Magnetic domain walls in cylindrical nanowires – From opportunities for fundamental science towards 3D storage media?

O. Fruchart et al.

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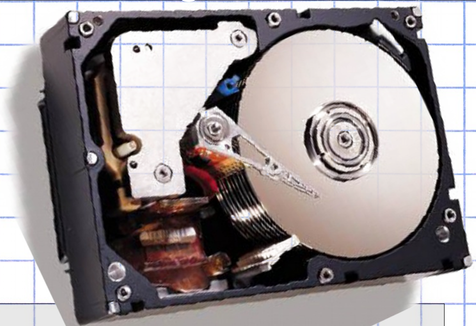
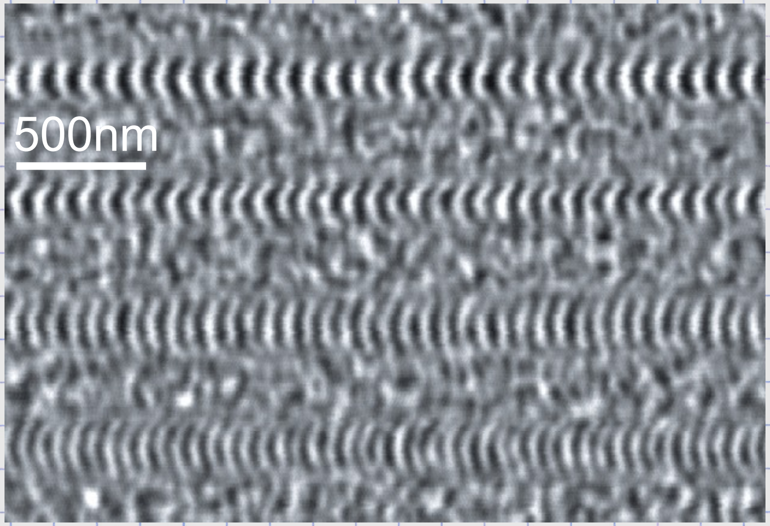
The research leading to these results has received funding from the European Unions's 7th Framework Programme under grant agreement n°309589 (M3d)



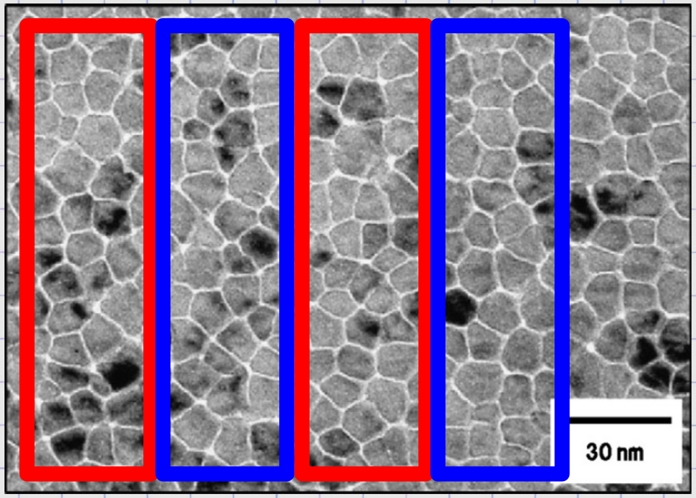
Magnetic bits on Hard Disk Drive

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)

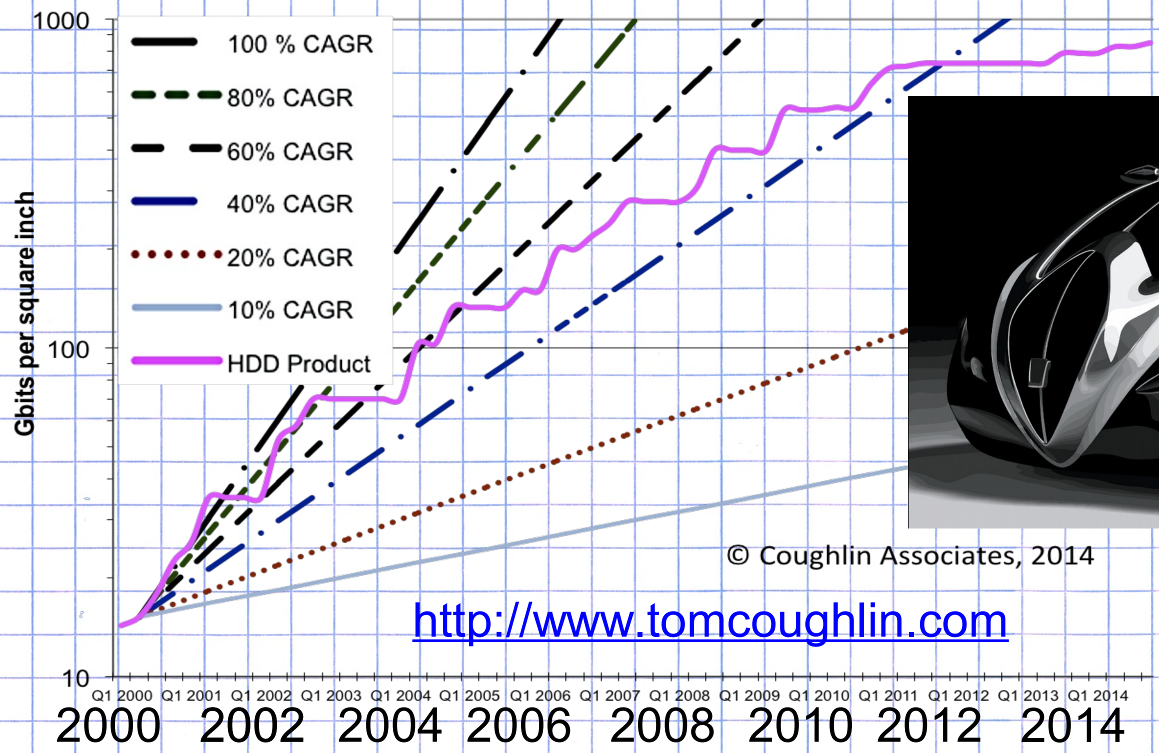
Gains in areal density

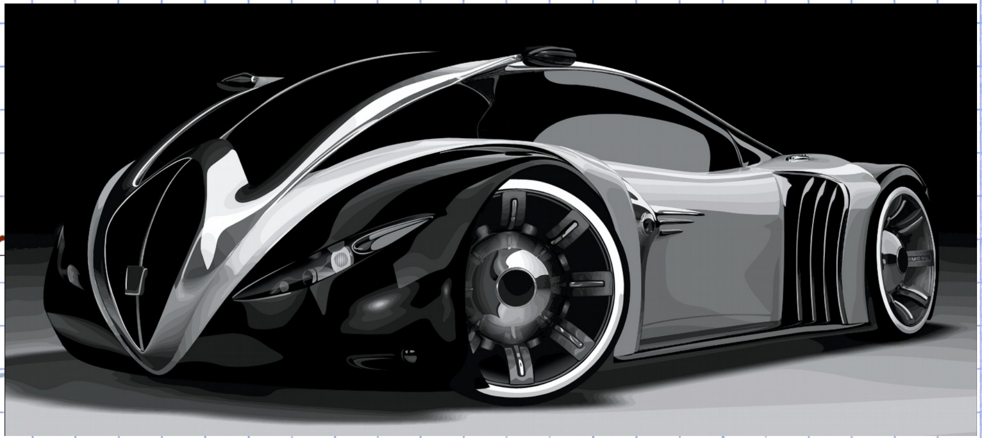
- Compromise : time stability, writability, readibility
- Relies on progress of technology and science

1956 RAMAC, IBM, first HDD

1986 Discovery of GMR

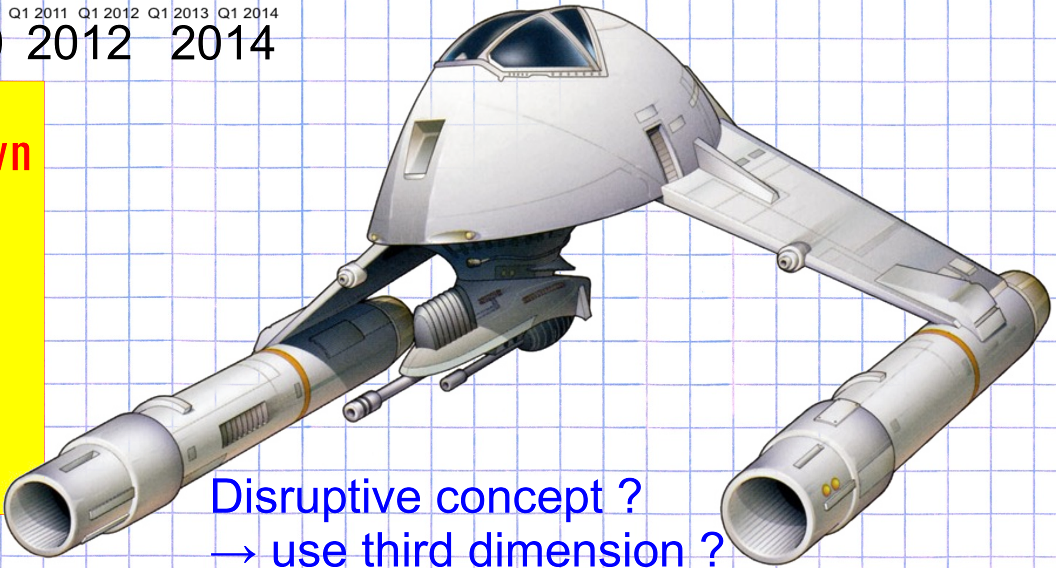
1998 GMR in read heads





http://www.tomcoughlin.com

- 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

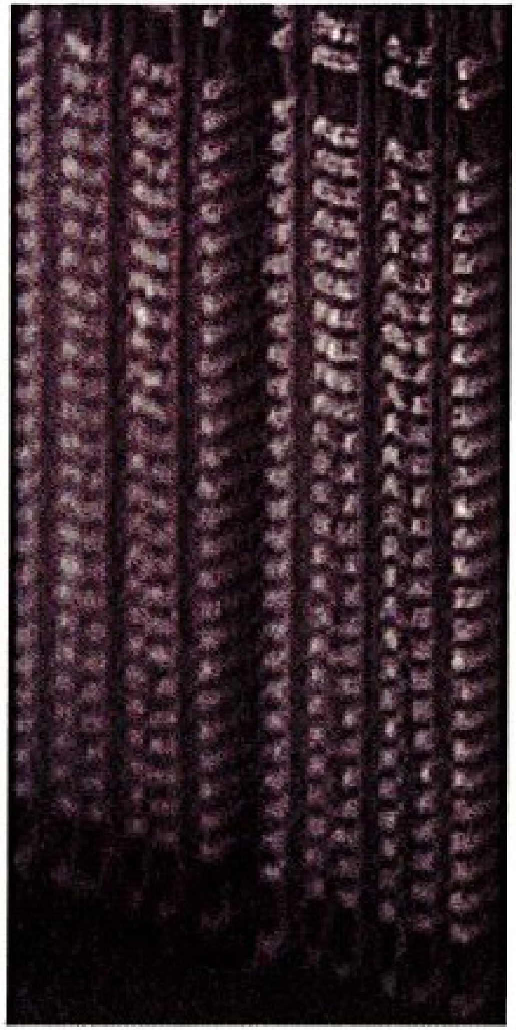


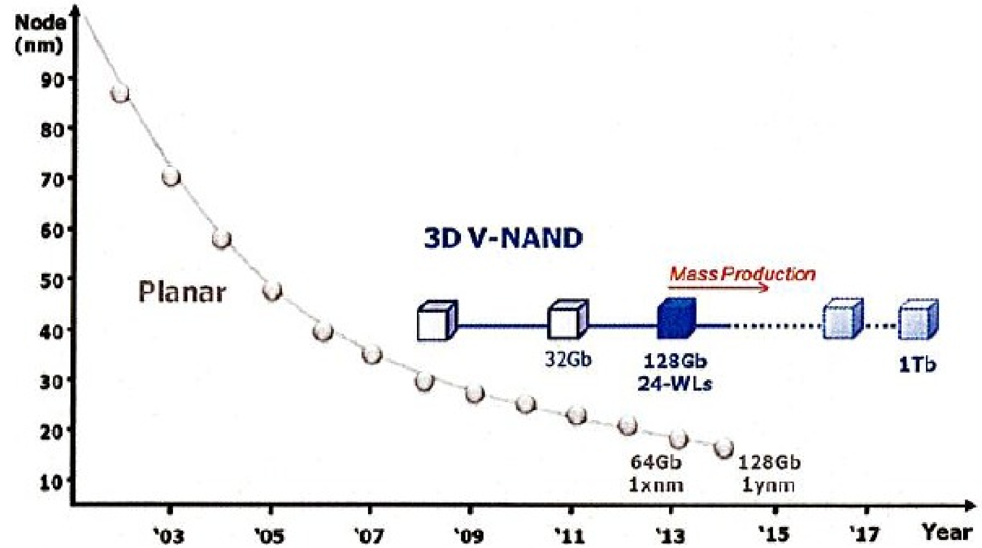
Disruptive concept ?
→ use third dimension ?

