Dynamics of magnetic domain wall motion in cylindrical nanowires

O. Fruchart [1]

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

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

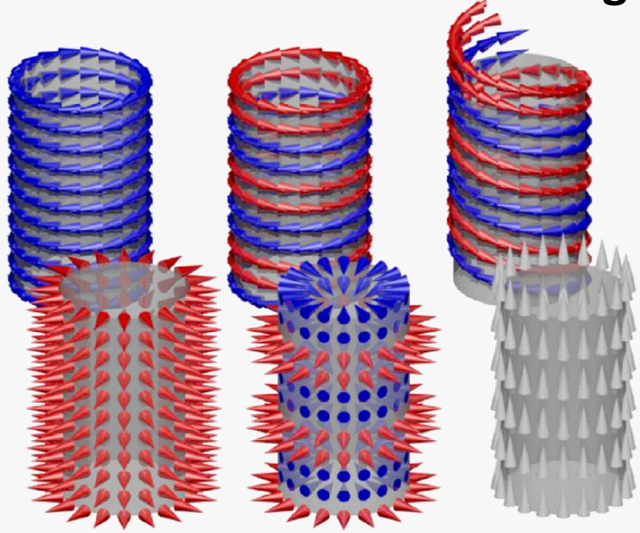
www.spintec.fr

email: olivier.fruchart@cea.fr

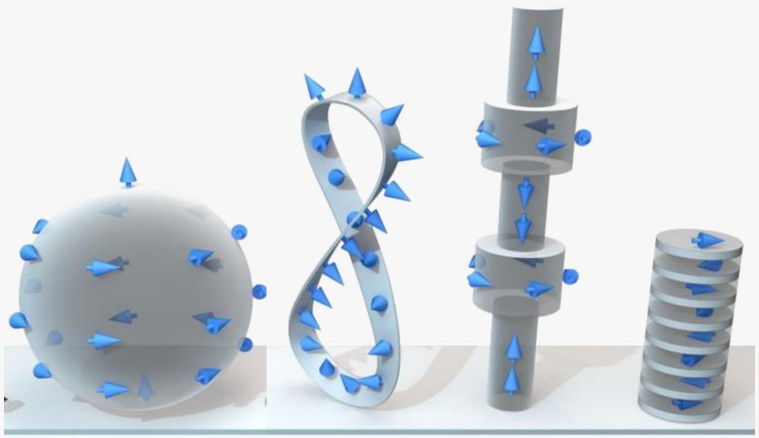
Slides: http://fruchart.eu/slides

Curvilinear magnetism – Київ, Україна – 23-24 May 2019

Fundamentals: curved and 3D magnetism

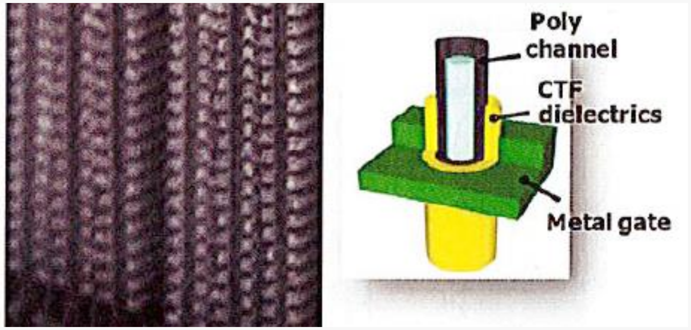


R. Streubel, J.Phys.D: Appl.Phys. 49, 363001 (2016)



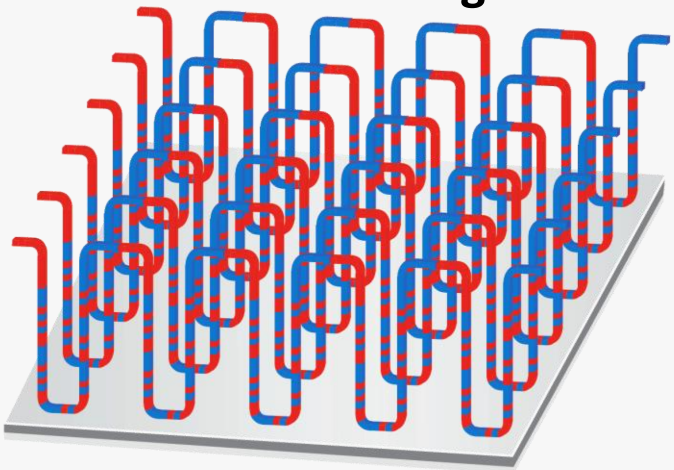
A. Fernandez-Pacheco, Nat. Comm. 8, 15756 (2017)

Note: 3D devices make the decision!



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

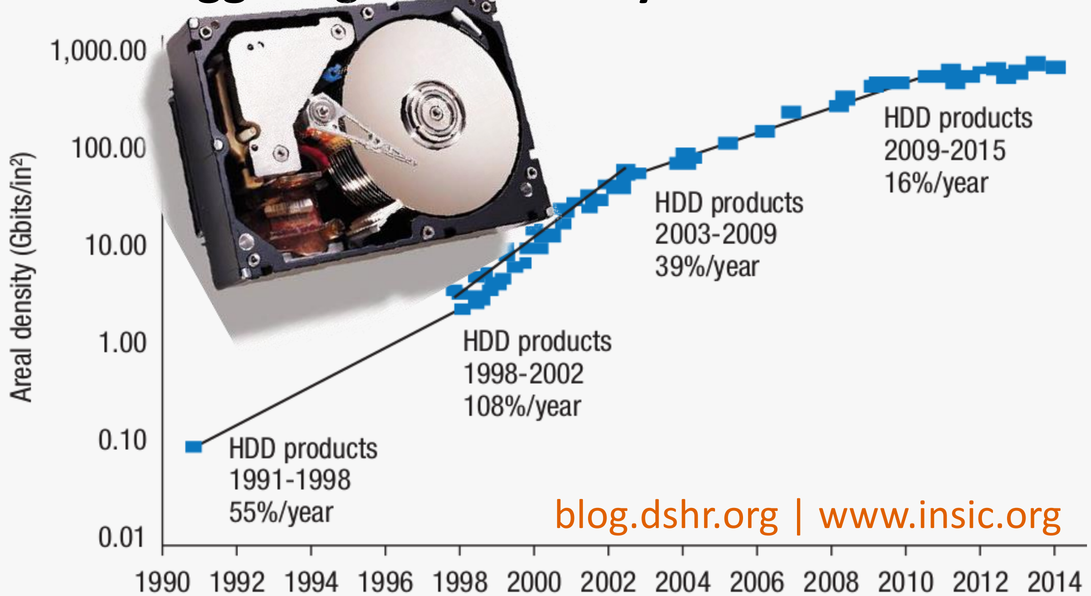
Dreams for a 3D storage device



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

MASS STORAGE DEVICES: areal storage

HDD: staggering areal density



blog.dshr.org | www.insic.org

Technologies go 3D

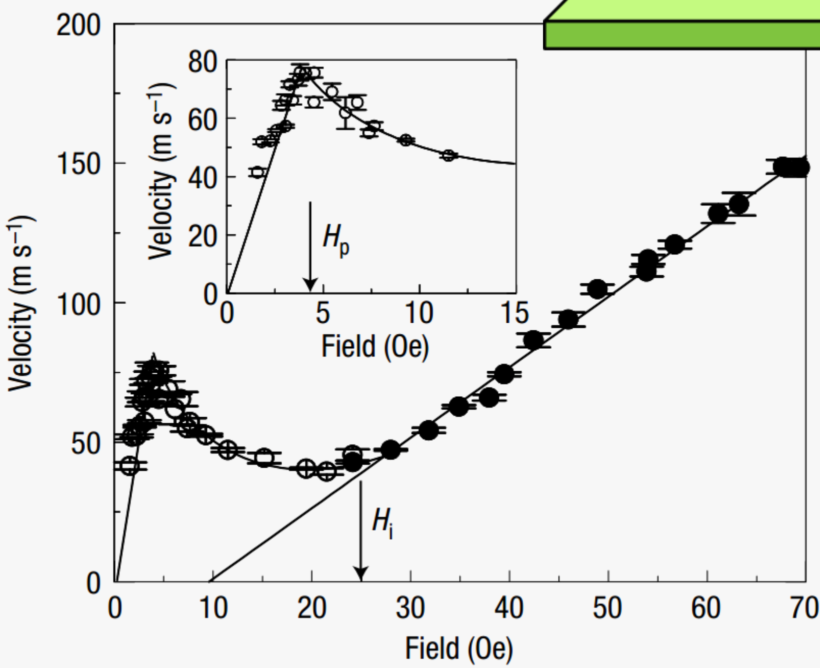
24-layer 3D NAND Flash

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

HDD vs Flash Cross-over in 2016

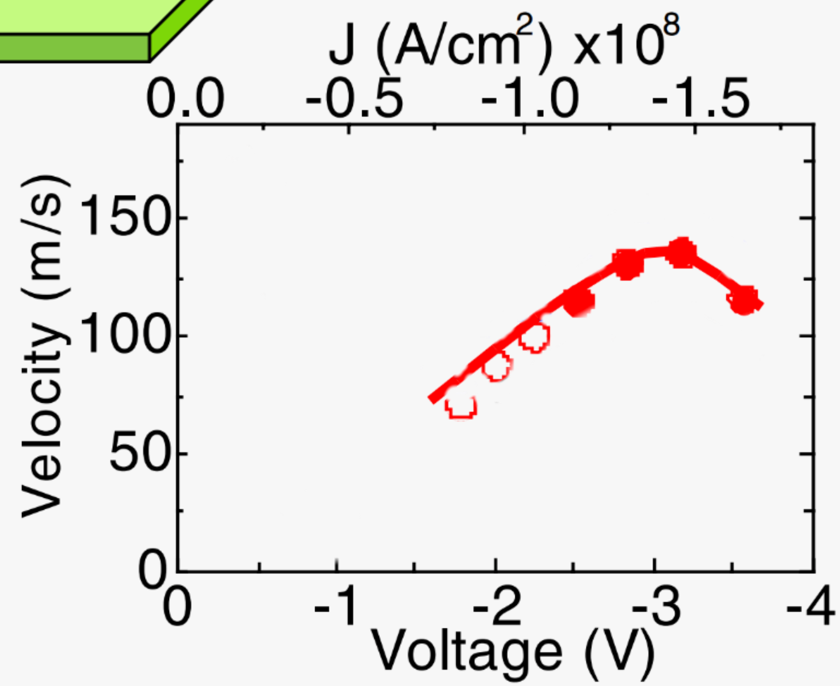
- **1Gb/mm2 → 600Gb/in2...**
- **Magnetic mass storage may only remain for niche applications**

Field-driven case



G. S. D. Beach et al., Nat. Mater 4, 741 (2005)

Current-driven case

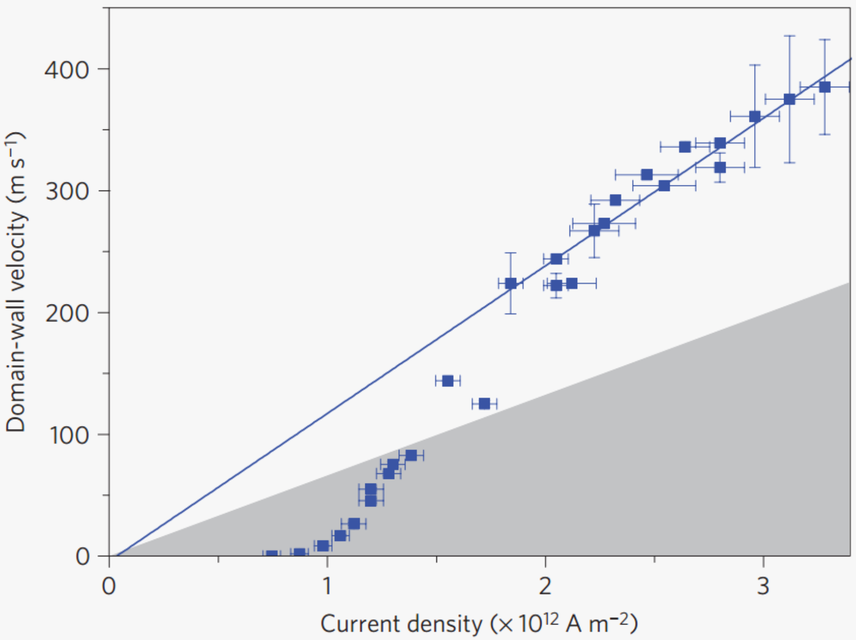


M. Hayashi et al., PRL 98, 037204 (2007)

- Physics: dynamic transformation of domain walls
- Average speed does not exceed much 100 m/s

