Surface imaging of flux-closure domains in thick micron-size self-assembled dots: a combined LEEM/XMCD-PEEM study

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Grenoble

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Nanomagnetism: many new effects over the past 20 years

Transport: GMR, CMR, TMR etc.

Switching: precessional, spin torque, F/AF

Materials: semiconductors, molecules, multiferroic

...thanks to improvements in:

Fabrication: films, lithography etc.

Characterization: structure, magnetism

Micromagnetic simulations

Cf talk by F. Petroff

C. R. Physique 6 (2005): Spintronics

Boosted or new applications

Memories: hard disks, MO disks, MRAMs

Sensors: sensitivity, down-scaling, read heads

Magnetic logic: prospective (reprogrammable)

Why still bother with static / quasi-static magnetization configurations?

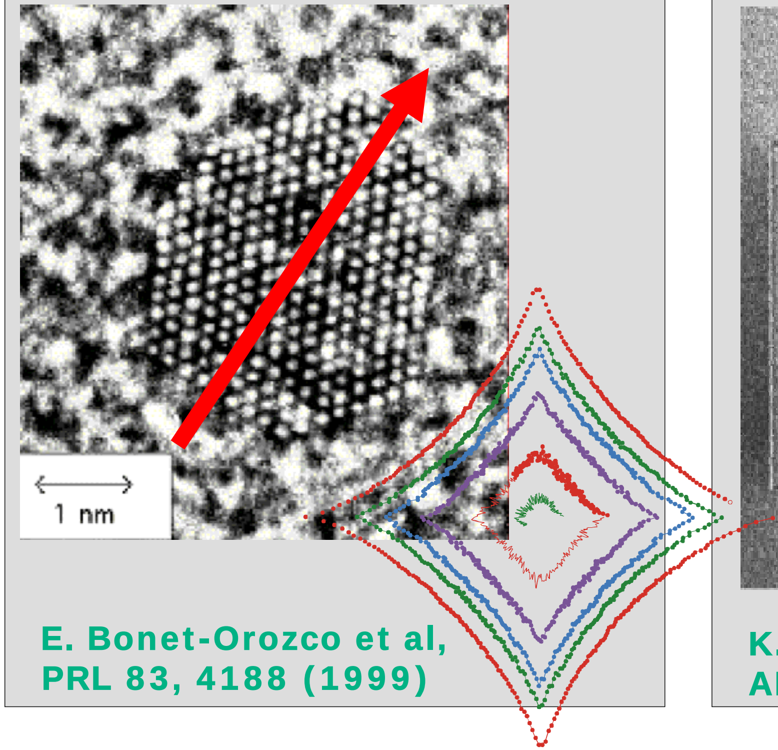
* Prerequisite for integrating concepts into devices
* Some properties modified at the nanoscale: exchange, length scales, anisotropy etc.

Magnetism in reduced dimensions, O. Fruchart, A. Thiaville, C. R. Physique 6, 921 (2005)

Magnetization states: from macrospins to bulk

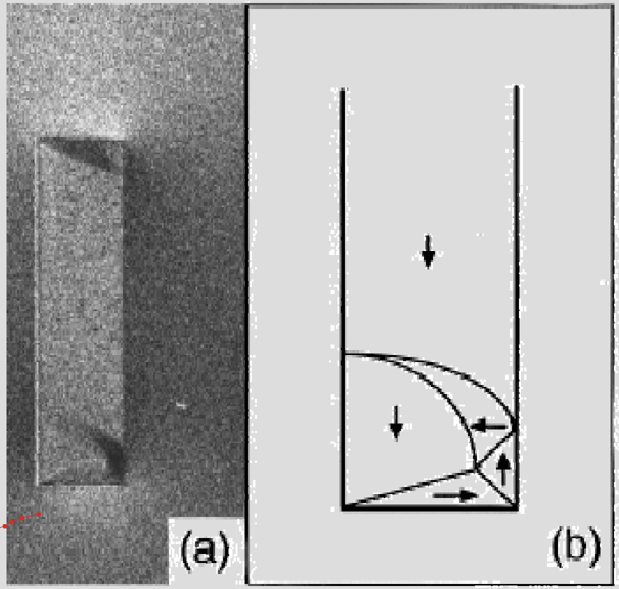
Increasing size

Macrospins



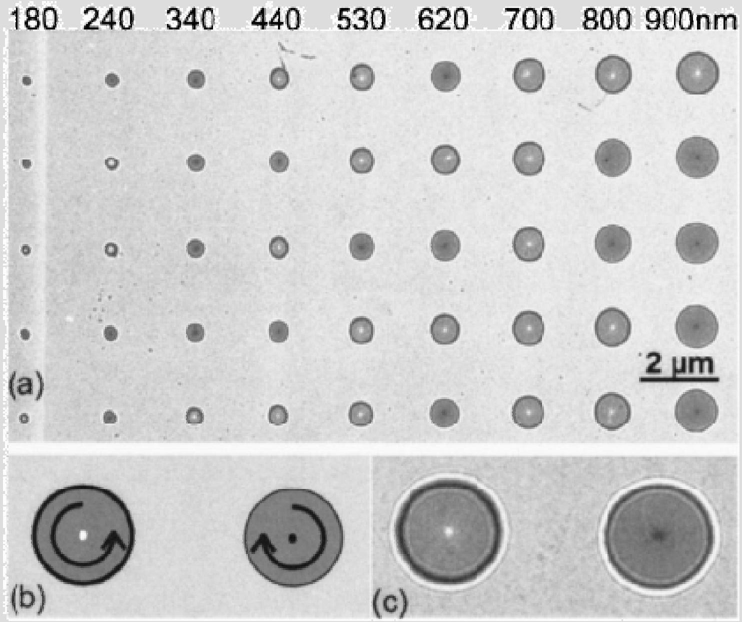
E. Bonet-Orozco et al, PRL 83, 4188 (1999)

Single domains



K. J. Kirk et al., APL 71, 539 (1997)

Closure domains (flat)



M. Schneider et al., APL 77, 2909 (2000)

Cf talk by C. H. Back

Issues for fundamental physics

* Nanomagnetism for 3D flux-closure magnetization?
* From nanostructures to bulk

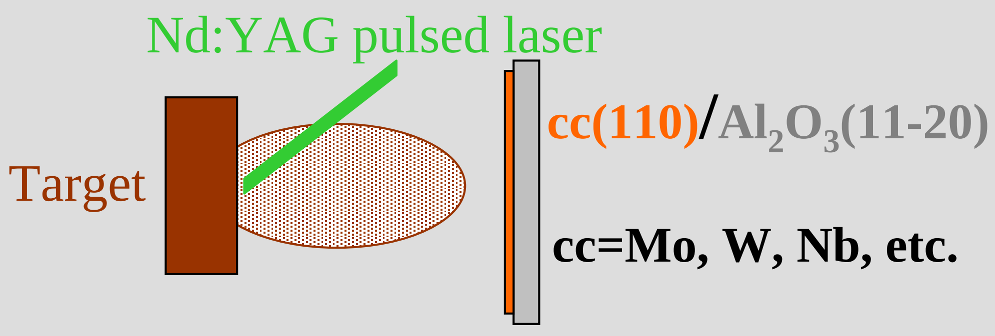
Very few reports:

M. Hehn et al., Science 272, 1782 (1996)
R. Hertel et al., PRB 60, 7366 (1999)
W. Rave et al., JMMM 190, 332 (1998)
J. K. Ha et al., PRB 67, 224432 (2003)

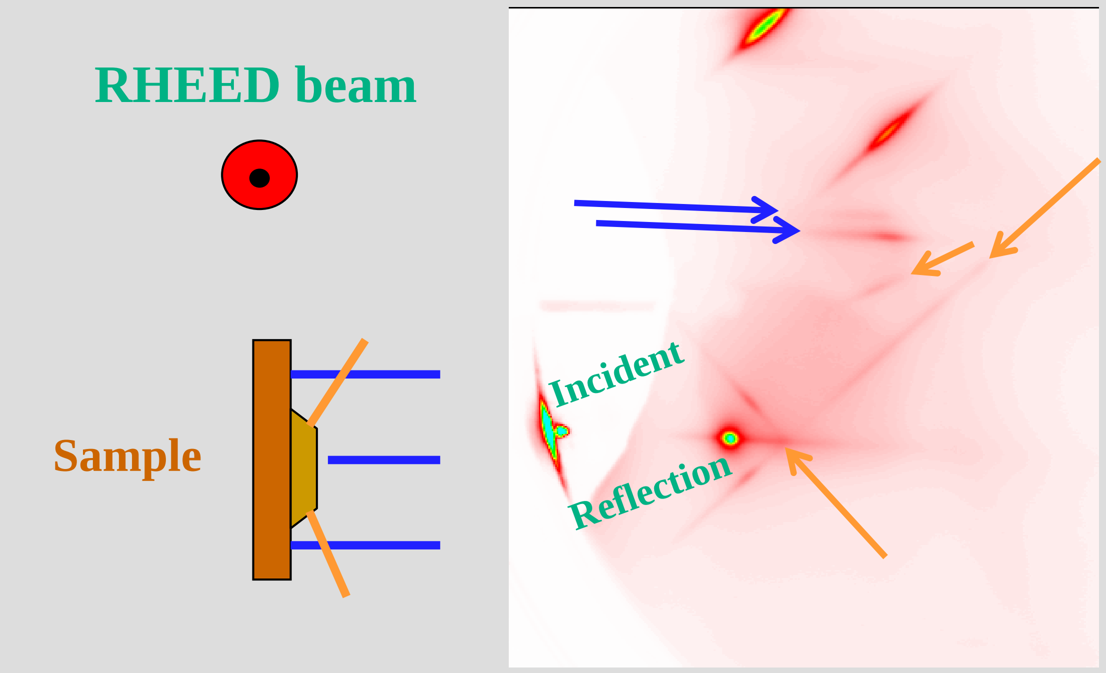
- **Micromagnetic state and hysteresis of domain walls (not domains)**
- **Confine domain walls in nanostructures:**
  - **Single walls > low complexity**
  - **Walls are pinned > can be manipulated**
  - **Constraints can be put on the wall**
- **Use self-assembled nanostructures for higher quality**

