Emerging Physics in 3D Nanomagnets

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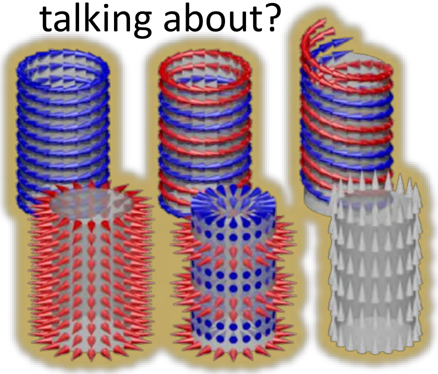
Slides: http://fruchart.eu/slides

Table of contents

- What are we talking about?



Emergent

The term emergent is used to evoke collective behaviour of a large number of microscopic constituents that is qualitatively different than the behaviours of the individual constituents

The modifier 'emergent' sometimes appears simply as a colloquial indication that a particular property is of great fundamental importance, and thus newsworthy and highly fundable

S. Kivelson, Defining emergence in physics, N. J. Phys. Quant. Mater. 1, 16024 (2016)

The concept of emergence is closely connected with the notions of antireductionism, unpredictability, and novelty. In many cases these latter concepts are explicated in mereological terms: very crudely, something is emergent when it (the whole) is greater than the sum of its parts

R. W. Batterman, Emergence in physics, Routledge Encyclopedia of Philosophy

The general notion of emergence is meant to conjoin these twin characteristics of dependence and autonomy. It mediates between extreme forms of dualism, which reject the micro-dependence of some entities, and reductionism, which rejects macro-autonomy

Timothy O'Connor, *Emergent properties*, Stanford encyclopedia of philosophy (2020)

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3D nanomagnets

- Philosophical question: is a domain a 3D object? Is a domain wall an object?

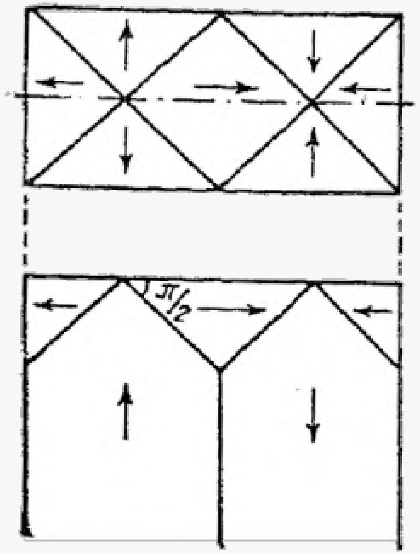
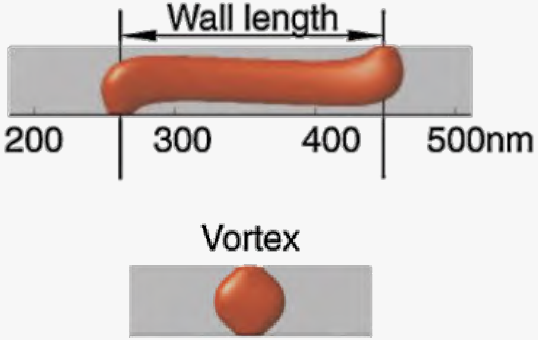


Fig. 3.

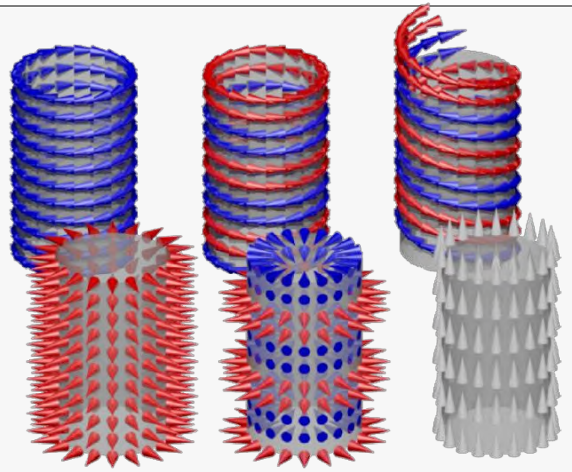
L. Landau,
Phys. Z. Sowjetunion 8, 153 (1935)



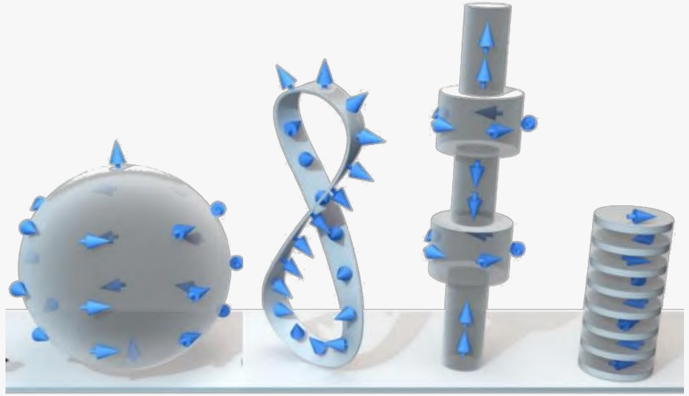
A. Masseboeuf, Phys. Rev. Lett. 104, 127204 (2010)

We will consider both 3D nanomagnets and 3D spin textures

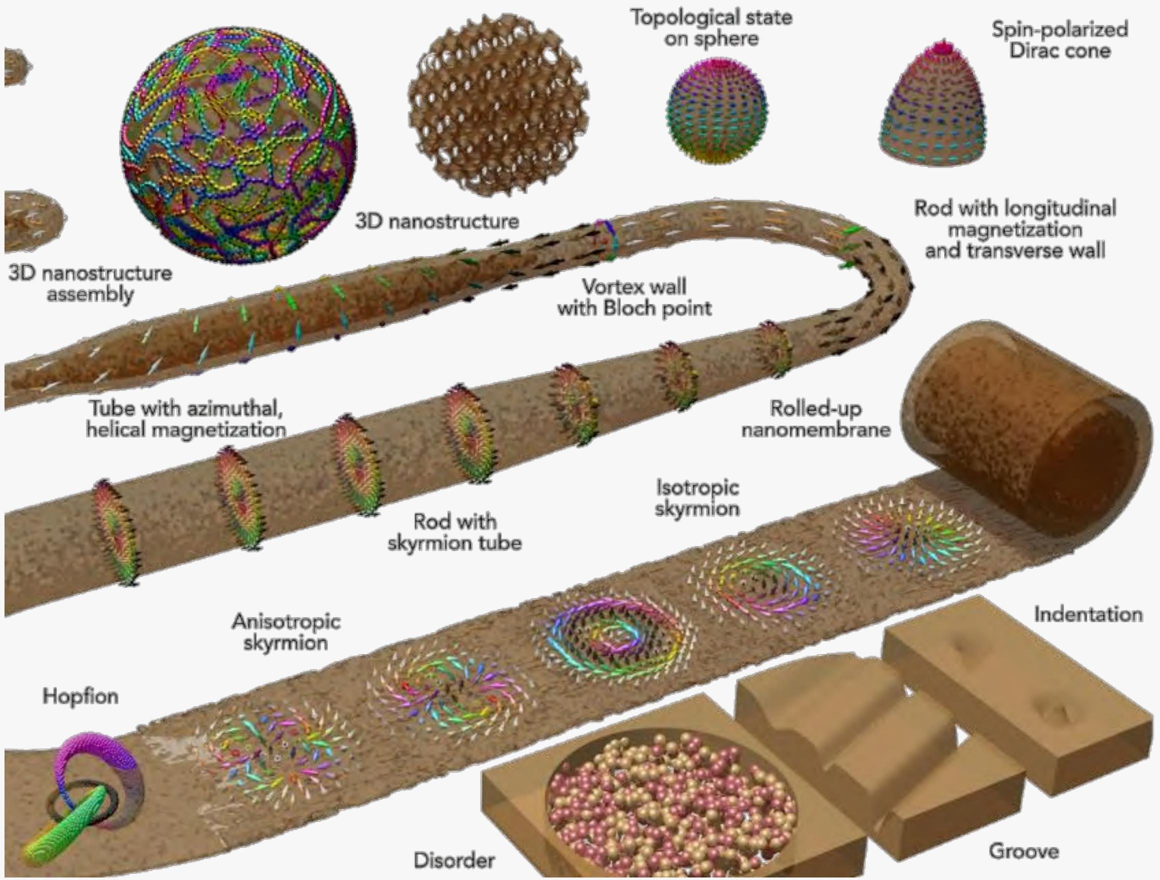
Sharp rise of contributions on 3D nanomagnetism



R. Streubel, J.Phys.D: Appl.Phys. 49, 363001 (2016)



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

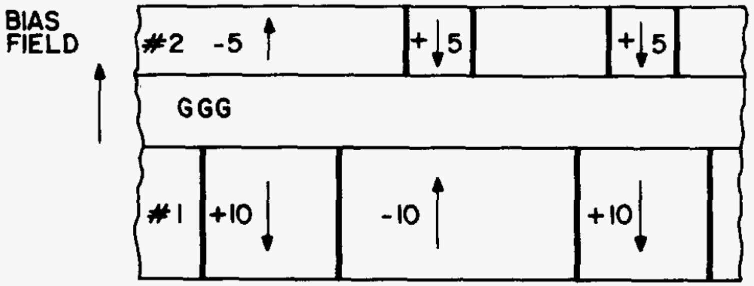


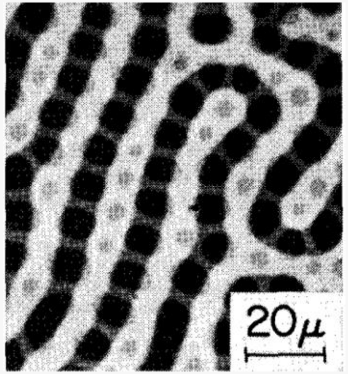
A. Fernandez-Pacheco, Nat. Comm., 8, (2017)

Emergent Physics or Emergent Nanomagnets?

Let us remain humble about emergent physics

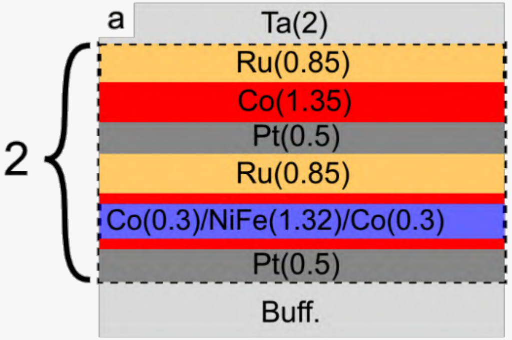
- Bubble media and memories

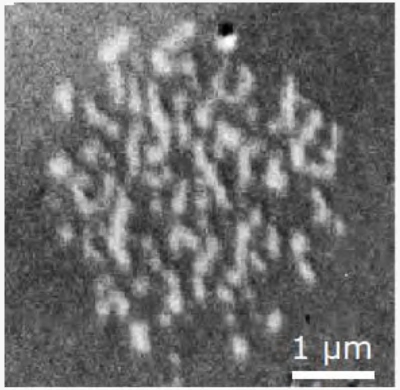




Magnetostatically-coupled bilayered bubble-media films

Y.S. Lin, Appl. Phys. Lett. 23, 485 (1973)

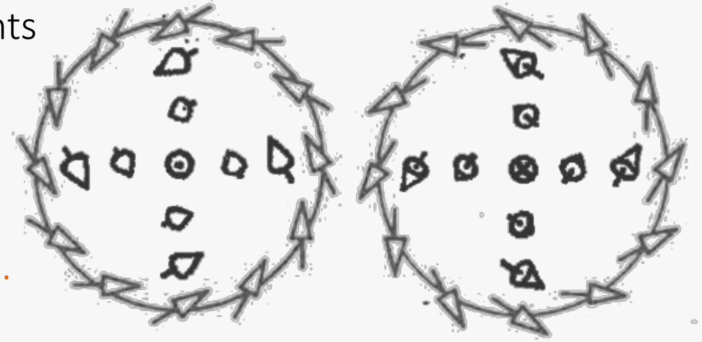




Skyrmions in synthetic antiferromagnets

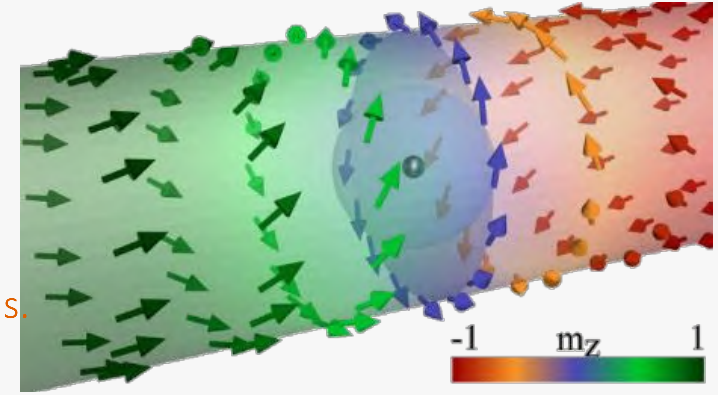
R. Juge, Nat. Comm. 13, 4807 (2022)

- Bloch points



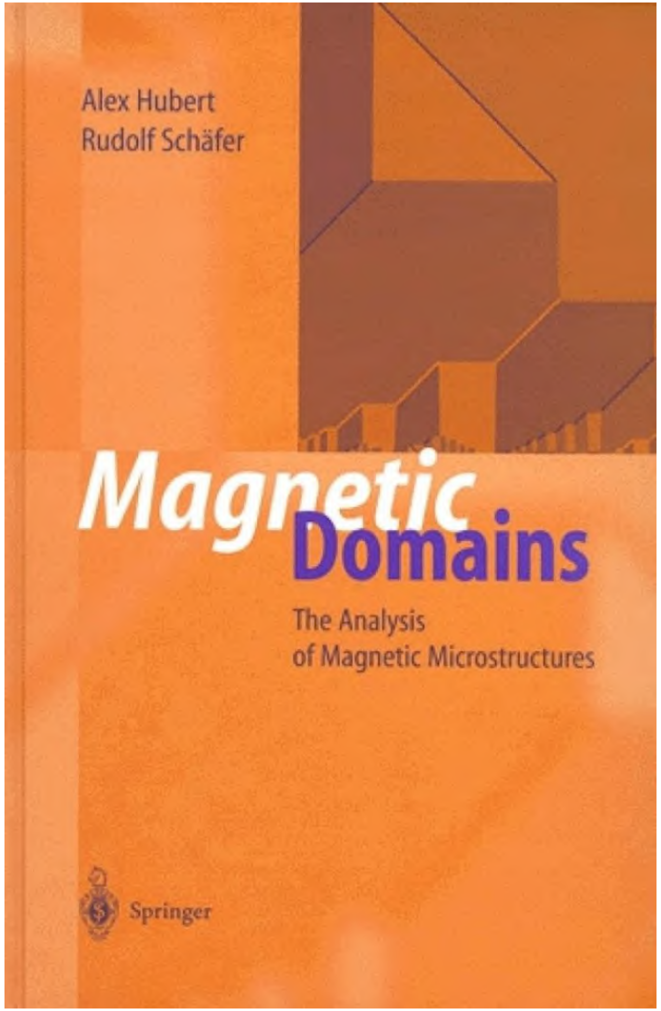
R. Feldtkeller, Z. Angew. Phys. 19, 350 (1965)

