Views on the 3D race-track memory

Staffa Island, Scotland

Magnetic domain walls in cylindrical nanowires – Fundamental challenges for a 3D storage media

O. Fruchart

1. Institut NÉEL, Univ. Grenoble Alpes / CNRS, France

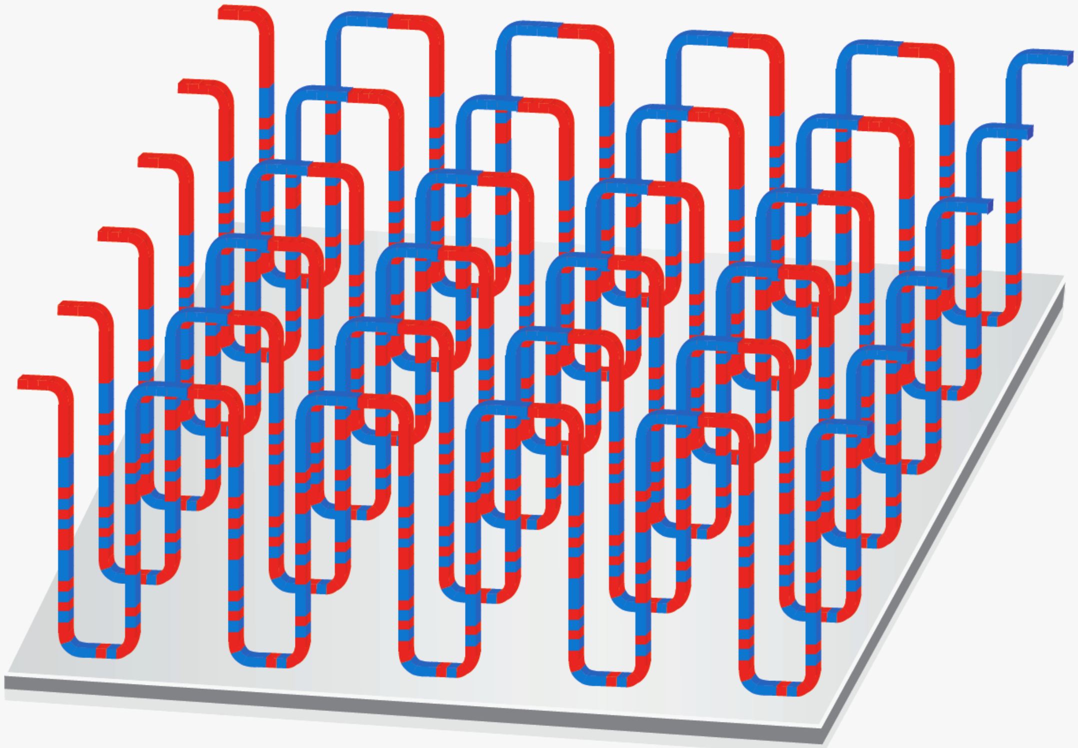
2. SPINTEC, Univ. Grenoble Alpes / CNRS / CEA-INAC, France

www.spintec.fr

email: olivier.fruchart@cea.fr

Slides: http://fruchart.eu/slides

Proposal for a 3D race-track memory



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

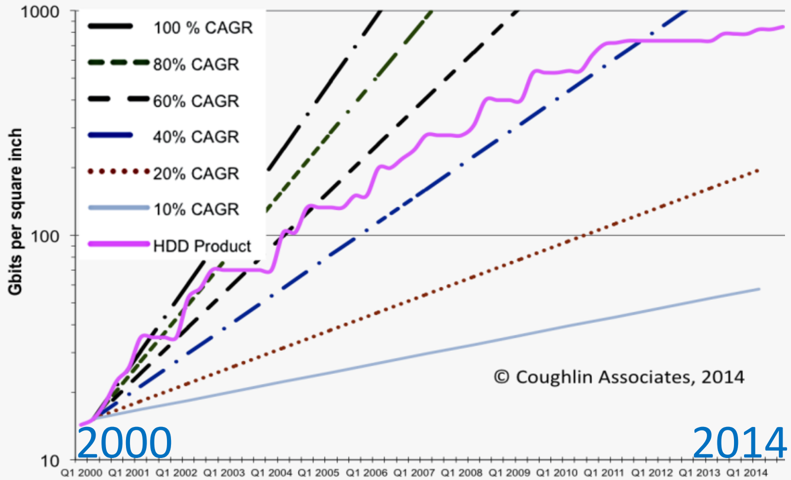
- What has been done?
- Dreams? Challenges?

Steady progress of HDD, however:
incremental, keeping the design

1956

Today

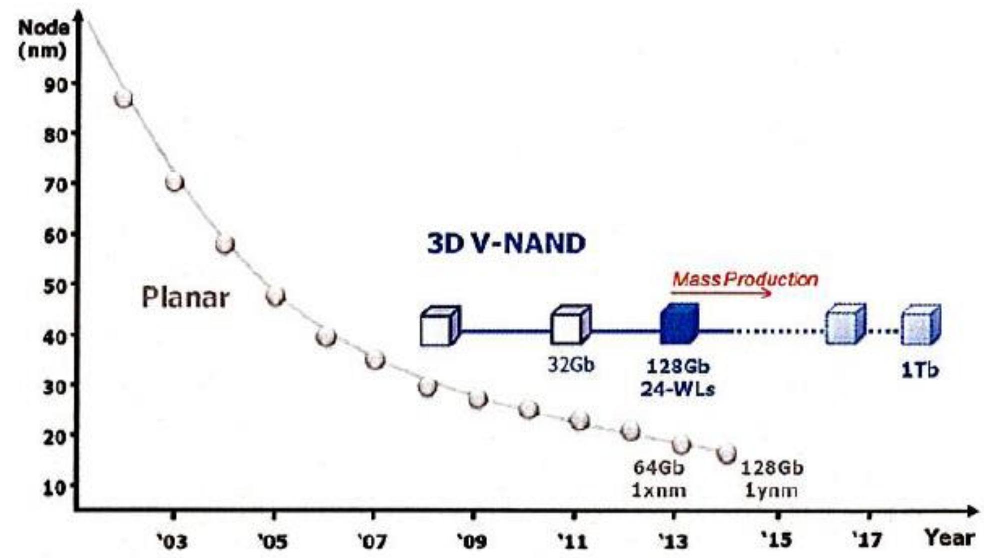
Staggering areal density



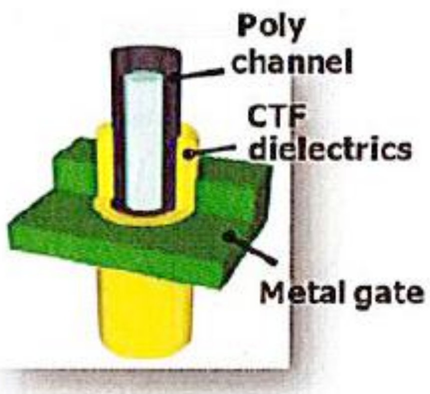
- Increasing fundamental and technological bottlenecks
- Any 2D-based technology is bound to face an end

BACKGROUND: areal storage

Competing technologies go 3D



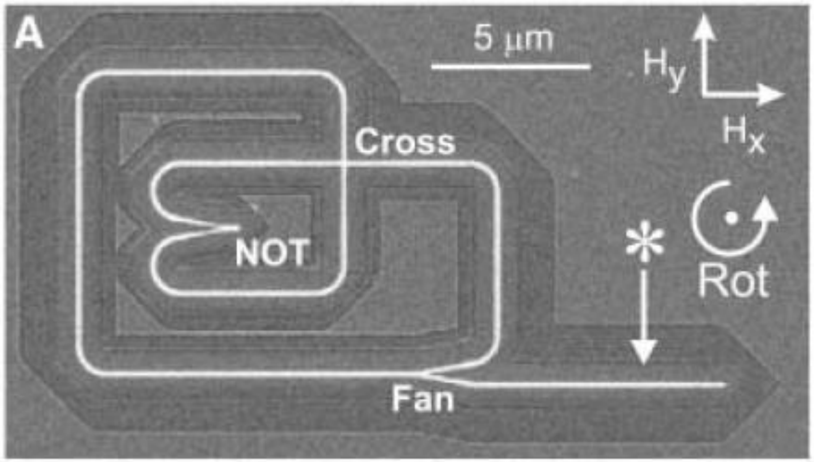
24-layer 3D NAND Flash



- 1Gb/mm2 → 600Gb/in2...
- Magnetic mass storage may only remain for niche applications

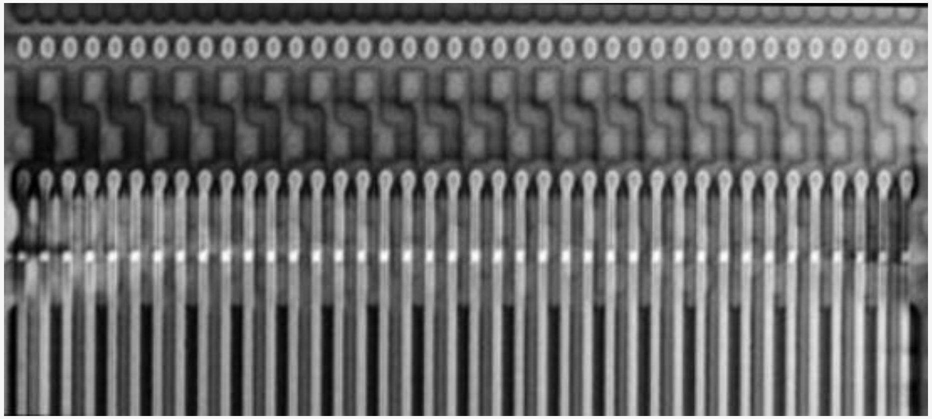
K. T. Park et al., IEEE J. Sol. State Circuits 50 (1), 204 (2015)

Logic (field-driven)



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

Memory (current-driven)

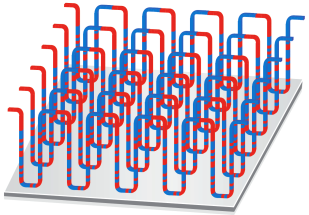


L. Thomas et al., IEEE International Electron Devices meeting (2011)

- **2D demonstrators. Competitive?**
- **3D appealing. Probably a dream with very severe bottlenecks**

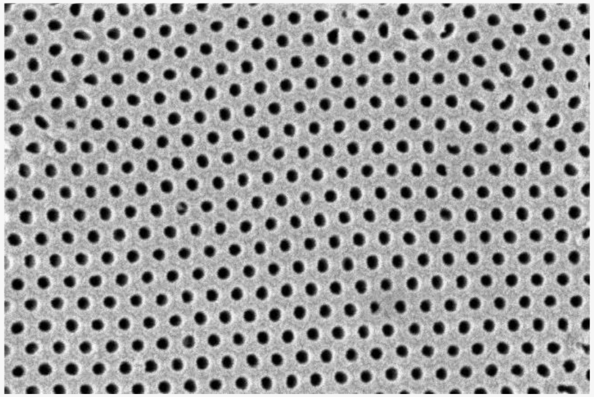
DISCUSSED SO FAR

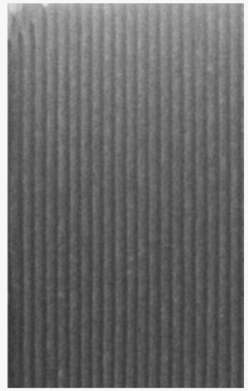
- Motivation



Synthesis strategy

- Anodization of aluminum -> template





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

- Electroplating -> Magnetic wires

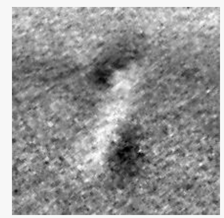
Simple metals and alloys : Co, Ni, $Fe_{20}Ni_{80}$, $Co_{20}Ni_{80}$

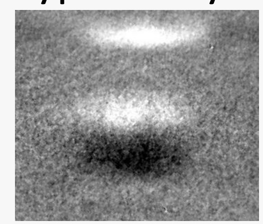
S. Da Col et al., APL 98, 112501 (2011)

