Three-dimensional magnetization textures

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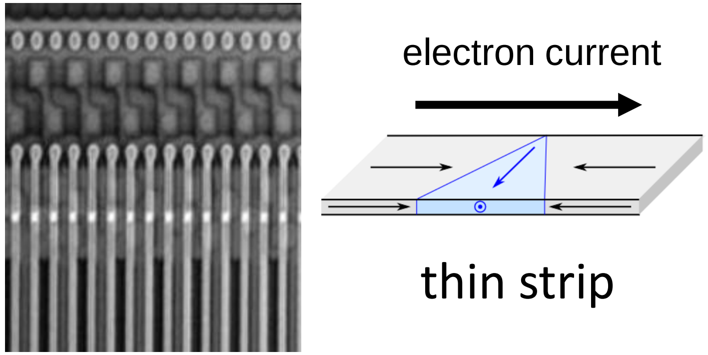
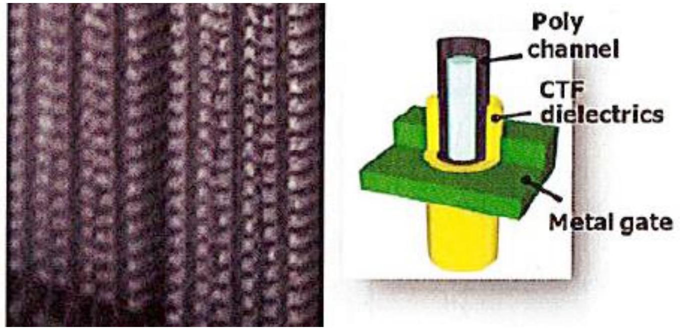
2D



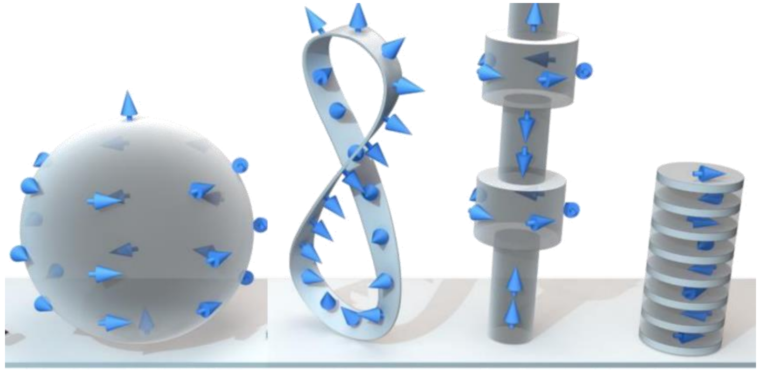
L. Thomas et al., IEEE IED meeting (2011)

3D

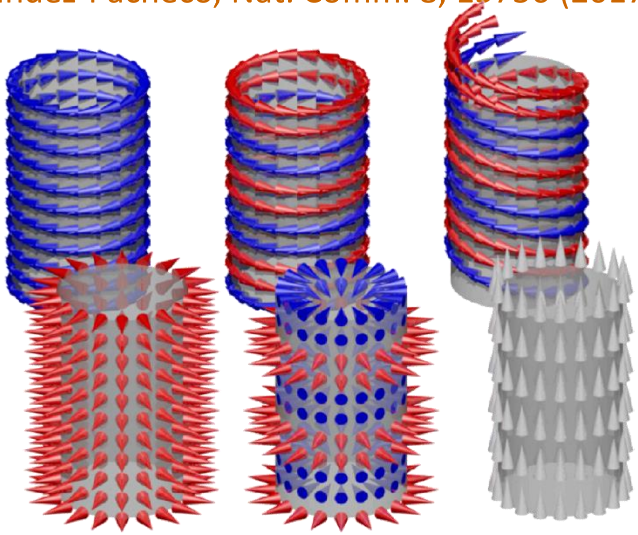


K. T. Park et al., IEEE J. Sol. State Cir. 50 (1), 204 (2015)

Magnetism in 3D structures

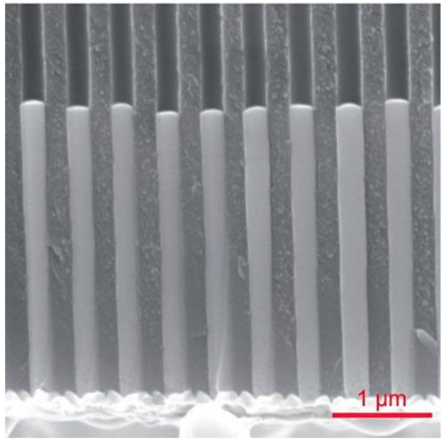


A. Fernandez-Pacheco, Nat. Comm. 8, 15756 (2017)



R. Streubel, J.Phys.D: Appl.Phys. 49, 363001 (2016)
Gaididei et al, PRL 112, 257203 (2014)
Sheka et al, JPhys. A Math Theor. 48, 125202 (2015)

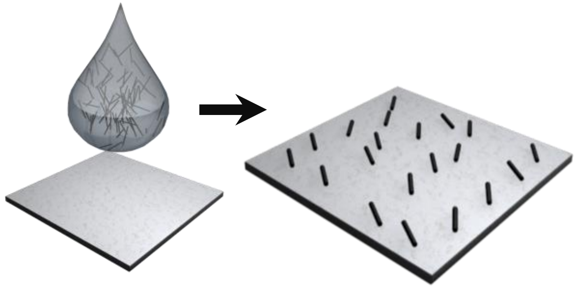
Electrodeposition of nanowires



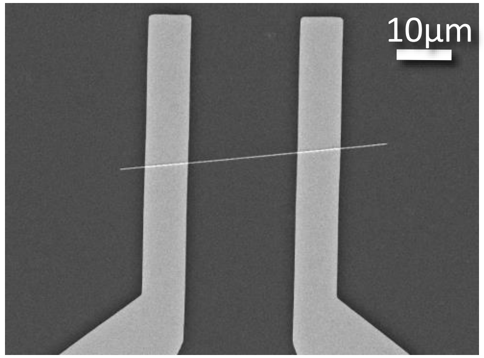
S. Bochmann *et al.*, RSC Adv., **7**, (2017)

- Electrochemical synthesis
- Tens of micrometres long
- Tens of nanometres diameter
- Materials: Ni, Co_xNi_y, $Fe_{0.2}Ni_{0.8}$

