A unified phase diagram of domain walls in 1D systems, ranging from strips to cylindrical wires

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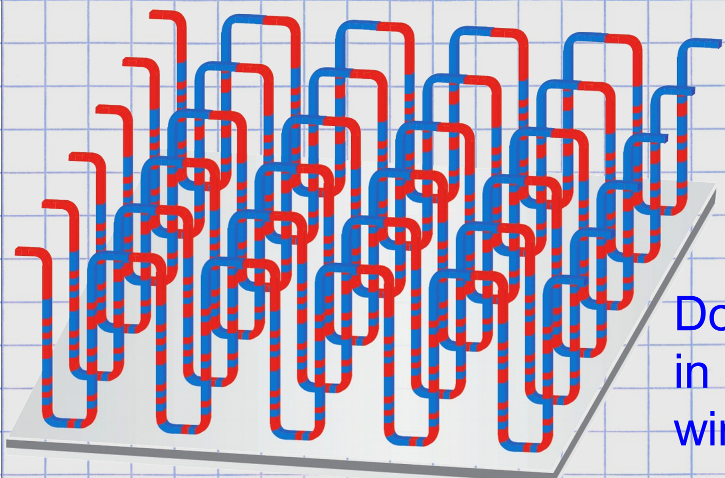
Motivation (general) : magnetism towards 3D

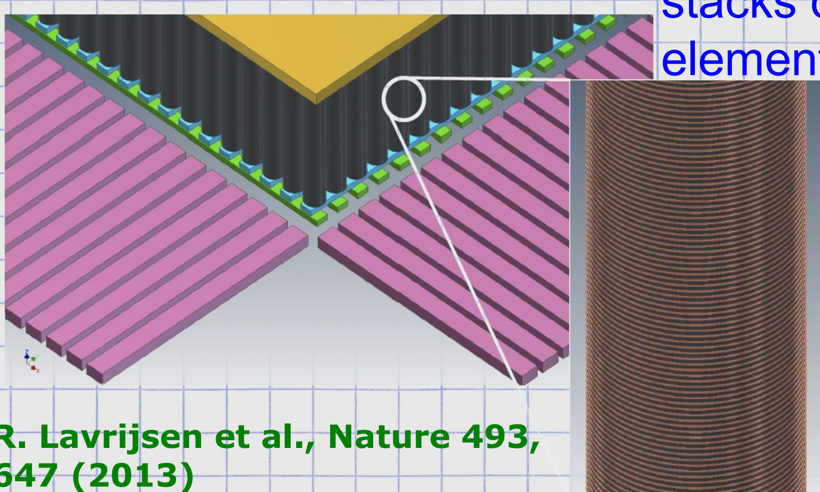
Concepts for devices



Domain walls in continuous wires

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

Solitons in stacks of elements



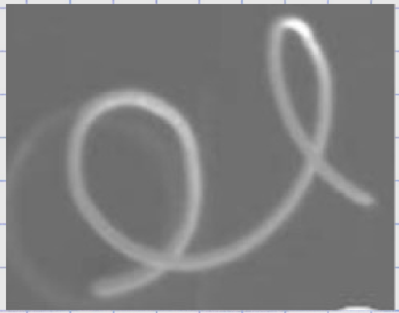
R. Lavrijsen et al., Nature 493, 647 (2013)

3D magnetic objects and textures

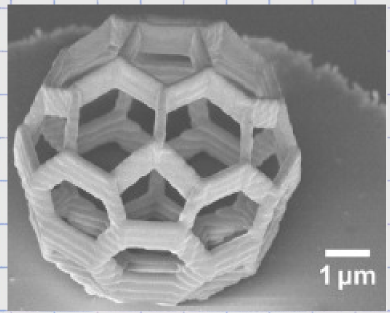
Magnetic meron

S. Wintz et al., PRL 110, 177201 (2013)

3D objects



A. Fernandez-Pacheco et al., Sci. Rep. 3, 1 (2013)

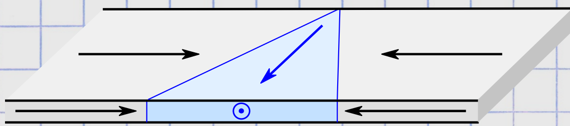


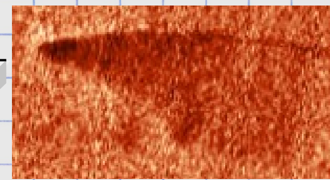
C. Donnelly et al., PRL 114, 115501 (2015)

Interest in examining and classifying 3D magnetic textures

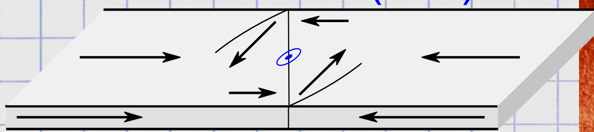
Flat strips

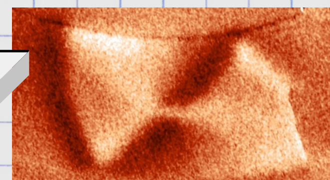
Transverse wall (TW)





Vortex wall (VW)



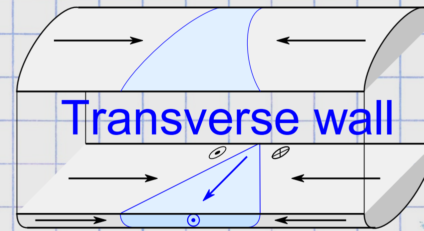


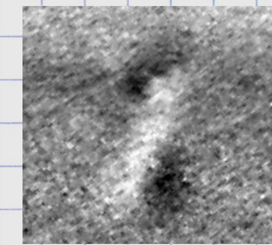
Transition for: $tW \approx 61\,\Delta_{\mathrm{d}}^{2}$

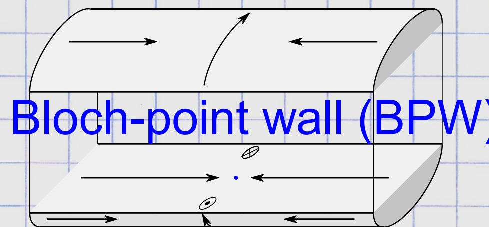
R. McMichael & M. Donahue, IEEE Trans. Mag. 33, 4167 (1997)

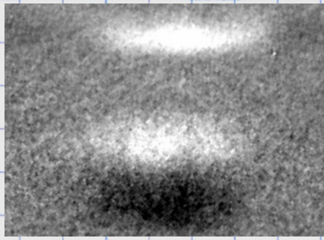
Y. Nakatani et al., J. Magn. Magn. Mater. 290-291, 750 (2005)

Cylindrical (or square) wires









Transition for: $d \approx 7\,\Delta_{\mathrm{d}}$

H. Forster et al., JAP91, 6914 (2002)

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

A. Thiaville et al., in : Spin dynamics in confined magnetic structures III, Springer (2006)

Open questions

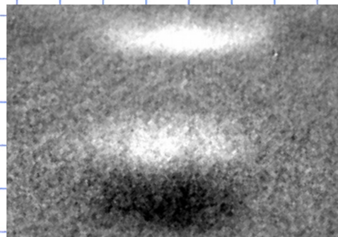
- What about VWs in wires ?
- Do BPWs exist in rectangular wires ?
- Difficulty to vizualize a 3D vector field

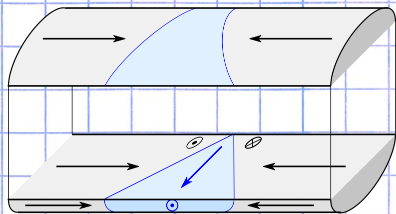
→ How to classify simply domain walls ?

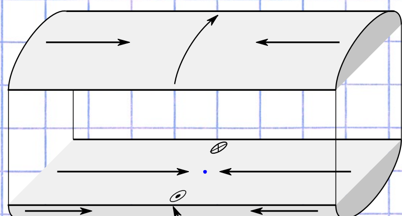
Example of confusing vocabulary for wires

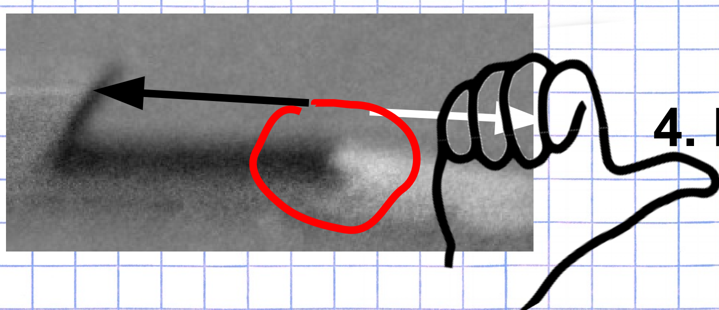
⇨ Bloch-point wall = Vortex wall, pseudo-vortex wall...