Our focus: identify bottlenecks

- Synthesis: deep and structured pores

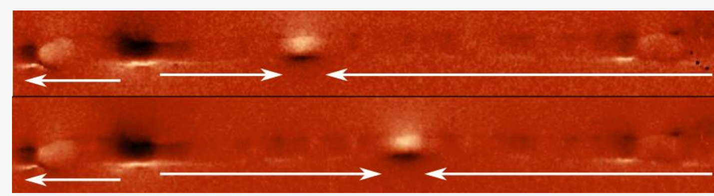
- Domain wall types in cylinders





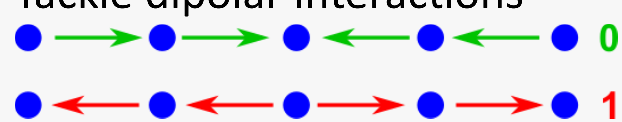
S. Da-Col et al., PRB (R) 89, 180405, (2014)

- Move domain walls

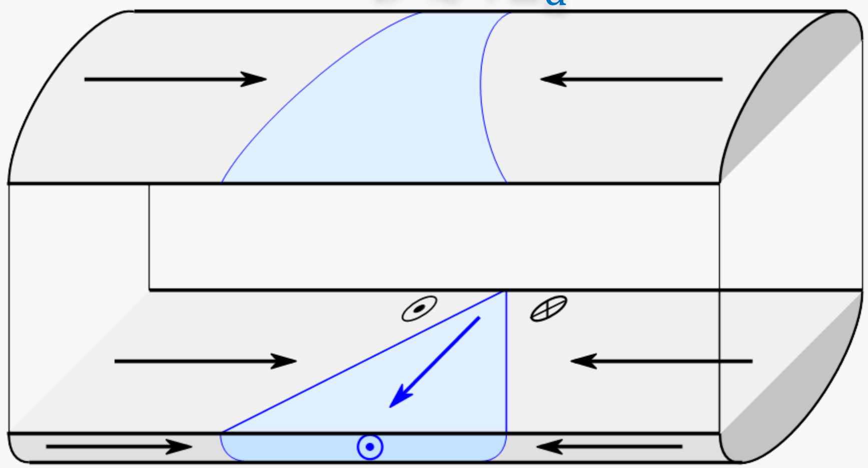


S. Da-Col et al., APL109, 062406 (2016)

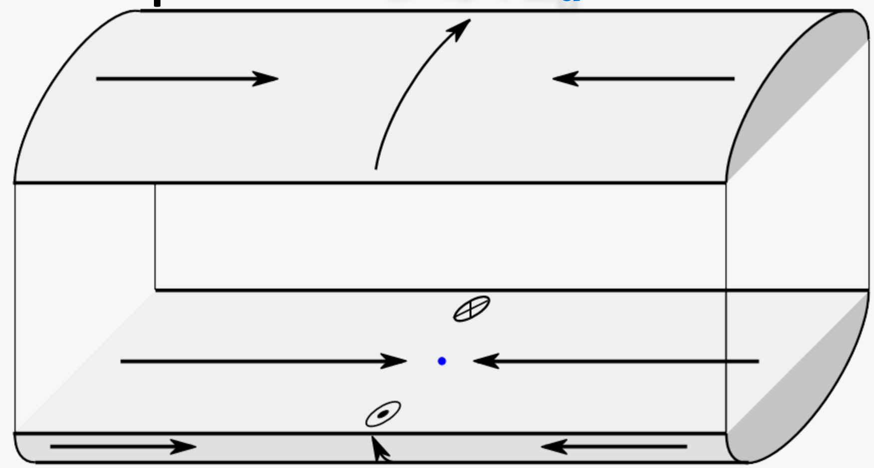
- Tackle dipolar interactions



Transverse wall $D \lesssim 7\Delta_d^2$



Bloch-point wall $D \gtrsim 7\Delta_d^2$

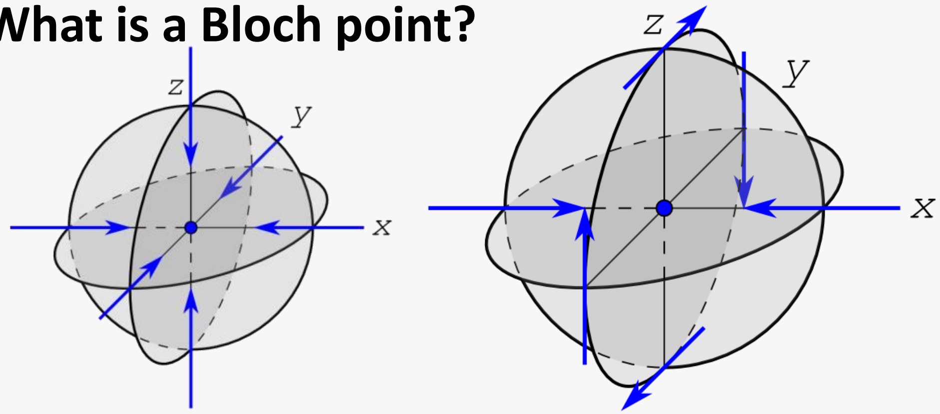


H. Forster et al., J. Appl. Phys. 91, 6914 (2002)

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

- Sometimes improperly called vortex wall

What is a Bloch point?



A magnetization texture with local cancellation of the magnetization vector

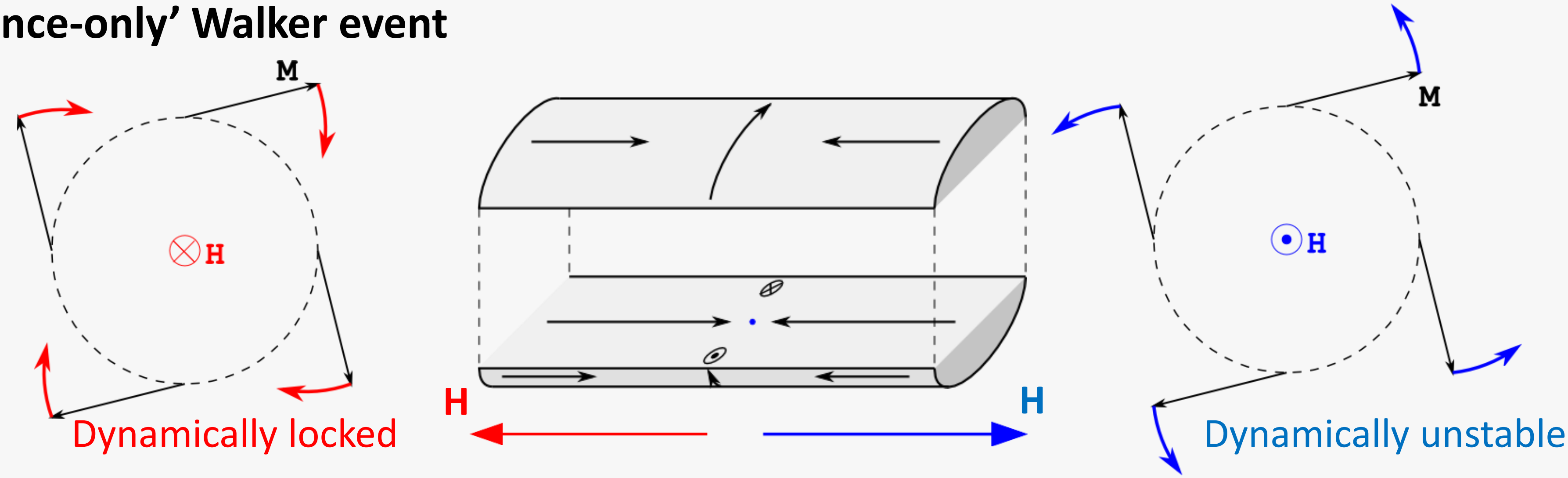
R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