Fe/Mo(110) dots: growth and structure

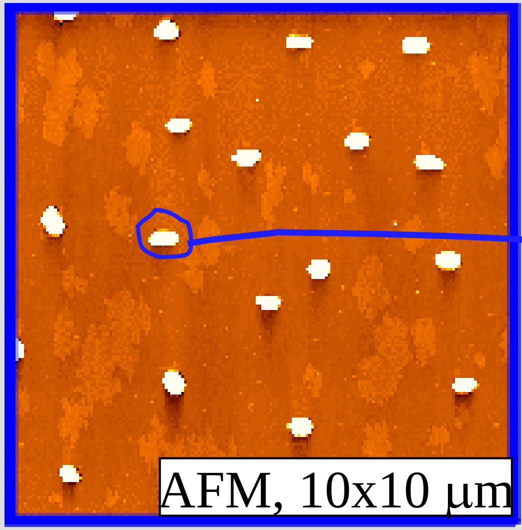
Pulsed Laser Deposition (DLP) in UHV



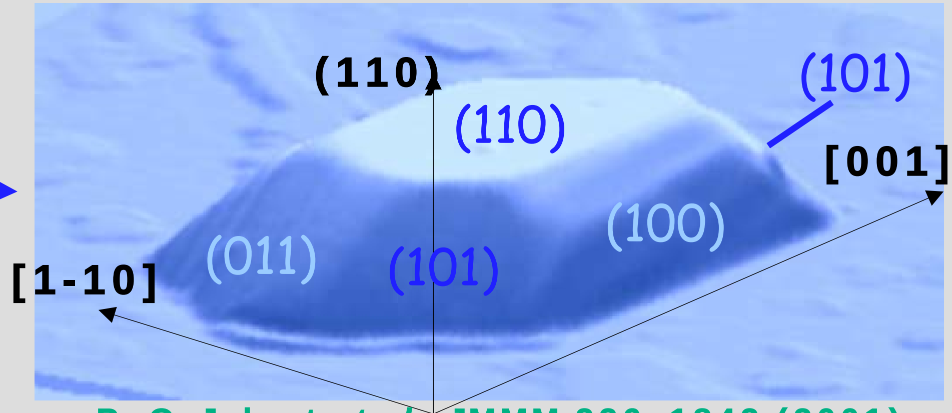
Atomically flat facets



Shape in real space



Fe/Mo(110) @ 450°C

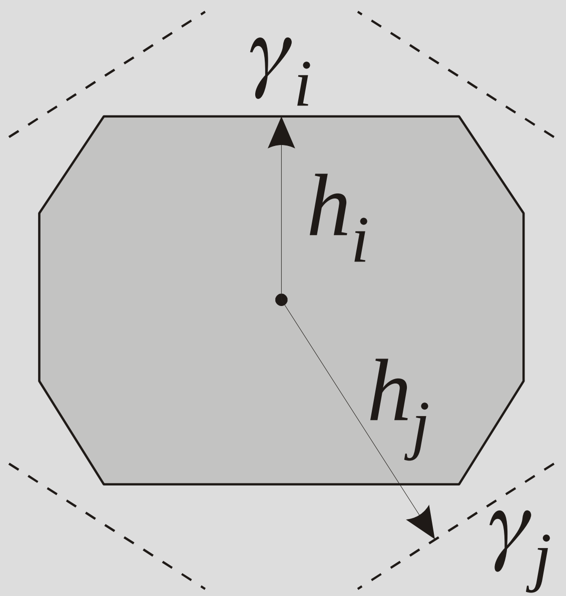


P.-O. Jubert *et al.*, JMMM 226, 1842 (2001)
P.-O. Jubert *et al.*, PRB64, 115419 (2002)

Wulff's theorem

Free standing crystal

$$\frac{\gamma_i}{h_i} = \text{Constant}$$

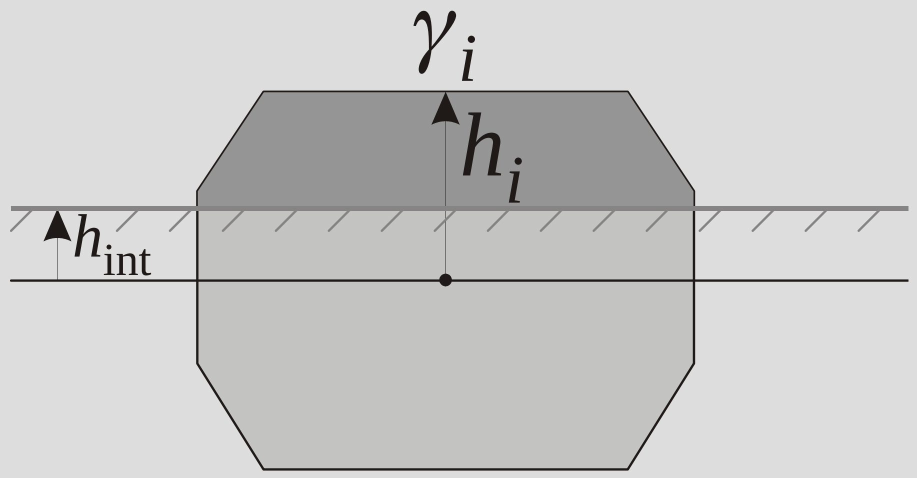


No facet with high surface energy

Wulff Kaishev's theorem

Supported crystal (growth on surfaces)

$$\frac{\gamma_i}{h_i} = \frac{\gamma_S - \gamma_{\text{int}}}{h_{\text{int}}} = \text{Constant}$$



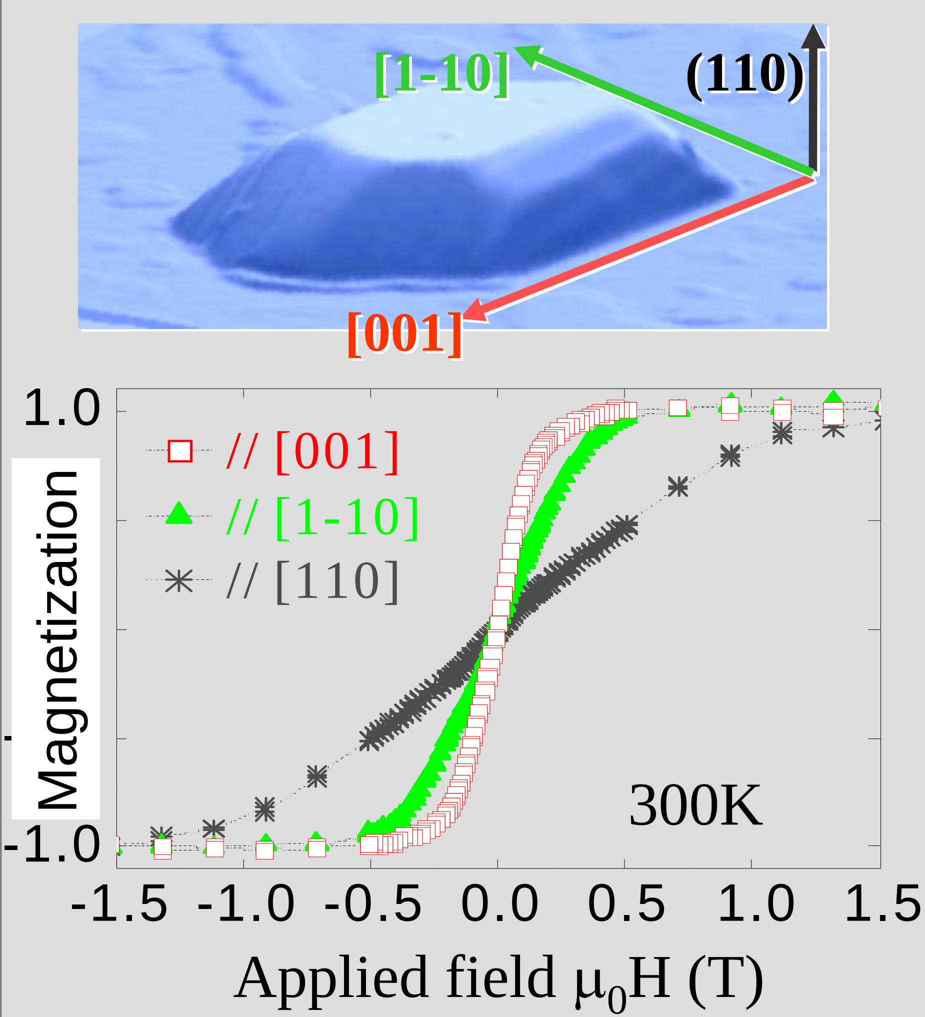
Truncated crystal

With strain:

Simulations or more complex models (e.g. small dots)

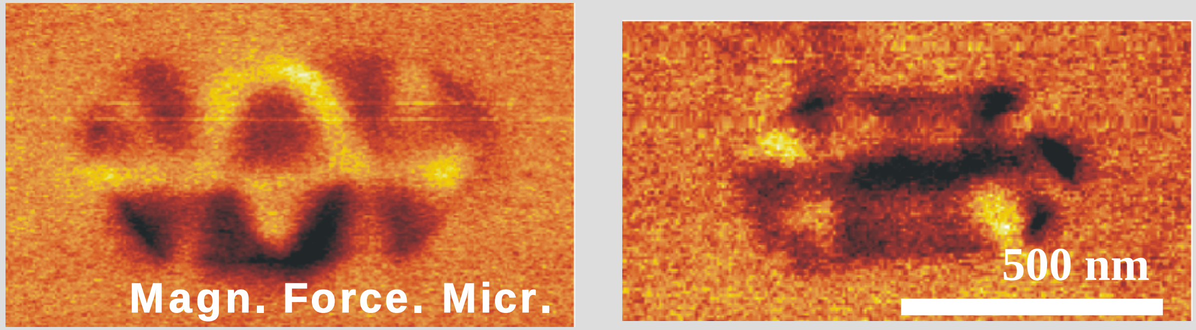
P. Müller and R. Kern,
Surf. Sci. 457, 229 (2000)

Hysteresis loops

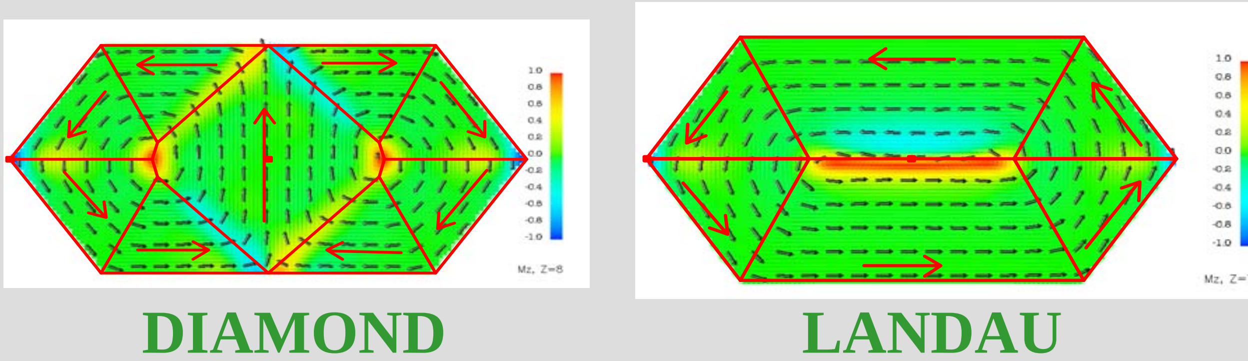


Magnetization states

Remanent states after saturation along [001]



Collabo. Y. Samson (CEA-Grenoble)



Finite-differences method (JC Toussaint)

P.-O. Jubert *et al.*, Phys. Rev. B64, 115419 (2002)
P.-O.Jubert *et al.*, Europhys. Lett. 63, 135 (2003)

Question:
Why two magnetic states can occur?
(Landau state has lower energy)

Hypothesis

Infinitely soft material (*K*=0) $e_{\mathrm{mc}} = 0$

Zero external magnetic field $e_{\mathrm{Z}} = 0$

2D geometry (neglect thickness)