⇨ Transverse wall = pseudo TW, asymmetric TW, vortex/antivortex wall, corkscrew...



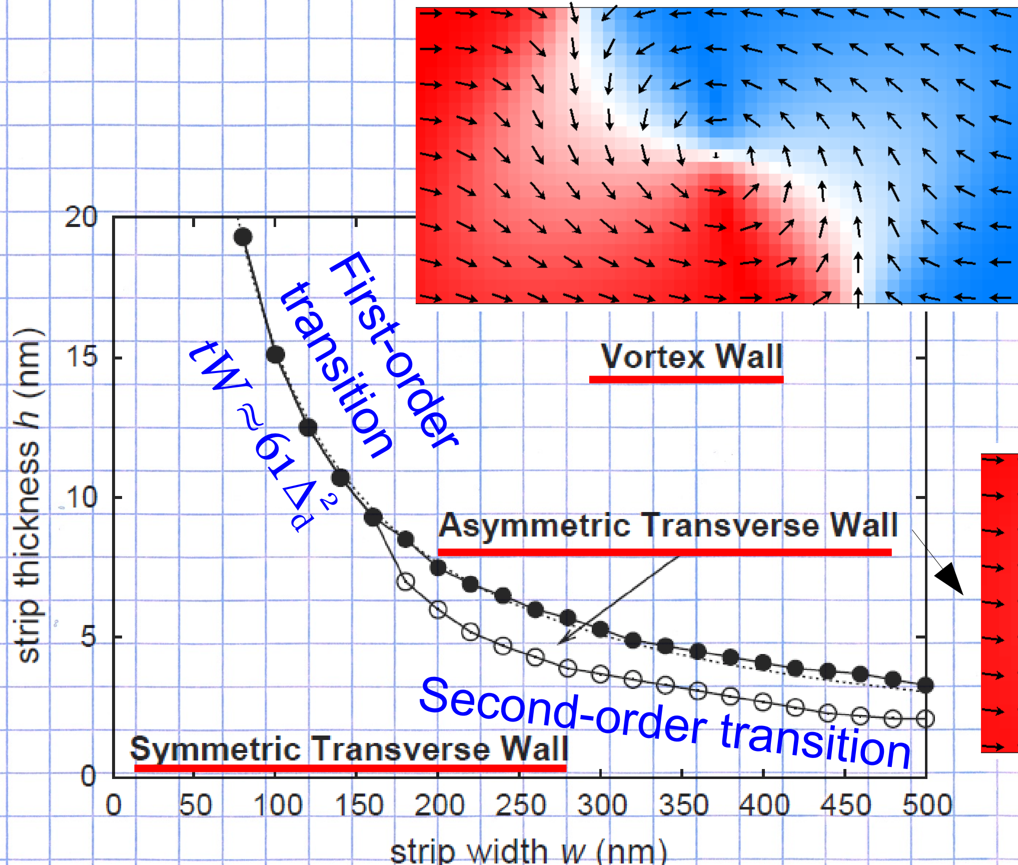


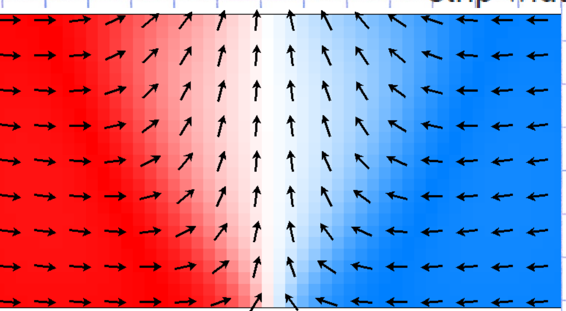




Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead (2015) [arXiv:1412.0679]

The known phase diagram for transverse and vortex walls in strips

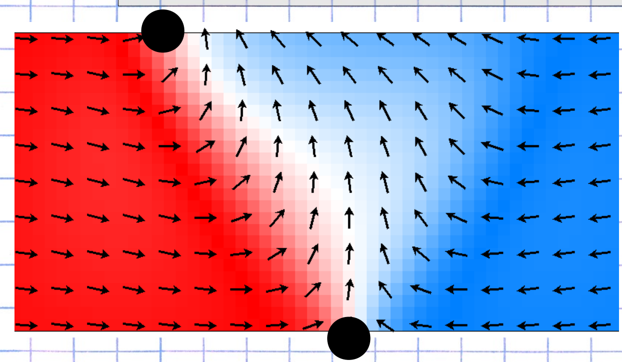




Y. Nakatani et al., JMMM290, 750 (2005)

First order transition

- Abrupt transformation between two separated energy wells
- Metastability of the two states



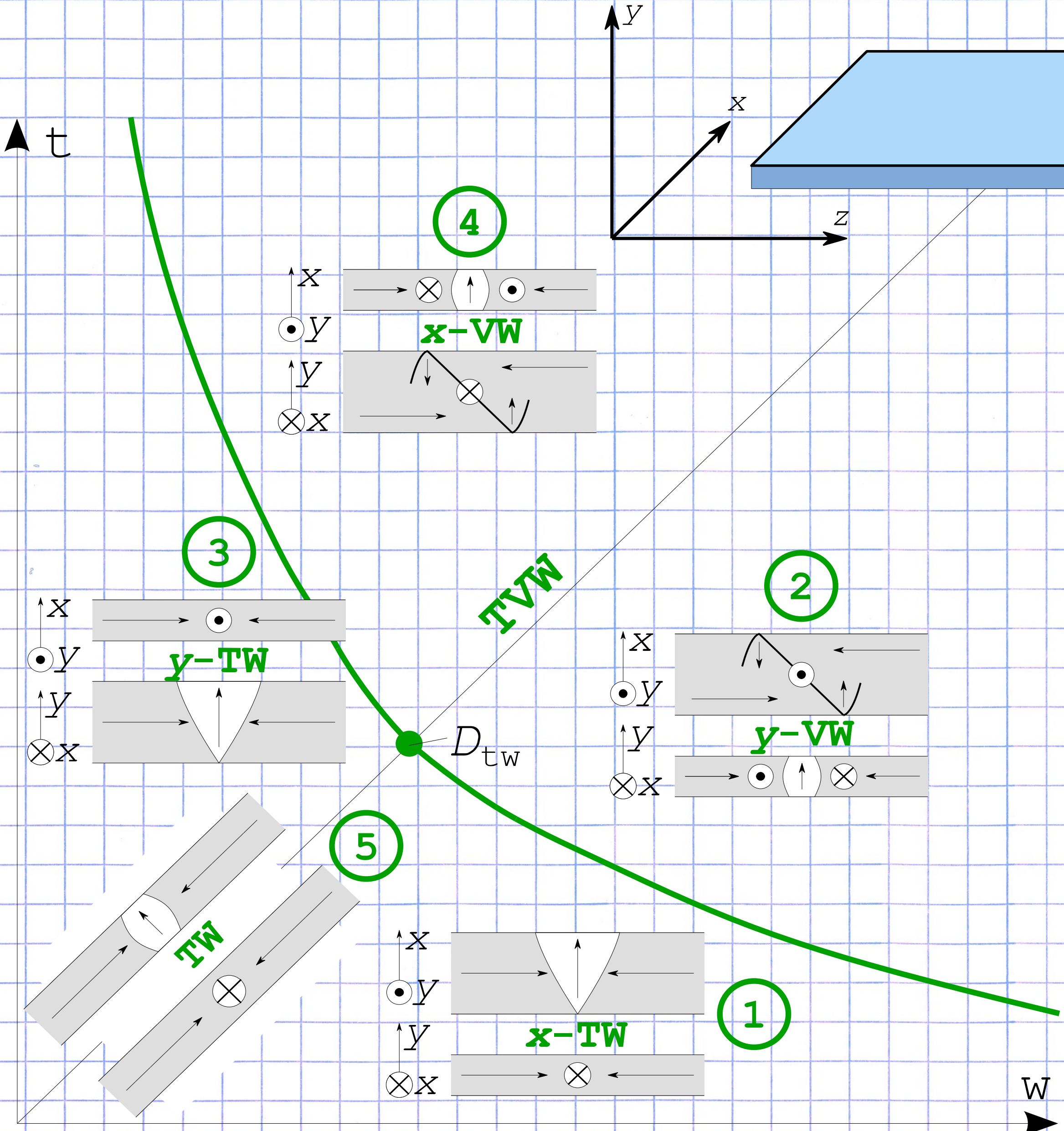
Second order transition

- Continuous transition with an order parameter
- No metastability : only one state exists at a time
- Breaking of symmetry

See phase transitions in micromagnetism :