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

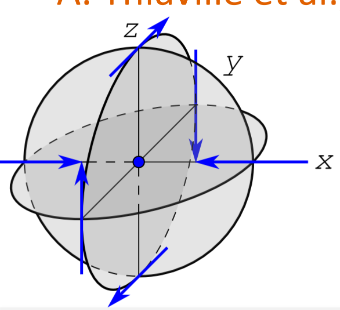
LLG equation

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

'Once-only' Walker event

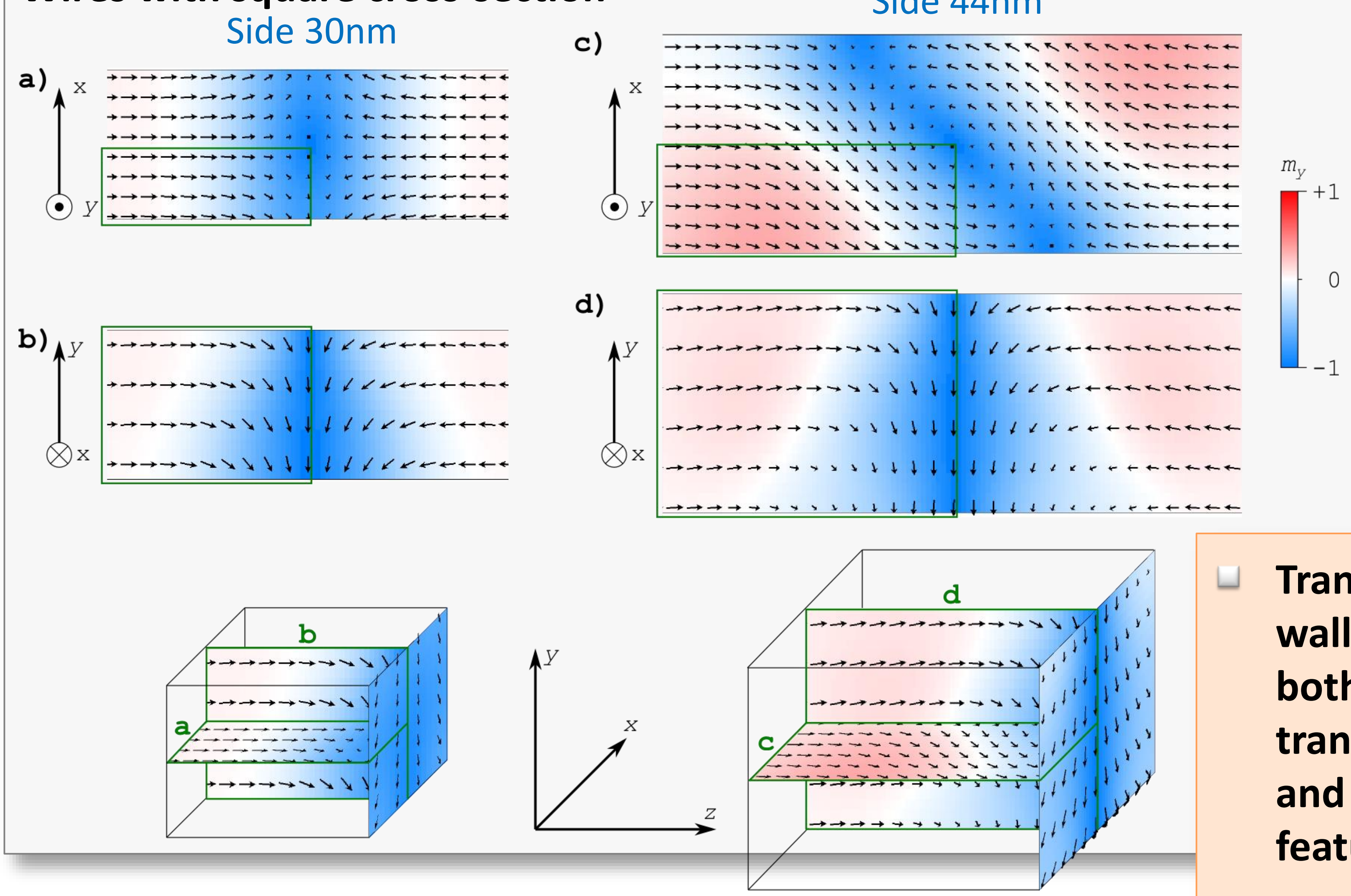


A. Thiaville et al., in Spin dynamics in confined magnetic structures III, p.161-206 (2006)



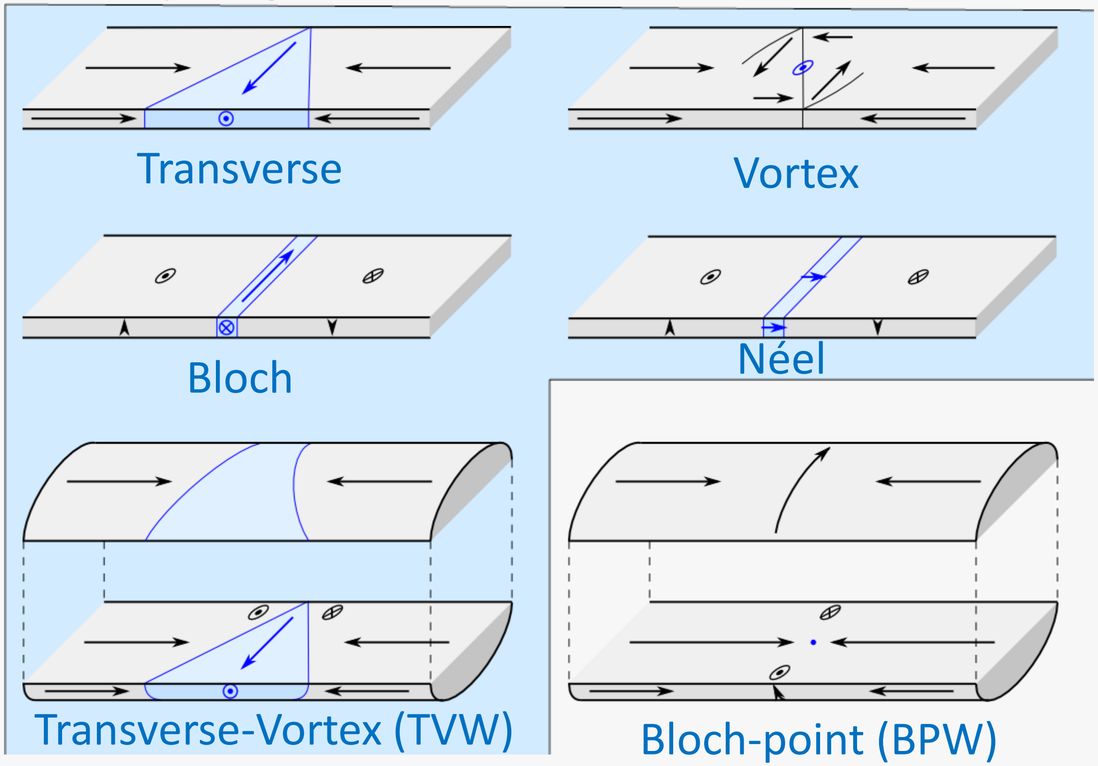
- **'Once-only' circulation Walker**
- **Right-hand rule vs direction of motion**
- **Same physics predicted (later) for tubes**

Wires with square cross-section



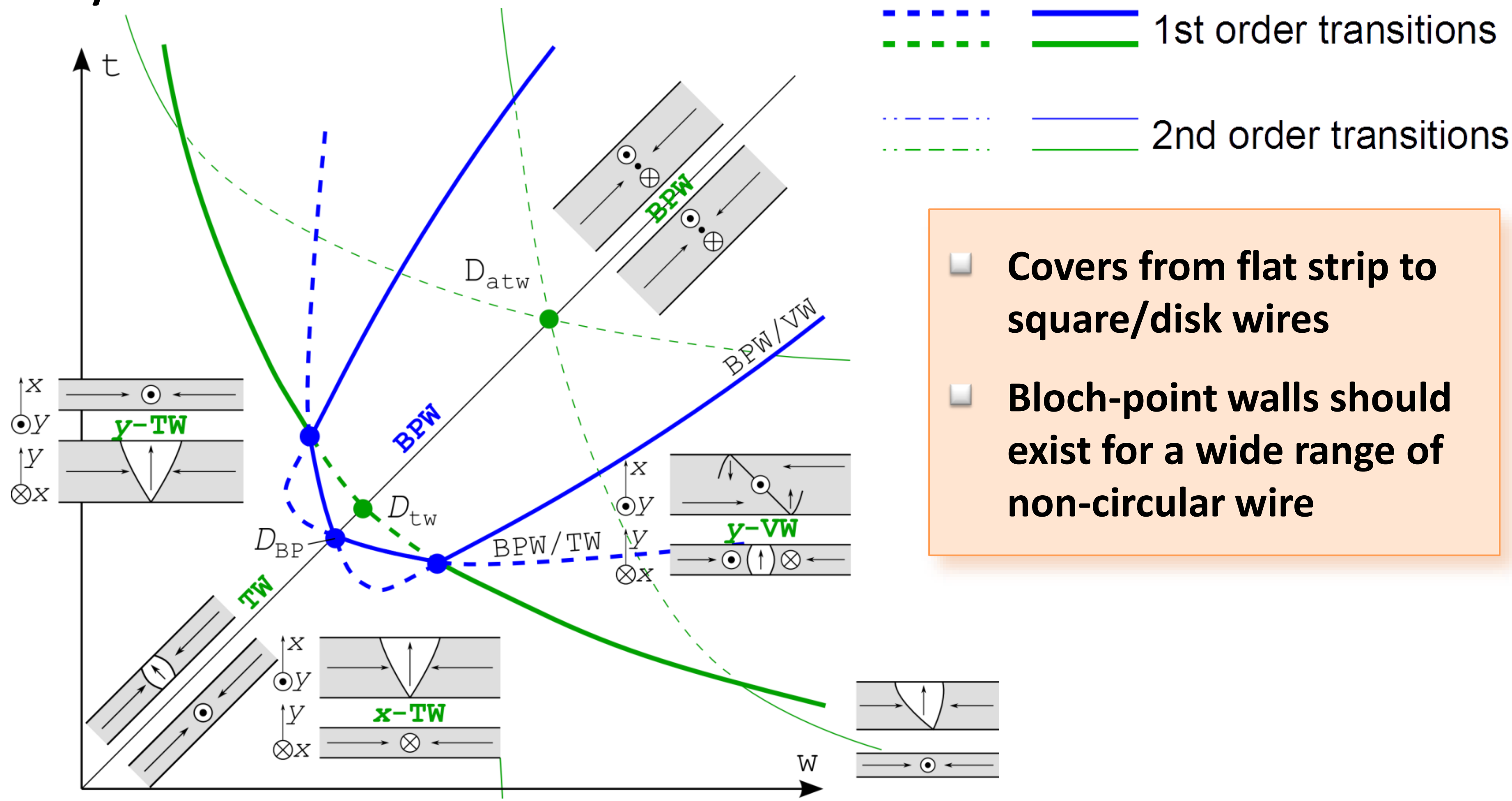
- **Transverse walls have both transverse and vortex features**

Two topologies for domain walls



- **Transverse and vortex walls share the same topology**
- **Also identical to Bloch and Néel walls for perp magnetization**
- **Walker field = changes of texture within the same family**
- **Bloch-point walls have a different topology**

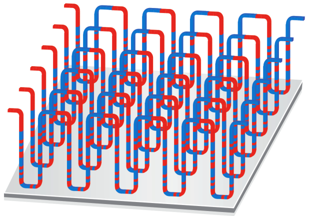
Analytics and simulation



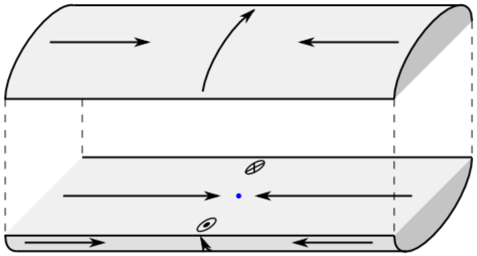
- Covers from flat strip to square/disk wires
- Bloch-point walls should exist for a wide range of non-circular wire

Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead (2015) (arXiv:1412.0679)

- Motivation



- Expectations for domain walls

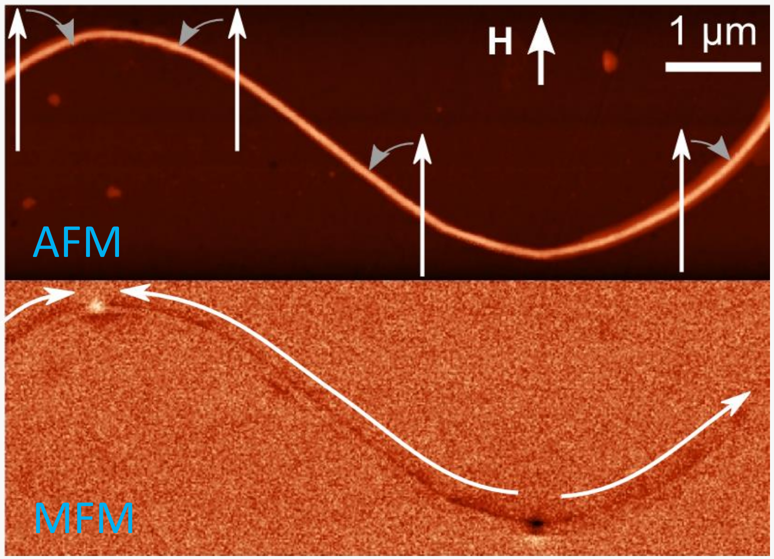


NUCLEATE DOMAIN WALLS

BOTTLENECK: how to nucleation domain walls in cylindrical wires?

Route 1: bends

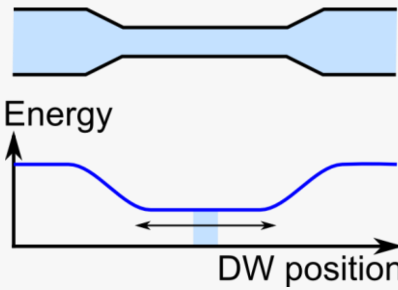
FeNi

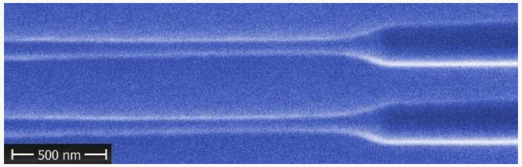


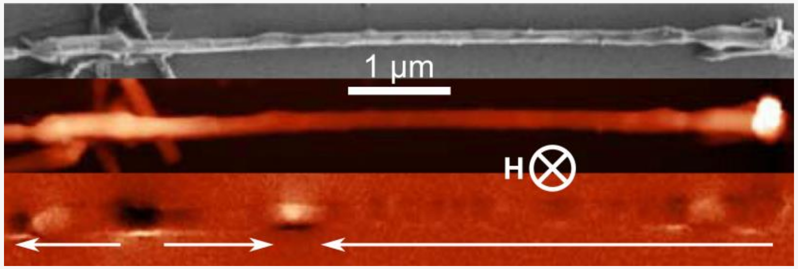
NB: similar to procedure with strips

T. Taniyama, Phys. Rev. Lett. 82, 2780 (1999)

Route 2: diameter modulations







SEM

AFM

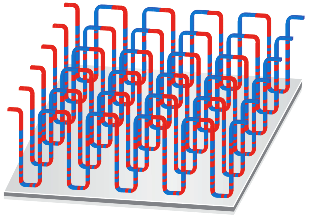
MFM

Increase of diameter induces an energy barrier for domain walls

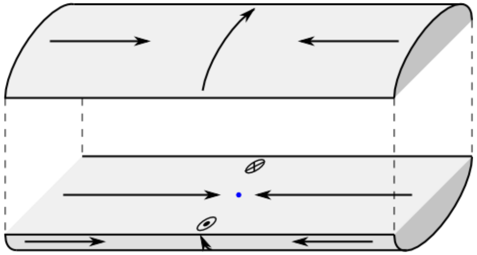
S. Da-Col et al., Appl. Phys. Lett. 109, 062406 (2016)