Size >> all magnetic length scales (wall width)

$e_{\mathrm{ex}} \longrightarrow 0$

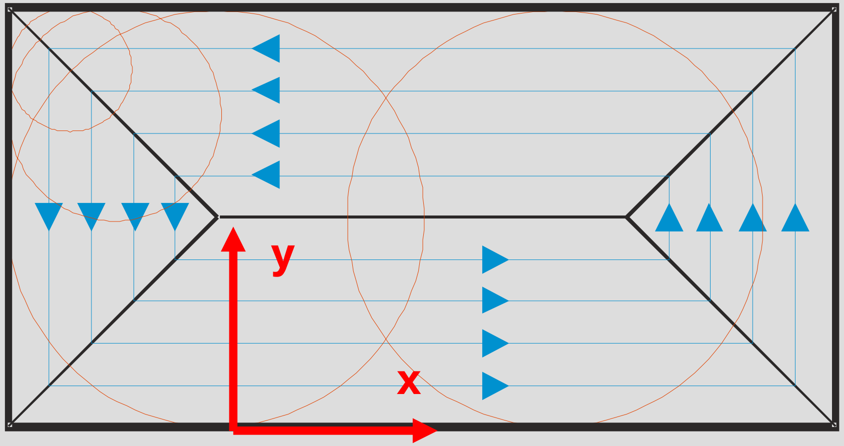
Solution

Looking for a solution with : $e_{\mathrm{d}} = 0$

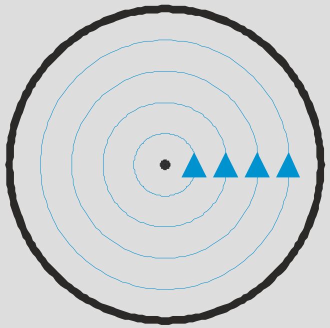
$-\mathrm{div}\mathbf{M} = 0$ (no volume charges)

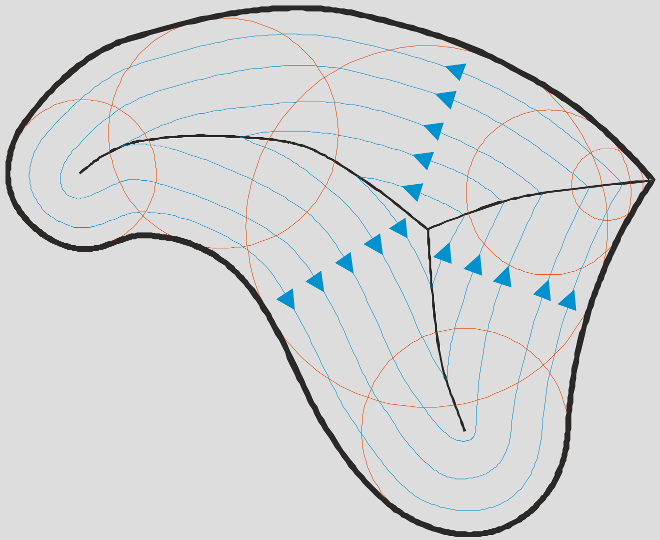
$\mathbf{M}.\mathbf{n} = 0$ (no surface charges)

« Flux closure »

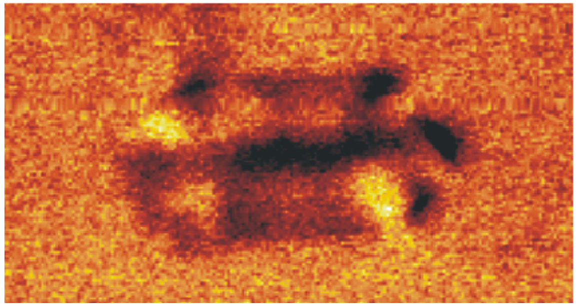


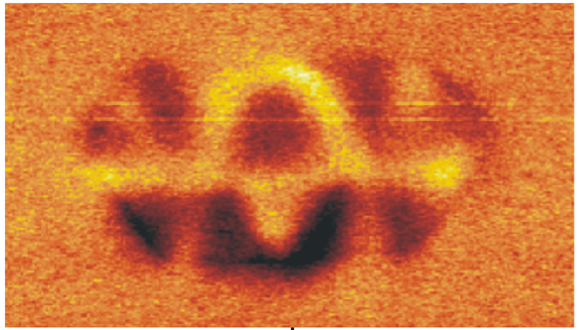
$$\mathrm{div}\mathbf{M} = \frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y}$$