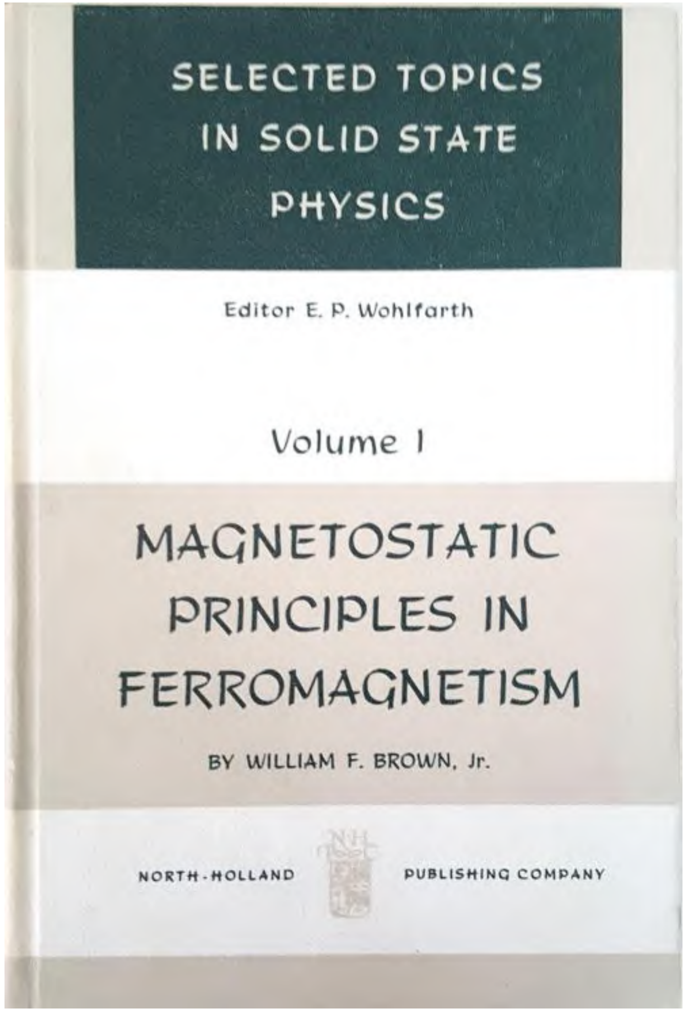
Abb. 9. Die beiden möglichen Umgebungskonfigurationen eines singulären Punktes, bei denen eine dem Punkt umschriebene Kugel insgesamt keine magnetische Ladung besitzt. Dargestellt ist die Magnetisierungskonfiguration einer dem singulären Punkt umschriebenen Kugeloberfläche, von der $\vartheta = 0$-Achse aus gesehen. Der Magnetisierungsvektor ist auf *beiden* Halbachsen $\vartheta = 0, \pi$ der einen Konfiguration zum singulären Punkt hin orientiert und auf beiden Halbachsen der anderen Konfiguration von ihm weg



R. Hertel, J. Phys. Condens. Matter. 28, 483002 (2016)

Some non-emergent references

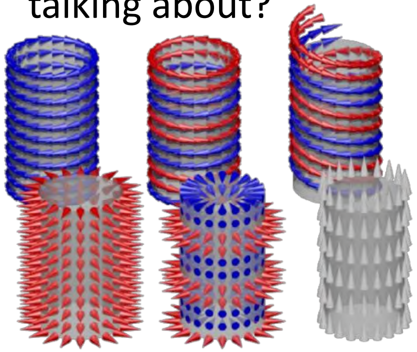




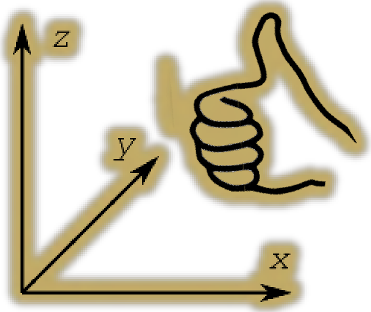
My purpose here

- Personal and light overview
- Keep in mind main ideas not detailed concepts and maths
- Not a research talk

- What are we talking about?



- General considerations

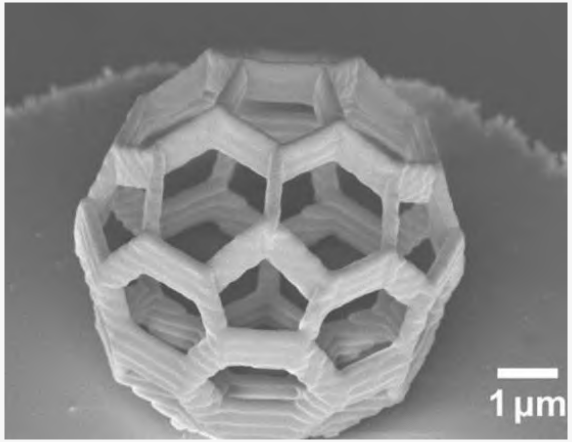


General considerations – What is 3D?

Space

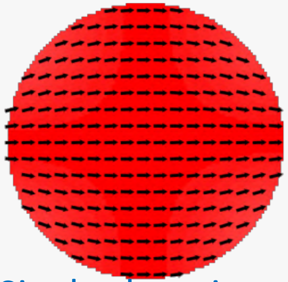
- Physical quantities (incl. magnetization) defined at any location in space

$$\mathbf{M} = \mathbf{M}(x, y, z)$$

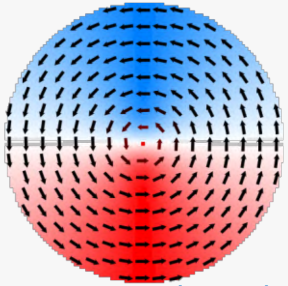


C. Donnnelly, Phys. Rev. Lett. 114, 115501 (2015)

- Features: shape, dimensions, dimensionality



Single-domain

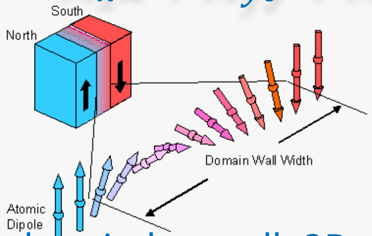


Size > magn. length scale

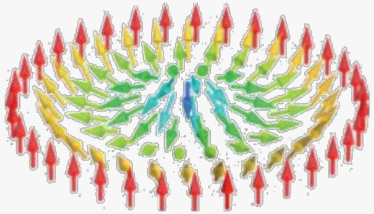
Magnetization components

- Vector field for magnetization has three components

$$\mathbf{M} = M_x\hat{\mathbf{x}} + M_y\hat{\mathbf{y}} + M_z\hat{\mathbf{z}}$$

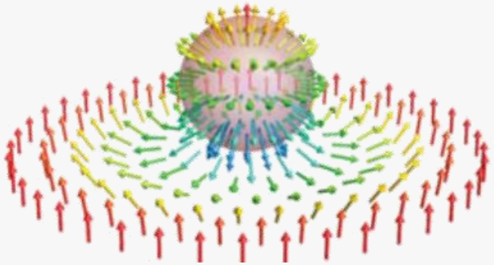


Simple spiral or wall: 2D

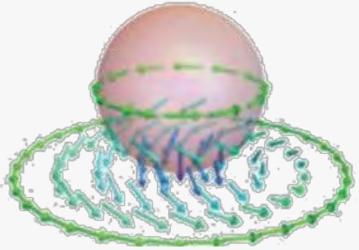


A. Fert, Skyrmion: 3D
Nat. Nanotech. 8, 152 (2013)

- Mapping magnetization on the unit sphere



Skyrmion



Vortex

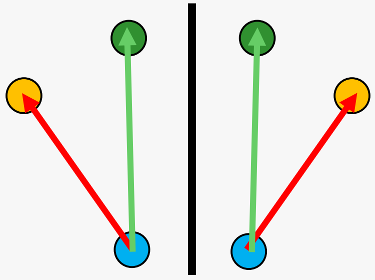
In: H.B. Braun, *Solitons in real space: domain walls, vortices, hedgehogs and skyrmions*, Springer (2018)

General considerations – Chirality

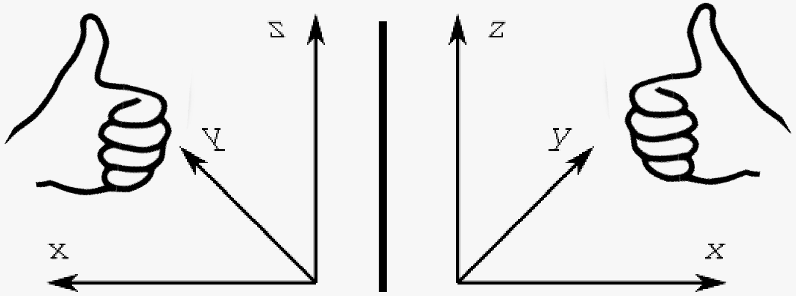
Definition

An object that cannot be superimposed onto itself, following a mirror symmetry

- Two vectors do not allow chirality (the image can be flipped 180°)

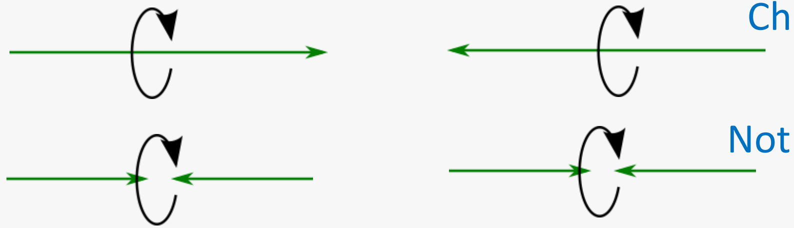


- Three vectors are required for chirality



(Counter-)examples

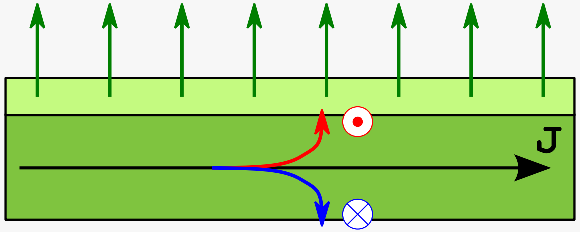
- Not all curling structures are chiral



- Competition or promotion with chiral physical effects, i.e., those involving a vector product

LLG equation

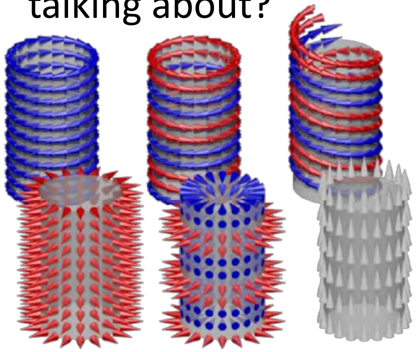
$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$



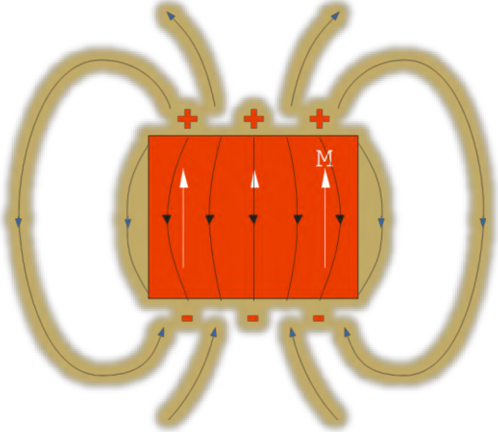
Spin-orbit torques

Table of contents

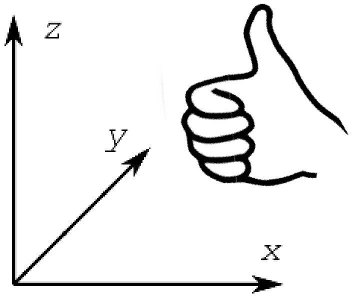
- What are we talking about?



- Magnetostatics in 3D



- General considerations



Analogy with electrostatics

Maxwell equation → $\boldsymbol{\nabla}\cdot\mathbf{H}_\mathrm{d} = -\boldsymbol{\nabla}\cdot\mathbf{M}$

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = -M_\mathrm{s}\iiint_{\mathcal{V}'}\frac{[\boldsymbol{\nabla}\cdot\mathbf{m}(\mathbf{r}')]\,(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}\mathcal{V}'$$

To lift the singularity that may arise at boundaries, a volume integration around the boundaries yields:

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = \iiint\frac{\rho(\mathbf{r}')\,(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}\mathcal{V}' + \oiint\frac{\sigma(\mathbf{r}')\,(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}\mathcal{S}'$$

Magnetic charges

$\rho(\mathbf{r}) = -M_\mathrm{s}\,\boldsymbol{\nabla}\cdot\mathbf{m}(\mathbf{r})$ → volume density of magnetic charges

$\sigma(\mathbf{r}) = M_\mathrm{s}\,\mathbf{m}(\mathbf{r})\cdot\mathbf{n}(\mathbf{r})$ → surface density of magnetic charges

Useful expressions

$$\mathcal{E}_\mathrm{d} = -\frac{1}{2}\mu_0\iiint_{\mathcal{V}}\mathbf{M}\cdot\mathbf{H}_\mathrm{d}\,\mathrm{d}\mathcal{V}$$

$$\mathcal{E}_\mathrm{d} = \frac{1}{2}\mu_0\iiint_{\mathcal{V}}\mathbf{H}_\mathrm{d}^2\,\mathrm{d}\mathcal{V}$$

$$\mathcal{E}_\mathrm{d} = \frac{1}{2}\mu_0\left(\iiint_{\mathcal{V}}\rho\phi\,\mathrm{d}\mathcal{V} + \oiint\sigma\phi\right)$$

- Always positive
- Zero means minimum

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Size considerations

$$\mathbf{H}_{\mathrm{d}}(\mathbf{r}) = \mathrm{Volume} + \oiint \frac{\sigma(\mathbf{r}')\,(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\mathrm{d}\mathcal{S}'$$

- Unchanged if all lengths are scaled: homothetic.
  NB: the following is a solid angle:

$$\mathrm{d}\boldsymbol{\Omega} = \frac{(\mathbf{r}-\mathbf{r}')\mathrm{d}\mathcal{S}'}{|\mathbf{r}-\mathbf{r}'|^3}$$

- H_d does not depend on the size of the body (long-range interaction)
- Forces and torques scale with $1/\mathrm{size}$

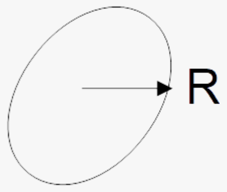
Applications

Magnetostatics – Range considerations

Range

Example: upper bound of dipolar field in thin films

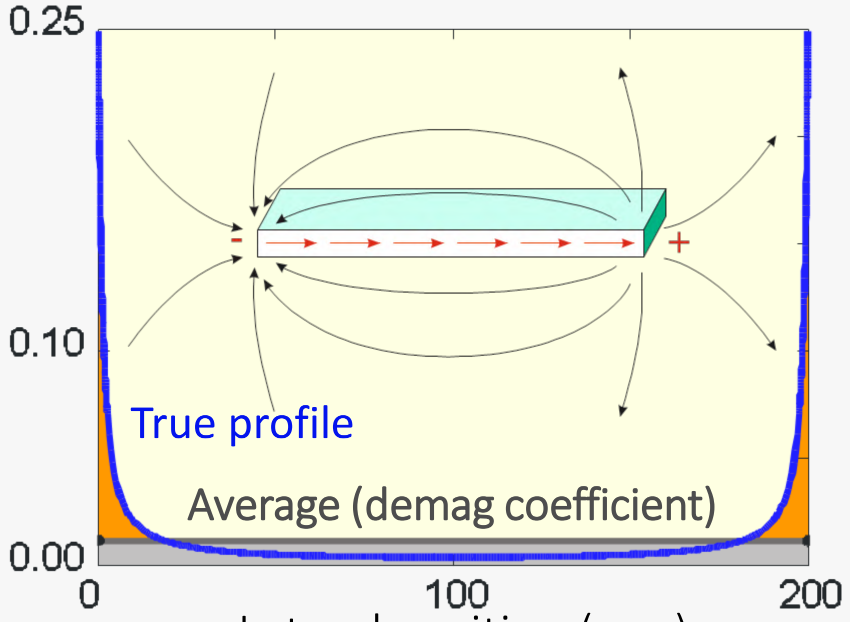
$$\|\mathbf{H}_\mathrm{d}(\mathbf{r})\| \leq M_\mathrm{s} t \int \frac{2\pi r}{r^3}\,\mathrm{dr}$$



$$\Rightarrow \|\mathbf{H}_\mathrm{d}(\mathbf{R})\| \leq \mathrm{Cste} + \mathcal{O}(1/R)$$

Non-homogeneity

Example: flat strip with aspect ratio 0.0125



- Dipolar fields are short-ranged and inhomogeneous in low dimensions
- Consequences: non-uniform magnetization switching, edge modes etc.