DISCUSSED SO FAR

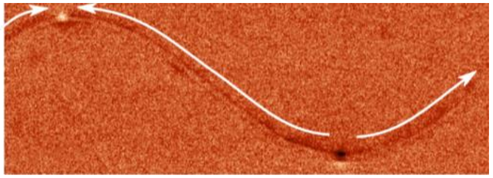
- Motivation



- Expectations for domain walls



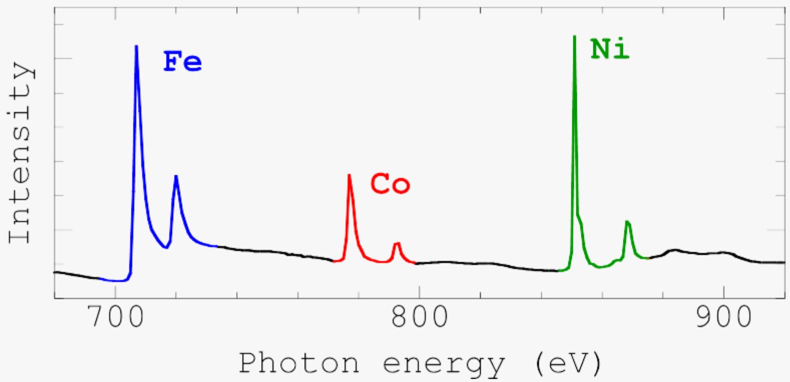
- Nucleate walls



XMCD-PEEM TECHNIQUE

X-Ray magnetic circular dichroism

- Element selectivity



- Magnetic sensitivity

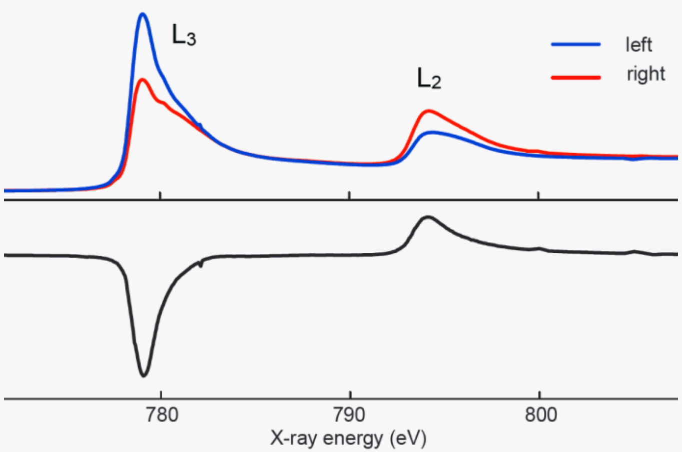
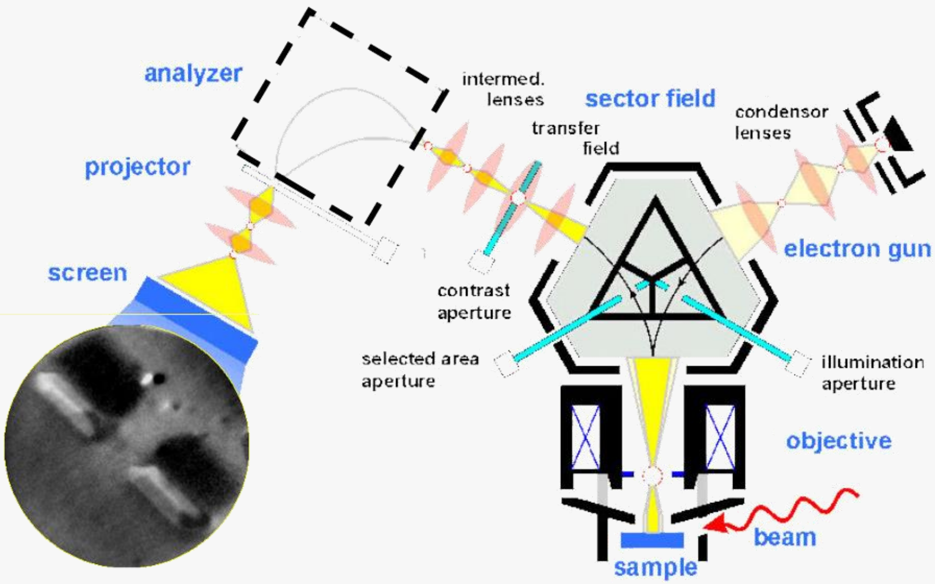


Photo-Emission Electron Microscopy



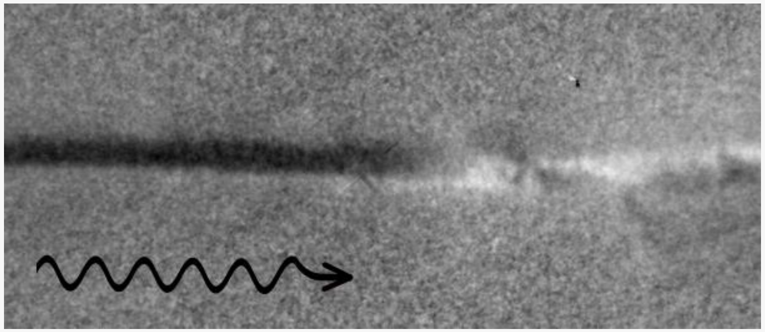
- **Synchrotron-based**
- **Secondary electrons -> surface sensitive**
- **25nm resolution in best case**

IMAGE BOTH WIRES AND SHADOW

Locate walls

FeNi

Beam along wire



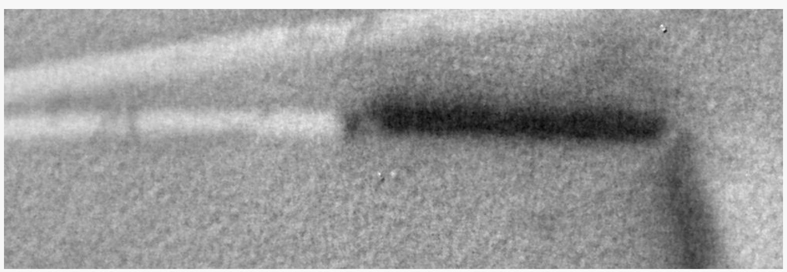
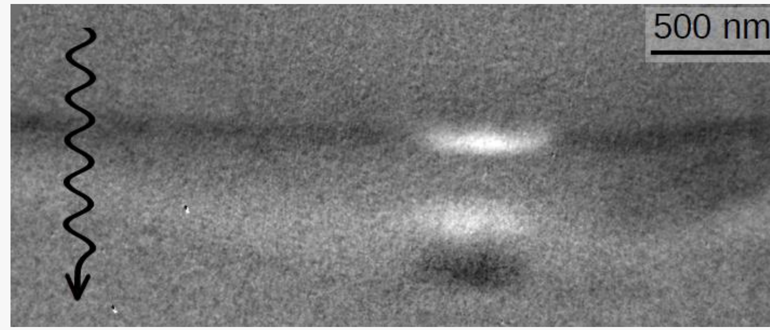
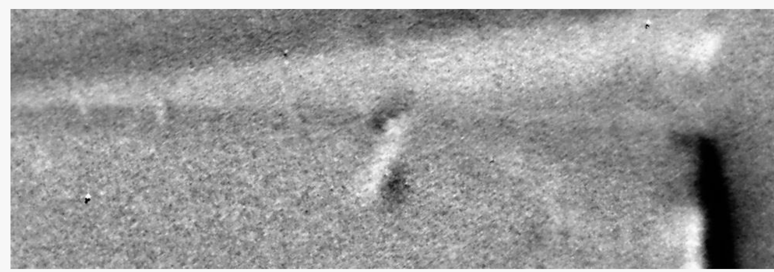