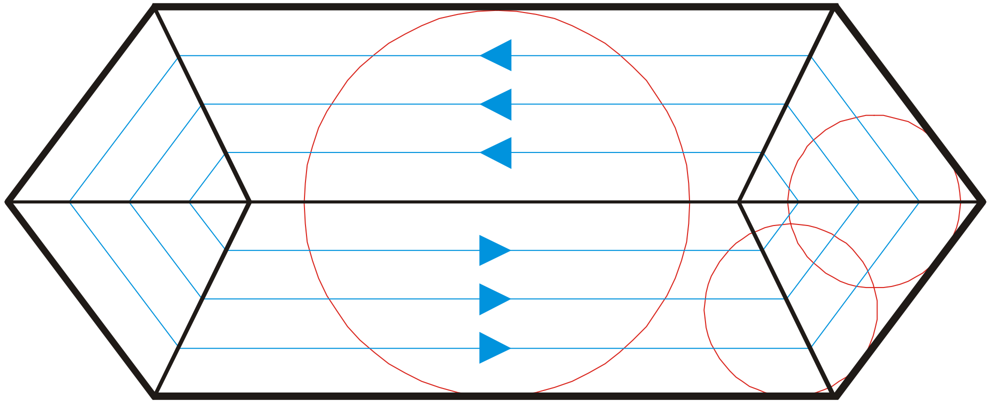


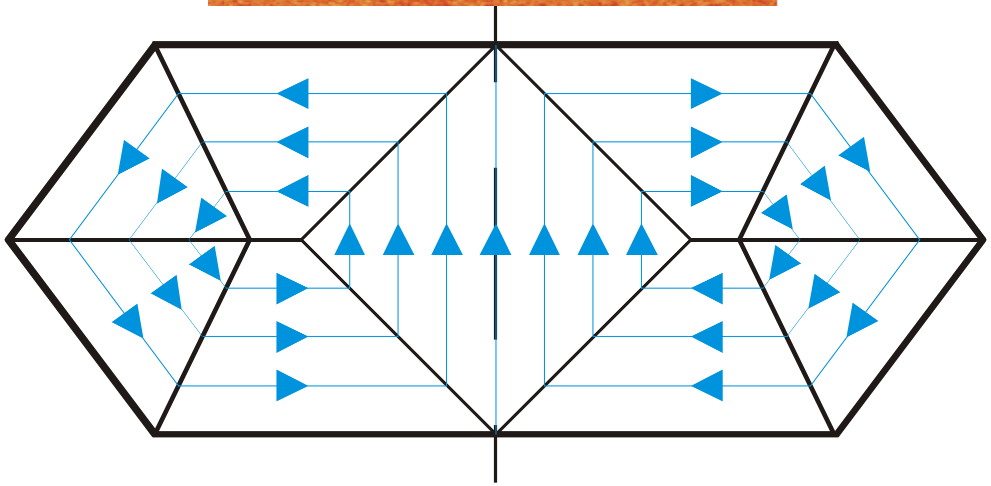


H. A. M. Van den Berg, *J. Magn. Magn. Mater.* 44, 207 (1984)





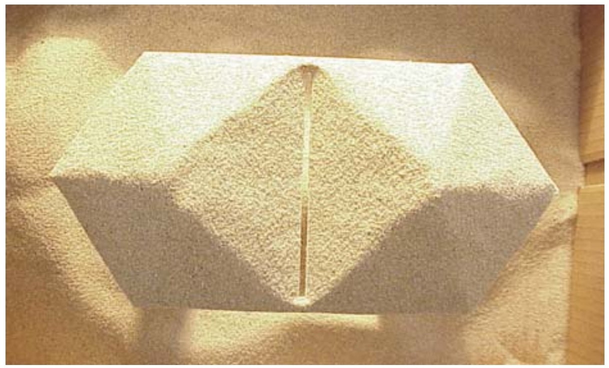




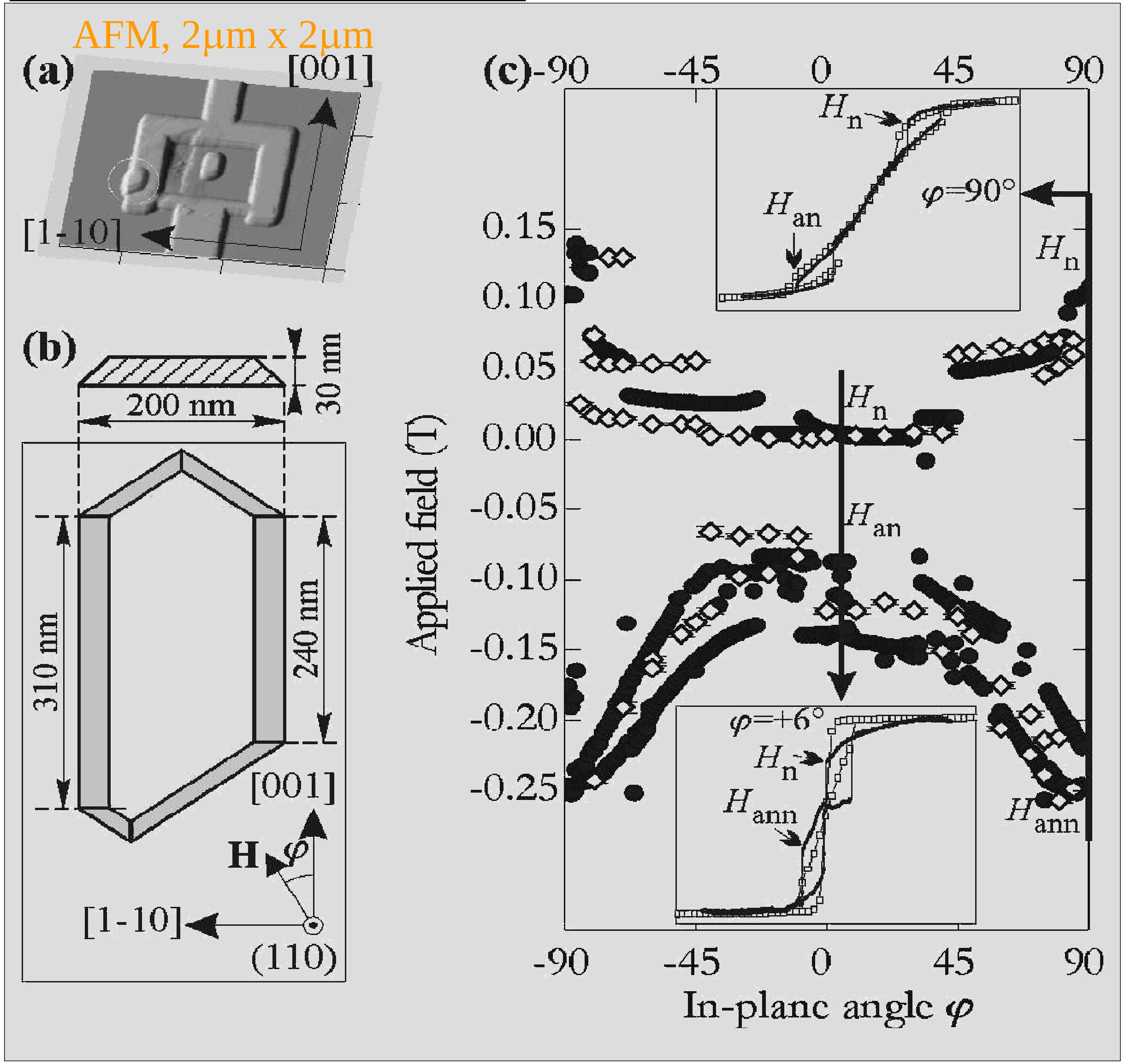
Landau

Diamond

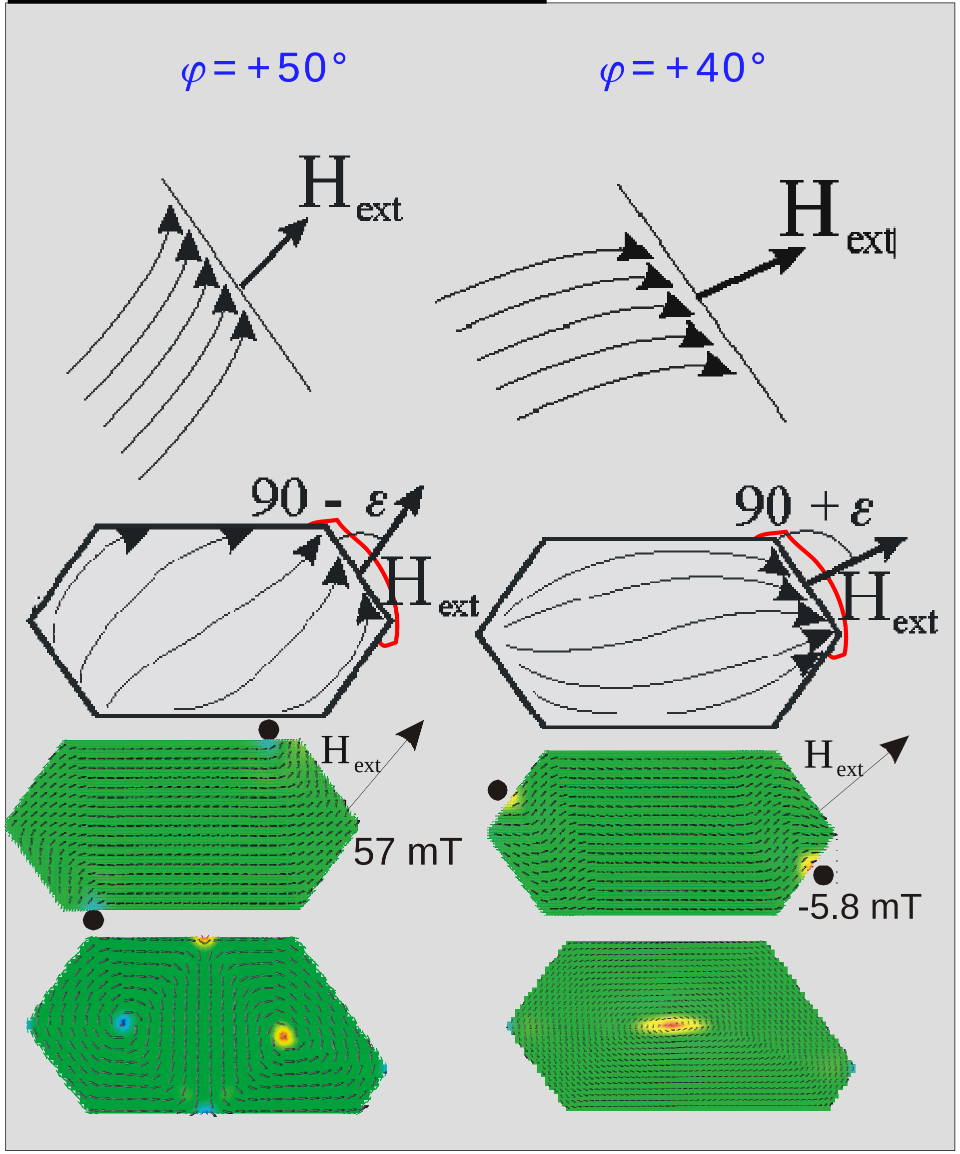
Models based on sandpiles



Measurement of single dots



Micromagnetic calculations

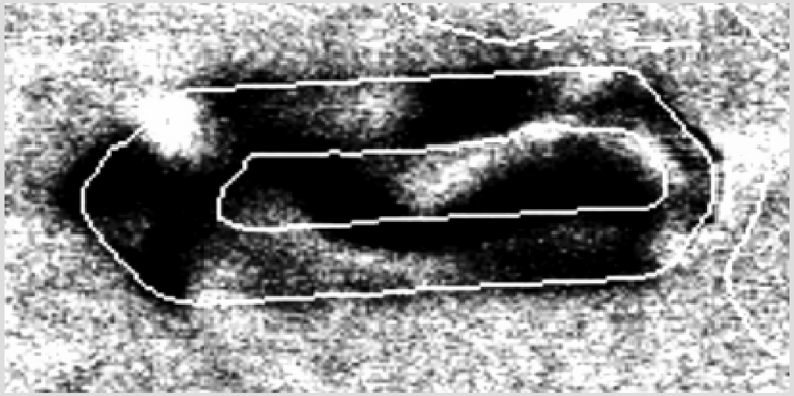


Coll: W. Wernsdorfer, LLN-Grenoble
D. Mailly, LPN-Paris

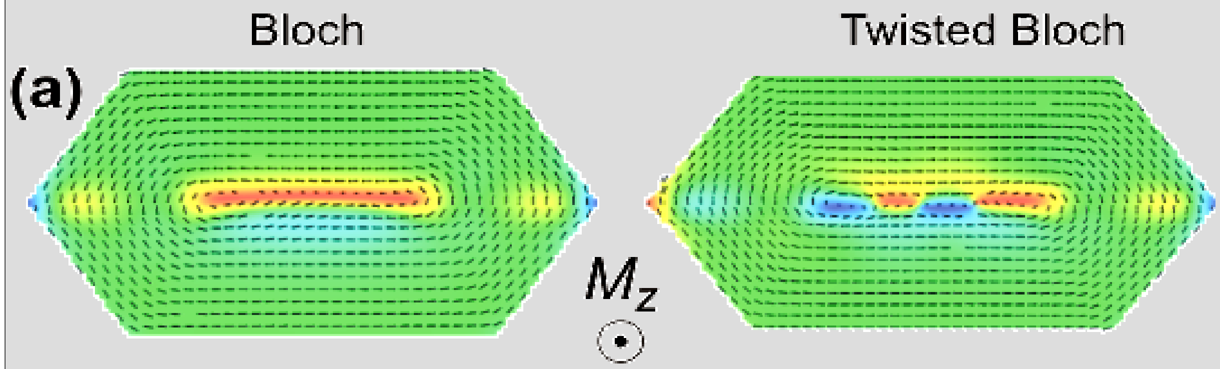
O. Fruchart *et al.*, PRB 70 (R), 172409 (2004)

Fe/Mo(110) dots – Issues to be clarified

Unclear MFM patterns



Bloch points predicted by simulations

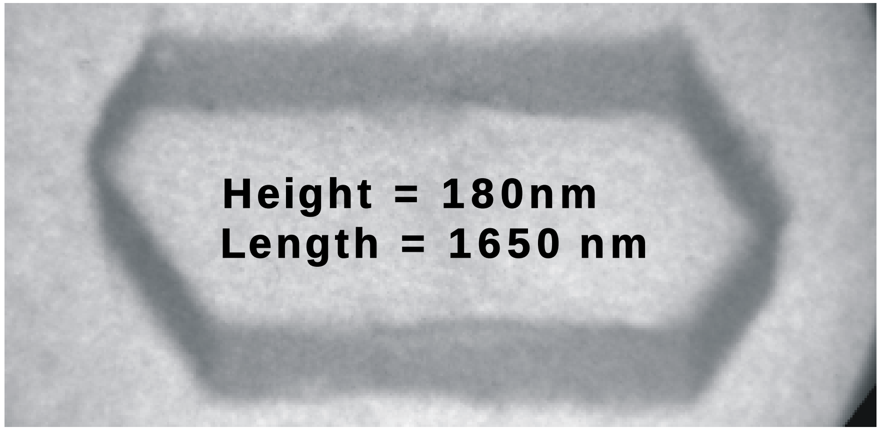


Need to image surface magnetization with high resolution for better insight.

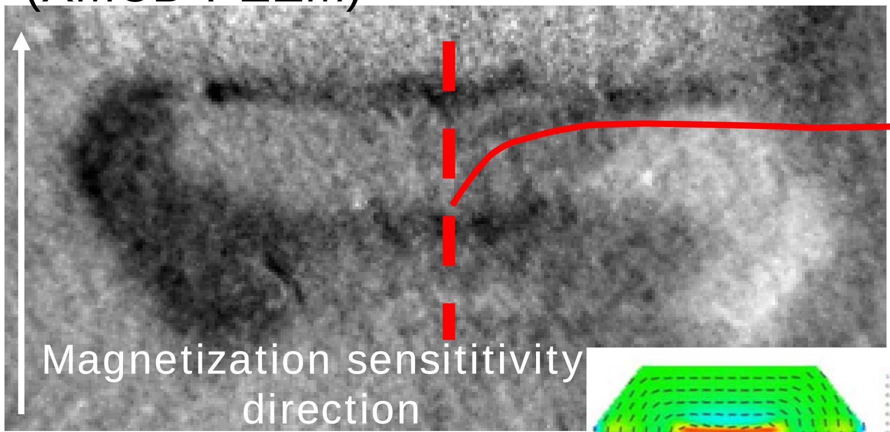
Thin versus thick dots:
From 2D nanostructures towards bulk materials

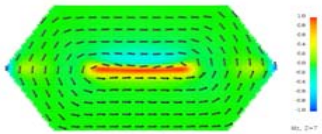
R. Hertel *et al.*, PRB 72, 214409 (2005)

Experiment: topography (LEEM)



Experiment: surface magnetization (XMCD-PEEM)

