Current-induced Domain Wall Dynamics

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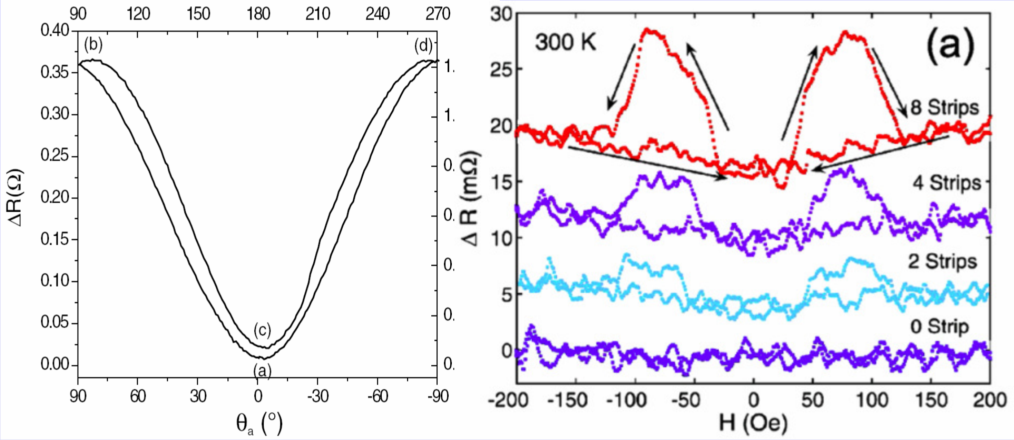
Starting Independent
Researcher Grant

- **Motivation: Physics & Applications**
- **Head-to-head domain wall spin structures**
- **Behaviour of domain walls at constrictions (pinning sites)**
- **Spin Torque Theory and simulations of CIDM**
- **Observation of CIDM in different materials (velocities, etc...)**
- **Current-induced domain wall quasiparticle excitations**
- **Magnetic Shift Register Device**

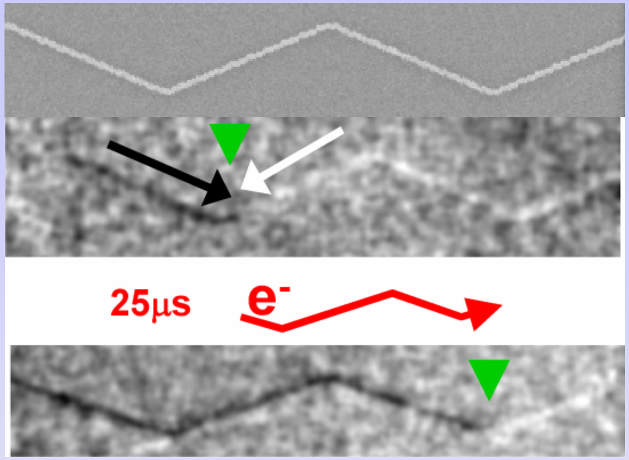
1. Domain walls & currents – exciting physics & applications

DW Magnetoresistance effects:

D. Buntinx et al., PRL **94**, 17204 (2005); A. Aziz et al., PRL **97**, 206602 (2006).

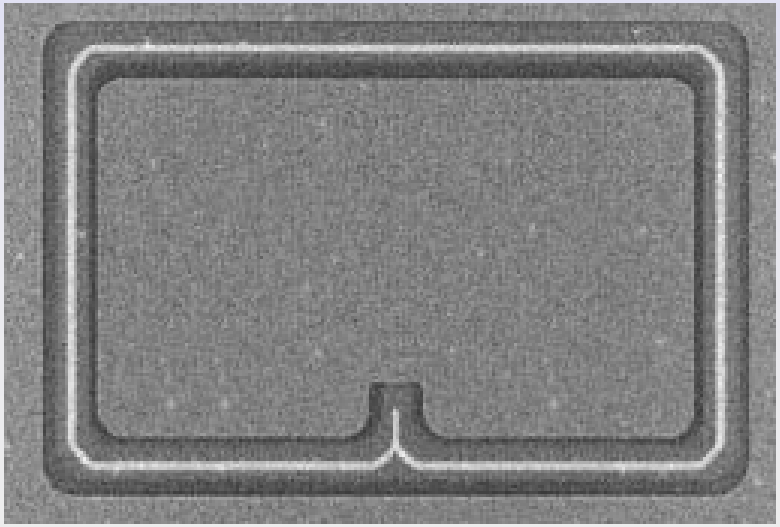


Current-induced domain wall motion (CIDM)



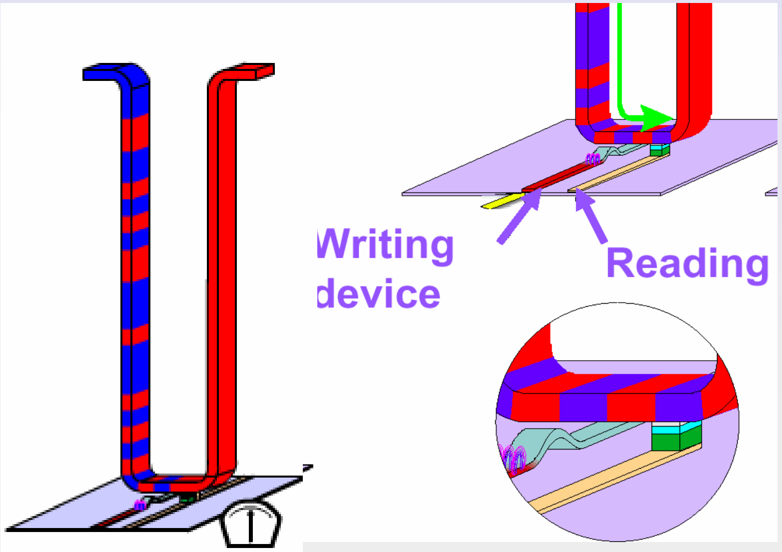
A. Yamaguchi, Phys. Rev. Lett. **92**, 77205 (2004)
M. Yamanouchi, Nature **428**, 539‘04
M. Kläui, et al. Phys. Rev. Lett.
94, 106601 (2005)
95, 26601 (2005)
96, 57207 (2006)
97, 46602 (2006)
99, 146601 (2007)
100, 66603 (2008)

Magnetic Logic – NOT gate



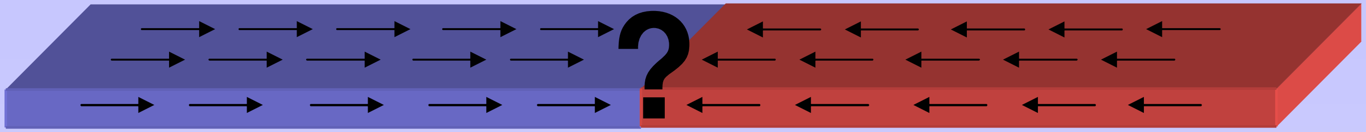
D. Allwood et al., Science **296**, 2003 (2002).