⇒ A 1D/2D system in space behaves very differently from a nano-bulk magnets

Magnetostatics – Curling

Historical background

Introduced in the context of the Brown paradox for magnetization reversal

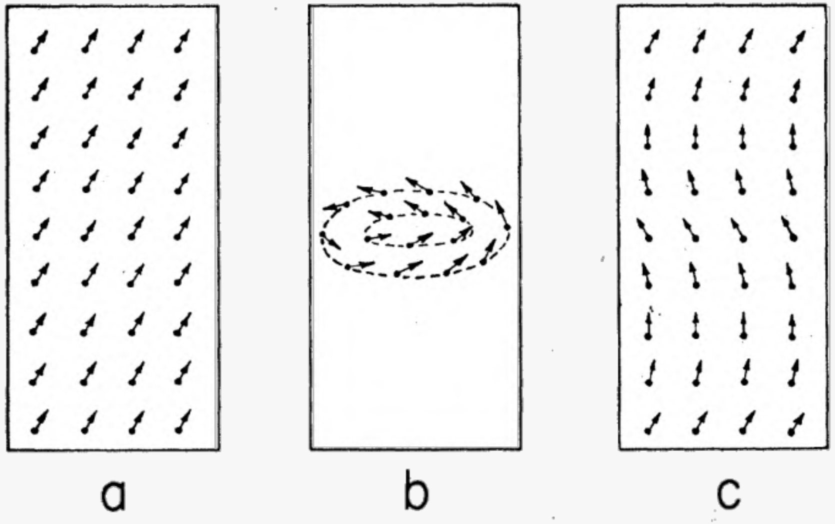
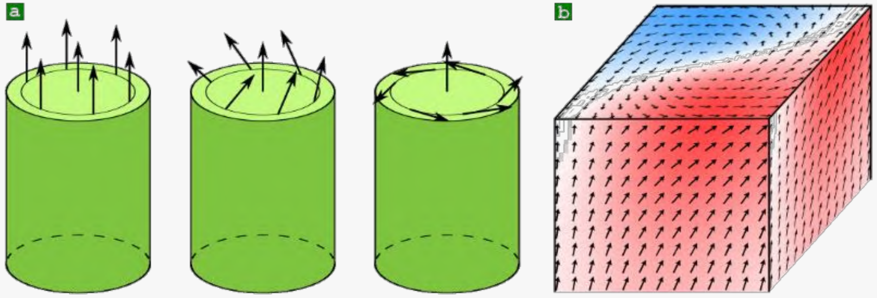


FIG. 2. Modes of magnetization change for the infinite cylinder: (a) spin rotation in unison; (b) magnetization curling; (c) magnetization buckling.

E. H. Frei, Phys. Rev. 106, 446 (1957)

Example in 3D nanomagnets

End curling in elongated 3D objects (wires etc.)



Curling spreads surface charges into volume charges

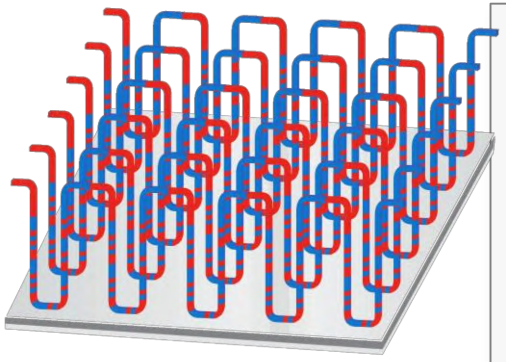
$$\sigma(\mathbf{r})=M_s\,\mathbf{m}(\mathbf{r})\cdot\mathbf{n}(\mathbf{r})$$

$$\rho(\mathbf{r})=-M_s\,\boldsymbol{\nabla}\cdot\mathbf{m}(\mathbf{r})=-M_s\frac{\partial m_z}{\partial z}$$

Notes

- Surface + volume charges is conserved
- Curling may develop whenever a dimension is larger than 7 dipolar exchange lengths $\Delta_d=\sqrt{2A/\mu_0 M_s^2}$

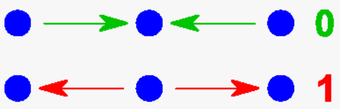
Magnetostatics – Interactions and information coding



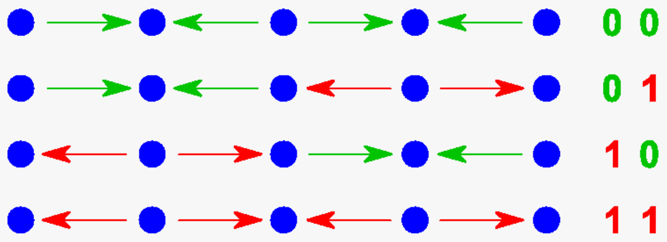
S. S. P. Parkin, Science 320, 190 (2008) + patents (IBM)

3D matrix needs to be globally with zero moment to avoid long-range cross-talks

- Basic building block with zero moment



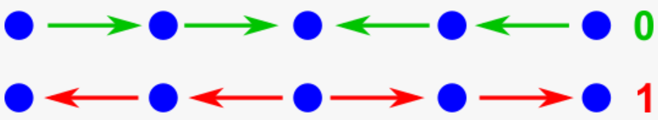
- Here: one bit per two physical sites
- Example, two bits:



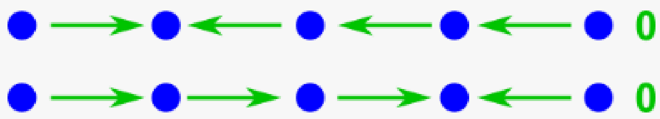
$4 = 2^2$ states

4 sites per two bits

Can be extended to fault-tolerant coding



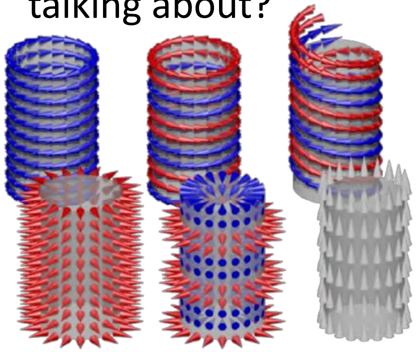
- The transition and its polarity are not lost if a DW is not shifted, or shifter twice



Hardware solution not necessary to decrease global interaction

Table of contents

- What are we talking about?



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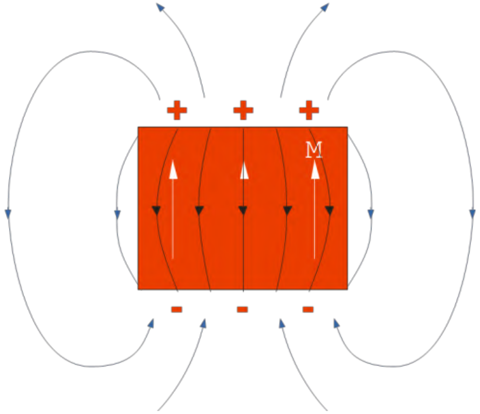
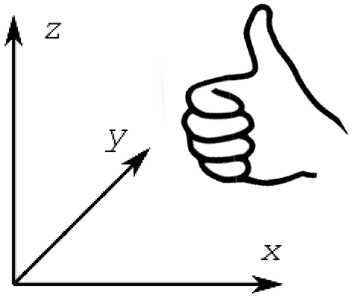
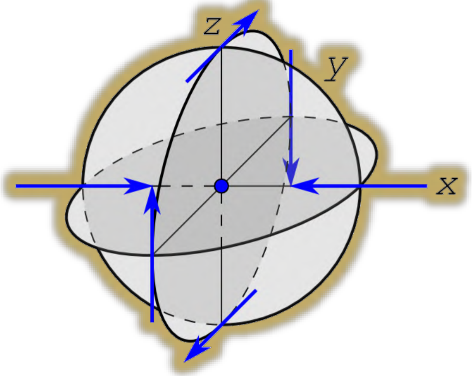


- General considerations

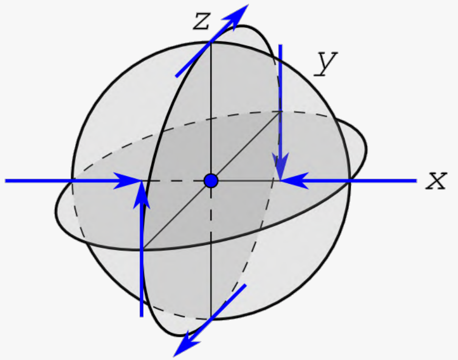


- Spin textures in 3D



Bloch point (0D)

Local vanishing of magnetization



- Imposed by boundary conditions
- Does not exist in 2D magnets
- The only singularity in a ferromagnetic body

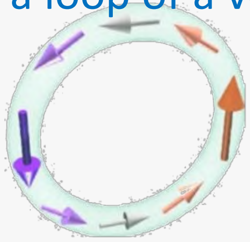
R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

W. Döring,
J. Appl. Phys. 39, 1006 (1968)

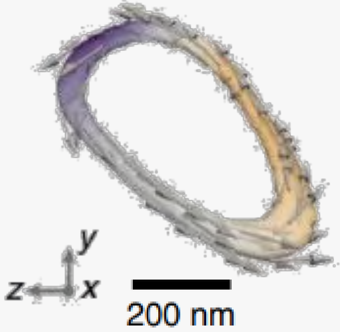
Vortex ring (1D)

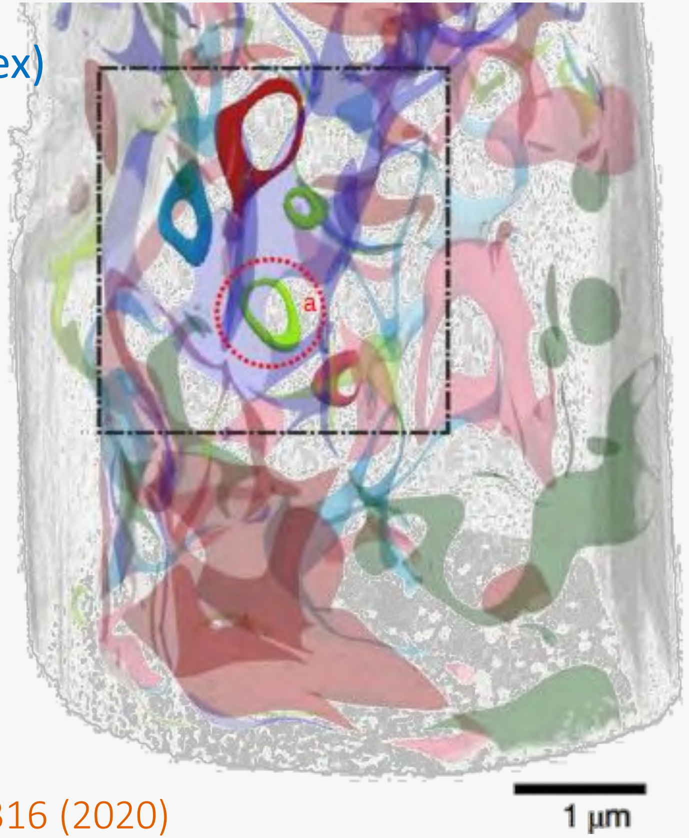
Loop of vorticity (not a loop of a vortex)

Polarization (core magnetization)



Vorticity

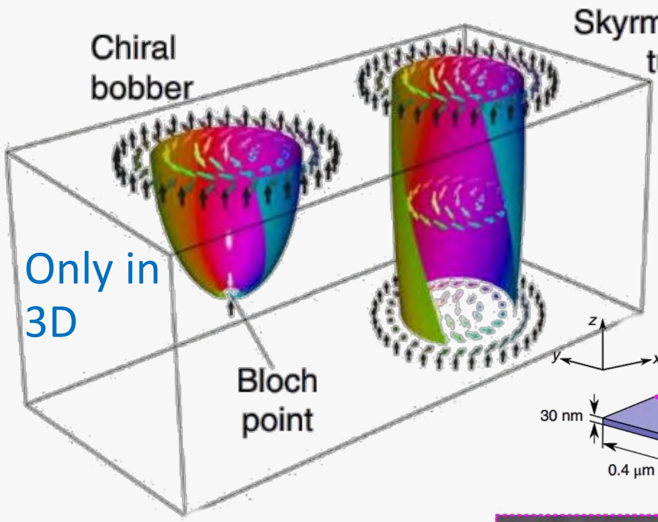




Experiments: C. Donnelly, Nat. Phys. 17, 316 (2020)
Prediction: N. R. Cooper, Phys. Rev. Lett. 82, 1554 (1999)
Vorticity: N. Papanicolaou, NATO, ASI series C404, 151 (1993)

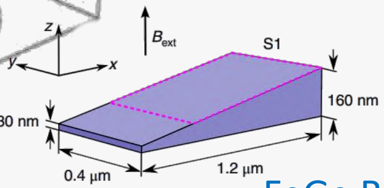
Spin textures – Zoology in a 3D body (2/2)

Skyrmion tubes and bobbers



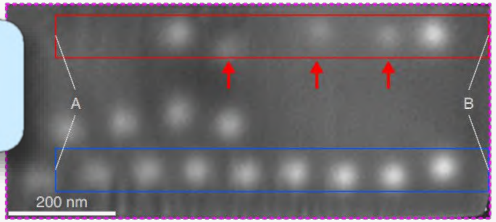
3D extrusion of a skyrmion

Only in 3D



FeGe B20

Electron holography (phase shift)



Prediction:

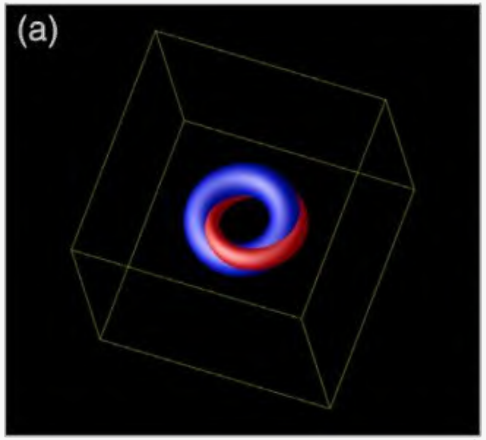
F. N. Rybakov, Phys. Rev. Lett. 115, 117201 (2015)

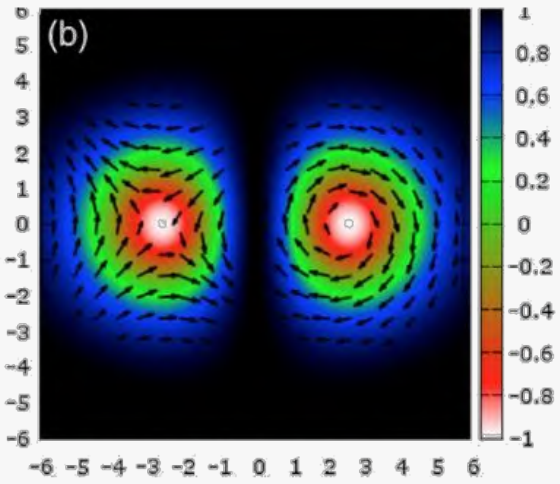
Experiments:

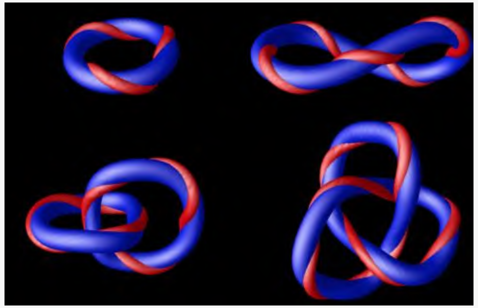
F. Zheng, Nat. Nanotech. 13, 451 (2018)