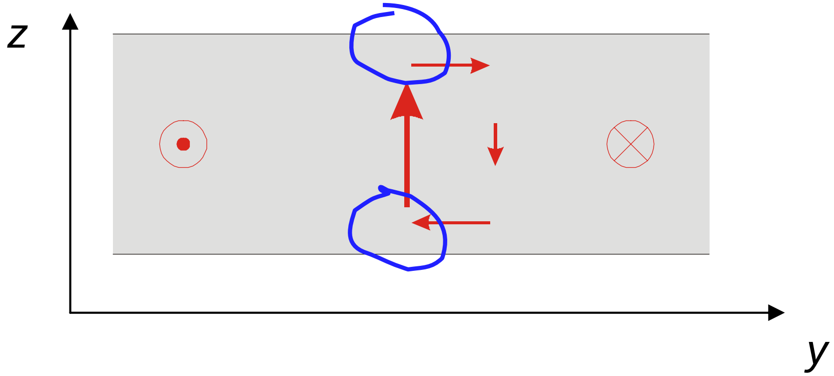




Néel caps occur to reduce surface and volume magnetic charges

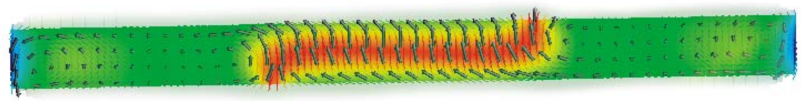
$\mathbf{M.n} = 0$

$$-\operatorname{div}\mathbf{M} = -\frac{\partial M_x}{\partial x} - \frac{\partial M_y}{\partial y} - \frac{\partial M_z}{\partial z}$$



Already known from near-2D states

R. Hertel *et al.*, PRB60, 7366 (1999)
P.-O.Jubert *et al.*, Europhys. Lett. 63, 135 (2003)



Finite elements method

R. Hertel, MPI-Halle, now at IFF-Jülich

PRINCIPLE

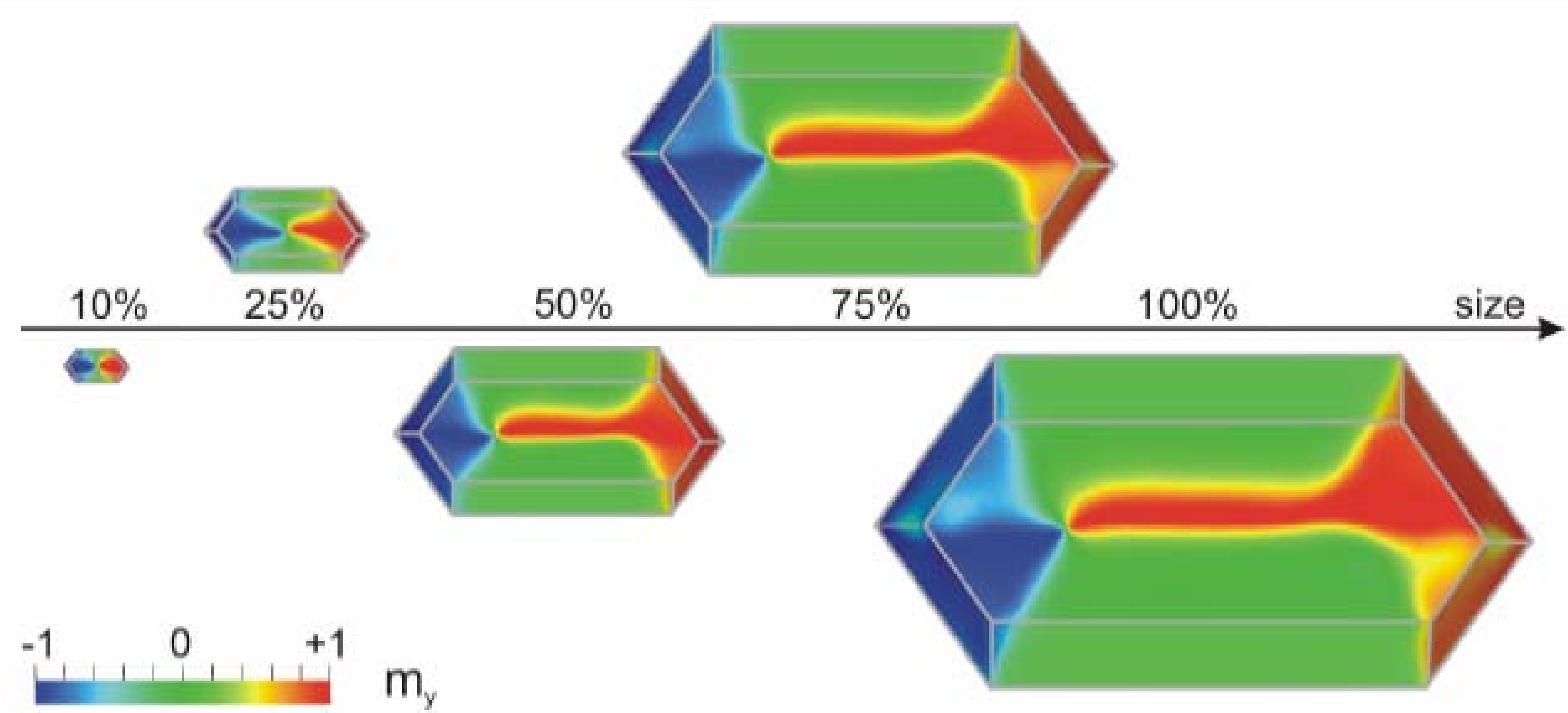
Discretization cells: tetrahedrons (instead of prisms for finite differences)

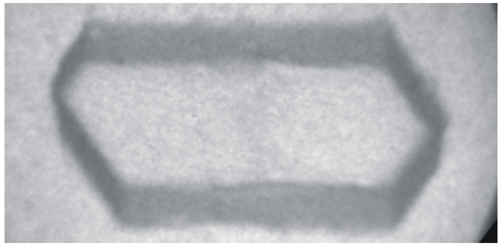
PROS

- Better physical description of curved or tilted boundaries
- Possibility of adaptative mesh

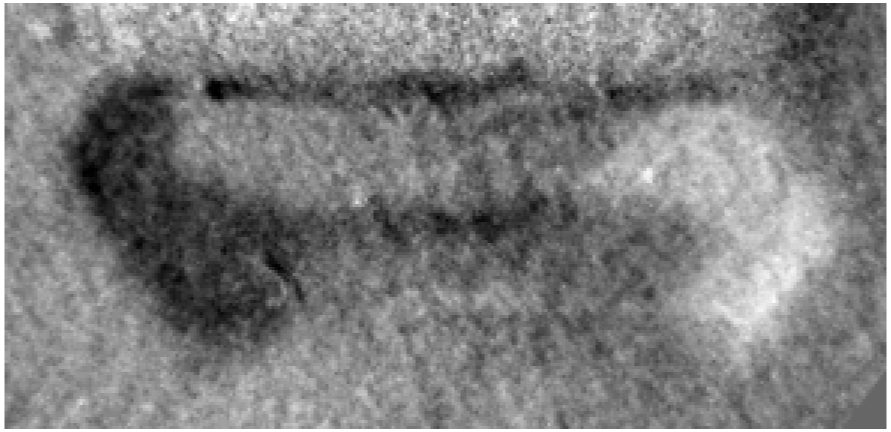
CONS

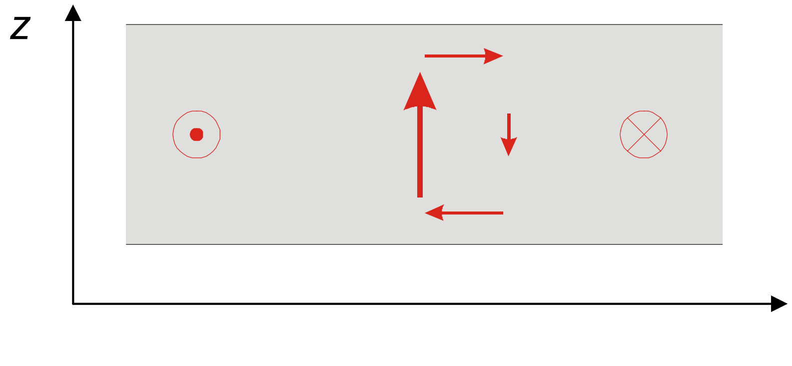
- More complex mathematical ground for the validity of equations
- Loss of translational symmetry, and thus of the Fast Fourier Transform for dipolar energy

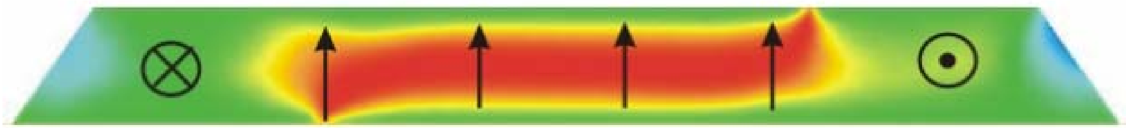




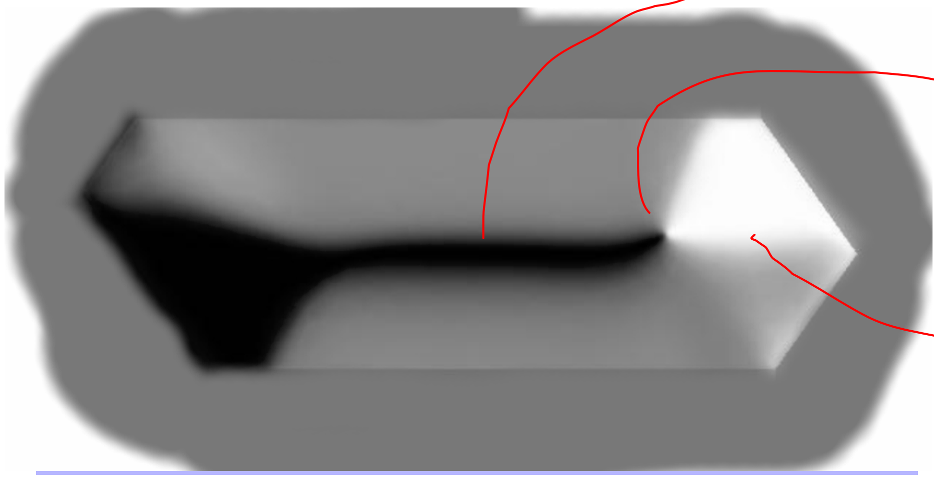
Experiment (top)







Simulation (top with facets)