Storage – Racetrack memory

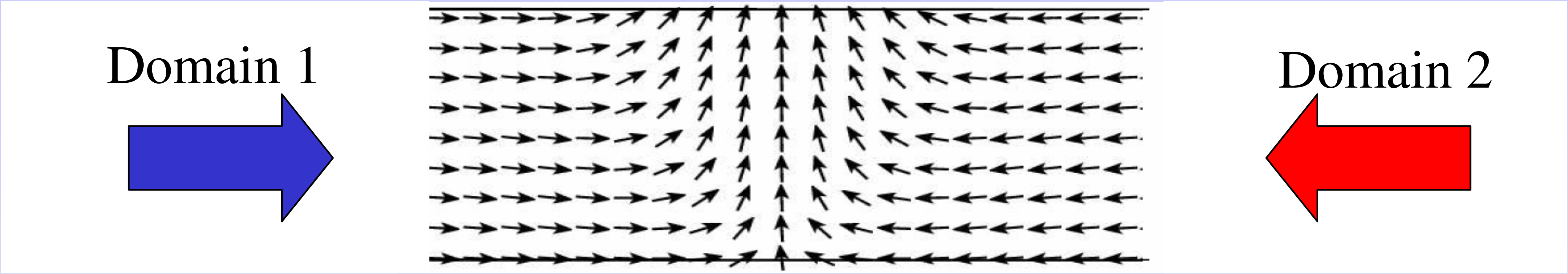


S. S. P. Parkin, Science **320**, 190 (2008); Patent 6834005.

2. Head-to-head Domain Walls - Theory

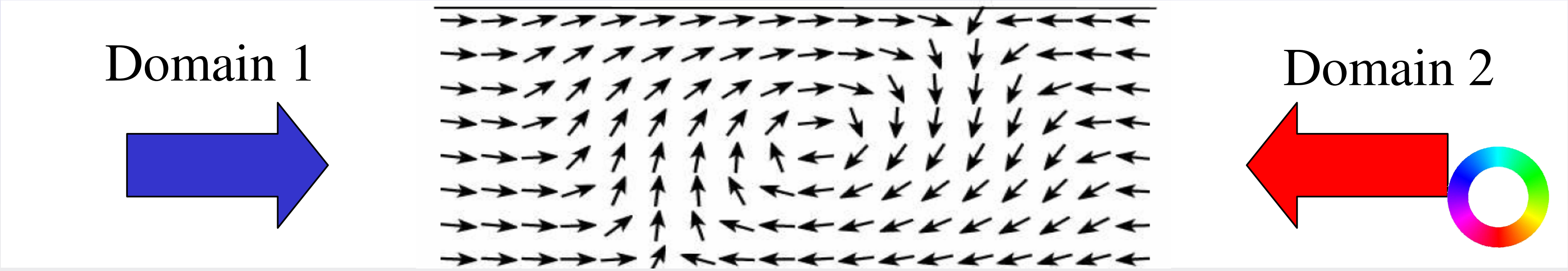


Transverse Walls



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

Vortex Walls

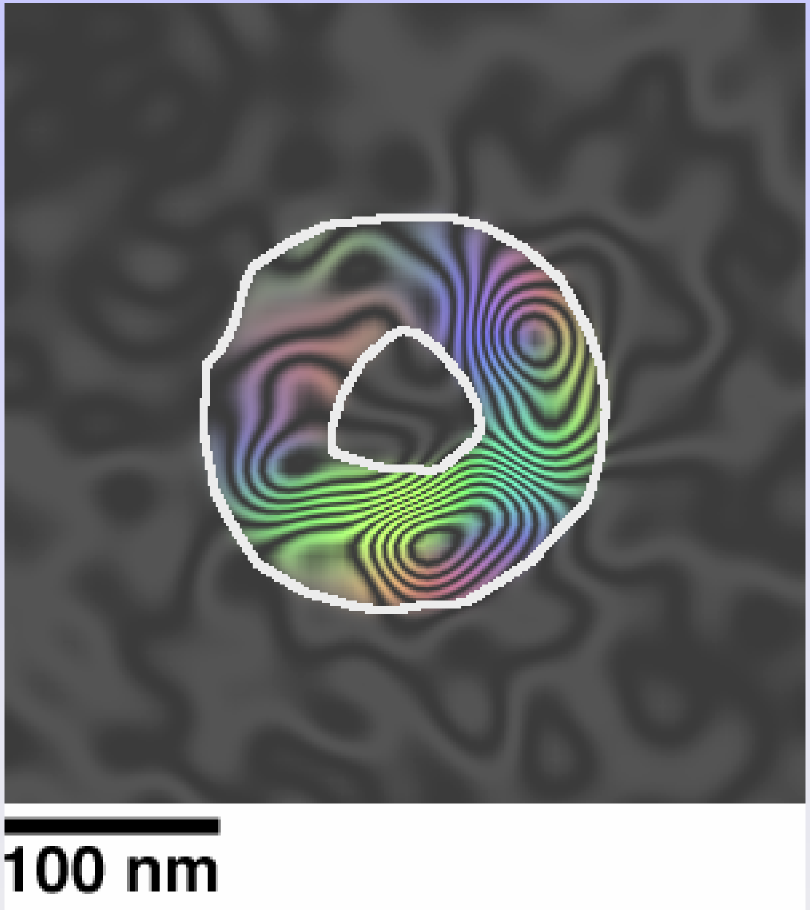