Image domain walls

FeNi

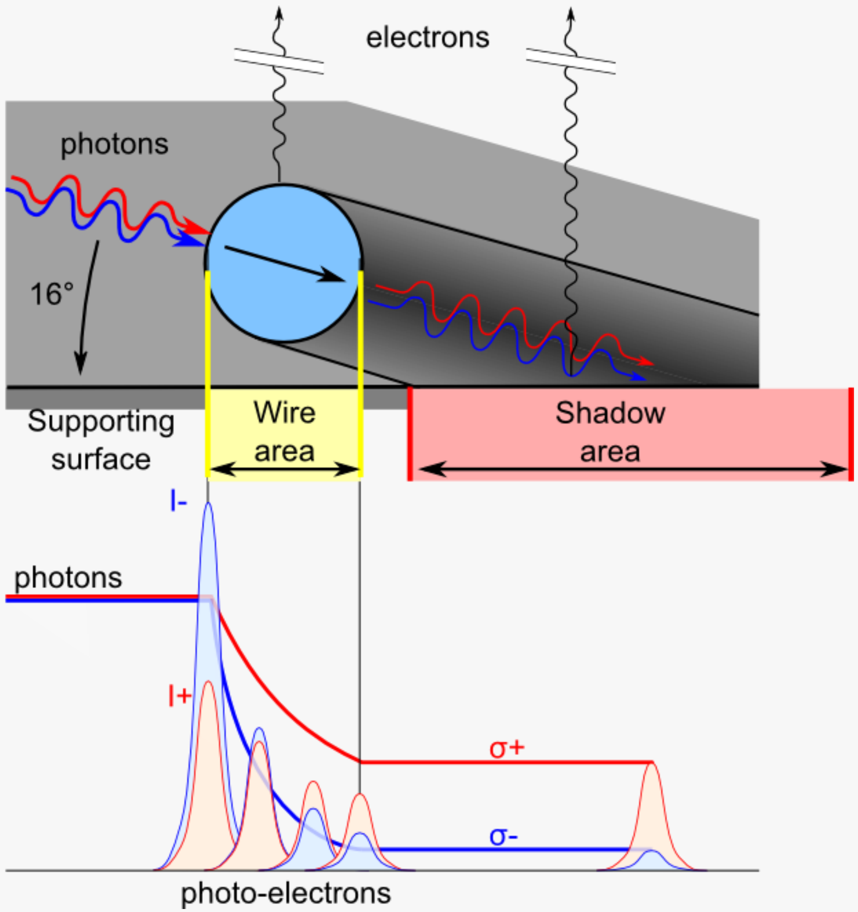
Beam across wire



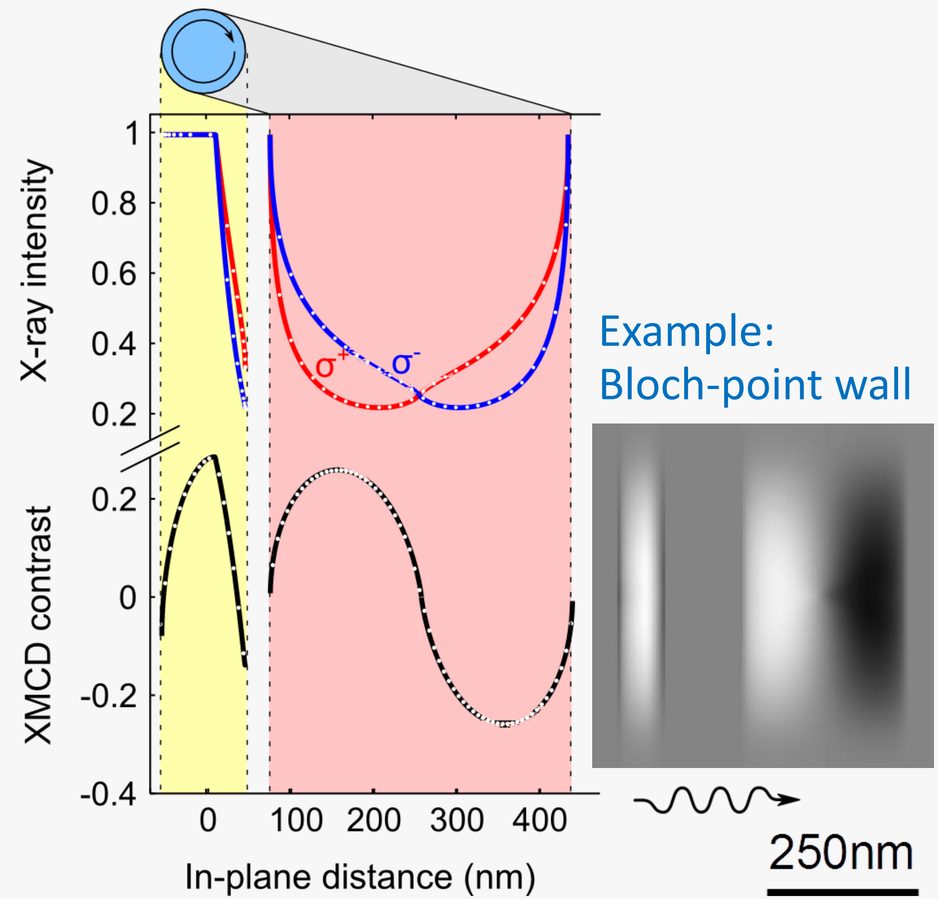


- **Non-trivial patterns**
- **Need for modeling**

SHADOW XMCD-PEEM



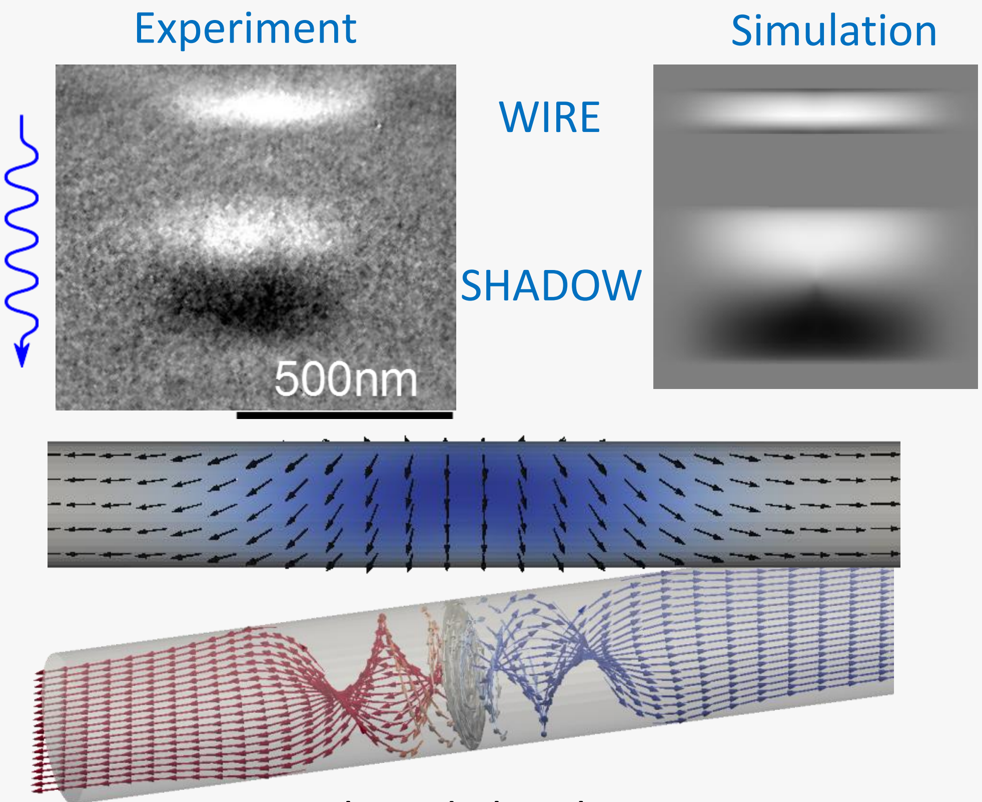
SIMULATION OF CONTRAST



S. Jamet et al., PRB92, 144428 (2015)

TWO WALL TOPOLOGIES OBSERVED

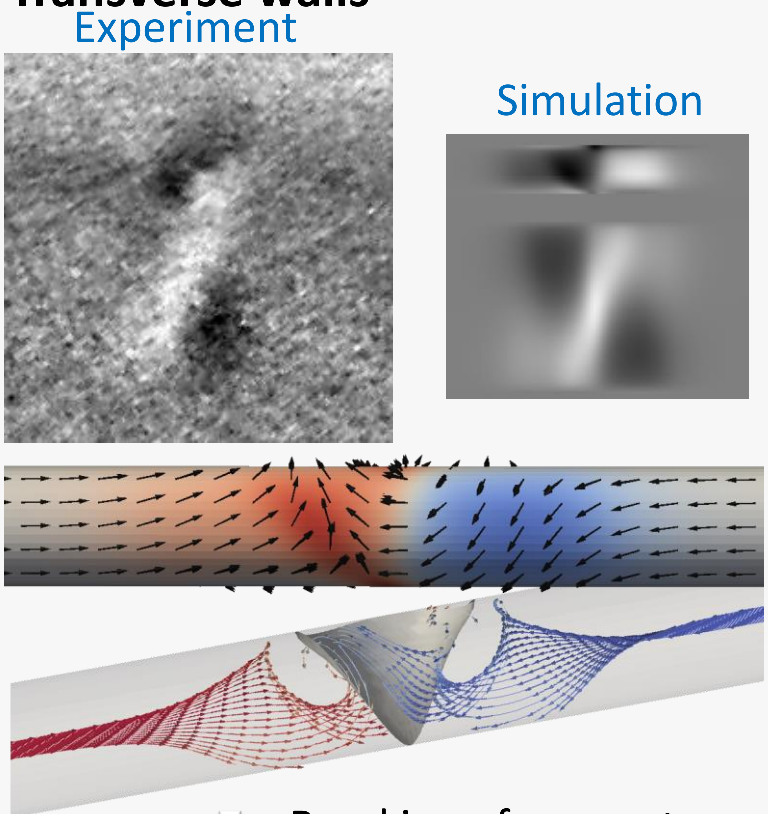
Bloch-point walls



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

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

Transverse walls

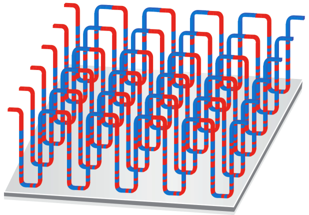


- Breaking of symmetry

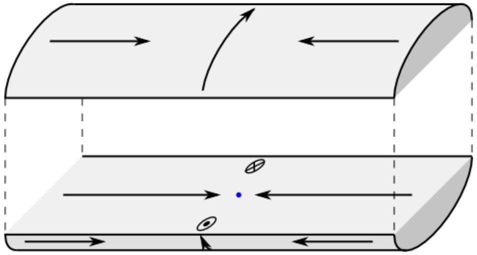
Also imaged with electron holography:

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

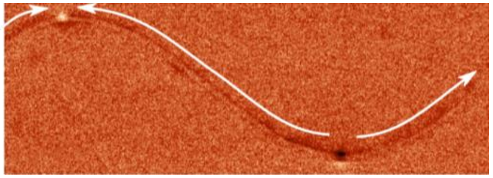
- Motivation



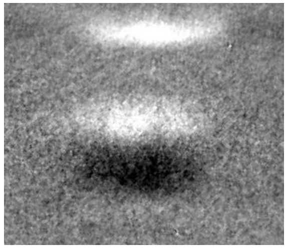
- Expectations for domain walls

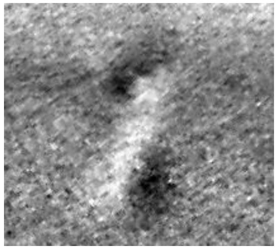


- Nucleate walls



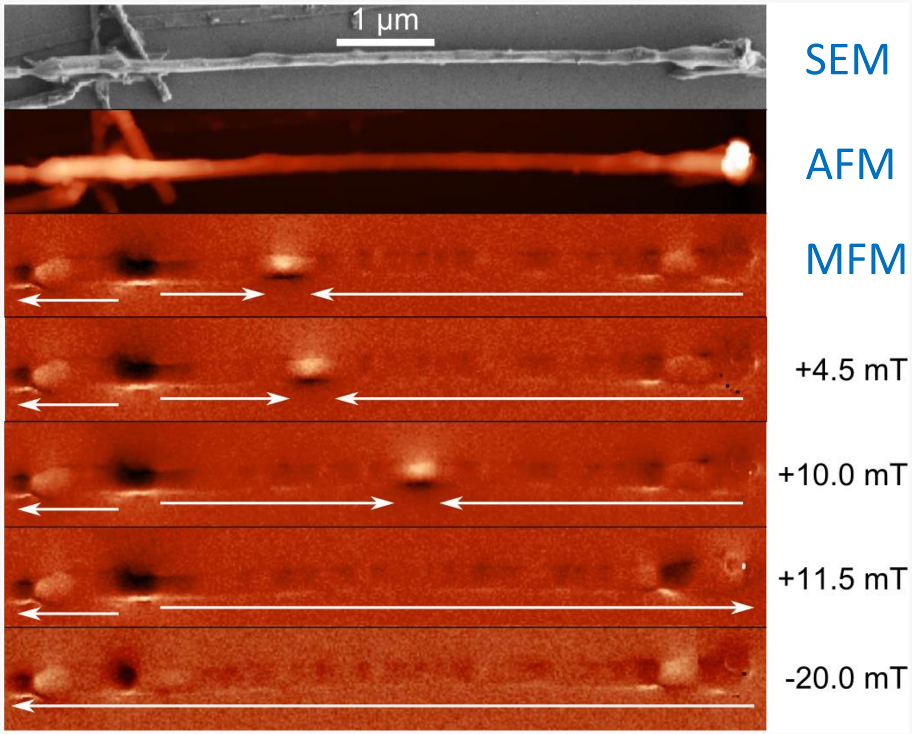
- Identify walls





Quasistatic motion

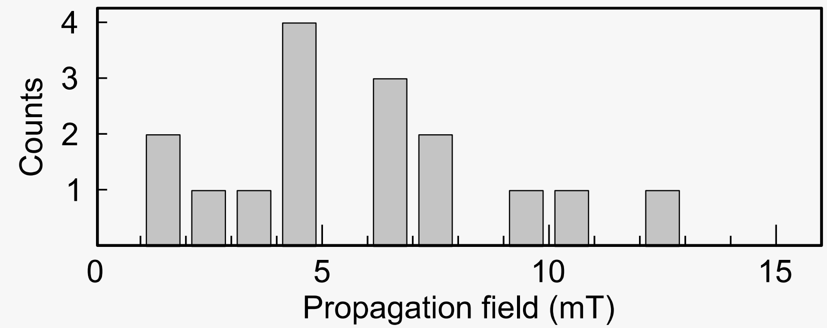
FeNi



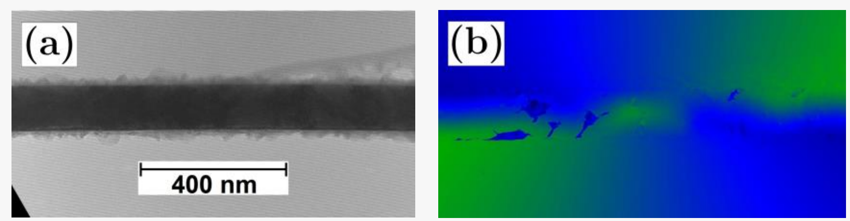
S. Da-Col et al.,
Appl. Phys. Lett. 109, 062406 (2016)