Néel cap displaced from median line

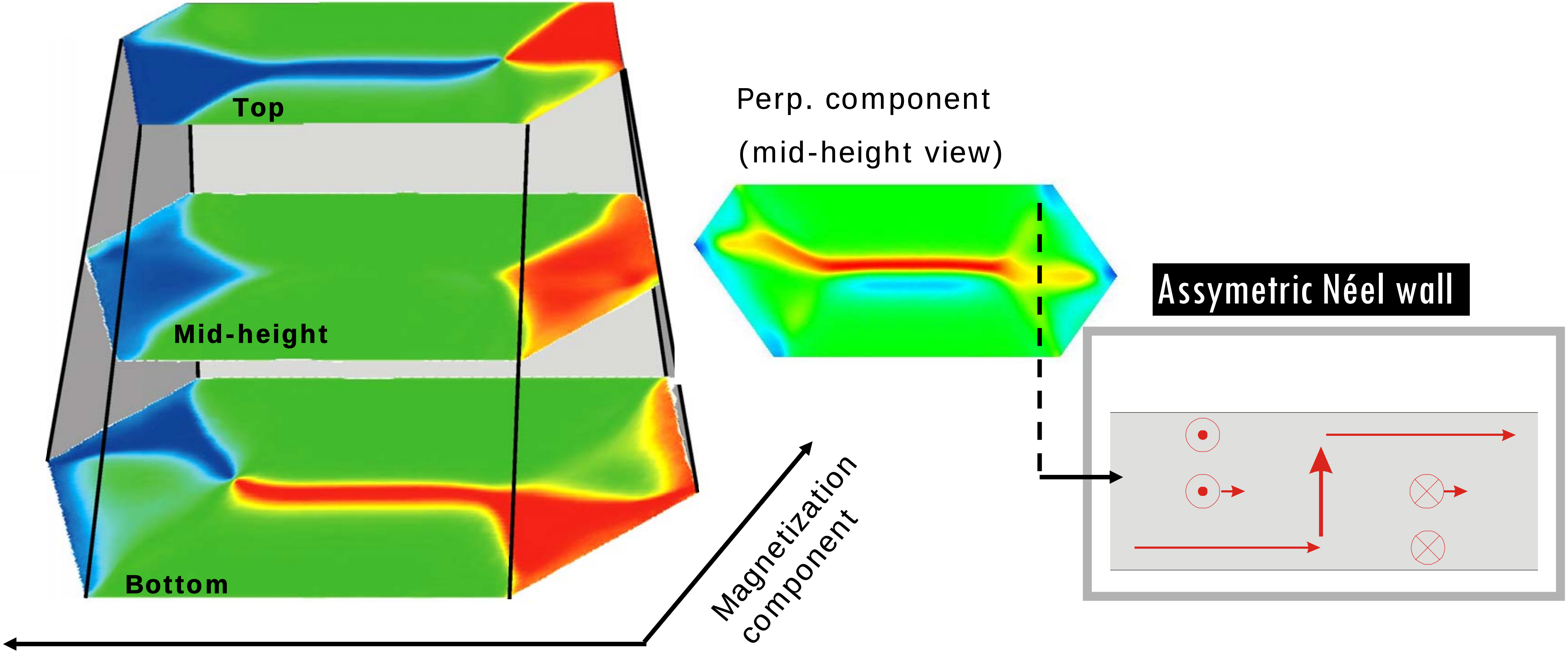
Asymmetry around vortex

Pseudo-2D

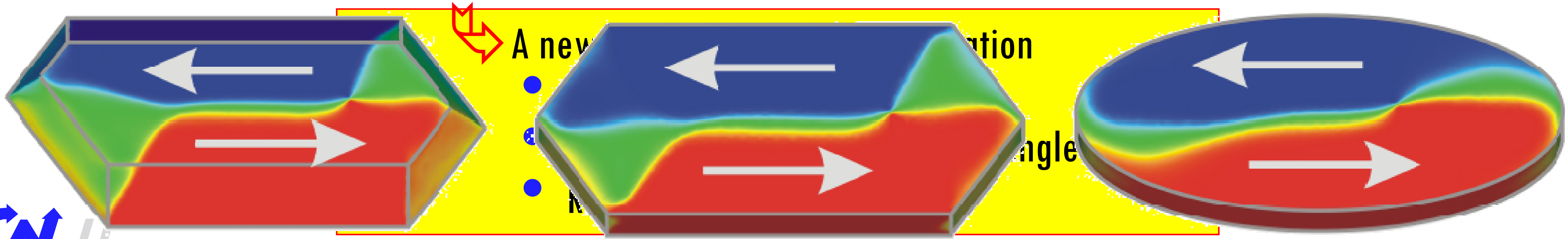
Strong asymmetry of end domains

3D

The main features are reproduced

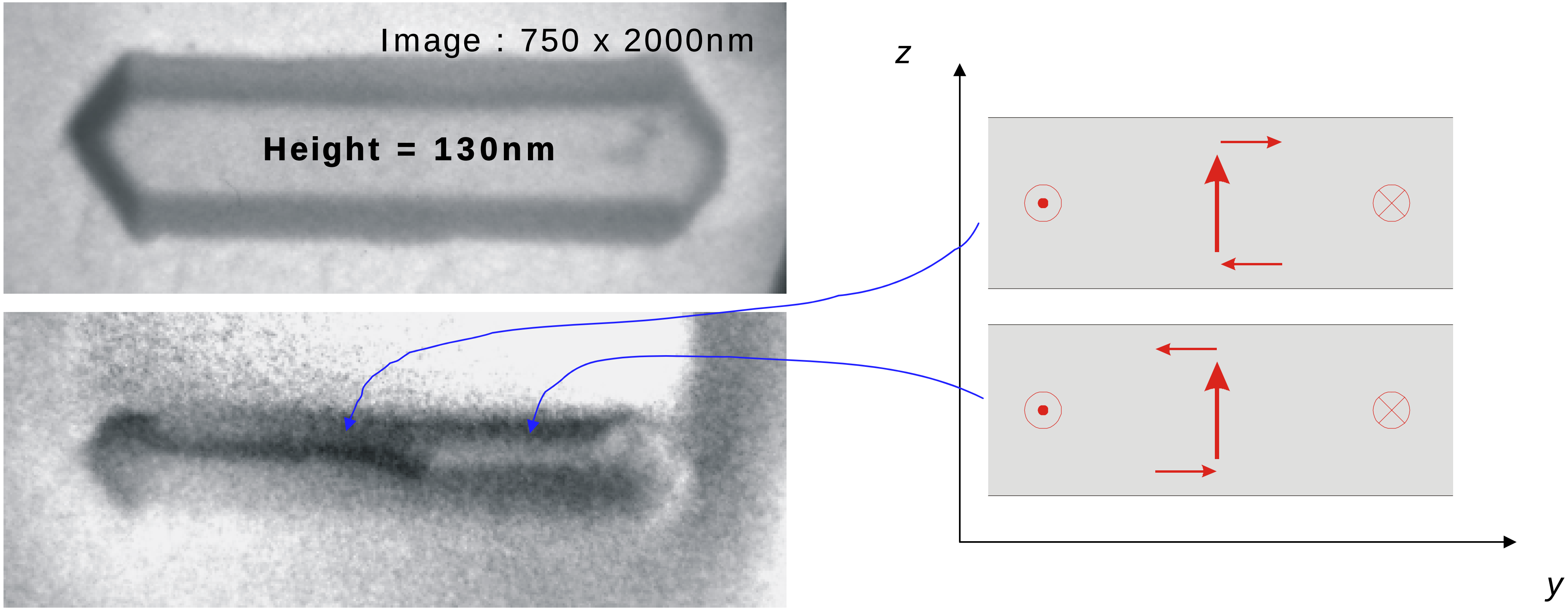


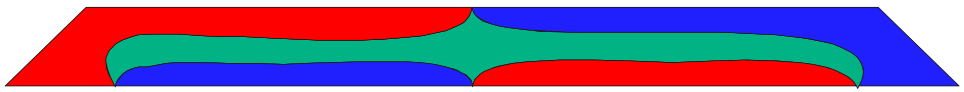
Top
Mid-height
Bottom
Magnetization component
Perp. component
(mid-height view)
Assymetric Néel wall



A new
ation
ngle

Switch of Néel-cap

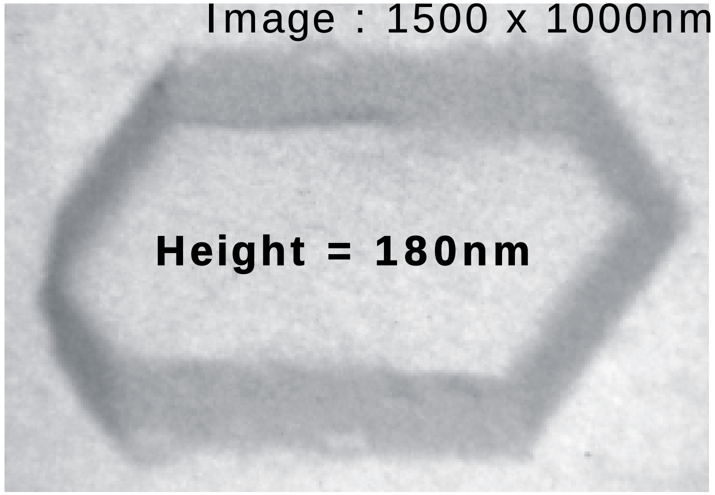




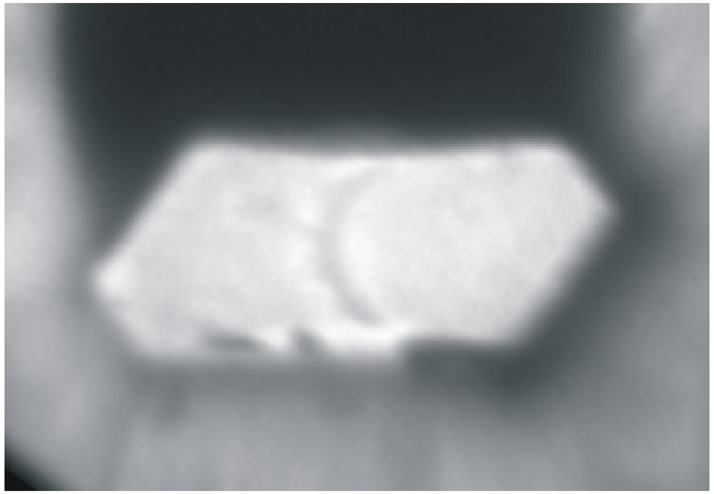
See Hubert's book for Néel cap and cap switches

- 2*N*+1 switches expected
  why 3 never observed?
- Numerical calculations: core switch rather than cap switch