Hopfions

Skyrmionic loops







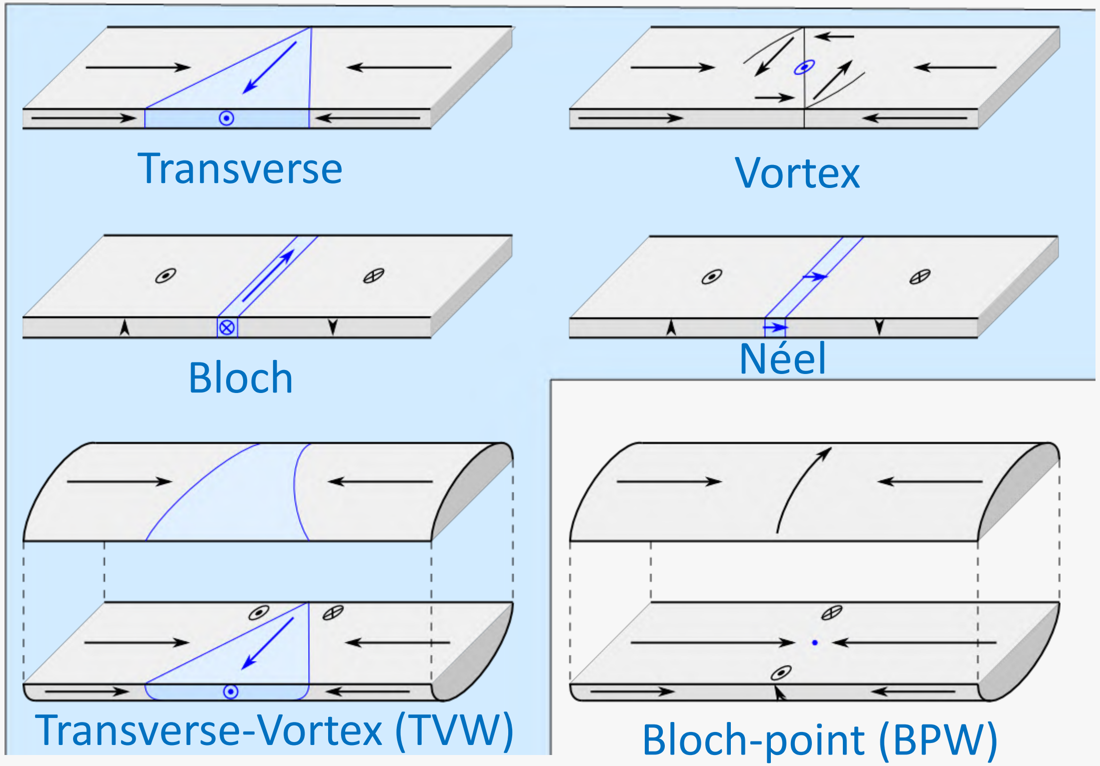
- Does not exist in 2D magnets
- Similarity with vortex loops
- Higher orders exist

P. Sutcliffe, Phys. Rev. Lett. 118, 247203 (2017)

Note: there are mathematically-defined topological numbers to characterize all these structures

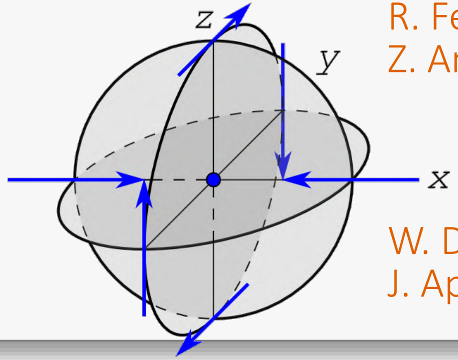
Spin textures – Domain walls in cylindrical structures (1/2)

Topology of domain walls in 3D conduits



H. Forster, JAP91, 6914 (2002); A. Thiaville, Spin dynamics in confined magnetic structures III, 101, (2006).

Bloch point



R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

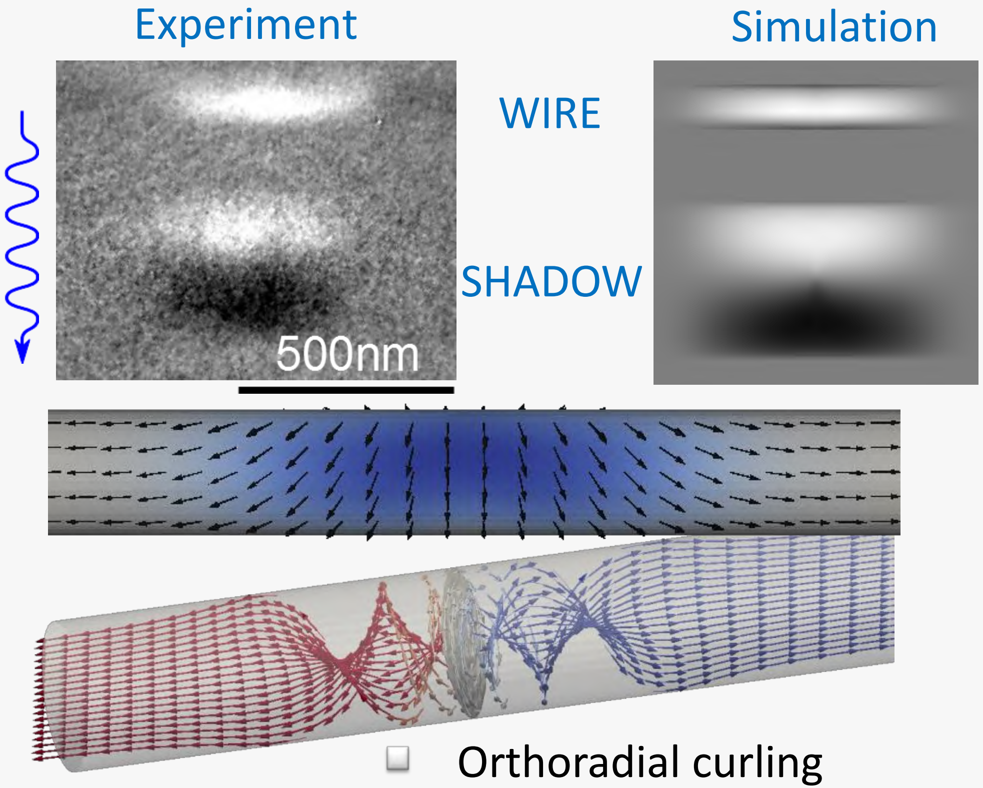
W. Döring,
J. Appl. Phys. 39, 1006 (1968)

- Transverse and vortex walls for films have same topology
- Bloch-point walls have a different topology
- BPW and TVW have the same charge

Review : S. Jamet, in Magnetic Nano- and Microwires, M. Vázquez Ed., Woodhead (2015) (arXiv:1412.0679)

Spin textures – Domain walls in cylindrical structures (2/2)

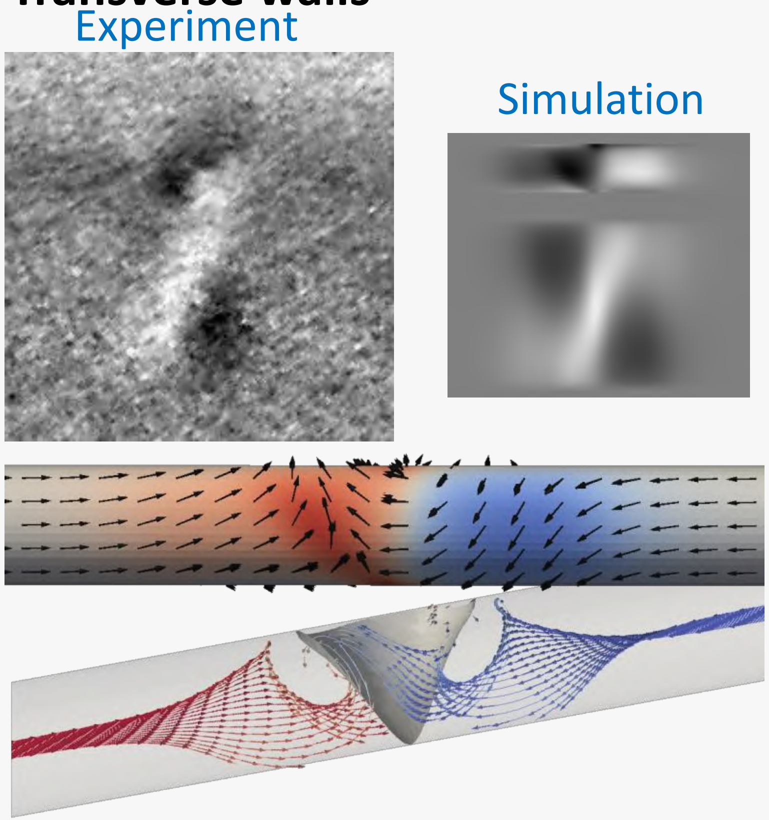
Bloch-point walls



- Orthoradial curling
- Symmetry with respect to plane perpendicular to axis

S. Da-Col et al., Phys. Rev. B (R) 89, 180405, (2014)

Transverse walls

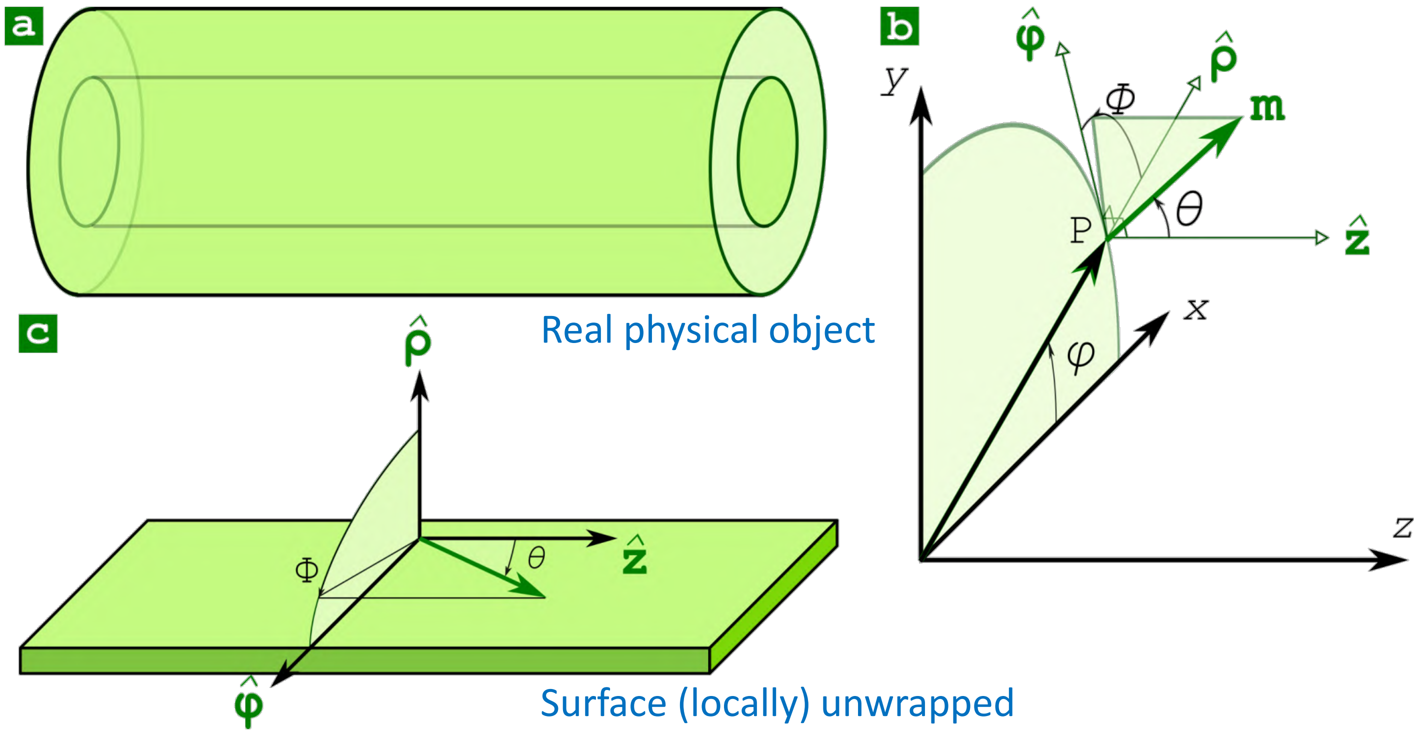


Also imaged with electron holography:

N. Bizière et al., Nanolett. 13, 2053 (2013)

Spin textures – Curvature, mapping of coordinates (1/2)

Example:
the cylindrical geometry



- Space: (ρ, φ, z)
- Magnetization: (θ, Φ)

Exchange energy

$$E_{\text{ex}} = A\left[\left(\frac{\partial\theta}{\partial\rho}\right)^2 + \frac{1}{\rho^2}\left(\frac{\partial\theta}{\partial\varphi}\right)^2 + \left(\frac{\partial\theta}{\partial z}\right)^2 + \sin^2\theta\left(\frac{\partial\phi}{\partial\rho}\right)^2 + \frac{\sin^2\theta}{\rho^2}\left(1 + \frac{\partial\phi}{\partial\varphi}\right)^2 + \sin^2\theta\left(\frac{\partial\phi}{\partial z}\right)^2\right]$$

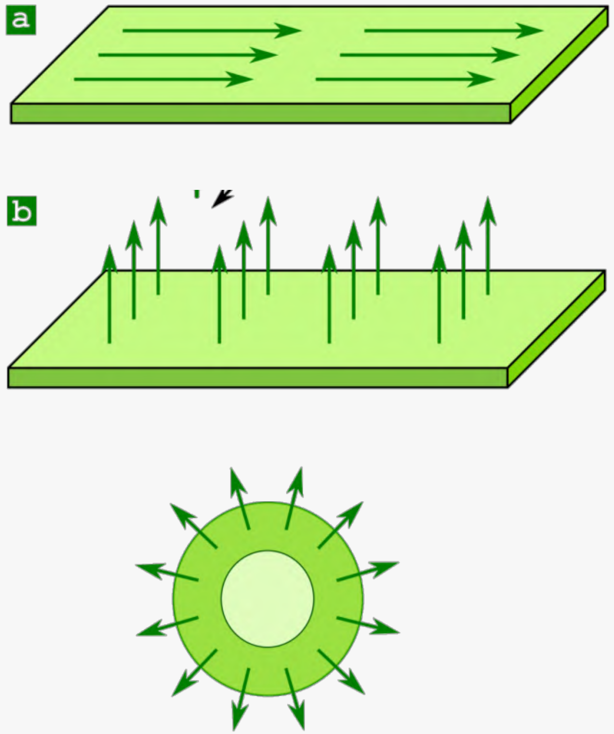
Curvature term once mapped to curvillinear coordinates

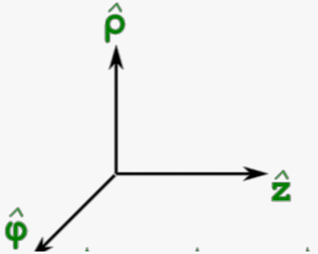
M. Stano, Magnetic nanowires and nanotubes, Handbook of Magnetic Materials 27, Elsevier (2018)

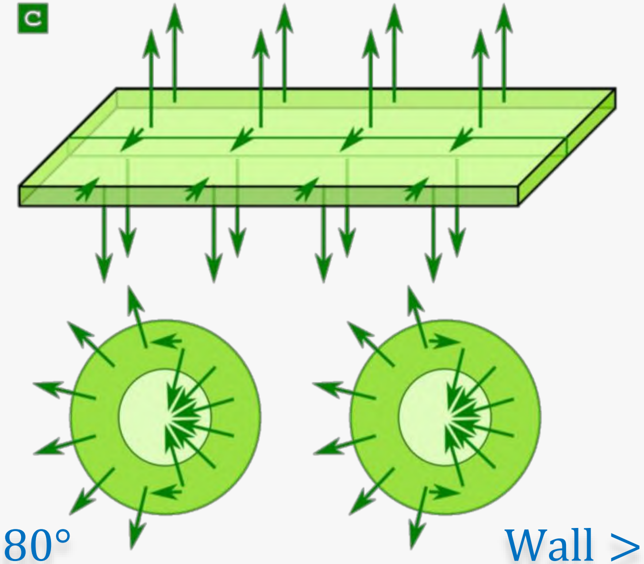
Effective anisotropy and Dzyaloshinskii-Moriya energy