Nanowire dispersion

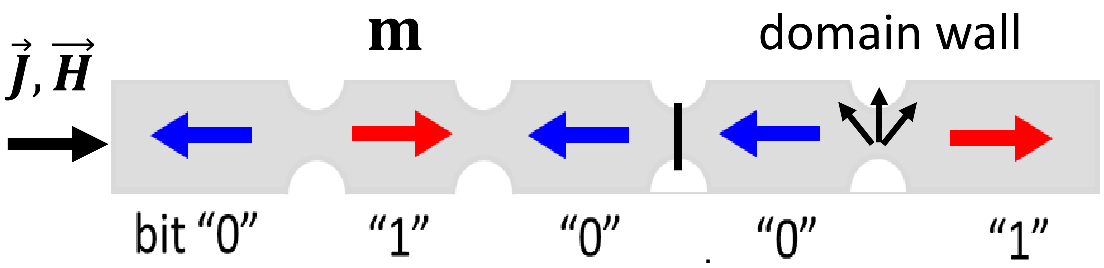


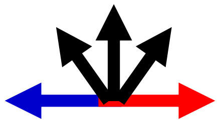
Ohmic contacts: isolated nanowire



Measured resistivities close to bulk values

Domain wall based magnetic memory

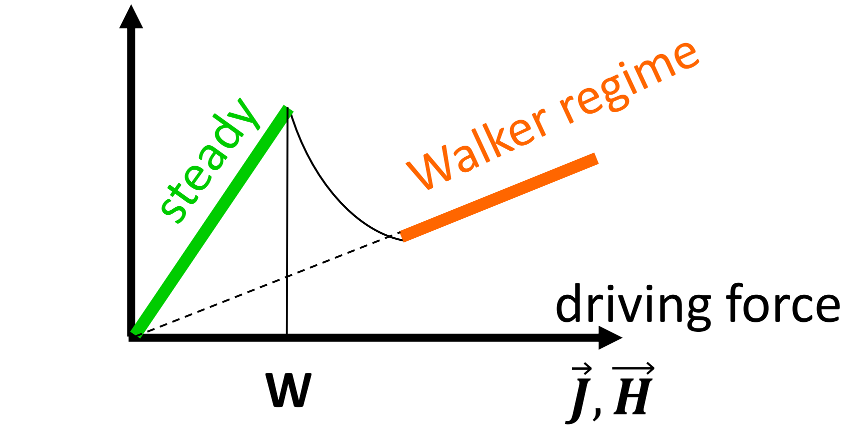




Magnetic texture properties to be studied:

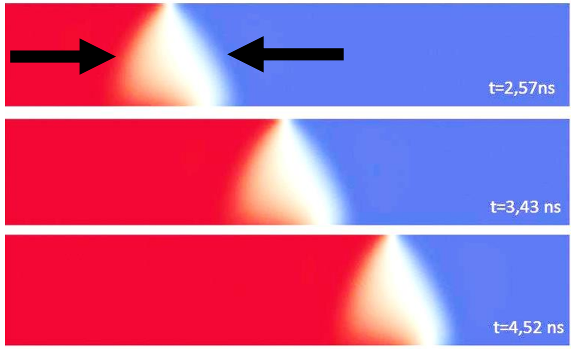
- DW type
- DW stability
- DW velocity

Example: dynamics in 2D strips



Steady regime

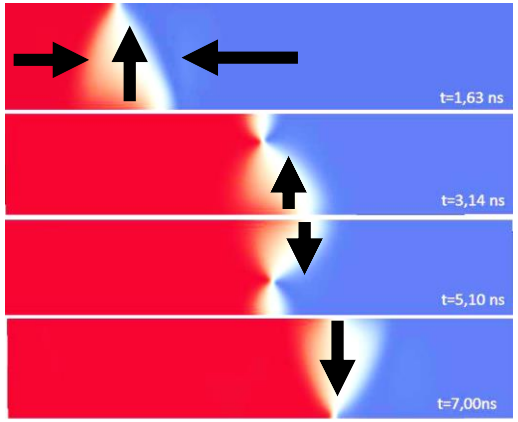
- no DW deformation
- high DW velocity



Transverse DW

Walker regime

- DW deformation
- slow DW



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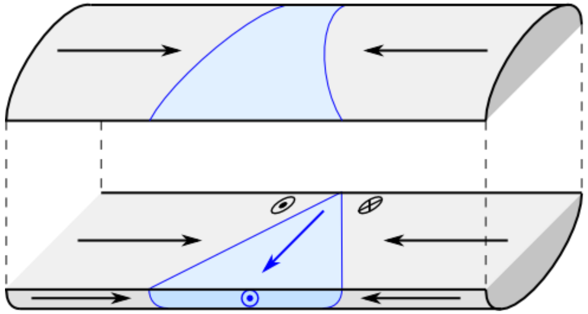
3D

Transverse Vortex wall TVW

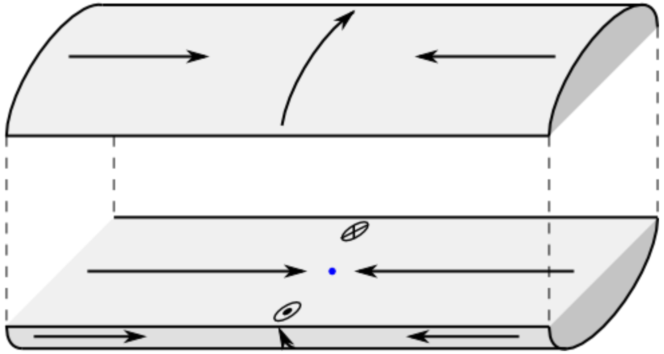
diam<7·l_{ex}



Walker = 0

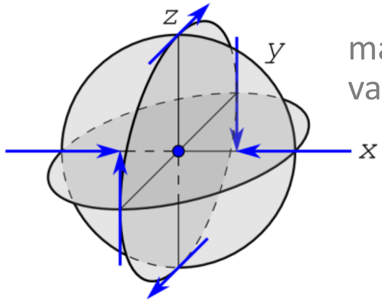
Bloch-Point wall BPW

diam>7·l_{ex} (here ∅ 90-200nm)



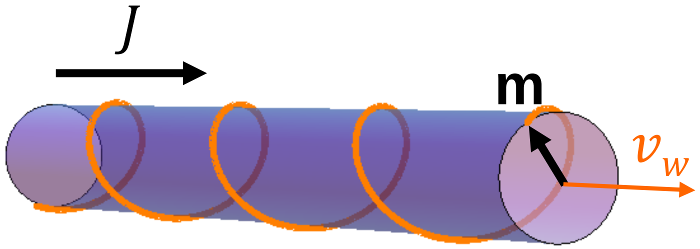
Walker → ∞

$$l_{ex} = \sqrt{\frac{2A}{\mu_0 M_s^2}}$$ exchange length

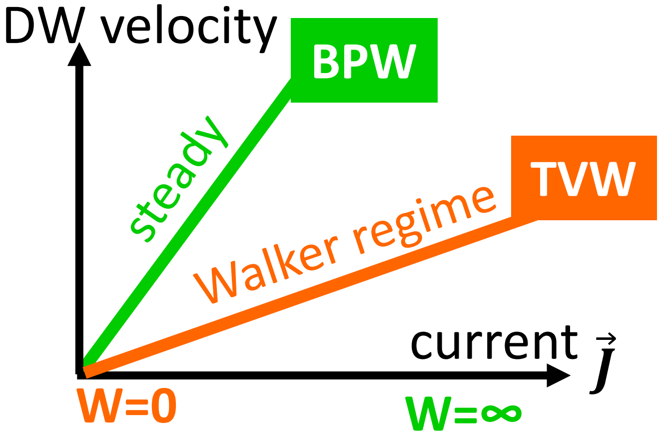


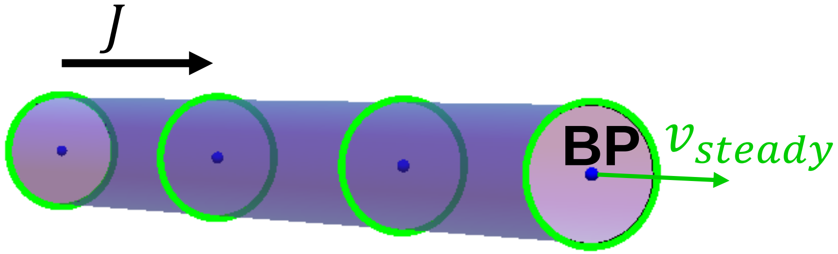
magnetic texture with local vanishing of magnetization

Döring, J. Appl. Phys., 39 (1968)
Feldtkeller, Z. Angew. Physik, 19 (1965)
Yan et al, PRL 104, 057201 (2010)
S. Da Col *et al.*, PRB, 89 (2014),
Fernández-Pacheco *et al.*, Nat. Comm., 8 (2017)



