Quantitative analysis of shadow XMCD-PEEM to unravel 3D magnetic configurations

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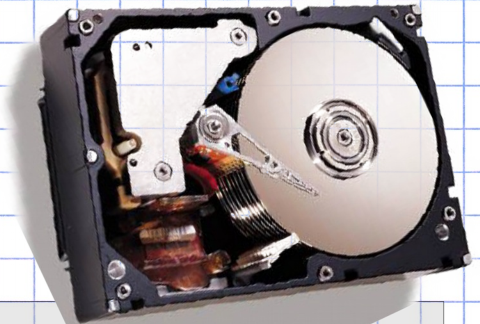
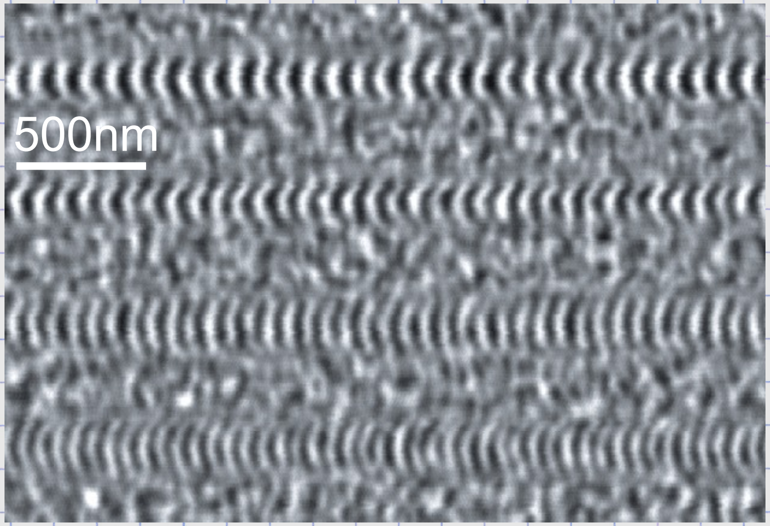
Smart Membranes
Halle, Germany

The research leading to these results has received funding from the European Unions's 7th Framework Programme under grant agreement n°309589 (M3d)



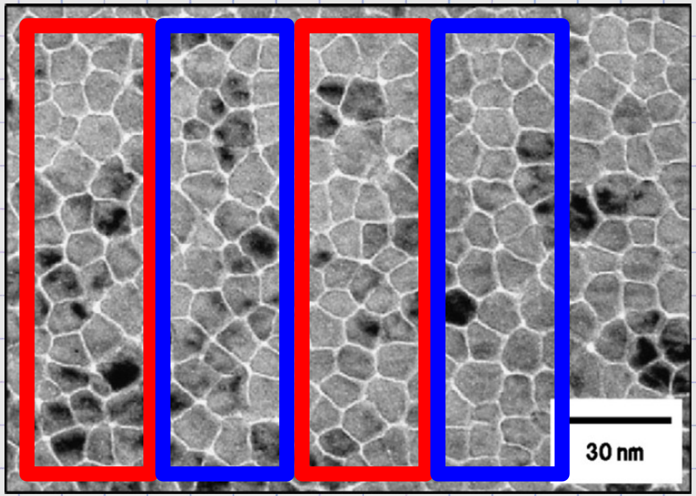
Magnetic bits on Hard Disk Drive

Co-based hard disk media : bits 50nm and below



B. C. Stipe, Nature Photon. 4, 484 (2010)

Underlying microstructure

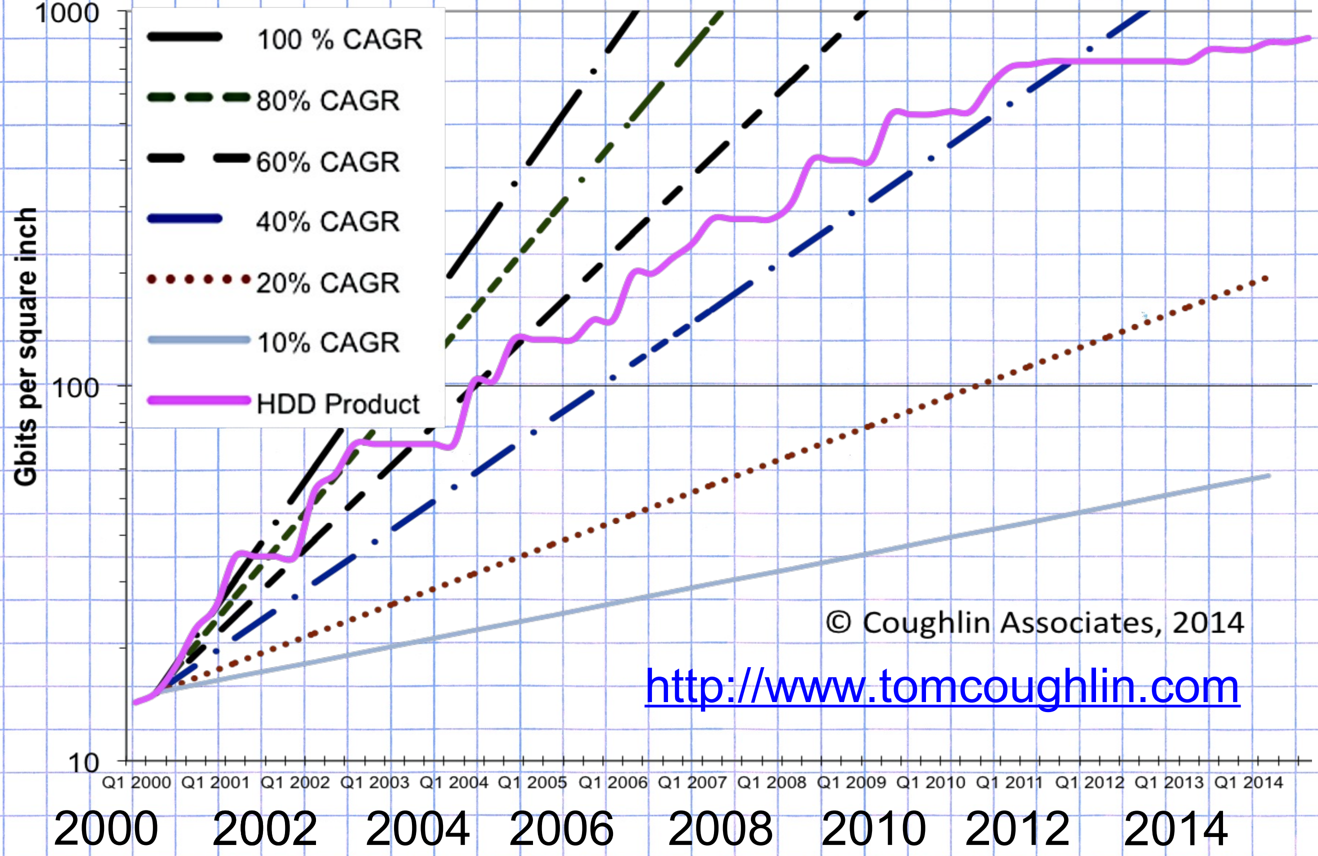


S. Takenoiri, J. Magn. Magn. Mater. 321, 562 (2009)

Gains in areal density

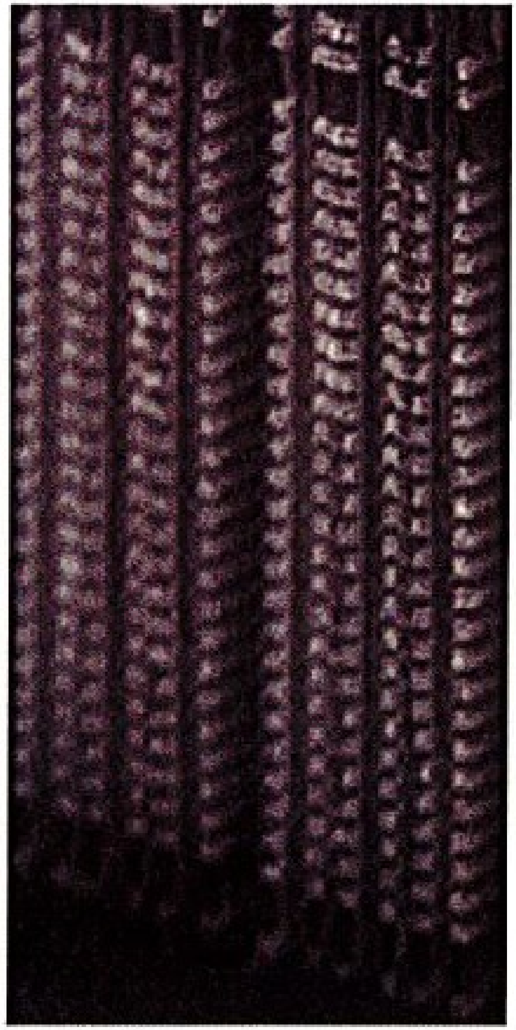
- Compromise : time stability, writability, readibility
- Relies on progress of technology and science

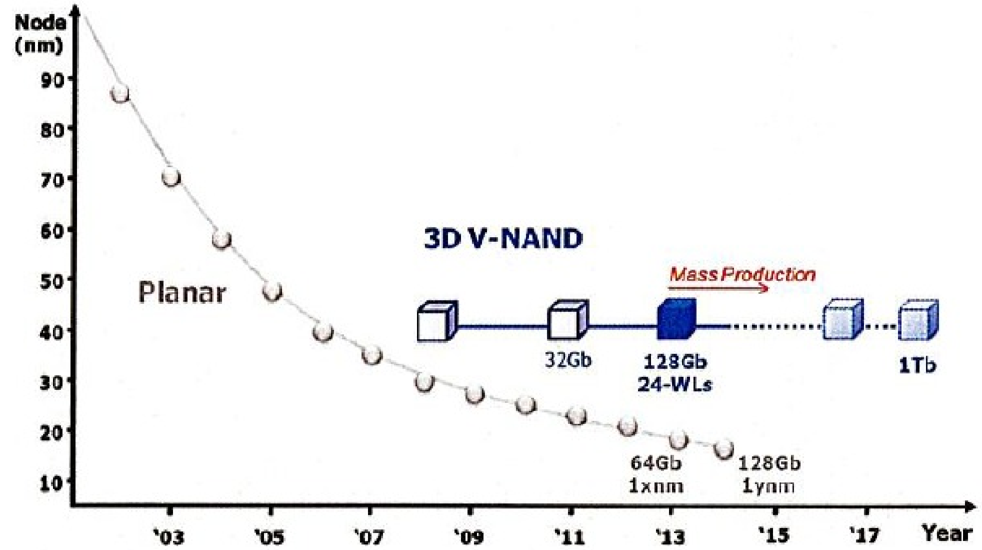
Motivation – Which future for magnetic data storage ?

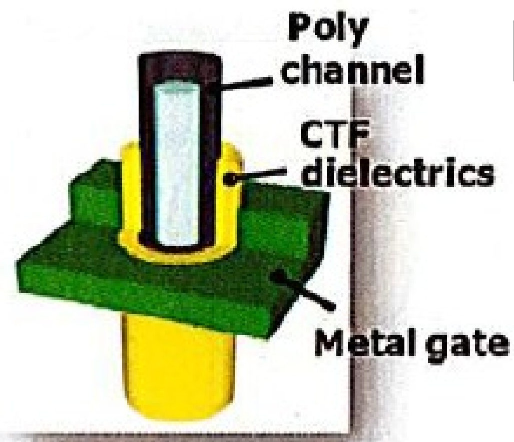


- Growth rate is seriously slowing down
- Major bottlenecks ahead
- Any 2D-based storage design will sooner or later face a limit in areal density, imposer by fundamental bottlenecks

Motivation – Flash are already significantly 3D







Facts

⇨ Incremental (multilevel patterning) however already 'quite 3D'

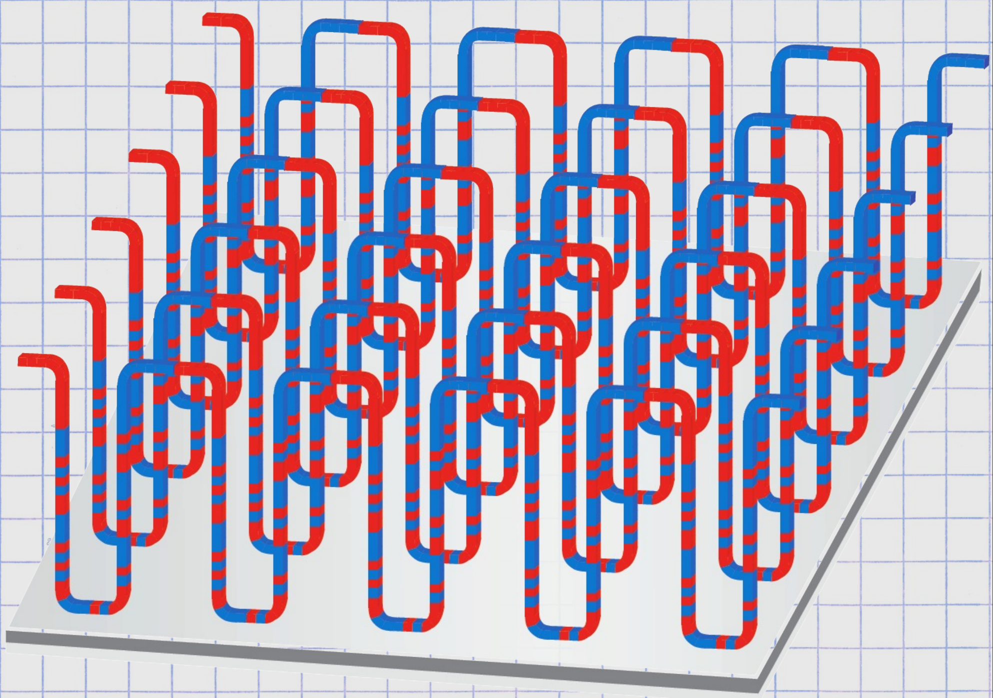
⇨ Technological node unchanged

⇨ 1Gb/mm2 → 600Gb/in^2...

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 50, NO. 1, JANUARY 2015

Motivation – Towards a 3D magnetic memory ?