Specific case: cylindrical geometry

- Curvature-induced anisotropy
- Curvature-induced chirality







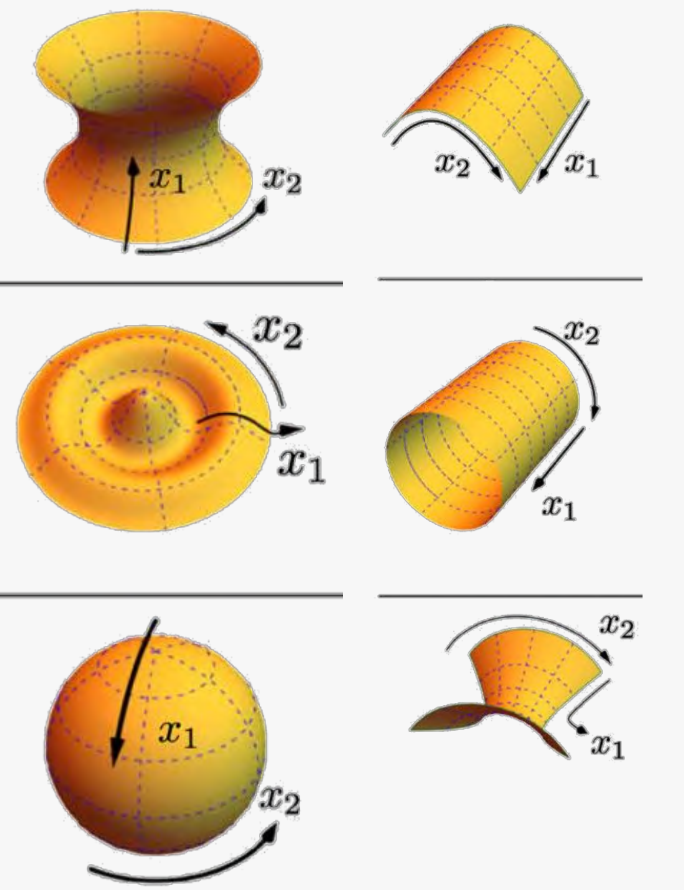
Wall < 180°

Wall > 180°

M. Stano, Magnetic nanowires and nanotubes, Handbook of Magnetic Materials 27, Elsevier (2018)

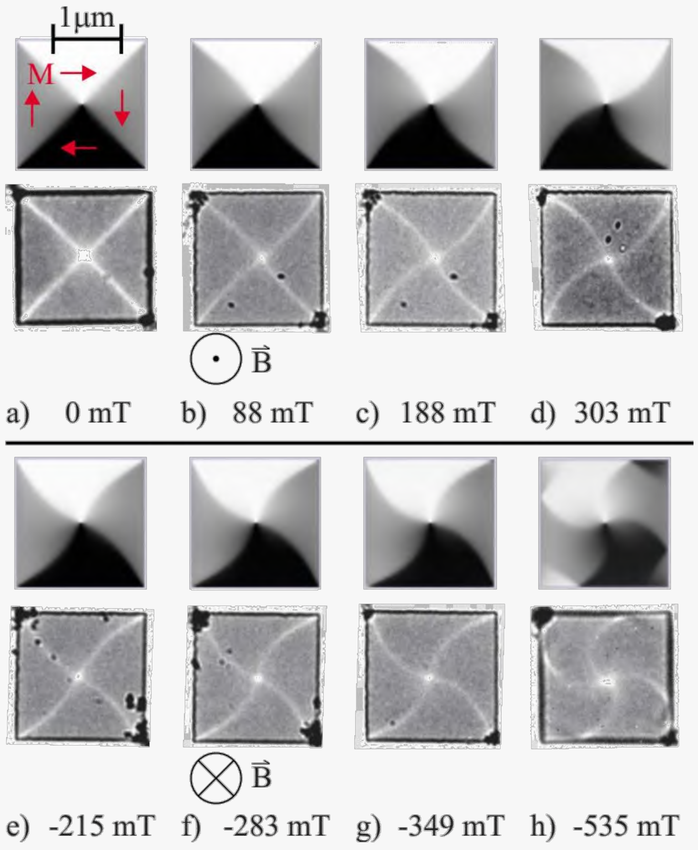
Spin textures – Curvature, examples (1/2)

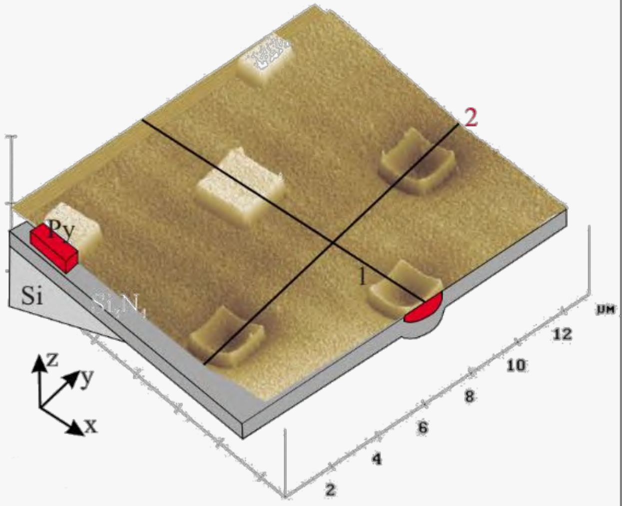
General situations



D. D. Sheka, Comm. Phys. 3, 128 (2020)

Example: elements with curved surface

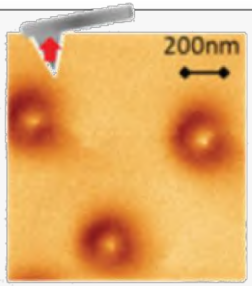




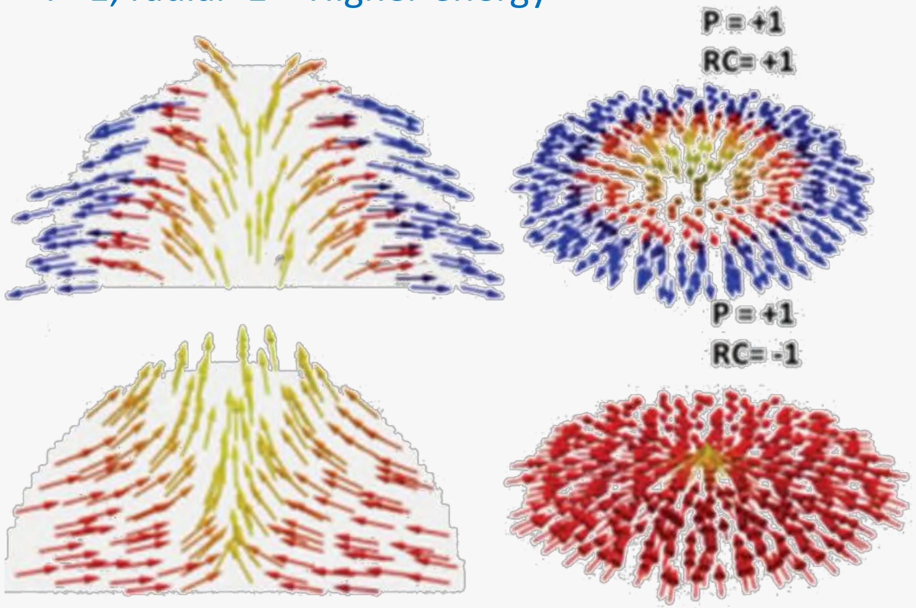
C. Dietrich, Phys. Rev. B 77, 174427 (2008)

Example: half-sphere nanodot

→ Usual Vortex state replaced with radial edges (see magnetostatics at sharp edges)



P=1, radial=1 – Higher energy

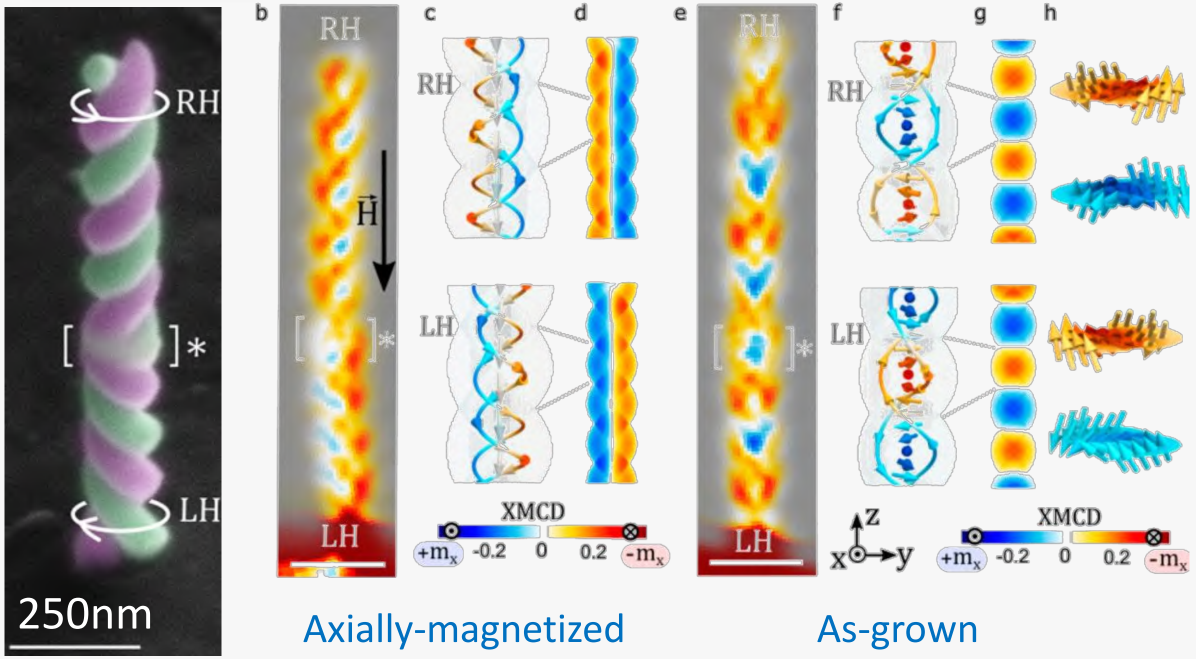


P=1, radial=-1 – Lower energy

E. Berganza, Nanoscale 12, 18646 (2020)

Example: magnetic chirality by geometry

FEBID Co



Axially-magnetized

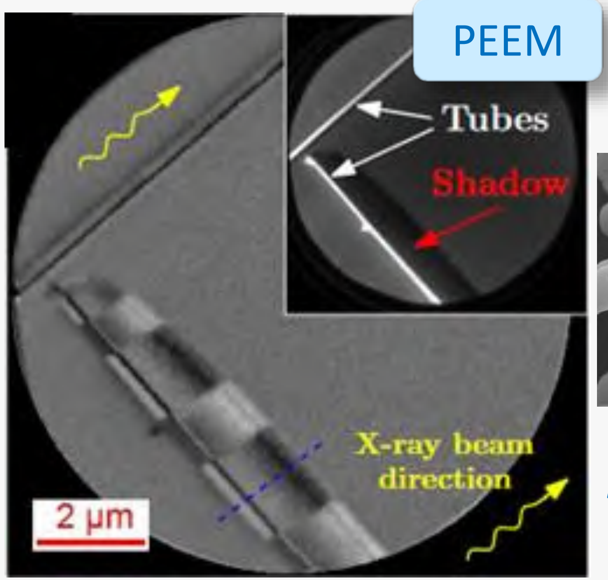
→ Chiral longitudinal helixes

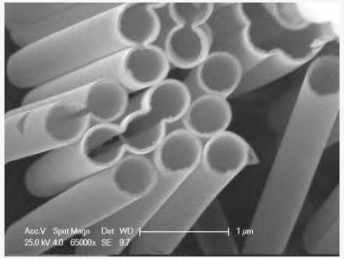
As-grown

→ Chiral transverse helixes

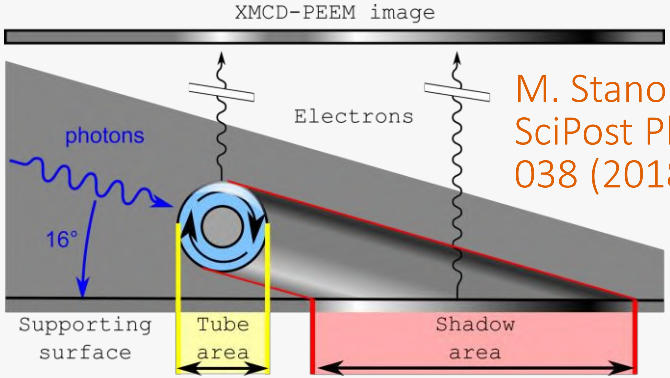
D. Sanz-Hernández, ACS Nano 14, 8084 (2020)

Growth-induced curvature-related magnetic anisotropy – Azimuthal magnetization

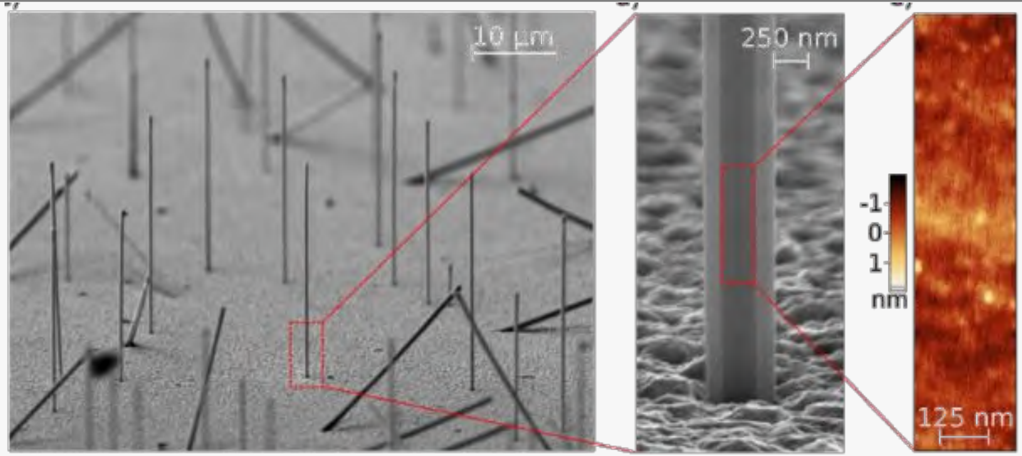




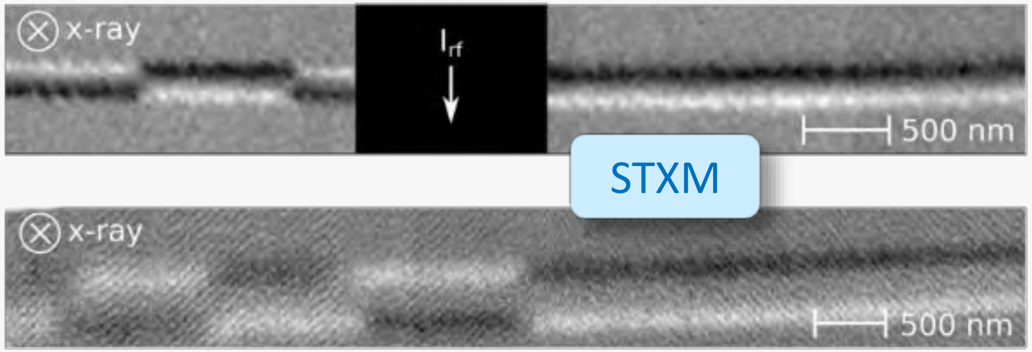
Electroless CoNiB, D=500nm



M. Stano et al., SciPost Phys. 5, 038 (2018)



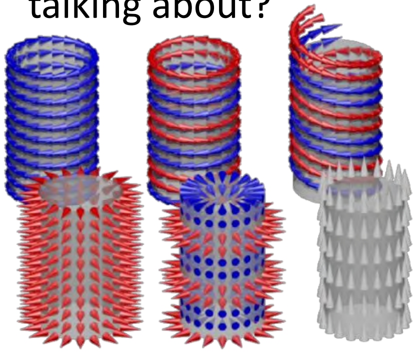
PVD-capped (permalloy)VLS GaAs hexagonal wires



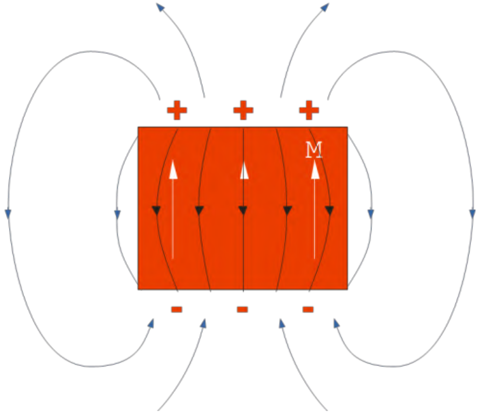
CVD: M. Zimmermann, NanoLett 18, 2828 (2018)
ALD: M.C. Giordano, ACS Appl. Mater. Interf. 12, 40443 (2020)

Table of contents

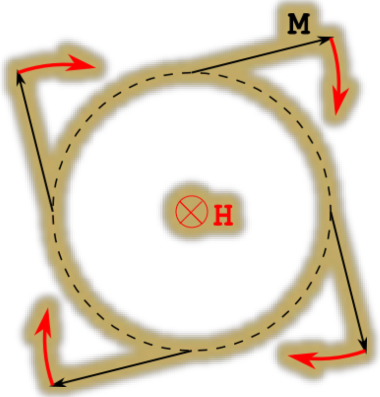
- What are we talking about?