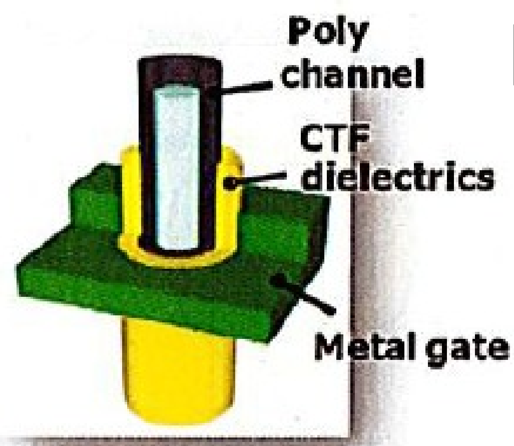
204 IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 50, NO. 1, JANUARY 2015

Three-Dimensional 128 Gb MLC Vertical NAND Flash Memory With 24-WL Stacked Layers and 50 MB/s High-Speed Programming

Ki-Tae Park, Sangwan Nam, Daehan Kim, Pansuk Kwak, Doosub Lee, Yoon-He Choi, Myung-Hoon Choi, Dong-Hun Kwak, Doo-Hyun Kim, Min-Su Kim, Hyun-Wook Park, Sang-Won Shim, Kyung-Min Kang, Sang-Won Park, Kangbin Lee, Hyun-Jun Yoon, Kuihan Ko, Dong-Kyo Shim, Yang-Lo Ahn, Jinho Ryu, Donghyun Kim, Kyunghwa Yun, Joonsoo Kwon, Seunghoon Shin, Dae-Seok Byeon, Kihwan Choi, *Student Member, IEEE*, Jin-Man Han, Kye-Hyun Kyung, Jeong-Hyuk Choi, and Kinam Kim





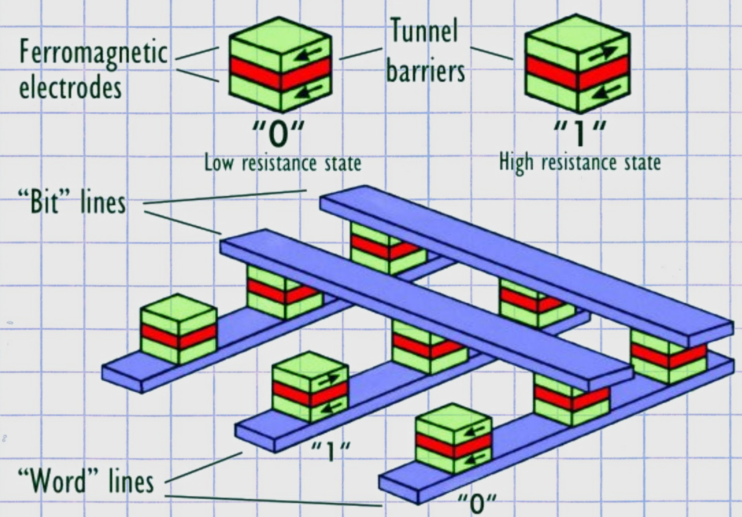


Facts

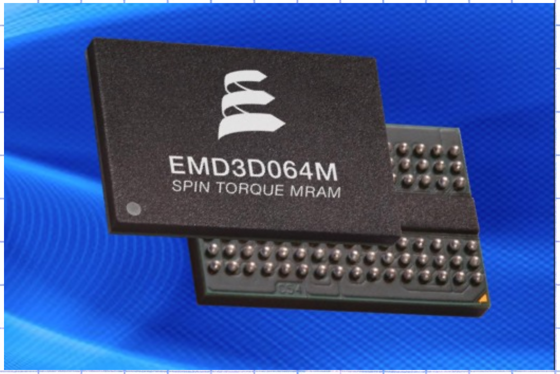
- ⇨ Incremental (multilevel patterning) however already 'quite 3D'
- ⇨ Technological node unchanged
- ⇨ 1Gb/mm2 → 600Gb/in^2...

MRAM = Magnetic Random Access Memory

Working principle

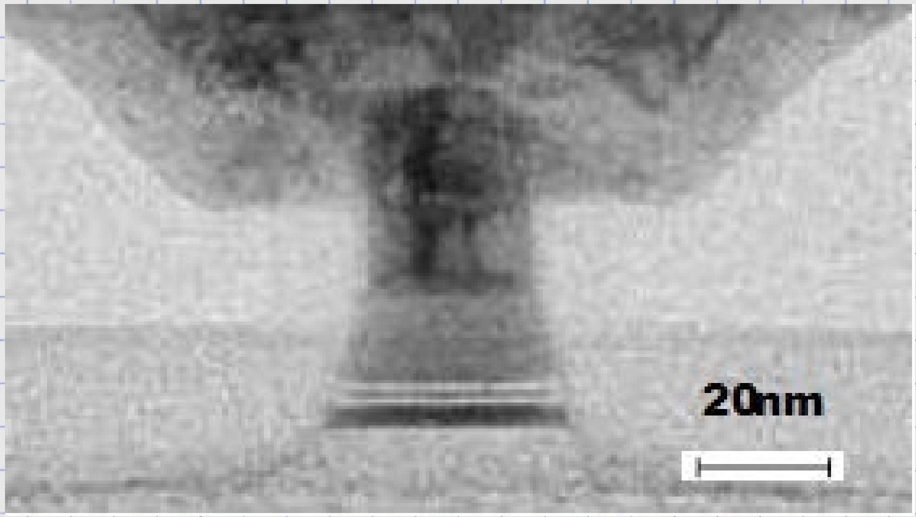


- Solid state, non-volatile, fast
- Issues being fixed → entered semiconductor roadmap in 2009
- No lethal competition with HDDs



Everspin

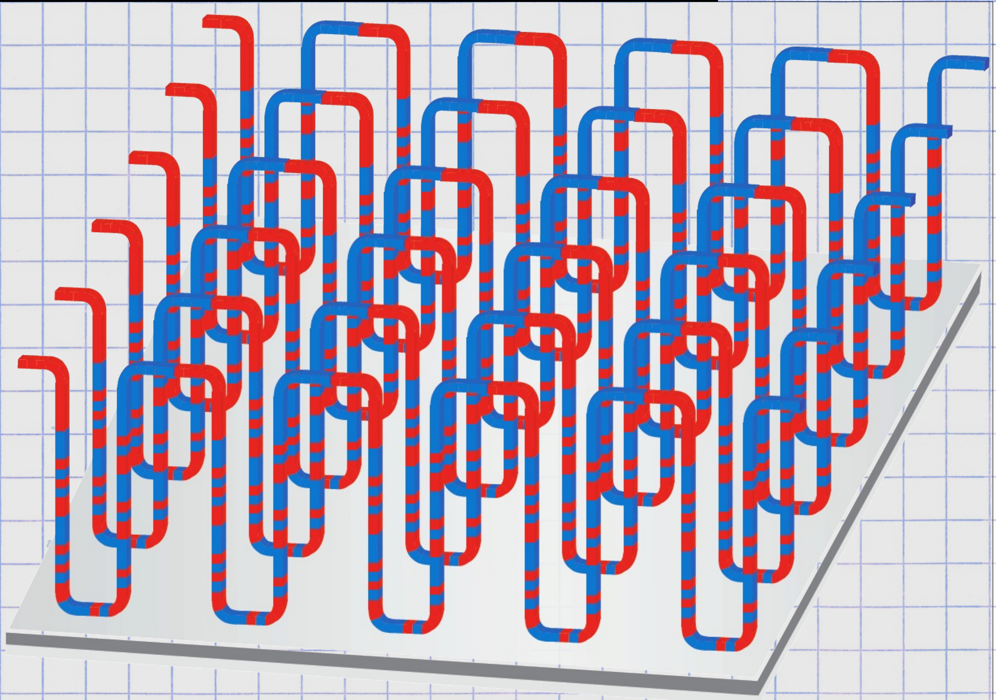
Detail of a cell



Toshiba

Not so far from physical / technological limits either

Proposal for a race-track memory in 3D



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

Pros

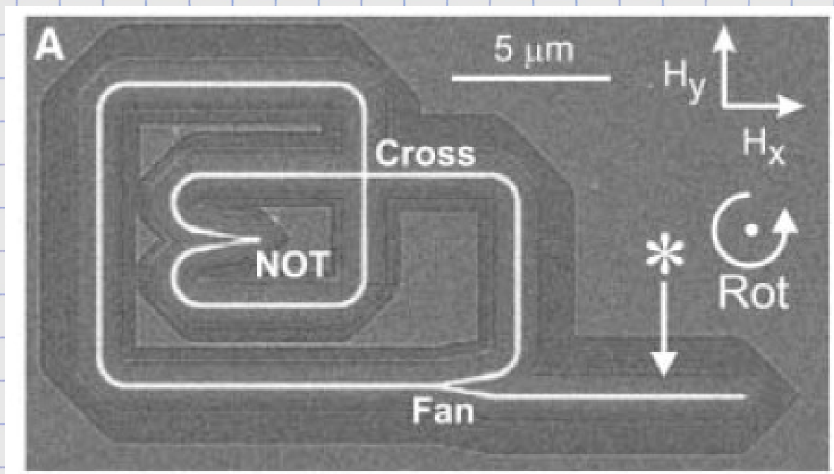
- Incremental progress made again possible along the depth
- One read/write cell per wire → cost remains moderate

Cons

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

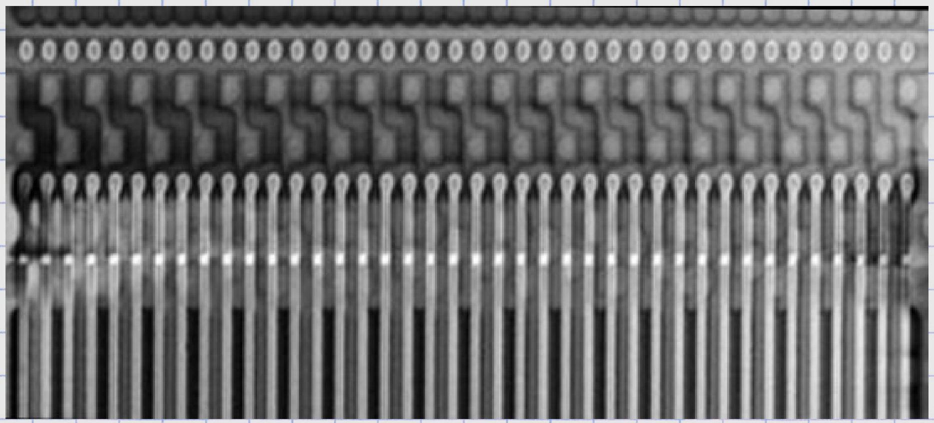
Demonstrators of 2D devices with domain walls

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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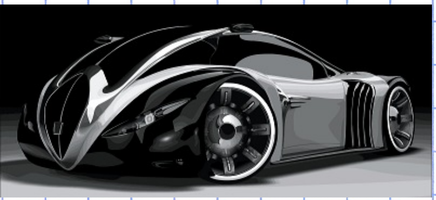
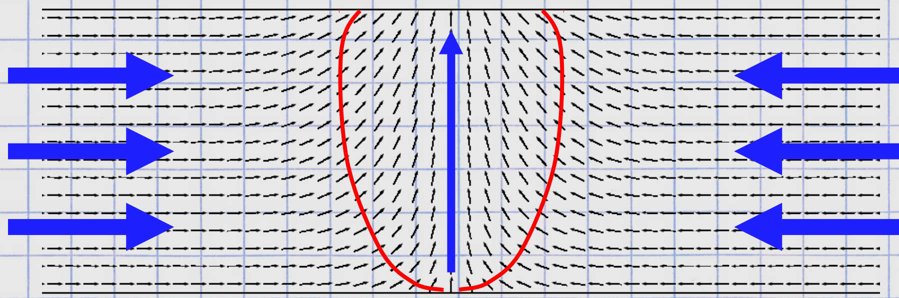
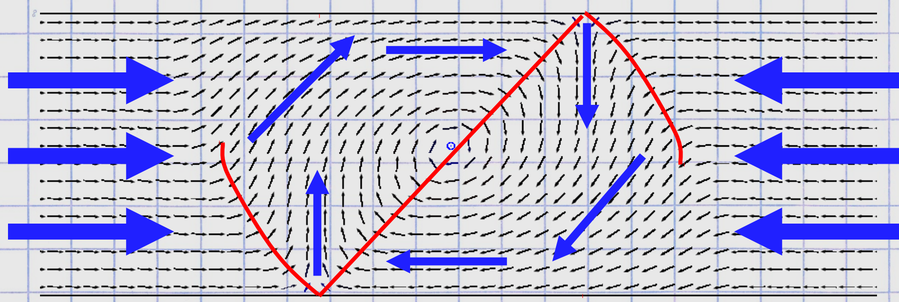


Transverse versus vortex wall

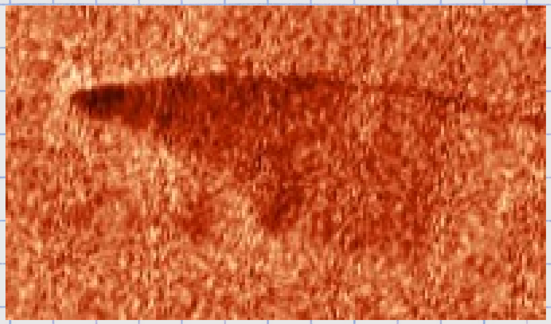
Thin and narrow strips



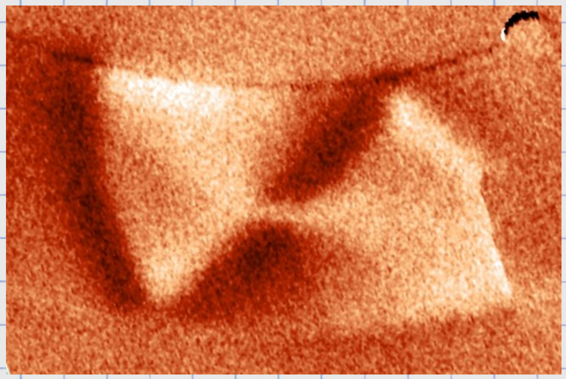
Thick and large strips



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



Magnetic Force Microscopy

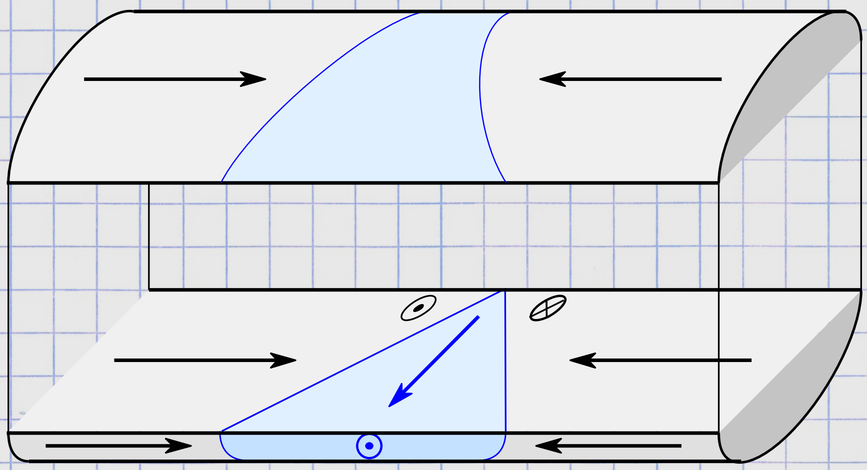


R. McMichael & M. Donahue,
IEEE Trans. Mag. 33, 4167 (1997)

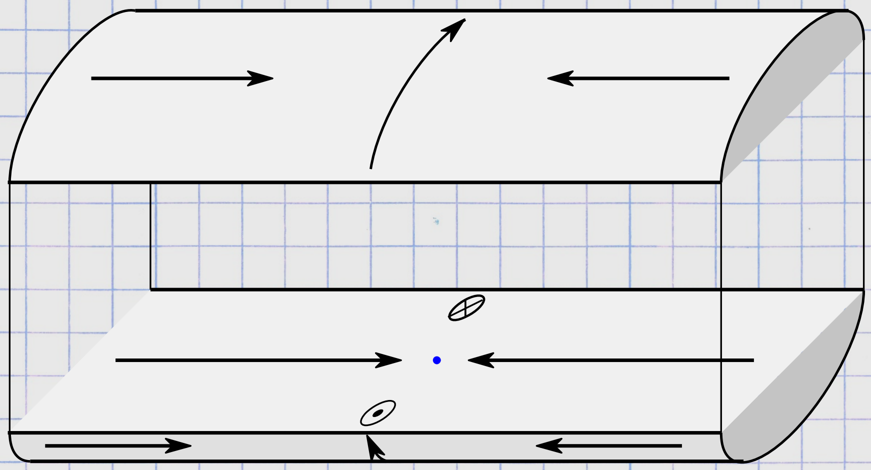
Y. Nakatani et al., J. Magn. Magn. Mater. 290-291, 750 (2005)