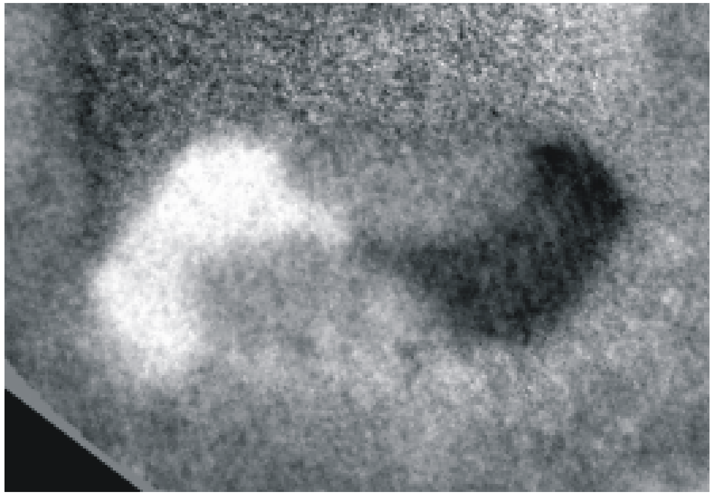
Stretched vortex state



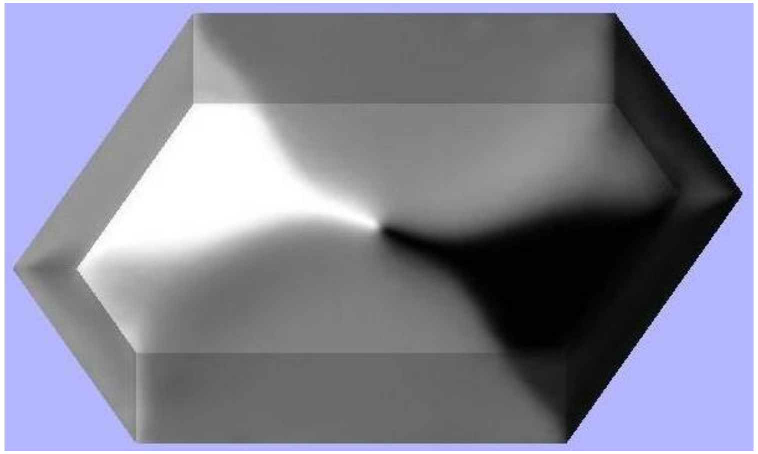
LEEM

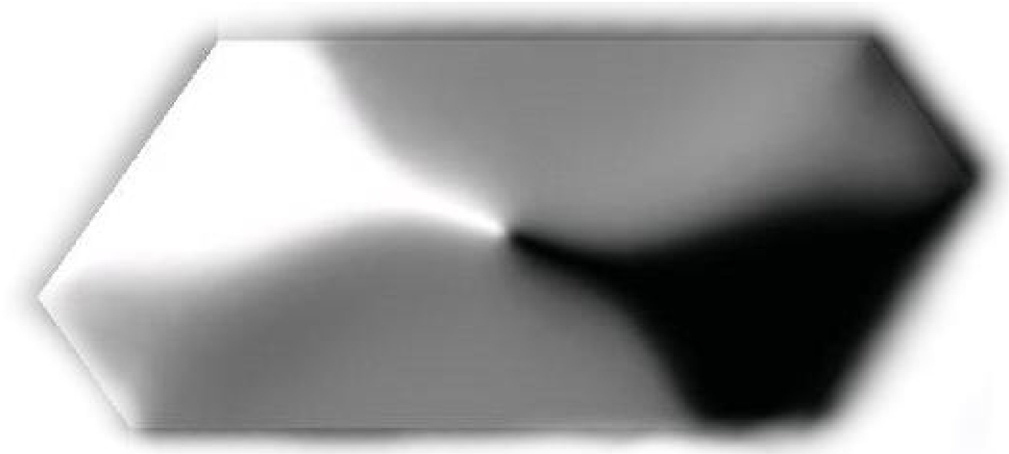


X-PEEM (sum)



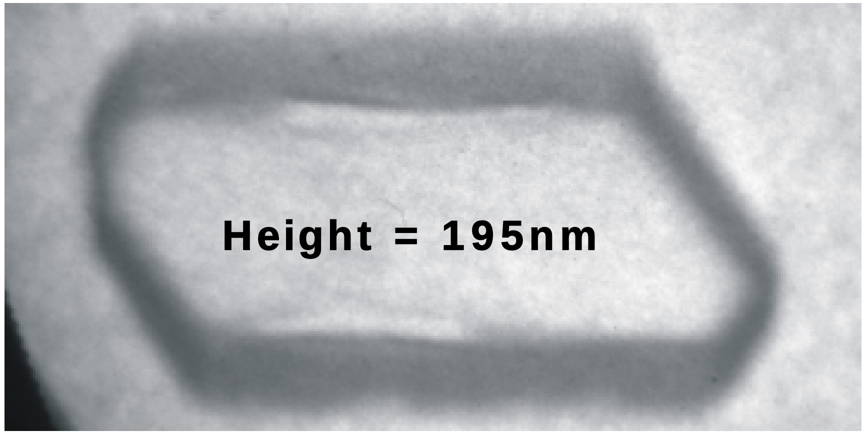
X-PEEM (XMCD)

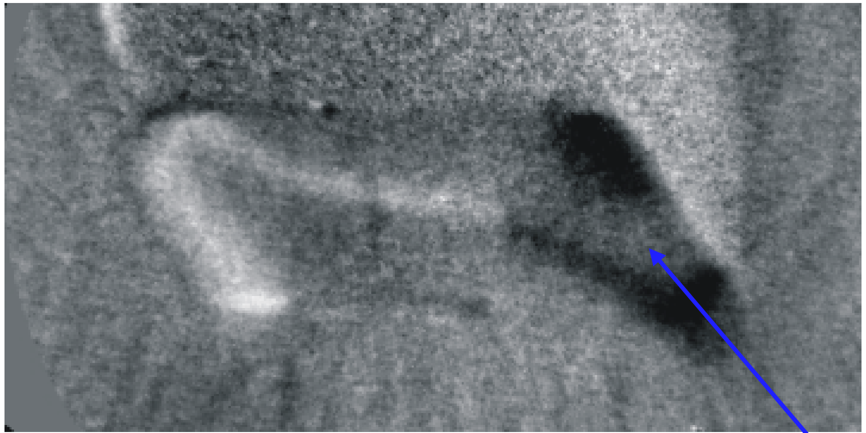




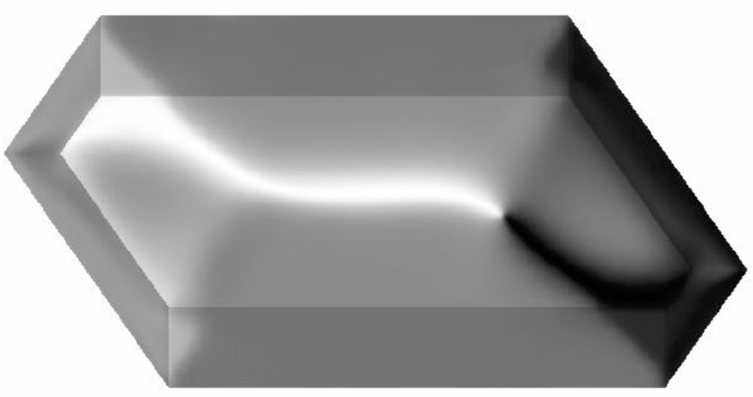
Is there a minimum length for Bloch walls?

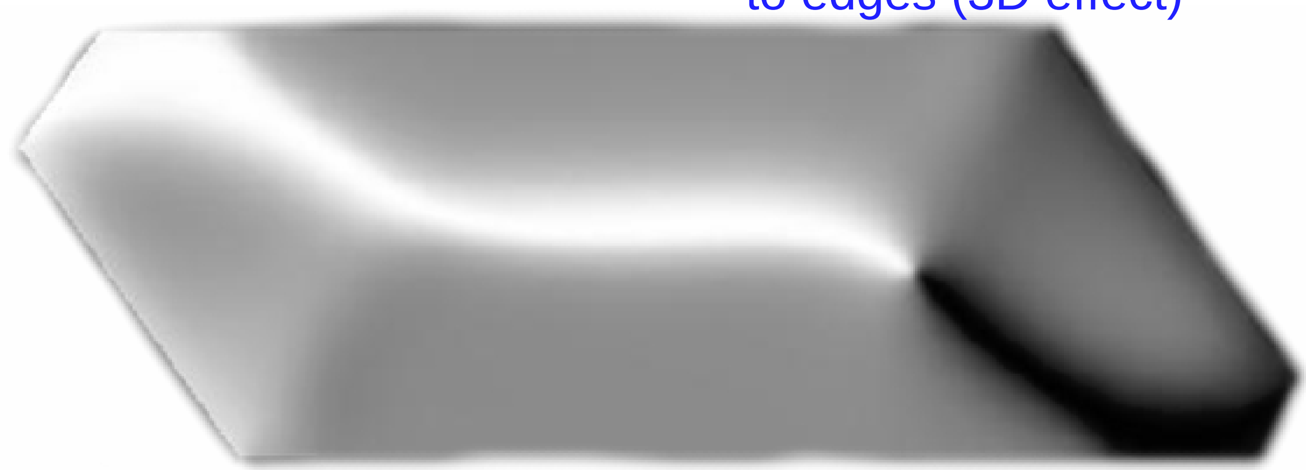
Image : 2000 x 1000nm





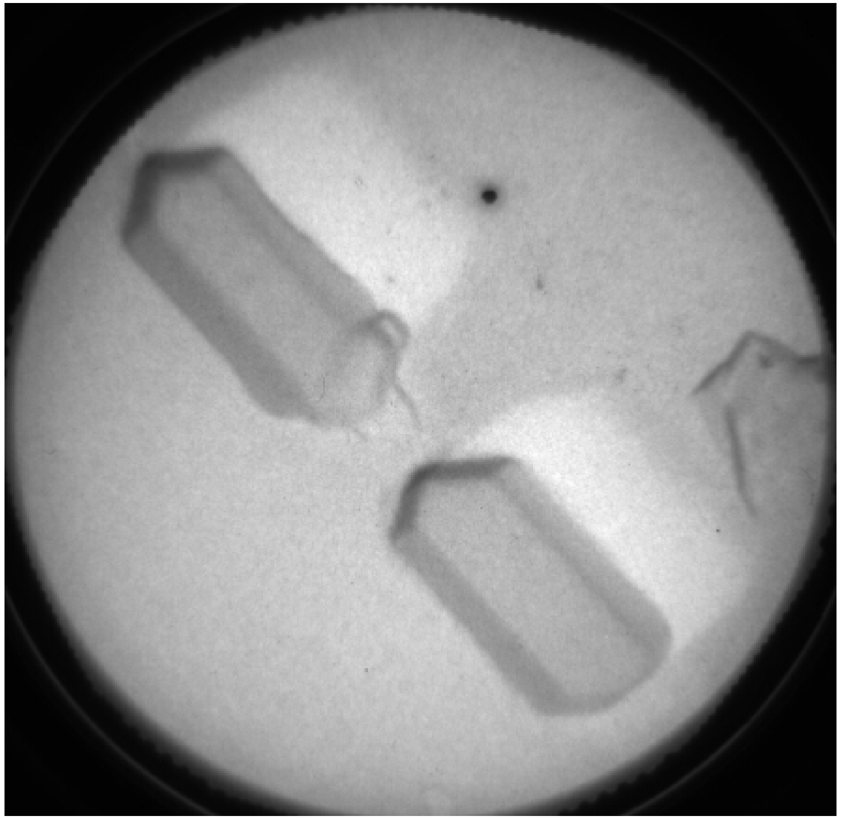
Magnetization not parallel to edges (3D effect)