$v_{walker} \propto J$



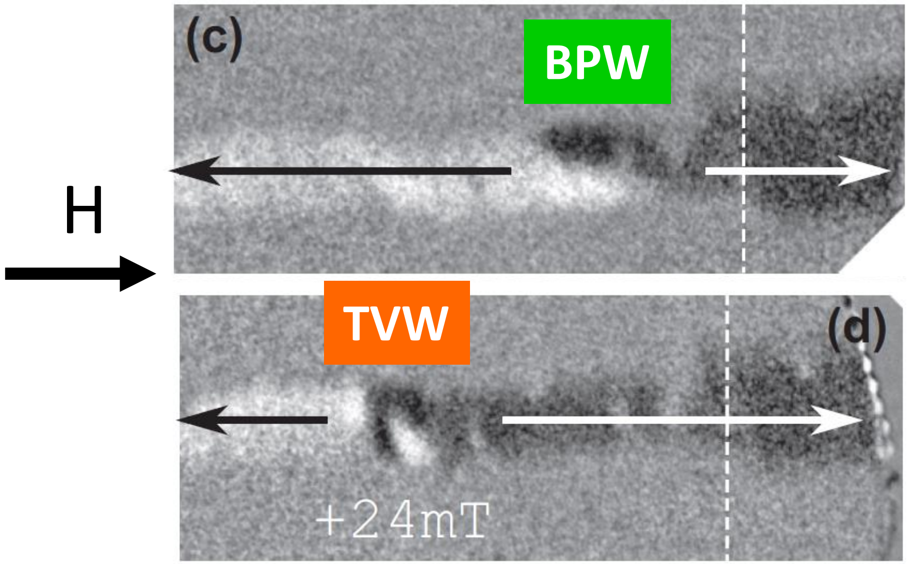


$v_{steady} \propto \frac{\beta}{\alpha} J$

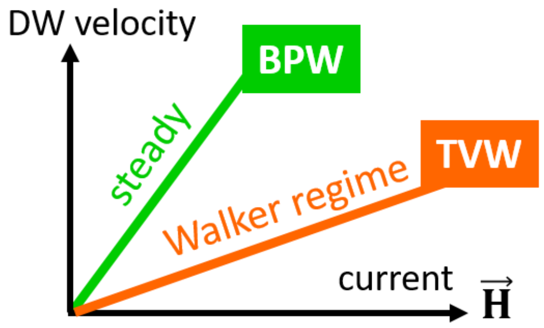
magnetically soft materials: $\beta > \alpha$

Bloch Point wall -> TVW transformation

A. Wartelle *et al*. PRB **99**, 024433 (2019)

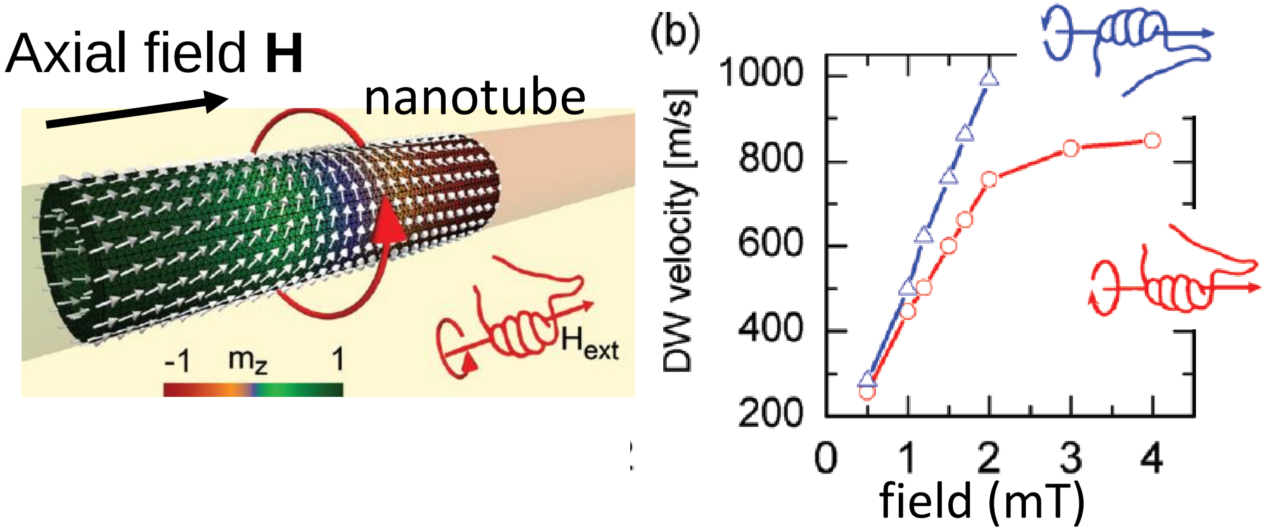


140-nm-diameter Fe20Ni80 nanowire



Velocity vs DW chirality

M. Yan *et al*. APL **100**, 252401 (2012)



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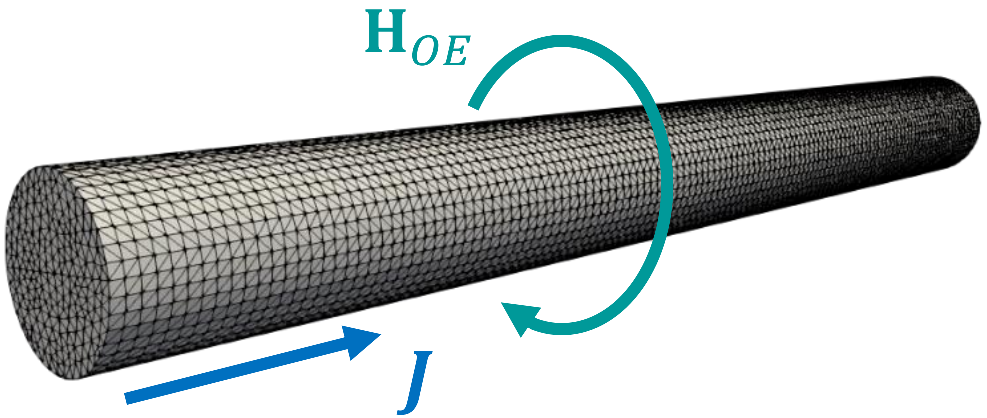
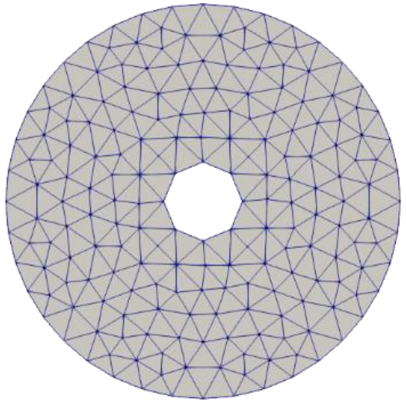
feeLLGood
finite element LLG object oriented development

http://feellgood.neel.cnrs.fr/

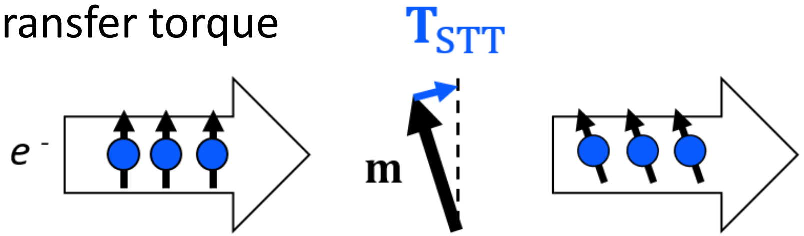




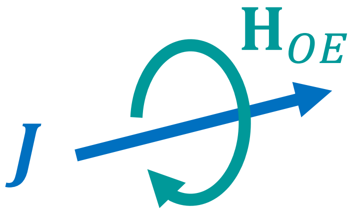
Landau-Lifshitz-Gilbert equation

$$\dot{\mathbf{m}} = \gamma_0(\mathbf{H}_{\text{eff}} + \mathbf{H}_{OE}) \times \mathbf{m} + \alpha \mathbf{m} \times \dot{\mathbf{m}} - \frac{P\mu_B}{eM_s}\{(J\cdot\nabla)\mathbf{m} + \beta\mathbf{m} \times [(J\cdot\nabla)\mathbf{m}]\}$$