Proposal for a race-track memory in 3D



S. S. P. Parkin, Science 320, 190 (2008)
Scientific American, June, 76 (2009)
+ patents (IBM)

Pros

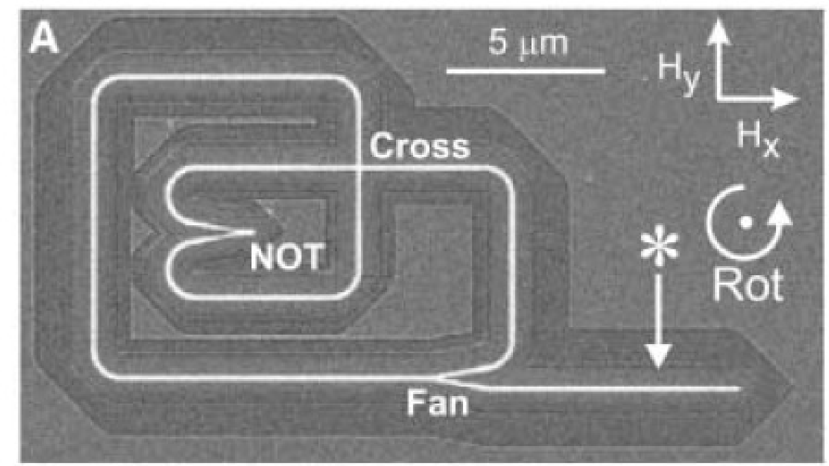
- Incremental progress made again possible along the depth
- One read/write cell per wire → cost remains moderate

Cons

- Fabrication is technologically challenging
- In-depth inspection of devices difficult

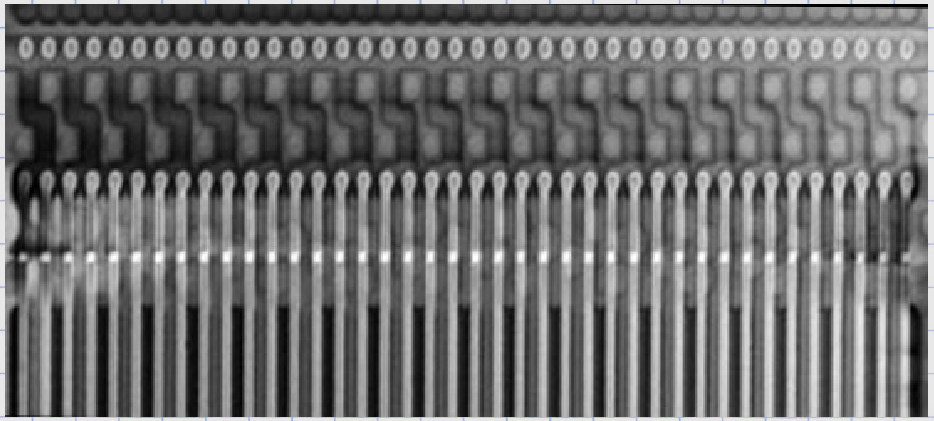
Motivation – Demonstrators of 2D devices with domain walls

Logic (Field driven)



D. A. Allwood et al., Science 309, 1688 (2005)

Memory (current-driven)



L. Thomas et al., IEEE International Electron Devices meeting (2011)

- Is time ripe to go back to 3D proposals ?
- What are the technological bottlenecks ?
- What new science may be made along the road ?

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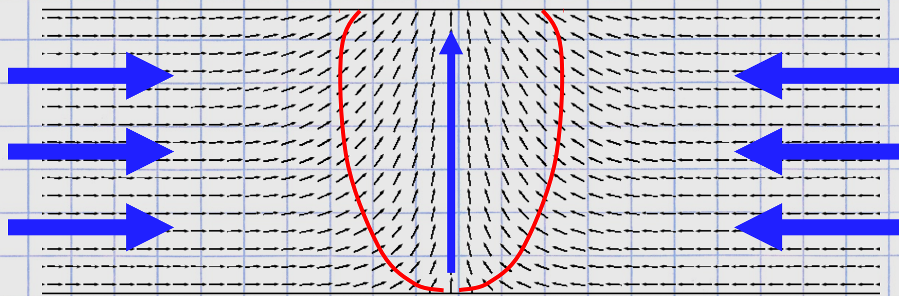
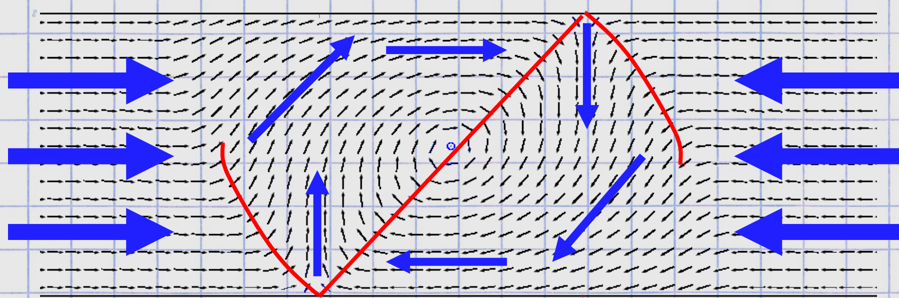
Transverse versus vortex wall

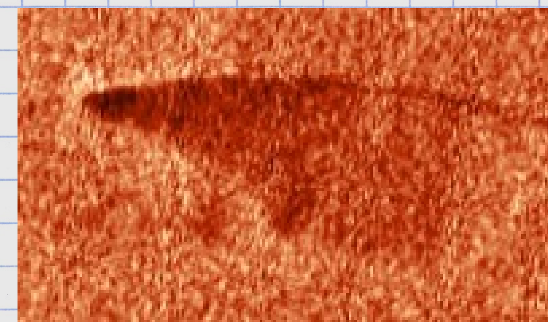
Thin and narrow strips



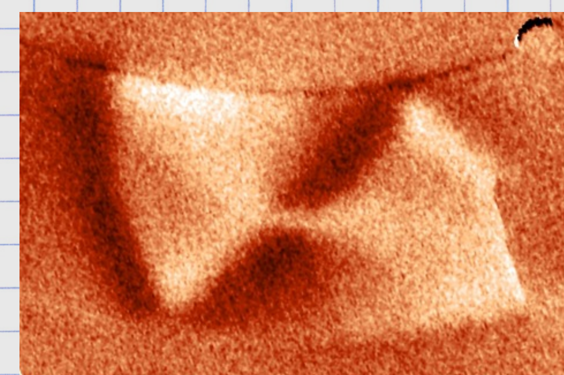
Thick and large strips



Transition for: $tW \approx 75\,\Delta_{\mathrm{d}}^2$



Magnetic Force Microscopy

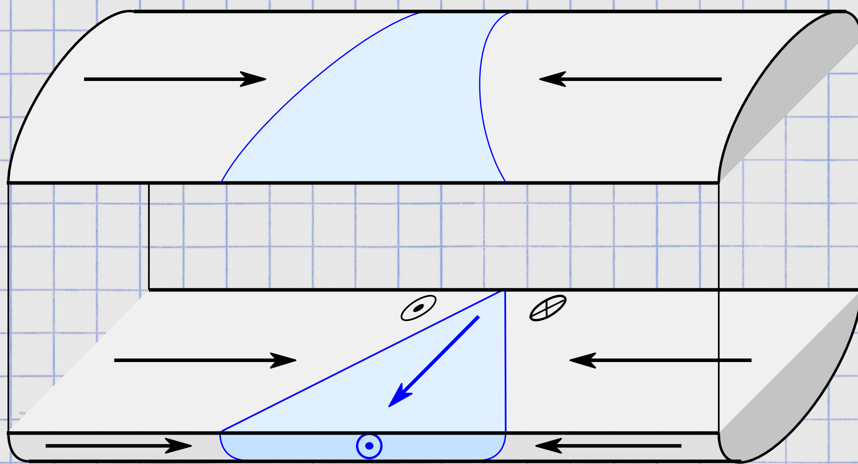


R. McMichael & M. Donahue, IEEE Trans. Mag. 33, 4167 (1997)

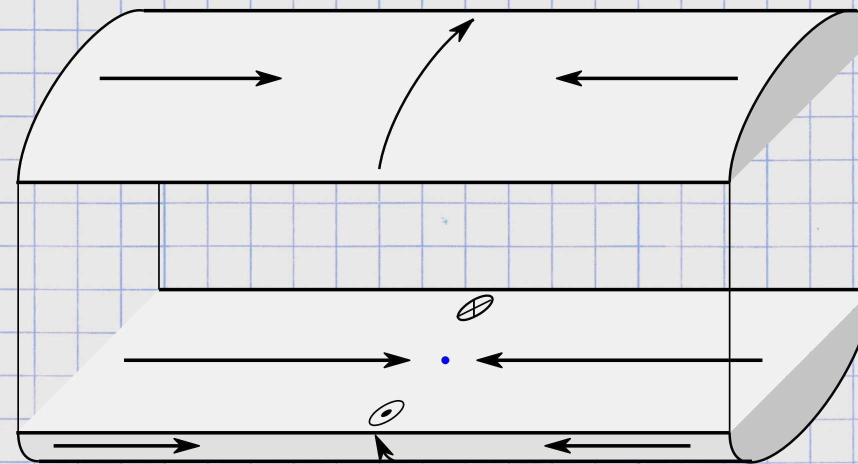
Y. Nakatani et al., J. Magn. Magn. Mater. 290-291, 750 (2005)

⇨ Experimentally well established

Transverse wall $D \lesssim 7\Delta_d$



Bloch-point wall $D \gtrsim 7\Delta_d$

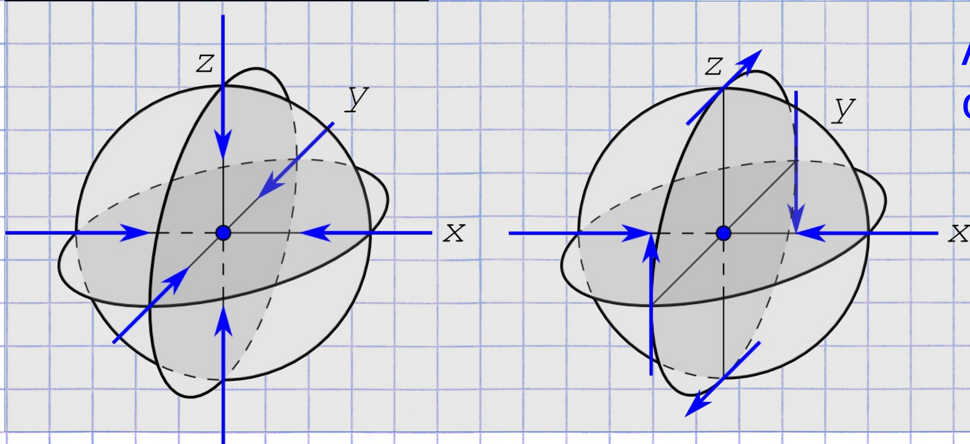


Sometimes improperly named vortex walls

H. Forster et al., J. Appl. Phys. 91, 6914 (2002)

A. Thiaville, Y Nakatani / B. Hillebrands, A. Thiaville (ed.),
Spin dynamics in confined magnetic structures III, 101, 161-206 (2006)

What is a Bloch-point ?



A magnetic texture with local cancellation of the magnetization vector

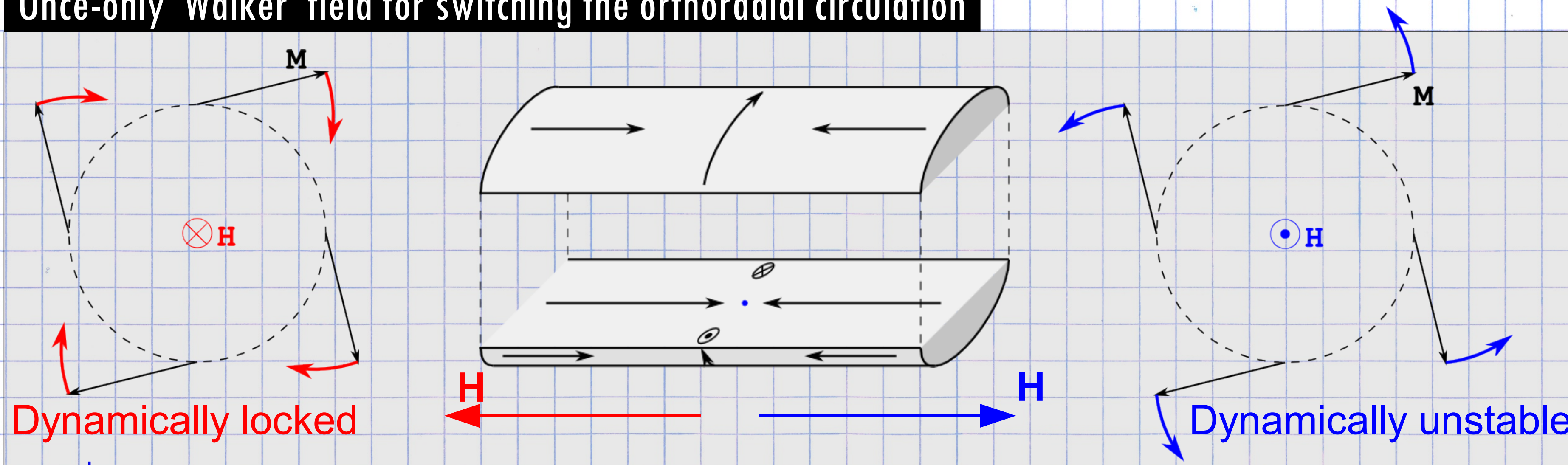
R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

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

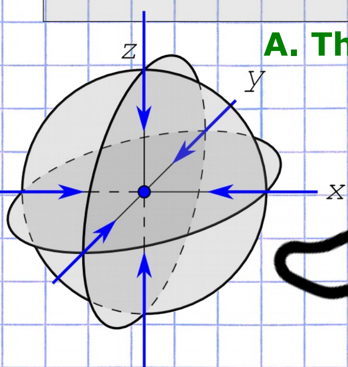
LLG equation

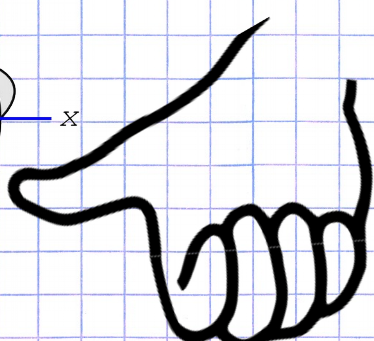
$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = \gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} \qquad \gamma_0 < 0$$