Pinning fields

- Measured distribution

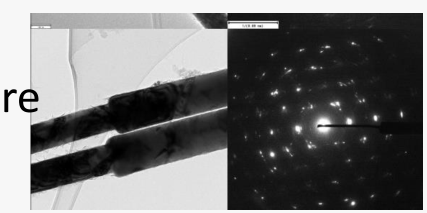


- Electron holography – No clear correlation with structure



M. Staňo et al., JMMM, submitted

- Optimization of material / structure

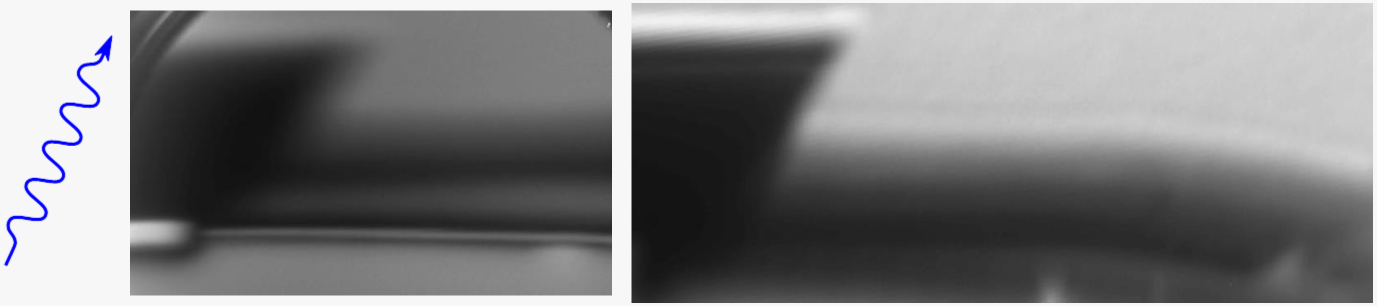


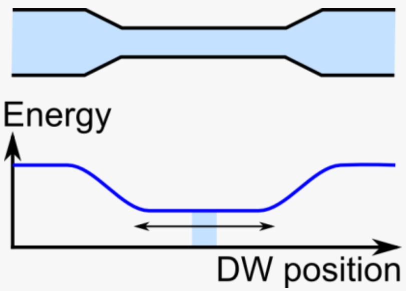
Modulated diameter to keep domain walls in wire

CoNi

Focus on wire

Focus on shadow

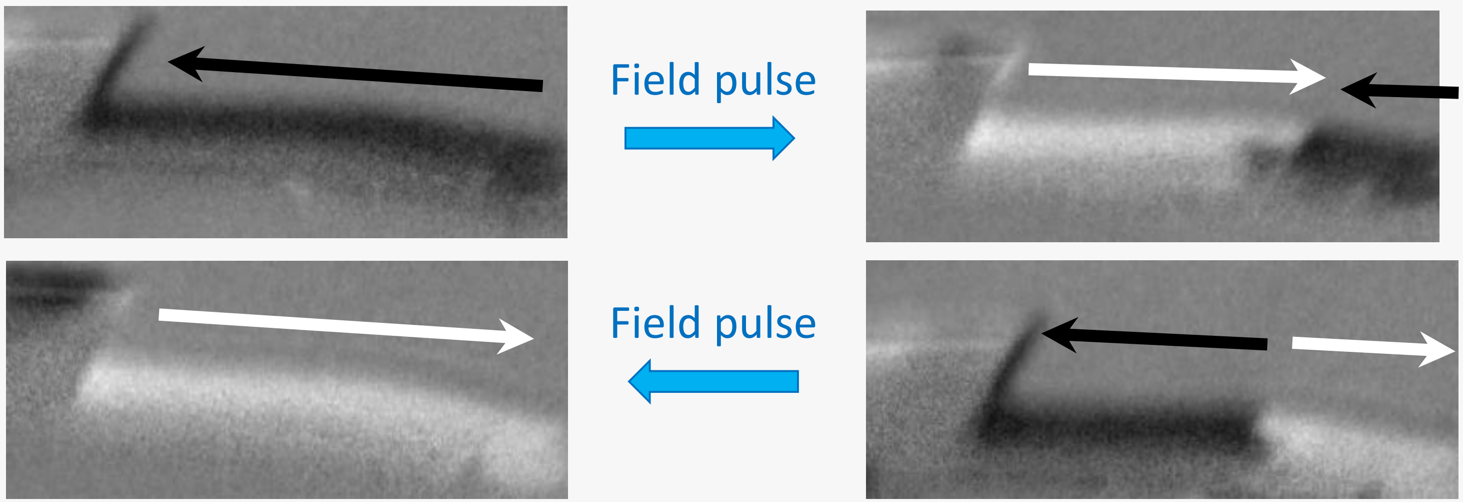




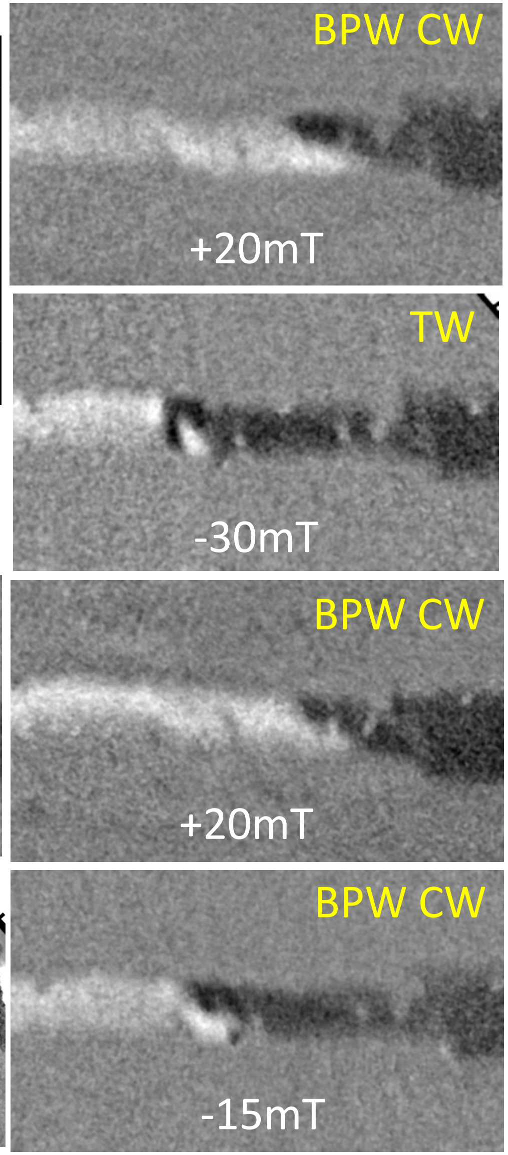
Selection of circulation (to be confirmed)

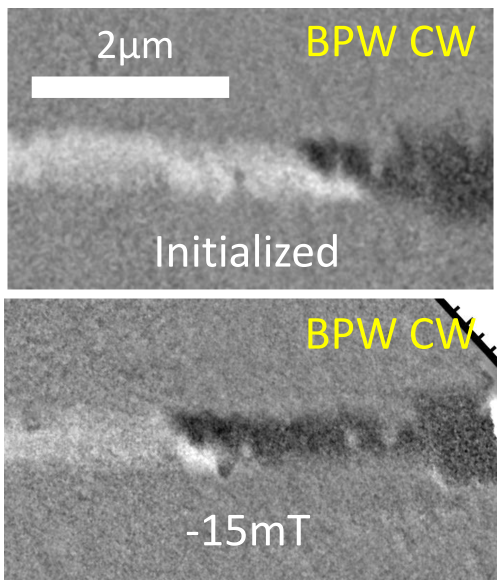
Initial

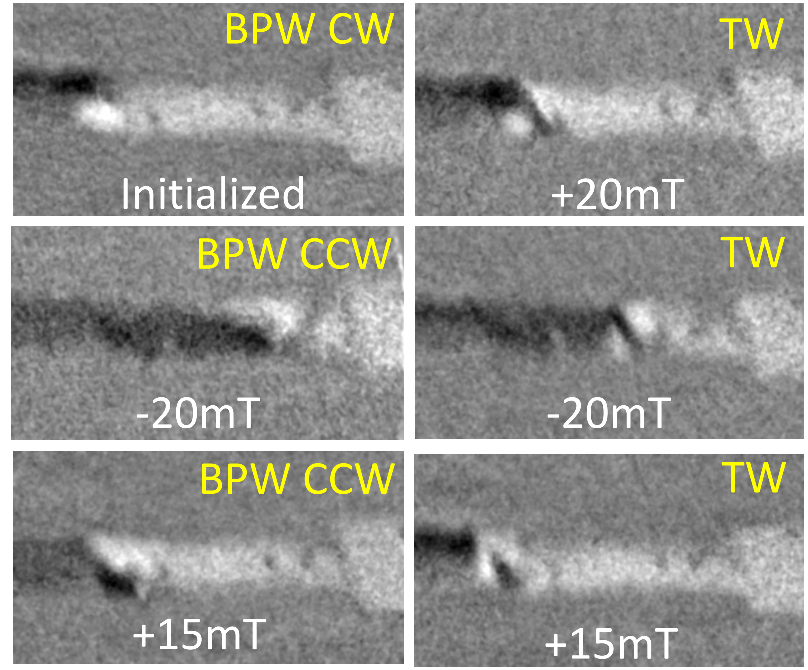
Final

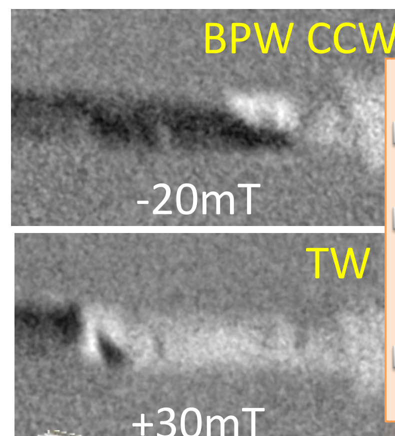


THE DARK SIDE





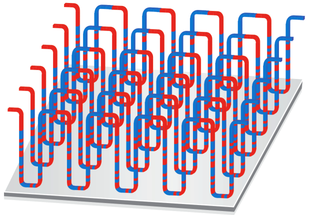




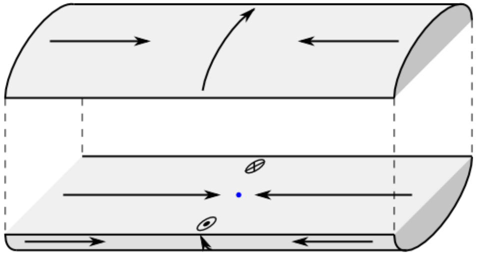
- Switch circulation
- No topological protection
- Work on material