Beating Walker with special materials

Dzyaloshinskii-Moriya interaction + Spin-Hall currents

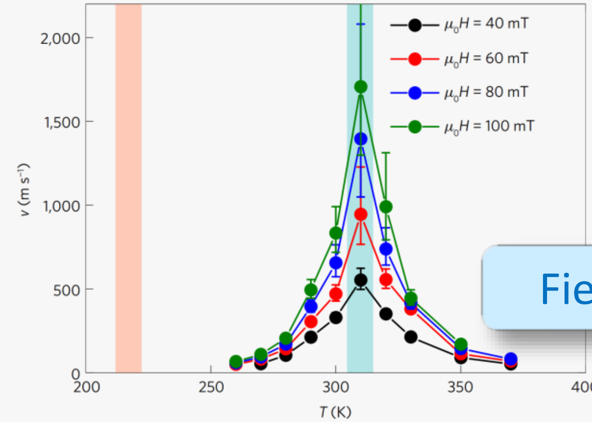


I.. M. Miron et al., Nat. Mater. 10, 419 (2011)

A. Thiaville et al., EPL100, 57002 (2012)

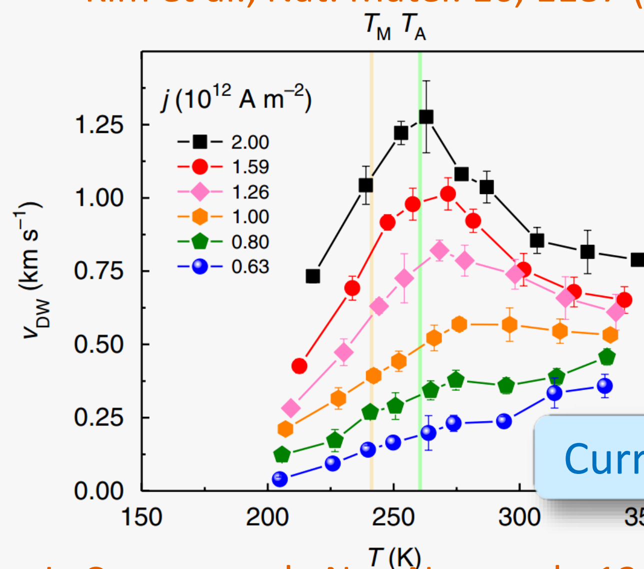
Is direct spin-transfer in ferromagnets not compatible with fast DW motion?

Ferrimagnetic materials



Field-driven

Kim et al., Nat. Mater. 16, 1187 (2017)

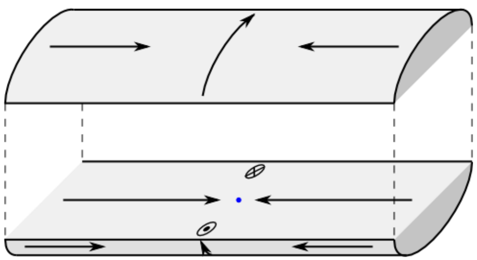


Current-driven

L. Caretta et al., Nat. Nanotech. 13, 1154, (2018)

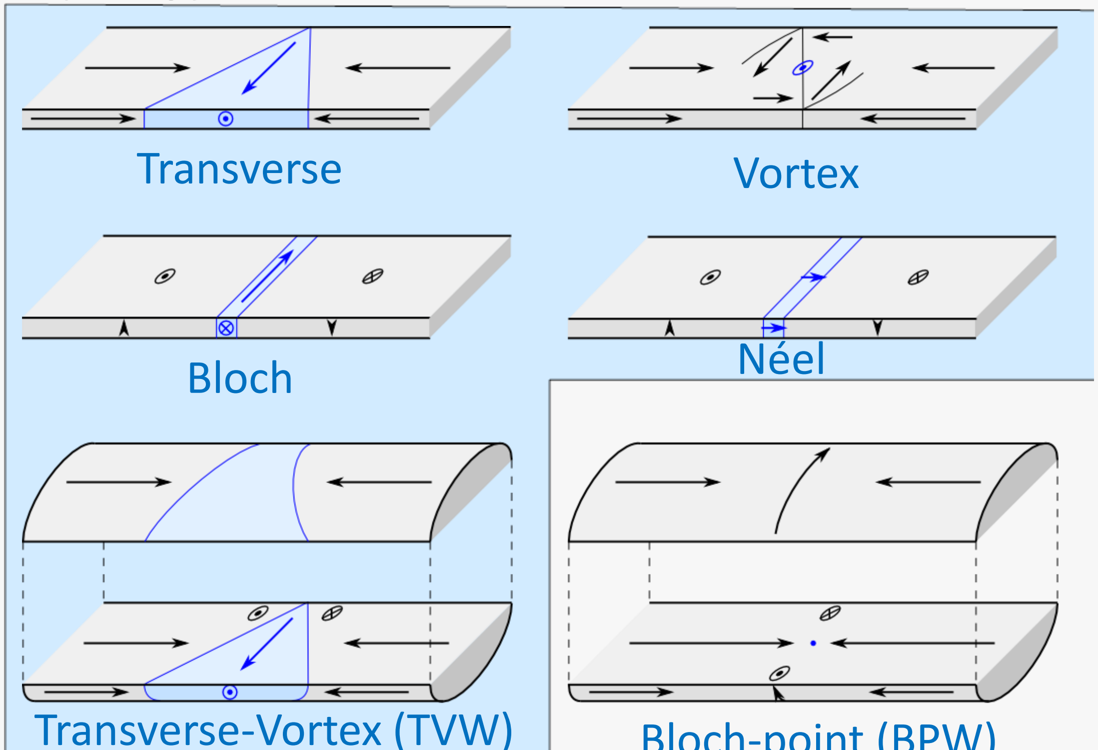
- Motivation

- Domain walls in wires
  Expectations



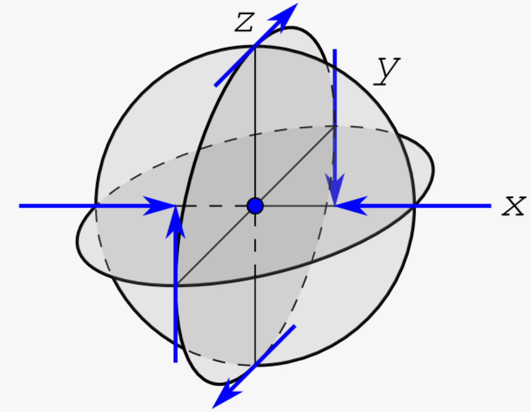
DOMAIN WALLS IN CYLINDERS

Topology of domain walls in 1D



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

What is a Bloch point?



Magnetization texture with local vanishing of magnetization

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

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

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

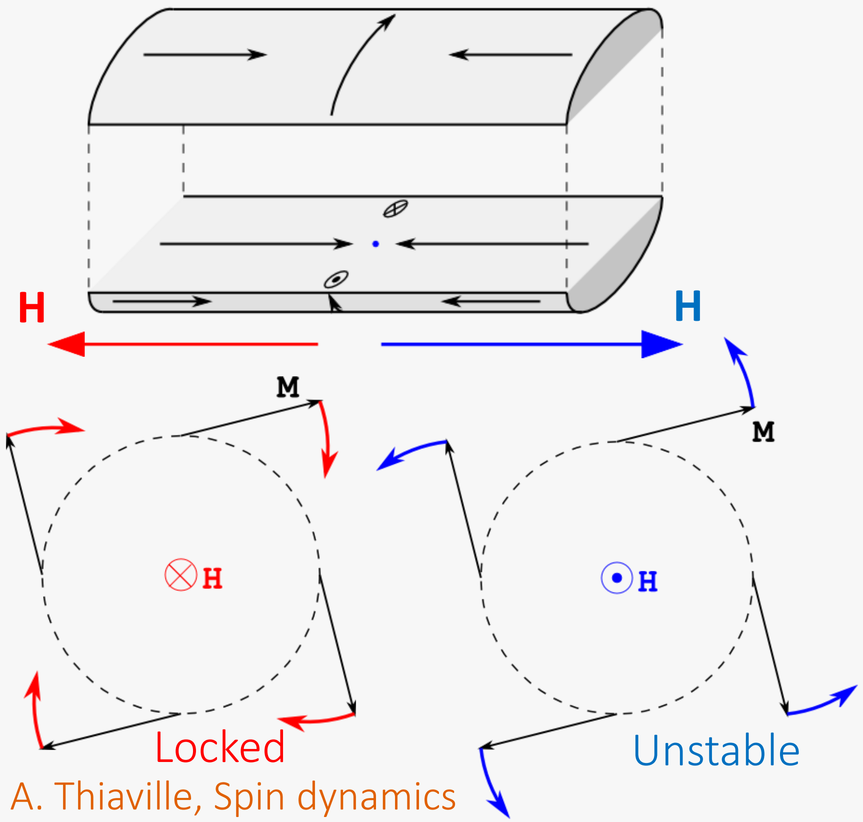
- Transverse and vortex walls for IP have same topology: subject to Walker field
- Bloch-point walls have a different topology

BLOCH-POINT WALLS DYNAMICS

LLG equation

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

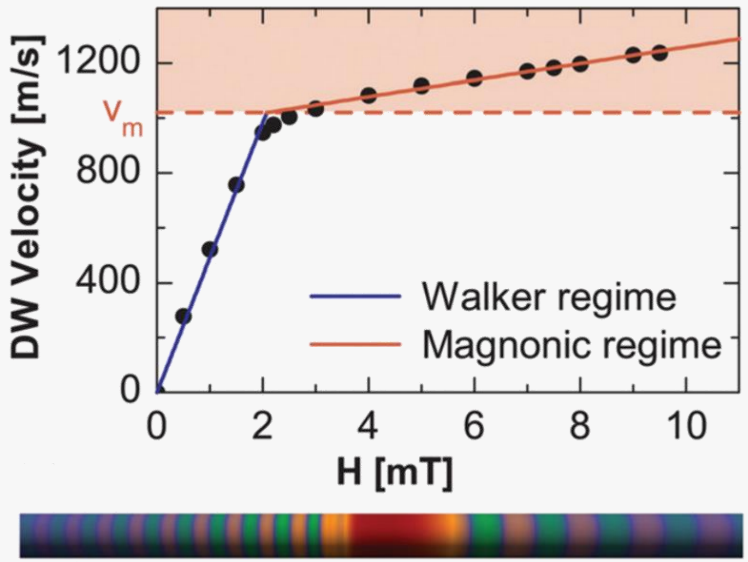
'Once-only' Walker event



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

Magnonic limit

Tubes (similar to wires)



R. Hertel, JPCM 28, 483002 (2016)

- Broad theoretical background
- No experimental report

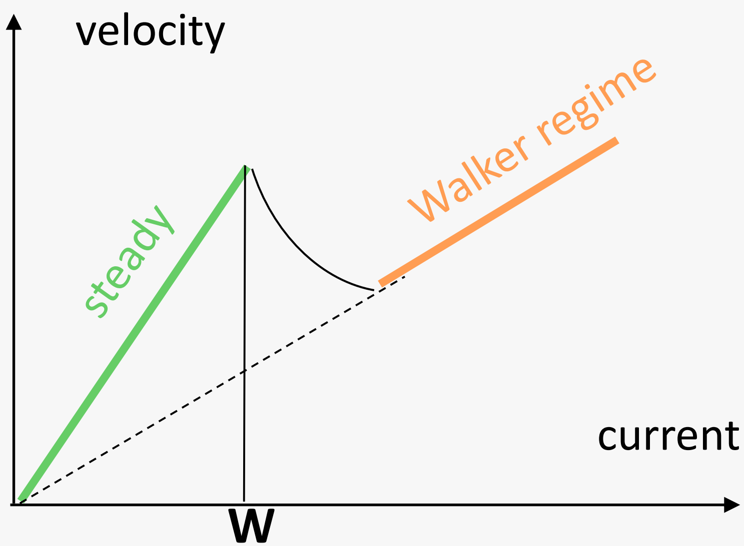
MOTION OF WALLS UNDER CURRENT

LLG equation

$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt} - (\mathbf{u}\cdot\nabla)\mathbf{m} + \beta\mathbf{m}\times[(\mathbf{u}\cdot\nabla)\mathbf{m}]$$

