Interactions between domain walls and spin polarized currents.

- M. Kläui, M. Laufenberg, D. Bedau, L. Heyne, P.-E. Melchy, P. Dagras, A. Biehler, U. Rüdiger, Universität Konstanz
- D. Backes, L. Heyderman, F. Nolting, PSI, Villigen
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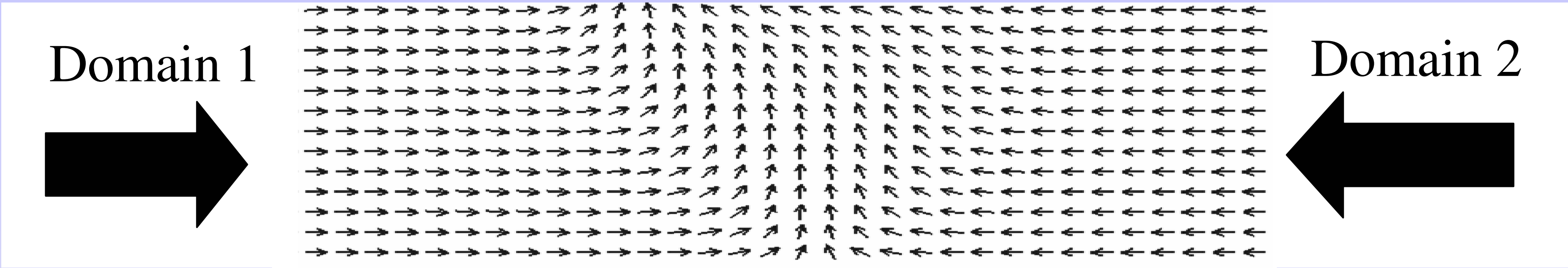
- G. Faini, L. Vila, LPN-CNRS, Marcoussis
- S. Cherifi, E. Bauer & SPELEEM Group, ELETTRA, Trieste

- **Introduction to head-to-head domain wall spin structures**
- **Domain wall phase diagrams and wall transformations**
- **Simulations of current-induced domain wall motion**
- **Observation of CIDM (velocities, wall transformations,…)**
- **Temperature dependence of the spin torque effect**

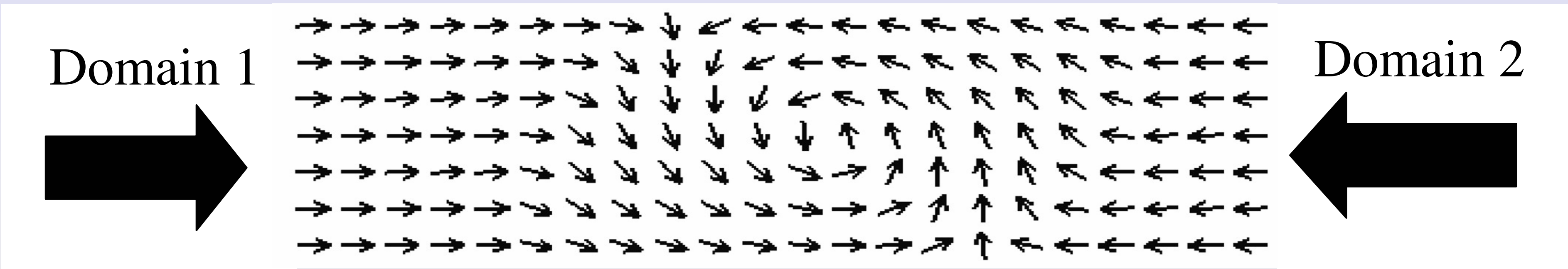
Head – to – head domain walls

Transverse Walls



- Large stray field → energetically favourable in thin and narrow structures.[1,2]

Vortex Walls



- Large exchange energy → energetically favourable in thick and wide structures.[1,2]

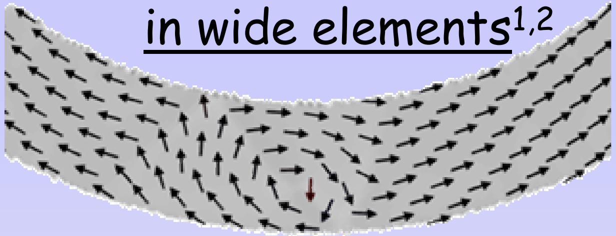
[1]R.D. McMichael et al., IEEE Trans. Mag. **33**, 4167 (1997), [2]Y. Nakatani JMMM **290**, 750 (2005)

Spin structure of head-to-head domain walls

D=1.7µm; W=0.4µm, 0.25µm; t=34nm fcc Co; SEMPA images by J. Unguris, NIST

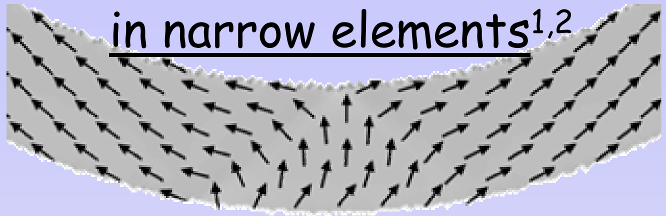
Vortex Walls

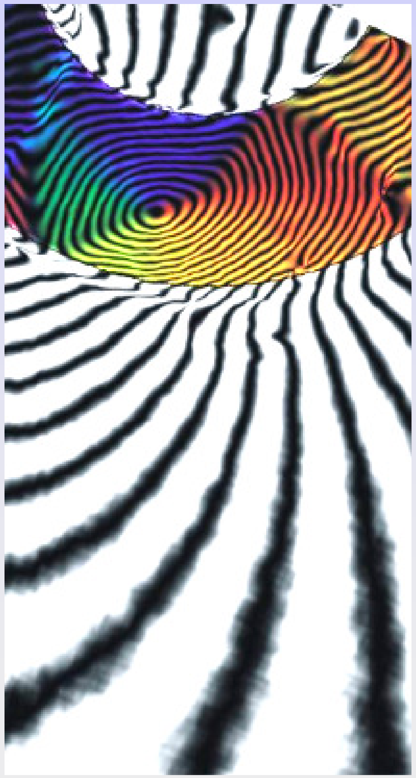
in wide elements[1,2]

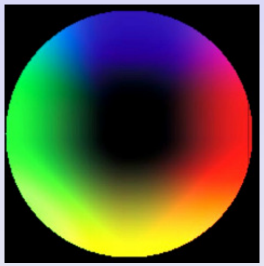


Transverse Walls

in narrow elements[1,2]



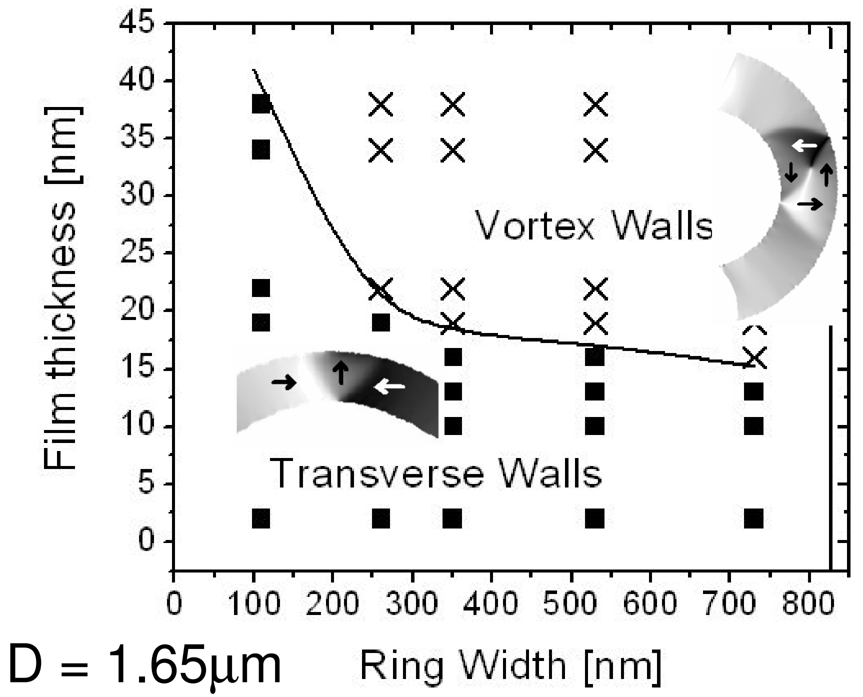


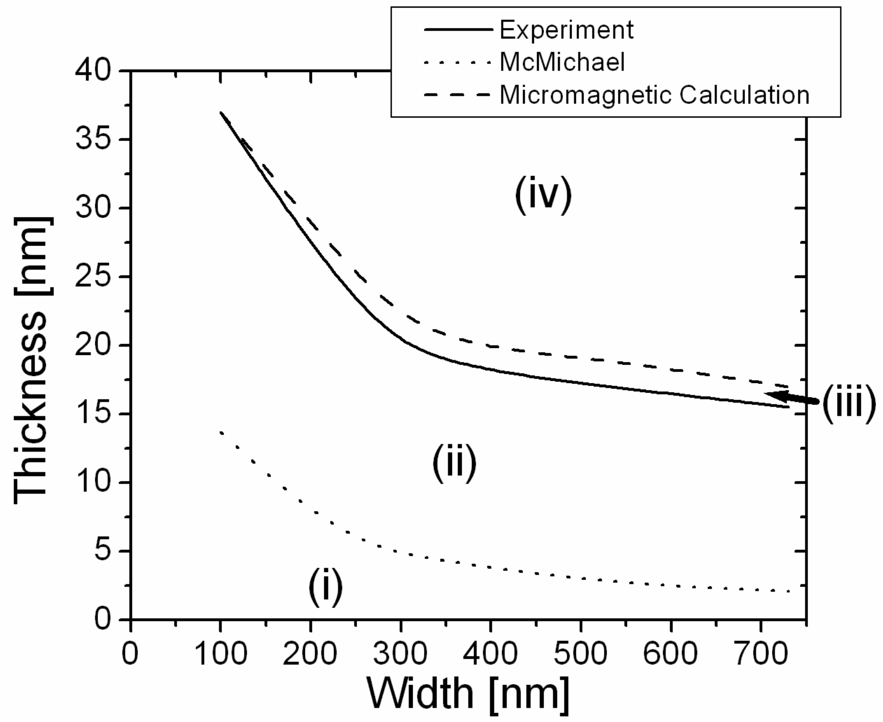


Electron Holography by
R. Dunin-Borkowski,
University of Cambridge

[1]M. Kläui et al., Phys. Rev. B **68**, 134426 (2003); Phys. Rev. Lett **86**, 1098 (2001)
Appl. Phys. Lett. **84**, 951 (2004); Appl. Phys. Lett. **86**, 32504 (2005);