⇒ Experimentally well established

Transverse wall $D \lesssim 7\Delta_d$



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

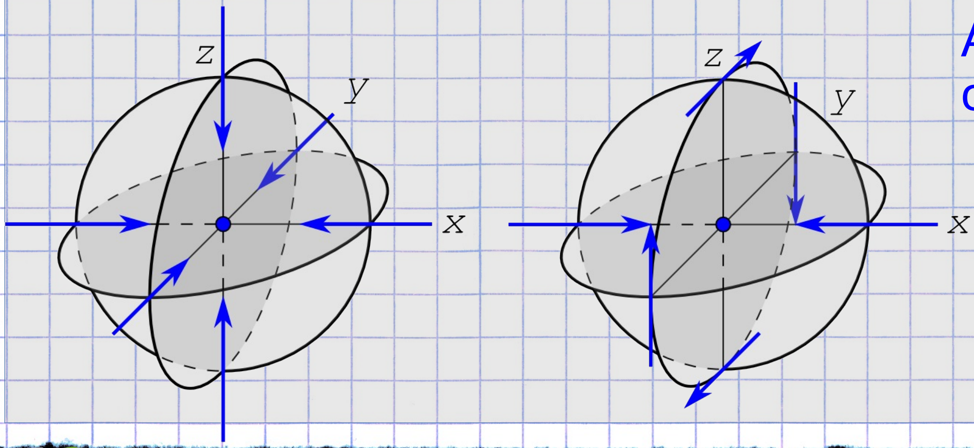


Sometimes improperly named vortex walls

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)

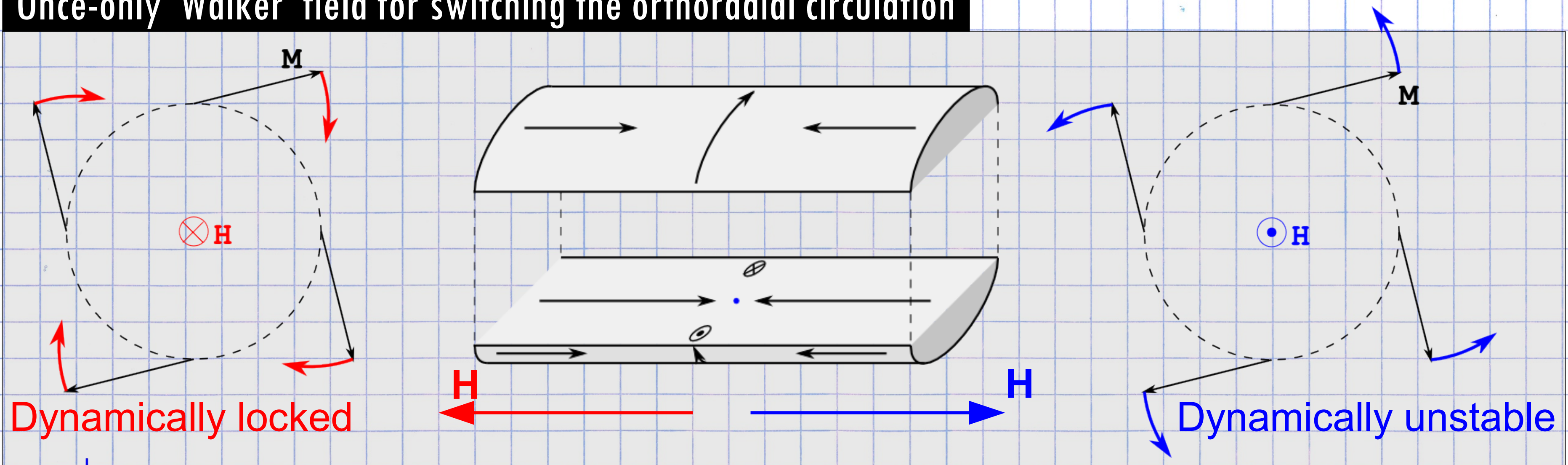
W. Döring,
J. Appl. Phys. 39, 1006 (1968)

Domain-wall motion in wires (here : under field)

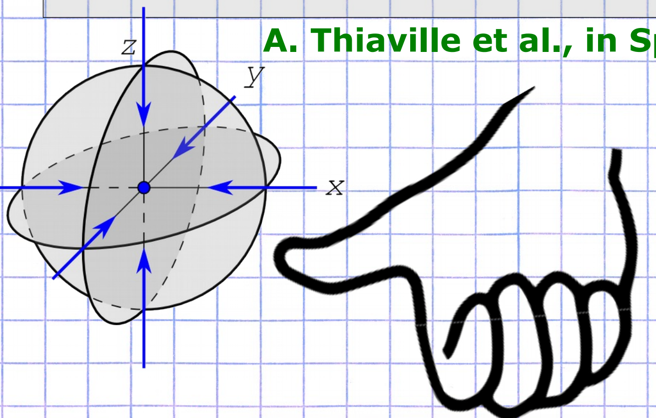
LLG equation

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

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

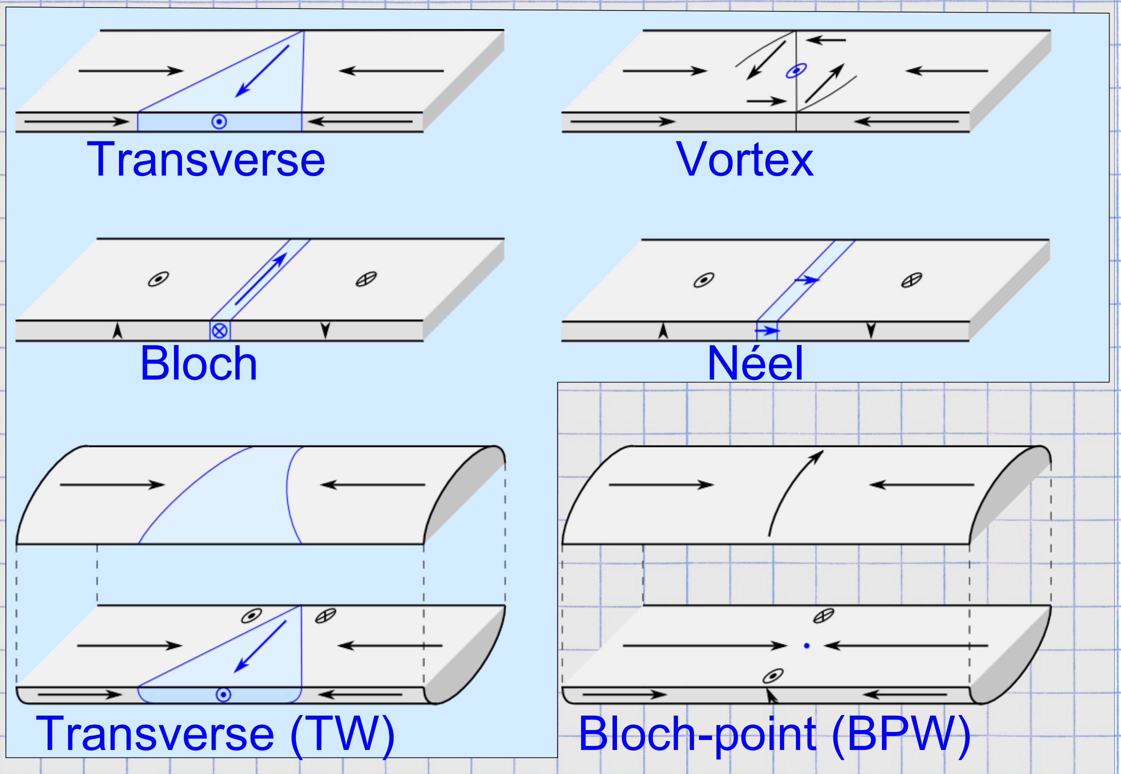


A. Thiaville et al., in Spin dynamics in confined magnetic structures III, p.161-206 (2006)



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

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

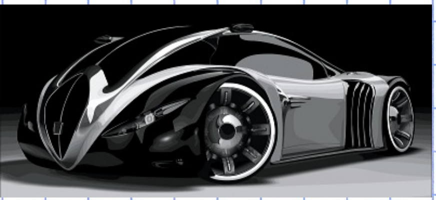
Strips and transverse walls

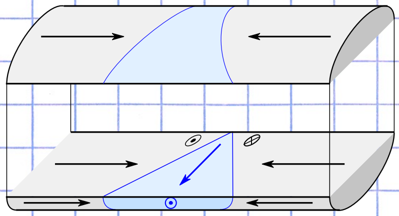
- Theory and experiments
- Domain-wall transformation
- Walker limit, low speed (~100m/s)

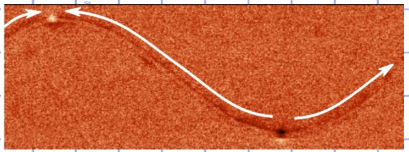
BPW in wires

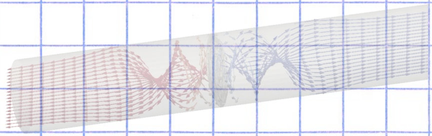
- Theory predictions ; no experiments
- No domain-wall transformation
- High speed expected (>1 km/s)

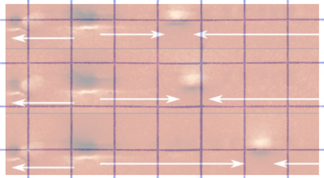
A. Thiaville et al., in Spin dynamics in confined magnetic structures III, p.161-206 (2006)

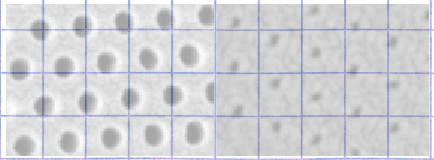






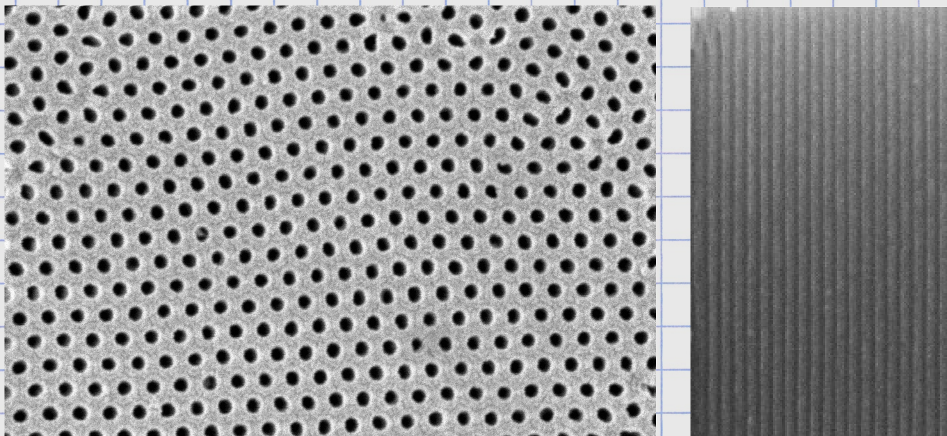






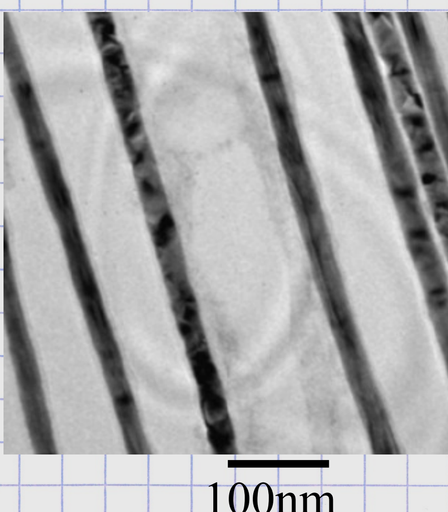
The basics

Anodization of aluminum → template



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

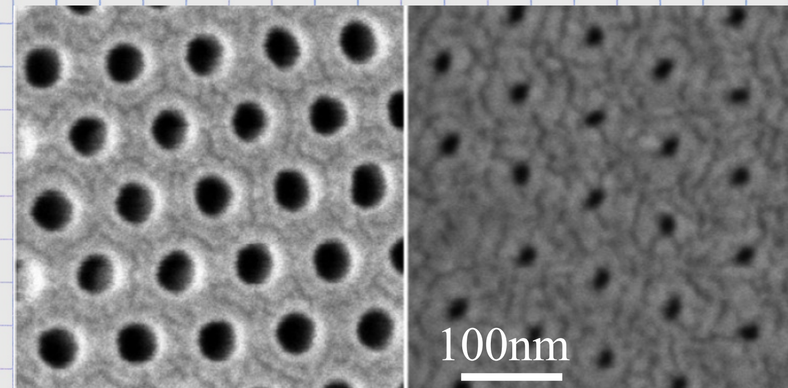
Electroplating → magnetic nanowires



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

Specific aspects

ALD to reduce pore diameter

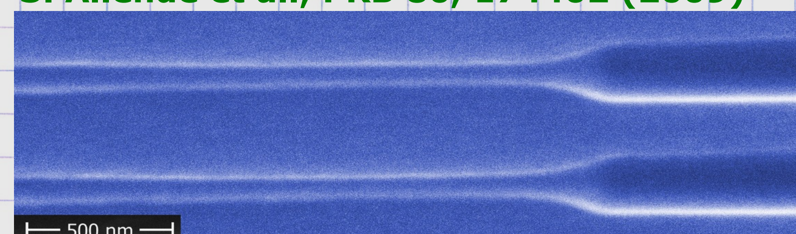


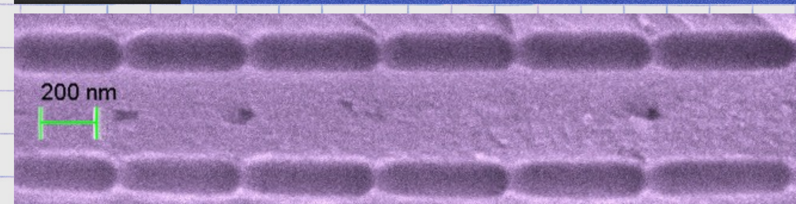
S. Da Col et al., Appl. Phys. Lett. 98, 112501 (2011)