Oersted field — spin-transfer torque



Oersted field



$$\mathbf{H}_{\text{Œ}}(\rho) = \frac{\rho J}{2}\mathbf{e}_\varphi$$

$$\text{D} = 90\text{nm}, J \sim 10^{12} Am^{-2}$$

$$\mu_0 H_{\text{Œ}} \sim 40\ \text{mT}$$

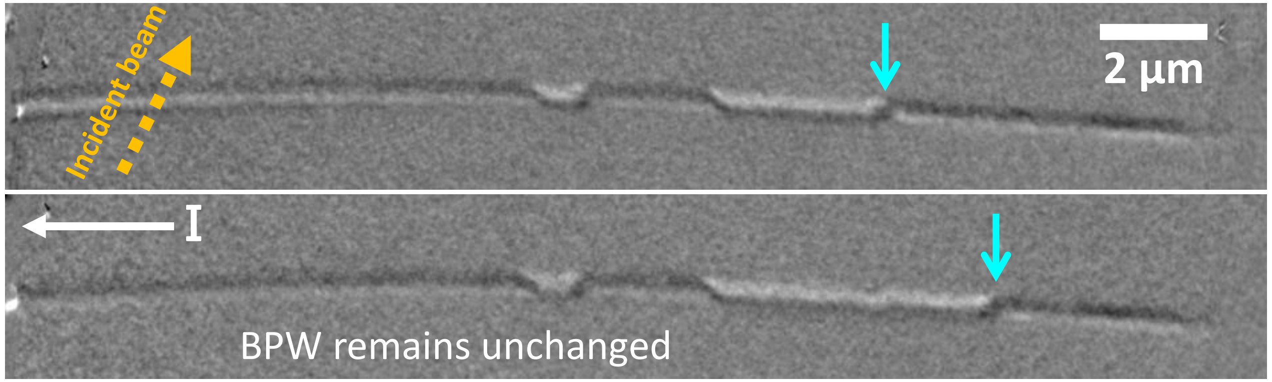
DW propagation induced by the electrical current

$Co_{0.4}Ni_{0.6}$ nanowire, diam. 90 nm

Shadow XMCD-PEEM of Bloch point DW motion

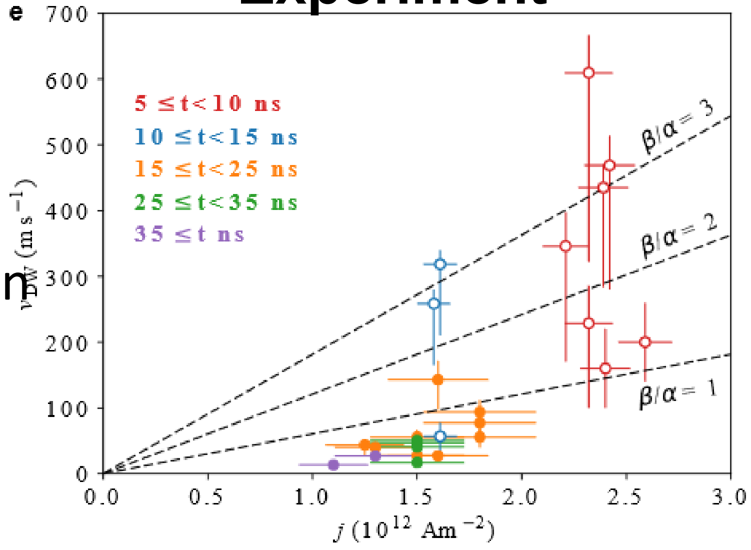
starting state

j = ~1.4×10^{12} A.m^{-2}
Pulse length: 20 ns



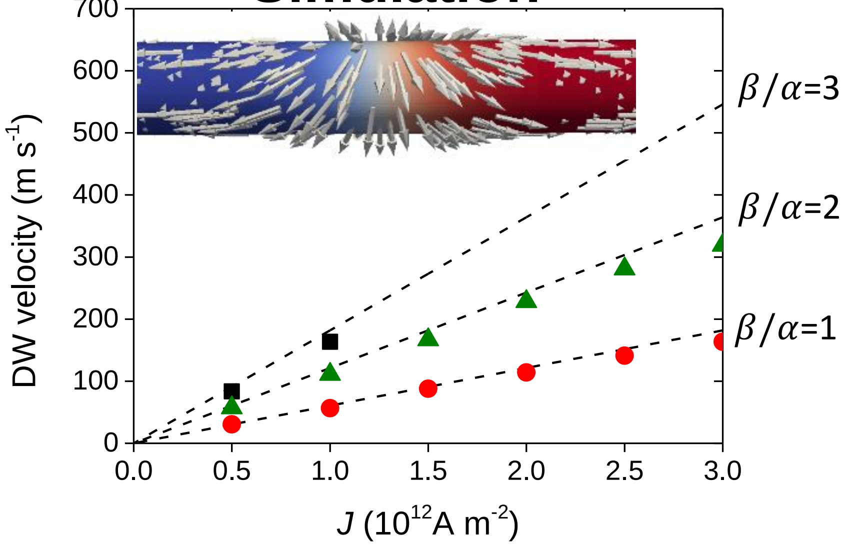
High DW speeds even in 'simple' systems

Experiment



$$v_{steady} \sim \frac{\beta}{\alpha} J$$

Simulation



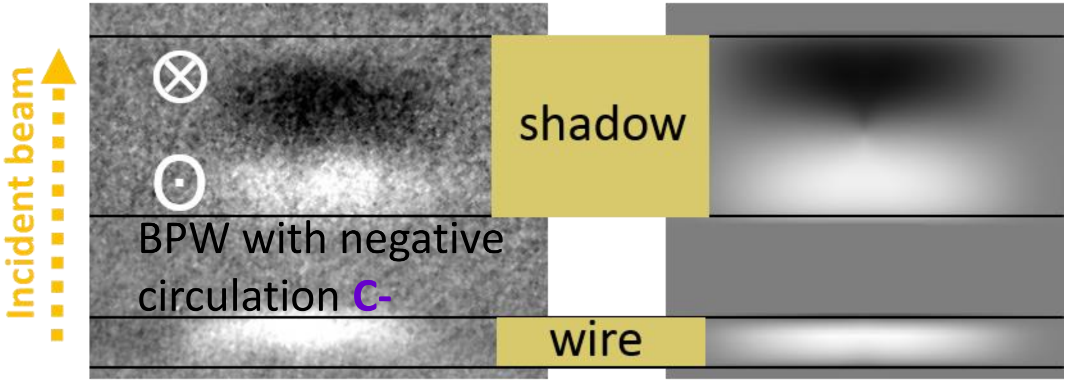
$\mu_0 M_s = 0.8$ T
$A_{ex} = 1.1$ Jm^{-1}