Domain Wall Phase diagramme in Cobalt rings

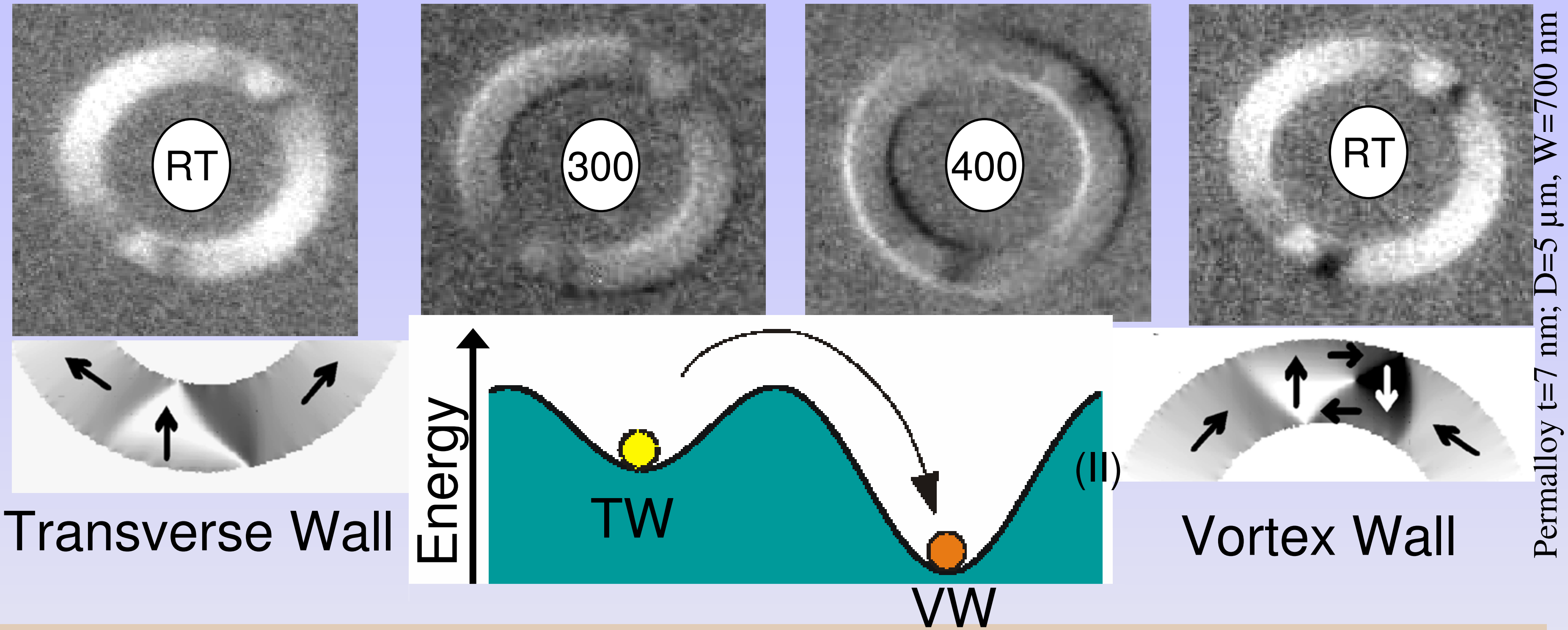




- Experimental Phase diagram shows clear phase boundary between wall types.
- Theoretical calculations of the wall energies according to Ref. 1 show lower boundary.
- Differences can be explained by the fact that transverse walls constitute a local energy minimum. To attain a vortex wall, an energy barrier has to be overcome.
- Micromagnetic calculations reproduce the experiment very well.
- The micromagnetic simulations are carried out at 0K, whereas in the experiment small barriers can be overcome by thermal excitations.[2]

[1]R.D. McMichael, M.J. Donahue, IEEE Trans. Mag. **33**, 4167 (1997); [2]M. Kläui et al., Appl. Phys. Lett. **84**, 951 (2004)

Domain Wall Phase diagramme for Permalloy rings



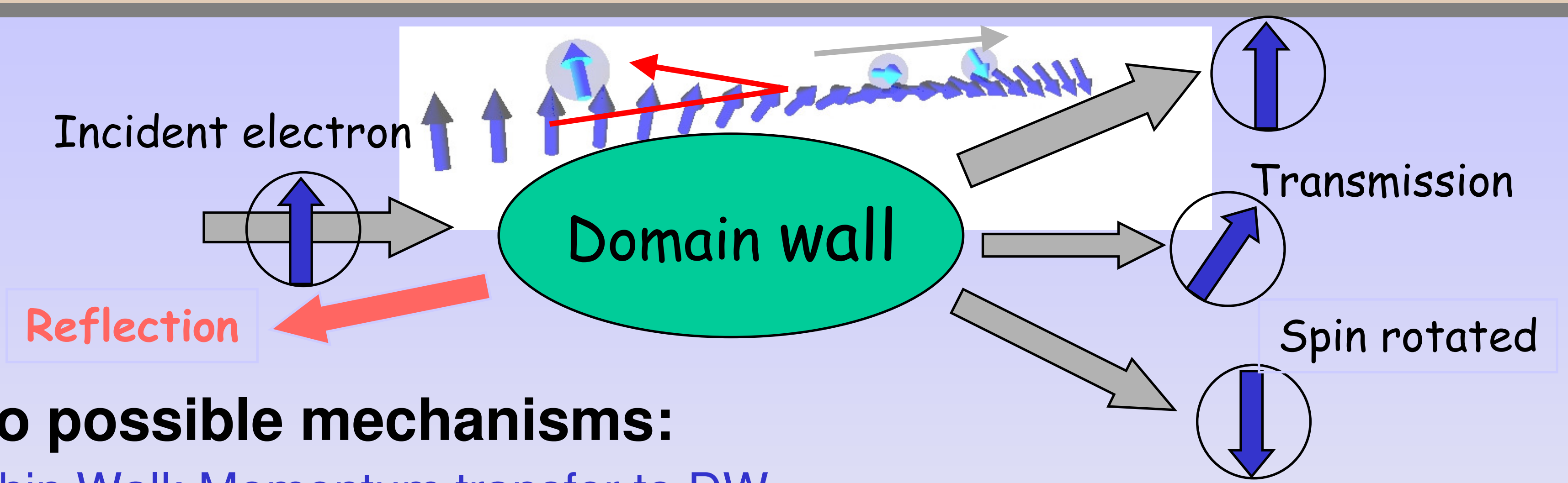
- The phase boundary at larger thicknesses is similar to that in Co.
- Look at geometry in area (II) where a transverse wall is observed but vortex walls are predicted to be energetically favourable (W=750nm, t=7nm).
- After initialization with a field, transverse wall is observed.
- Heating to 400° C shows transformation to vortex wall, which is stable at RT.
  → Thermally assisted transformation from TW to lower energy VW.
- Second phase boundary at ultra-low thicknesses due to morphology.

[1] R.D. McMichael, IEEE Trans. Mag. **33**, 4167 (1997); [2] M. Laufenberg et al. Appl. Phys. Lett. **88**, 52507 (2006)

Current induced domain wall motion

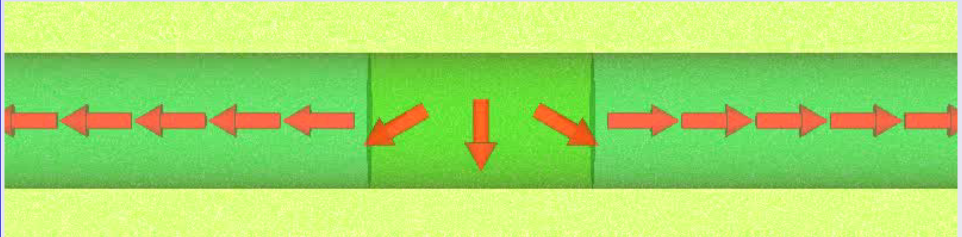
L. Berger, J. Appl. Phys. 49, 2156 (1978); A. Thiaville et al., J. Appl. Phys. 95, 7049 (2004); G. Tatara et al., Phys. Rev. Lett. 92, 86601 (2004)