A. Wartelle, in preparation

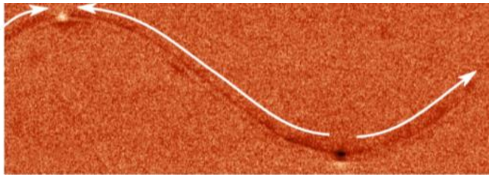
- Motivation



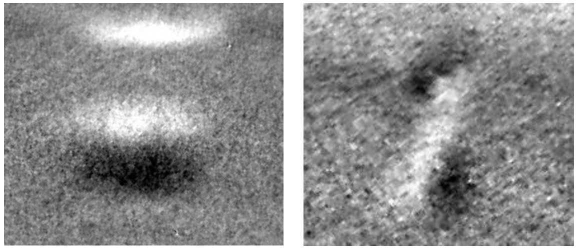
- Expectations for domain walls



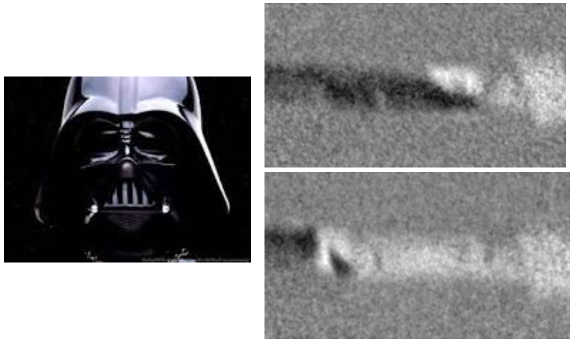
- Nucleate walls



- Identify walls



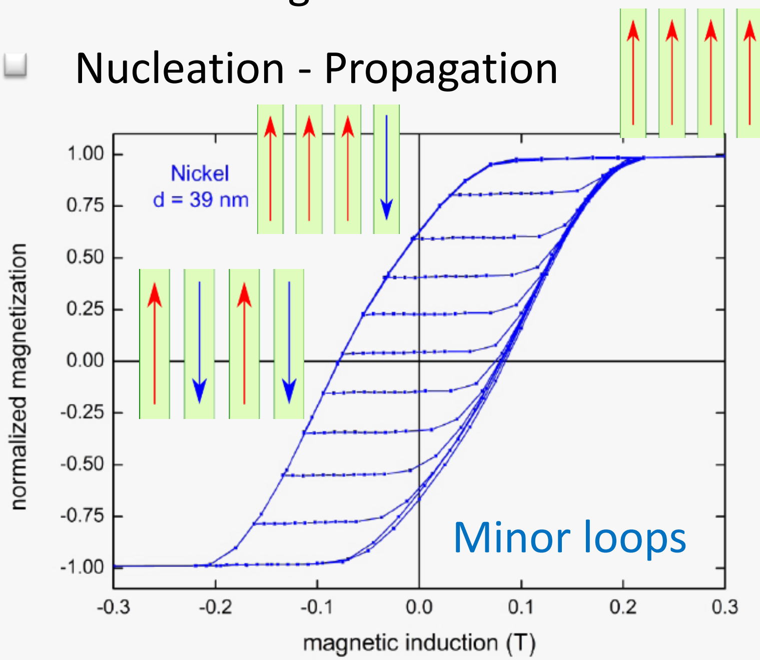
- Move walls



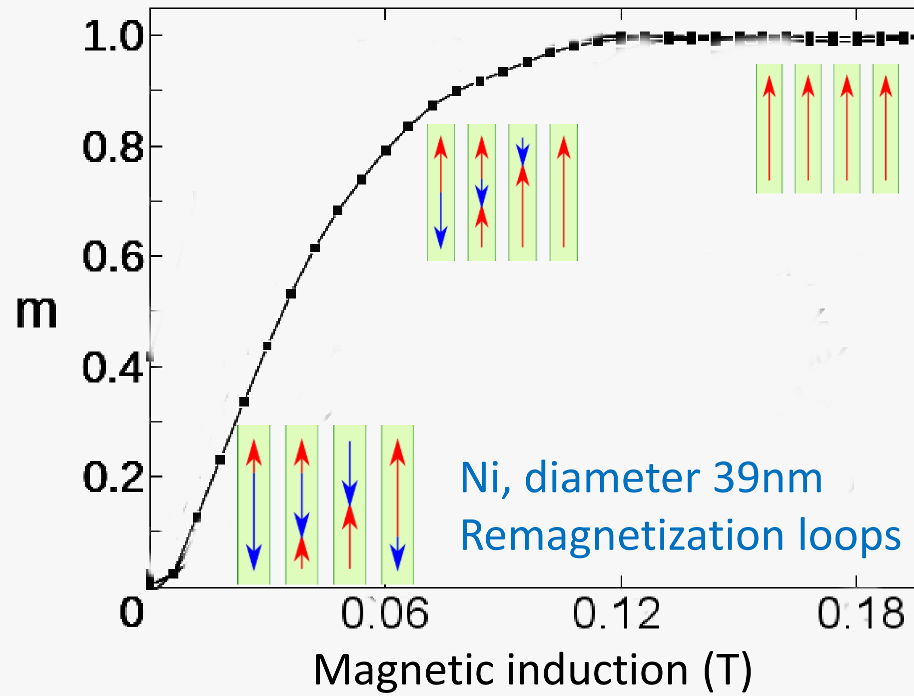
EVIDENCE DIPOLAR INTERACTIONS

Magnetization process

- Dominated by shape anisotropy for soft magnetic materials
- Nucleation - Propagation



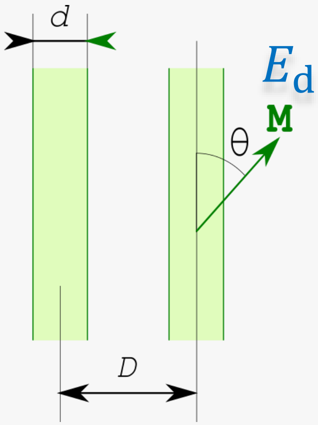
Applies to remagnetization with wall motion



- **Shear largely dominated by inter-wire dipolar interactions**
  -> Cross-talk

- **Solutions are needed to avoid cross-talk**

Shear related to demagnetization factor

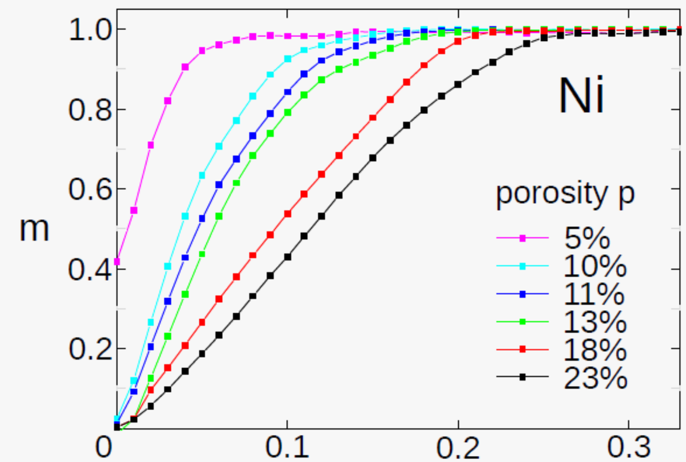


$$E_\mathrm{d} = \frac{1}{2}\mu_0 M_s^2 \left(\frac{3p-1}{2}\right)\cos^2\theta$$

Matrix porosity: $p = \frac{\pi}{2\sqrt{3}}\left(\frac{d}{D}\right)^2$

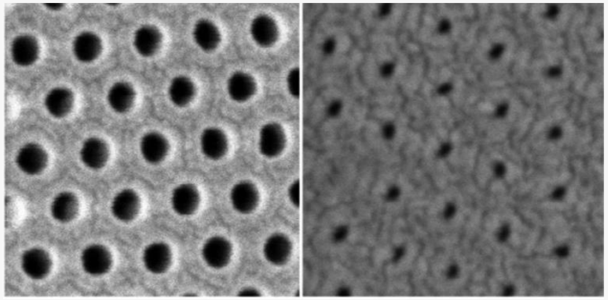
A. Encinas-Oropesa et al., PRB 63, 104415 (2001)

Application to domain walls



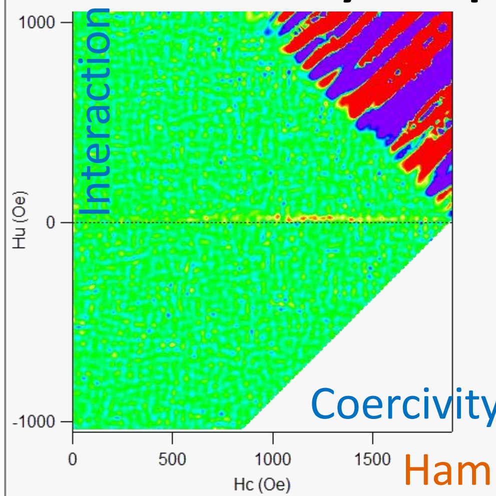
Reduce porosity

- Apply atomic layer deposition to reduce inner diameter at constant pitch



S. Da Col et al., APL 98, 112501 (2011)

Scalable to very low porosity



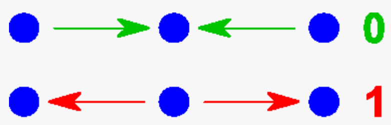
$p = 0.3\%$

FORC measurements

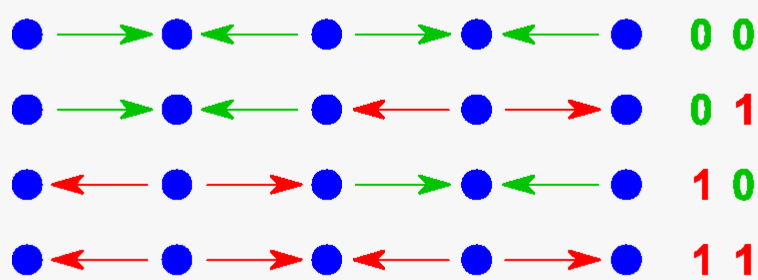
Coll. Univ. Hamburg & Erlangen

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

- Basic building block with zero moment



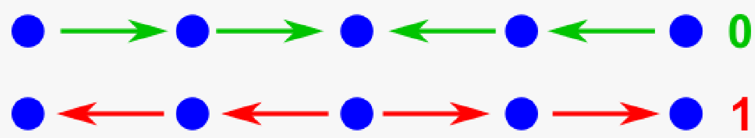
- Here: one bit per two physical sites
- Example, two bits:



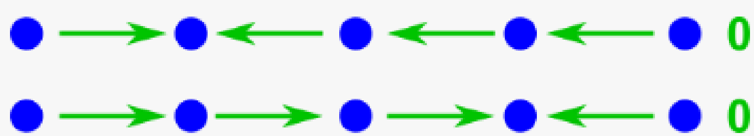
$4 = 2^2$ states

4 sites per two bits

Can be extended to fault-tolerant coding



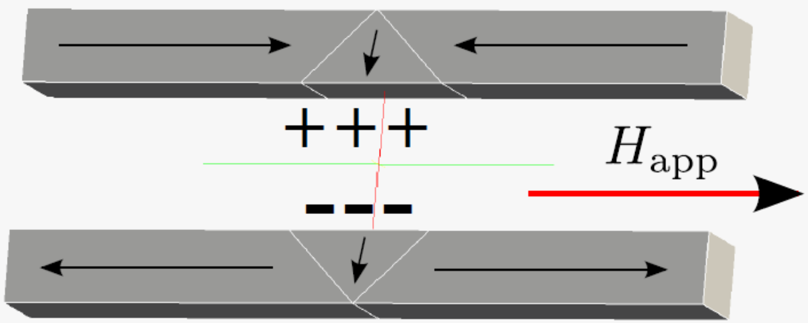
- The transition and its polarity are not lost if a DW is not shifted, or shifter twice



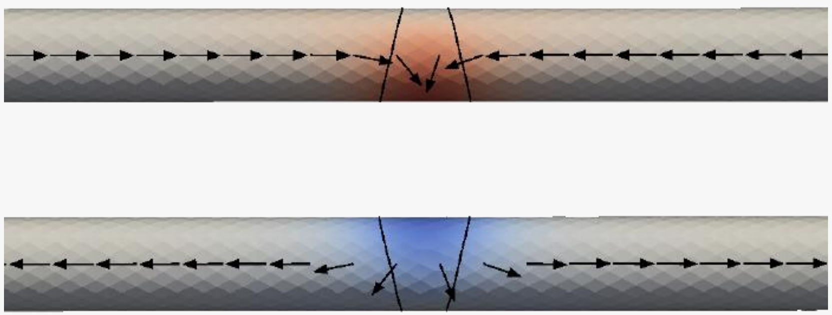
- **Hardware solution not necessary for global interaction. But…**