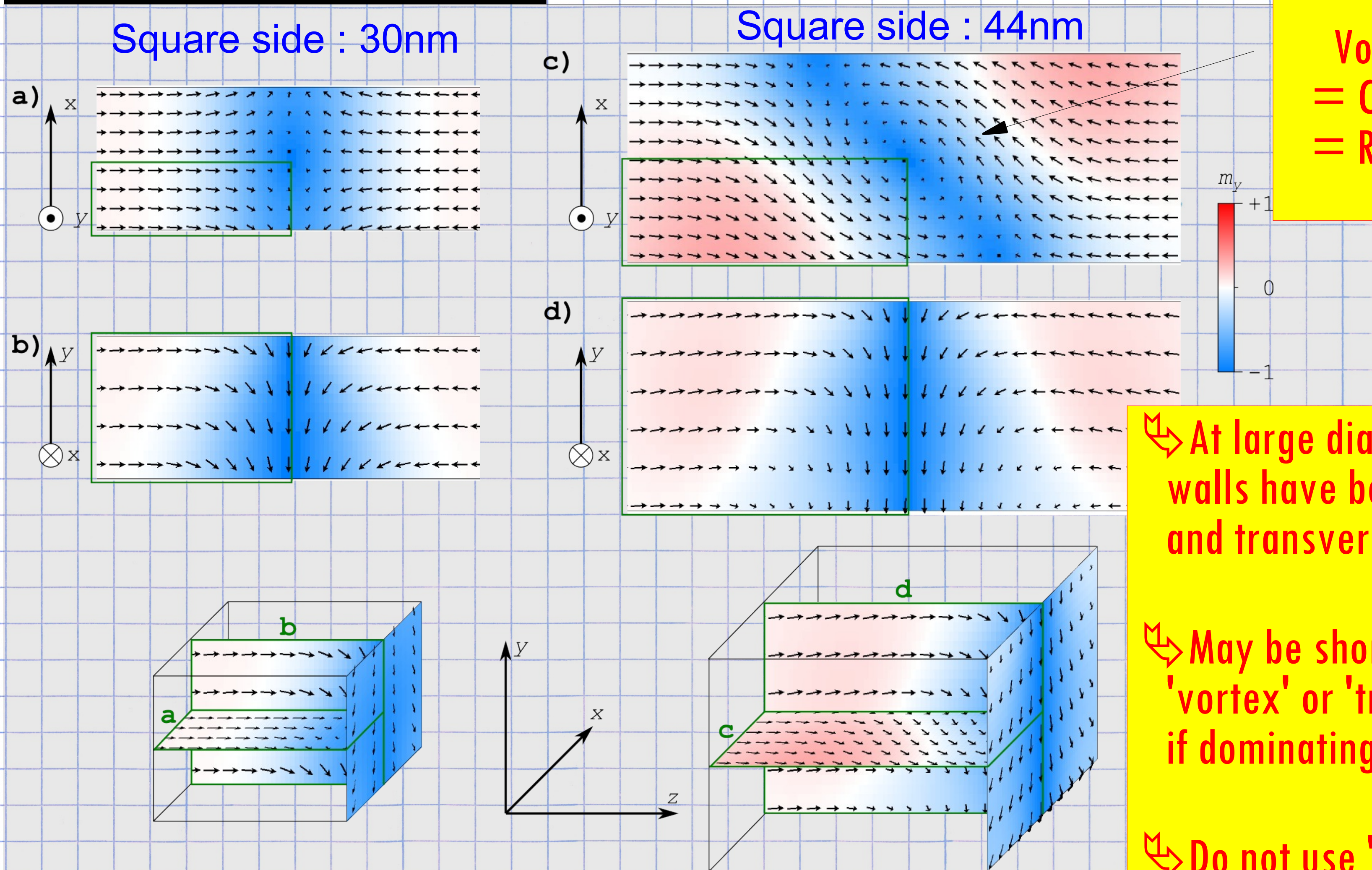
A. Hubert et al., Physica Stat. Solidi B 211, S815 (1999)

First-order transitions between transverse and vortex walls



- It is possible to transform continuously a transverse wall into a vortex wall
- They share the same topology
- They should be degenerate on the diagonal
- The equilibrium line is symmetric with the diagonal

Different views of transverse walls



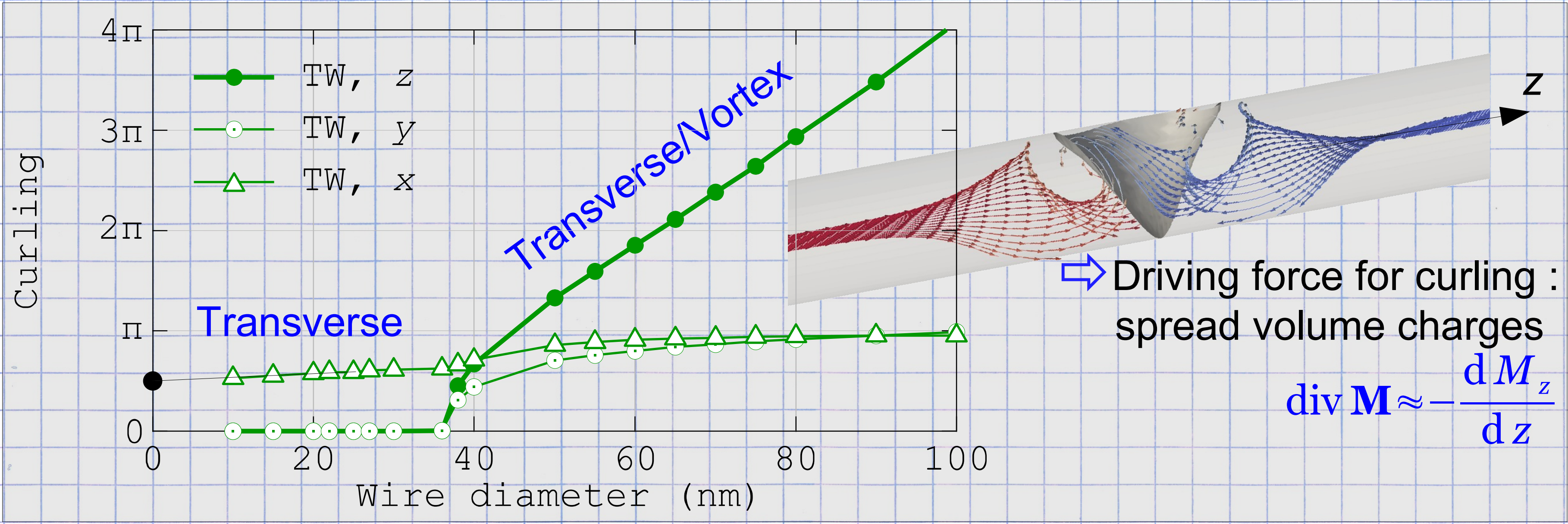
$D \lesssim 7\,\Delta_d$

$D \gtrsim 7\,\Delta_d$

Vorticity
= Curling
= Rotational

- At large diameter walls have both vortex and transverse features
- May be shortened to 'vortex' or 'transverse' if dominating feature
- Do not use 'vortex' for 'Bloch-point' to avoid confusion