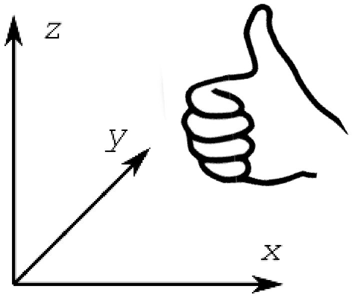
- Magnetostatics in 3D



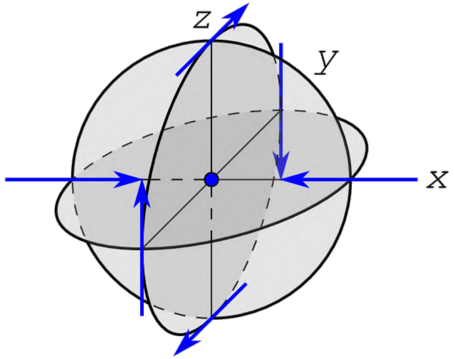
- Magnetization dynamics



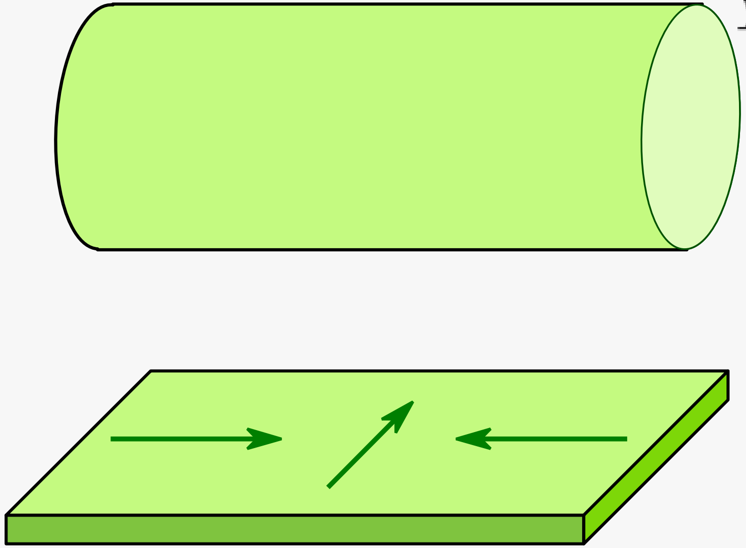
- General considerations

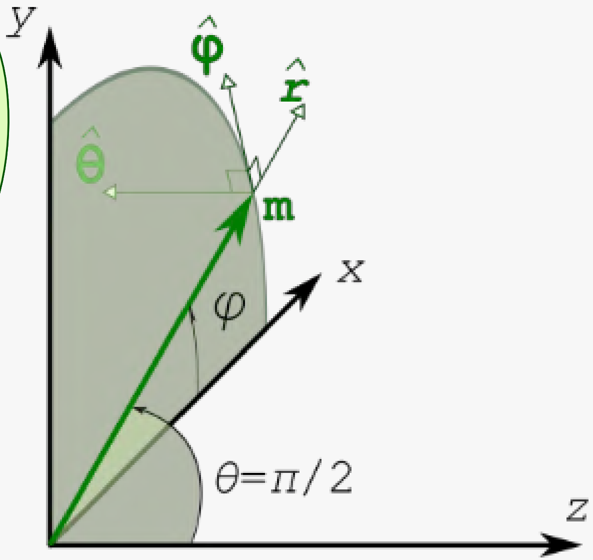


- Spin textures in 3D



Precessional dynamics of transverse walls under magnetic field





Precessional dynamics under magnetic field

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\,\mathbf{m}\times\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

A. Thiaville, Y. Nakatani, Domain-wall dynamics in nanowires and nanostrips, in *Spin dynamics in confined magnetic structures {III}*, Springer (2006)

Wall speed

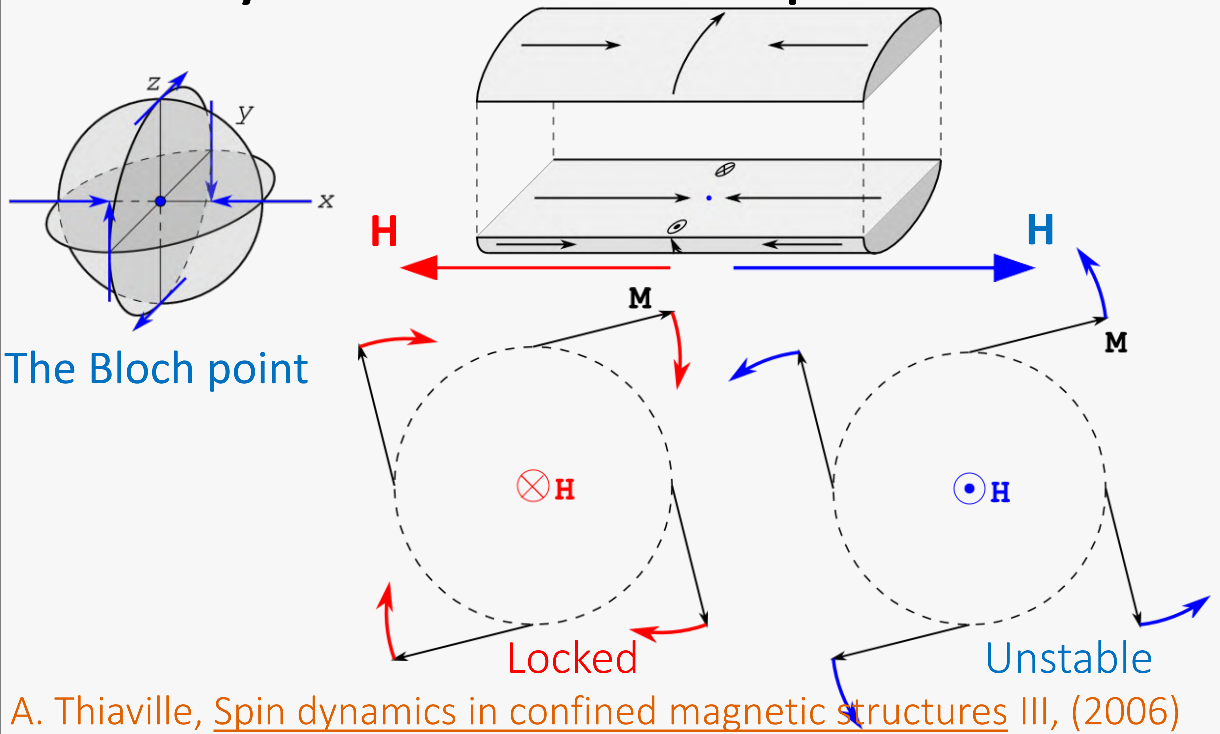
$$v = \alpha|\gamma_0|\Delta H$$

$$v = |\gamma_0|\Delta H/\alpha$$

- Walker field $H_W = \alpha M_s/2$ $\approx$ few mT
- Walker speed $v = |\gamma_0| M_s \Delta/2$

up to $\approx$ 100 m/s, to km/s

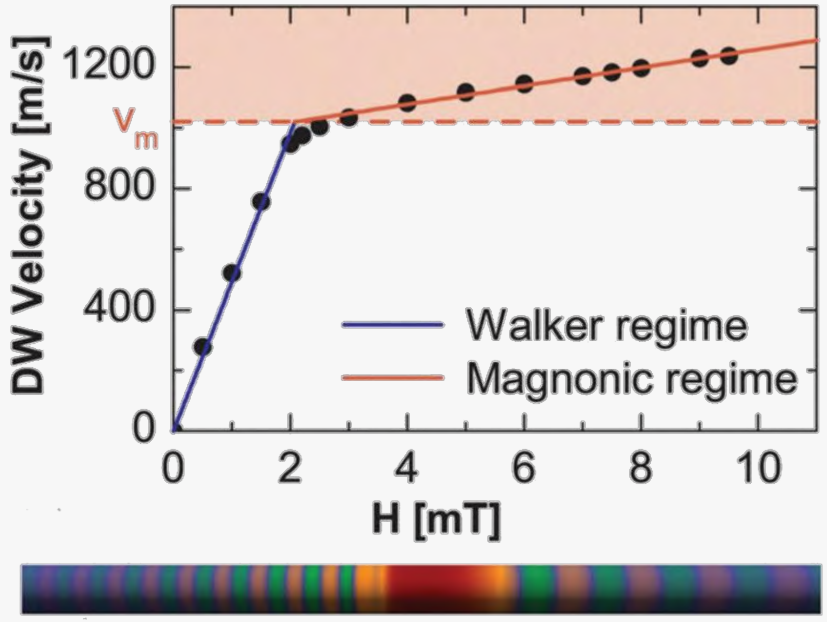
‘Once-only’ Walker event in Bloch-point walls



A. Thiaville, Spin dynamics in confined magnetic structures III, (2006)

Magnonic limit

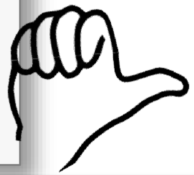
Tubes (similar to wires)



M. Yan et al., Appl. Phys. Lett. 99, 122505 (2011)

LLG equation

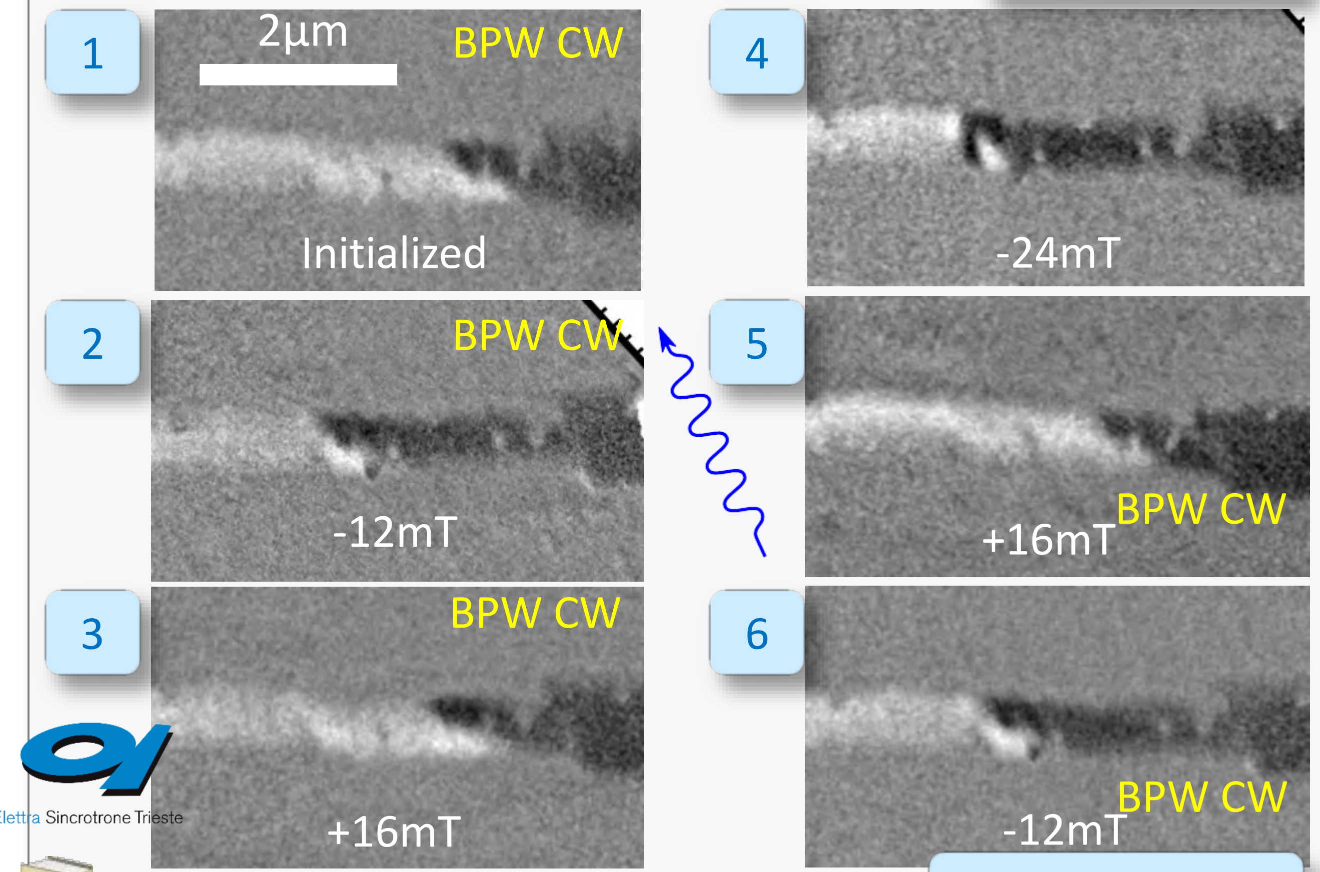
$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt}$$



- Circulation related to direction of motion
- Curvature-&-LLG-induced dynamics chirality

Motion under quasistatic magnetic field

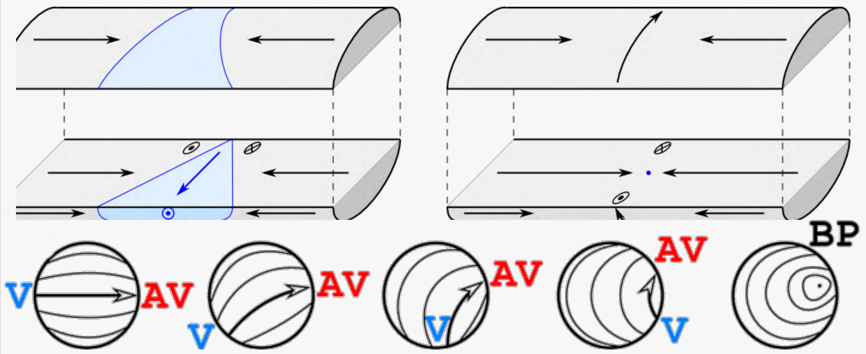
XMCD-PEEM



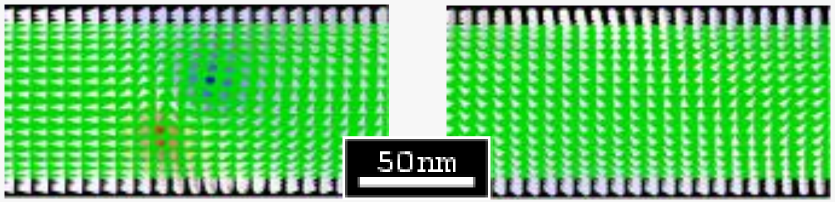
Fe$_{20}$Ni$_{80}$, 140nm

A. Wartelle, PRB99, 024433 (2019)

How does topology change?