⇨ Control pitch vs diameter

Modulation of pore diameter

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

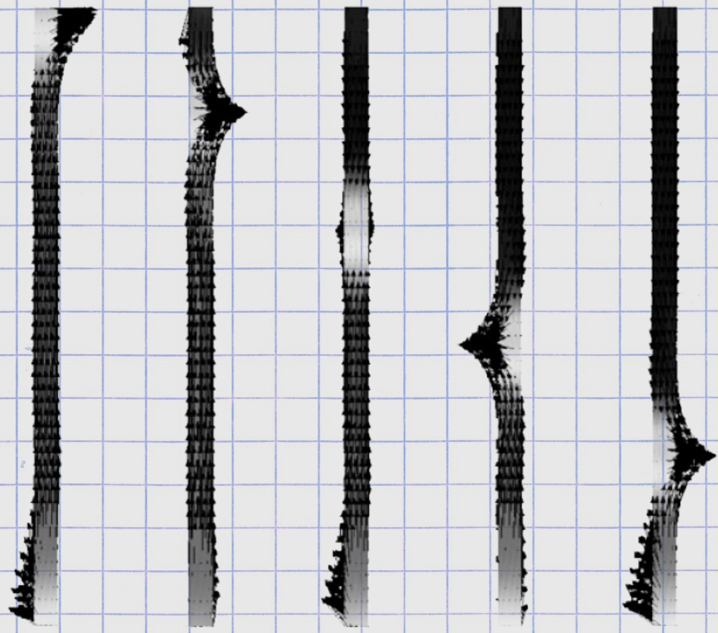




⇨ Landscape for domain walls

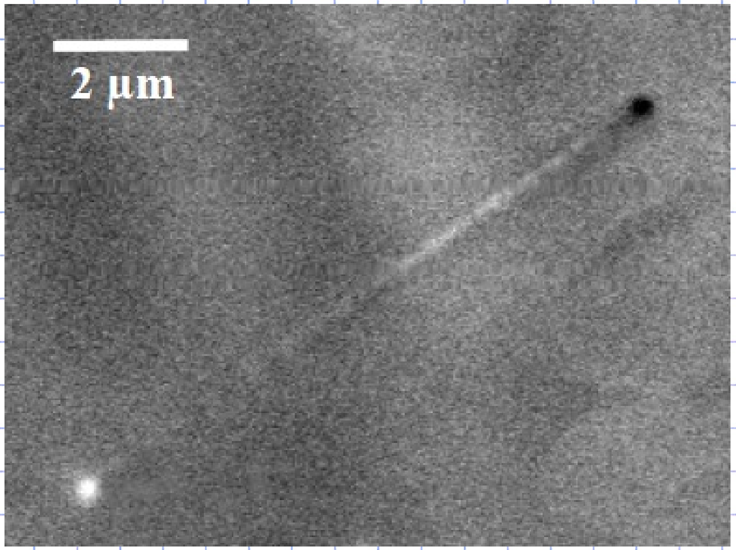
Nucleation – Propagation mechanism

Sequence of magnetization reversal



R. Hertel et al., J. Magn. Magn. Mater. 249, 251 (2002)

Single-domain wire (MFM)



Y. Henry et al., Eur. Phys. J. B 20, 35 (2001)

Explains why domain walls hardly reported in cylindrical nanowires

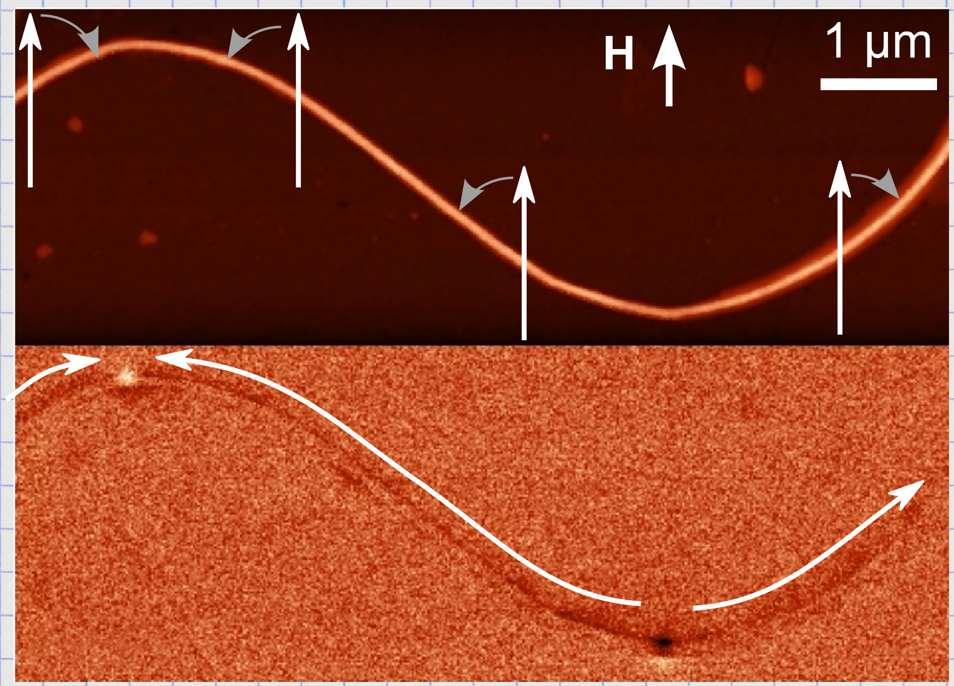
Preparation

- ⇨ Alumina matrix dissolved
- ⇨ Solution blown on surface

Nucleation

AFM

MFM



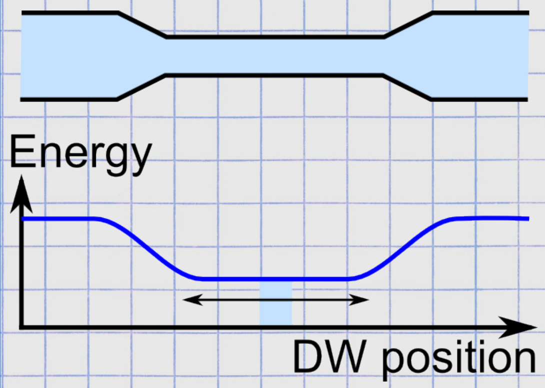
⇨ Step 1 : wire magnetized along the bends radii

⇨ 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)**

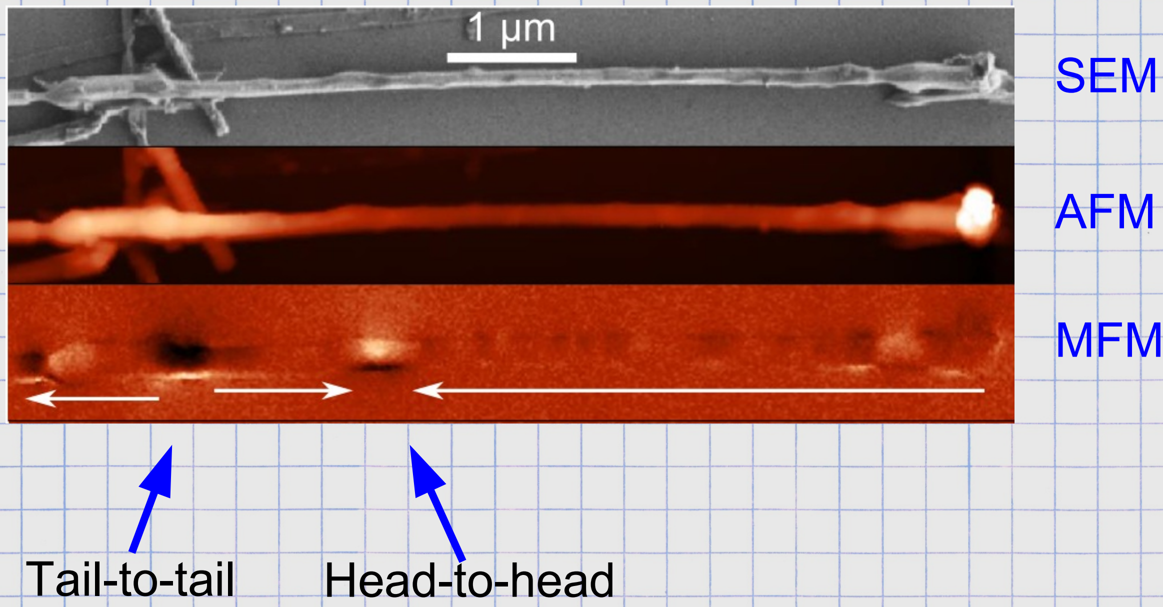
Principle



- 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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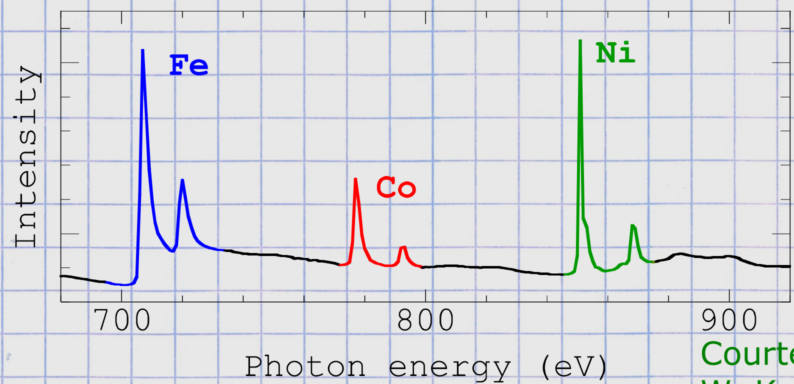
XMCD