Intra-wire and inter-wire interactions remain between neighboring domain walls

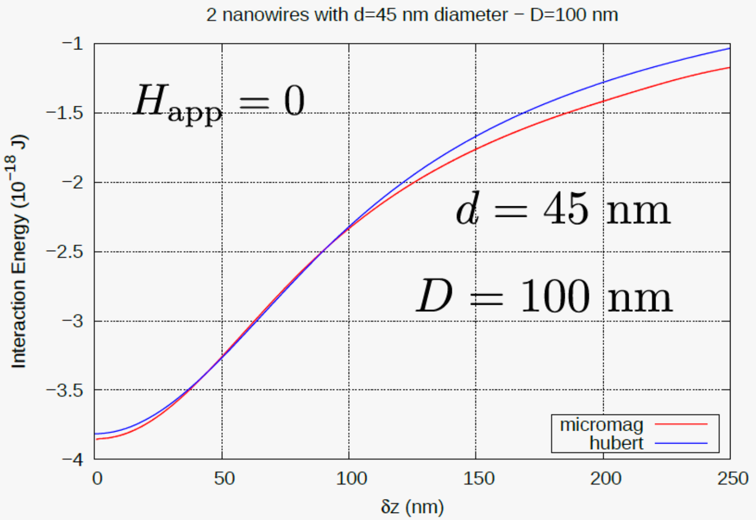
Analytical modeling



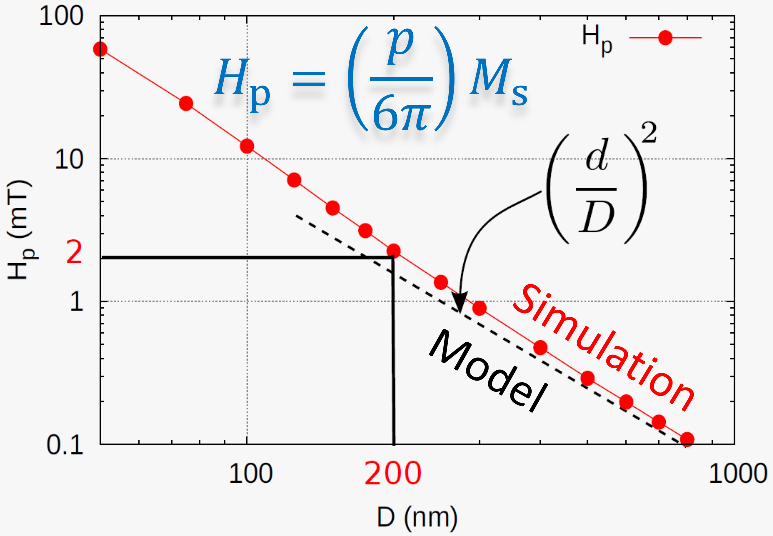
Micromagnetic simulations



Interaction energy



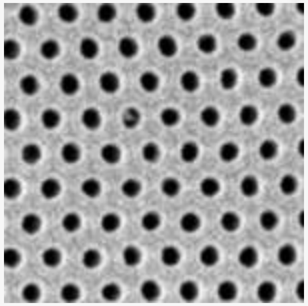
Scaling law for interaction field



Simple discussion based on inter-wire interaction

- One neighbor:

$$H_d = \left(\frac{p}{6\pi}\right) M_s \qquad p = \frac{\pi}{2\sqrt{3}}\left(\frac{d}{D}\right)^2$$



- Six neighbors:

$$H_d = \left(\frac{p}{\pi}\right) M_d$$

Longer range: each bit seen as a quadrupole

- Field due to dipole: $H_\mu \approx \frac{1}{4\pi R^3}\frac{\pi d^2}{4}\lambda M_S$
- Field due to quadrupole: $H_Q \approx \frac{3}{16}\frac{d^2\lambda^2}{R^4} M_S$
- Upper bound for integrated quadrupoles: $H_d \approx 3\pi p M_S$

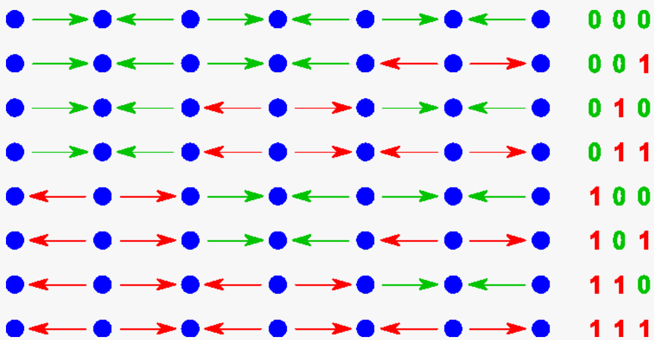
- **Still, hardware reduction of porosity is important**

Underway

- **Counting all possible states**
- **Provide exact number for interaction field**
- **Highlight distribution tails and rare configurations**

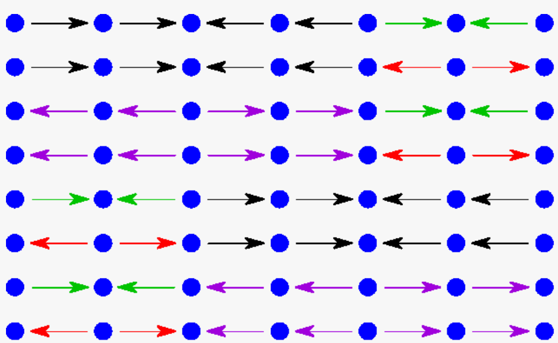
REFINED CODING ALGORITHMS

Example of zero-moment states not covered



$8 = 2^3$ states

⇒ 6 sites per three bits



⇒ Extra 8 states per 6 sites

- 6 sites per 4 bits
- 1.5 sites per bit

O. Fruchart, in preparation

Generalization

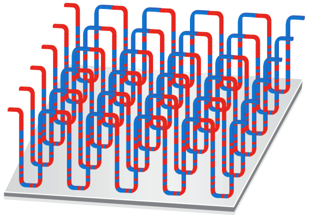
Number of bits per site for ℓ sites

$$n_{\mathrm{bps}} = \frac{\ln(N_{\mathrm{states}})}{\ell \ln 2}$$

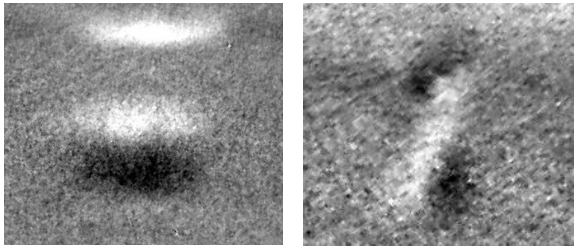
- **May increase quadrupolar cross-talk**
- **Makes the counting algorithm important**

DISCUSSED TODAY

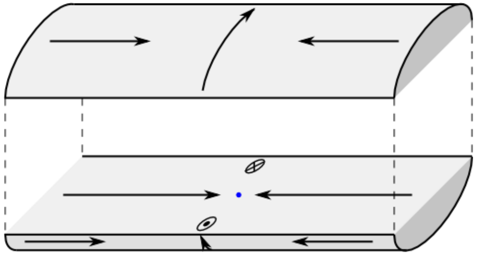
- Motivation



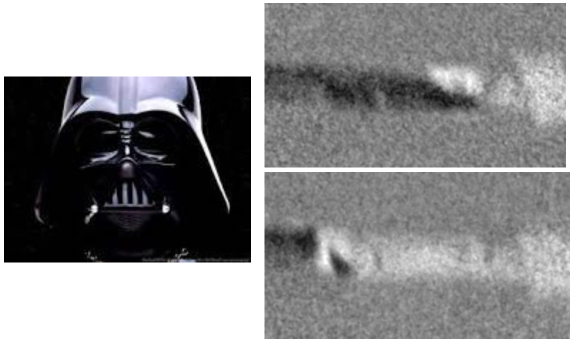
- Identify walls



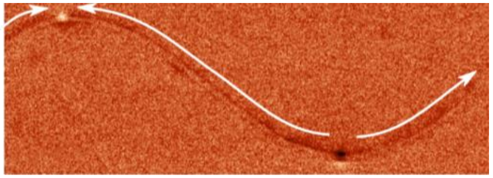
- Expectations for domain walls



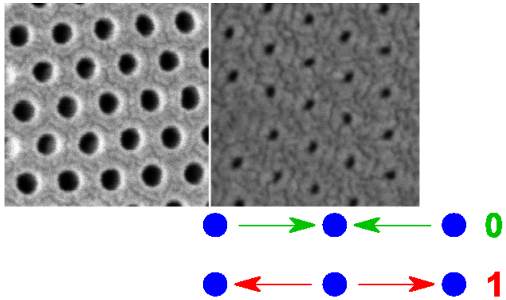
- Move walls



- Nucleate walls



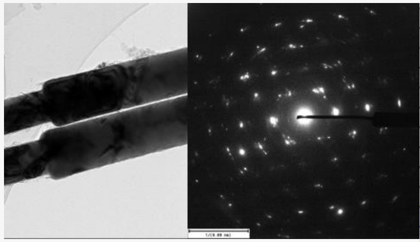
- Reduce interactions

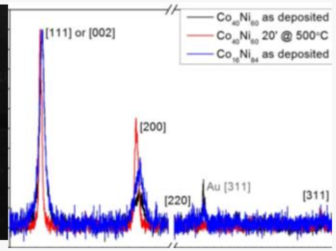


WORK UNDER WAY

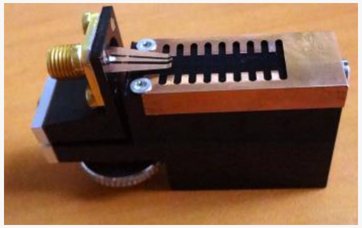
Physics of wall motion

- Material science – Reduce defects



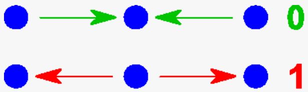


- Determine wall mobility

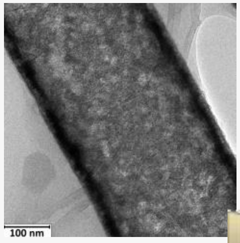


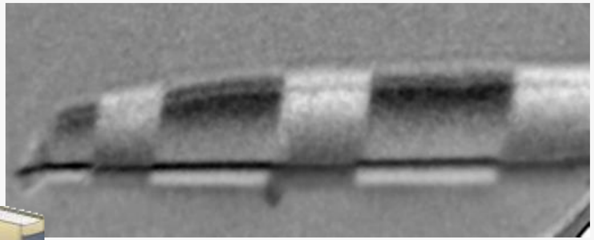
Reduce interaction

- Determine best algorithm



- New routes – Flux-closure nanotubes

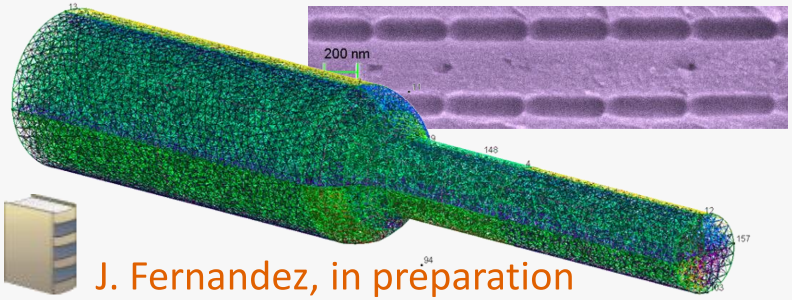




M. Stano, in preparation

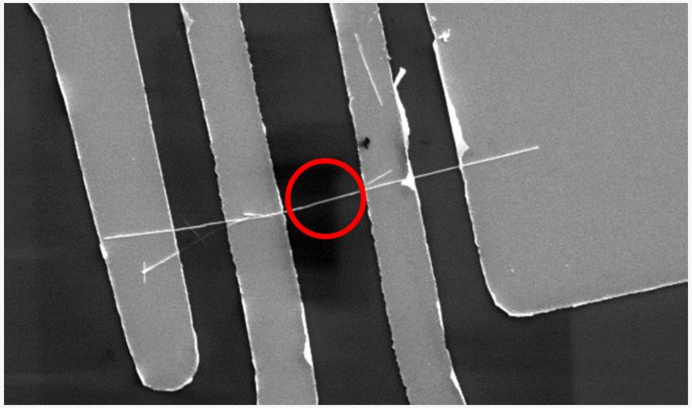
Walls in segments

- Develop robust clocking schemes



J. Fernandez, in preparation

Move towards spintronics



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Thank you for your attention !

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email: olivier.fruchart@cea.fr

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