Once-only 'Walker' field for switching the orthoradial circulation



A. Thiaville et al., in Spin dynamics in confined magnetic structures III, p.161-206 (2006)

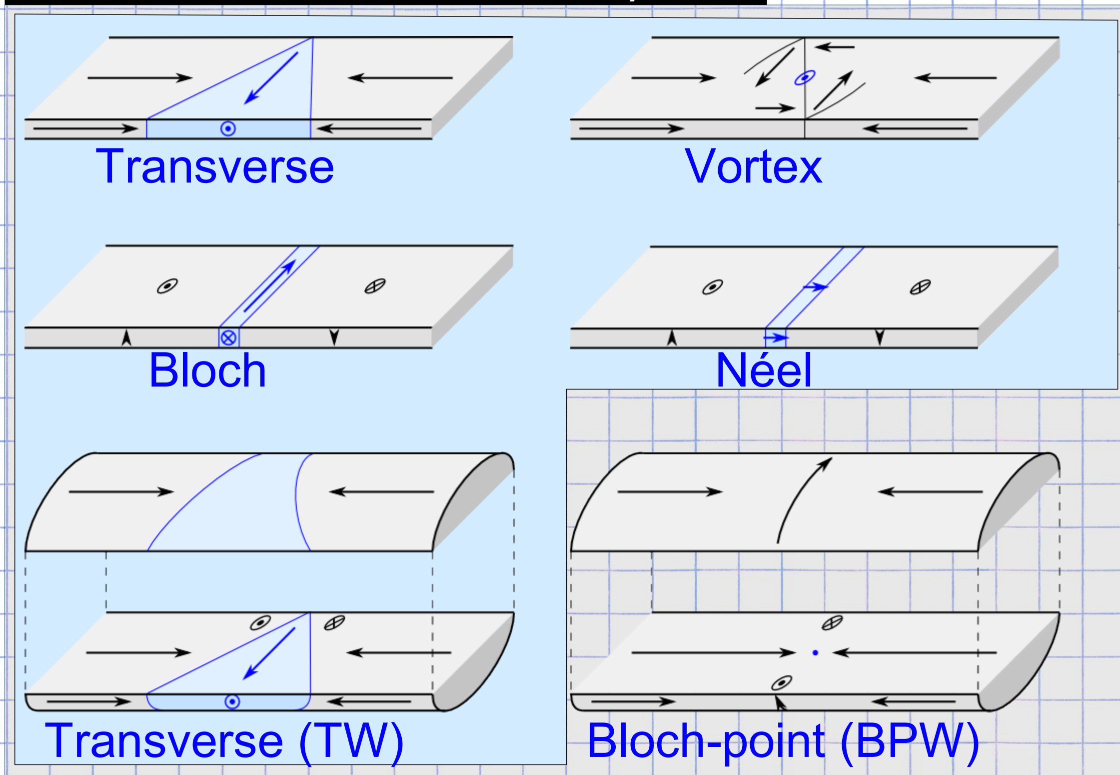




- Once-only 'Walker' process for the circulation
- Right-hand rule : DW direction of motion vs circulation
- Same physics predicted (later) for nanotubes

Motivation – Domain-wall motion in strips and wires : overview

Domain walls in one-dimensional systems



- Transverse and vortex walls share the same topology
- Bloch-point domain walls are of a different class → Topological protection
- Need to characterize 3D magnetization textures

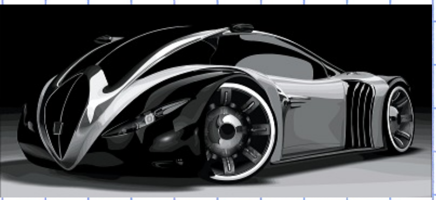
Strips and transverse walls

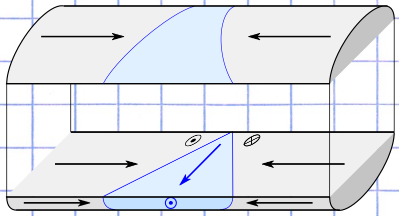
- Theory and experiments
- Domain-wall transformation
- Walker limit, low speed (~100m/s)

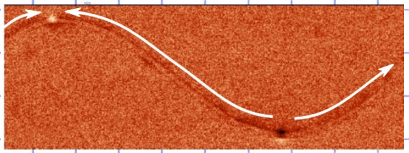
BPW in wires

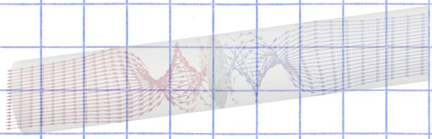
- Theory predictions ; no experiments
- No domain-wall transformation
- High speed expected (>1 km/s)

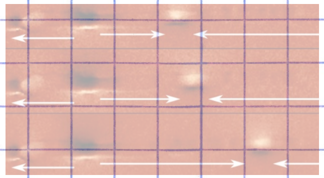
A. Thiaville et al., in Spin dynamics in confined magnetic structures III, p.161-206 (2006)





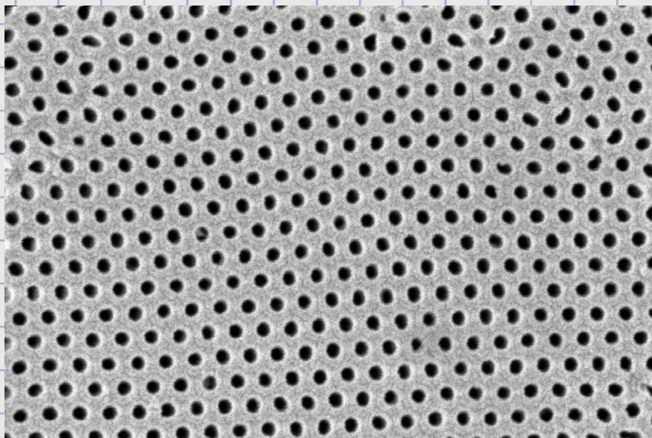






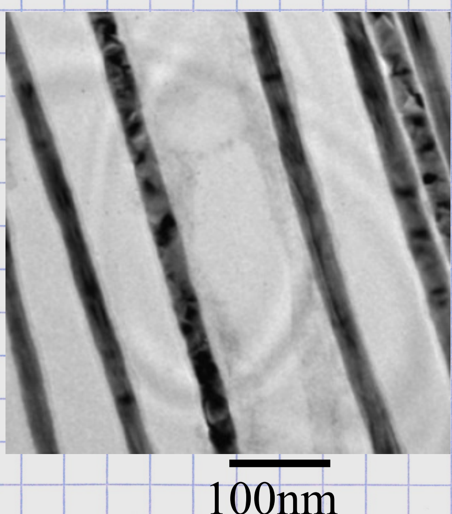
The basics

Anodization of aluminum → template



H. Masuda, Science 268, 1466-1468 (1995)

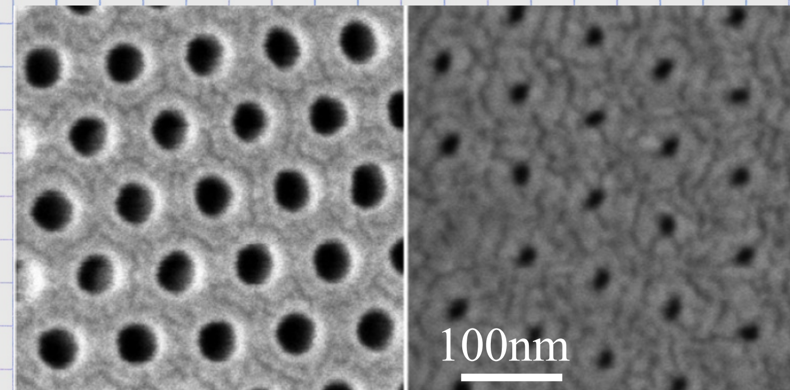
Electroplating → magnetic nanowires



⇨ Simple metals and alloys :
Co, Ni,
$Fe_{20}Ni_{80}$ $Co_{20}Ni_{80}$

Specific aspects

ALD to reduce pore diameter

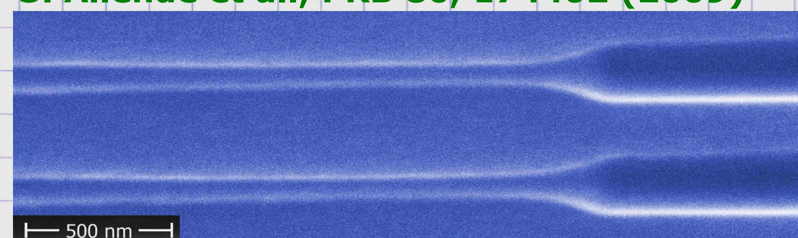


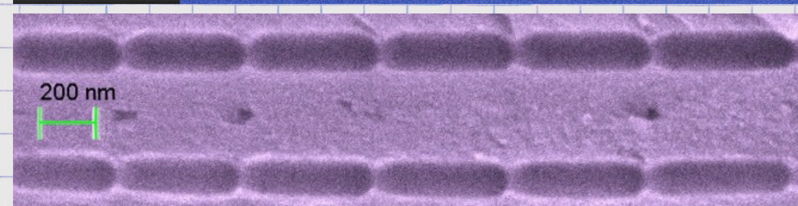
S. Da Col et al., Appl. Phys. Lett. 98, 112501 (2011)

⇨ Control pitch vs diameter

Modulation of pore diameter

S. Allende et al., PRB 80, 174402 (2009)





⇨ Landscape for domain walls

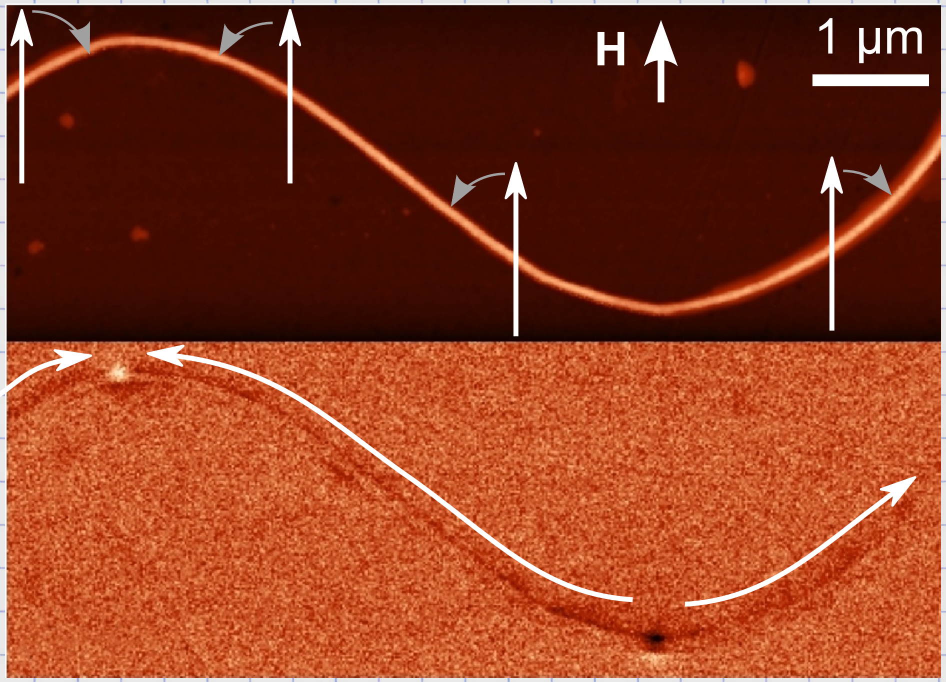
Preparation

- Alumina matrix dissolved
- Solution blown on surface

Nucleation

AFM

MFM

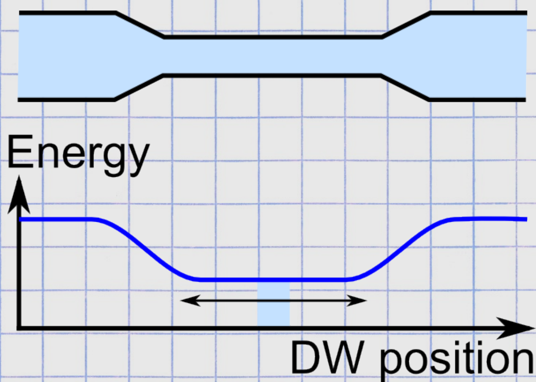


- Step 1 : wire magnetized along the bends radii
- At remanence, head-to-head and tail-to-tail domain walls at the bends

NB : similar to procedure for flat stripes : **T. Taniyama, Phys. Rev. Lett. 82, 2780 (1999)**

Note recent result on 3D wires (EBID) : **A. Fernandez-Pacheco, Sci. Rep. 3, 1 (2013)**

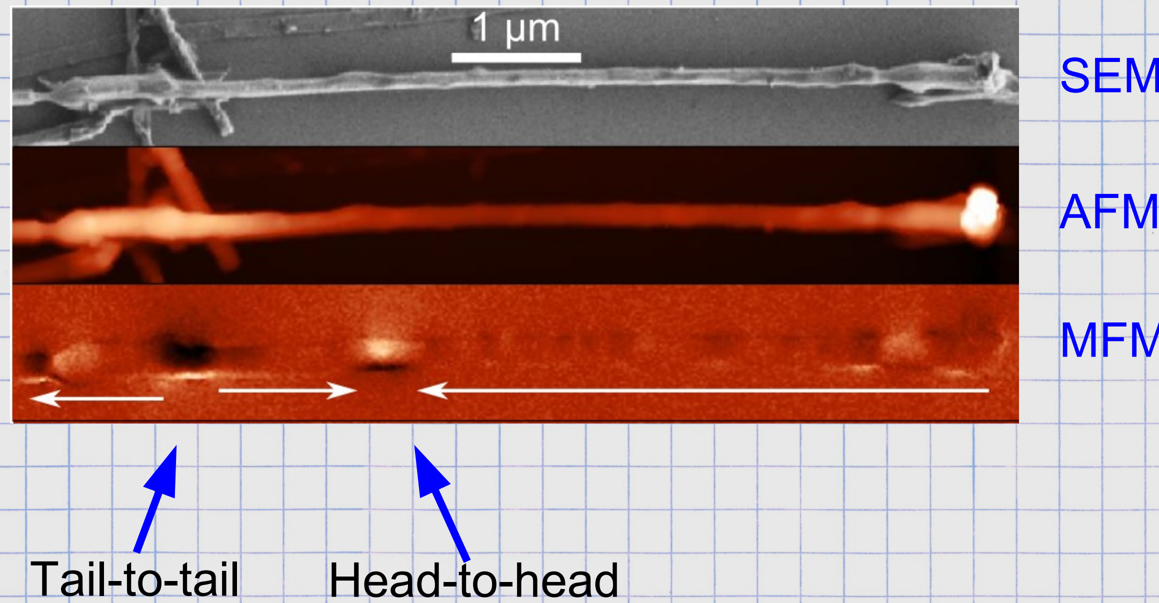
Principle



- Provides energy landscape for domain walls
- NB : reports with modulations however no domain walls