M. Schöbitz *et al. Phys. Rev. Lett. 123, 217201* (2019)

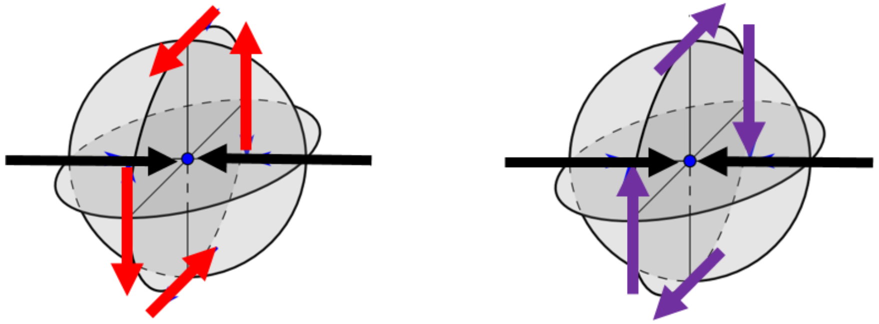
A De Riz *et. al*. PRB **103**, 054430 (2021)

Imaging Bloch-Point walls

Shadow XMCD-PEEM　　Simulation of

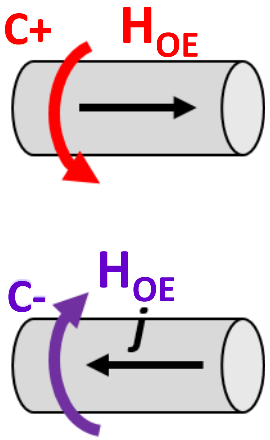


Positive circulation C+　　Negative circulation C-



S. Da Col *et al.*, Phys. Rev. B, **89** (2014), S. Jamet *et al.*, Phys. Rev. B, **92** (2015)

Shadow XMCD-PEEM of Bloch point DW switching

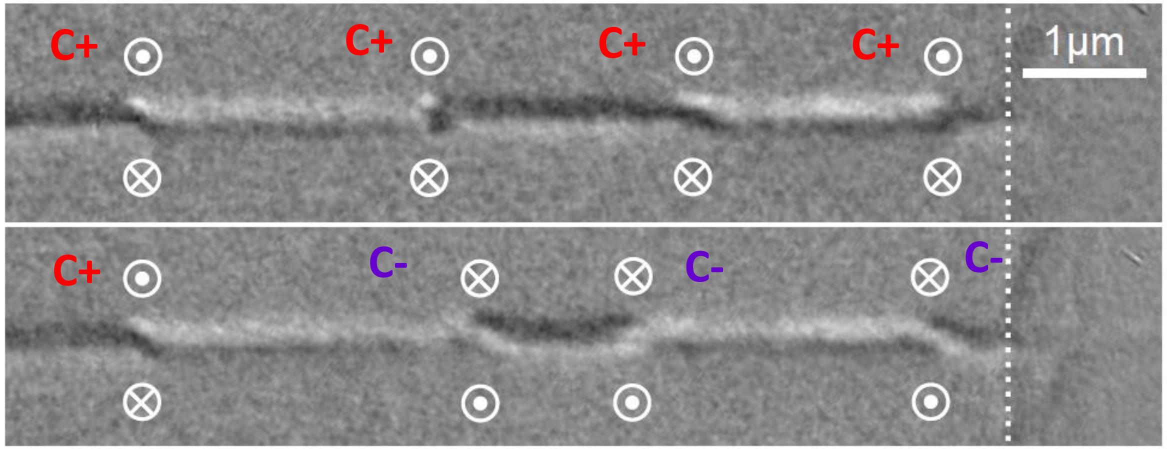


$J_{app} > J_{crit}$

initial state

after 15 ns

75% of switching probability



C+ locked

C- locked

M. Schöbitz et al. PRL 123, 217201 (2019)

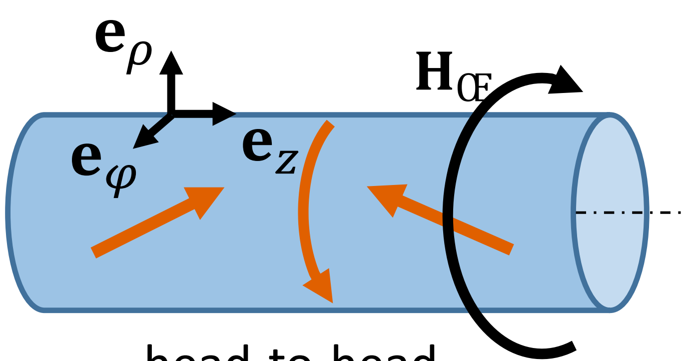
Oersted field triggers two effects:

- **Favors Bloch Point wall formation**
- **Select Bloch Point wall circulation**

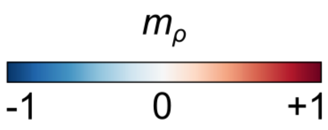
Switching mechanism of Bloch-Point circulation

Out-of-plane magnetization

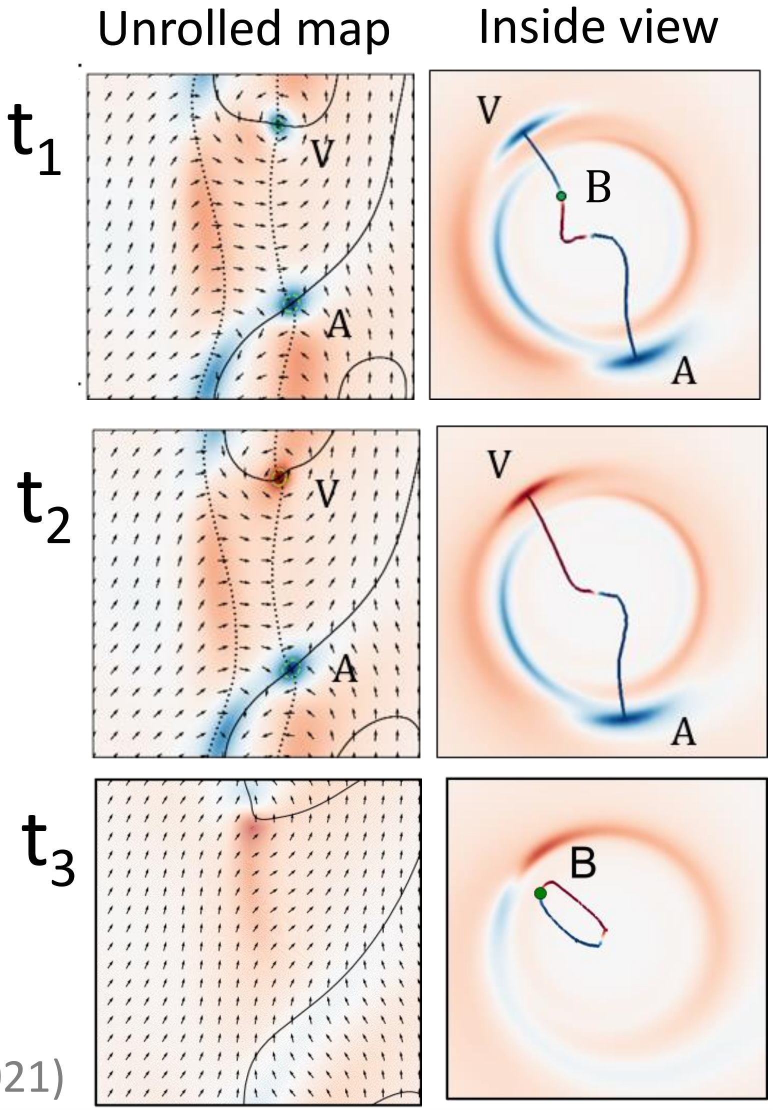
m_ρ



head-to-head



A De Riz *et. al*. PRB **103**, 054430 (2021)