Precession | Damping | Adiabatic | Non-adiabatic

Strips: Walker breakdown

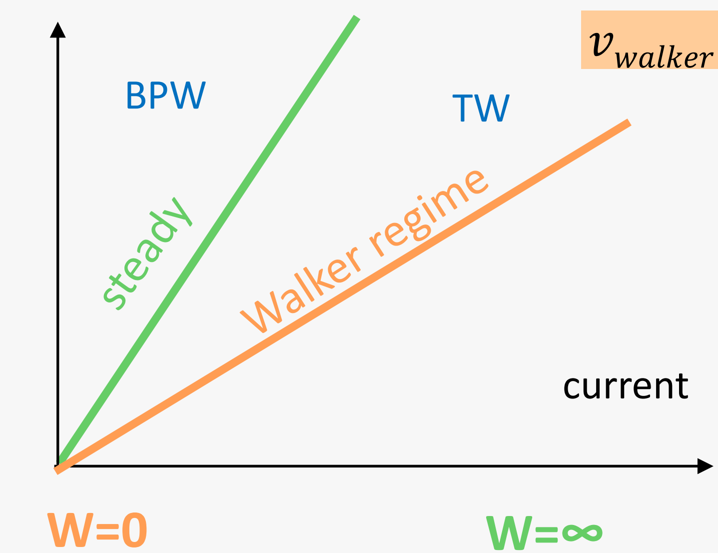


Cylinders: no Walker

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

$v_{walker} \propto J$ TVW

velocity

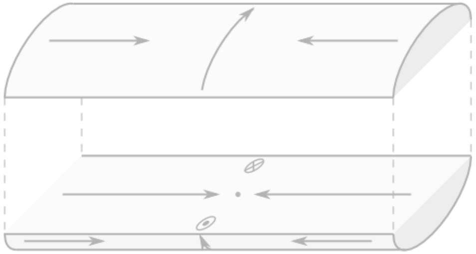


R. Wieser et al., Phys. Rev. B 82, 144430 (2010)

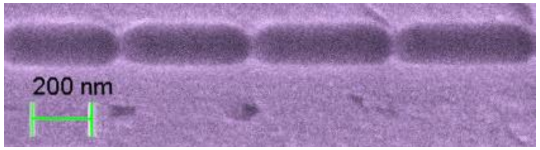
Magnetically-soft materials: $\beta > \alpha$

- Motivation

- Domain walls in wires
Expectations



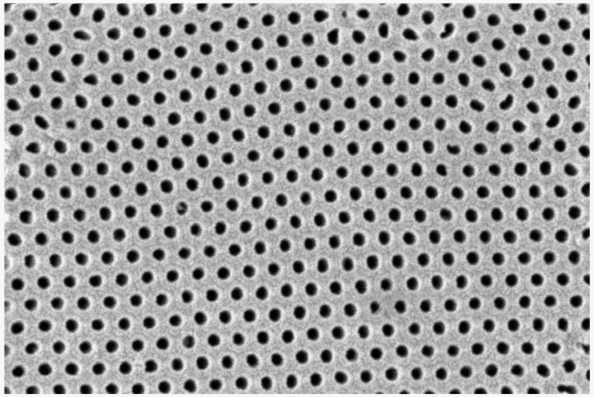
- Synthesis

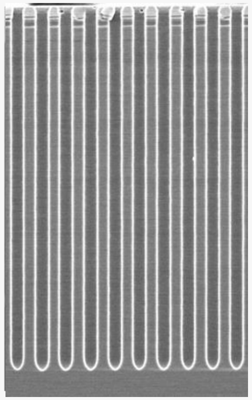


SYNTHESIS

Standard

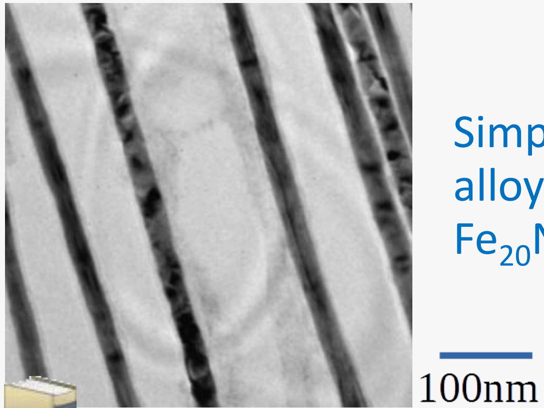
- Anodization of aluminum -> template





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

- Electroplating -> Magnetic wires

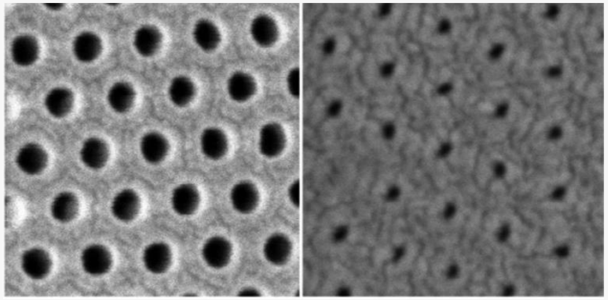


Simple metals and alloys : Co, Ni, $Fe_{20}Ni_{80}$, $Co_{20}Ni_{80}$

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

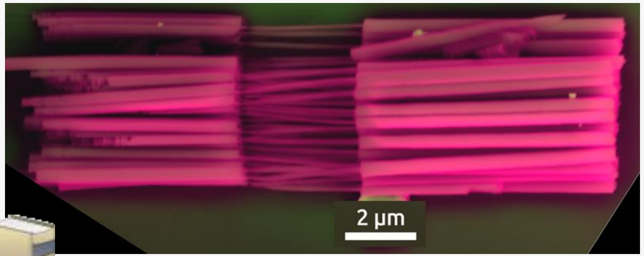
Diameter engineering

- Atomic layer deposition to reduce inner diameter at constant pitch



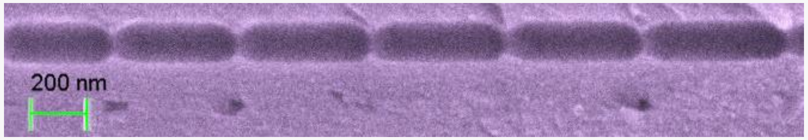
S. Da Col et al., APL 98, 112501 (2011)

- Sequences of anodization/ALD/etching



S. Bochmann, JAP 124, 163907 (2018)

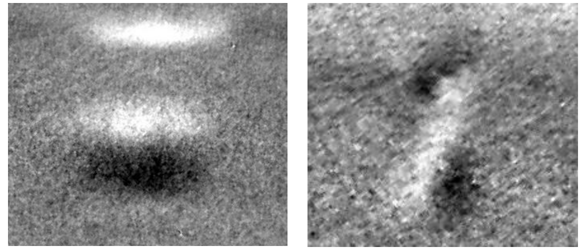
- Pulsed anodization



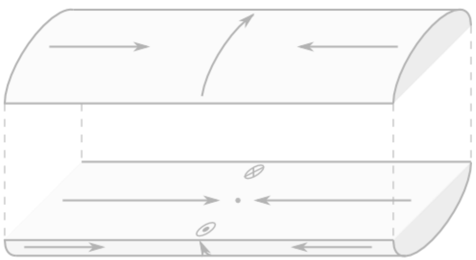
DISCUSSED SO FAR

- Motivation

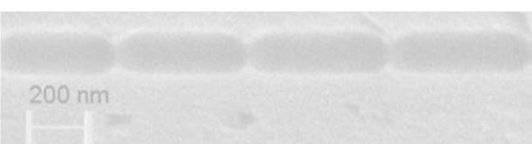
- Identify walls



- Domain walls in wires
  Expectations

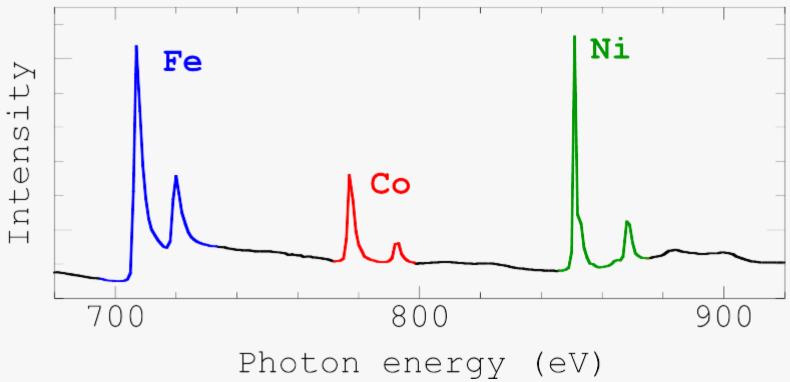


- Synthesis



X-Ray Magnetic Circular Dichroism

- Element selectivity



- Magnetic sensitivity

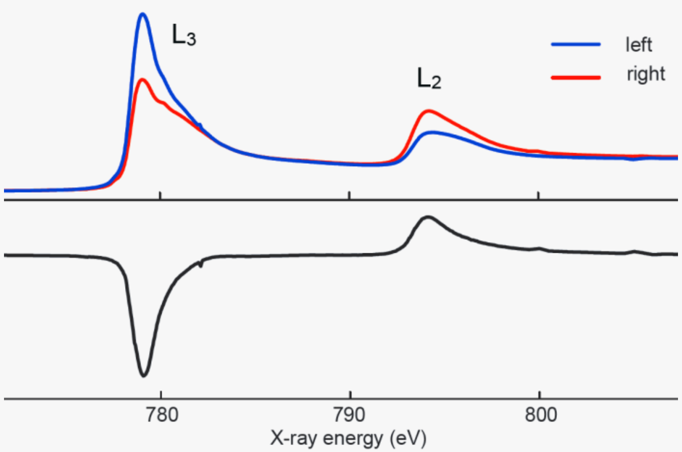
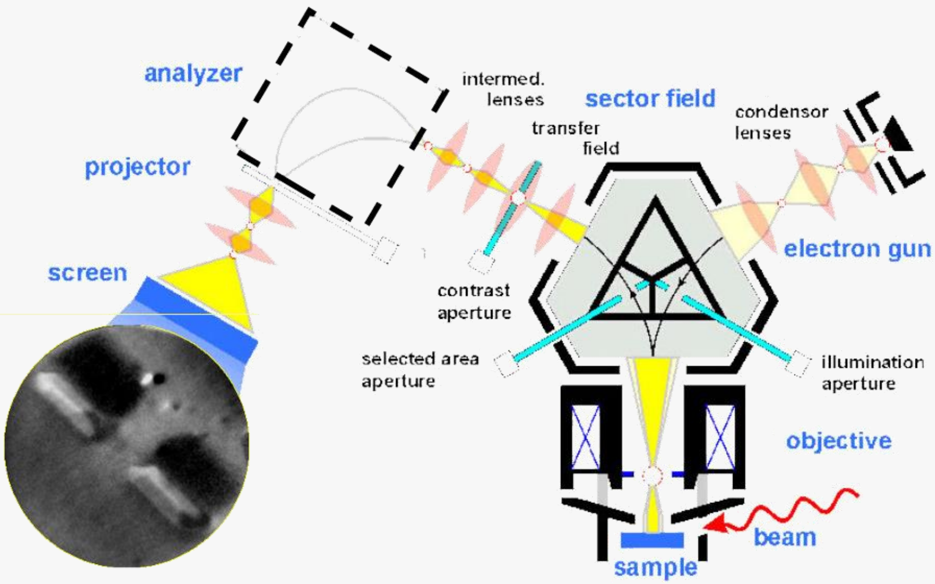


Photo-Emission Electron Microscopy



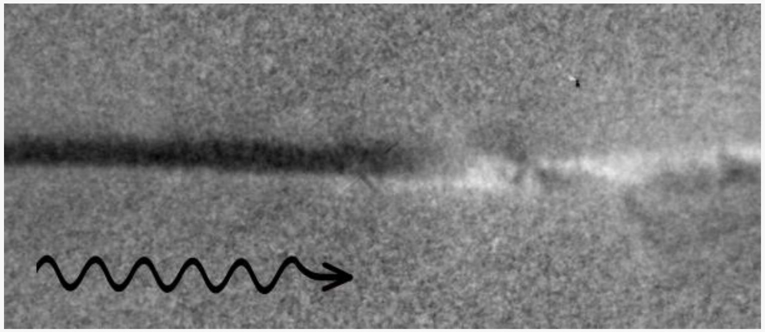
- **Synchrotron-based**
- **Secondary electrons -> surface sensitive**
- **25nm resolution in best case**

IMAGE BOTH WIRES AND SHADOW

Locate walls

FeNi

Beam along wire



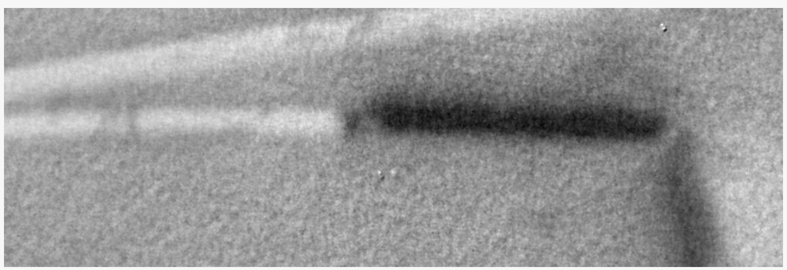
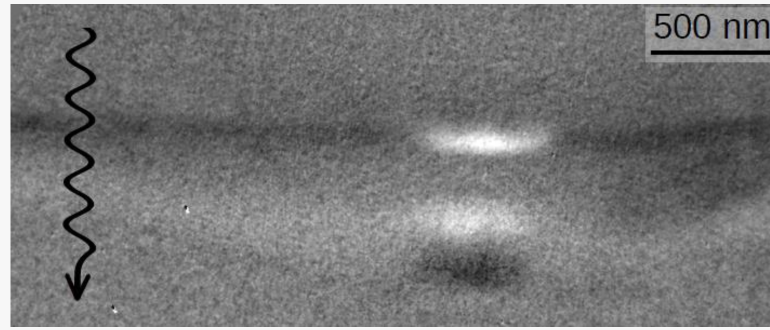
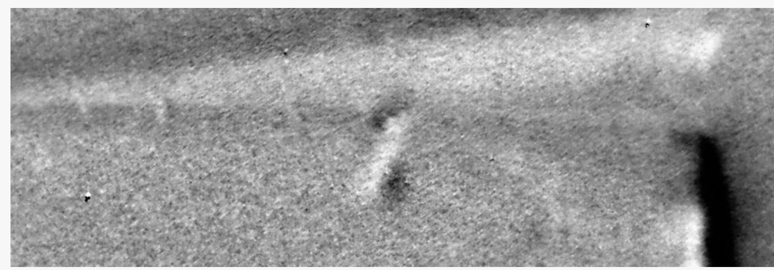