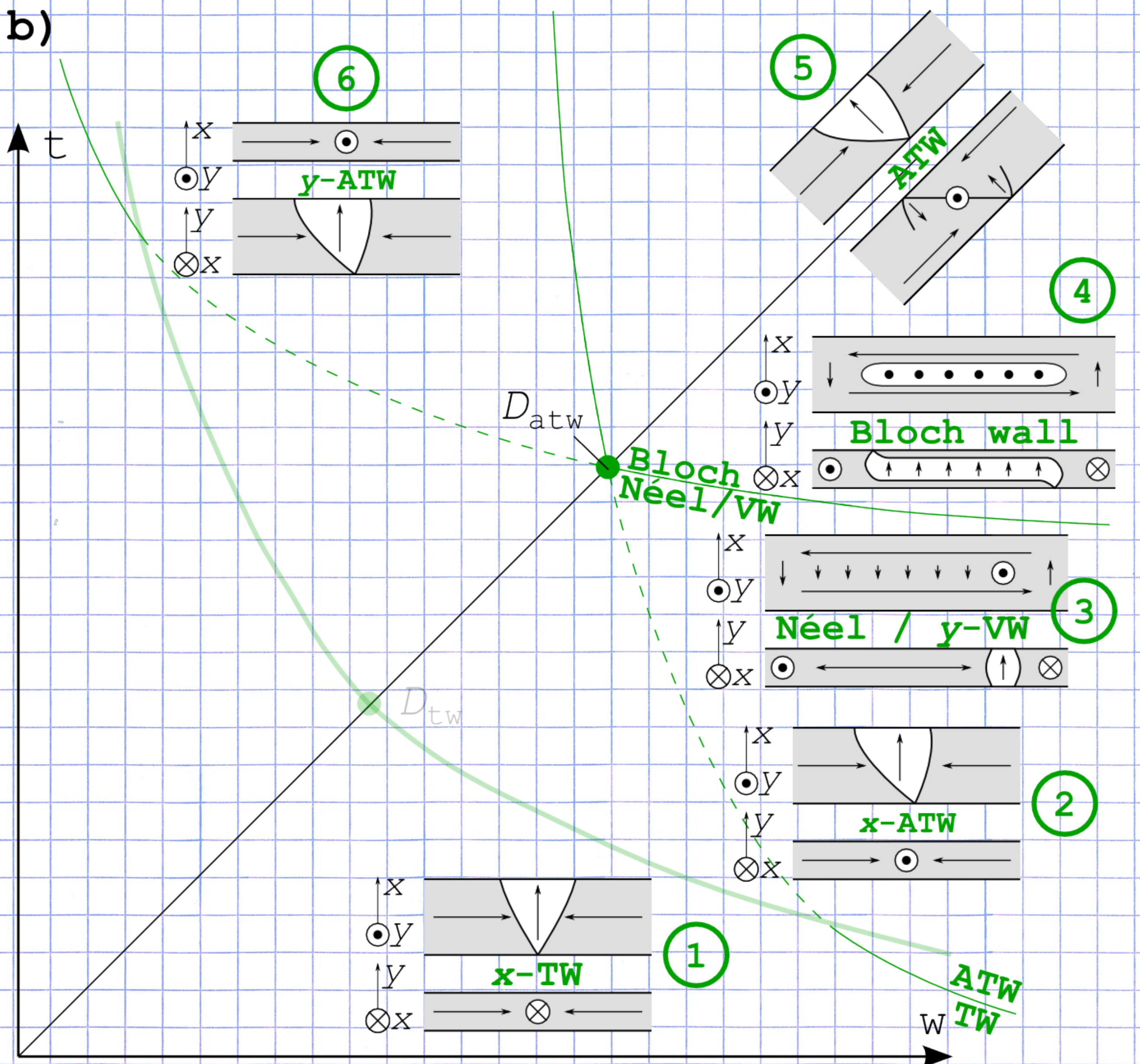
Circulation of magnetization → Quantify curling



⇨ Driving force for curling : spread volume charges

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

- Vortex feature = transverse curling
- Second-order transition for $D \approx 7\,\Delta_\mathrm{d}$
- Longitudinal curling arises to decrease dipolar energy

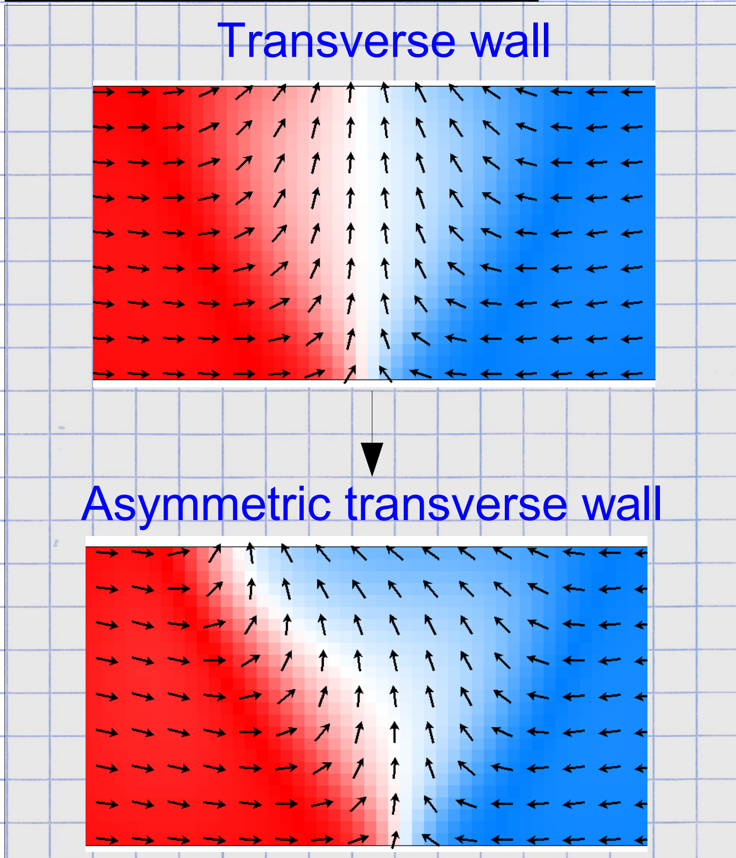


1 : TW
2,6 : Asymmetric TW
3 : Néel walls
4 : Bloch walls
5 : TVW

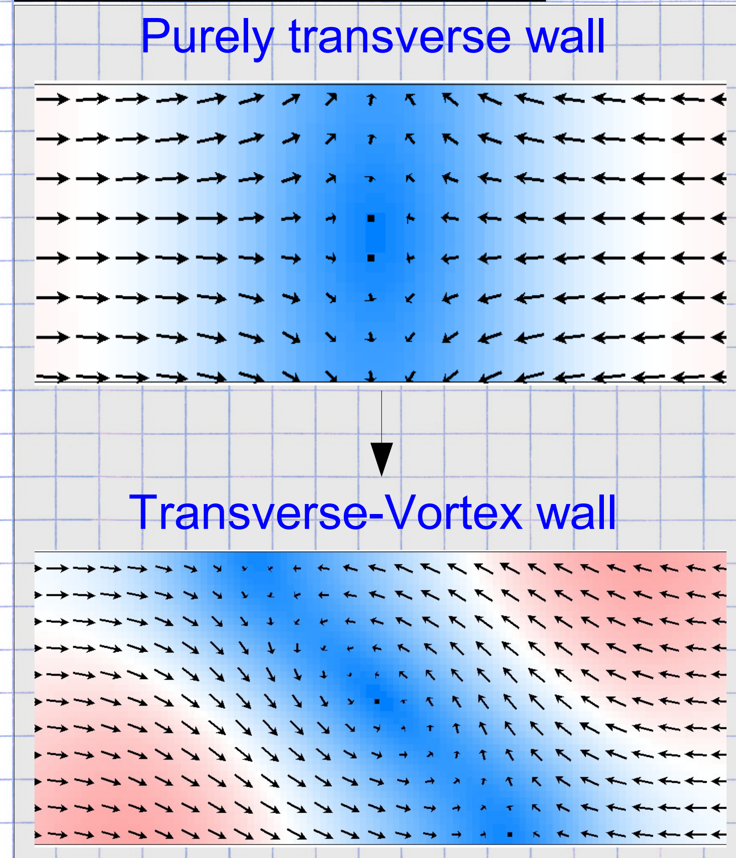
- Analogy between the asymmetric transverse wall and the Néel / Bloch wall transition
- What about asymmetry versus vorticity ?

Second-order transition : simulation tells about asymmetry versus curling

2nd order transition in strips



2nd order transition in wires



$t \lesssim 7\,\Delta_{\mathrm{d}}$ → $t \gtrsim 7\,\Delta_{\mathrm{d}}$

- Both instabilities arise in order to decrease magnetostatic energy (split charges apart)
- Curling takes over asymmetric walls foro thickness larger than $7\,\Delta_{\mathrm{d}}$
- Curling can be viewed as built with opposite asymmetries on either side

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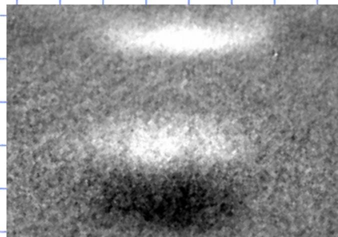
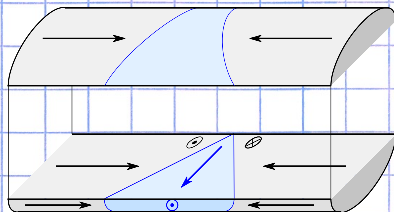
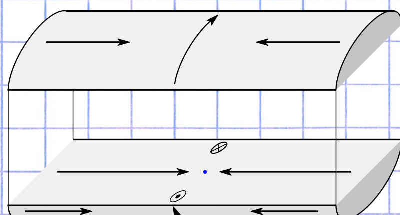
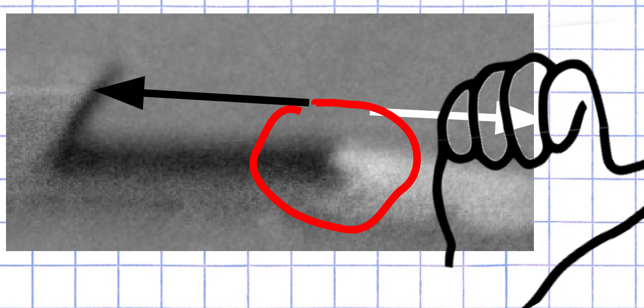