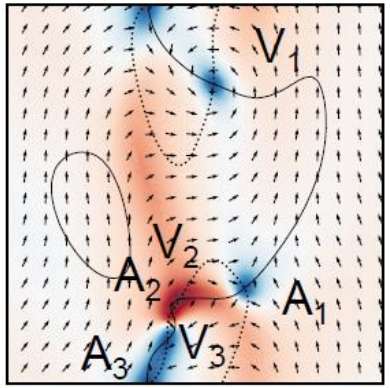
topological number

$$w = \frac{1}{4\pi}\int_M \mathbf{m}\cdot(\partial_1\mathbf{m}\times\partial_2\mathbf{m})dx_1dx_2$$

	$\mathbf{t_1}$	$\mathbf{t_2}$	$\mathbf{t_3}$	Δw
w_{surf}	$-\frac{1}{2}+\frac{1}{2}$	$\frac{1}{2}+\frac{1}{2}$	0	1
w_{vol}	-1	0	-1	1

$$\Delta w_{surf} = \Delta w_{vol}$$

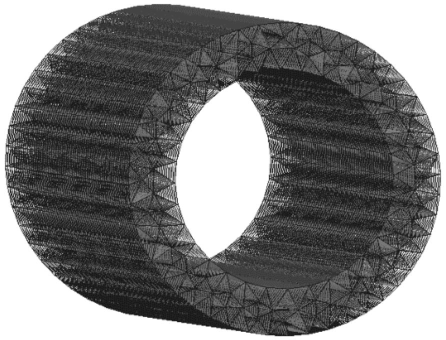
multiple V-A pairs for higher currents

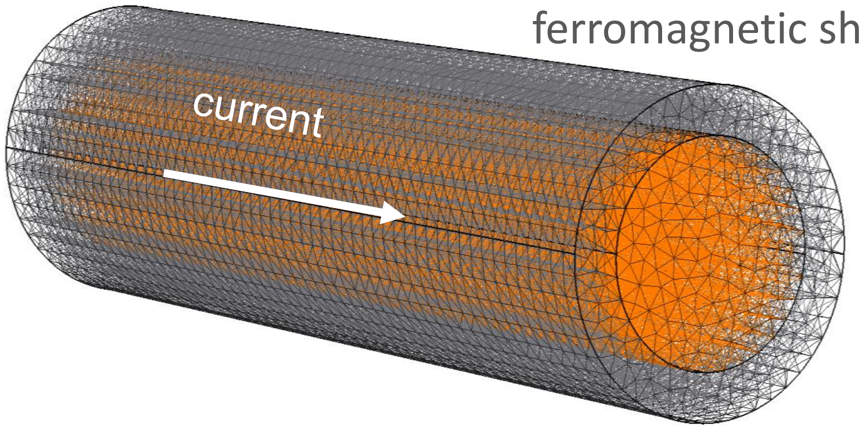


From tubes to wires

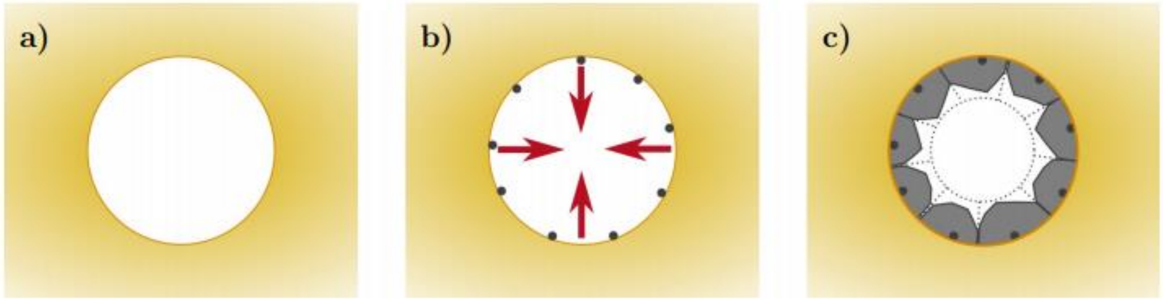
Motivation for tubes

- Additional degree of freedom compared to wires (wall thickness)
- New area – Very little experiments
- Towards core-shell. Analogy with multilayered films, need for spintronics

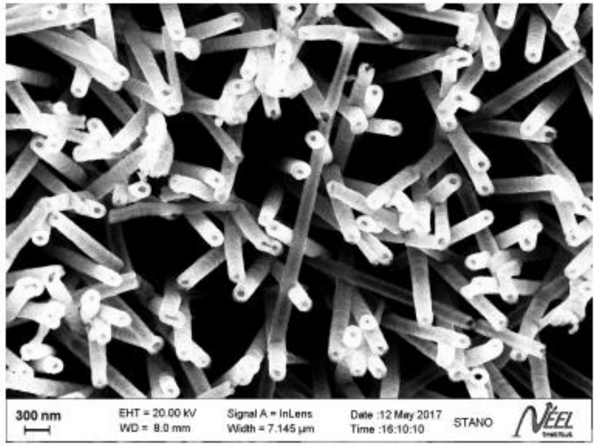




Electroless plating inside porous polycarbonates membranes



Granular structure of CoNiB nanotubes



(a) Bundle of CoNiB nanotubes

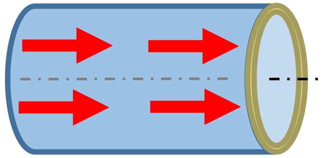
Length ~ 6-7 µm
Diameter ~ 100-200 nm
Thickness ~ 30-40 nm

Michal Staňo, PhD, Grenoble (2017)

- NiCo, FeNi nanocrystalline tubes. Multiscale grains.
- Diameter 80-300nm, length 30µm, wall thickness 20-50nm

Expectation (theory)

axial



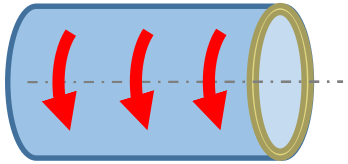
$$E[\boldsymbol{m}] = VK$$

Phase diagram of axial versus orthoradial magnetization: longitudinal magnetization expected from dipolar energy

C. Sun, JMMM 355, 121 (2014)

Observation: azimuthal domains in thin nanotubes - inverse magnetostriction effects