Image domain walls

FeNi

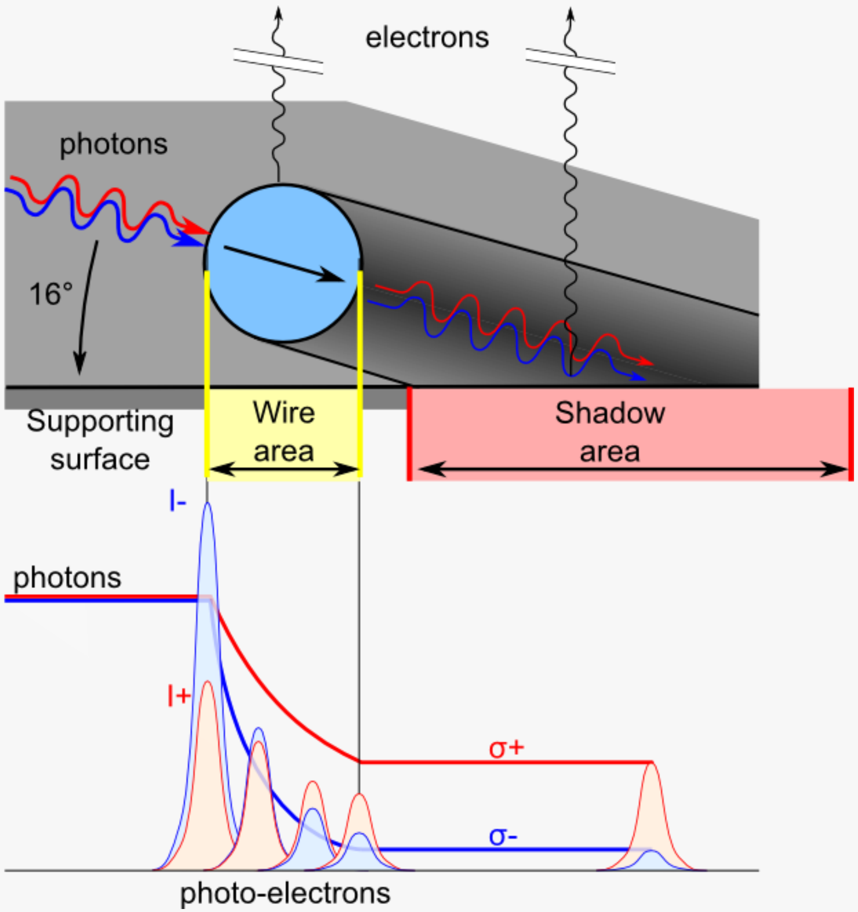
Beam across wire



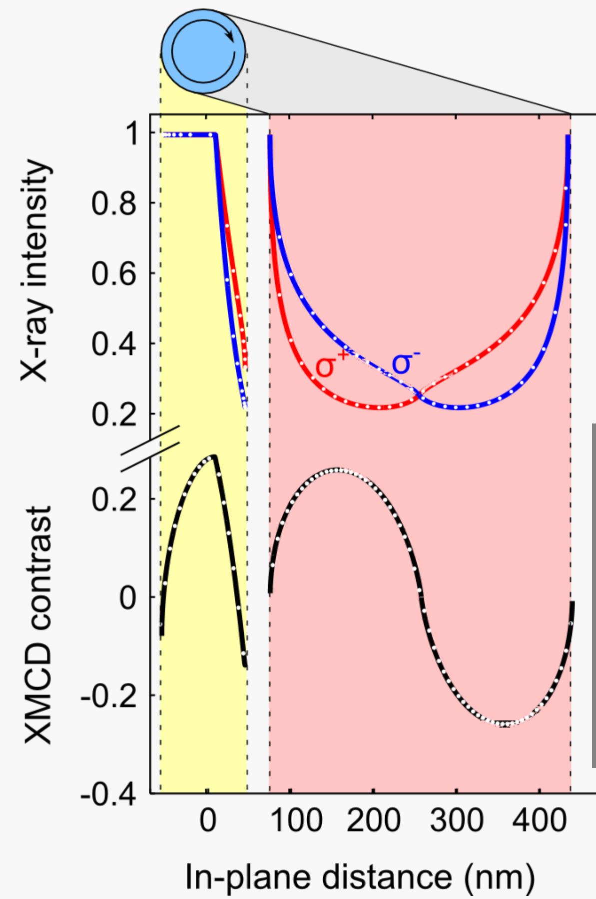


- **Non-trivial patterns**
- **Need for modeling**

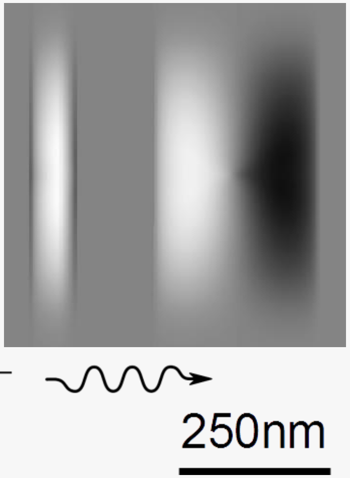
SHADOW XMCD-PEEM



SIMULATION OF CONTRAST

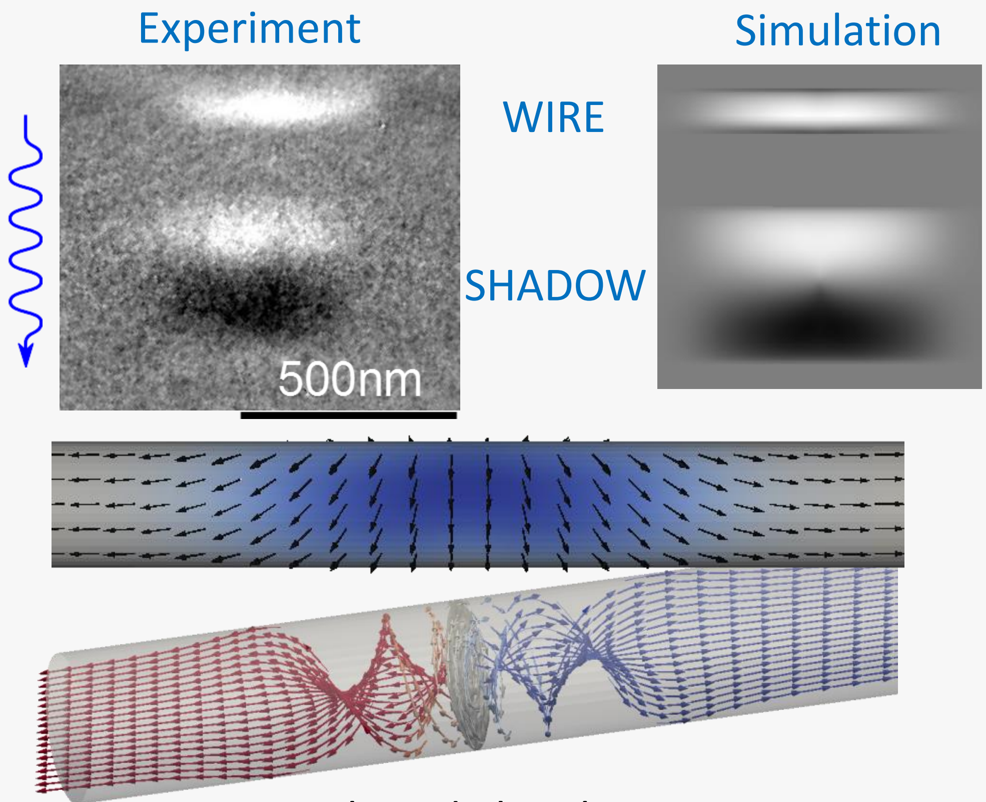


Example:
Bloch-point wall



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

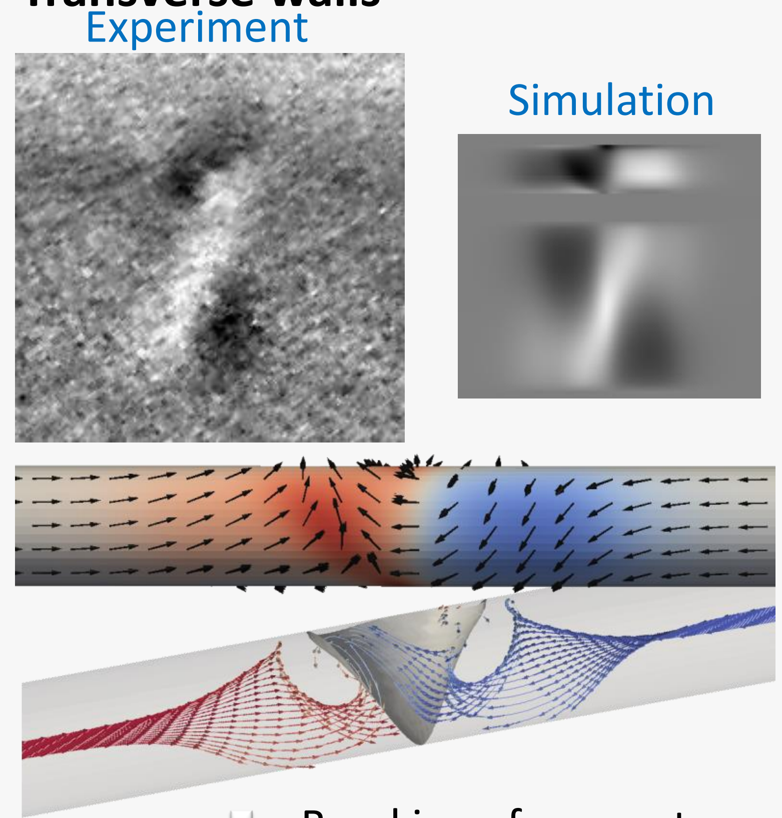
Bloch-point walls



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

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

Transverse walls



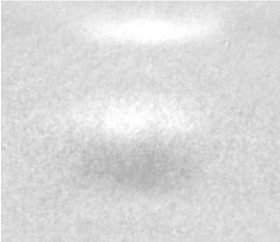
- Breaking of symmetry

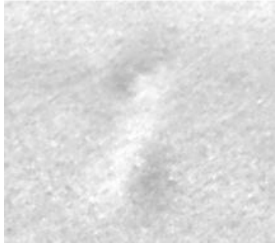
Also imaged with electron holography:

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

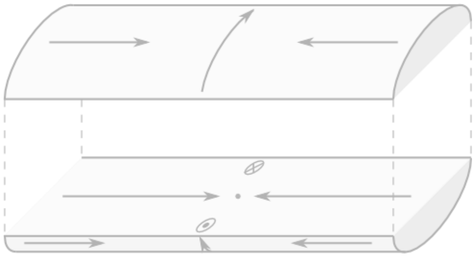
- Motivation

- Identify walls

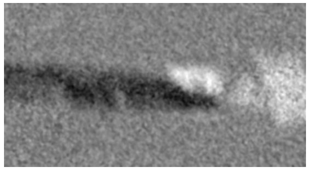


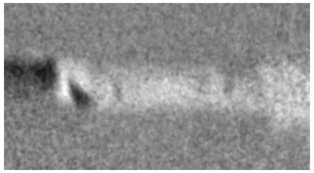


- Domain walls in wires
  Expectations



- Move walls under field

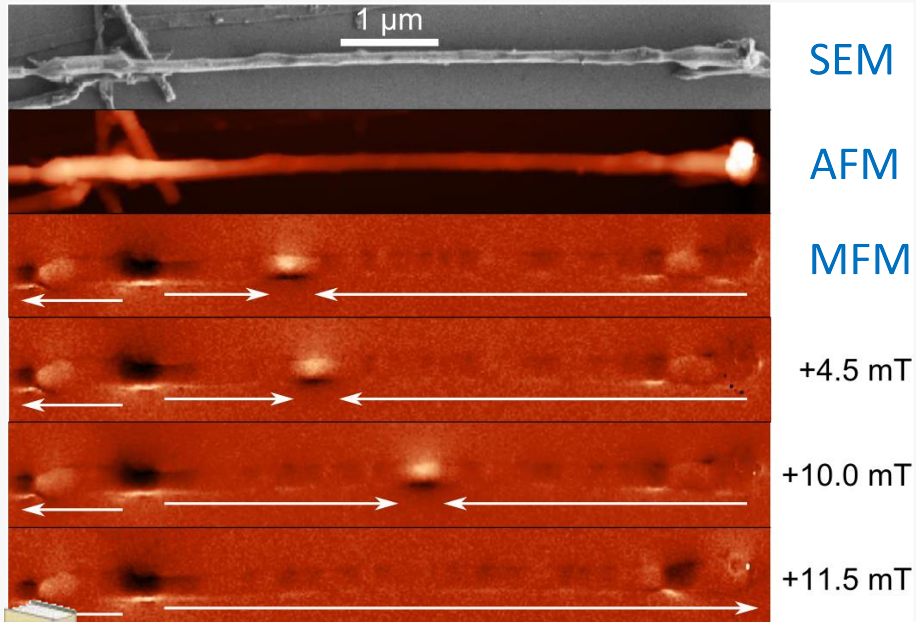




- Synthesis

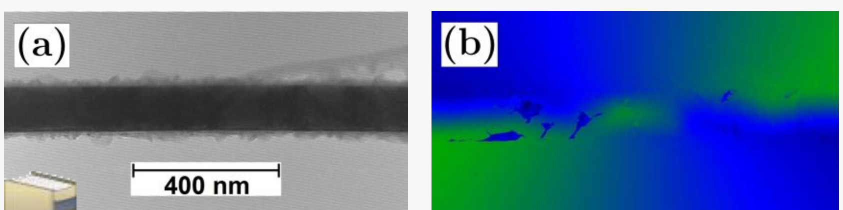
Quasistatic motion

FeNi



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

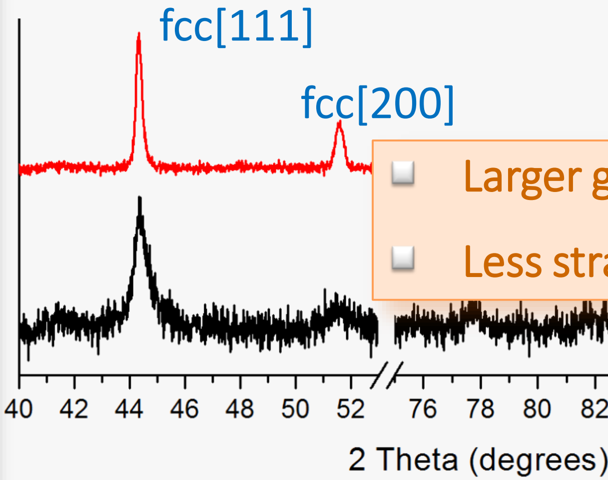
- TEM – No clear correlation with structure



M. Staňo et al., J. Phys. Conf. Series (2017)

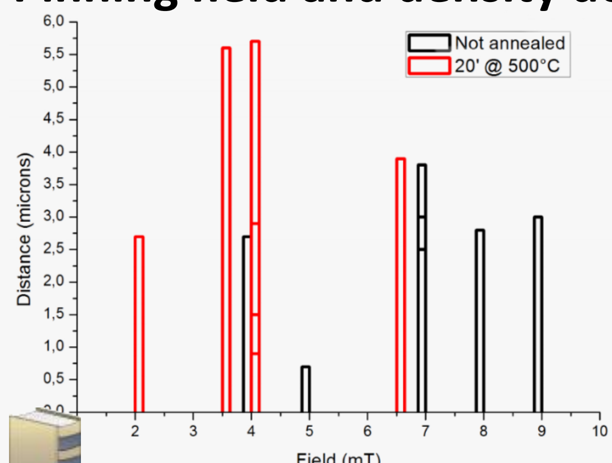
Pioneering with MFM: Y. Henry et al., EPJB 20, 35 (2001)

Material improvement – Annealing



- Larger grain size
- Less strain distribution

Pinning field and density decreased

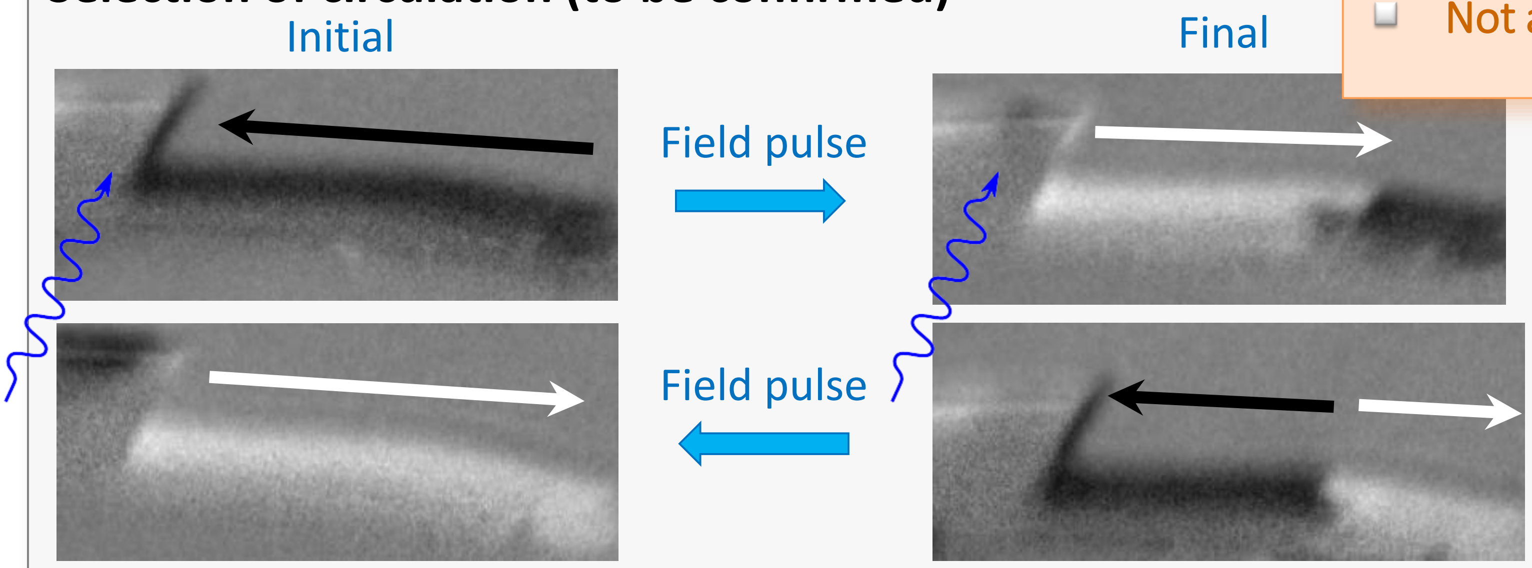


B. Trapp, in preparation

Modulated diameter to keep domain walls in wire

CoNi

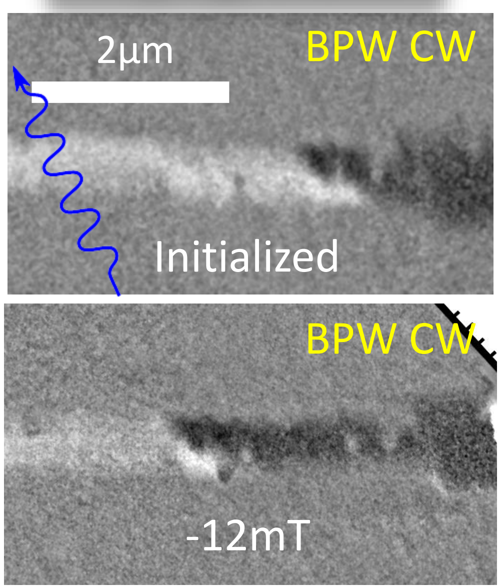
Selection of circulation (to be confirmed)