- Effects of a current: 1. Oerstedt field, 2. joule heating, 3. spin torque

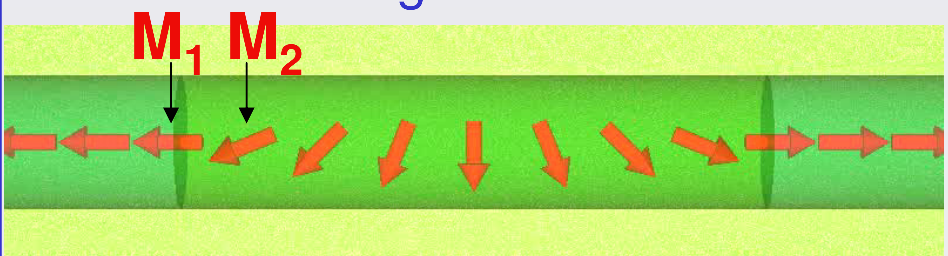


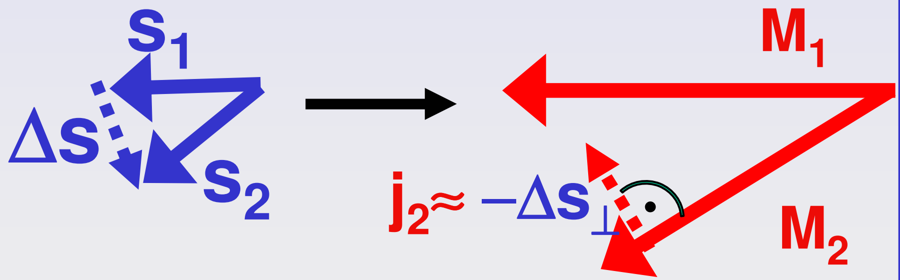
Two possible mechanisms:

1. Thin Wall: Momentum transfer to DW



2. Thick wall: Angular momentum transfer





courtesy of G. Tatara

Current-induced domain wall motion theory

L. Berger, JAP 55, 1954 (1984); A. Thiaville, EPL 69, 990 (2005); S. Zhang, PRL. 93, 127204 (2004); J. Ohe; PRL 96, 27204 (2006); S. E. Barnes et al., PRL 95, 107204 (05)

- Magnetization Dynamics: Landau Lifschitz Gilbert equation:

$$\dot{\vec{m}} = \gamma_0 \vec{H} \times \vec{m} + \alpha \vec{m} \times \dot{\vec{m}}$$

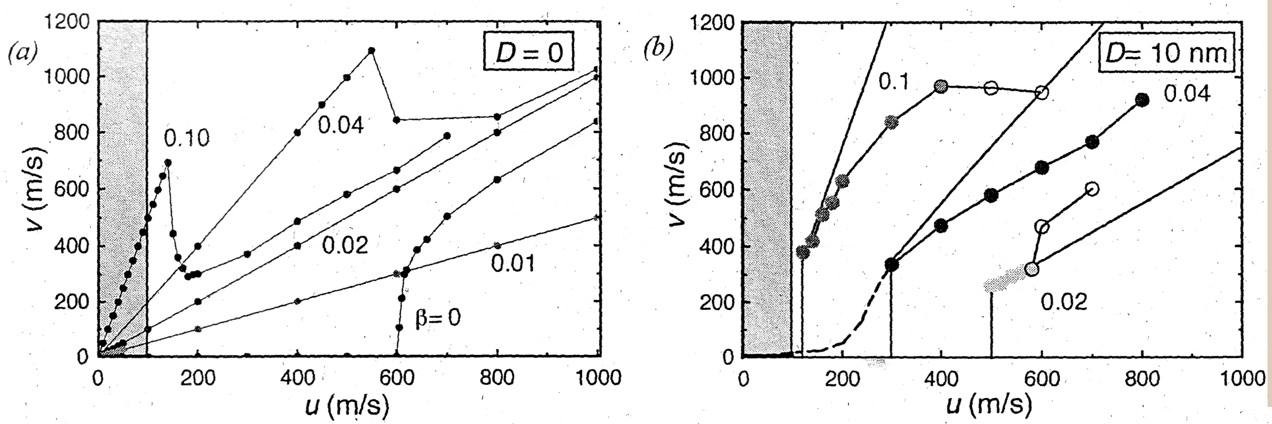
- Spin-transfer model (continuous version of the LLG equation shown by J. Miltat):

$$\dot{\vec{m}} = \gamma_0 \vec{H} \times \vec{m} + \alpha \vec{m} \times \dot{\vec{m}} - (\vec{u} \cdot \vec{\nabla})\vec{m} + \beta \vec{m} \times [(\vec{u} \cdot \vec{\nabla})\vec{m}]$$

$$\vec{u} = \vec{j} g P \mu_B / (2eM_s)$$ $\beta = (\lambda_J/\lambda_{sf})^2$ = (exchange length/spin-flip-length)^2

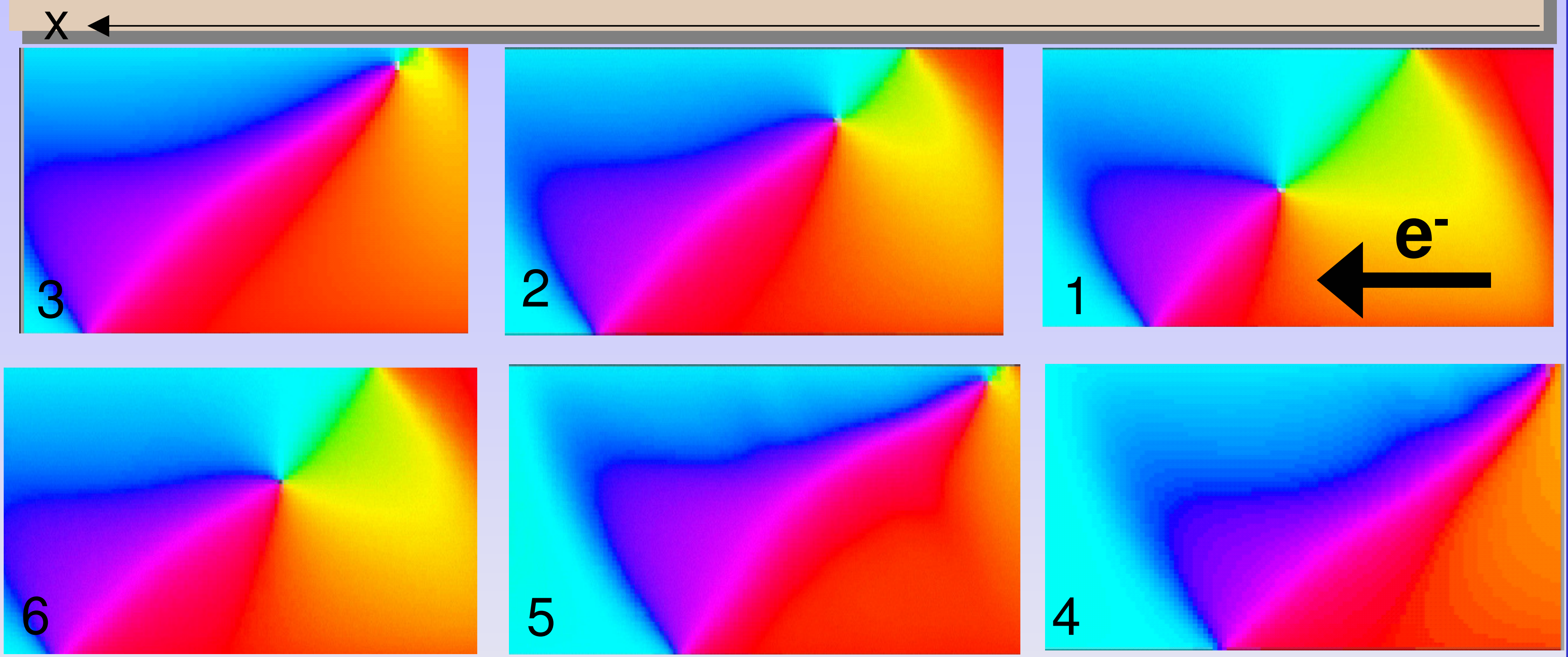
- Adiabatic term: proportional to j, P; Non-adiabatic term: proportional to β
- Angular momentum conservation → „spin transfer torque“.
- Domain walls move in the direction of the electron flow.

*A. Thiaville et al., Europhys. Lett. **69**, 990 (2005)*



- **For β=0:**
  -No DW motion for **u < u$_c$**.
- **For β≠0:**
  -DW motion at any finite **u**;
  -DW velocity **v** increases with β.
- Transverse and vortex walls behave similarly.
- Introducing roughness yields finite threshold u even for **β≠0.**
- Thermal excitations are excluded

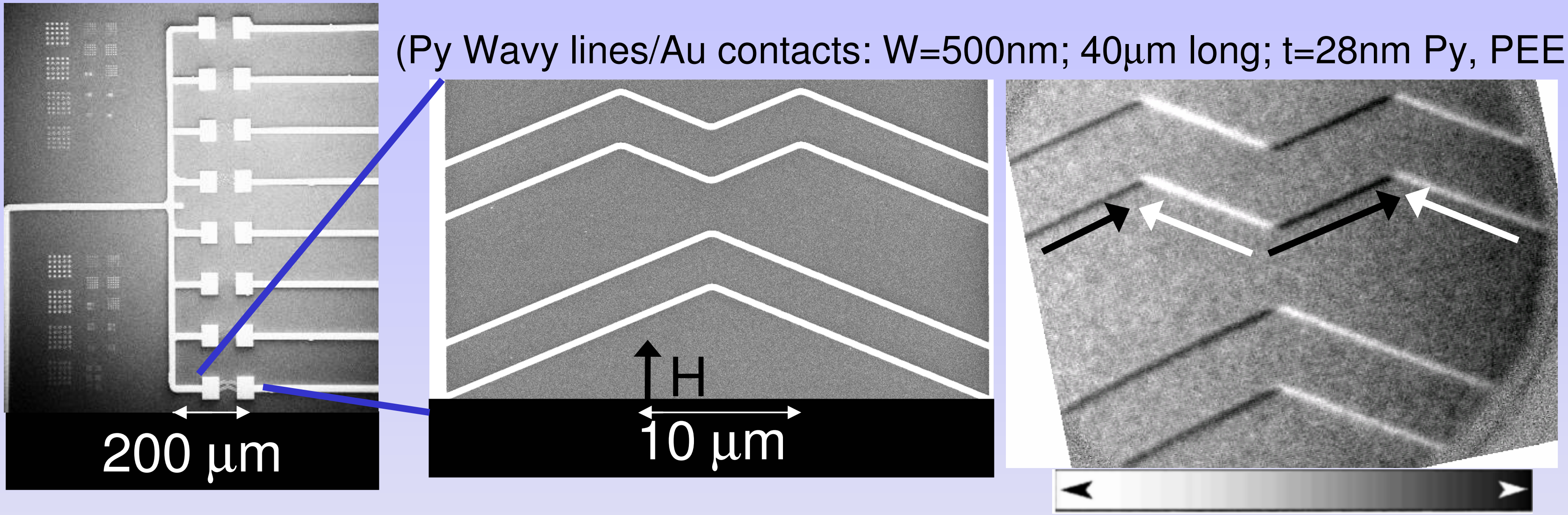
Current-induced domain wall motion calculations