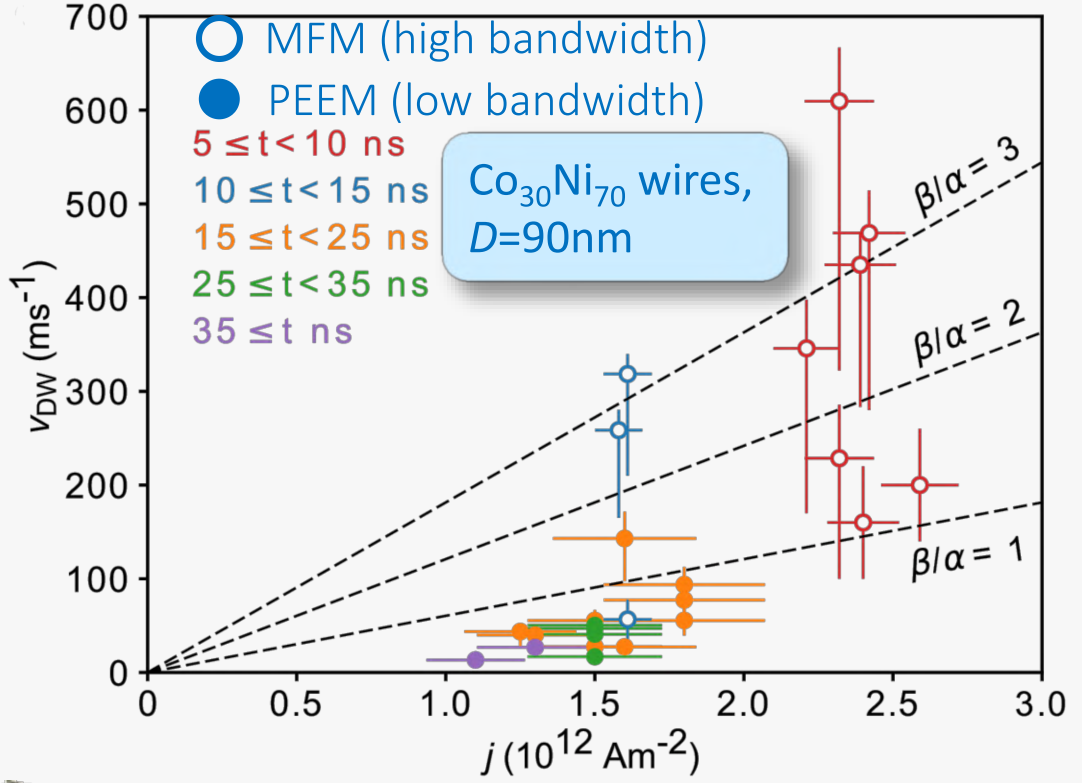


Simulations



- No topological protection !
- Not predicted previously

Bloch-point wall motion under current



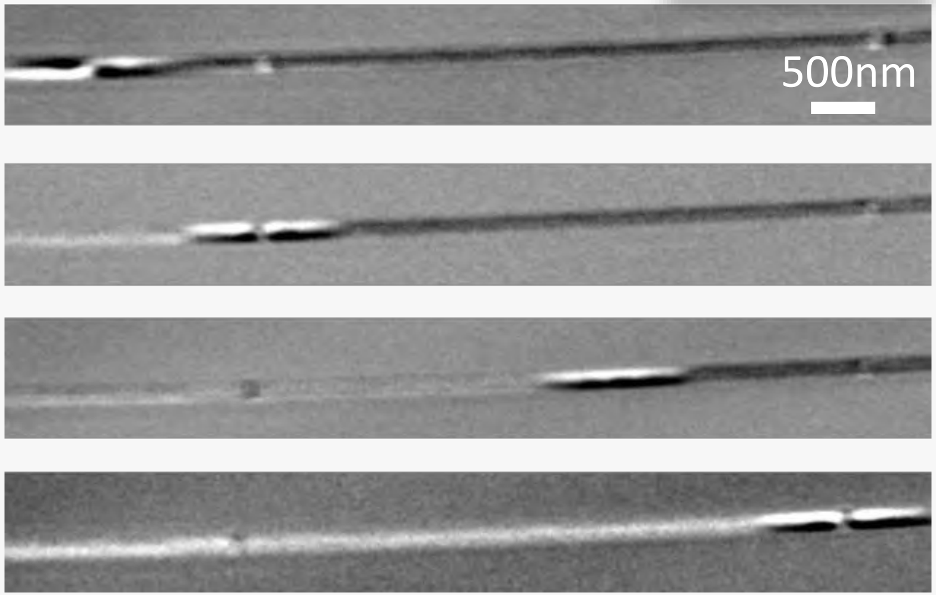
M. Schöbitz et al, PRL123, 217201 (2019)

- Largest STT speed in ferromagnetic material
- Compatible only with below-Walker regime
- The magnonic regime is at hand

$\ell = 100$ nm $\quad D = 130$ nm

$j = 2.6 \times 10^{12}$ A/m^2 (1 ns)

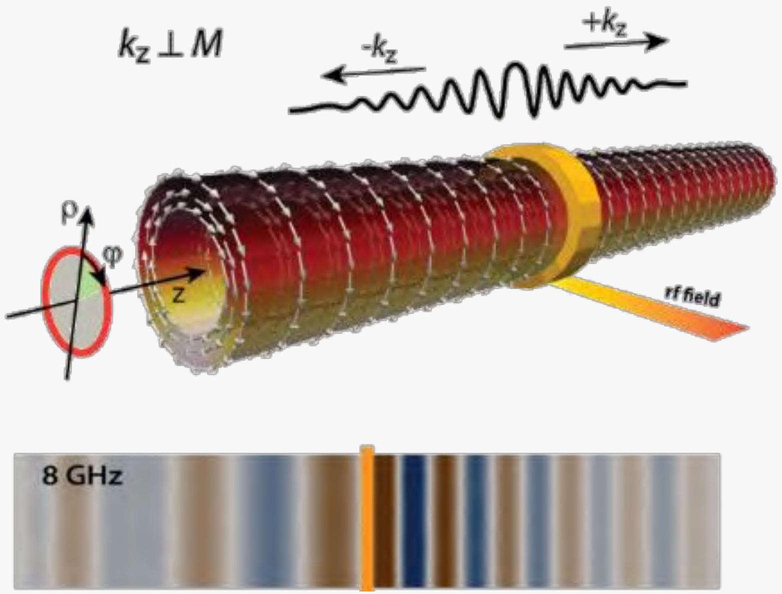
XMCD TXM



Note similar recent experimental report C. Bran et al, arXiv 2210.01480 (2022)

Spin waves : non-reciprocity

Magnetization: azimuthal



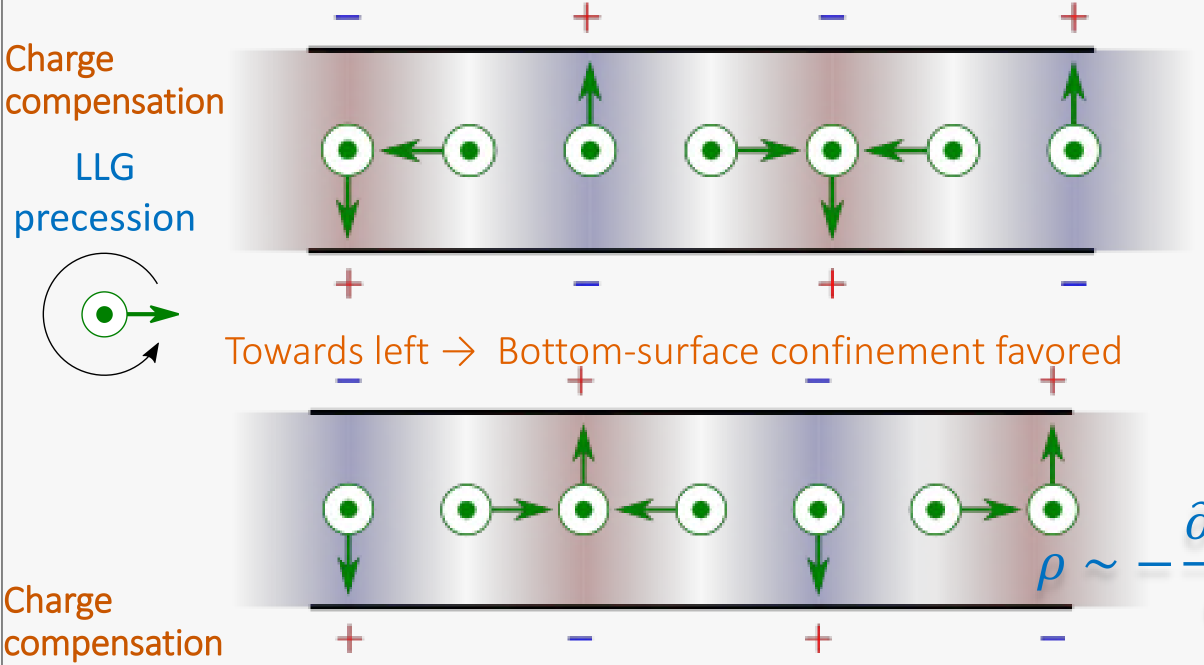
J. A. Otálora, Phys. Rev. Lett. 117, 227203 (2016)

LLG equation

$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt}$$

Underlying physics

Daemon Eshbach geometry: **M** and **k** orthogonal



$\rho \sim -\frac{\partial m_x}{\partial x}$

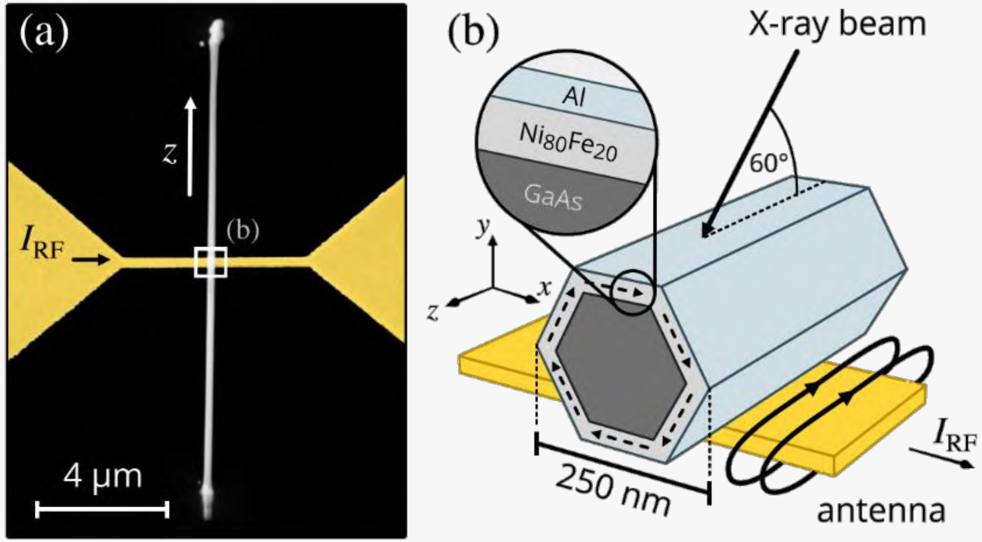
$\sigma \sim \mathbf{m}\cdot\mathbf{n}$

- Outer and inner surfaces of tube are inequivalent
- Physics = combination of LLG chirality and curvature of tube

Magnetization dynamics – Non-reciprocal spin-wave dispersion (2/2)

Material and setup

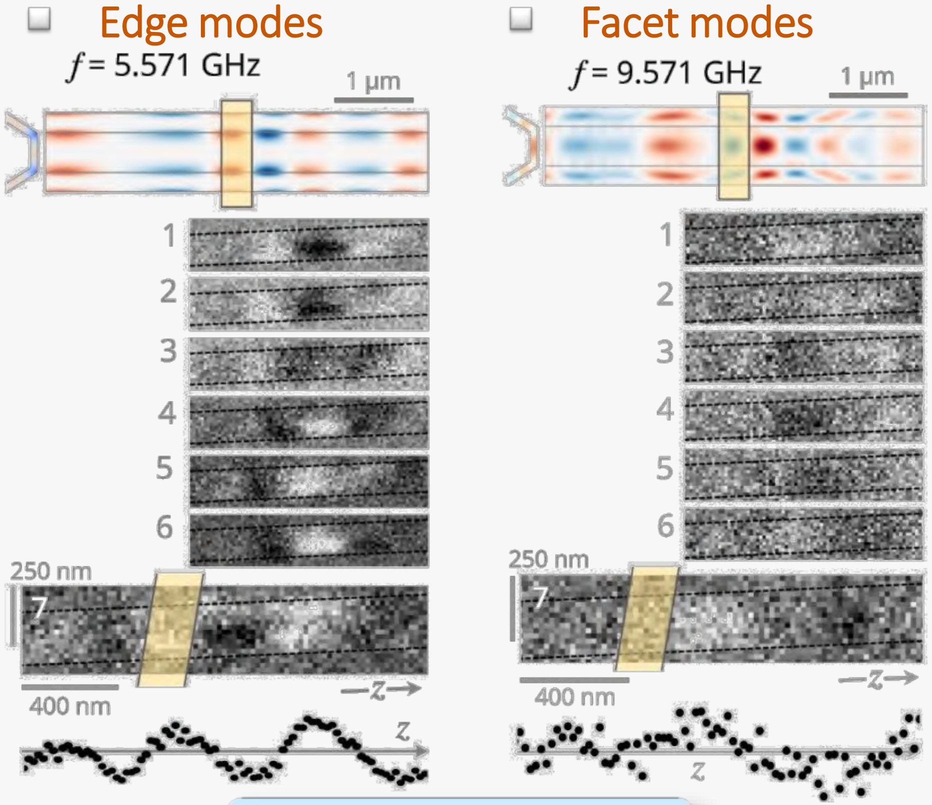
Nanotube with azimuthal magnetization excited locally with a narrow antenna



L. Körber, Phys. Rev. B 104, 184429 (2021)

Magnetization dynamics

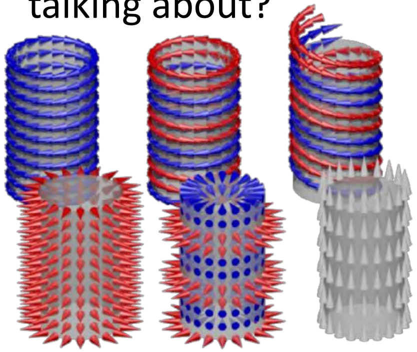
- Edge modes
- Facet modes



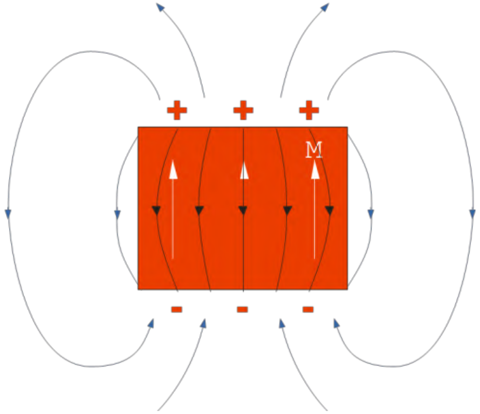
Time-resolved STXM

Table of contents

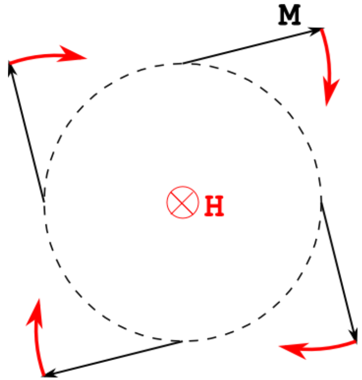
- What are we talking about?