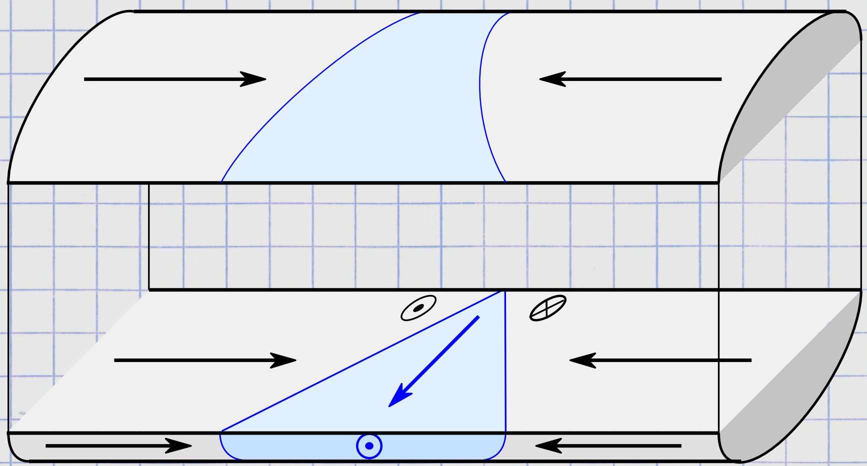




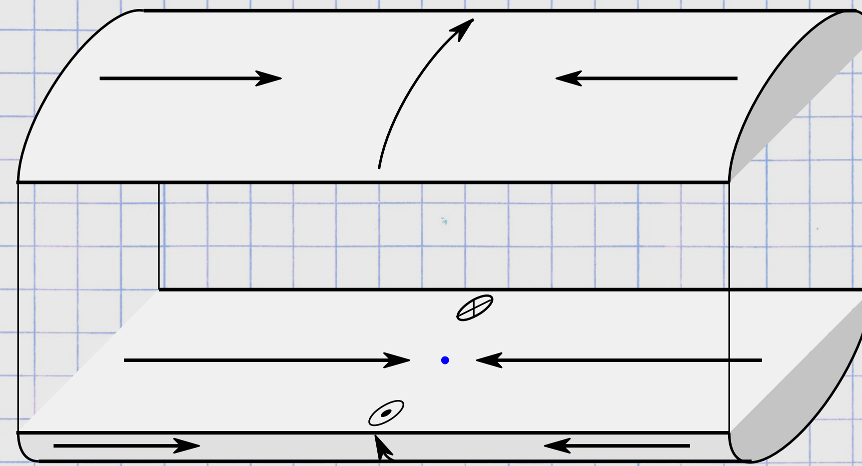
Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead (2015) [arXiv:1412.0679]

The known transition for domain walls in wires (disks or squares)

Transverse wall $D \lesssim 7\Delta_d$



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

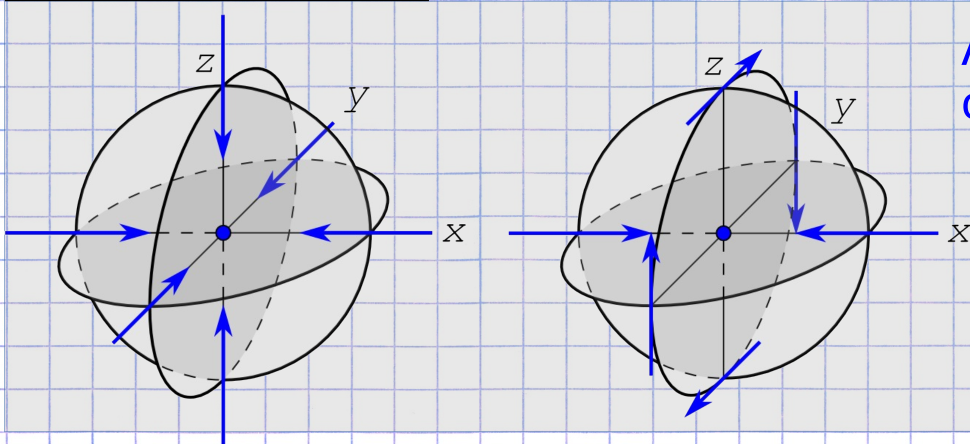


Sometimes improperly named vortex walls

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)

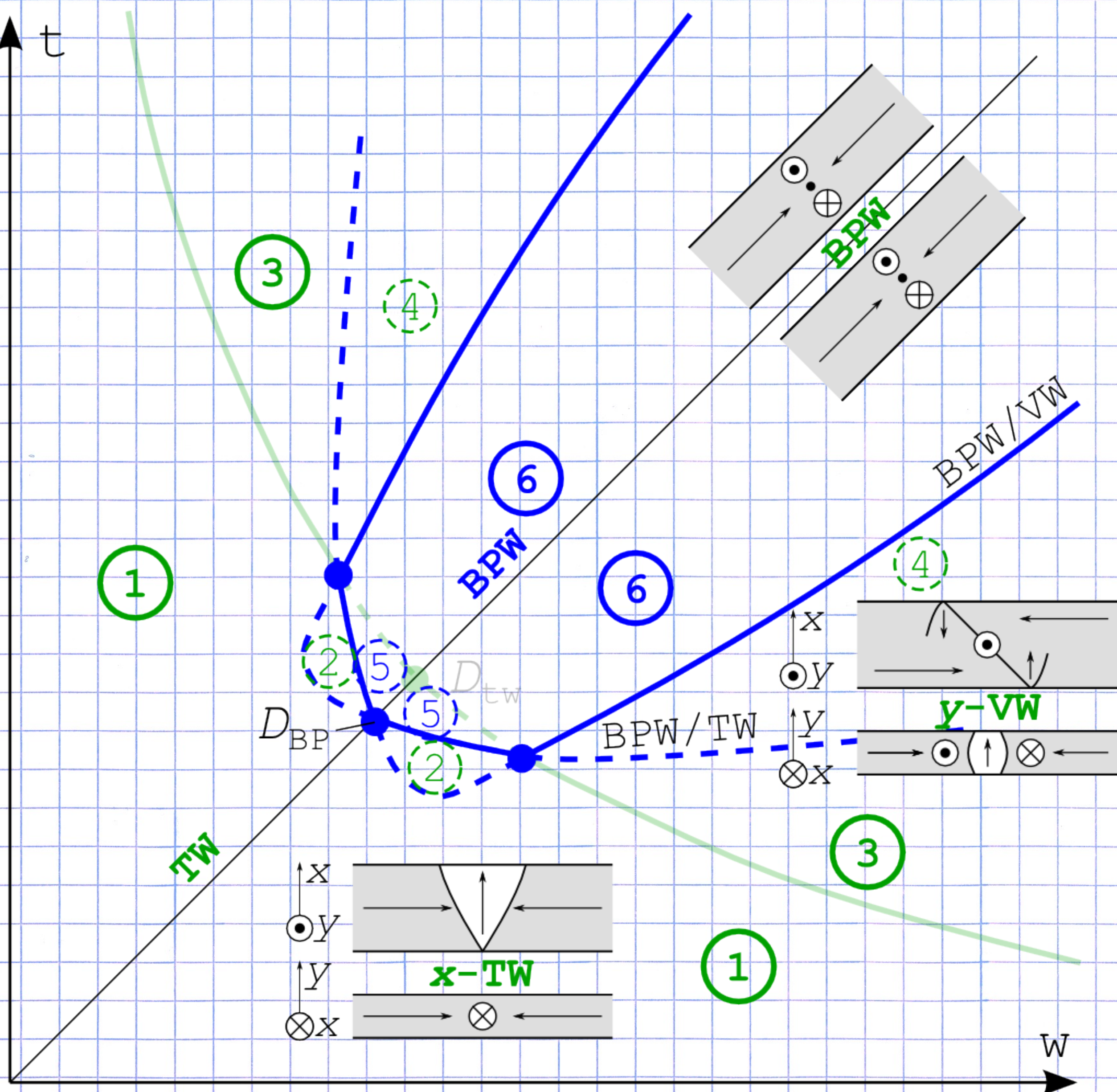
What is a Bloch-point ?