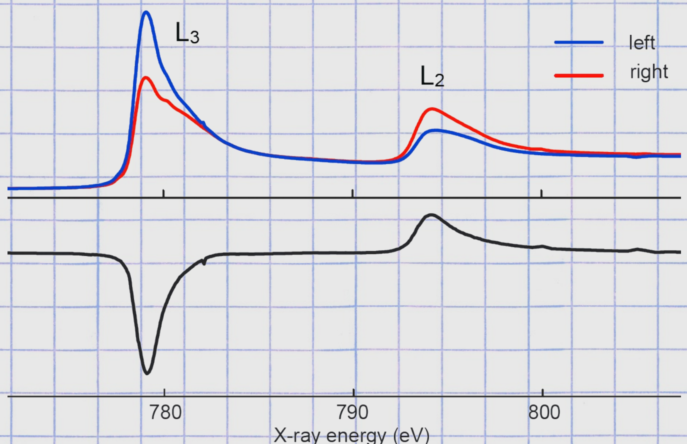
X-ray Magnetic Circular Dichroism

⇨ Element selectivity



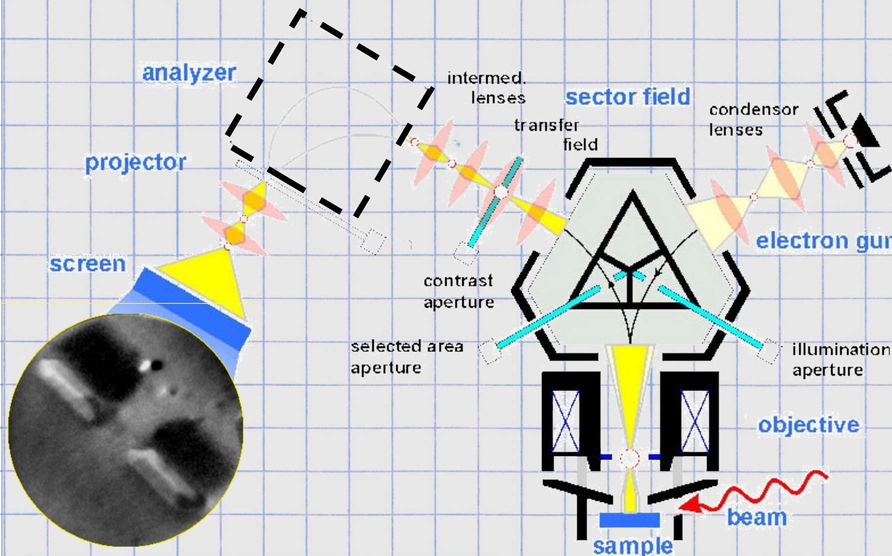
Courtesy: W. Kuch

⇨ Magnetic sensitivity



PEEM

Photo-Emission Electron Microscopy



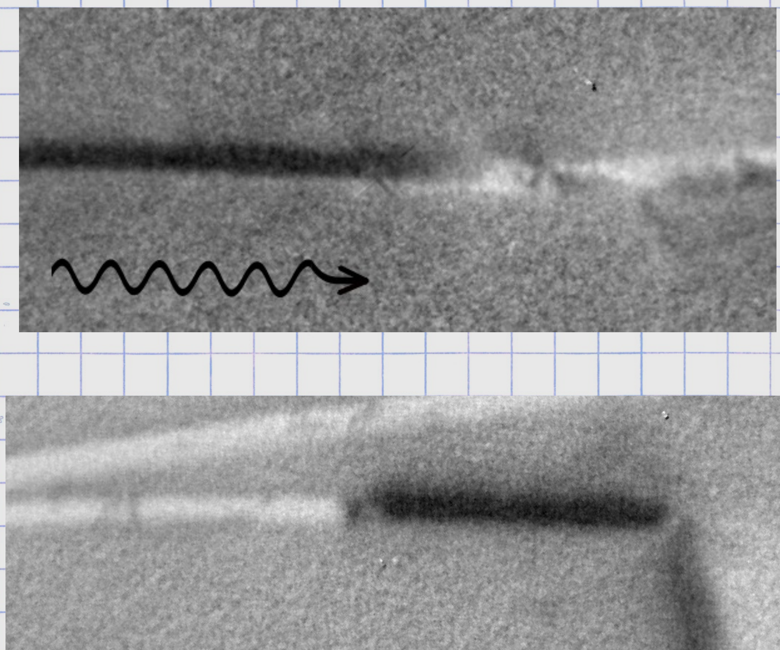
Features

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

Two examples

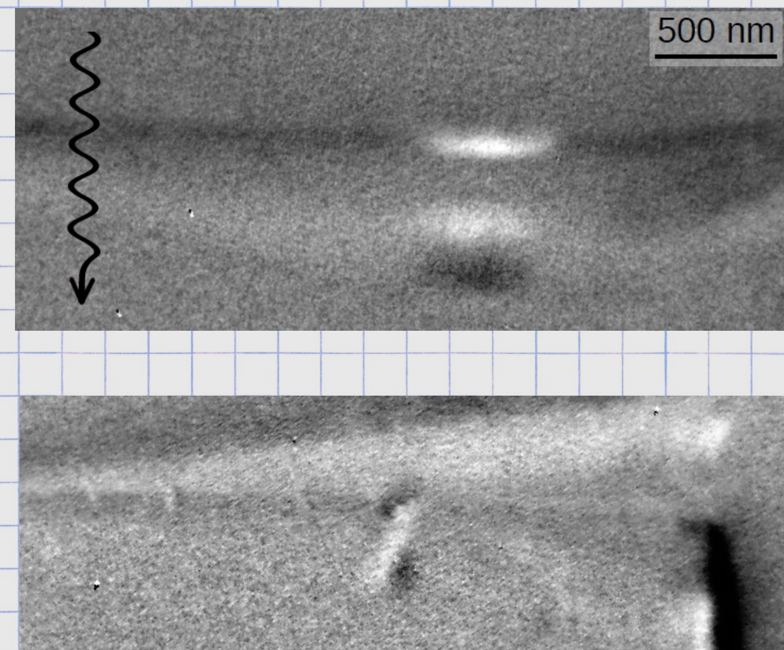
Beam along wire

⇨ Locate domain walls



Beam across wire

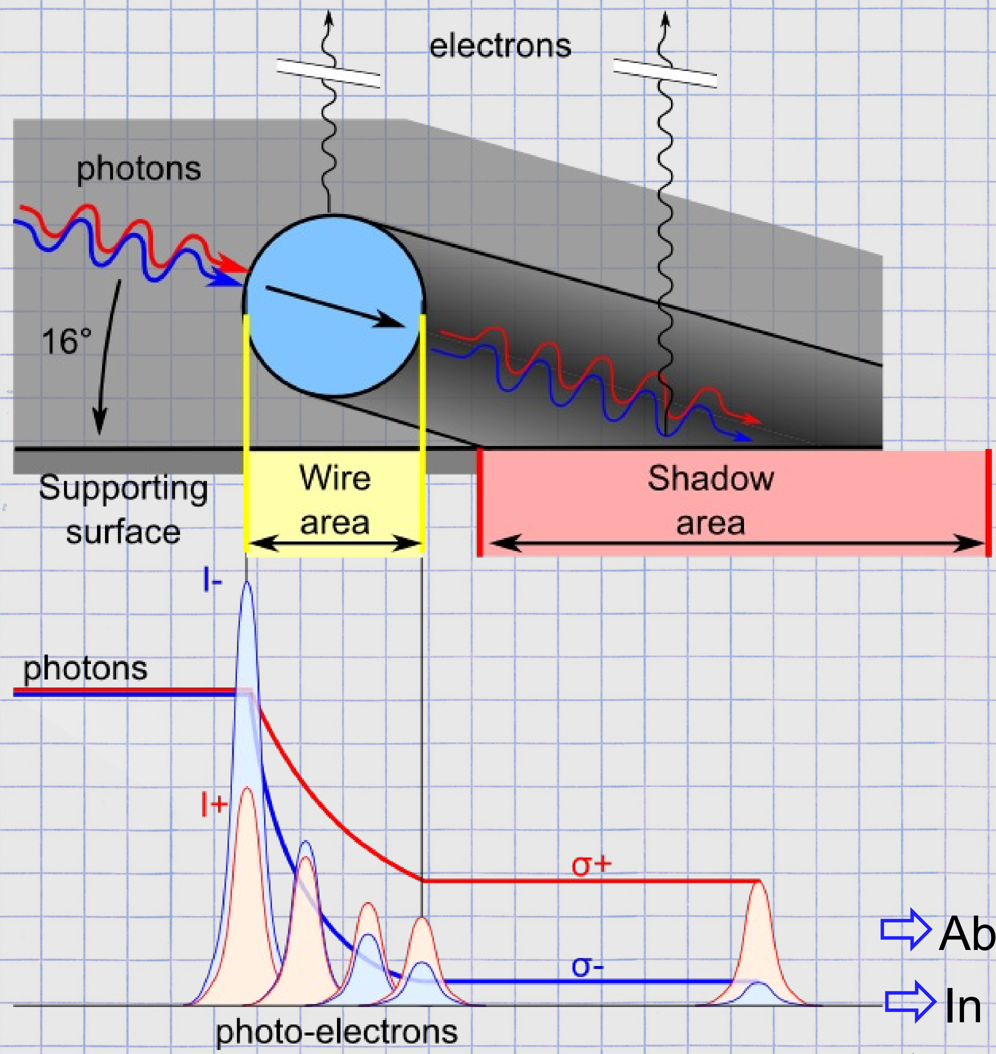
⇨ Inspect domain wall

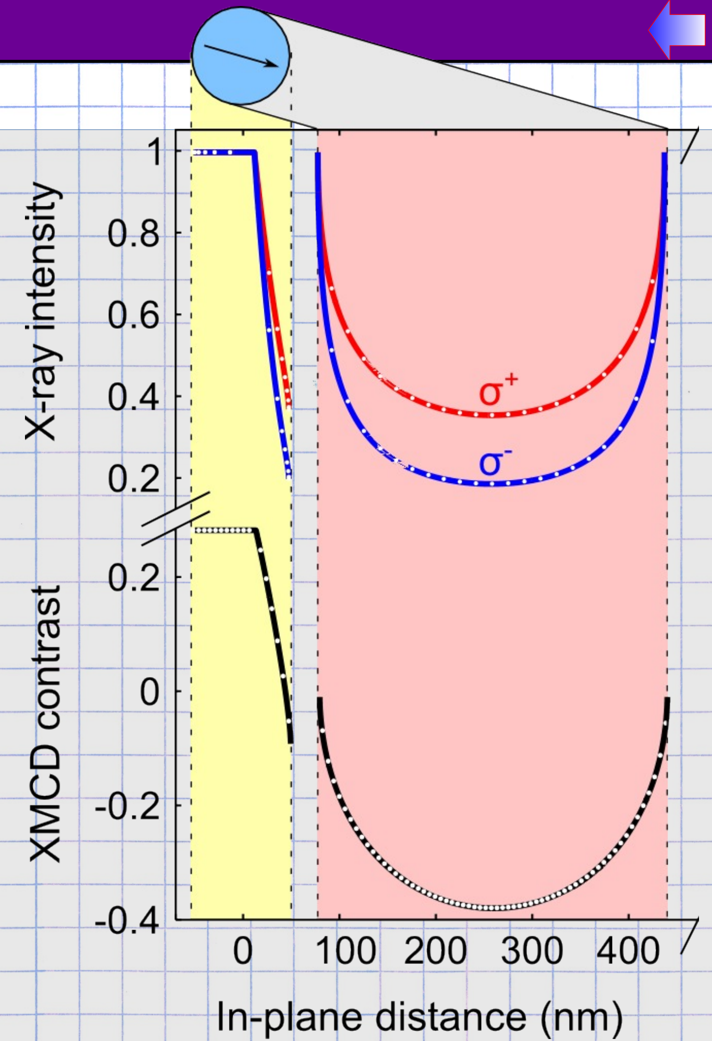


↳ Several non-trivial patterns

↳ Need for modelling

Schematics

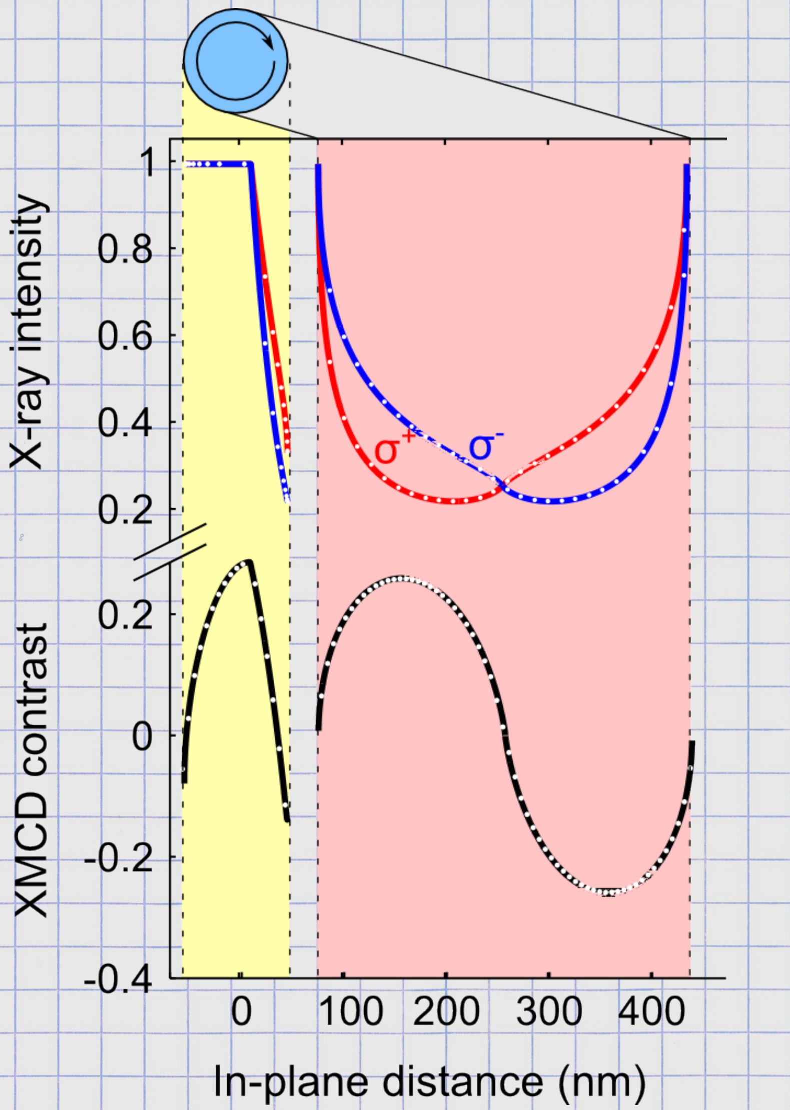




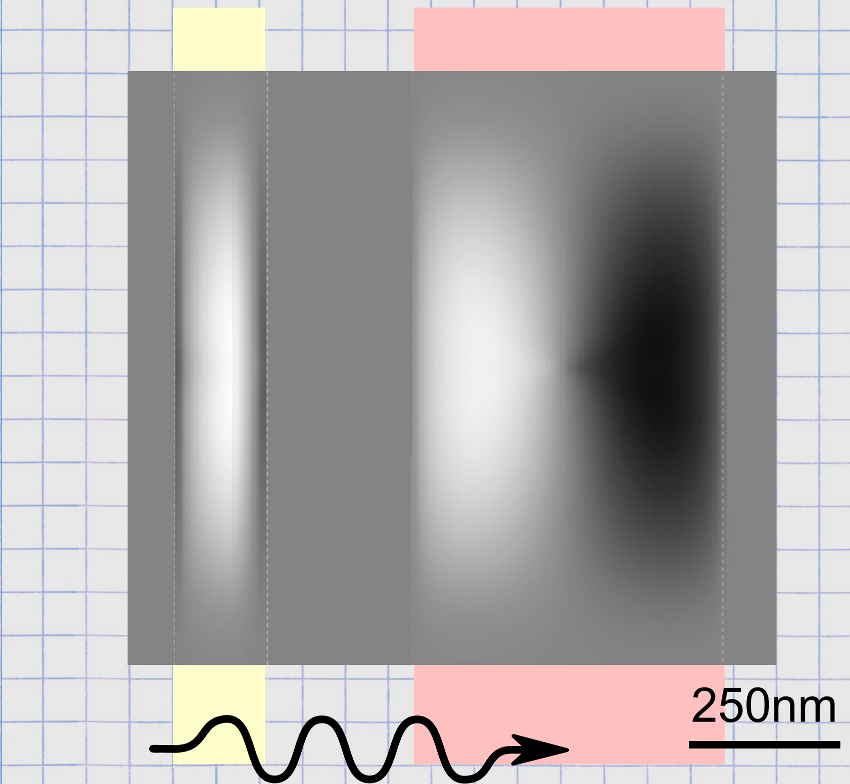
- Above wire : surface magnetization
- In the shadow : volume magnetization
- Non-linear, even change of sign

S. Jamet et al., arXiv:1506.02866

Simulation of XMCD



Resulting image



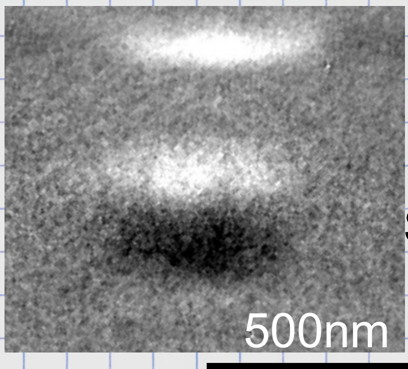
- Surface and volume information
- Bloch-point domain wall identified from <u>symmetry and volume curling</u>

S. Jamet et al., arXiv:1506.02866

Bloch-Point Wall (BPW)

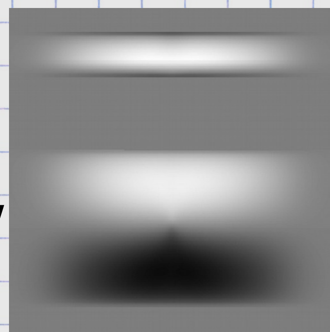
Wire diameter : 95nm

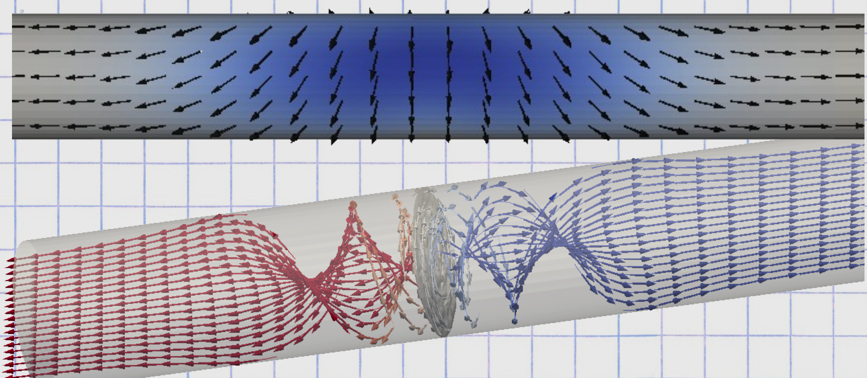
Experiment | Simulation



Wire

Shadow





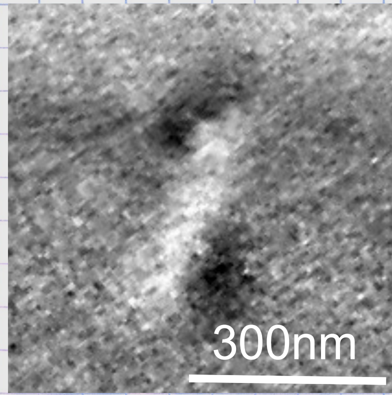
⇨ Orthoradial curling

⇨ Symmetry with respect to plane perpendicular to axis

Transverse Wall (TW)