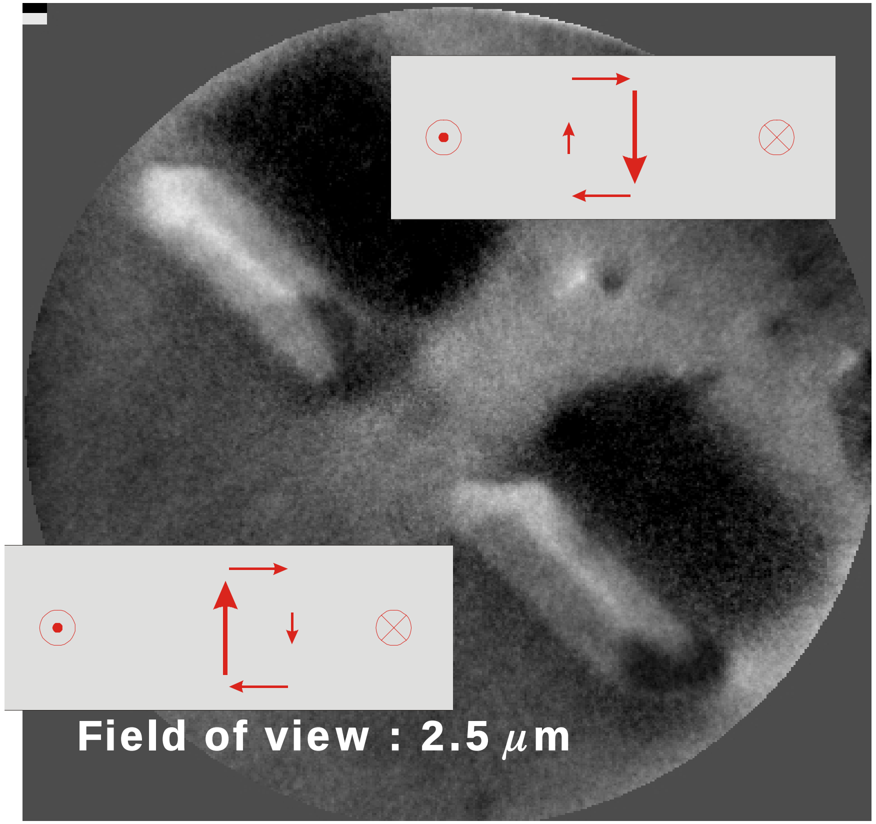




State induced by the asymmetric shape of the dot

Illustration of the high level of near-degeneracy



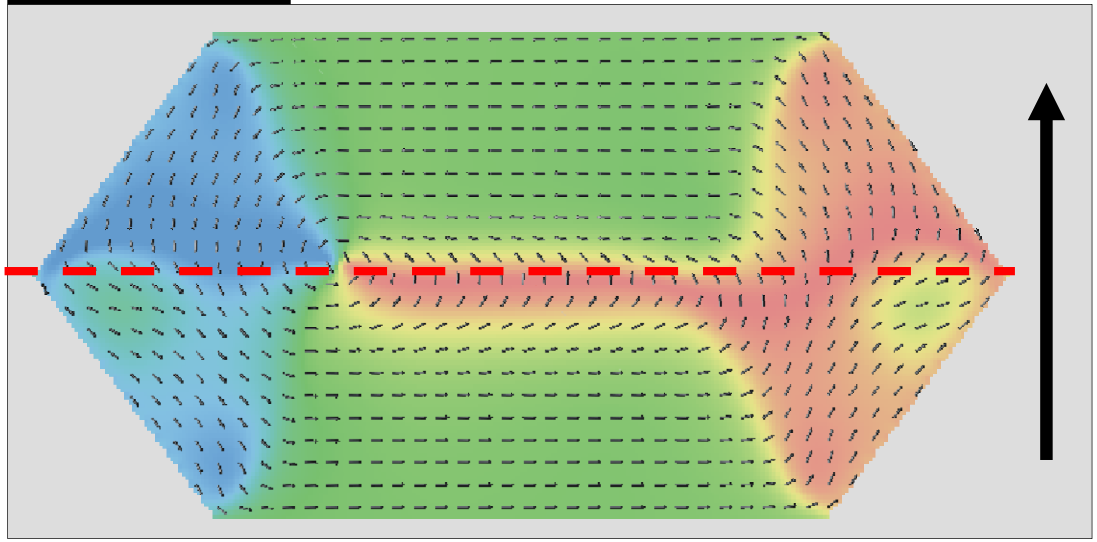


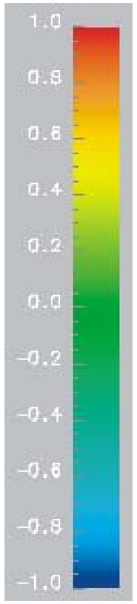
3 degrees of freedom

- Perpendicular magnetization of Bloch wall core
- Circulation of main domains (clock- versus anticlock-wise)
- Direction of Néel cap (Bloch wall asymmetry)

Example: additional degrees of freedom

Bottom view
End domains not centro-symmetric?

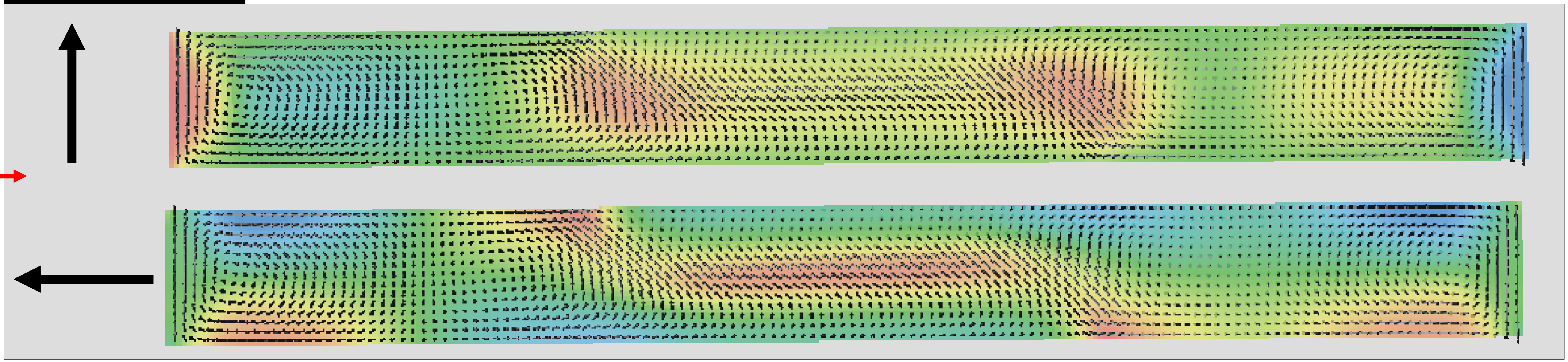




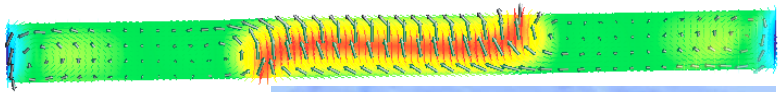
Prospects

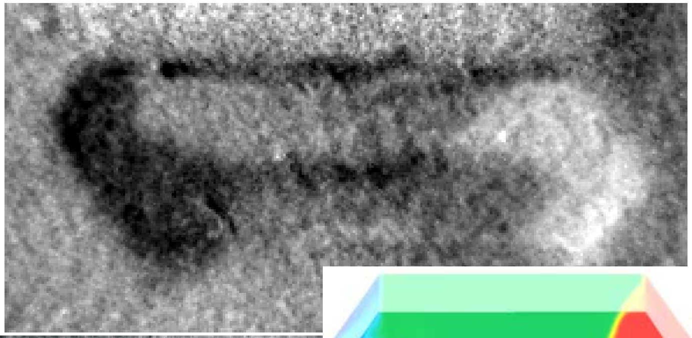
- Additional degrees of freedom
- Magnetization processes of domain walls
- **Requires applied fields**

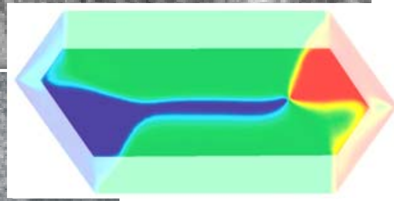
Cross-sections
3D flux-closure, and additional degrees of freedom

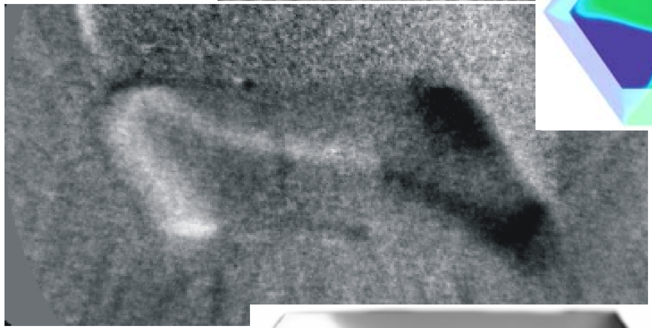


Conclusion – From near-2D towards bulk domain states







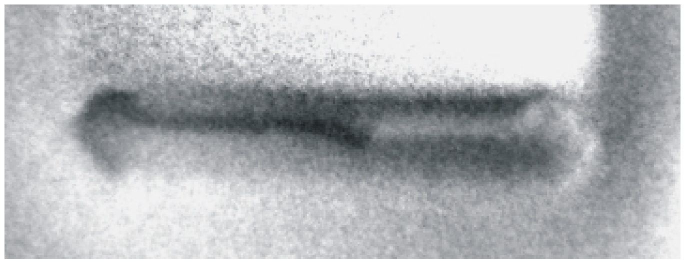


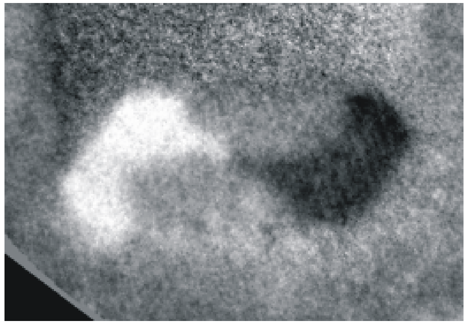
- **Imaging of surface magnetization with XMCD-PEEM with 30nm lateral resolution. LEEM used for the shape.**

- **Use self-assembled dots as a microlaboratory for confining and constraining domain walls**
  <u>From 2D to bulk behavior</u>

- **Arrangement of Néel caps confirmed:**
  - **Connection with end domains**
  - **Shift from median line**
  - **Asymmetry close to surface vortex**

- **Strong deviations from near-2D micromagnetism:**
  - **Strong asymmetry of end domains**
  - **In-plane component of magnetization not parallel to the edge**





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MPI-Halle (Mikrostrukturphysik) / CNRS-Grenoble (Laboratoire Louis Néel)

EU contract

(HPRI-CT-1999-00033)

Overview of magnetic microscopies better than 50nm

	Sp-STM	SEMPA	SPLEEM	Lorentz	XMCD-PEEM	XMCD-microscopy (Fresnel ZP)	EMCD TEM (Posters)
Resolution	<1nm	10nm	10nm	10nm	25nm	30-50nm	?
In-field	YES	local	No?	Yes…	No?	YES	?
Versatile*	No	Yes	No-Yes?	Limited	Yes	Depends	Limited
Dynamics	No	No	No	No	Yes	Yes	No
Element-sensitive	Limited	No	Limited	No	Yes	Yes	Yes

**Versatile* may mean: Sample preparation, measurement of brought-in samples etc.

Conclusions

- Worse is best
- Combine synchrotron with lab (and the reverse!)
- Keep developing all