(µmag calc. - adiabatic and non-adiabatic terms;

- Calculations for a slab using the diffusive model with adiabatic and non-adiabatic terms (geometry: W = 500 nm, t = 10 nm Permalloy)
- Current density above u_c
- Current moves vortex wall moves in the direction of the electron flow
- Vortex core is pushed towards edge of the wire, annihilated and renucleated
  → Periodic transformation of wall spin structure:
  Vortex Wall → Transverse Wall → Vortex Wall

Structures for direct CIDM observations

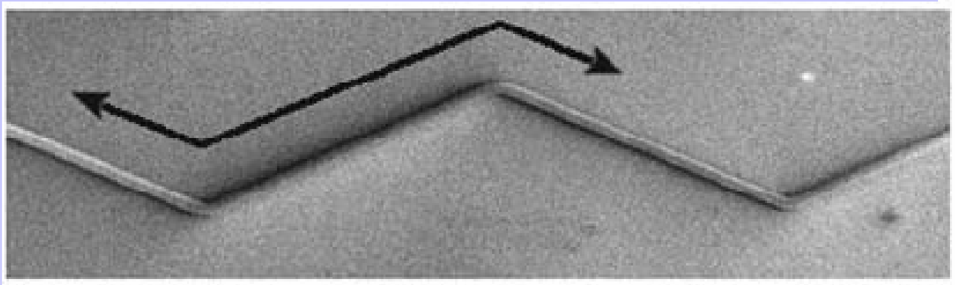


(Py Wavy lines/Au contacts: W=500nm; 40µm long; t=28nm Py, PEEM)

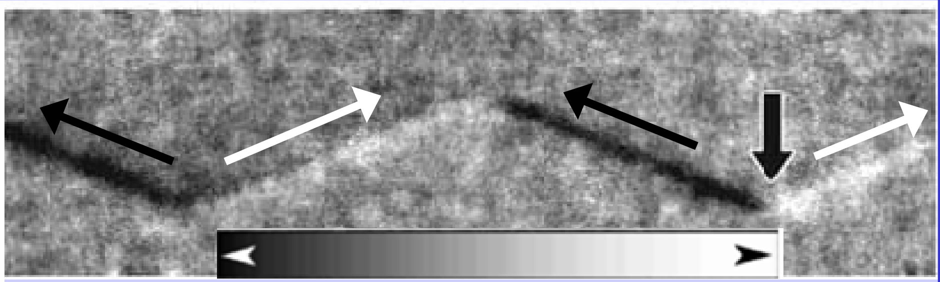
- Zig-zag permalloy wires (widths: 100nm-1500nm, thicknesses 4nm-34nm) are used.
- Depending on the geometry you get transverse or vortex walls.
- Zig-zag wires allow one to generate head-to-head domain walls at the kinks by applying the field in the direction indicated by the arrow.
- The magnetization is pointing in opposite directions in adjacent branches of the wire.
- The kinks are ¼ ring elements with a radius >> wire width (smooth).