azimuthal



$$E[\boldsymbol{m}] = \frac{AV}{\lambda^2}$$

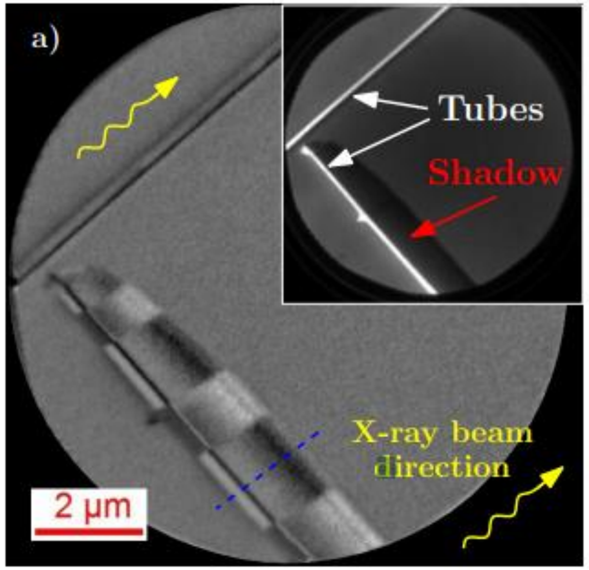
$$K > K_1 = \frac{A}{\lambda^2}$$

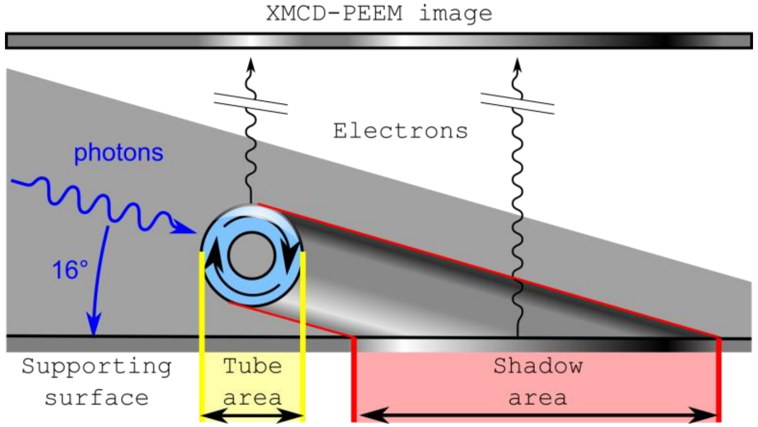
Key parameter: azimuthal anisotropy

$$K_{exp} \simeq 10^4\ \mathrm{J/m^3}$$

D. Tiwari, PhD

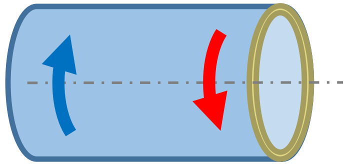
SHADOW XMCD-PEEM



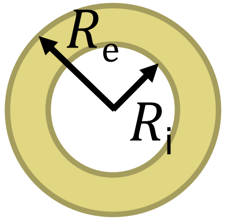


Domain wall topology in tubes with azimuthal anisotropy

Domain wall stability



$$K_2 = A\left(\frac{1}{l_{ex}^2} + \frac{1}{\lambda^2}\right)$$



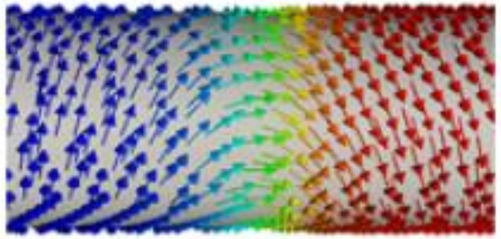
geometrical factor

$$\lambda = \sqrt{(R_e^2 - R_i^2)/[2\log(R_e/R_i)]}$$

$K < K_2$

Néel-like

long DW



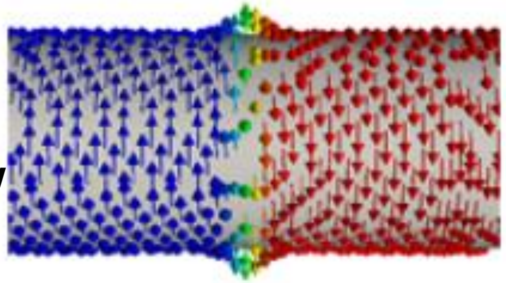
DW width

$$\Lambda_0 = \sqrt{A/(K - K_1)}$$

$K > K_2$

Bloch-like

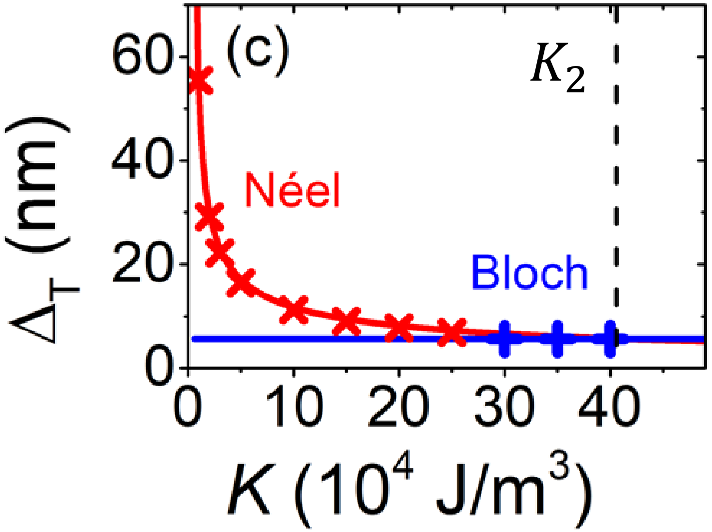
short DW

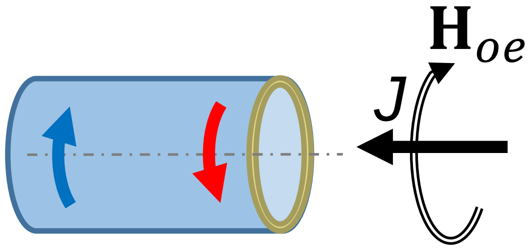


DW width

$$l_{ex} = \sqrt{2A/\mu_0 M_s^2}$$

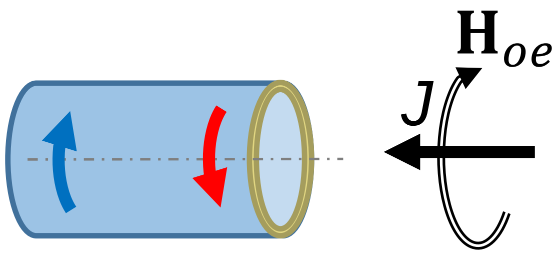
DW width vs anisotropy parameter K





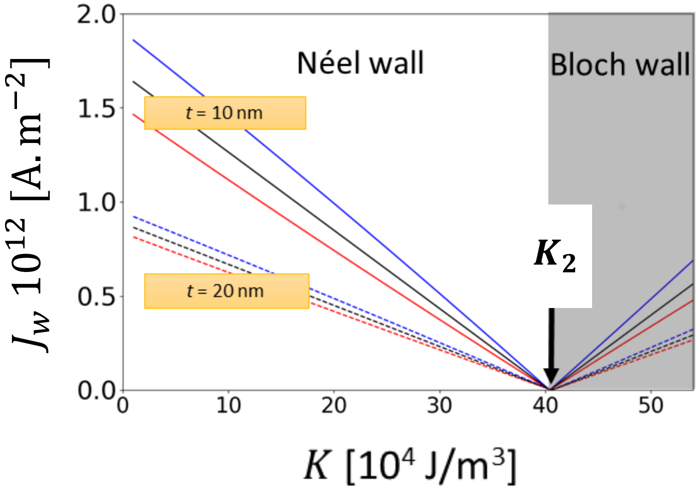
Differences in current induced dynamics for Néel-like and Bloch-like walls?