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)



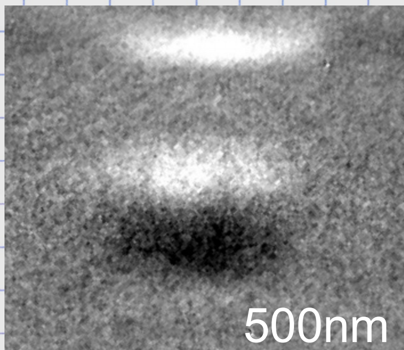
1 : TW < VW < BPW
2 : TW < BPW < VW
3 : VW < TW < BPW
4 : VW < BPW < TW
5 : BPW < TW < VW
6 : BPW < VW < TW

- Two equilibrium lines exist : BPW/x-TVW, and BPW / y-TVW
- The equilibrium lines are symmetric with each other around the diagonal
- If $D_{BP} < D_{TW}$ there must exist three triple points

Quantify domain wall length

Experiments

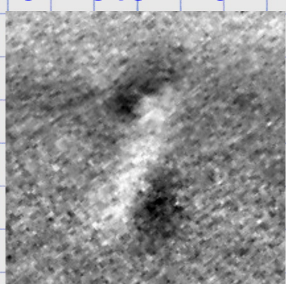
Diameter 95nm



Wire

Shadow

Diameter 70nm



Wire

Shadow

↳ Sharp increase of length with diameter

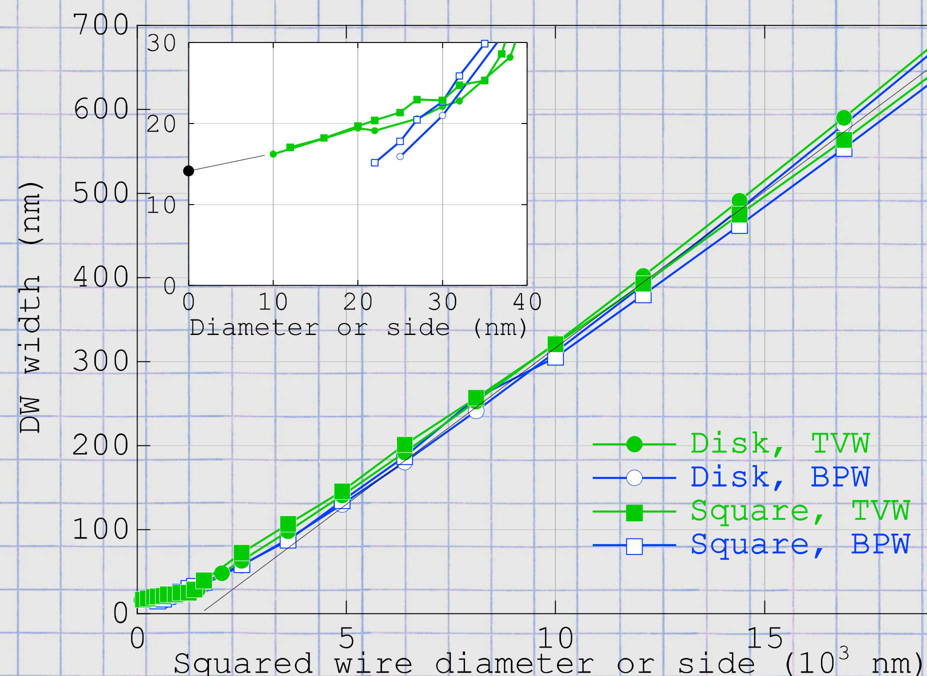
↳ Longitudinal curling is shared by the TVW and BPW

Analytics

Physics : balance exchange and dipolar energies

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

Simulations

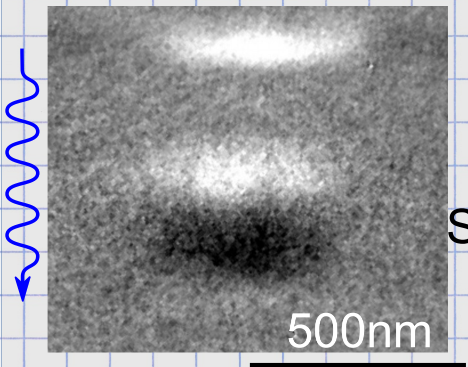


↳ Confirmation of scaling law for wall length $L \sim R^2/\Delta_d$

Bloch-Point Wall (BPW)

Wire diameter : 95nm

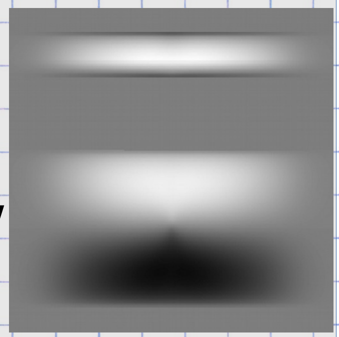
Experiment

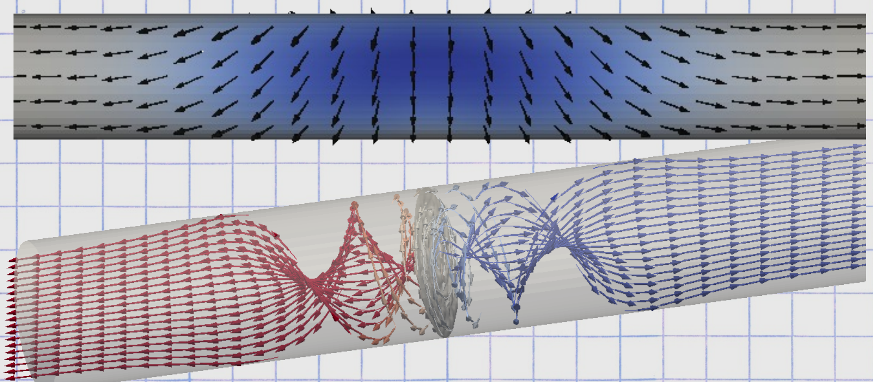


Wire

Shadow

Simulation





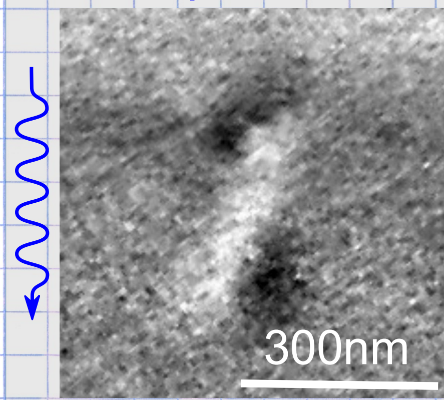
⇨ Orthoradial curling

⇨ Symmetry with respect to plane perpendicular to axis

Transverse Wall (TW)