M. Kläui et al., Appl. Phys. Lett. **88**, 232507 (2006)

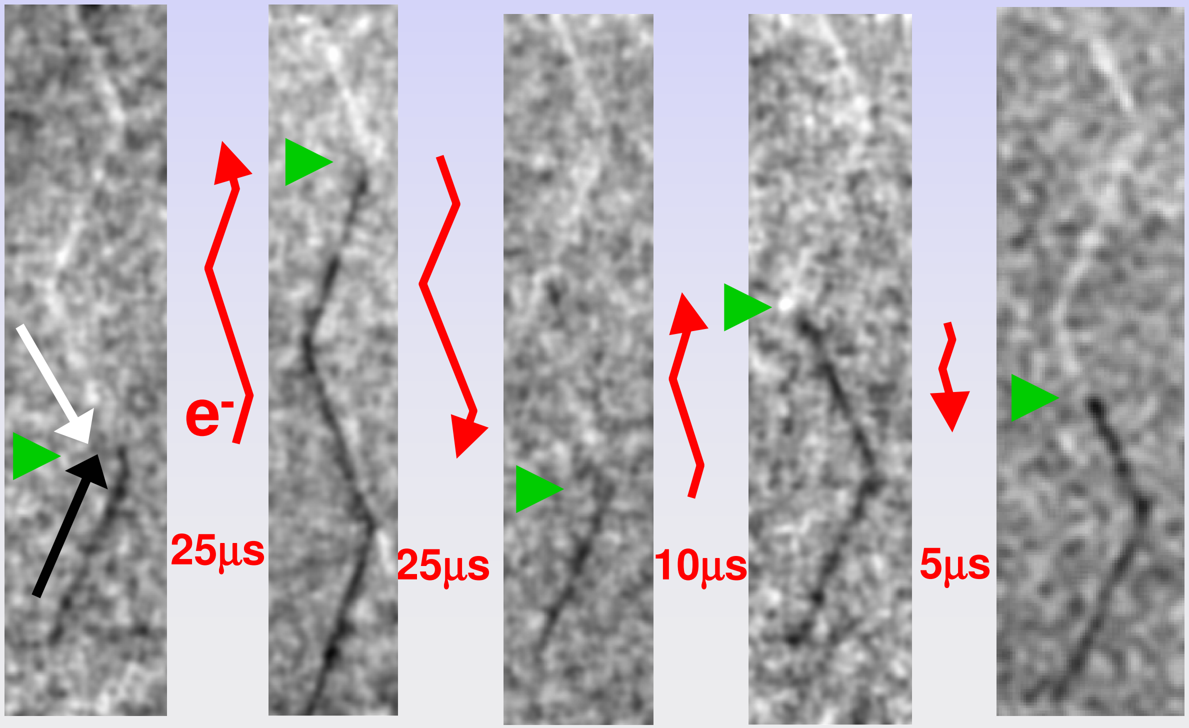
Direct CIDM observations with Spin-SEM



SEM topography image



Spin-SEM magnetization image

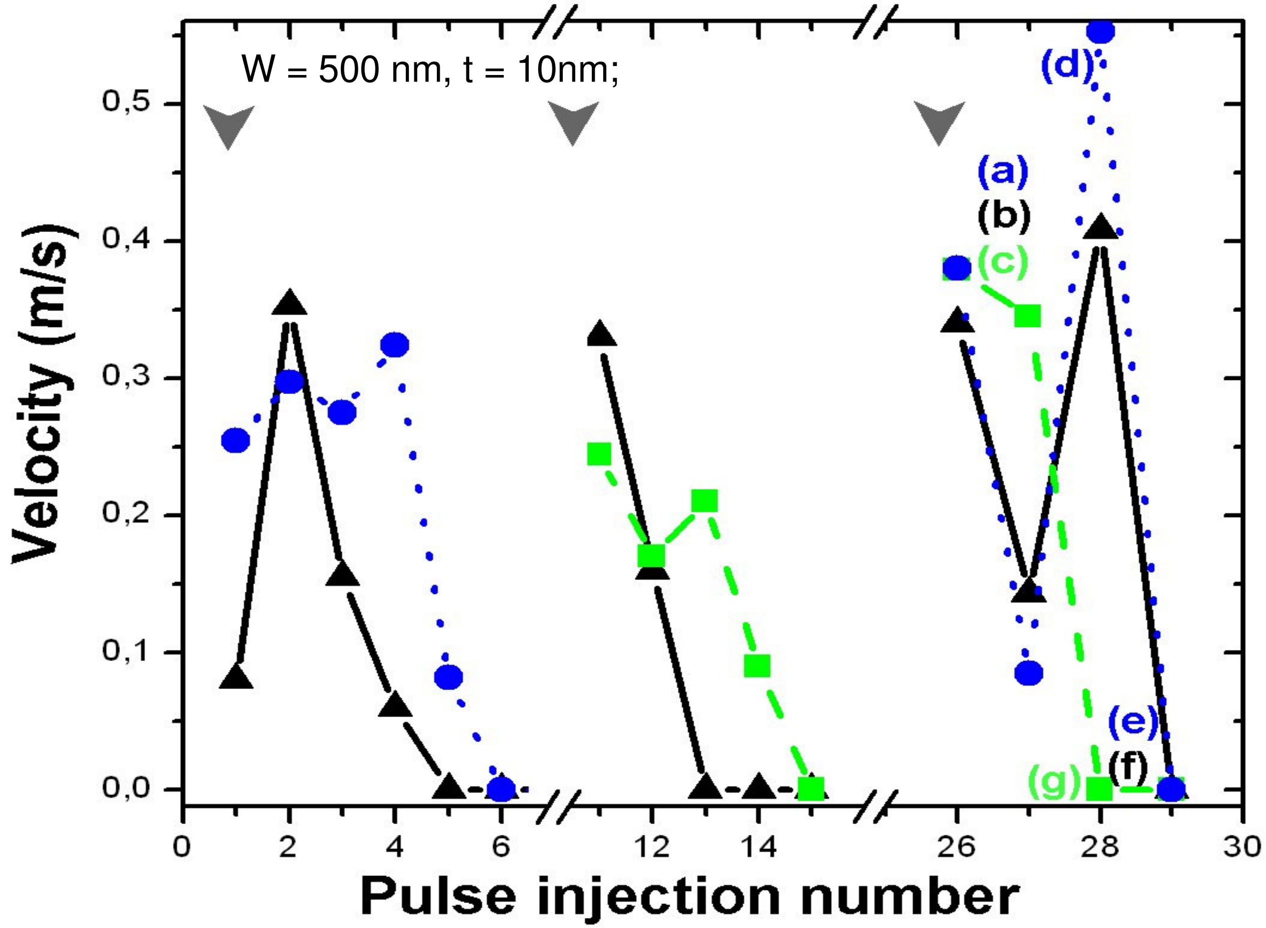


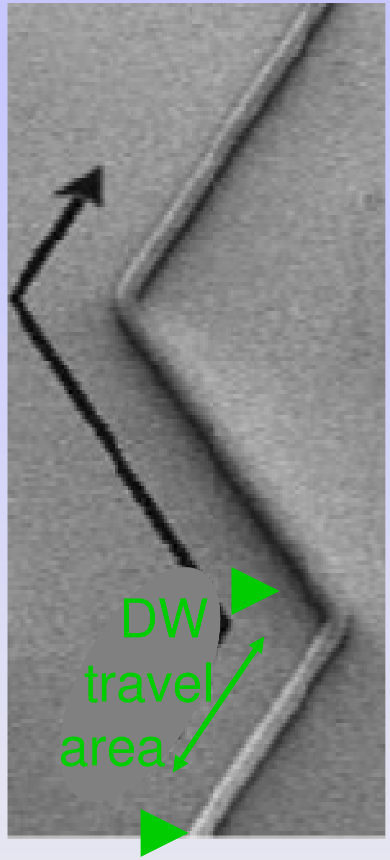
- Head-to-head vortex walls are formed at kinks.
- j_{crit}=2,3×10^{12} A/m^2
- Walls move in the direction of the electron flow.
- Pulse length Δt is varied.
- Velocity is independent of the pulse length: 1 m/s
- Walls move beyond kinks.

W=300nm; 60µm long; t=27nm Py, SEMPA measurement)

M. Kläui et al., PRL **95**, 026601 (2005); P.-O. Jubert et al. JAP **99,** 08G523 (2006);

Domain wall motion velocity evolution

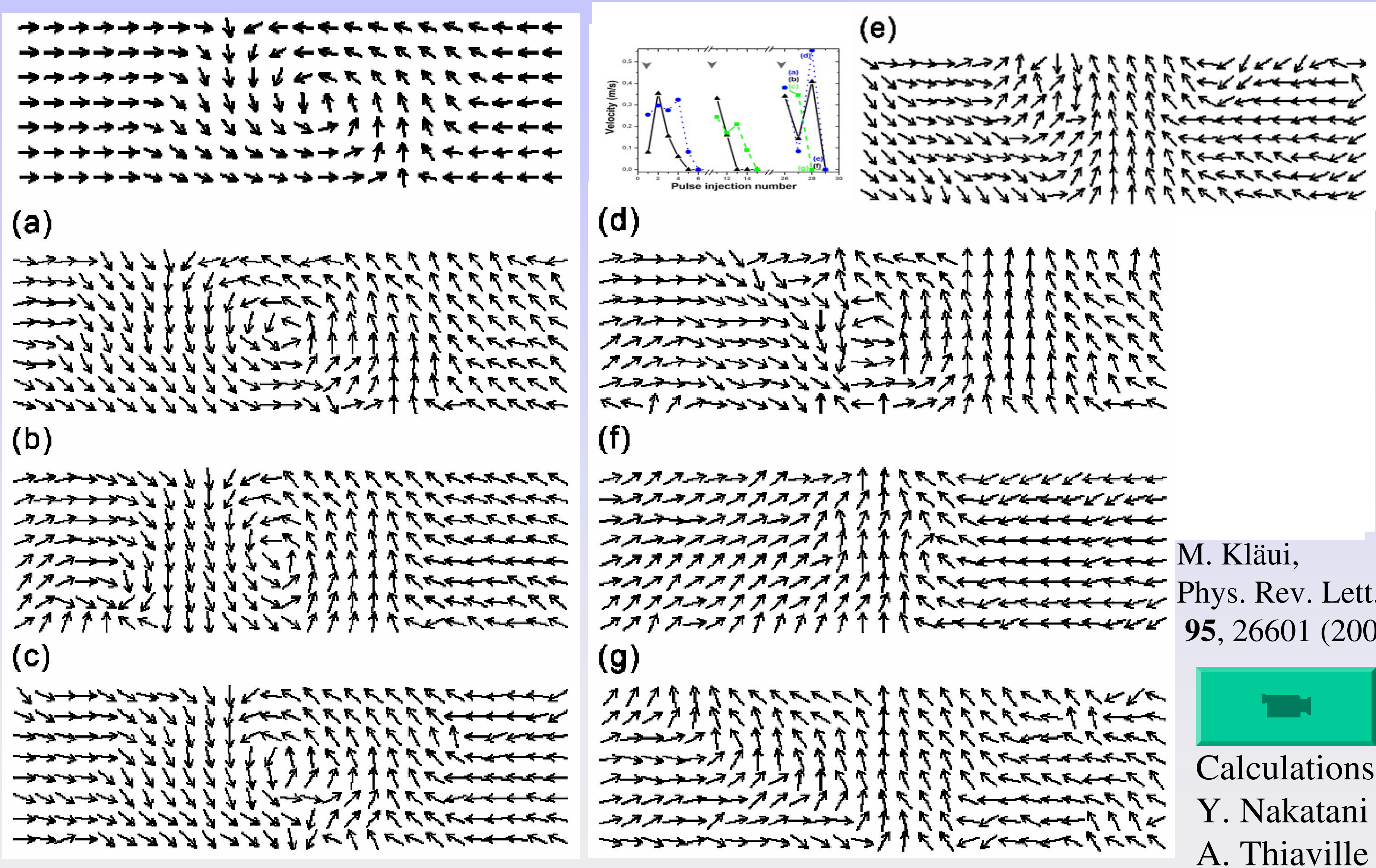




- Wall velocity is constant at first but starts to vary.[1]
- After a few injections the wall might stop.
- Applying a magnetic field, resets the system
  ➔ stopping not related to defects or degradation.

[1]M. Kläui et al., Phys. Rev. Lett. **95**, 026601 (2005)

High resolution imaging of domain wall transformation

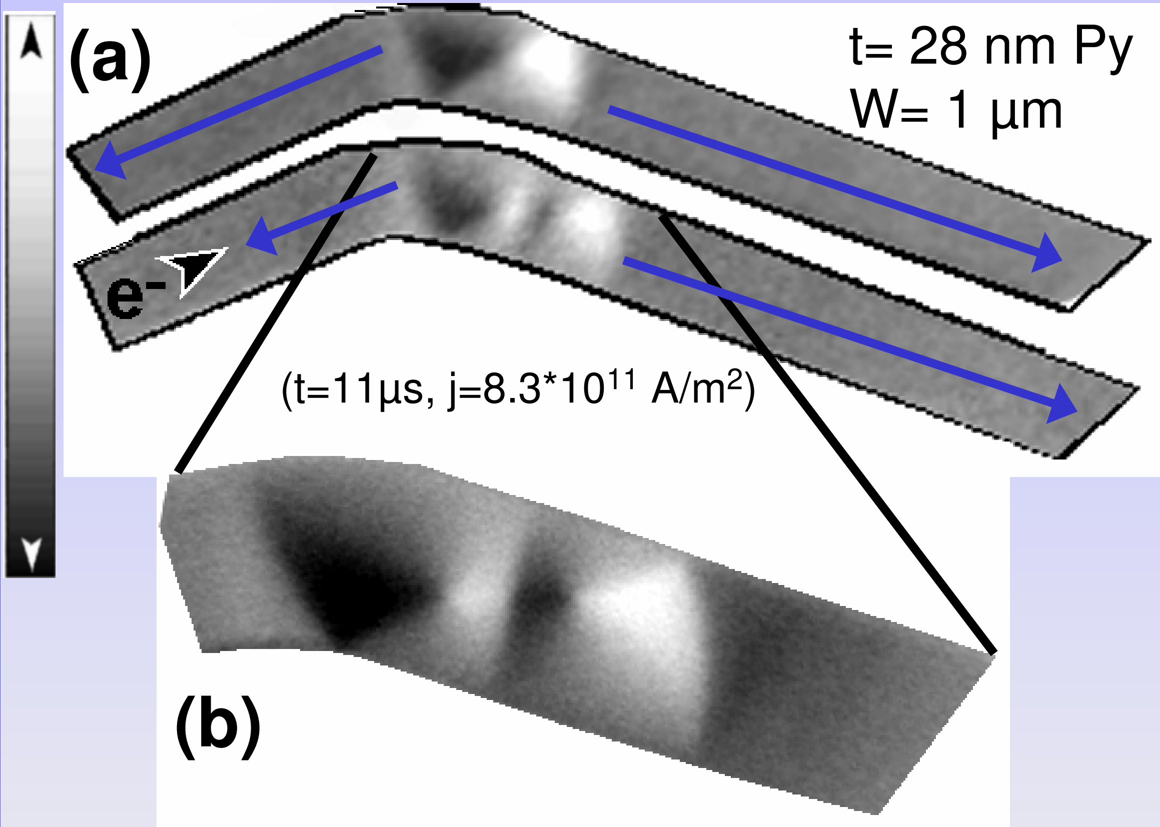


M. Kläui,
Phys. Rev. Lett.
95, 26601 (2005)

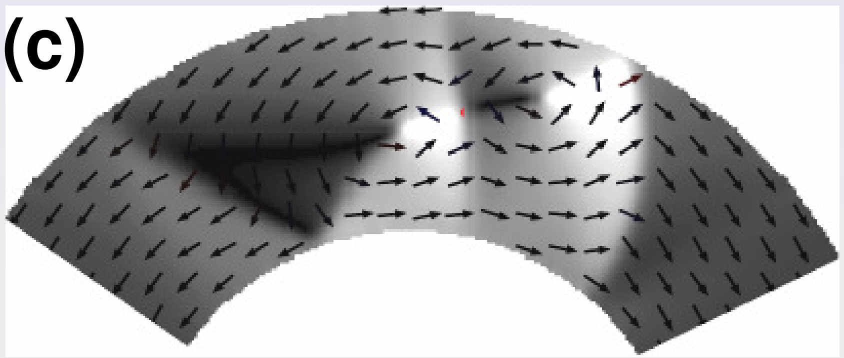
Calculations:
Y. Nakatani
A. Thiaville

- The walls stop, since they are deformed by the current (vortex core annihilation)!