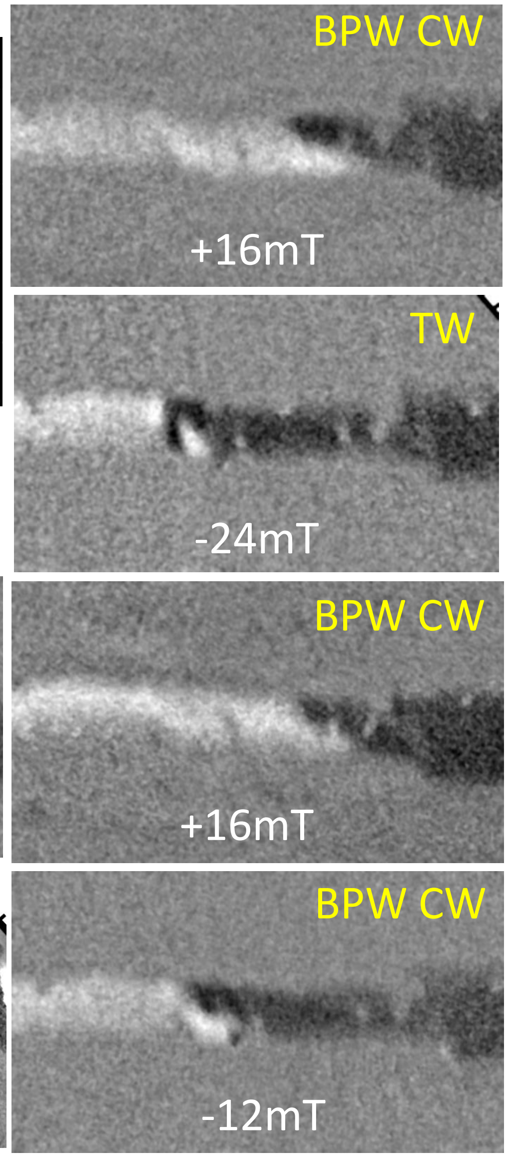


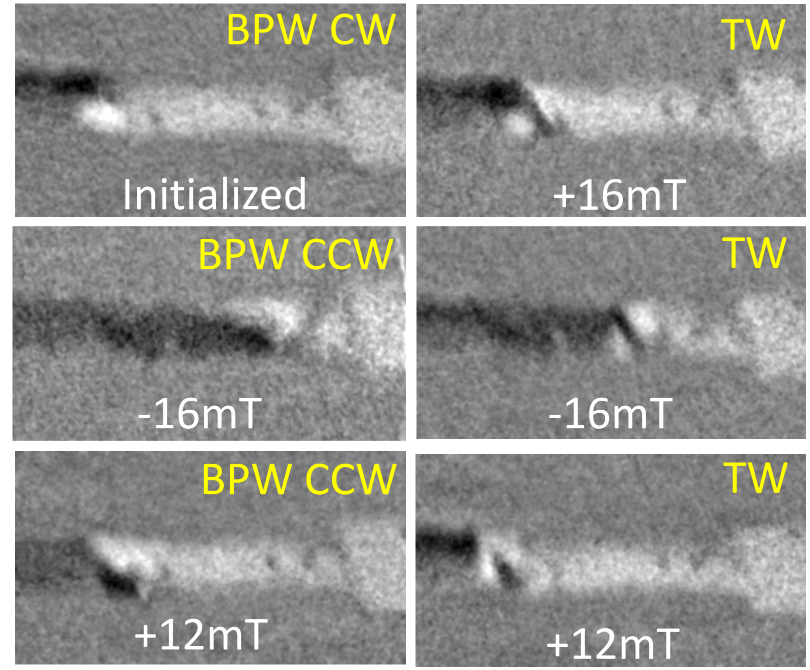
- Not a 100% correlation

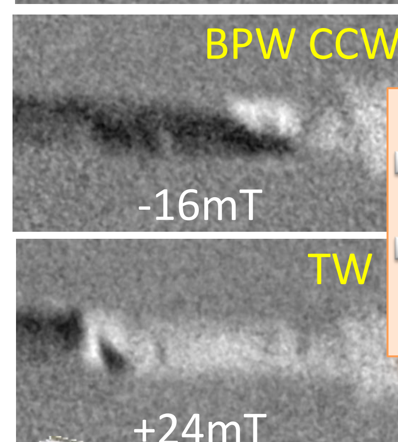
THE DARK SIDE

$Fe_{20}Ni_{80}$, 140nm







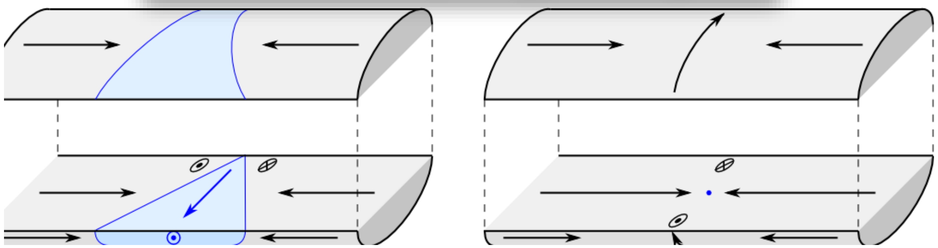


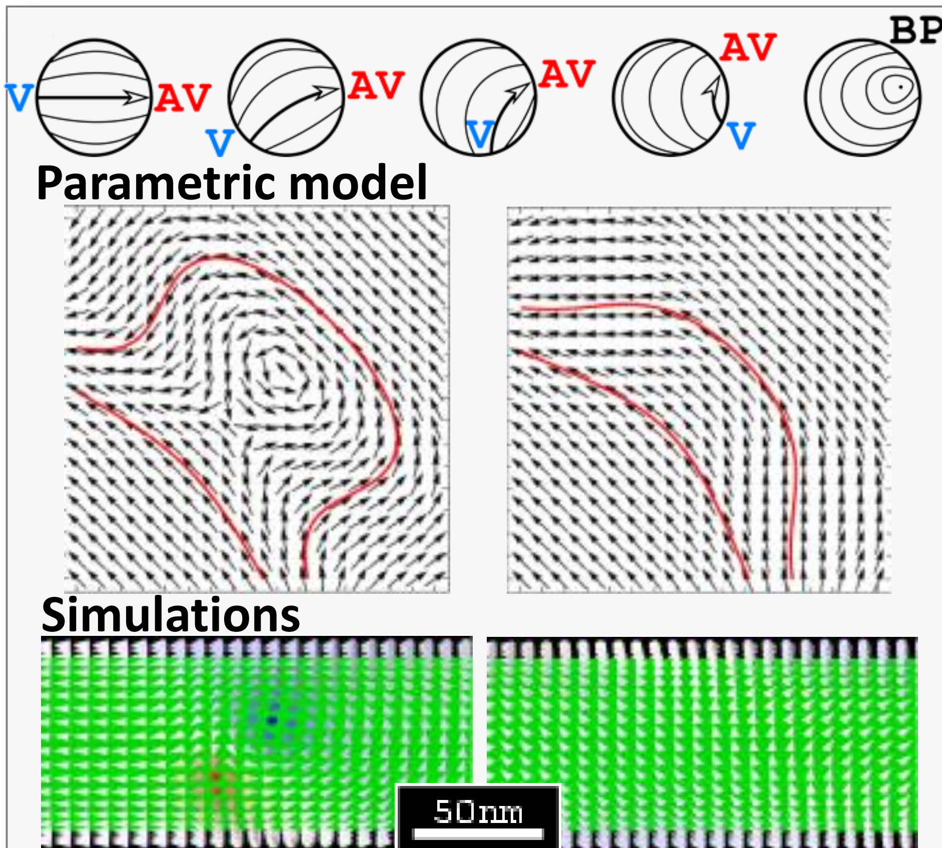
- Switch circulation
- No topological protection

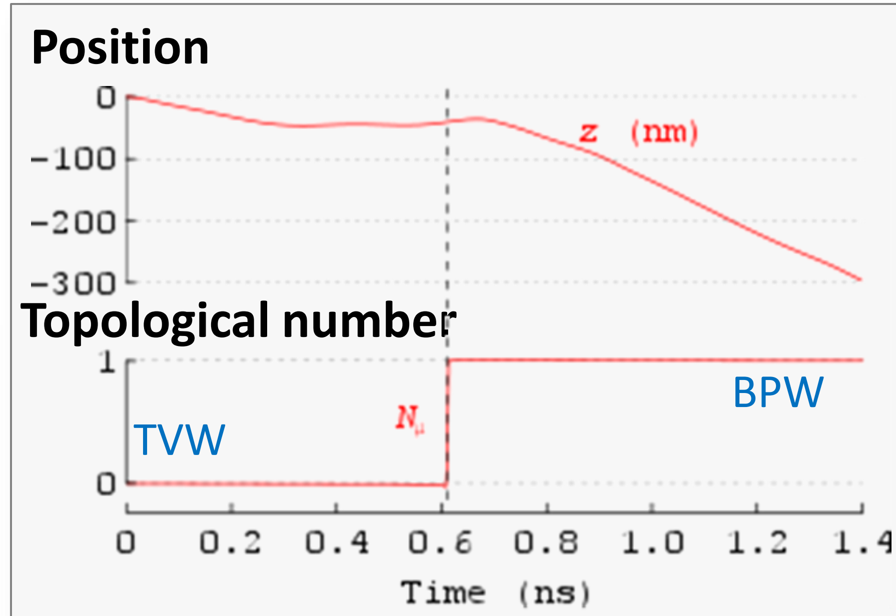
A. Wartelle, PRB99, 024433 (2019)

DW TRANSFORMATION - SIMULATIONS

How does topology change?







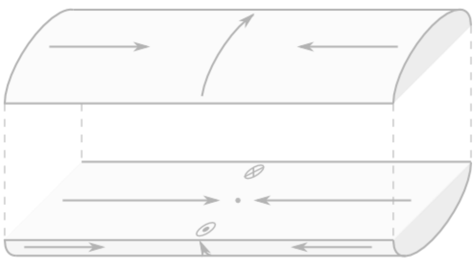
- Driven by dynamics
- TVW -> BPW: induction tube twists and unwinds
- BPW -> TVW: still unclear
- Opens computational and material science challenges