Wire diameter : 70nm

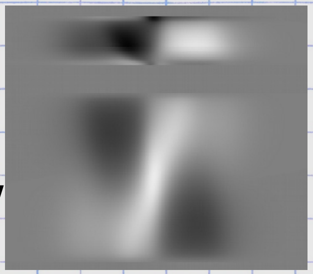
Experiment

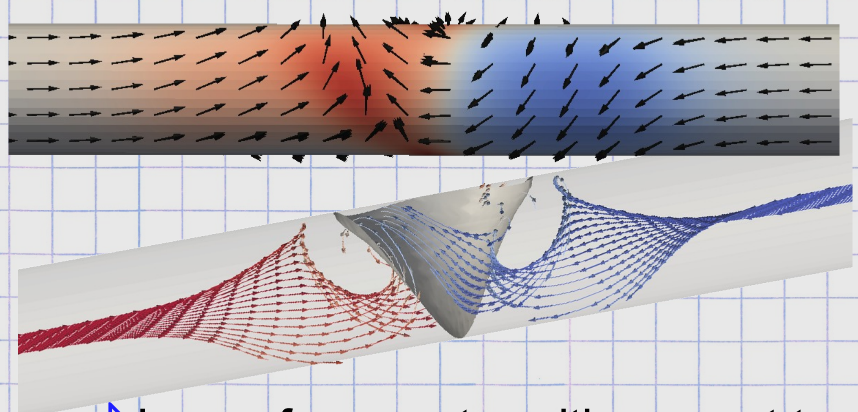


Wire

Shadow

Simulation





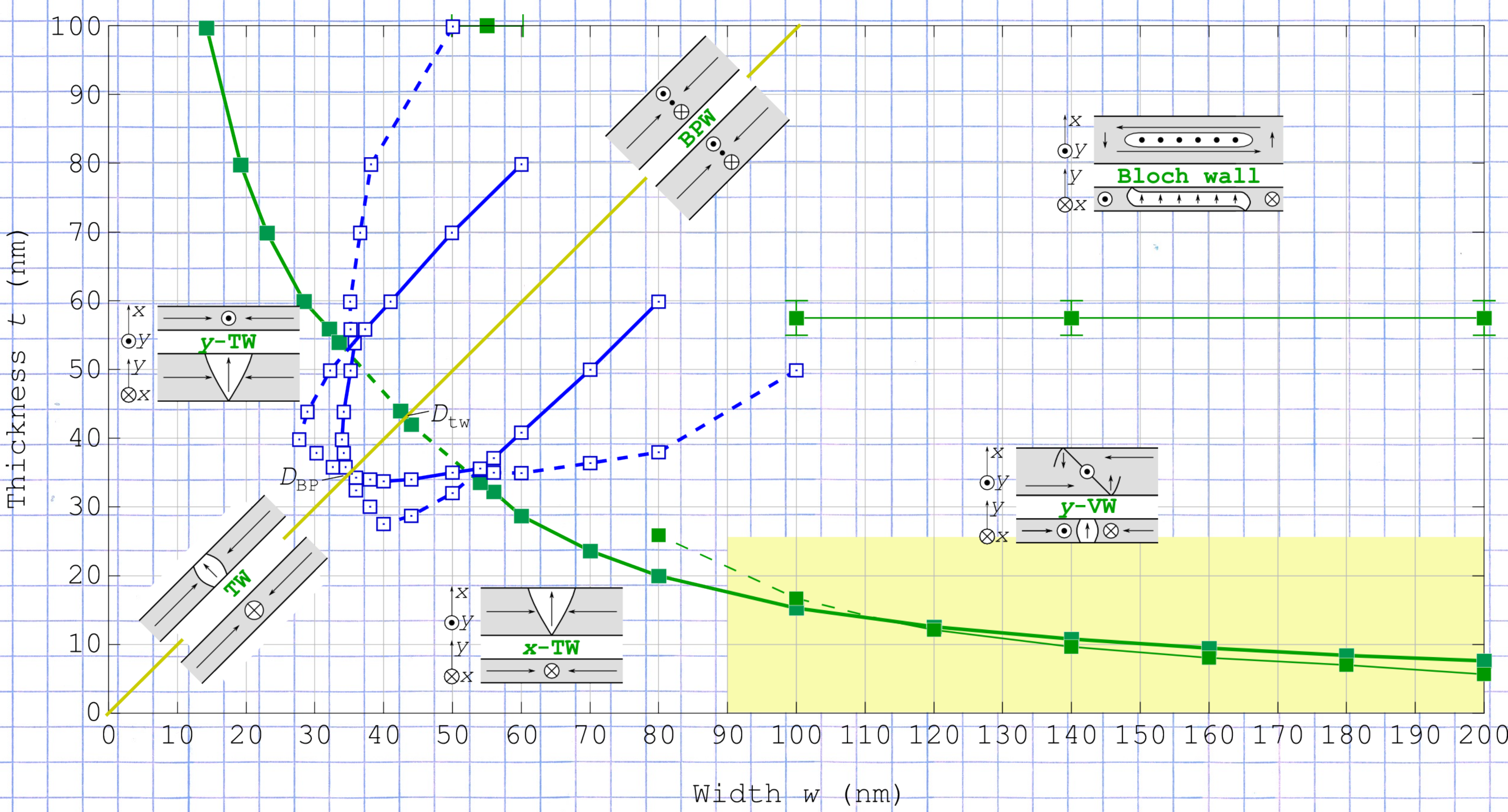
⇨ Loss of symmetry with respect to plane perpendicular to axis

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

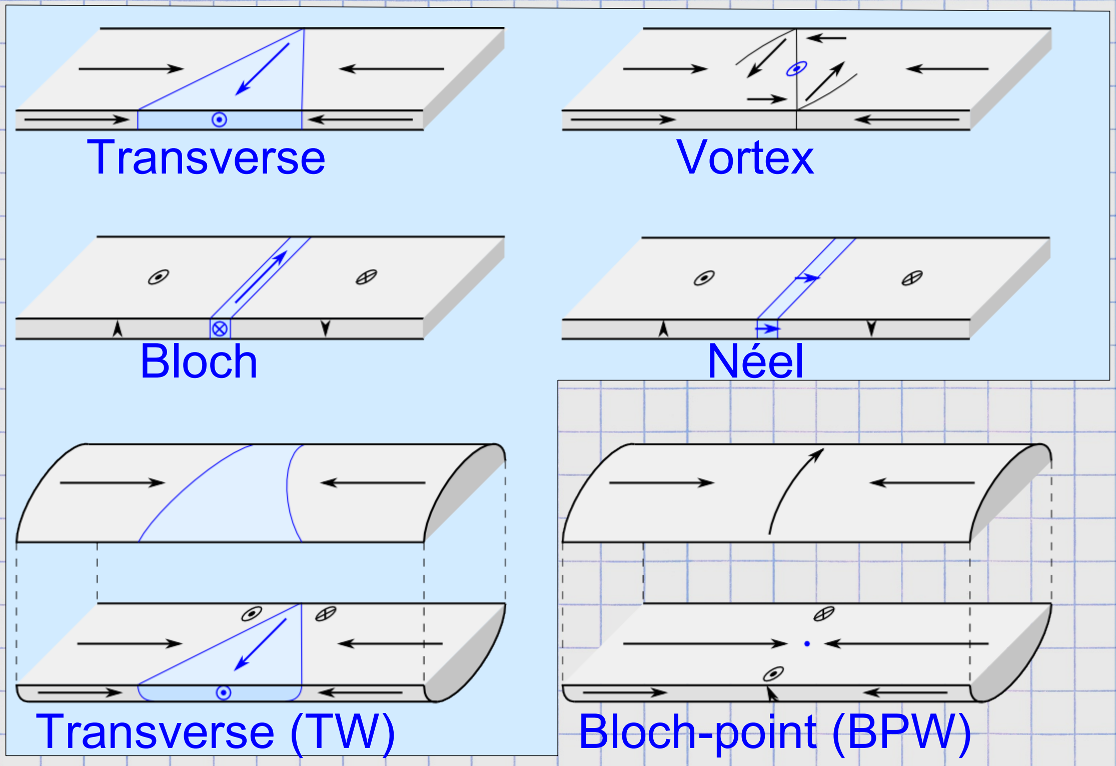
→ Transverse wall imaged with electron holography

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

Phase diagram confirmed by simulation



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 (similar physics for tubes)

- 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)

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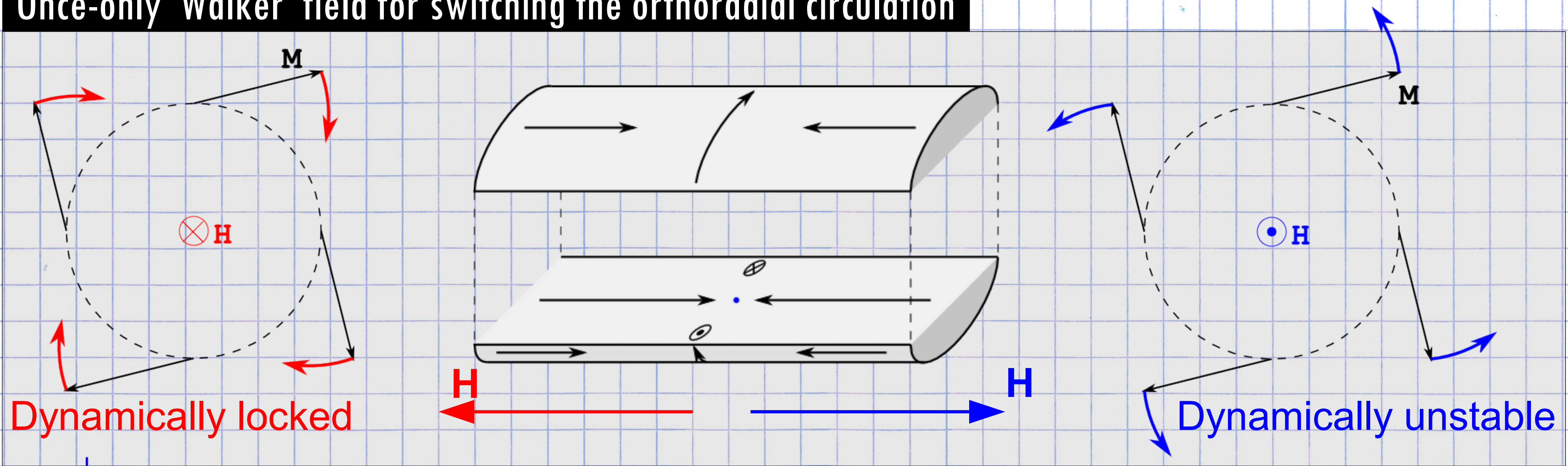
Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead (2015) [arXiv:1412.0679]

