SIMULATION:
the field/current is gradually increased until the DW passes through the barrier

The dynamics of the DW is studied by looking at the average magnetization...

Prepared states

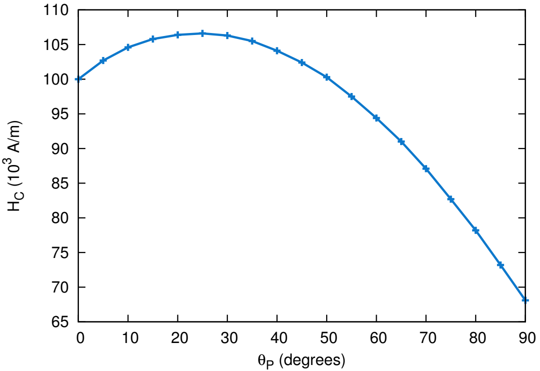
When pushing a DW towards the barrier. . .



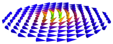
These are the initial states in the two cases.

Field-driven DW pushing

The field, H_{crit}, required to push the DW through the barrier as function of the pinning angle in the barrier.

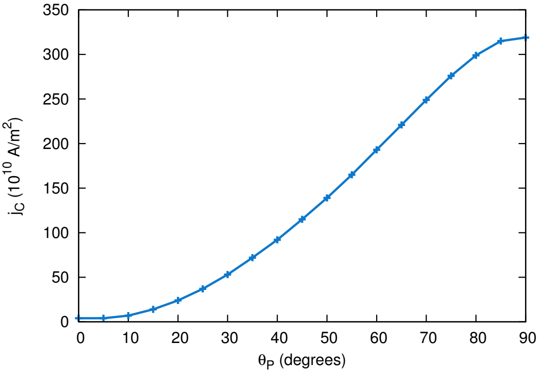


- H_{crit} varies between 68.05 and 106.65 KA/m
- minimum for $\theta_{\mathrm{P}} = 90^{\circ}$
- maximum for $\theta_{\mathrm{P}} = 0^{\circ}$
- **reduced** by 36% when going from 0° to 90° (likely due to magnetostatic field)

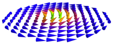


Current-driven DW pushing

The current density, j_{crit}, required to push the DW through the barrier as function of the pinning angle in the barrier.



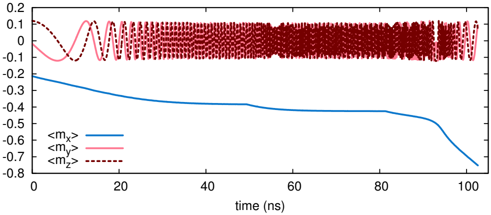
- j_{crit} varies between 0.0239 and 3.185 $\times 10^{12}\ \mathrm{A/m^2}$
- minimum for $\theta_{\mathrm{P}} = 0^{\circ}$
- maximum for $\theta_{\mathrm{P}} = 90^{\circ}$
- **increased** by a factor **130** when going from 0° to 90°



Comparison of dynamics for $\theta_P = 0^\circ$ and $\theta_P = 20^\circ$

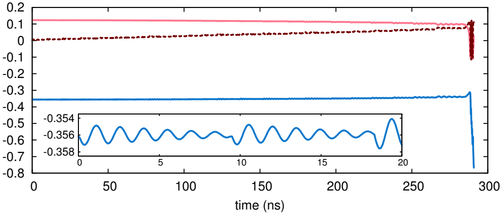
We analyze the dynamics of the normalized magnetization $\langle \vec{m} \rangle$.

$\langle m_x \rangle \Rightarrow$ DW position (-0.5 at barrier) $\langle m_y \rangle, \langle m_z \rangle \Rightarrow$ DW rotation



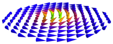
$\theta_P = 0^\circ$

- magnetization is **free to rotate**,
- **gradual and steady** compression
- accumulation of STT effect!



$\theta_P = 20^\circ$

- magnetization rotationally bound,
- $\langle m_x \rangle$ **oscillates quickly** (inset),
- but is constant on a large scale,
- sudden switching



Instant VS accumulated

$$\frac{1}{\gamma}\frac{\mathrm{d}\vec{m}}{\mathrm{d}t} = -\overbrace{\vec{m}\times\vec{H}}^{\text{Precession}} - \overbrace{\alpha\vec{m}\times(\vec{m}\times\vec{H})}^{\text{Damping}}$$
$$+\underbrace{\frac{1+\alpha\xi}{\gamma}v\frac{\mathrm{d}\vec{m}}{\mathrm{d}x}}_{\text{Adiabatic STT}} - \underbrace{\frac{\xi-\alpha}{\gamma}v\,\vec{m}\times\frac{\mathrm{d}\vec{m}}{\mathrm{d}x}}_{\text{Non-adiabatic STT}}$$

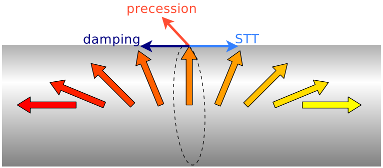


Figure: Time-evolution of the precession frequency.