K. Pitzschel et al., J. Appl. Phys. 109, 033907 (2011)

Nucleation of domain walls



Protrusions create a 'box' for domain walls

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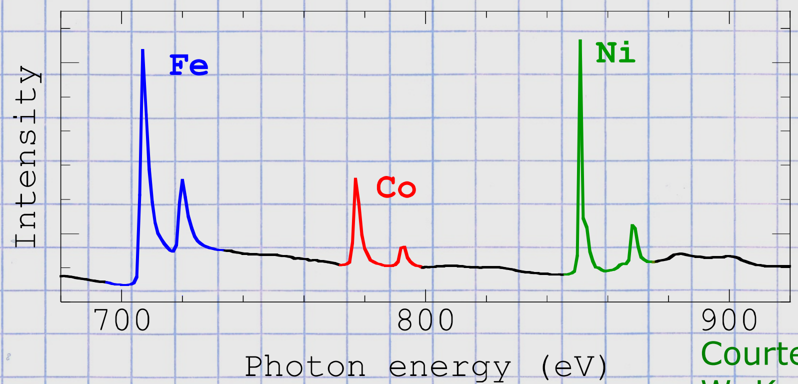
Identification of domain walls – XMCD-PEEM technique

XMCD

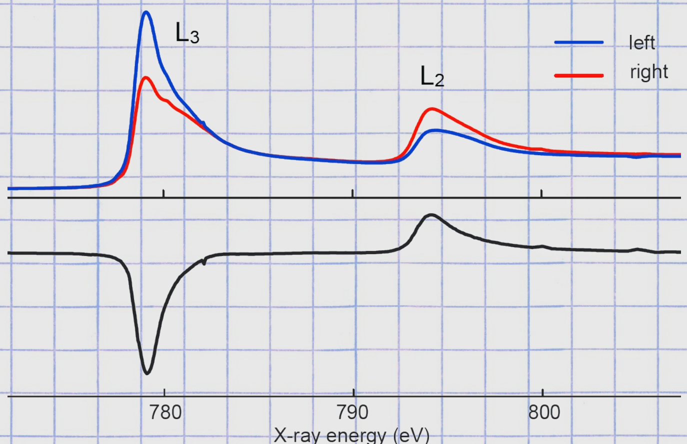
X-ray Magnetic Circular Dichroism

⇨ Element selectivity



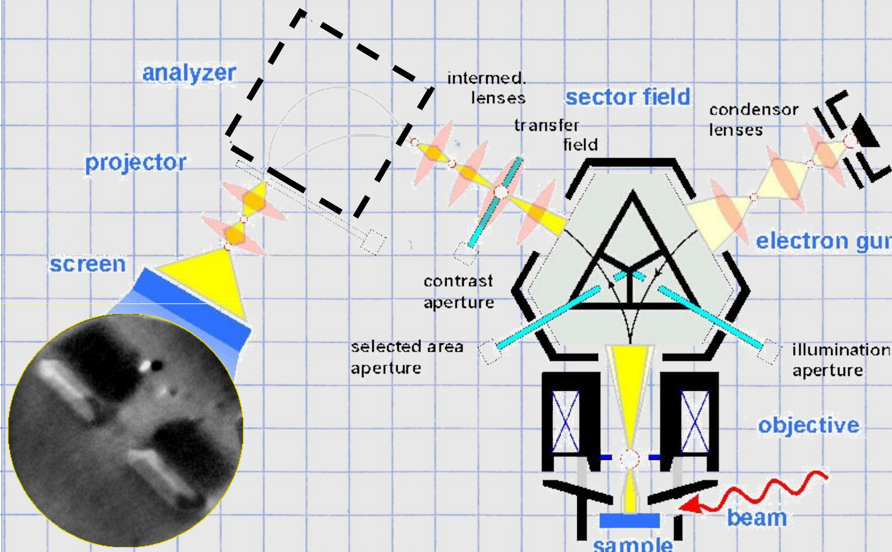
Courtesy: W. Kuch

⇨ Magnetic sensitivity



PEEM

Photo-Emission Electron Microscopy



Features

- Synchrotron-based technique
- Secondary electrons → surface sensitive
- Spatial resolution : 25nm

Experimental contrast

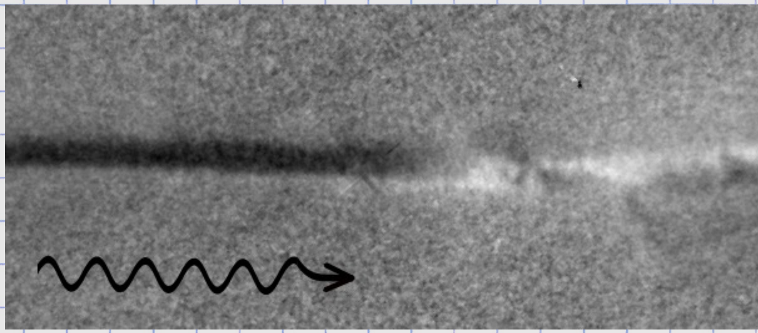
Two examples

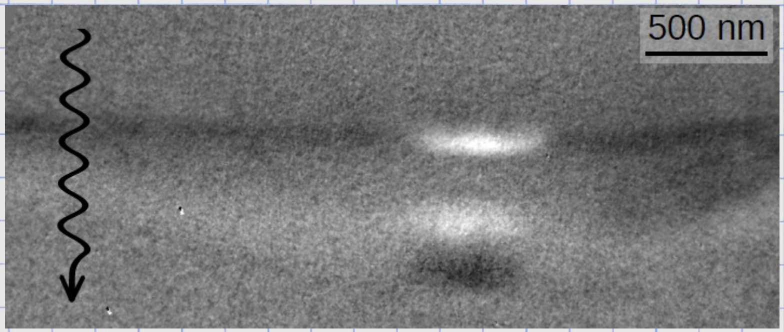
Beam along wire

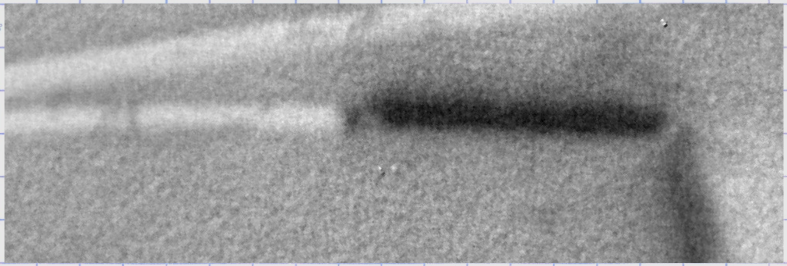
⇨ Locate domain walls

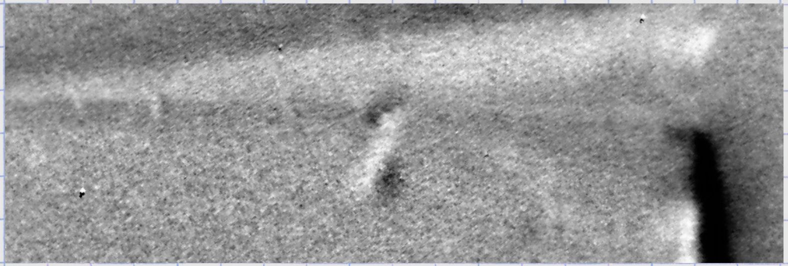
Beam across wire

⇨ Inspect domain wall





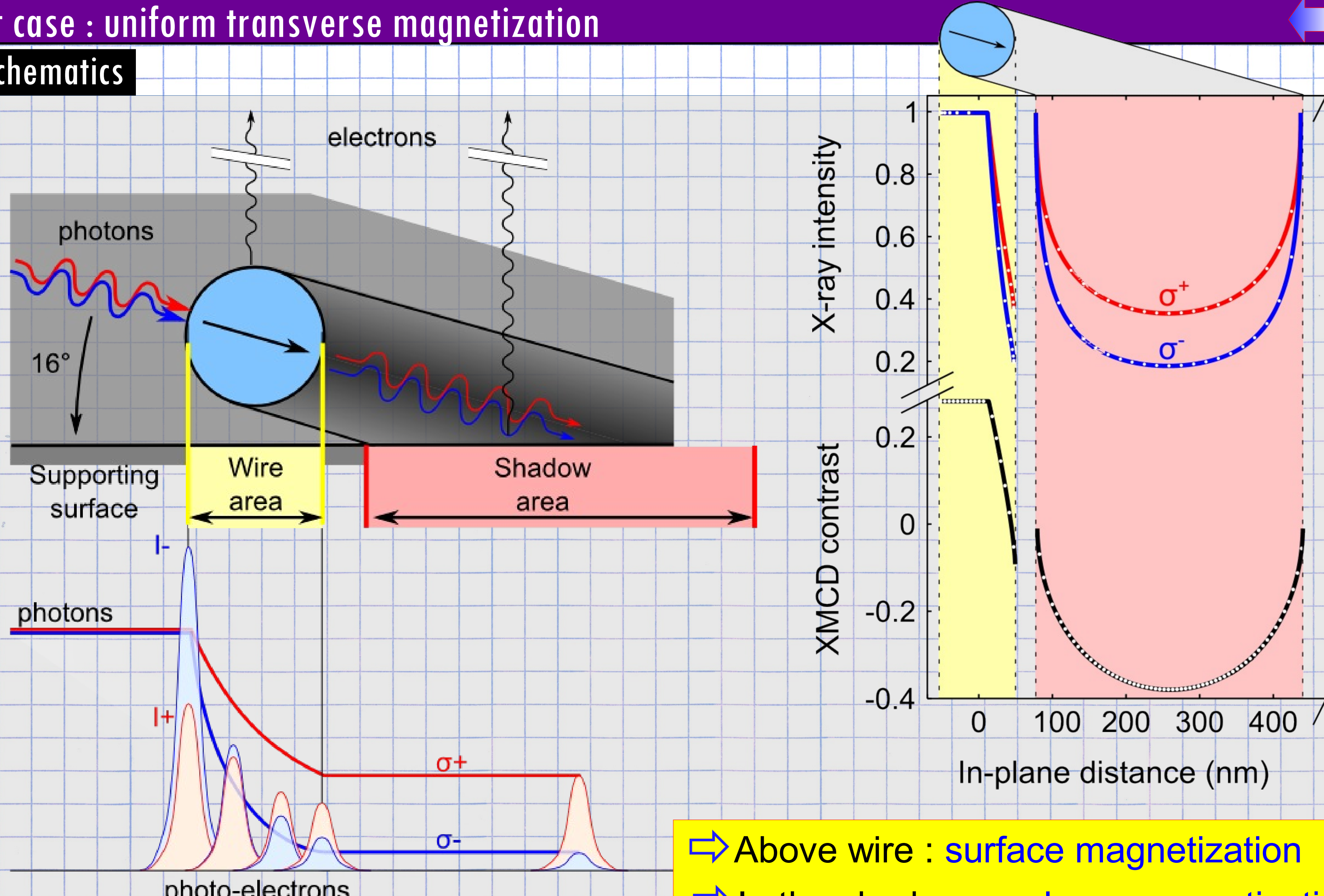




- Several non-trivial patterns
- Need for modelling

Test case : uniform transverse magnetization

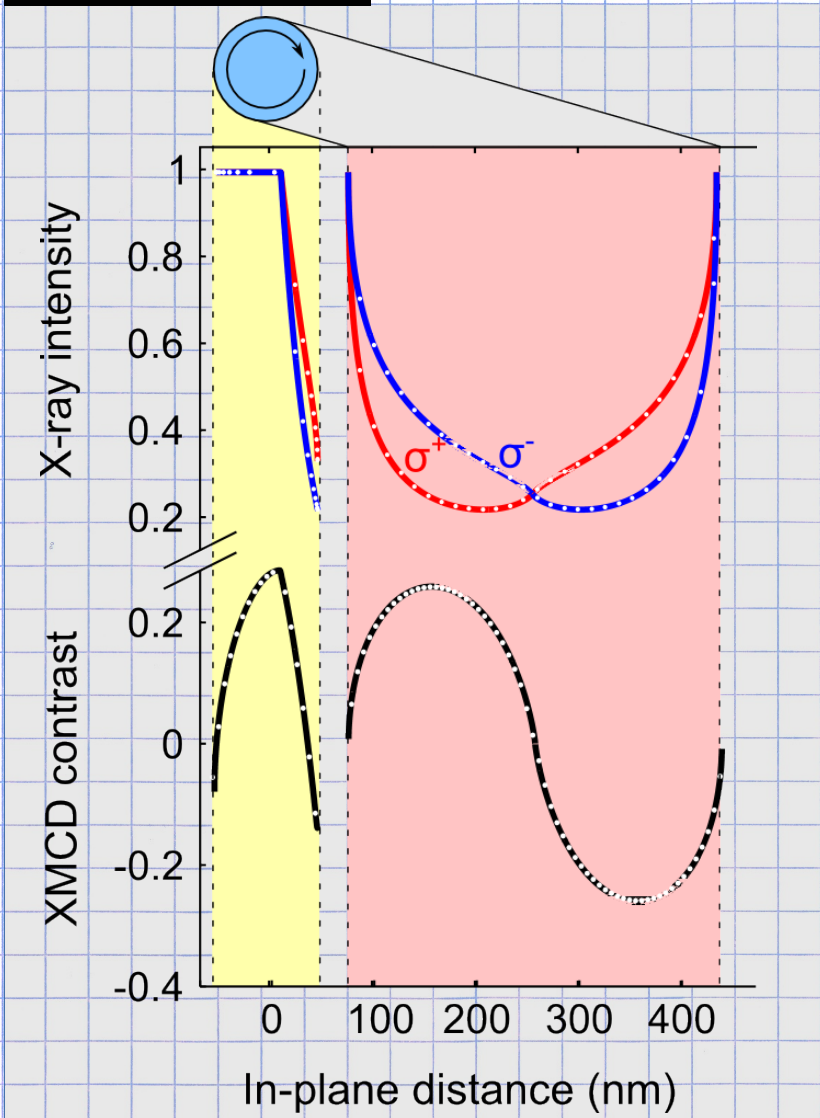
Schematics



$$\frac{\mathrm{d}I_{X,\sigma\pm}}{\mathrm{d}\ell} = -\left[\frac{1}{2}\mu_+(1 \pm \hat{\mathbf{k}}\cdot\mathbf{m}) + \frac{1}{2}\mu_-(1 \mp \hat{\mathbf{k}}\cdot\mathbf{m})\right] I_{X,\sigma\pm}$$