Wall transformation by vortex core nucleation



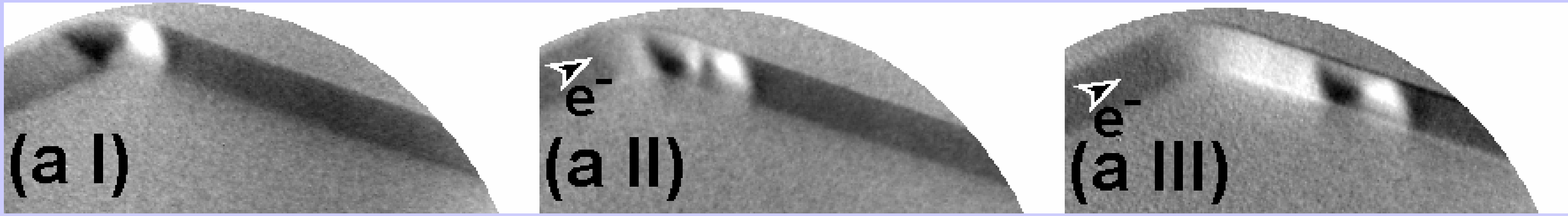
- (a) Vortex wall after remagnetization. Injection of a pulse → vortex nucleation transformation double vortex.
- (b) High resolution image of double vortex wall.
- (c) Micromagnetic simulation of such a wall. (counter-clockwise circulation direction of both vortices.
- (d) Image of an extended vortex wall with a cross-tie structure in the centre.



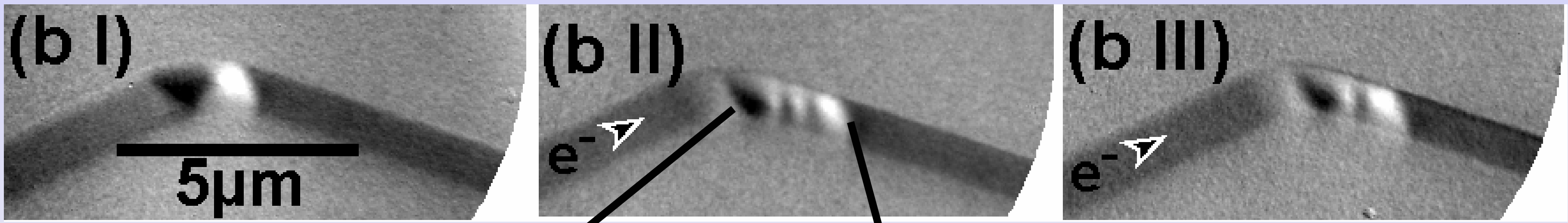
PEEM imaging at ELETTRA

M. Kläui et al., APL **88,** 232507 (2006)

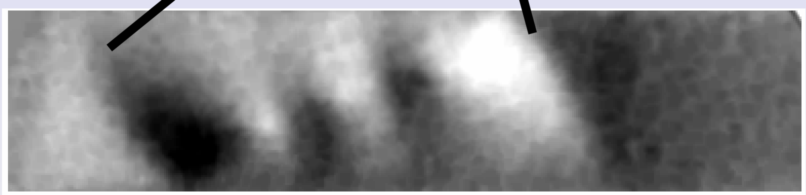
Vortex core nucleation and annihilation



- Vortex core nucleation (II) and annihilation (III) during subsequent pulse injections (11µs, $8.7*10^{11}$ A/m^2) → periodic transformation.



Heating < 100K
→ $T_{sample} << T_{Curie}$

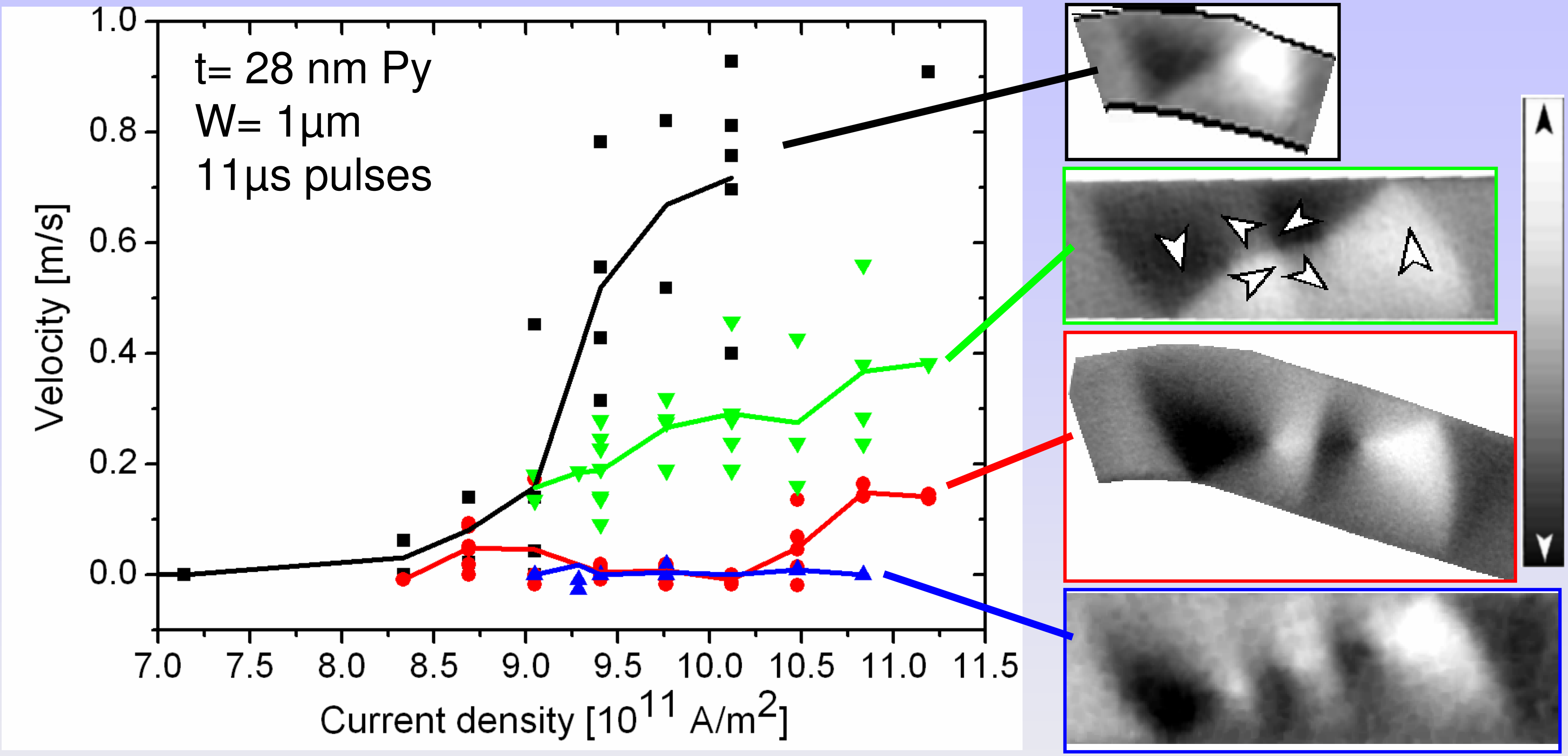


t= 28 nm
W= 1µm

- Nucleation of two vortices yields triple vortex wall (II) and annihilation of one vortex transforms wall back to double vortex (III).
- High resolution image of triple vortex shows three vortices with same circulation direction (counter-clockwise).
- Nucleation and annihilation of vortices due to spin torque is observed.