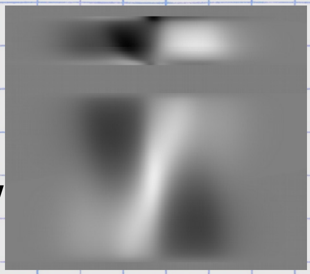
Wire diameter : 70nm

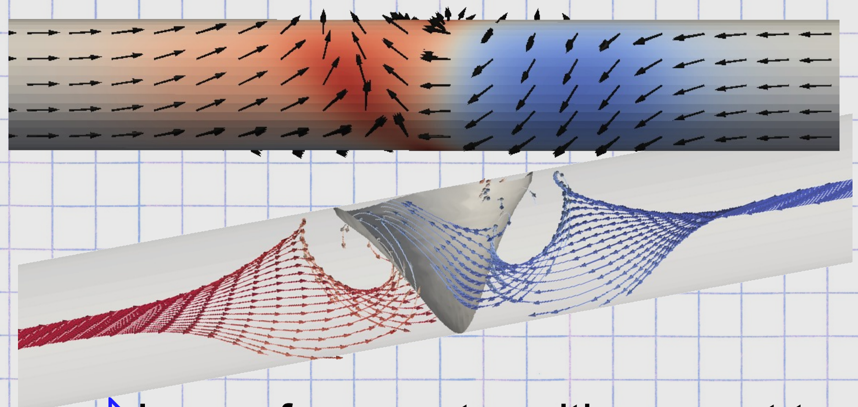
Experiment | Simulation



Wire

Shadow





⇨ Loss of symmetry with respect to plane perpendicular to axis

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

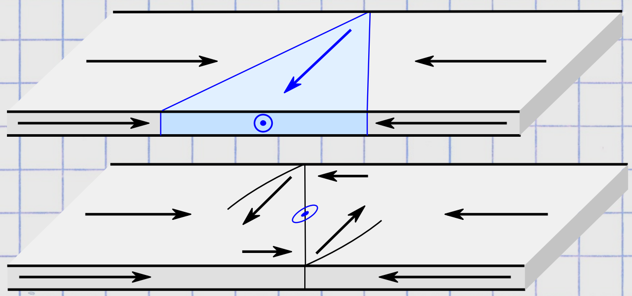
→ Transverse wall imaged with electron holography

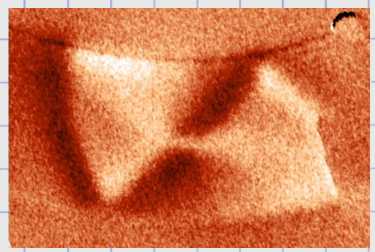
S. Da-Col et al., Phys. Rev. B (R) 89, 180405, (2014) arXiv:1311.7368

Motivation :

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

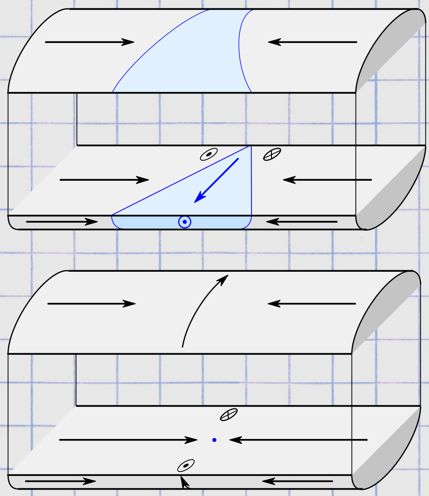
Flat strips

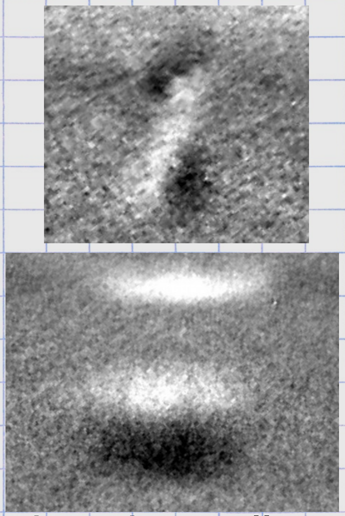




⇨ Transverse and vortex

Cylindrical wires





⇨ Transverse and Bloch-point walls

⇨ Confusion between Bloch-point and vortex

Emergence of square or rectangular wires

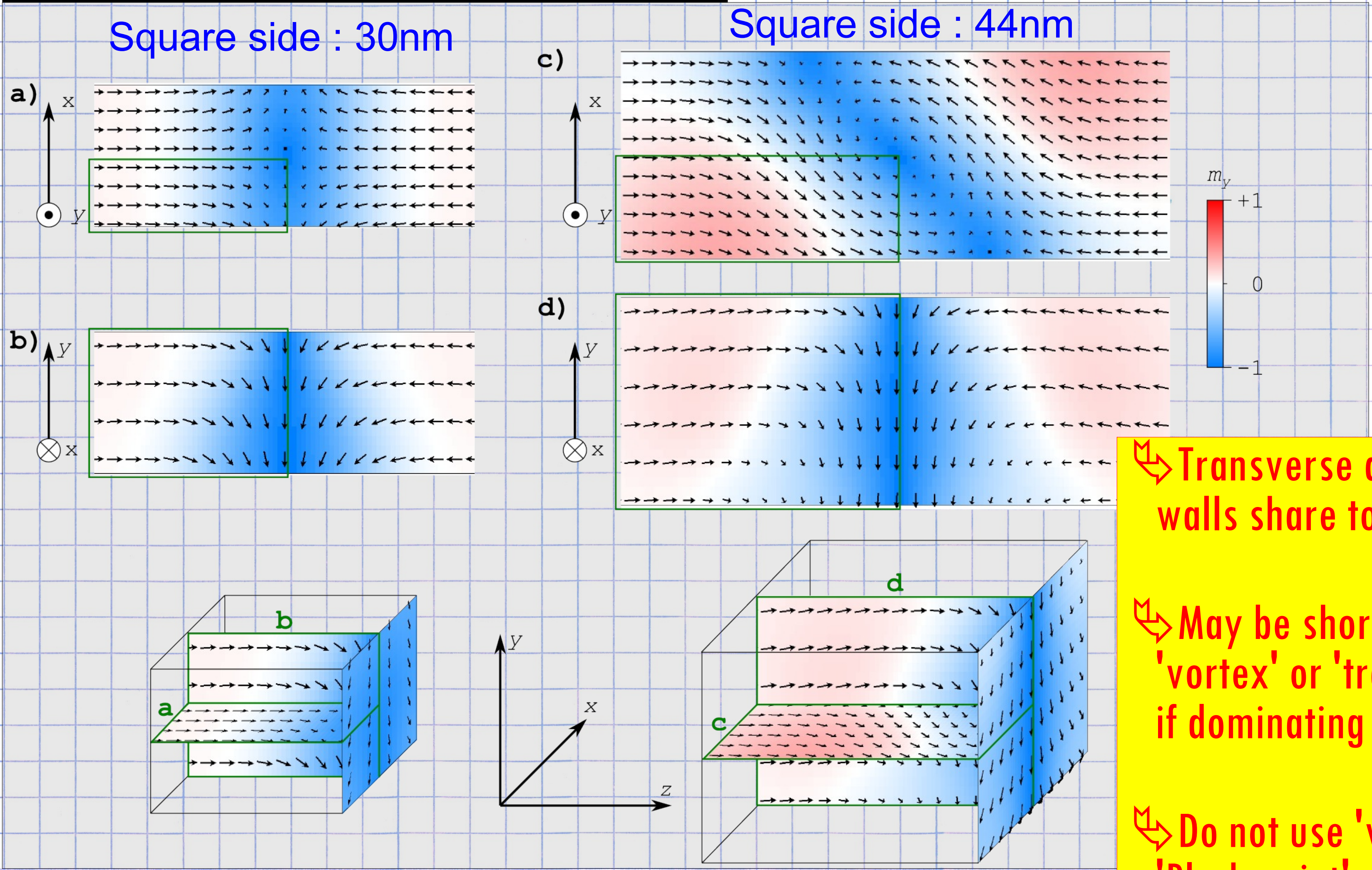
⇨ Top-down + bottom-up / Planar templates

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 ?

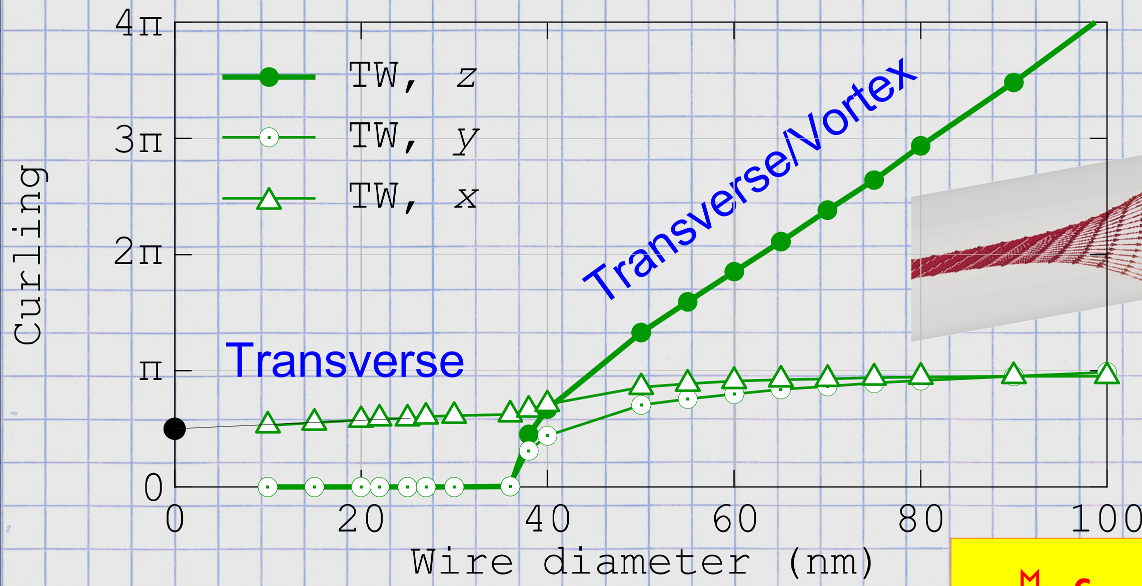
Topology of the transverse – vortex wall family

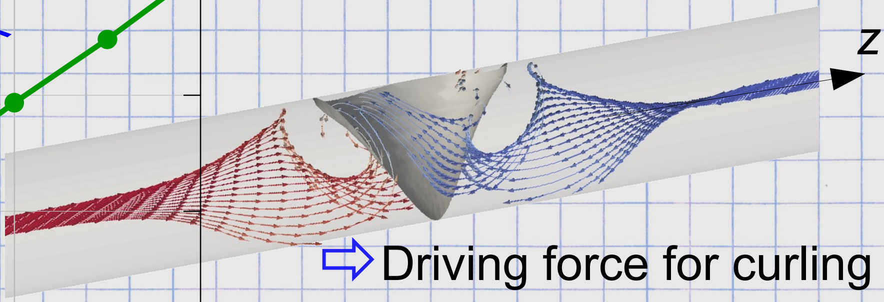


- Transverse and vortex walls share topology
- May be shortened to 'vortex' or 'transverse' if dominating feature
- Do not use 'vortex' for 'Bloch-point'

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)

Circulation of magnetization → Quantify curling



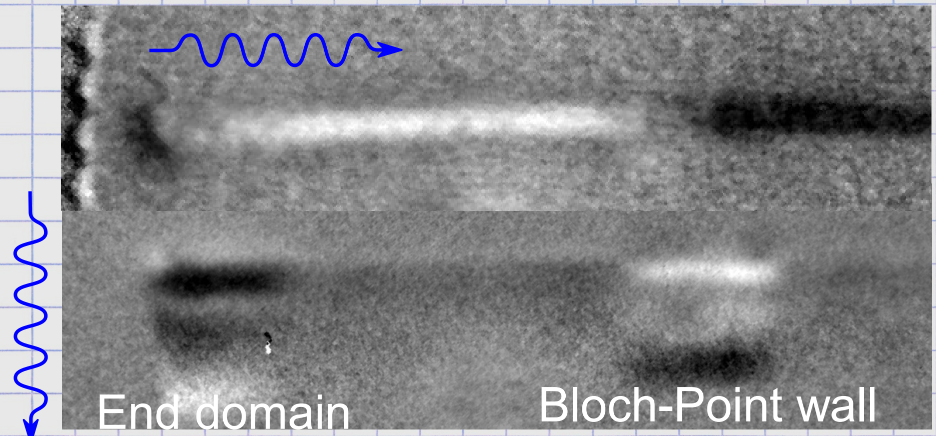


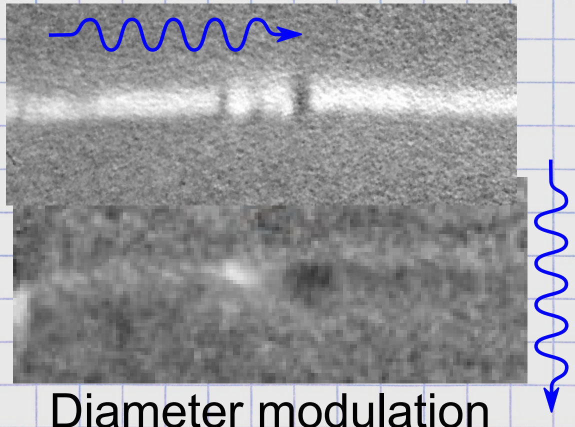
⇨ Driving force for curling : spread volume charges