A. Wartelle, PRB99, 024433 (2019)

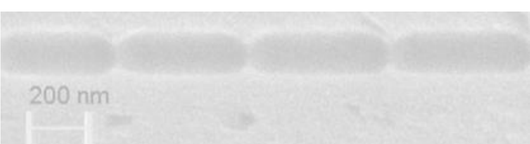
DISCUSSED SO FAR

- Motivation

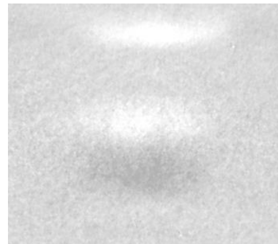
- Domain walls in wires
  Expectations

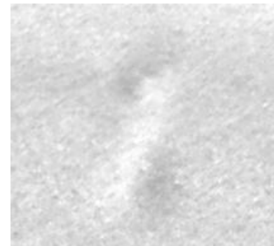


- Synthesis

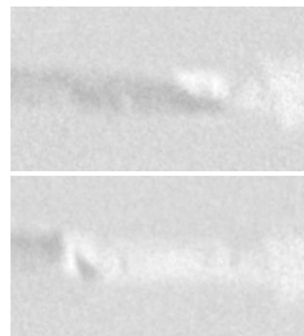


- Identify walls

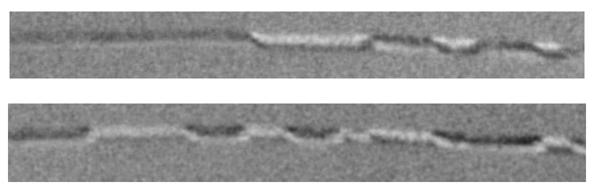




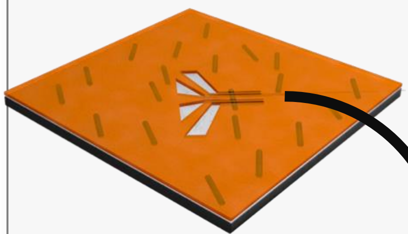
- Move walls under field



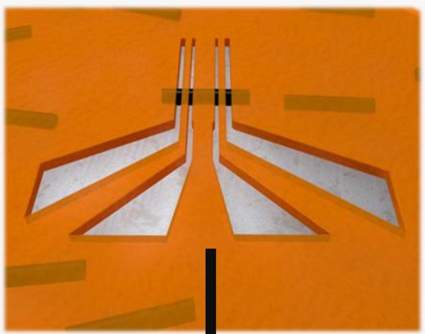
- Move walls under current



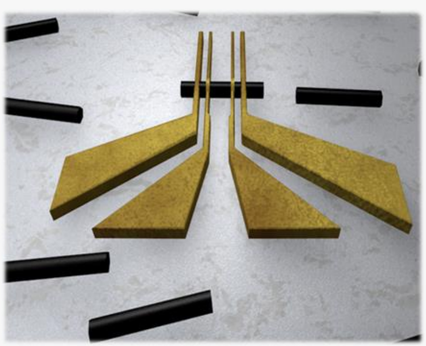
Process



Optical mask

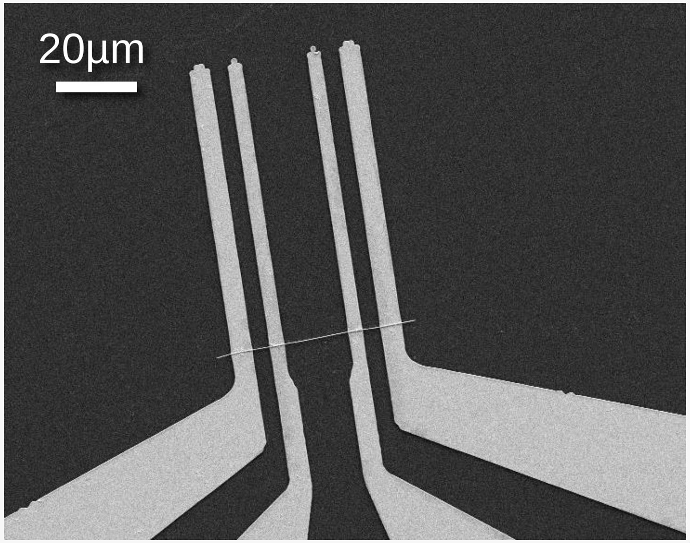


Tranfer to resist + Etching



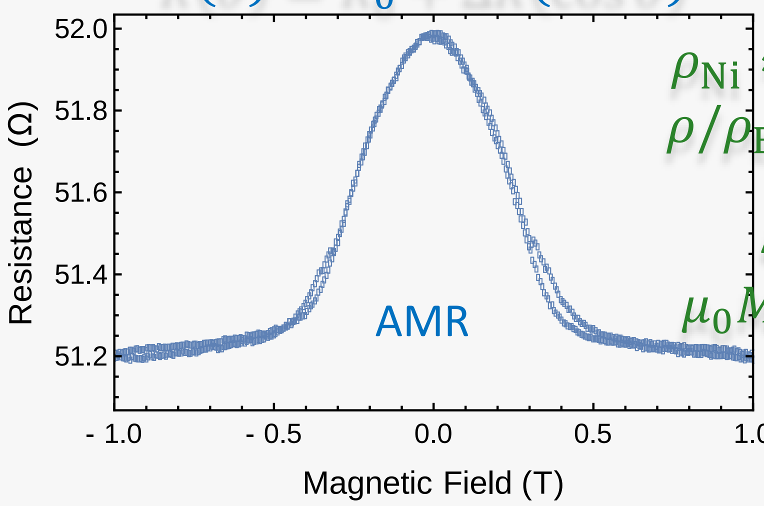
Ti\Au + lift-off

Output



Two- or four contacts

$$R(\theta) = R_0 + \Delta R(\cos\theta)^2$$



$R \approx 50\ \Omega$

$\rho_{\mathrm{Ni}} \approx 10^{-7} \Omega \cdot \mathrm{m}$

$\rho/\rho_{\mathrm{Bulk}} \approx 1.3$

$\Delta R/R_0 \simeq 1.6$

$\mu_0 M_s \simeq 650\ \mathrm{mT}$

Ni, 200nm diameter

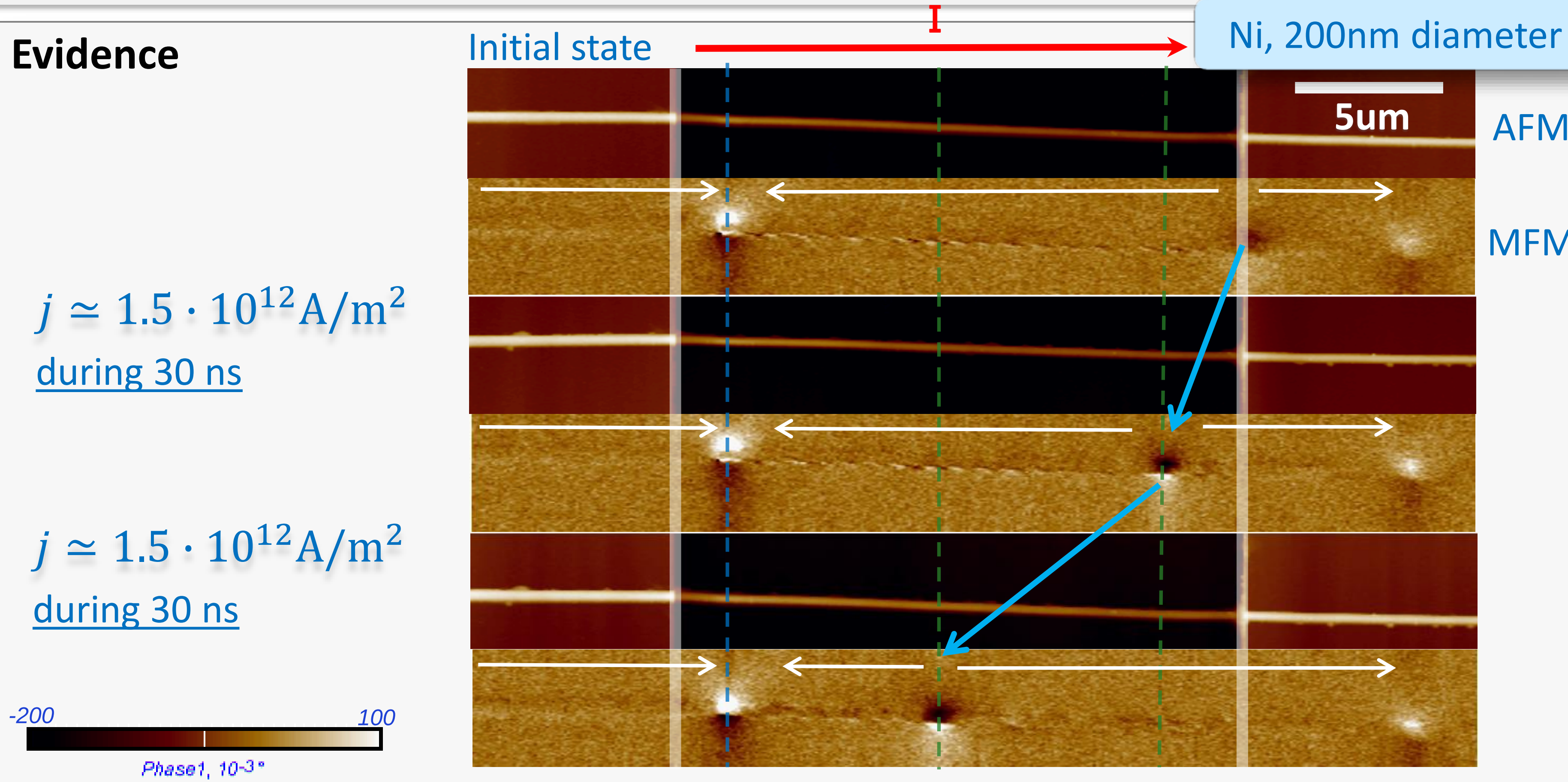
Evidence

$j \simeq 1.5 \cdot 10^{12} \mathrm{A/m^2}$

during 30 ns

$j \simeq 1.5 \cdot 10^{12} \mathrm{A/m^2}$

during 30 ns



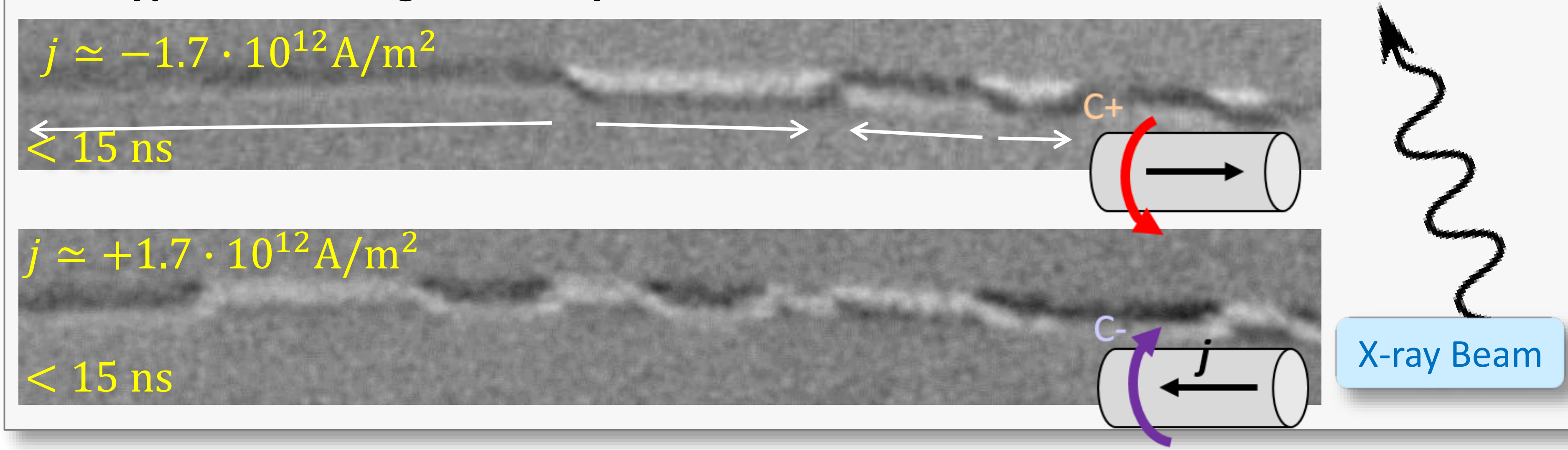
- Lower bound for domain-wall speed $v \gtrsim 350\ \mathrm{m/s}$
- Hint of high mobility for Bloch-point domain wall?

$Co_{40}Ni_{60}$ wires, diameter 100nm. FoV 9µm

$\rho_{\mathrm{CoNi}} \approx 3.5 \cdot 10^{-7}\ \Omega \cdot \mathrm{m}$

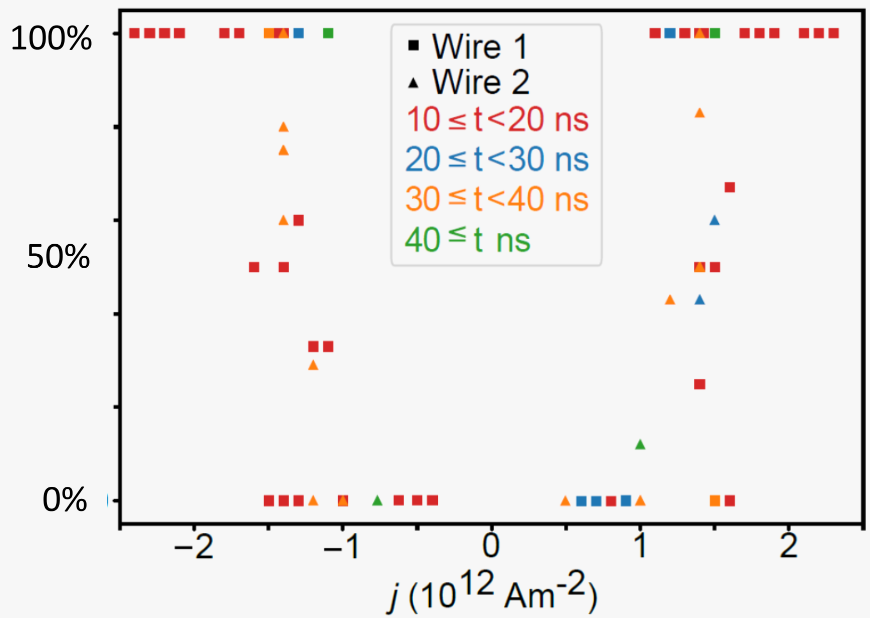
$\rho_{\mathrm{bulk}} \approx 10^{-7}\ \Omega \cdot \mathrm{m}$

Wall type – Switching of Bloch-point wall circulation



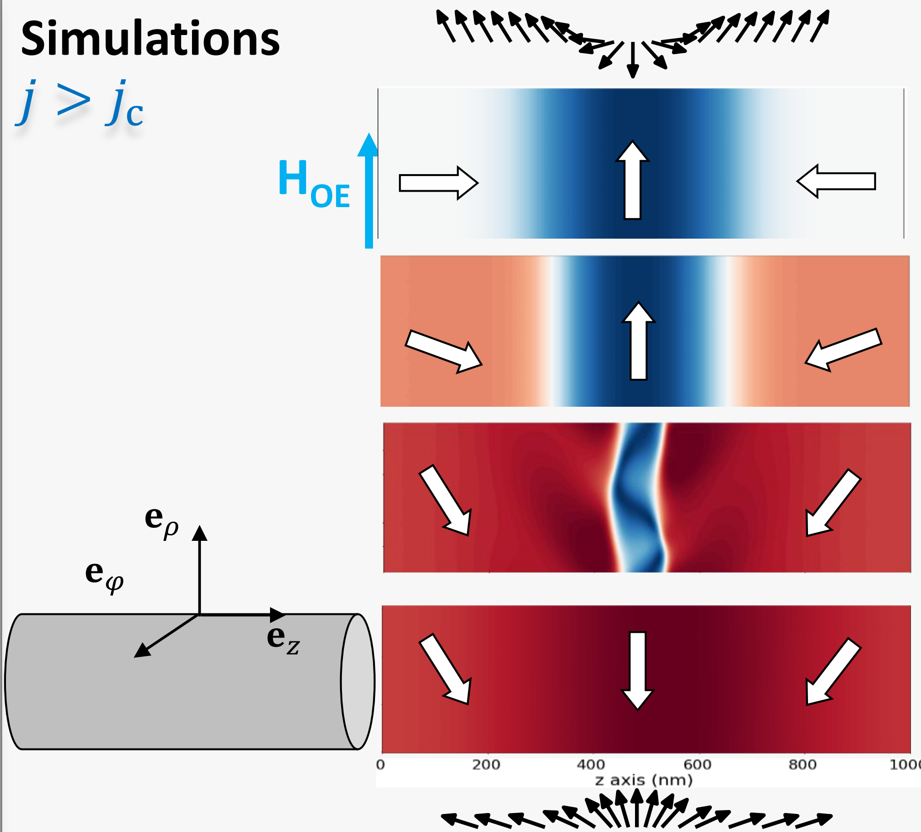
- Striking difference with field-driven case: only Bloch-point walls
- Circulation of magnetization determined by sign of current
- Contrary to predictions: does not depend on direction of motion

Experiments:
probability for switching circulation



Simulations

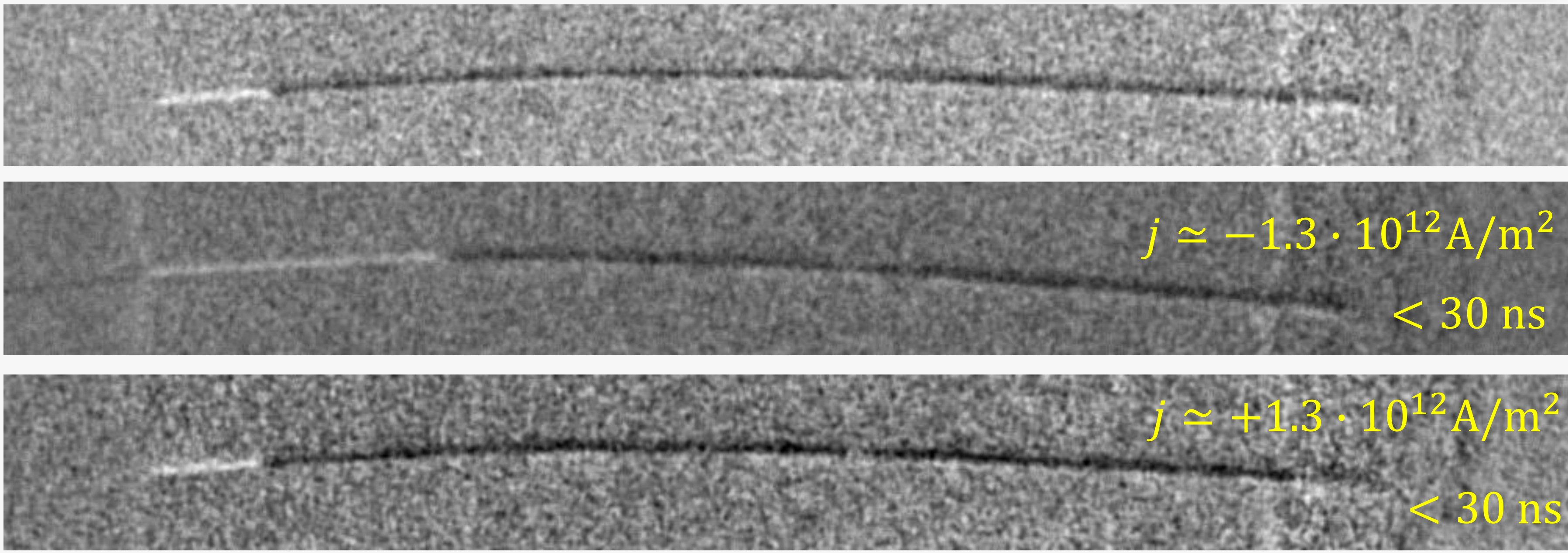
$j > j_c$

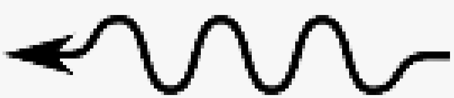


- Threshold current for switching
- Driving force: Œrsted field, disregarded so far
- Quantitative agreement between experiments and simulation