M. Kläui et al., APL **88** 232507 (2006)

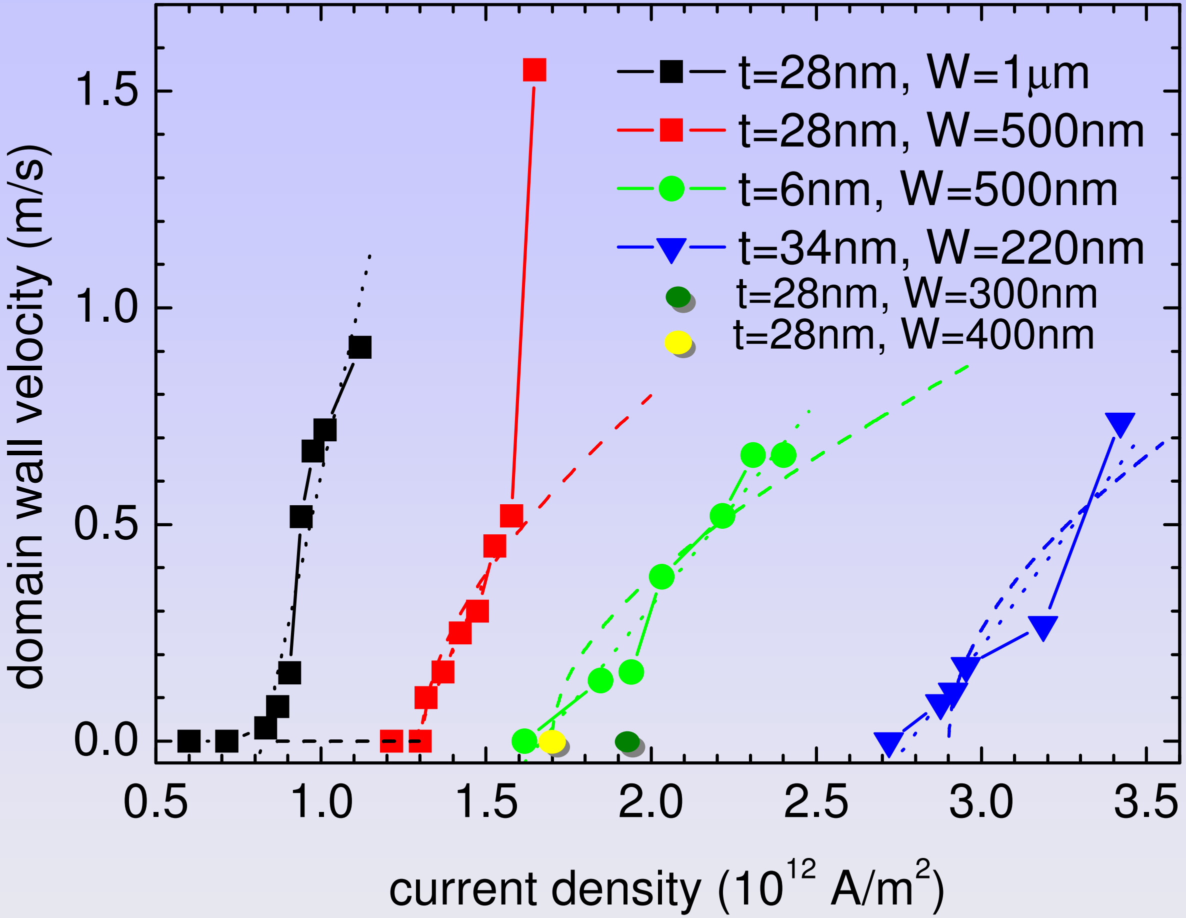
Velocity dependence on wall spin structure



- Velocity of single vortex walls with no transformations increases with increasing current density (black squares and black line).
- Velocity depends on the wall spin structure and the number of vortices.
- Extended vortices move more slowly (green down triangles).
- Multi-vortices (double vortex: red; triple vortex: blue) hardly move.

M. Kläui et al., APL **88** 232507 (2006)

Systematic study of domain wall velocities

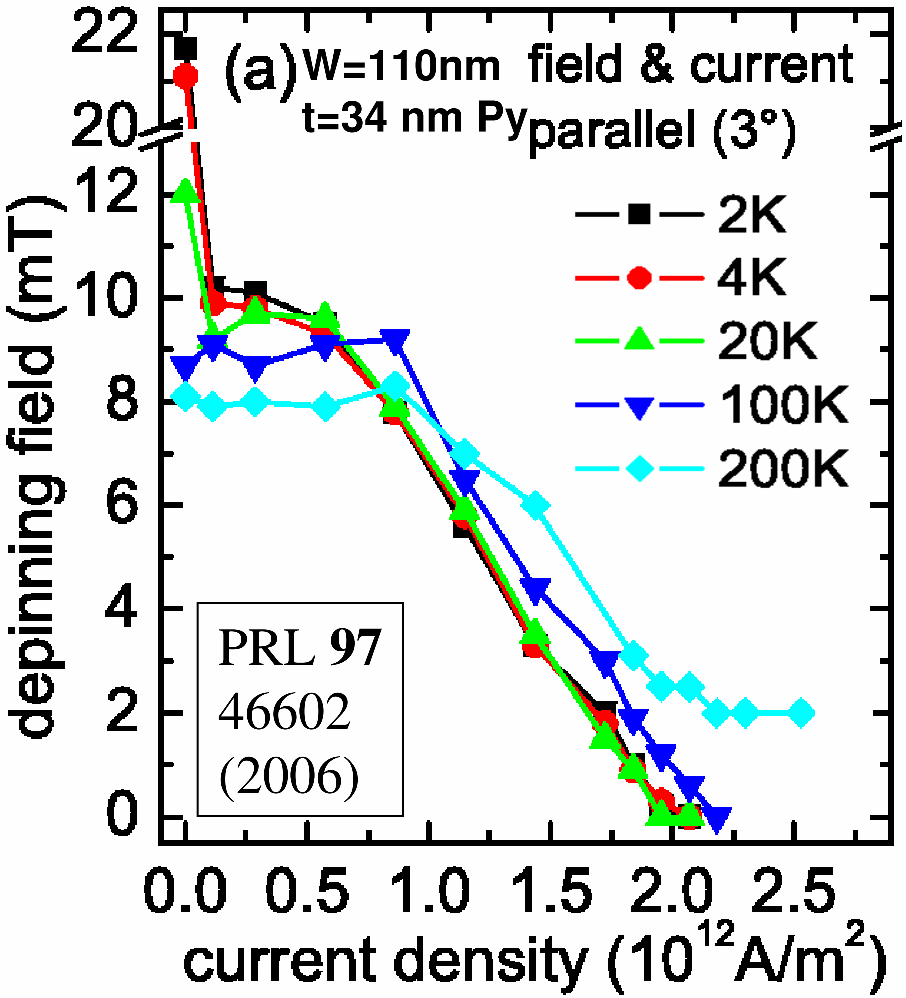


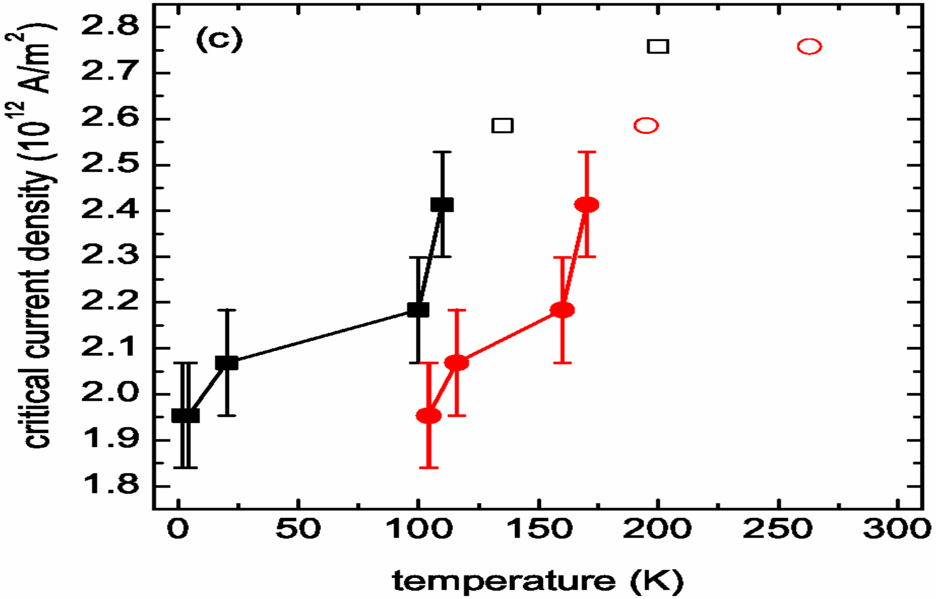
- Critical current density is decreasing with increasing wire width
- Models predict linear or square root dependence of velocity on j.
- Reliable switching for wire geometries with no transformations (far away from phase boundaries[1]):
  t=10nm, W=500nm: VW→TW;
  t=28nm, W=1µm VW→DVW
  t=28nm, W=2µm VW-DVW;
  t=28nm, W= 300nm no transformations).

- Experimental values are far below theoretically calculated values of 6-10 m/s or 100-800 m/s.[2] Spin torque effect less efficient than predicted!
- Possible influence of dispersion due to spin waves (0K calcs. vs. 300K exp.)?[3]

[1]M. Laufenberg et al., APL **88**, 52507 (2006);
[2]A. Thiaville et al., EPL **69**, 990 (2005); S. Zhang and Z. Li, PRL **93**, 127204 (2004)
[3]J. Fernandez-Rossier, Phys. Rev. B **69** 174412 (2004); J. Ohe et al., PRL **96**, 27204 (2006)