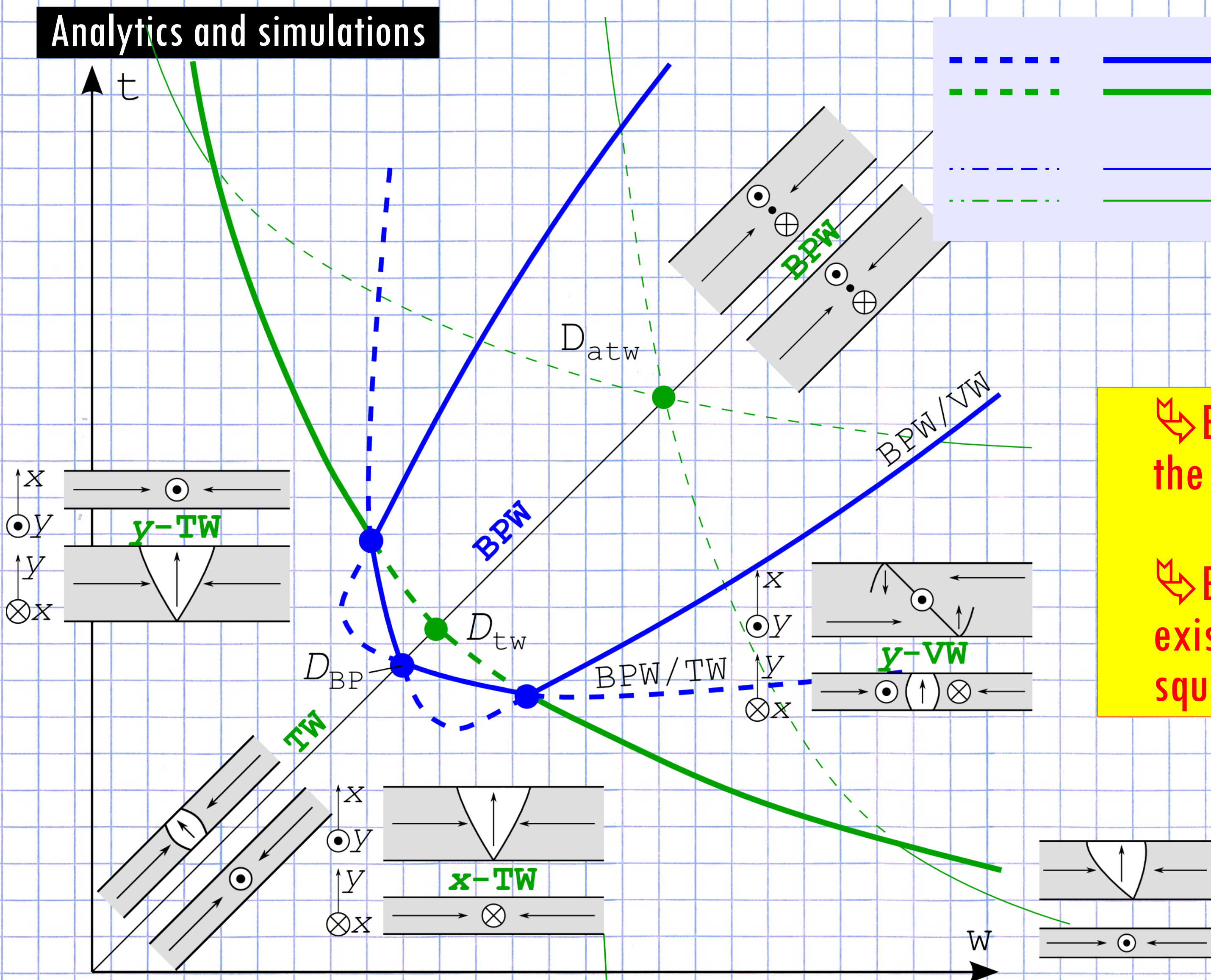
$$\mathrm{div}\,\mathbf{M} \approx -\frac{\mathrm{d}M_z}{\mathrm{d}z}$$

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

Imaging the general character of curling





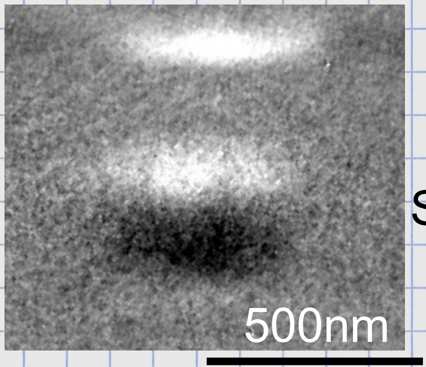


- Extensive coverage of the width/thickness space
- Bloch-point walls should exist away from disk or square cross-section

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

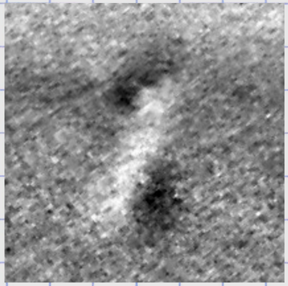
Diameter 95nm



Wire

Shadow

Diameter 70nm



Wire

Shadow

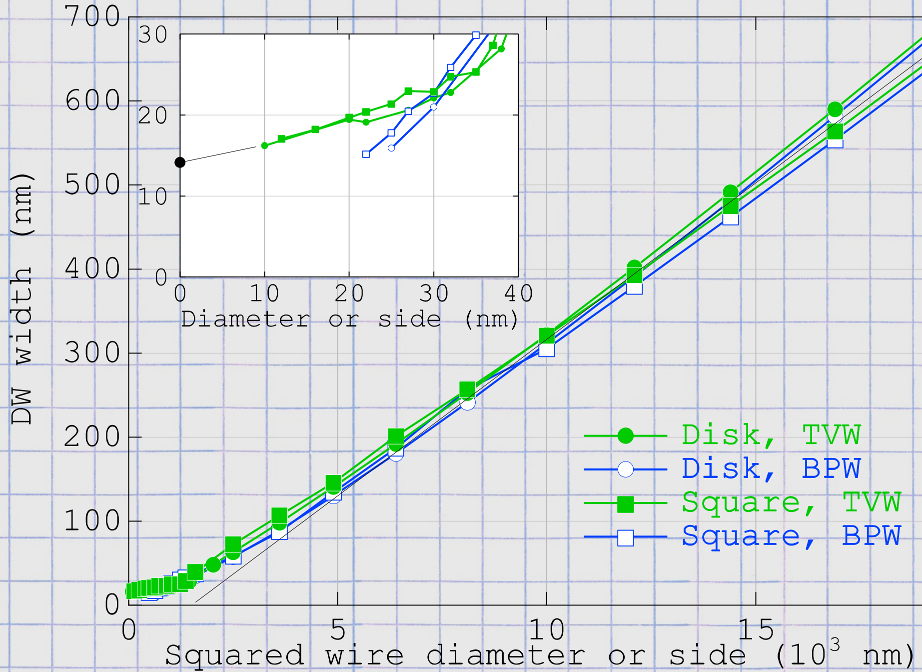
↳ Sharp increase of length with diameter

Analytics

Physics : balance exchange and dipolar energies

Energy : $\mathcal{E} \sim AR^2/\Delta_d$ Wall length : $L \sim R^2/\Delta_d$

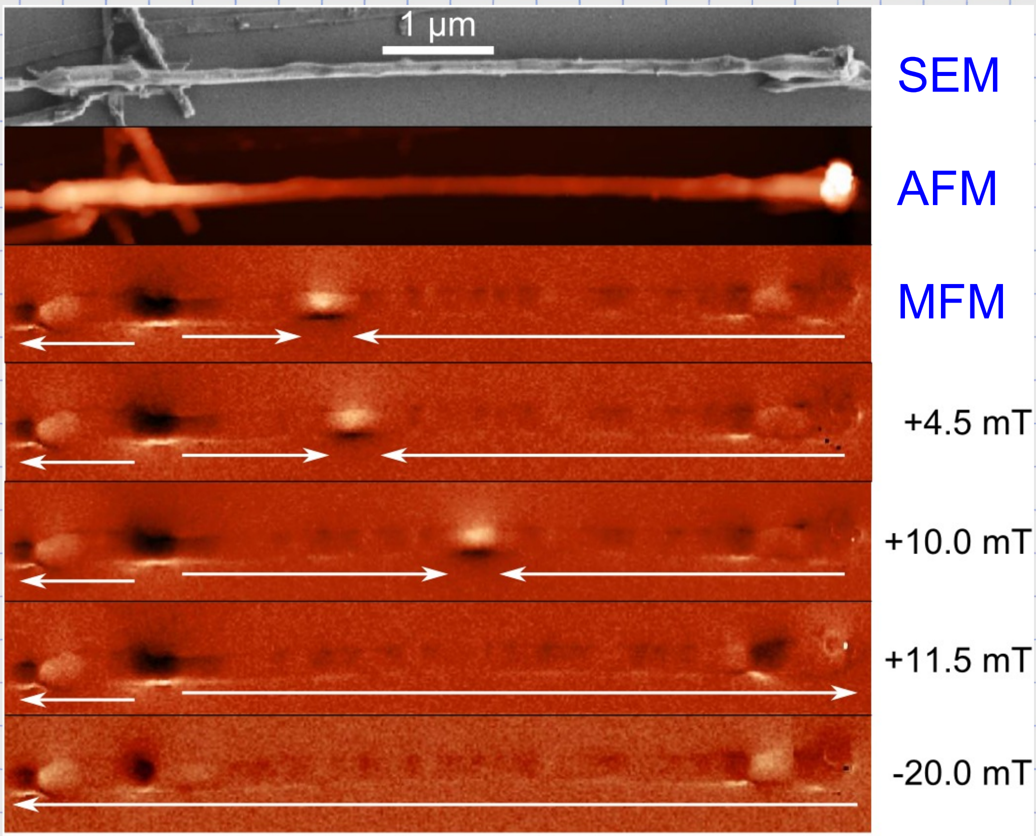
Simulations



↳ Confirmation of scaling law for wall length $L \sim R^2/\Delta_d$

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)