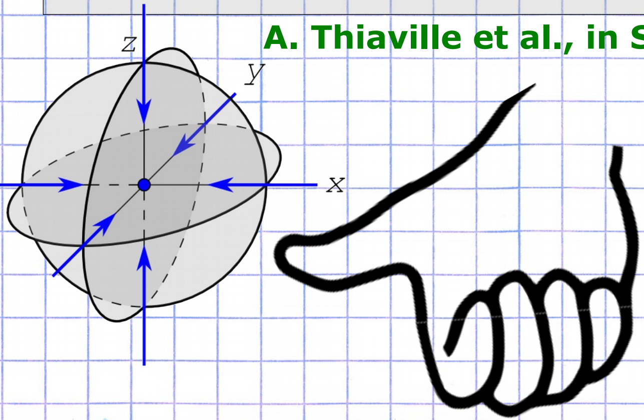
LLG equation

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

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



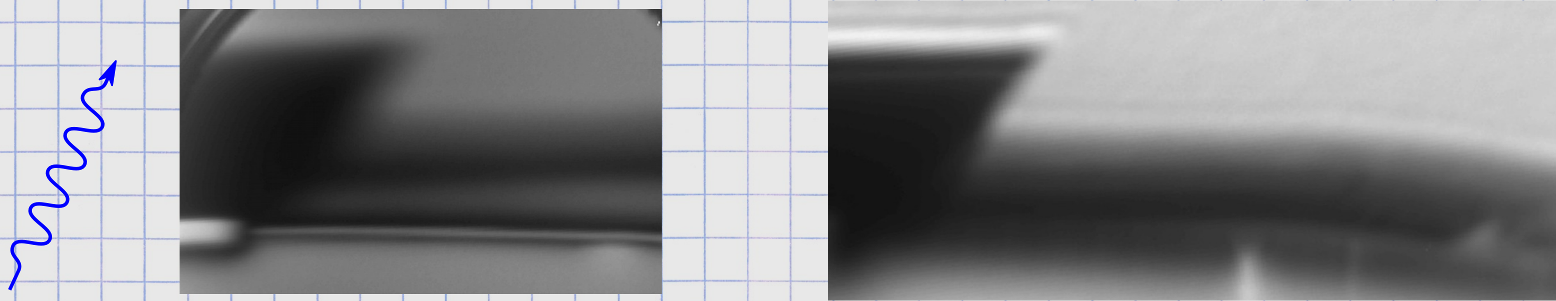
A. Thiaville et al., in Spin dynamics in confined magnetic structures III, p.161-206 (2006)



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

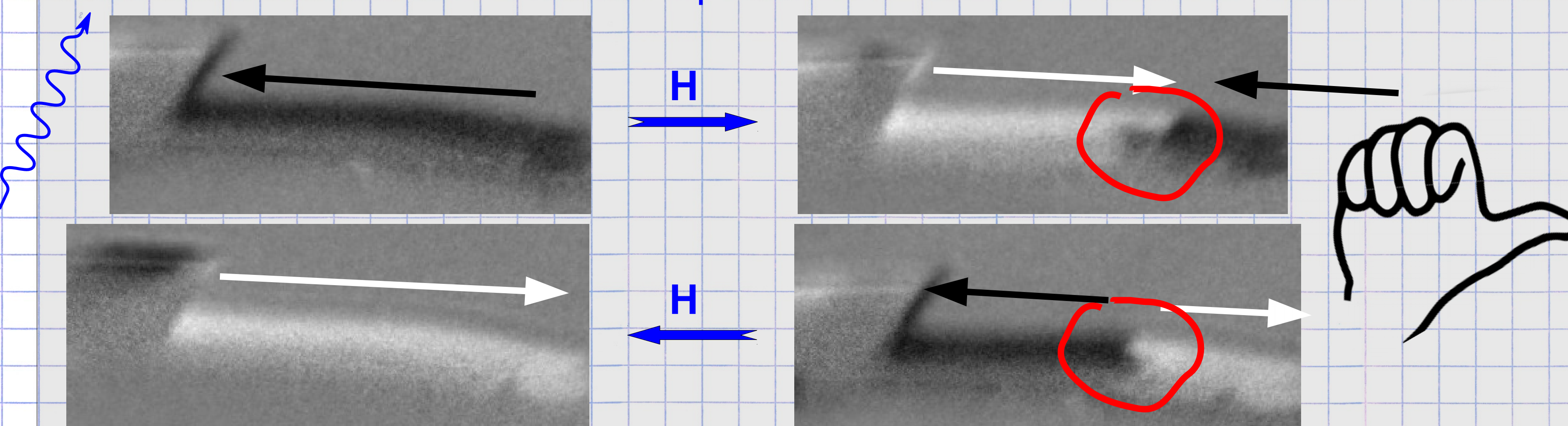
Structure

Focus on wire | Focus on shadow



Motion and circulation

Initialize | Field pulse | Final state

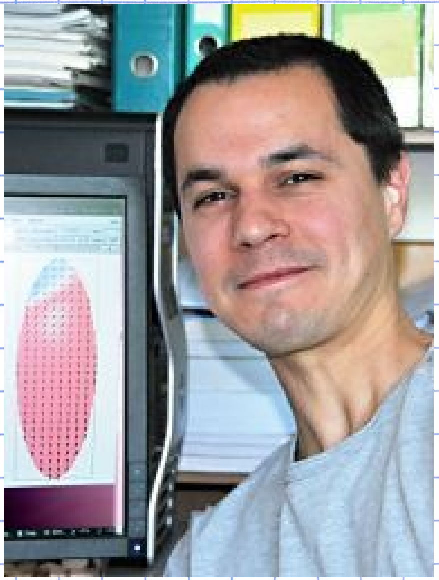


Bloch-Point walls with same circulation

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

Conclusions and VIPs

S. Jamet



N. Rougemaille

C. Thirion

J. C. Toussaint

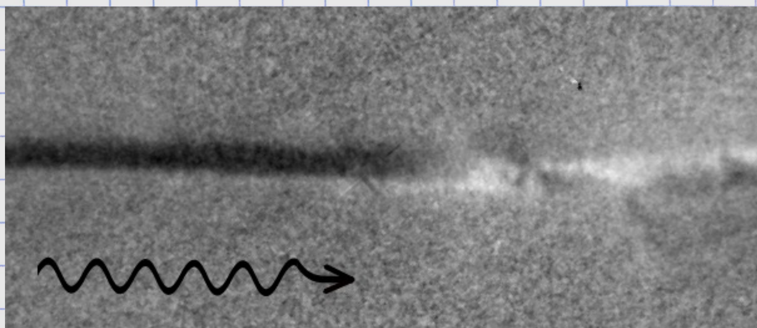
- Only two topologies : transverse/vortex and Bloch-point walls
- Full phase diagram width / thickness derived
- Curling and asymmetries described as second-order transitions. They allow to decrease magnetostatic energy for $D \gtrsim 7\,\Delta_{\mathrm{d}}$
- No asymmetric TWs in wires (transverse is more efficient to decrease energy)
- Bloch walls exist ad is ground state for a large range of geometries

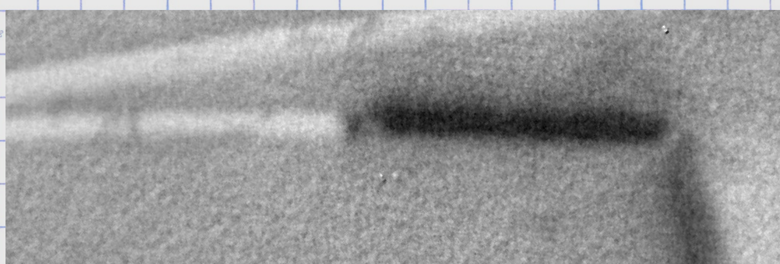
Review chapter : S. Jamet et al., in Magnetic Nano- and Microwires: Design, synthesis, properties and applications, M. Vázquez Ed., Woodhead (2015) [arXiv:1412.0679]

Two examples

Beam along wire

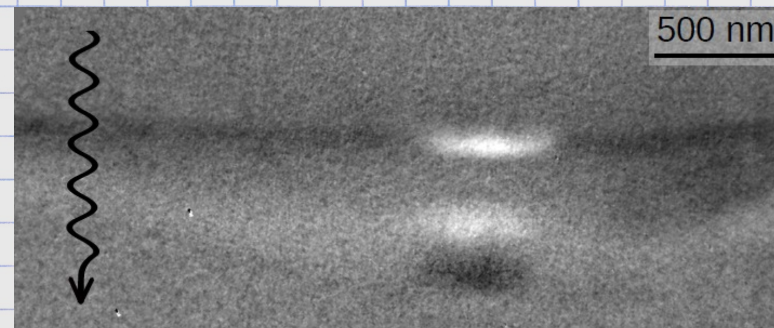
⇨ Locate domain walls





Beam across wire

⇨ Inspect domain wall



- Several non-trivial patterns
- Need for modelling