Temperature dependent measurements of j_{crit}



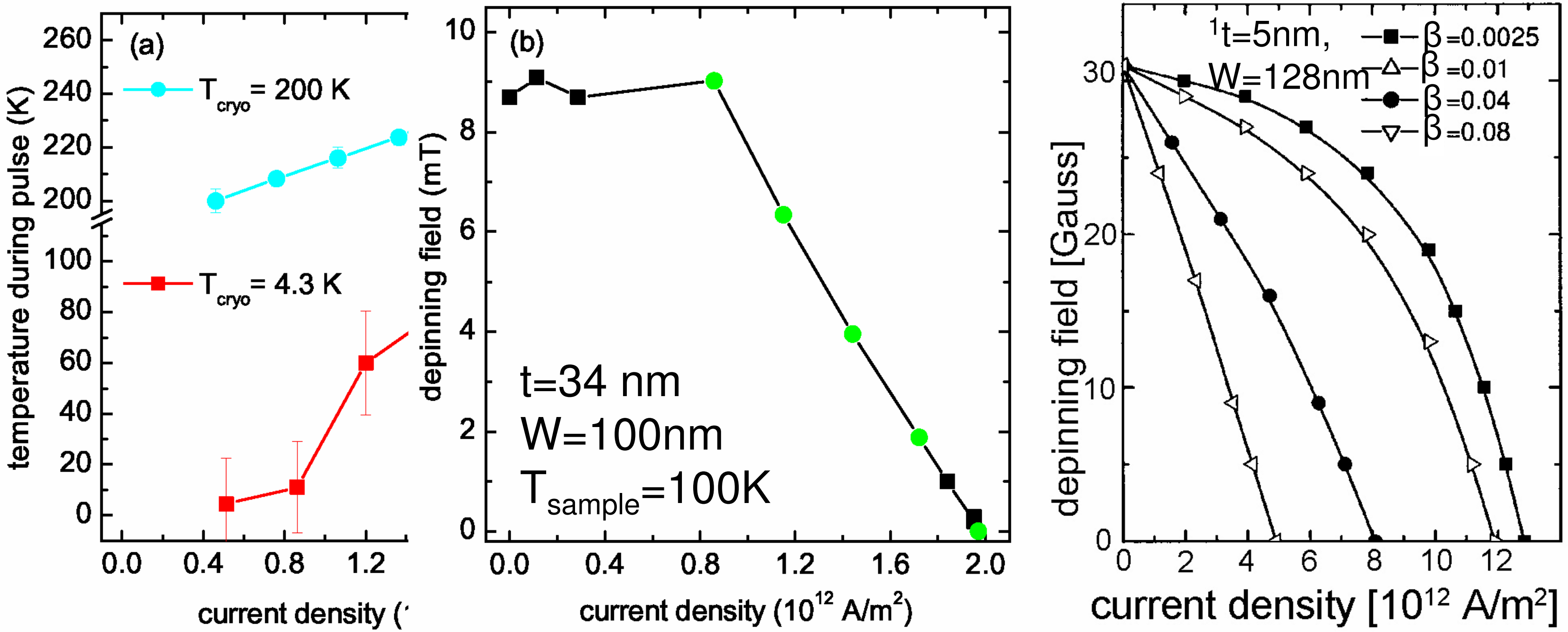


- At 0 current: exponential decay of depinning field → thermal activation[1]
- At 0 field: j_{crit} increases with T. →Spin torque more efficient at low T!
- Influence of polarization and thermal spin waves?[2]

Low current densities: decrease of H_{depin} due to heating (effect on vortex core?)
No significant effect of spin torque below thrshold current density 10^{12} A/m^2.
Reduction of depinning field down to zero at j_{crit} (CIDP) with increasing current.

[1]A. Himeno et al., JMMM **286**, 167 (2005); [2]M. Laufenberg et al., PRL **97**, 46602 (2006); J. Fernandez, PRB **69**, 174412 (2004)

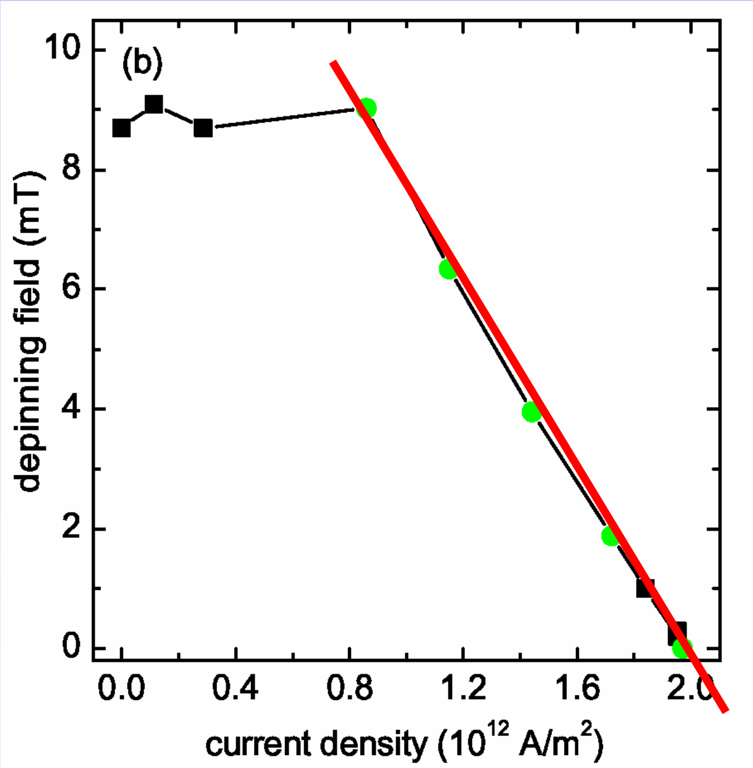
Temperature dependent measurements of j_{crit}

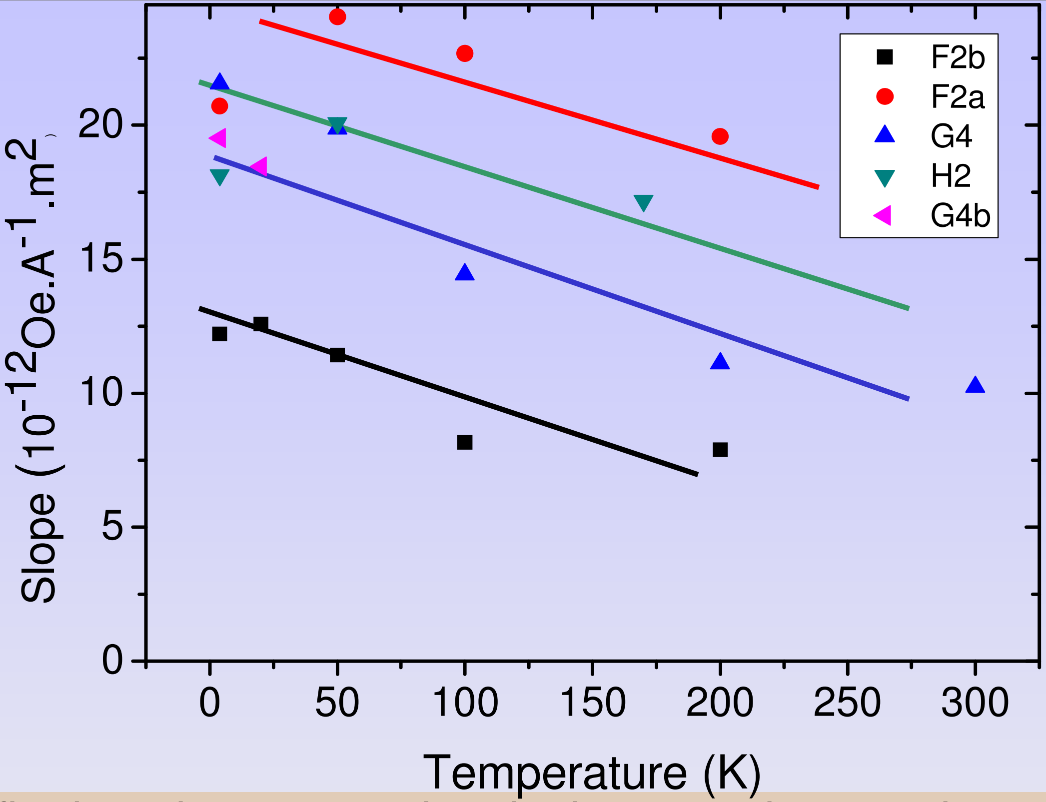


- Quantify effects of heating: Measure resistance during pulse injection using 4-point measurement setup to exclude influence of leads.
- Measure R(T) with low currents and comparison yields $T_{sample}(\mathbf{j})$
- Heating up to 100K at 4K and 60K at 200K → $T_{sample} << T_C$ (also for PEEM).
- Determination of $H_{depin}(T_{sample})$ to compare with theoretical calculations at constant T to determine β.[1]

[1]J. He et al., JAP **98**, 16108 (2005) [2]J. Fernandez-Rossier, PRB **69**, 174412 (2004); M. Laufenberg et al., PRL **97**, 46602 (2006)

Temperature dependent measurements of j_{crit}





- The dependence of the propagation field on the current density is approximately linear and the slope can be extracted.[1]
- This slope depends for transverse walls on the non-adiabaticity parameter β.[2]
- For the domain walls a decrease of the slope with increasing temperature is observed.
- This might imply that β is increasing with decreasing temperature. But β=(exchange length/spin flip length)^2 and should rather decrease with decreasing temperature.
- Other mechanisms not included in theory so far (spin waves, polarization)?

[1]M. Laufenberg et al., PRL **97**, 46602 (2006); [2]J. He et al., JAP **98**, 16108 (2005)

Summary

1. Wall spin structures depend on geometry
   (vortex walls, transverse walls, phase diagram, stray fields thermally activated transformations, etc.)
2. Spin torque induces wall propagation and vortex core nucleation and annihilation (transformations)
   (movement of TW and VW in electron flow direction, geometry dependent wall transformations, velocity depends on geometry and wall structure, etc.)
3. The spin torque effect is more efficient at low T
   (critical current densities increase with T, spin waves?)
4. Using other materials (highly spin-polarized halfmetallic ferromagnets or materials with large anisotropies, etc.) lower critical current densities and higher velocities are obtained.

Acknowledgements:
C. König, G. Güntherodt, RWTH Aachen,R. Dunin-Borkowski, H. Ehrke, F. Junginger, Cambridge Univ.; Y. Nakatani, UEC; A. Thiaville, LPS Paris-Sud, EPSRC, DAAD, DFG SFB 513, EU TMR Network SpinSwitch

Review of domain walls: M. Laufenberg et al., Adv. Solid State Phys. 46, (2006)