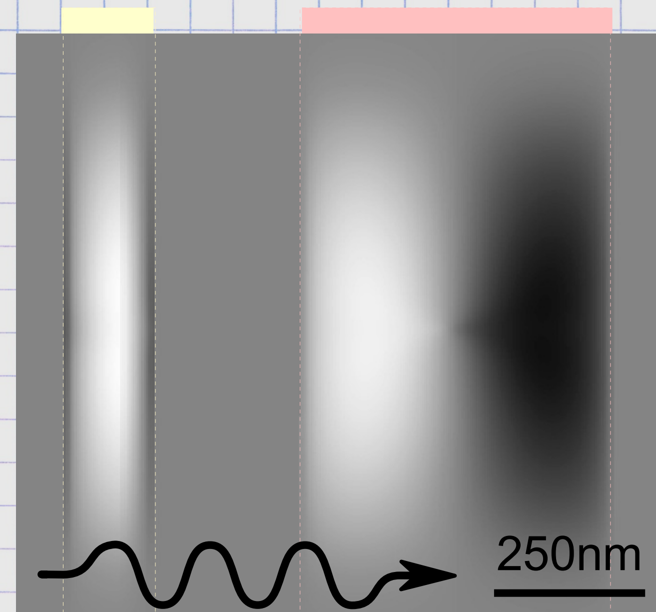
- ⇨ Above wire : surface magnetization
- ⇨ In the shadow : volume magnetization
- ⇨ Non-linear, even change of sign

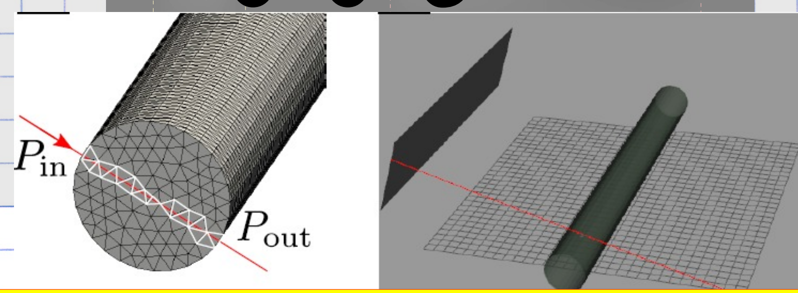
Simulation of XMCD



S. Jamet et al., arXiv:1506.02866

Resulting image



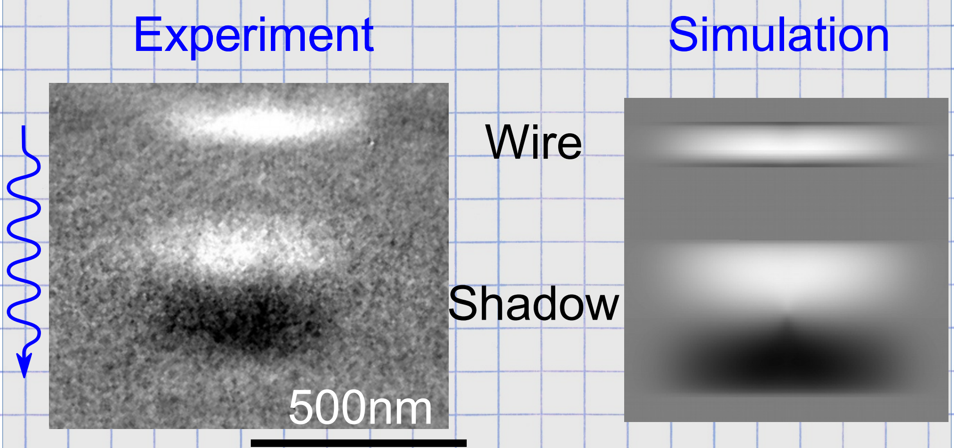


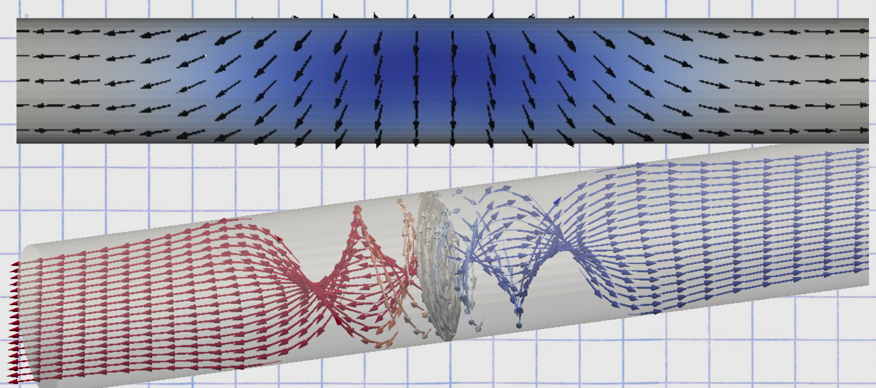
- Surface and volume information
- Bloch-point domain wall identified from symmetry and volume curling
- Enhanced spatial resolution

Formal identification of domain walls

Bloch-Point Wall (BPW)

Wire diameter : 95nm



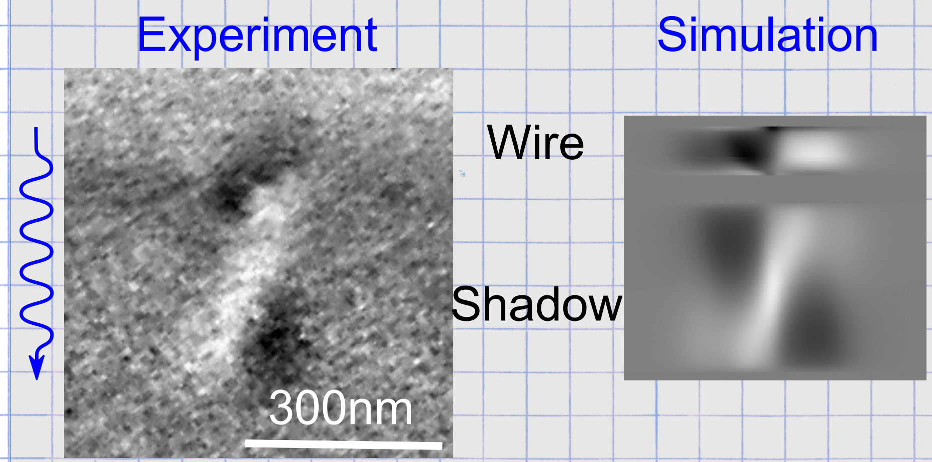


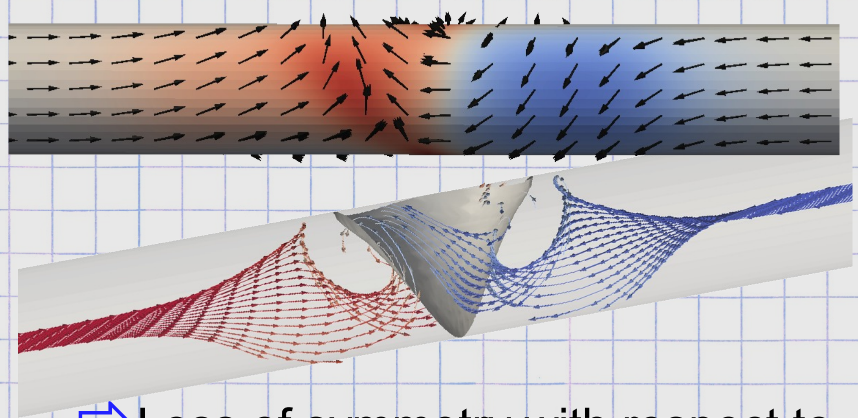
⇨ Orthoradial curling

⇨ Symmetry with respect to plane perpendicular to axis

Transverse Wall (TW)

Wire diameter : 70nm





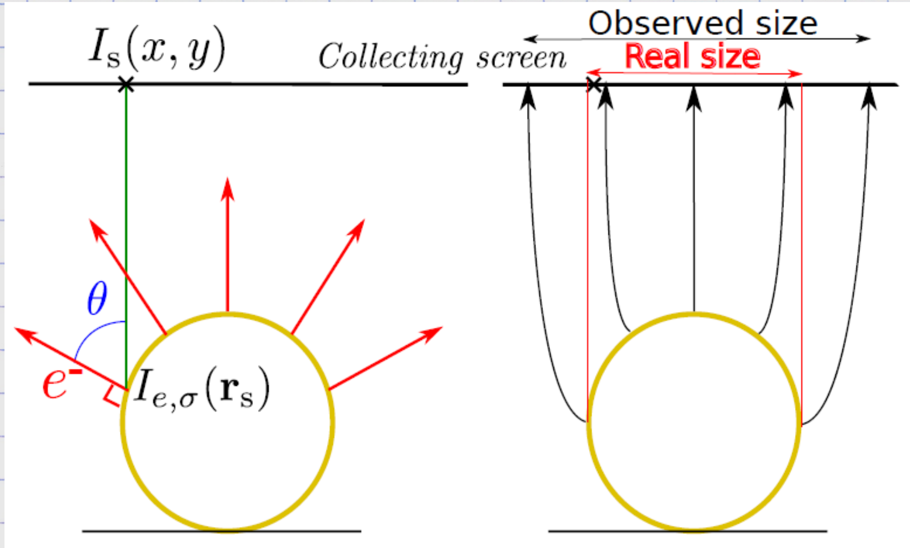
⇨ Loss of symmetry with respect to plane perpendicular to axis

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

→ Transverse wall imaged with electron holography

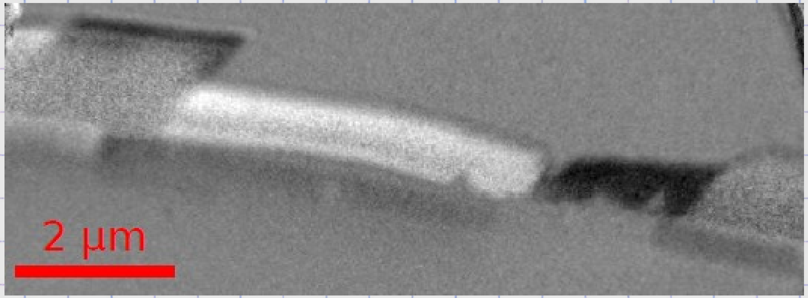
S. Da-Col et al., Phys. Rev. B (R) 89, 180405, (2014) arXiv:1311.7368

Imaging curved surfaces : specific features

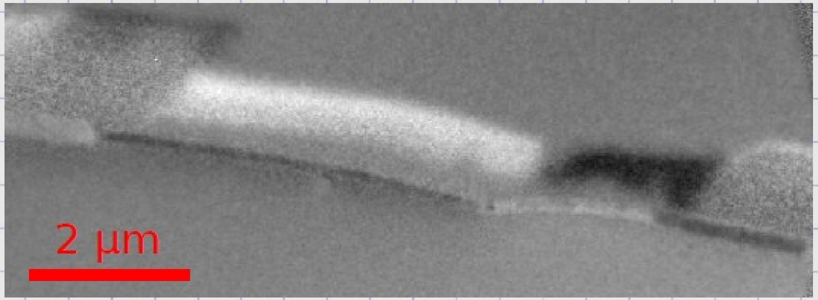


- Sample is part of the optics
- Enlarged size of the direct image
- Different focus settings on sample and supporting surface, despite large depth of focus

Example



Focus on background

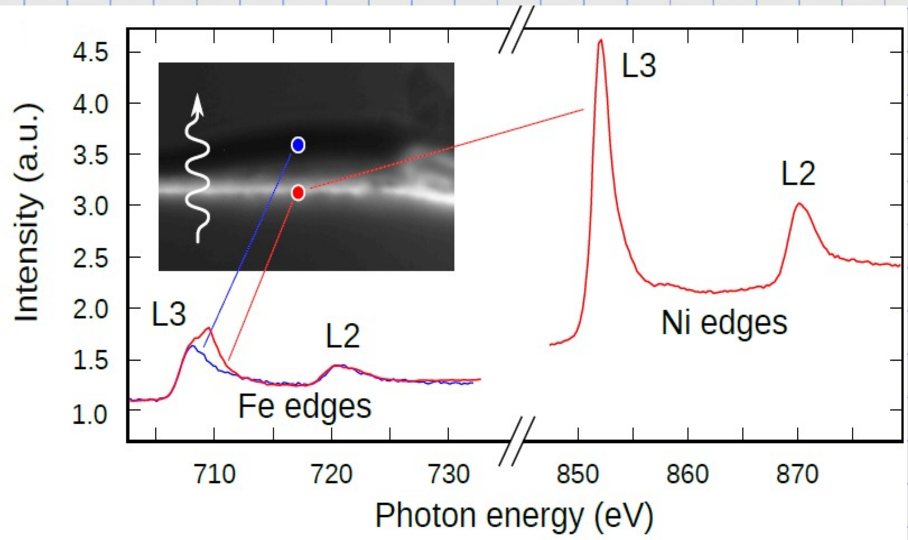


Focus on wire

- Sets sharpness and contrast

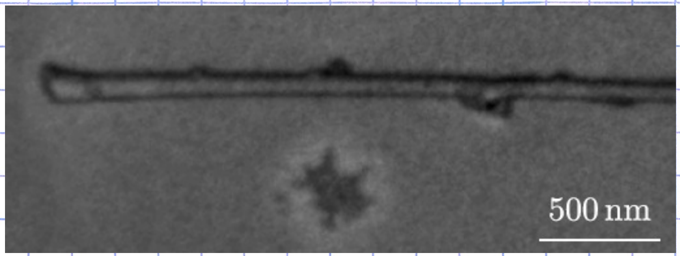
S. Jamet et al., arXiv:1506.02866

Determine the proper edge energy



⇨ Slight oxidation of Fe at the surface

⇨ Tune the energy in the background to optimize the dichroic contrast



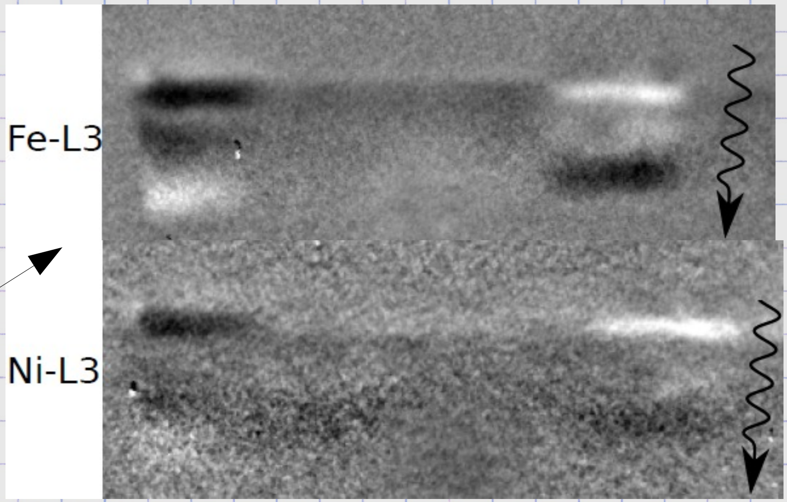
S. Jamet et al., arXiv:1506.02866

Chose the edge for best contrast (?)