J. Hurst et al. PRB 103, 024434 (2021)

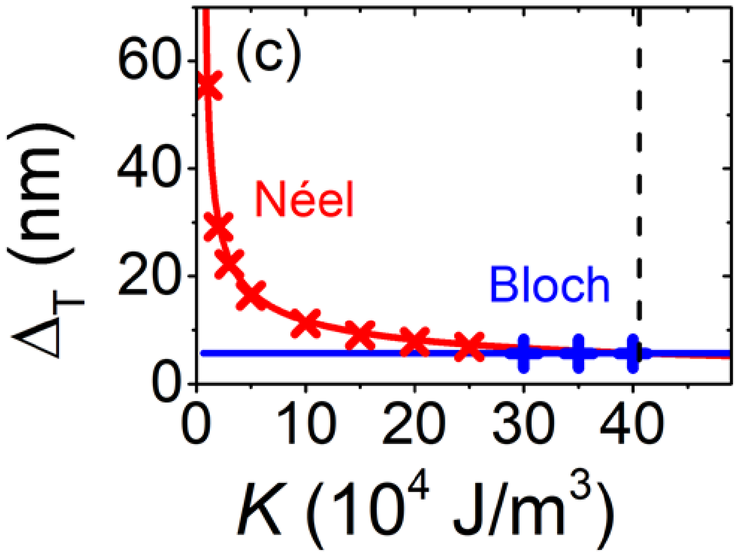


Walker limit

$$J_w \propto \left(\frac{1}{l_{ex}^2} + \frac{K_1 - K}{A}\right)\left[1 \pm \frac{\mu_B P}{2e\Lambda_w \bar{R}}(\alpha - \beta)\right]^{-1}$$



DW width vs anisotropy parameter K



$J < J_w$: Steady regime

$$|v_{steady}| \simeq \frac{\gamma_0 \boldsymbol{\Delta}}{\alpha} h_{oe} \pm \left(\frac{\beta}{\alpha}\right) \frac{\mu_B P}{e M_s} J$$

Oe field driven STT driven

$J > J_w$: Walker regime

$$\langle v_{Walker} \rangle_t \simeq \alpha \gamma_0 \langle \boldsymbol{\Delta} \rangle h_{oe} \pm \frac{\mu_B P}{e M_s} J$$

Oe field driven STT driven

Néel: H_{OE} dominated

Bloch: STT dominated

J. Hurst et al. PRB 103, 024434 (2021)

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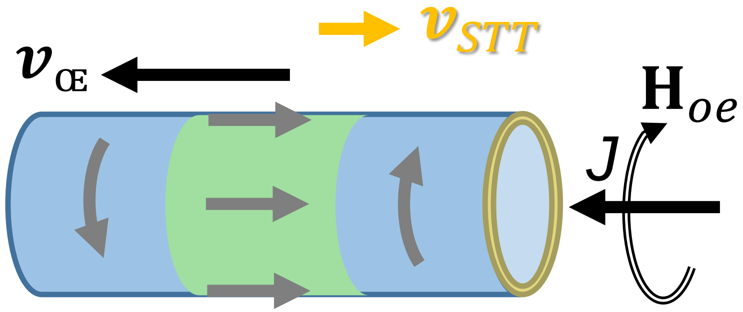
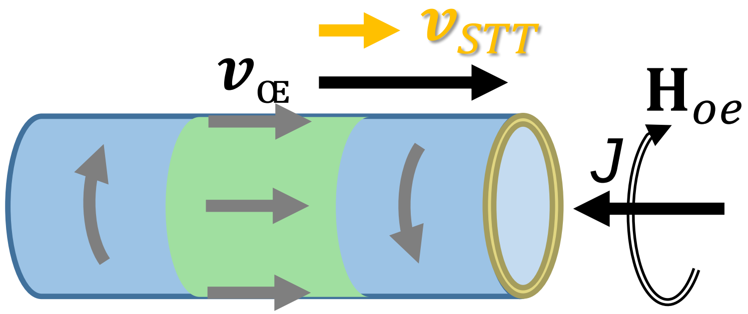
Long Néel DW:

- Oersted field dominated dynamics



STT and H_{OE} compete

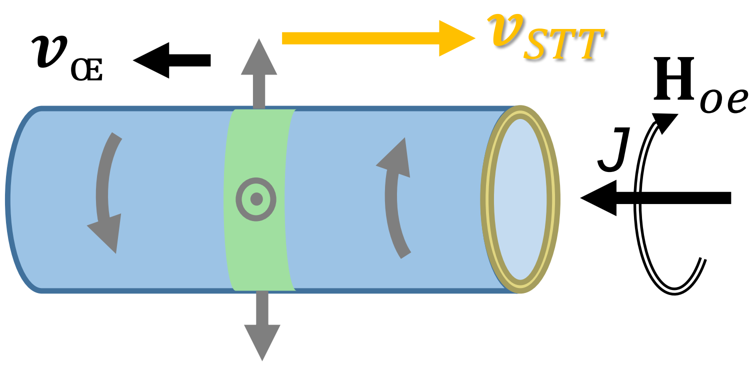


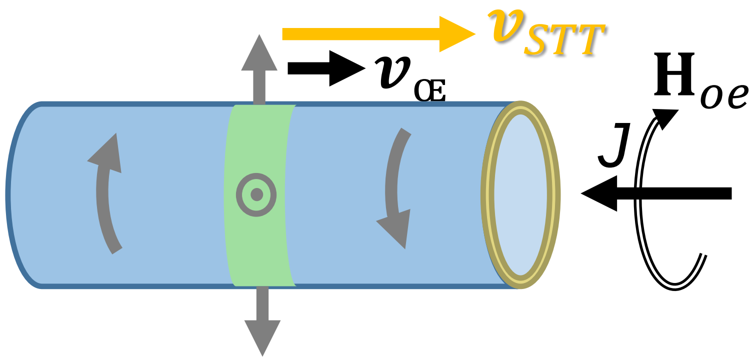
STT and H_{OE} cooperate

Néel: H_{OE} dominated
(+) High velocity
(+) High Walker limit
(-) Direction of motion depends on initial configuration

Short Bloch DW:

- STT dominated dynamics





Bloch: STT dominated
(+) Follows electron flow for all configurations
(-) moderate velocity
(-) V/AV formation

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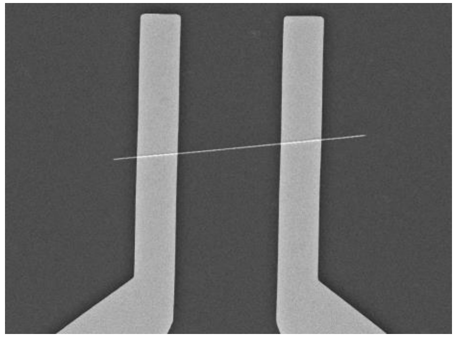
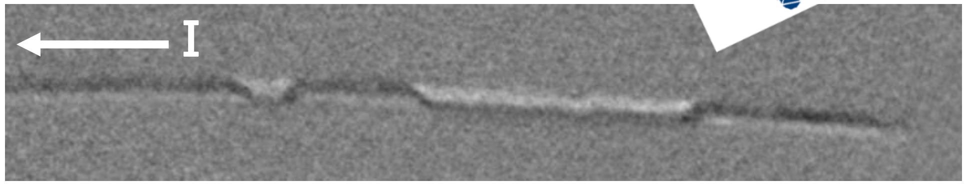
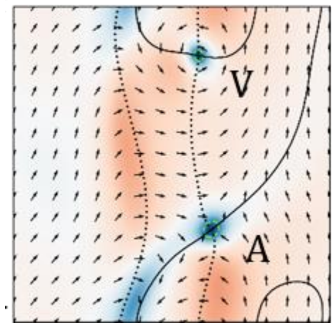
Thank you for your attention !

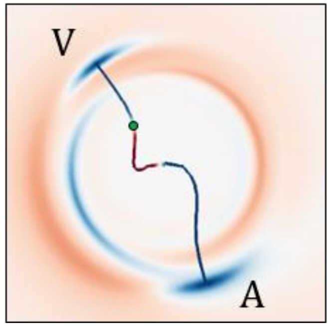


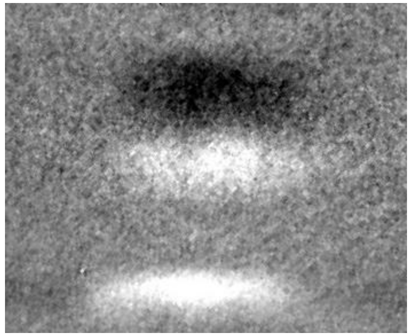
feeLLGood

finite element LLG object oriented development









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