CoNi wires, diameter 100nm.
FoV 17µm

Motion under current



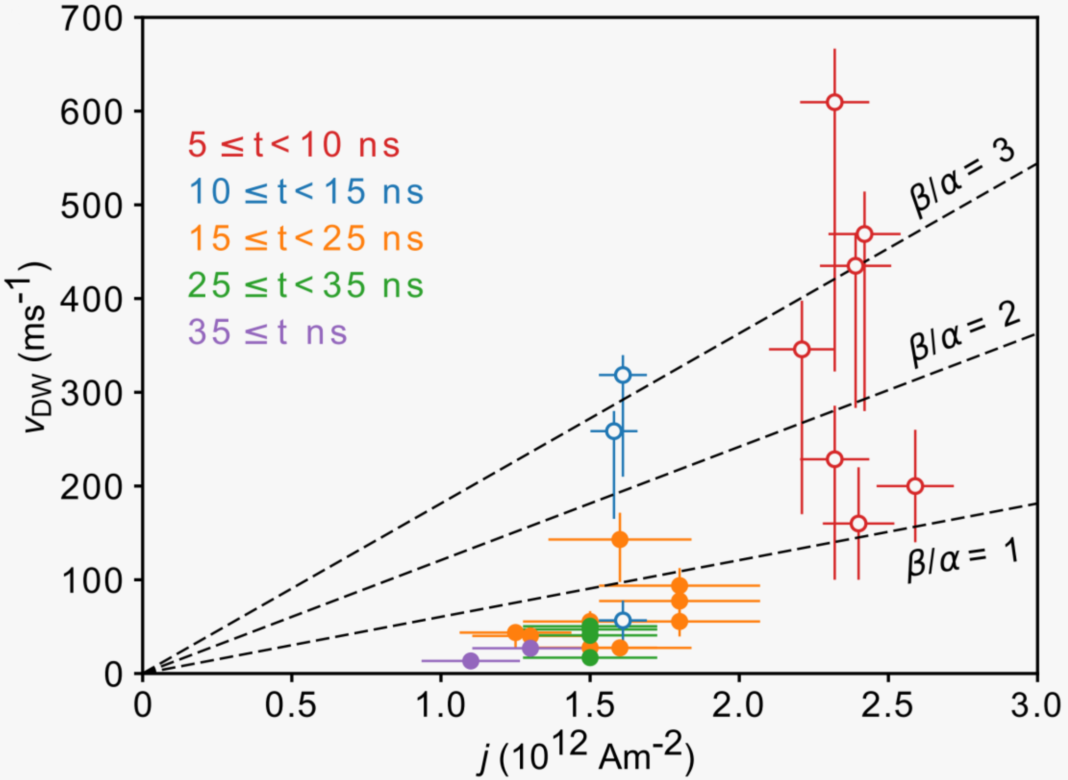


X-ray Beam

$\rho_{\mathrm{CoNi}} \approx 3.5 \cdot 10^{-7}\ \Omega \cdot \mathrm{m}$

$\rho_{\mathrm{bulk}} \approx 10^{-7}\ \Omega \cdot \mathrm{m}$

Statistics on Bloch-point wall speed



- MFM (high bandwidth)
- PEEM (low bandwidth)

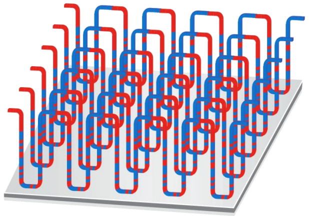
$Co_{40}Ni_{60}$ wires, diameter 100nm

- Pinning: shorter pulse provides larger speed
- Compatible only with below-Walker regime
- Fivefold-largest STT speed in ferromagnetic material
- The magnonic regime is at hand

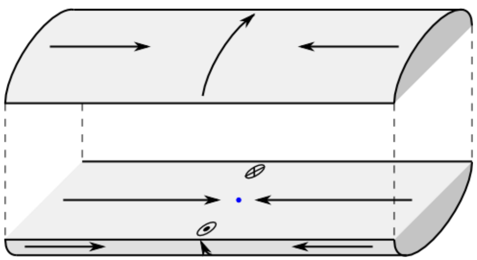
M. Schöbitz et al, arXiv: 1903.08377

TAKE-AWAY MESSAGES

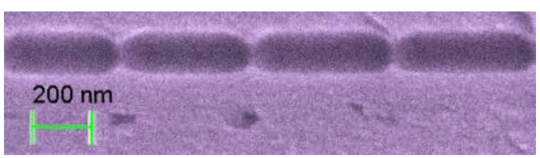
- Motivation



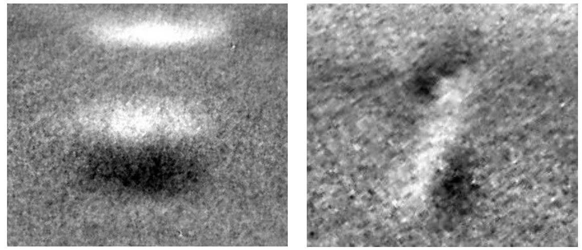
- Domain walls in wires
Expectations



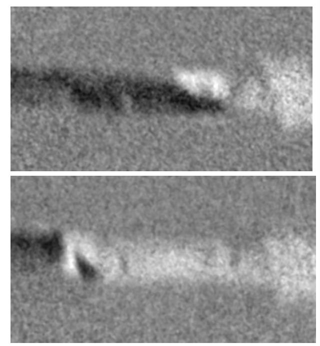
- Synthesis



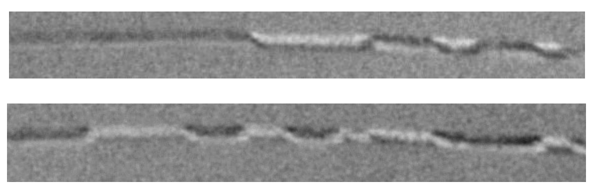
- Identify walls



- Move walls under field



- Move walls under current

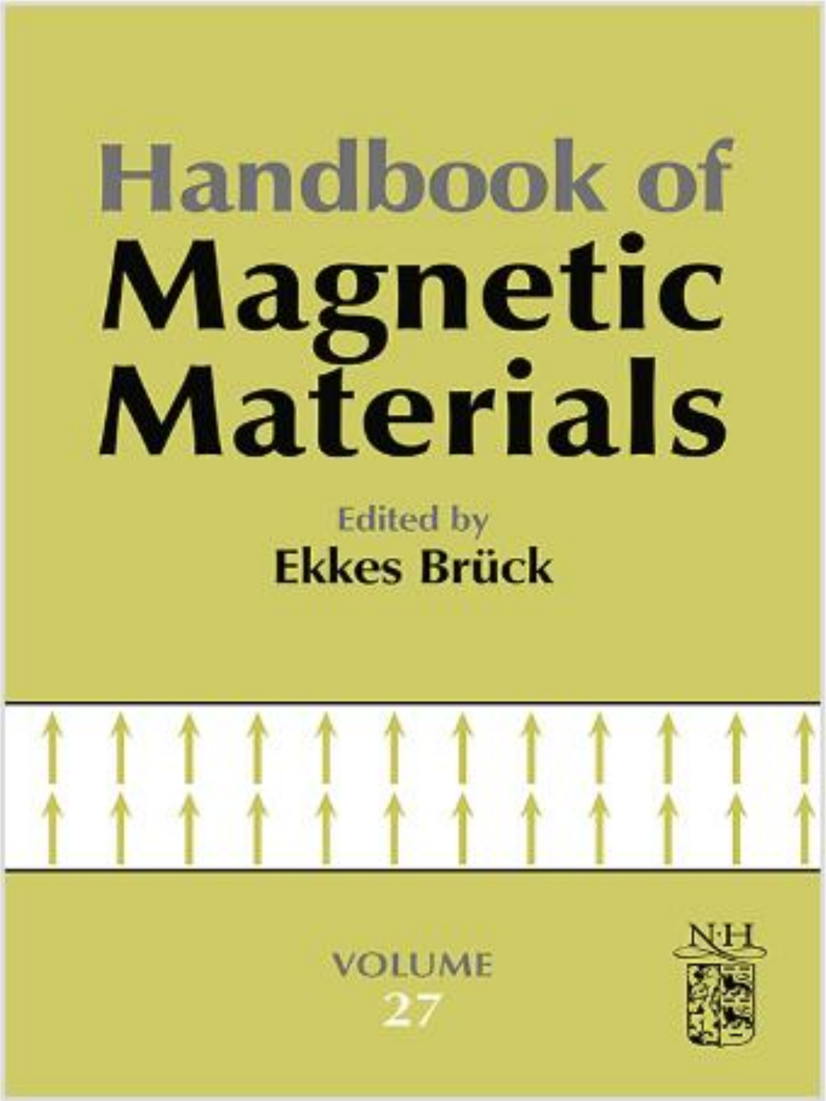


- Wall topology may change under field.
Intrinsic + defects?
- Œrsted field stabilizes BPW. High speed, no Walker breakdown
- Record for STT-driven wall in ferromagnet
- The magnonic regime may be at hand

A. Wartelle, PRB99, 024433 (2019)

M. Schöbitz et al, arXiv: 1903.08377

Review



M. Stano, O. Fruchart,

Magnetic Nanowires and nanotubes

(2018)

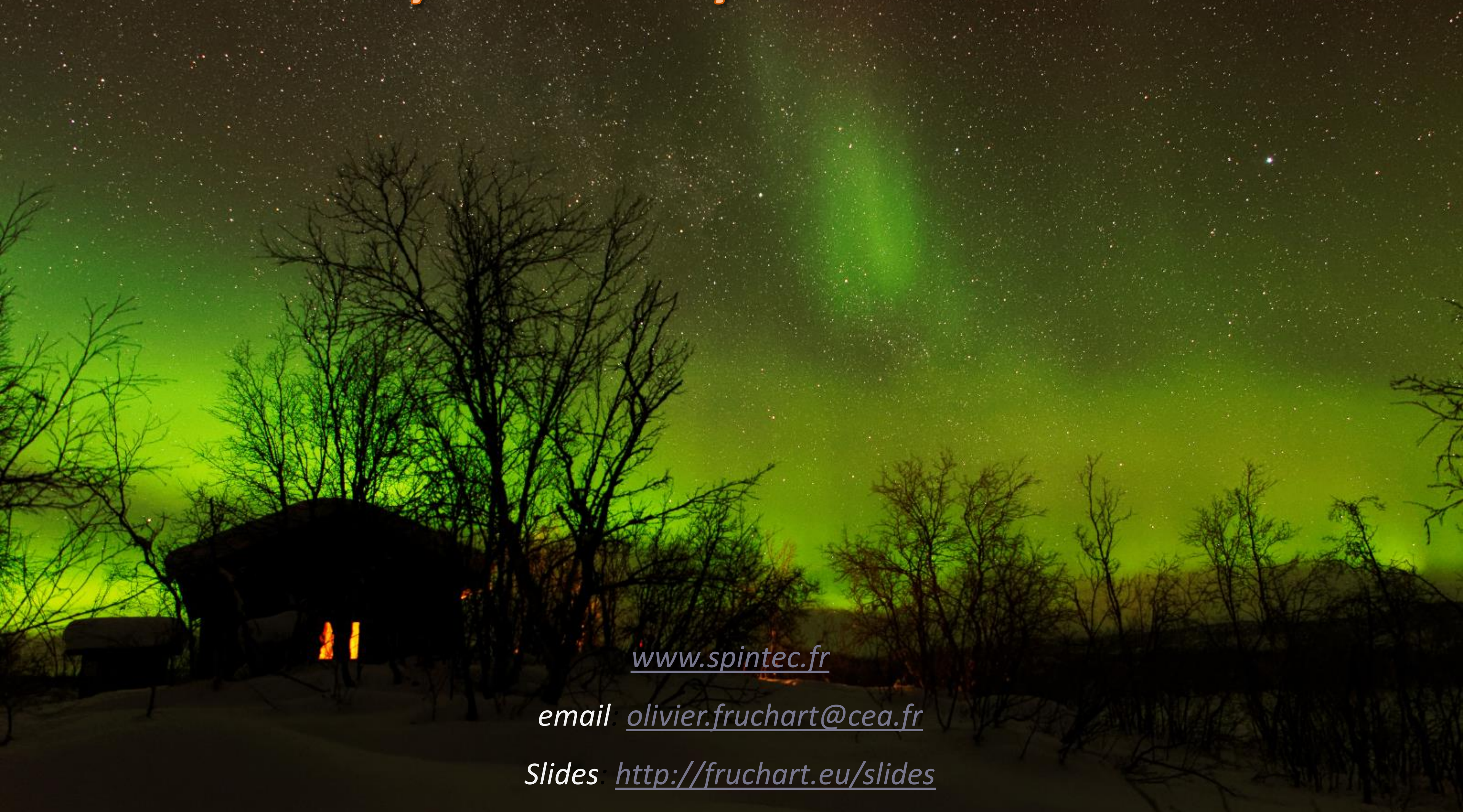
arXiv: 1808.04656

ACKNOWLEDGEMENTS

- SPINTEC / NEEL A. Wartelle, B. Trapp, M. Stano, M. Schöbitz A De Riz, S. Martin, C. Thirion, L. Cagnon, J. Vogel, D. Gusakova, J. C. Toussaint
- Univ. Erlangen-Nürnberg S. Bochmann, J. Bachmann
- ELETTRA T. O. Mentes, A. Locatelli, F. Genuzio; ALBA M. Foerster; L. Aballe
- CEMES A. Masseboeuf, C. Gatel

This project has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 309589 (M3d).

Thank you for your attention !



www.spintec.fr

email: olivier.fruchart@cea.fr

Slides: http://fruchart.eu/slides