Table I: Absorption coefficients μ at the different absorption edges. Figures for pure elements are derived from [21]

Edge	μ (nm^{-1})	Fe	Ni	$Fe_{20}Ni_{80}$
Fe L2	μ_-	0.03	≈ 0	0.006
	μ_+	0.04	≈ 0	0.008
Fe L3	μ_-	0.09	≈ 0	0.018
	μ_+	0.05	≈ 0	0.010
Ni L2	μ_-	0.017	0.017	0.017
	μ_+	0.017	0.021	0.020
Ni L3	μ_-	0.017	0.053	0.046
	μ_+	0.017	0.040	0.035

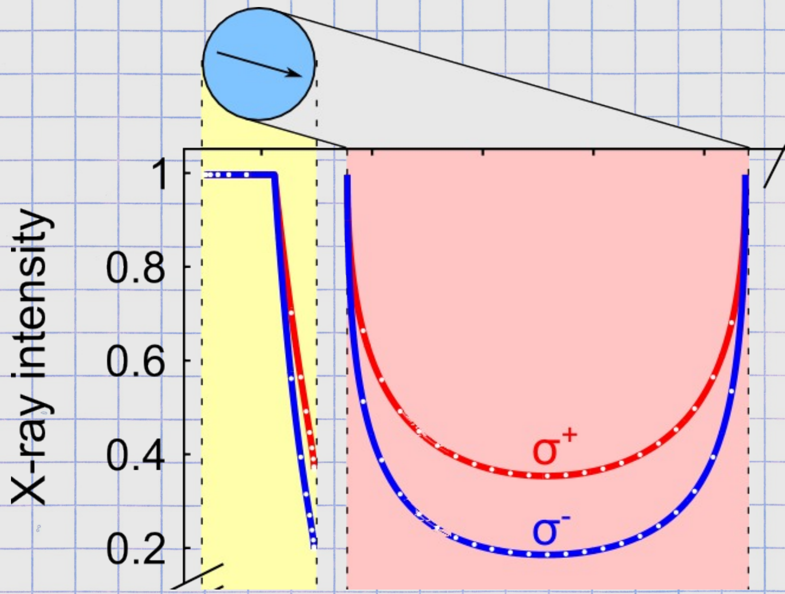
⇨ Fe20Ni80 : expect same contrast at Fe and Ni edges



⇨ Lower contrast at Ni edges

⇨ Surface / shadow ratio is changed

Effects



Background level in microscope

- ⇨ Is NOT the camera background
- ⇨ Not afffected by field or contrast apertures
- ⇨ Reason ?..

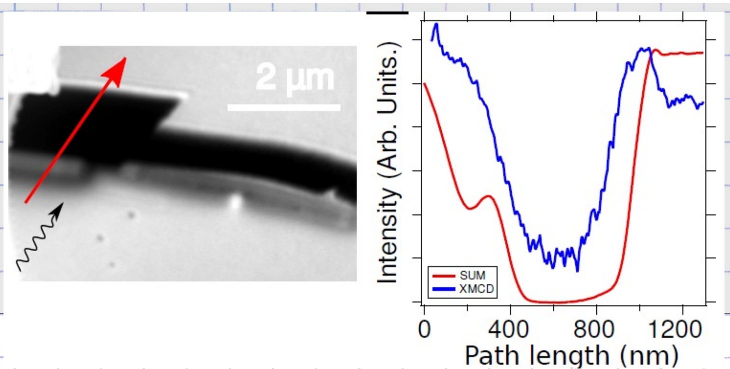
Consequences

- ⇨ Reduction of XMCD contrast
- ⇨ Sharper reduction in the shadow (less counts)
- ⇨ Need for correction of background

Background correction

$$I_{\mathrm{XMCD},0} = (I_{e,\sigma_-} - I_{e,\sigma_+})/(I_{e,\sigma_-} + I_{e,\sigma_+} - 2I_{e,\mathrm{b}})$$

- ⇨ Measure background in deep shadows
- ⇨ Subtract background

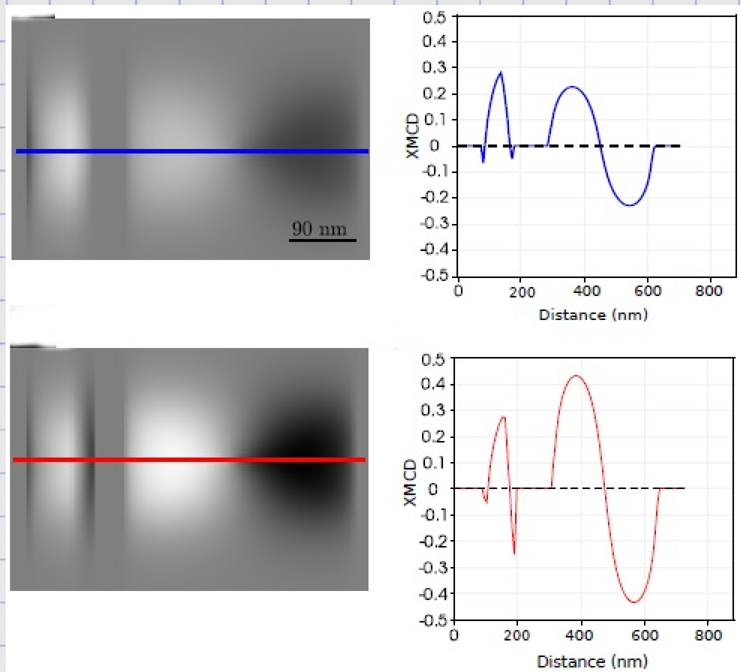


S. Jamet et al., arXiv:1506.02866

Fine points – Microscope background level

Principle

Raw

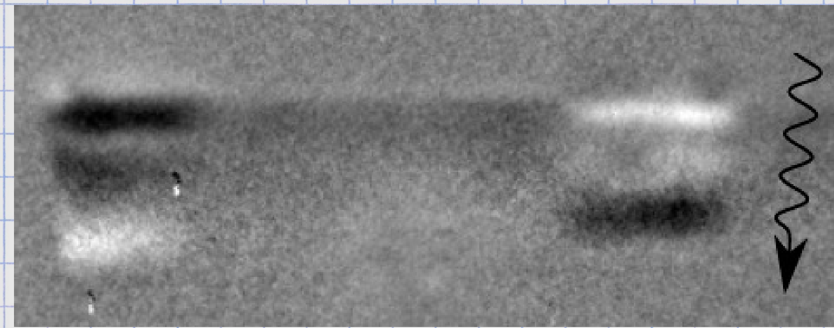


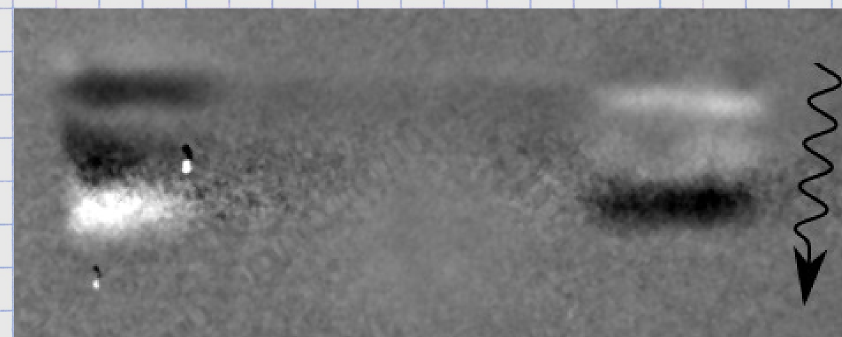
Corrected

Implementation

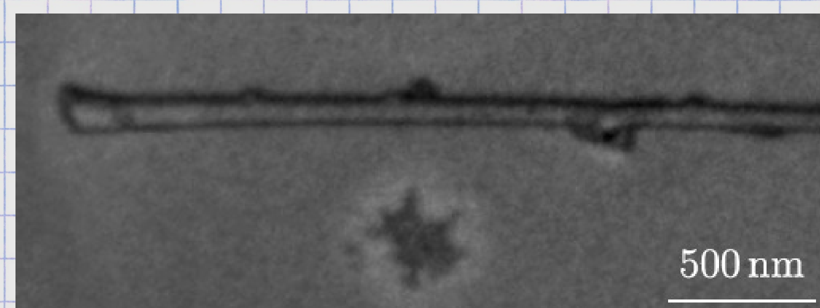
Raw

Fe L3 edge





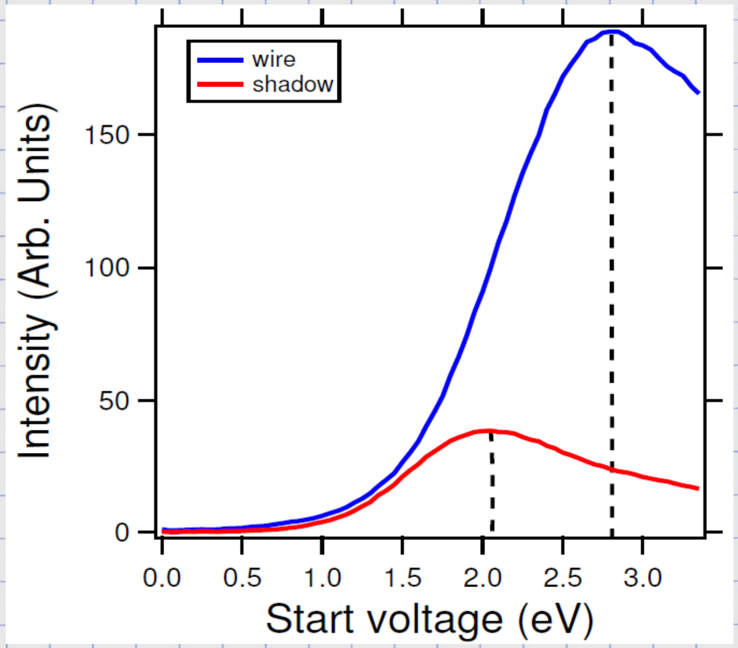
Corrected



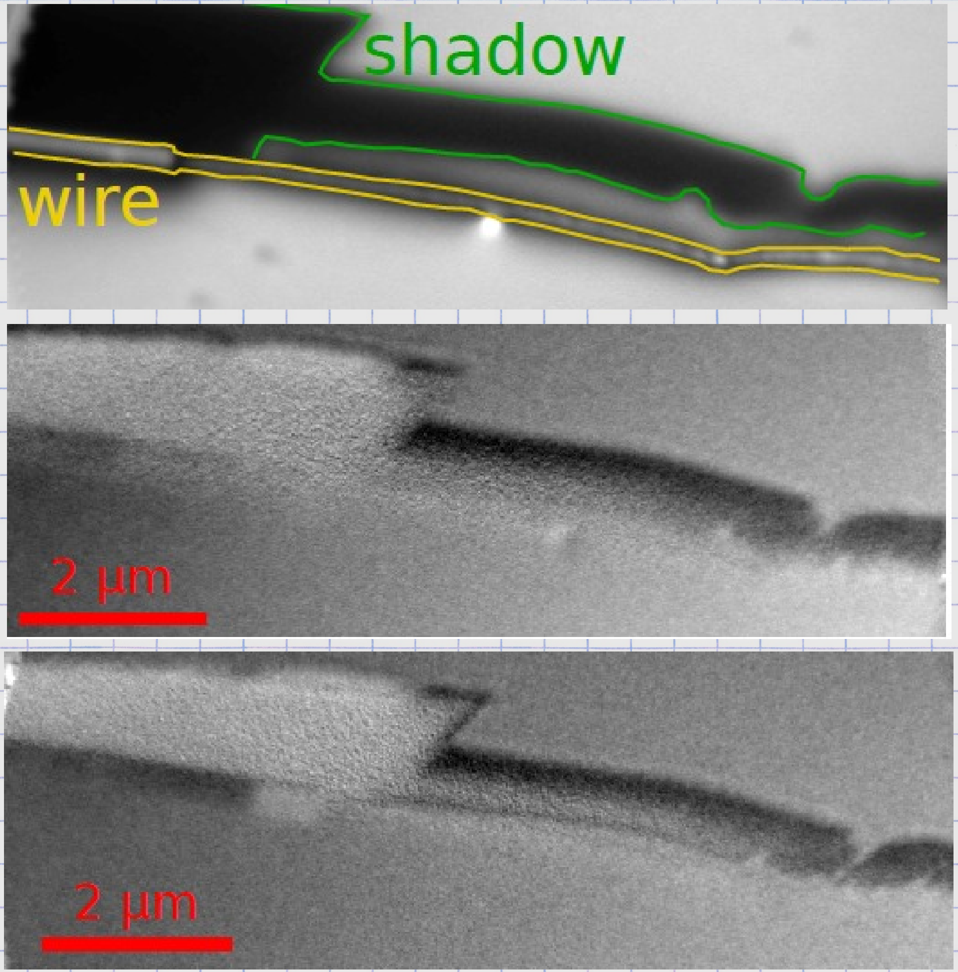
S. Jamet et al., arXiv:1506.02866

Physics

⇨ Workfunction influences ratio of direct versus shadow



Consequence



⇨ Affects the dichroic signal <u>due to the background level</u>

S. Jamet et al., arXiv:1506.02866

Personal views on transmission magnetic microscopies

XMCD-PEEM

- Probes magnetization along beam
- Provides both surface (sensitivity) and volume information
- Enhanced spatial resolution along the beam direction