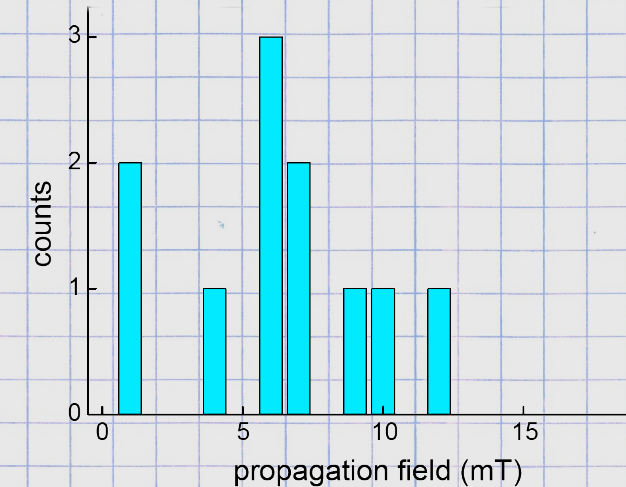
Experiments



S. Da-Col et al., in preparation

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

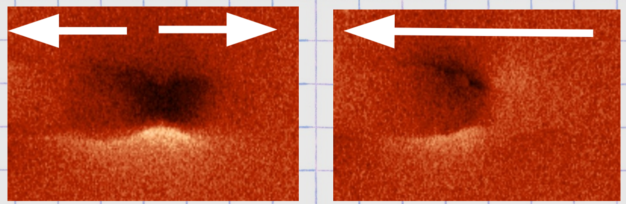
Straight sections



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

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

Protrusions and constrictions

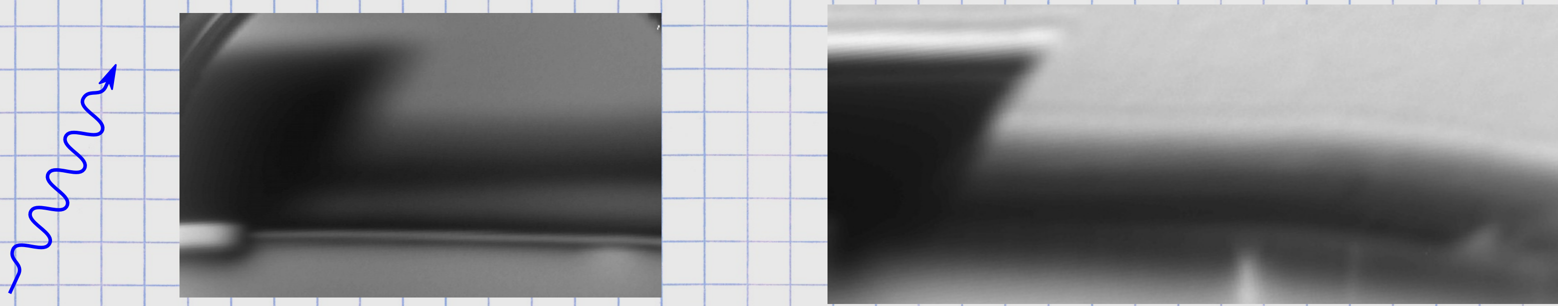


- Pinning field ~30mT

Propagation and selection of circulation : preliminary data

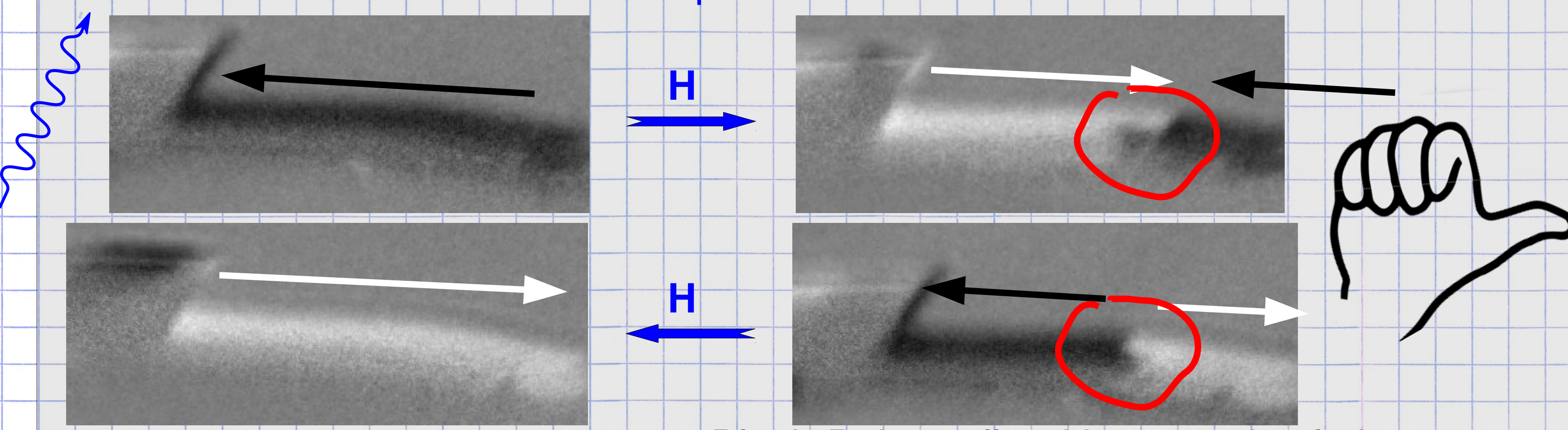
Structure

Focus on wire | Focus on shadow



Motion and circulation

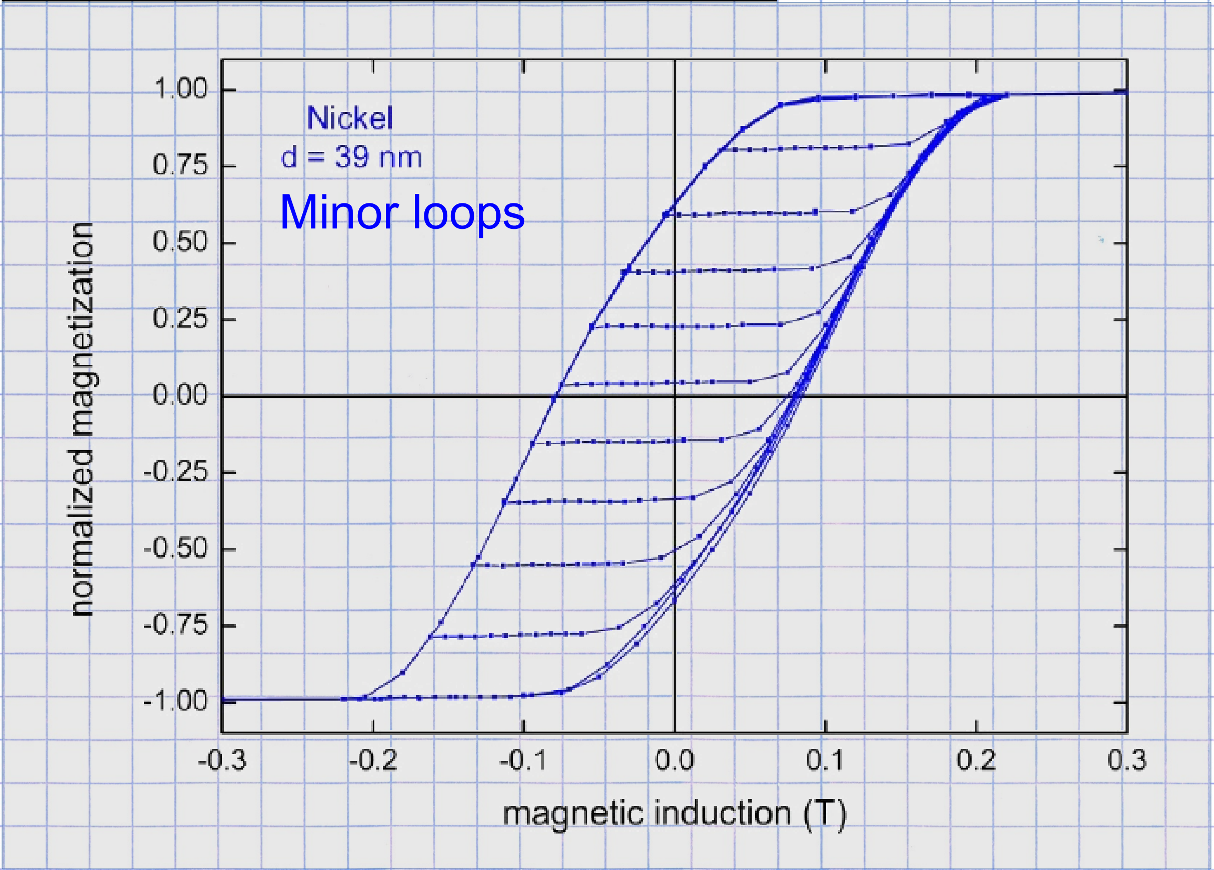
Initialize | Field pulse | Final state



Bloch-Point walls with same circulation

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

Magnetization switching of arrays of wires

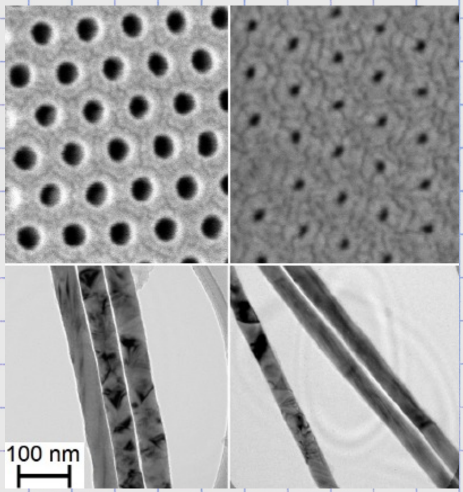


S. Da-Col et al., Appl. Phys. Lett. 98, 112501 (2011)

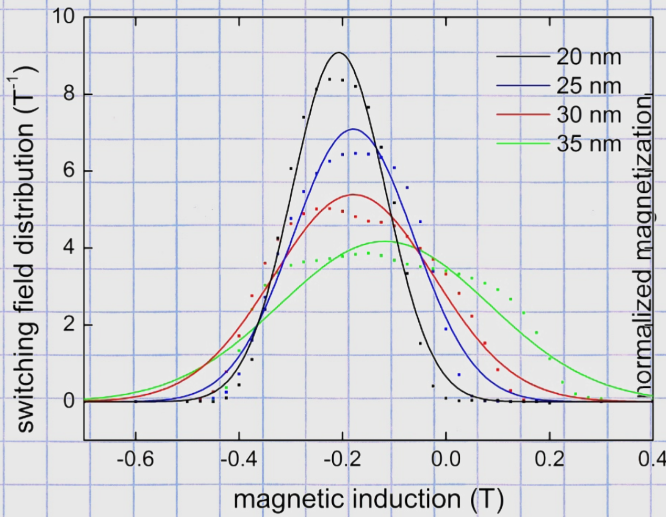
- Nucleation – Propagation mechanism
- Large influence of demagnetizing interactions

Magnetostatic interactions : global demagnetization effect

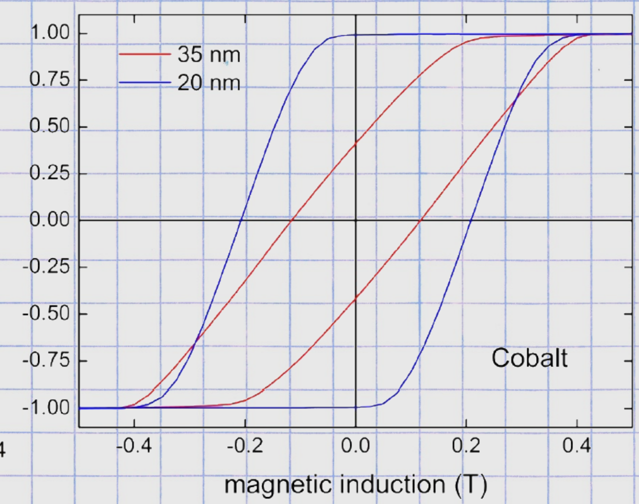
Raw | 100 ALD cycles



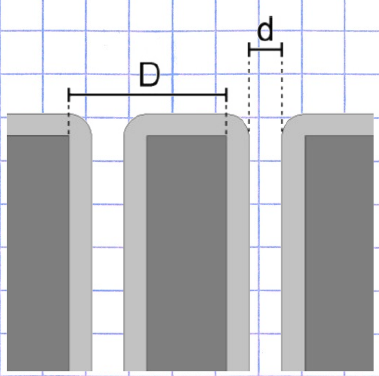
Switching field distribution



Full hysteresis loops



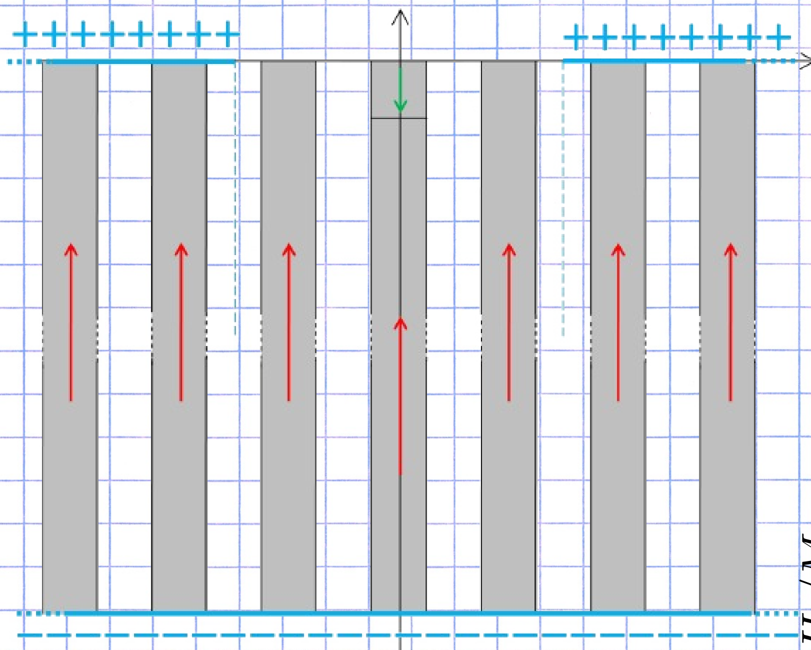
S. Da-Col et al., Appl. Phys. Lett. 98, 112501 (2011)



- Atomic layer deposition reduces inter-wires dipolar interactions
- Full remanence may be recovered

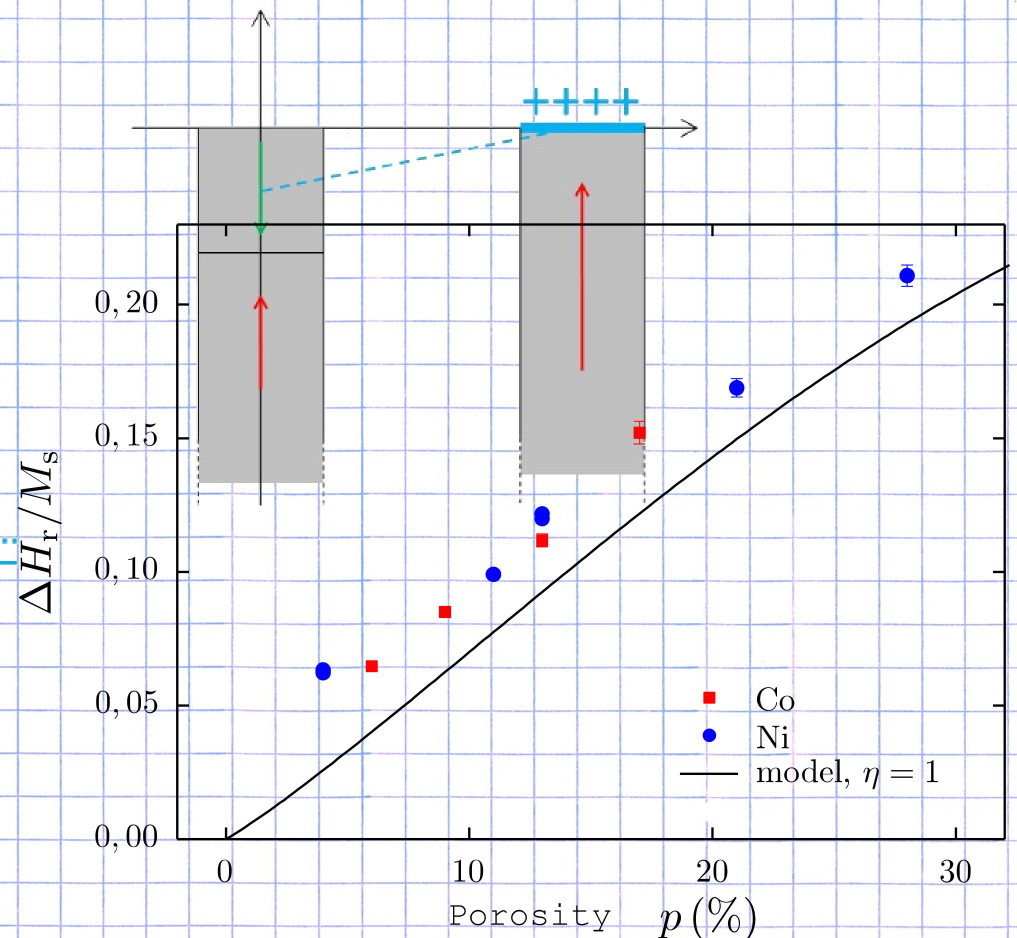
$$\frac{H_\mathrm{d}}{M_s} = -\frac{\pi}{4\sqrt{3}}\left(\frac{d}{D}\right)^2 - \frac{\pi}{6\sqrt{3}}\eta\left(\frac{d}{D}\right)^3\left[1-\frac{2}{9}\eta^2\left(\frac{d}{D}\right)^2\right] - \frac{3\eta}{8}\left(\frac{d}{D}\right)^3\left[1-\frac{3}{2}\eta^2\left(\frac{d}{D}\right)^2\right]$$

Bottom — Top, long range — Top, first shell

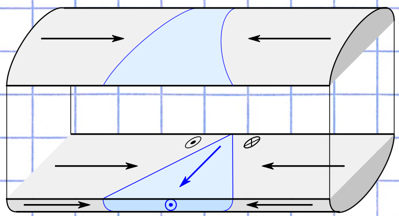


Model adapted from : T. Wang et al., Appl. Phys. Lett. 92, 192504 (2008)

- Good agreement with experiments
- NB : cannot use field from pinpoint dipole !

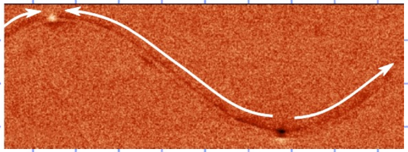


Take-away messages

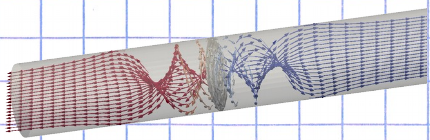


1. [Science]

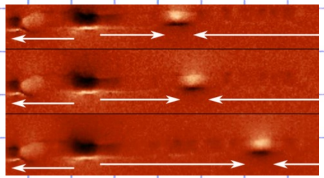
Why addressing cylindrical magnetic nanowires ?



2. Nucleate domain walls ✓



3. Identify domain walls ✓

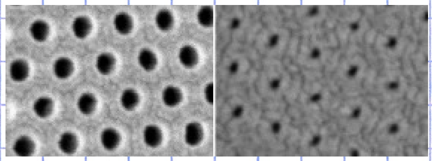


4. Move domain walls ✓

⇨ 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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