Instant VS accumulated

$$\frac{1}{\gamma}\frac{\mathrm{d}\vec{m}}{\mathrm{d}t} = -\overbrace{\vec{m}\times\vec{H}}^{\text{Precession}} - \overbrace{\alpha\vec{m}\times(\vec{m}\times\vec{H})}^{\text{Damping}} + \underbrace{\frac{1+\alpha\xi}{\gamma} v \frac{\mathrm{d}\vec{m}}{\mathrm{d}x}}_{\lesssim 50\,\mathrm{KA/m}} - \underbrace{\frac{\xi-\alpha}{\gamma} v\, \vec{m}\times\frac{\mathrm{d}\vec{m}}{\mathrm{d}x}}_{\lesssim 0.5\,\mathrm{KA/m}}$$

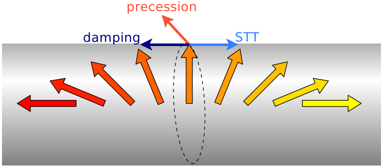


Figure: Time-evolution of the precession frequency.

Instant VS accumulated

$$\frac{1}{\gamma}\frac{\mathrm{d}\vec{m}}{\mathrm{d}t} = -\overbrace{\vec{m}\times\vec{H}}^{300\,\mathrm{KA/m}} - \overbrace{\alpha\vec{m}\times(\vec{m}\times\vec{H})}^{3\,\mathrm{KA/m}}$$

$$+\underbrace{\frac{1+\alpha\xi}{\gamma}v\frac{\mathrm{d}\vec{m}}{\mathrm{d}x}}_{\lesssim 50\,\mathrm{KA/m}} - \underbrace{\frac{\xi-\alpha}{\gamma}v\,\vec{m}\times\frac{\mathrm{d}\vec{m}}{\mathrm{d}x}}_{\lesssim 0.5\,\mathrm{KA/m}}$$

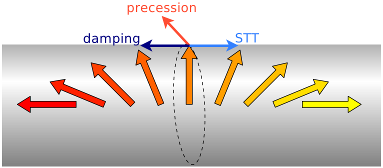


Figure: Time-evolution of the precession frequency.

Summary

- Current/field driven transverse DWs in cylindrical nanowires,
- Key role of rotational freedom/cylindrical symmetry,
- The symmetry reduces the critical current by a factor 130,
- While the critical field doesn't care about symmetry,
- Theoretical studies so far motivate experimental investigations.

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!

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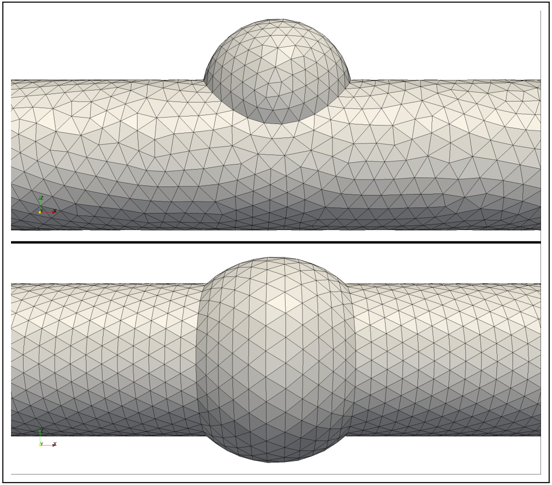
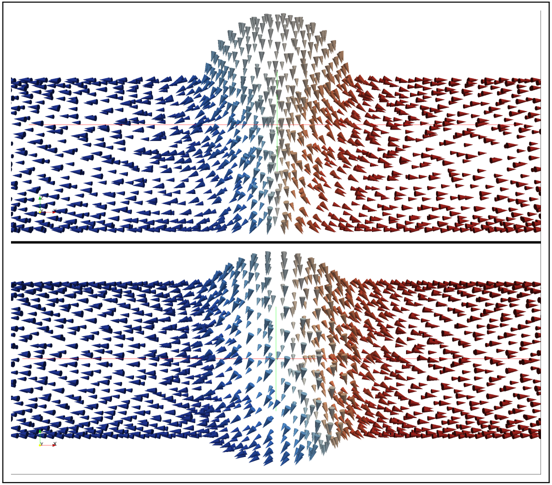
Concrete examples



Examples of symmetric and asymmetric barriers.

Concrete examples



Examples of symmetric and asymmetric barriers.