(S)TXM

- Probes magnetization along beam
- Several components of magnetization through sample tilt
- Compatible with applied fields

Lorentz / Holography

- Probes magnetization perp to beam
- Higher spatial resolution
- Compatible with applied fields

Frontiers

- Image processing (knowledge of microscope physics)
- Quantitative analysis
- Towards vectorial tomography

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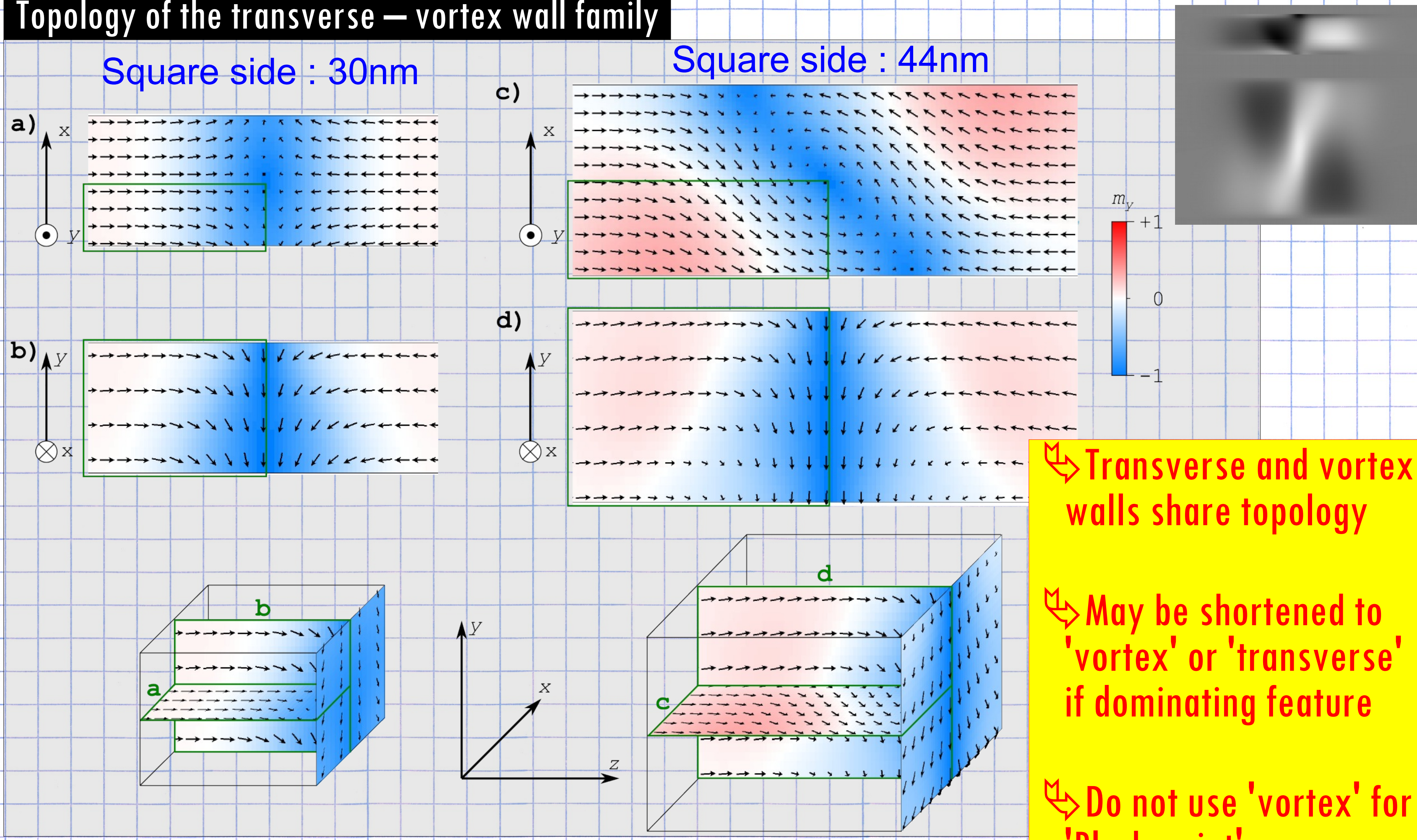
Topology of the transverse – vortex wall family

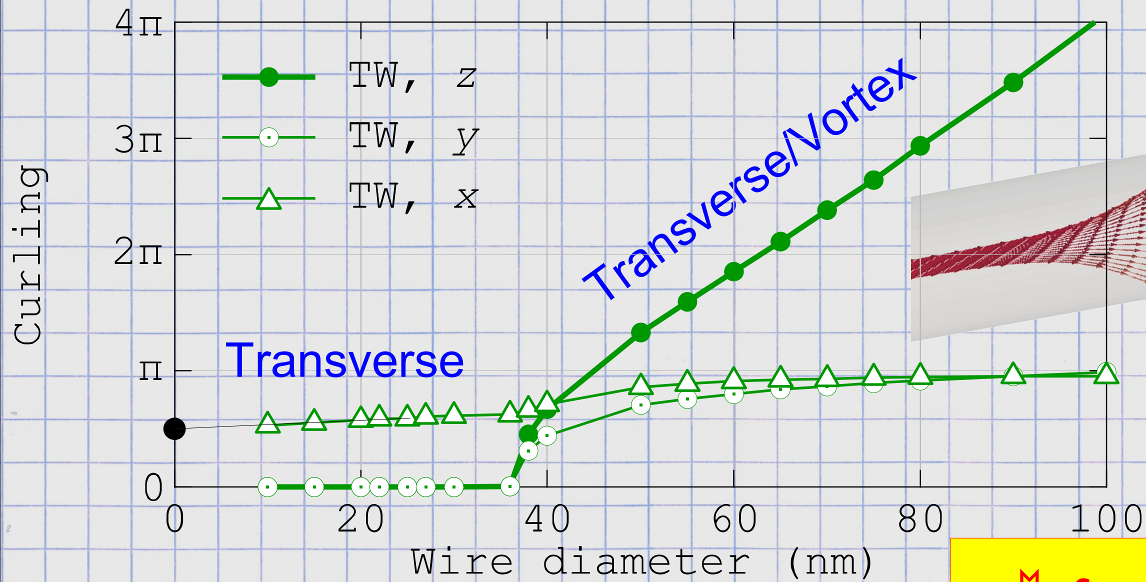


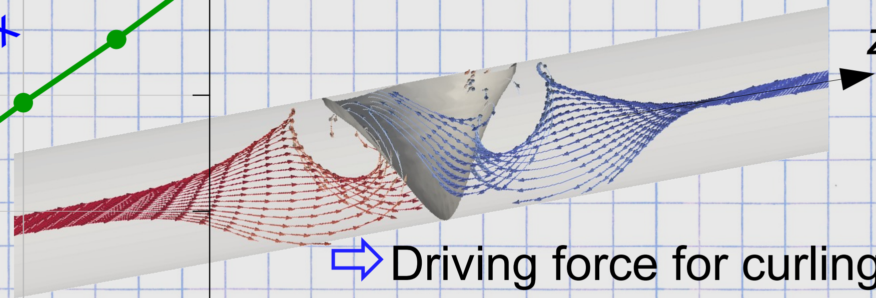
- Transverse and vortex walls share topology
- May be shortened to 'vortex' or 'transverse' if dominating feature
- Do not use 'vortex' for 'Bloch-point'

Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead, in press. (arXiv:1412.0679)

Quantify curling in the Transverse/Vortex wall

Circulation of magnetization → Quantify curling



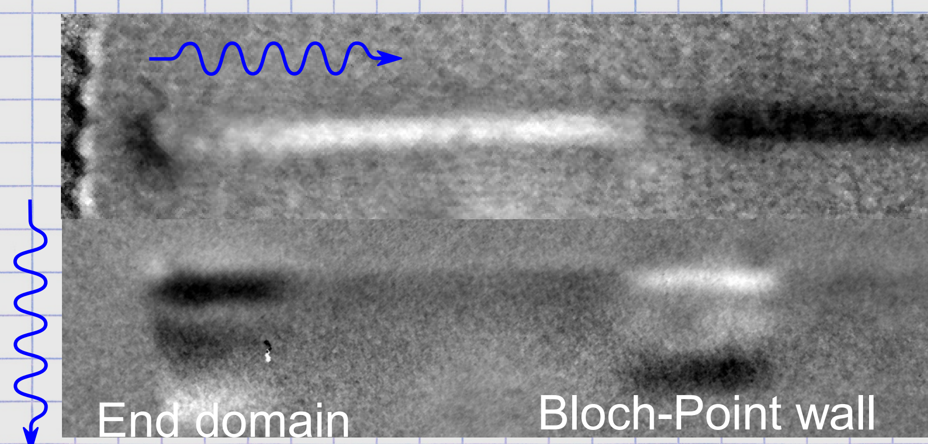


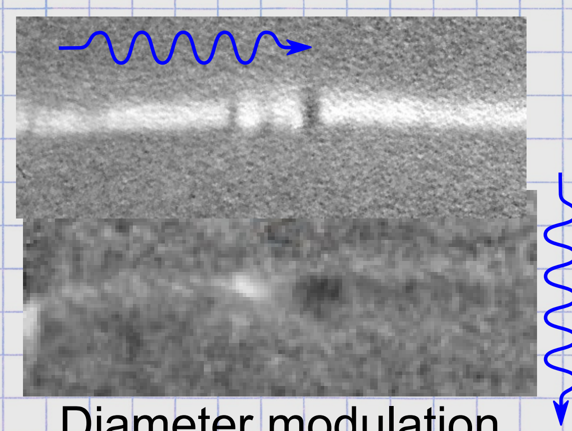
⇨ Driving force for curling : spread volume charges

$$\operatorname{div}\mathbf{M} \approx -\frac{\mathrm{d}M_z}{\mathrm{d}z}$$

Second-order transition for $D \approx 7\Delta_\mathrm{d}$

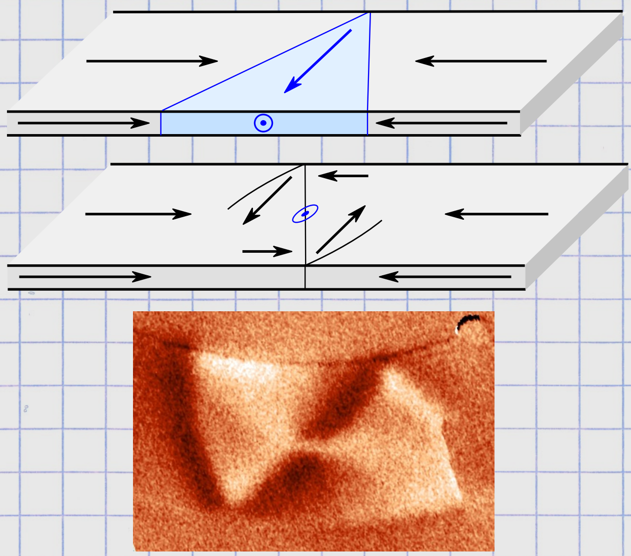
Imaging the general character of curling





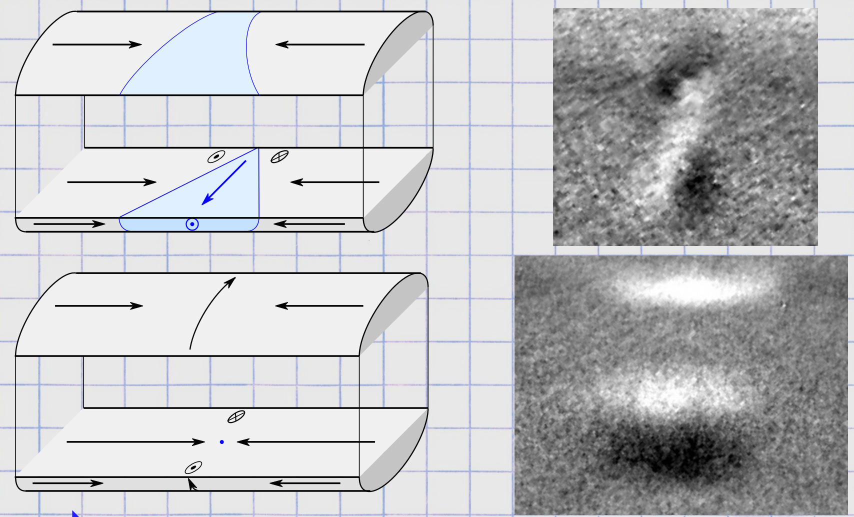
Motivation :
Provide a unified picture of domain walls in (nearly) one-dimensional systems