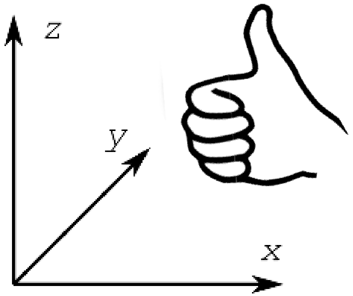
- Magnetostatics in 3D



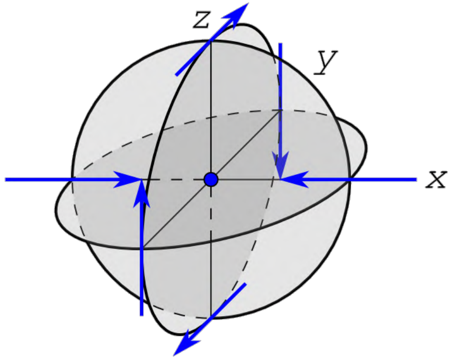
- Magnetization dynamics



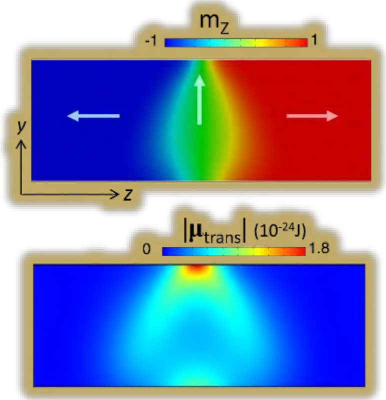
- General considerations



- Spin textures in 3D



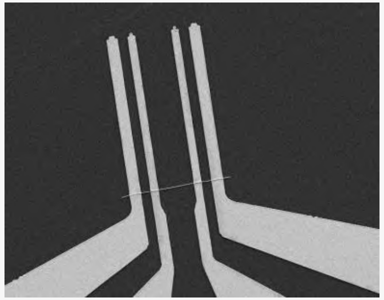
- Spintronics in 3D

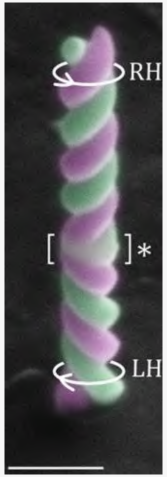


Spintronics in 3D – Field is largely ahead of us

Material and patterning challenges

- Implement other effects than STT, such as magnetoresistance and spin-orbit torques. Requires core-shell multilayers
- Electrical contacting
- Materials with low electrical resistance





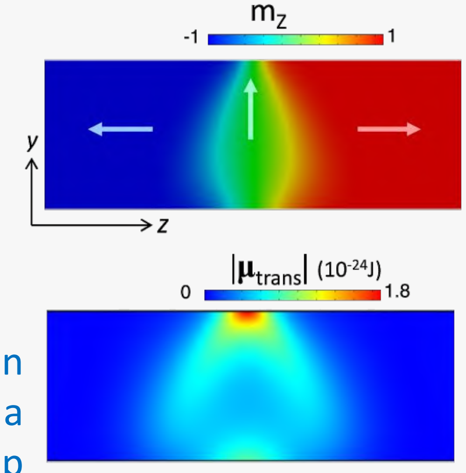
Heat management

- Cool free-standing 3D nanomagnets
- Temperature gradients at modulations of section

Spin accumulation

- Curvature and spin accumulation
- Interaction with spin textures with large gradients, such as Bloch points

Example: transverse spin accumulation across a transverse wall in a strip



M. Sturma, Phys. Rev. 94, 104405 (2016)

Quantum effects

- Diffusive versus ballistic regimes
- Quantum coherence of edge currents (TI etc.)

Spintronics in 3D – Critical role of Œrsted fields (1/3)

Œrsted fields

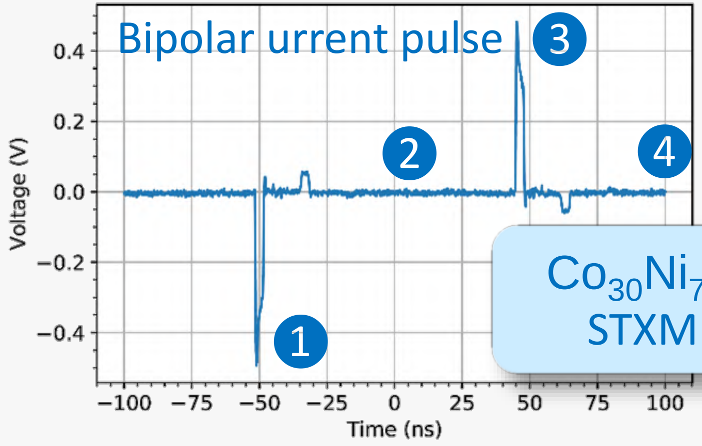
- 3D -> Larger than for flat films
- Note: similar issue in point-contact STNO

$$\mu_0 H_{Œ}(r) = \frac{1}{2}\mu_0 j r \qquad r = 50\ \text{nm}$$

$$j = 10^{12}\ \text{A/m}^2$$

➡ $\mu_0 H_{Œ} = 30\ \text{mT}$

Direct evidence

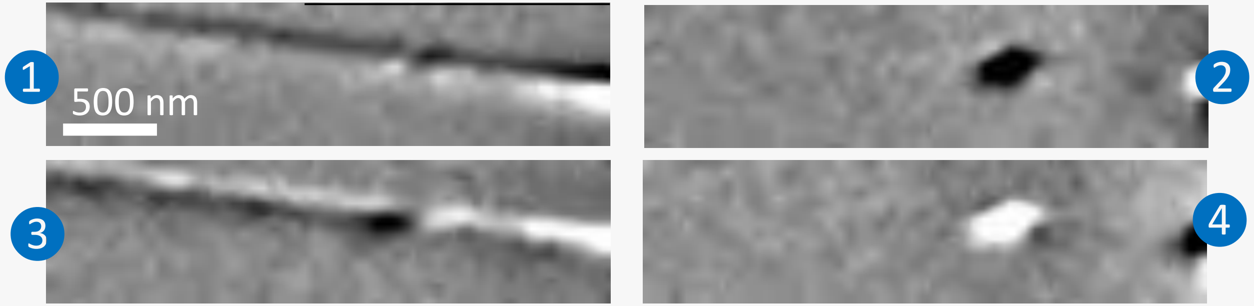


$Co_{30}Ni_{70}$ wire, diameter 100nm
STXM + XMCD + pump-probe

Averaged still frames

Pulse - (3 ns)

Interpulse (100 ns)



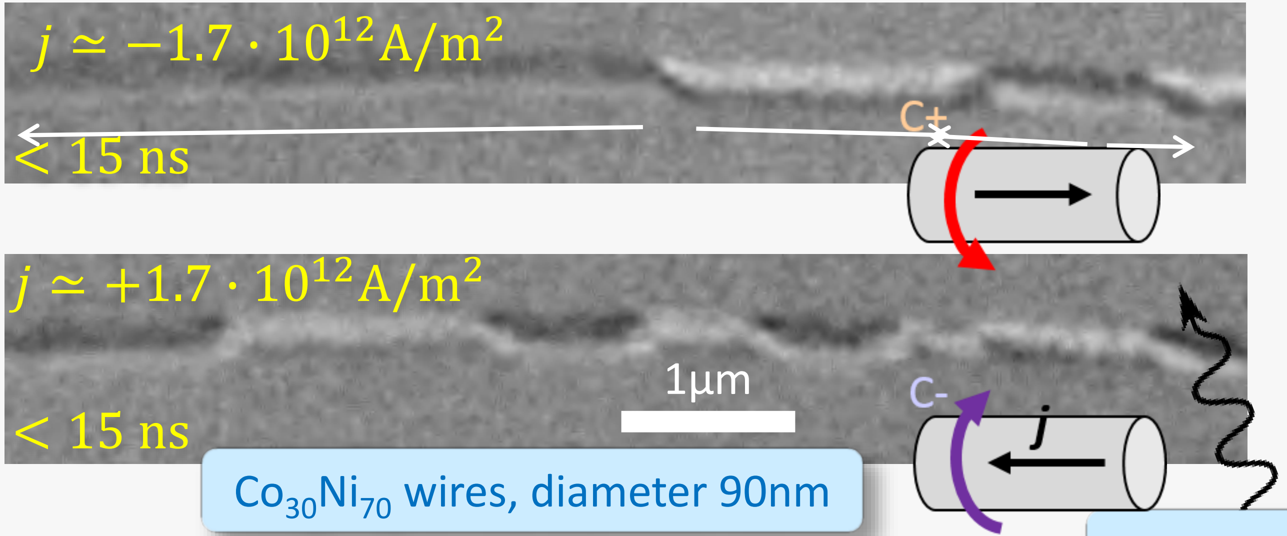
Pulse + (3 ns)

Interpulse (100 ns)

M. Schöbitz et al., APL 118, 172411 (2021)

spintec
SPIN IN ELECTRONICS

Experiments: only Bloch-point wall with a given circulation



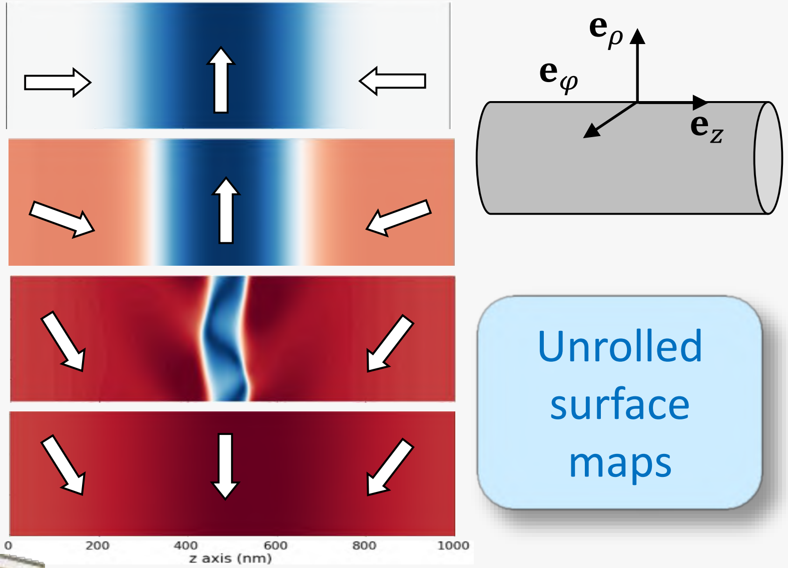
$Co_{30}Ni_{70}$ wires, diameter 90nm

X-ray Beam

M. Schöbitz et al, PRL123, 217201 (2019)

ALBA

Simulations of the switching current



Unrolled surface maps

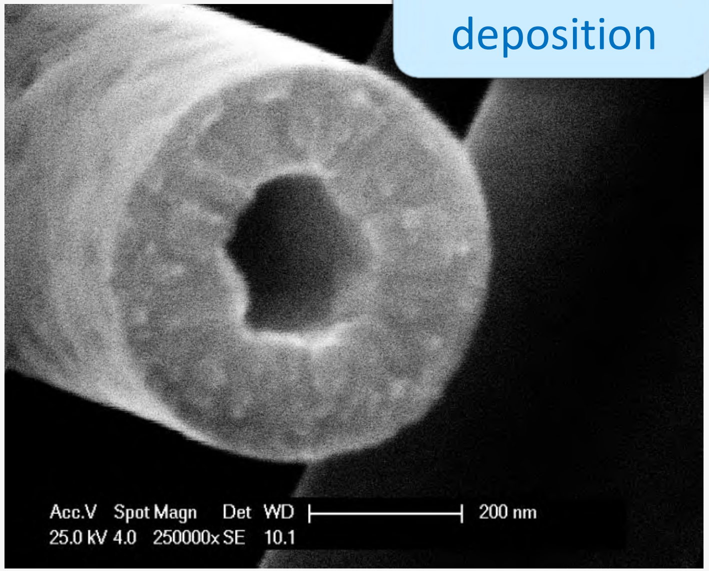
A. De Riz et al., PRB 103, 054430 (2021)

- Stabilizes Bloch-point domain walls (contrasts with field-driven case)
- Contrary to predictions: chirality negative with direction of motion

Spintronics in 3D – Critical role of Œrsted fields (3/3)

Material

Electroless deposition



- CoNiB shell: (34 ± 4) nm
- Cu core: (117 ± 13) nm
- External diameter: (578 ± 5) nm

Domain wall motion driven by Œrsted field

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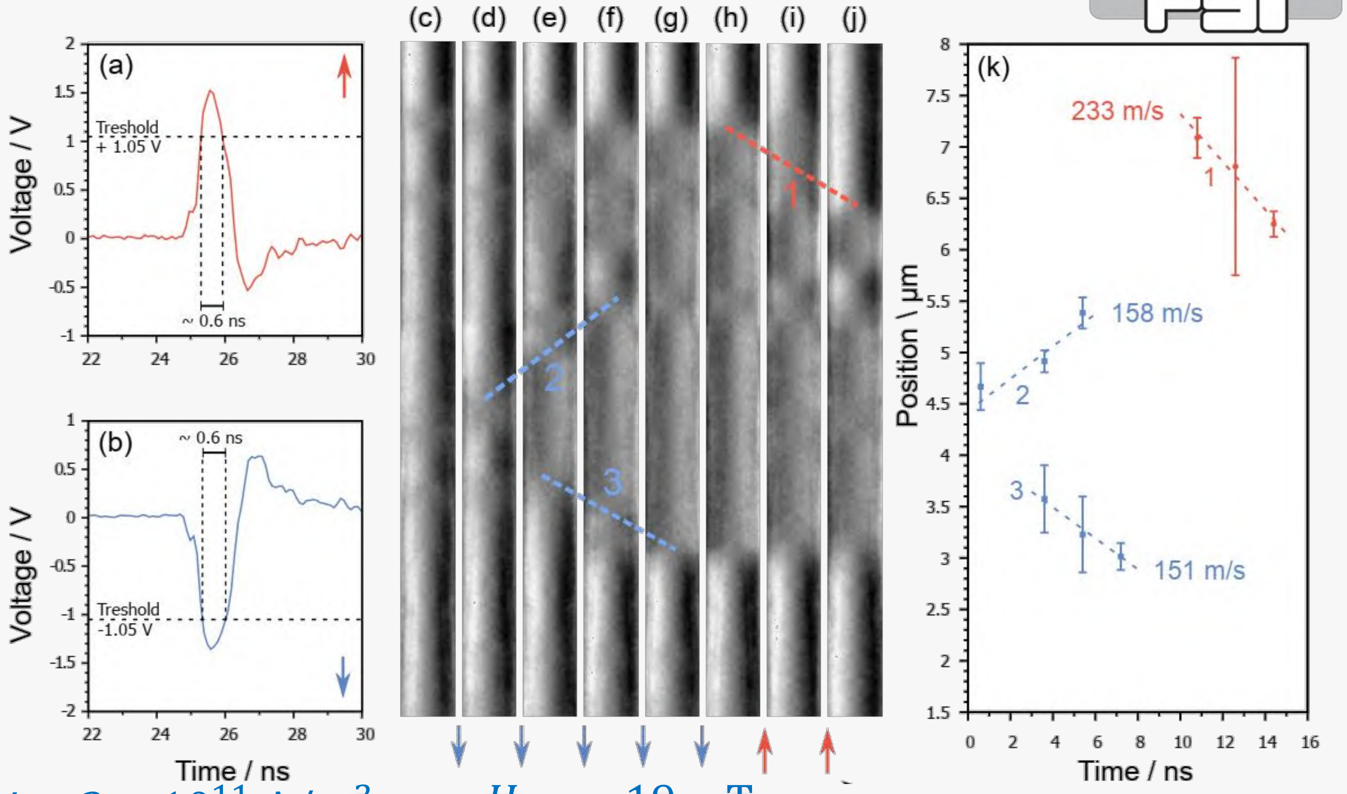

$j \approx 2 \times 10^{11}\ \mathrm{A/m^2}$ $\mu_0 H_{\mathrm{OE}} \approx 19\ \mathrm{mT}$

- Simple : rotational symmetry, periodic boundary conditions
- Short and intense pulses of magnetic field

A few references

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