Flat strips



⇨ Transverse and vortex

Cylindrical wires



⇨ Transverse and Bloch-point walls

⇨ Confusion between Bloch-point and vortex

Emergence of square or rectangular wires

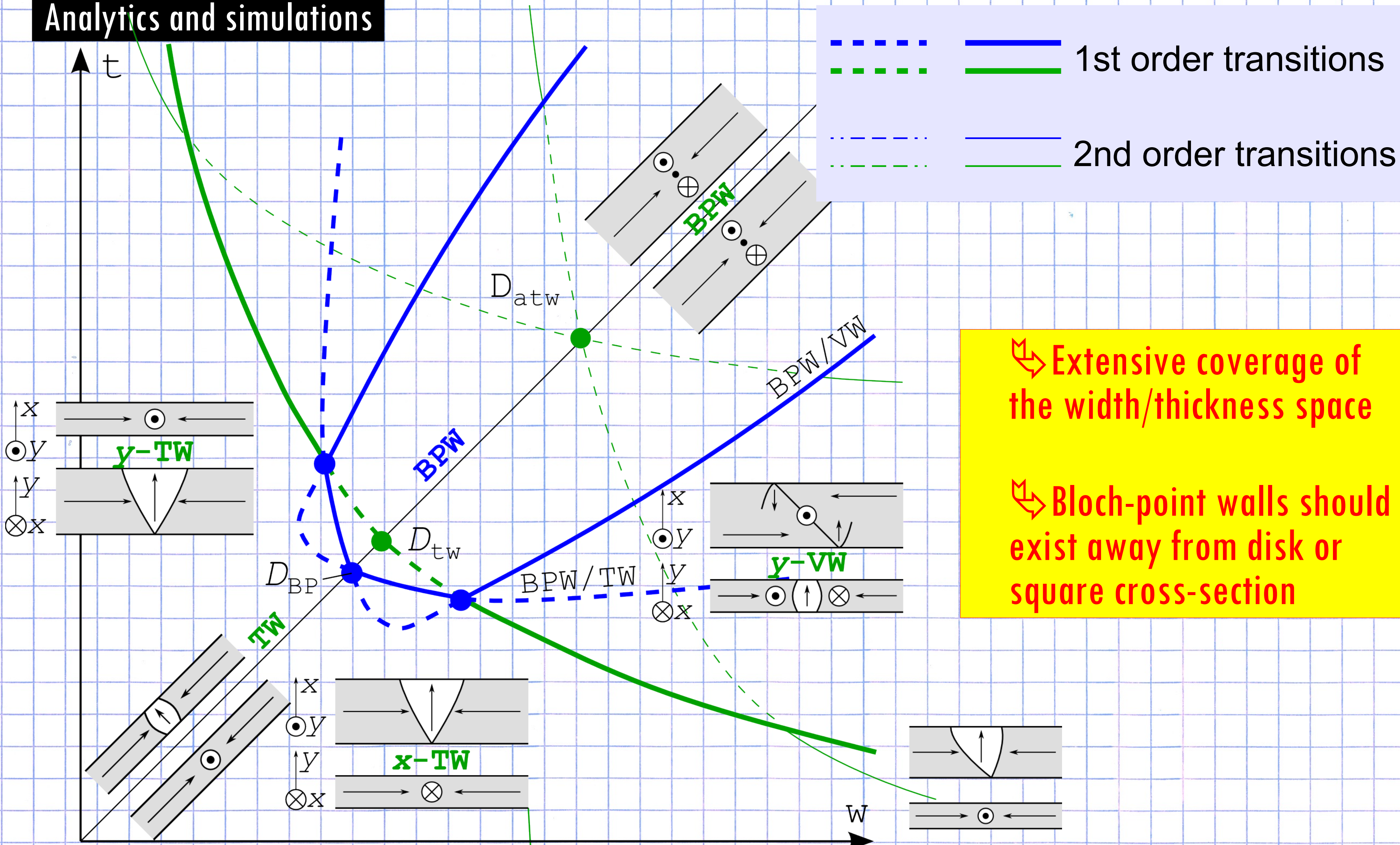
⇨ Top-down + bottom-up / Planar templates

P. Sergelius et al., Nanotech. 25,504002 (2014)

Open issues

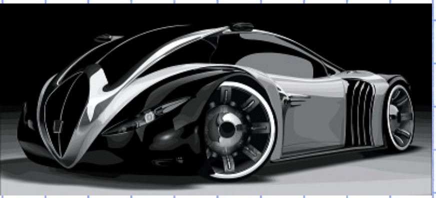
- Span strips to wires
- Clear and simple classification
- May Bloch-point walls be found in rectangular wires ?

Analytics and simulations

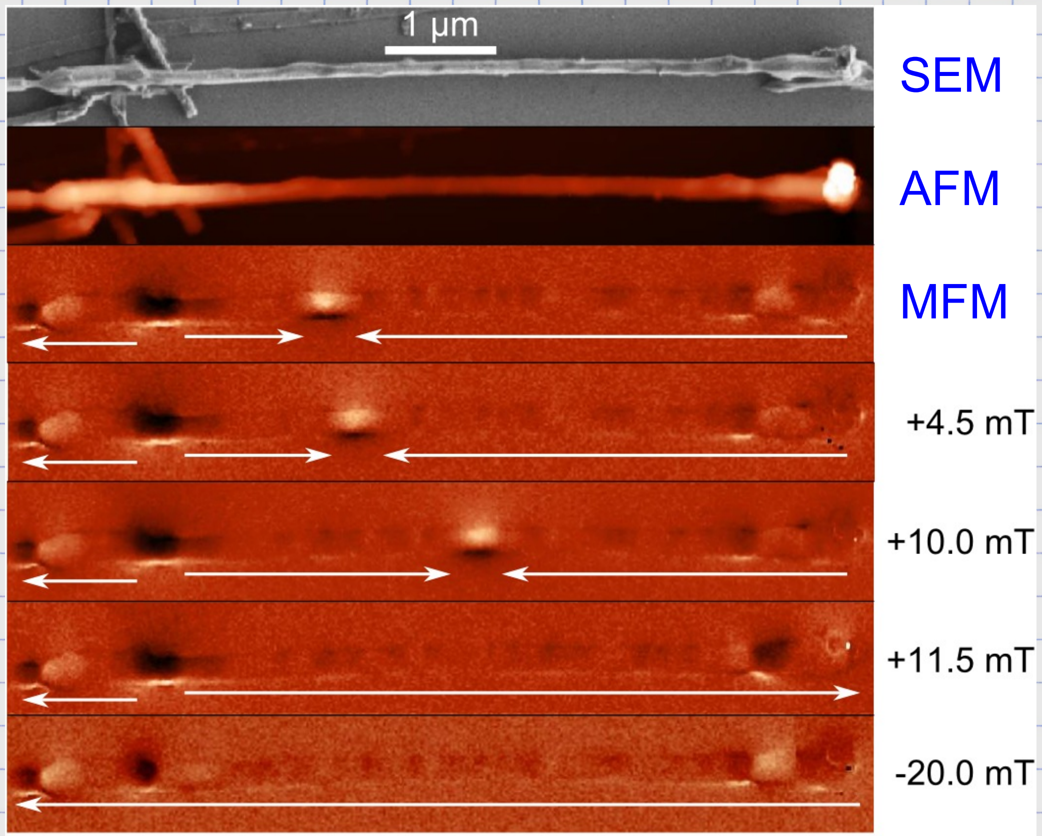


- Extensive coverage of the width/thickness space
- Bloch-point walls should exist away from disk or square cross-section

Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead, in press. (arXiv:1412.0679)

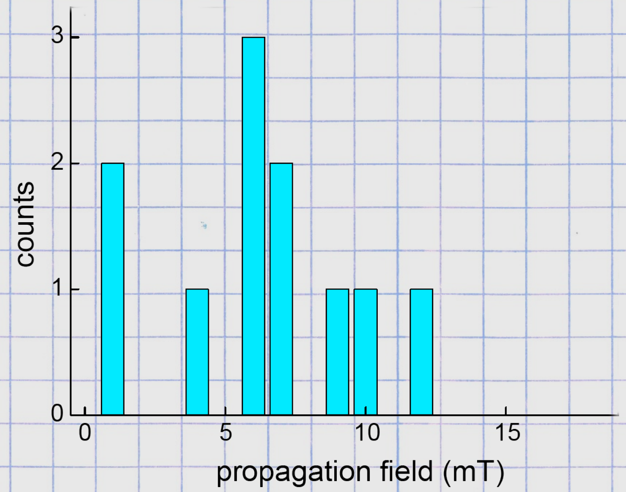


Experiments



S. Da-Col et al., in preparation

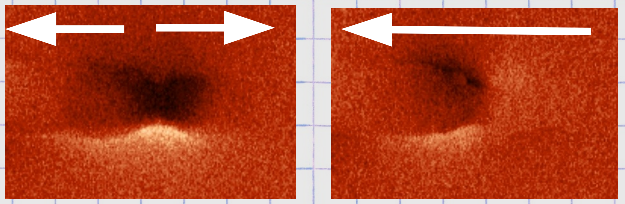
Straight sections



- Distribution of propagation fields, range 1-10mT
- Similar to the case of strips

J. Sampaio et al., J. Appl. Phys. (2013)

Protrusions and constrictions



- Pinning field ~30mT

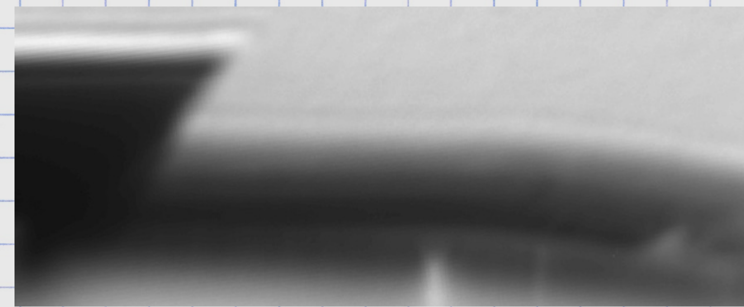
- Domain-wall motion demonstrated (range 1-10mT)
- Pinning at modulations of diameter

Propagation and selection of circulation : preliminary data

Structure

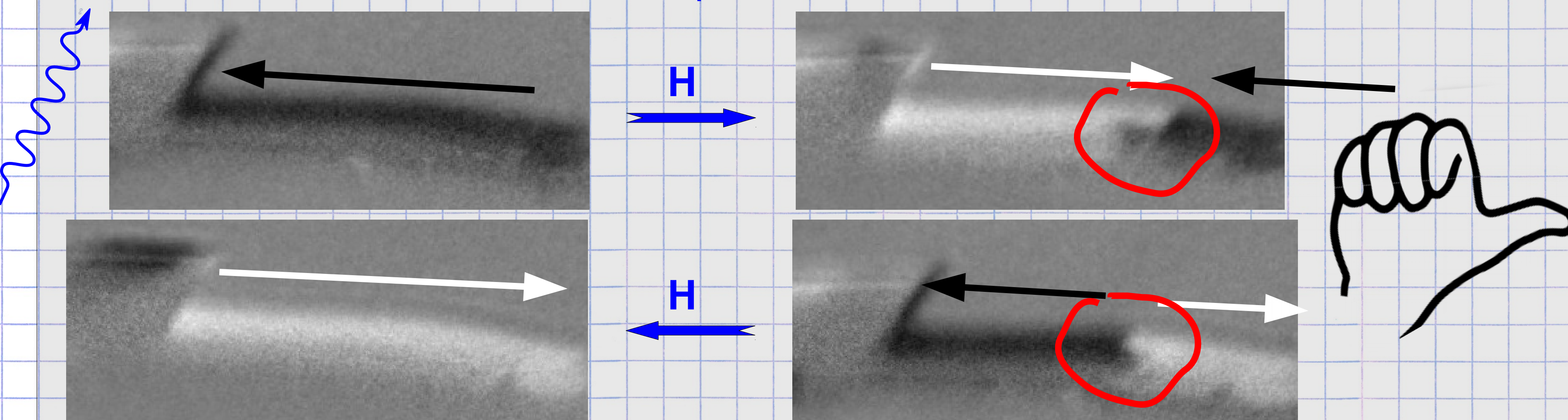
Focus on wire

Focus on shadow



Motion and circulation

Initialize | Field pulse | Final state



Bloch-Point walls with same circulation

Confirmation : selection of circulation with once-only Walker switch (preliminary)

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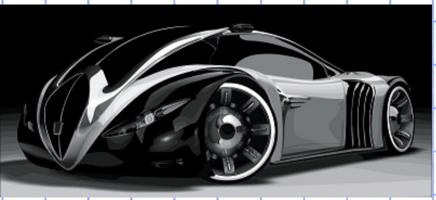
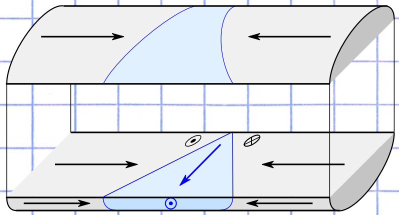
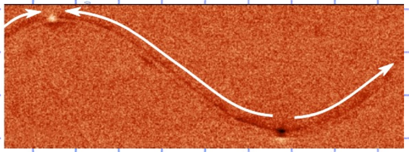
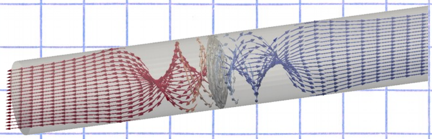
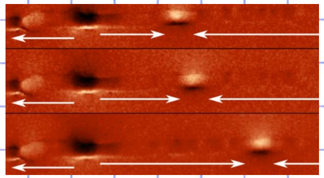


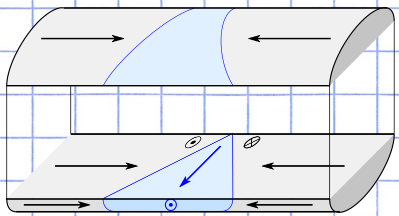






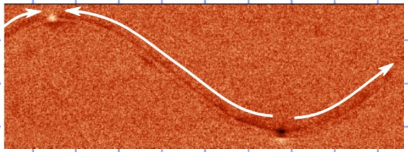


Take-away messages

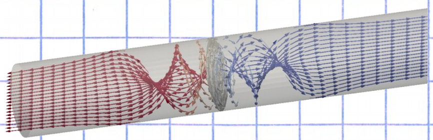


1. [Science]

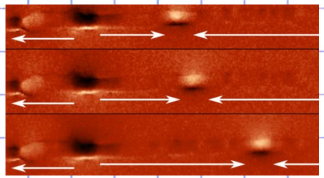
Why addressing cylindrical magnetic nanowires ?



2. Nucleate domain walls

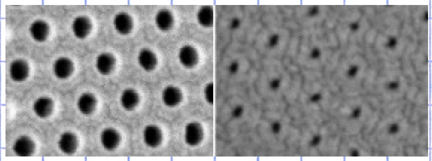


3. Identify domain walls



4. Move domain walls

- ⇨ Confirm once-only Walker
- ⇨ Confirm high speed
- ⇨ (...)



5. Dipolar interactions in a 3D medium

On-going work

- ⇨ Define bits and coding – Implement robust clocking
- ⇨ Shift to current-induced motion
- ⇨ (...)

S. Da Col, S. Jamet, A. Wartelle, R. Afid, S. Pizzini, J. Vogel, M. Bonfim, L. Cagnon, N. Rougemaille, C. Thirion, J. C. Toussaint, O. Fruchart
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