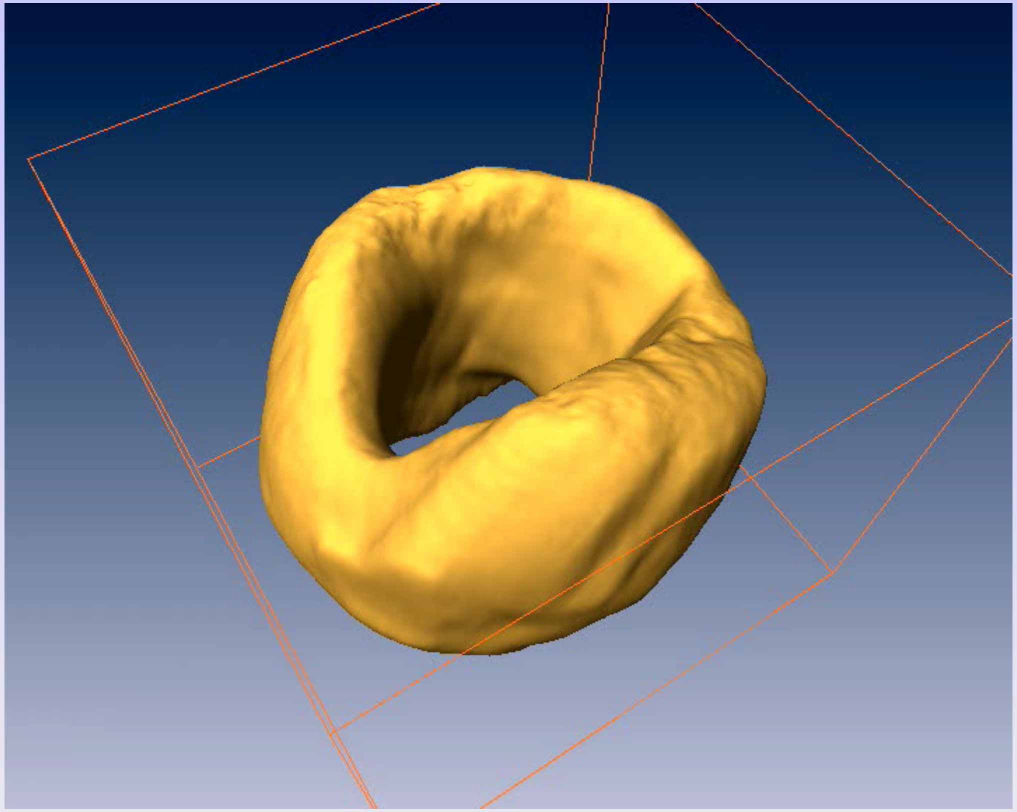
- Large exchange energy → energetically favourable in thick and wide structures.[1,2]

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

2. Head-to-head Domain Walls - Experiment

Co Rings, D=1.7µm; W=0.4 µm, 0.25 µm; t=34 nm; Spin-SEM & Electron holography



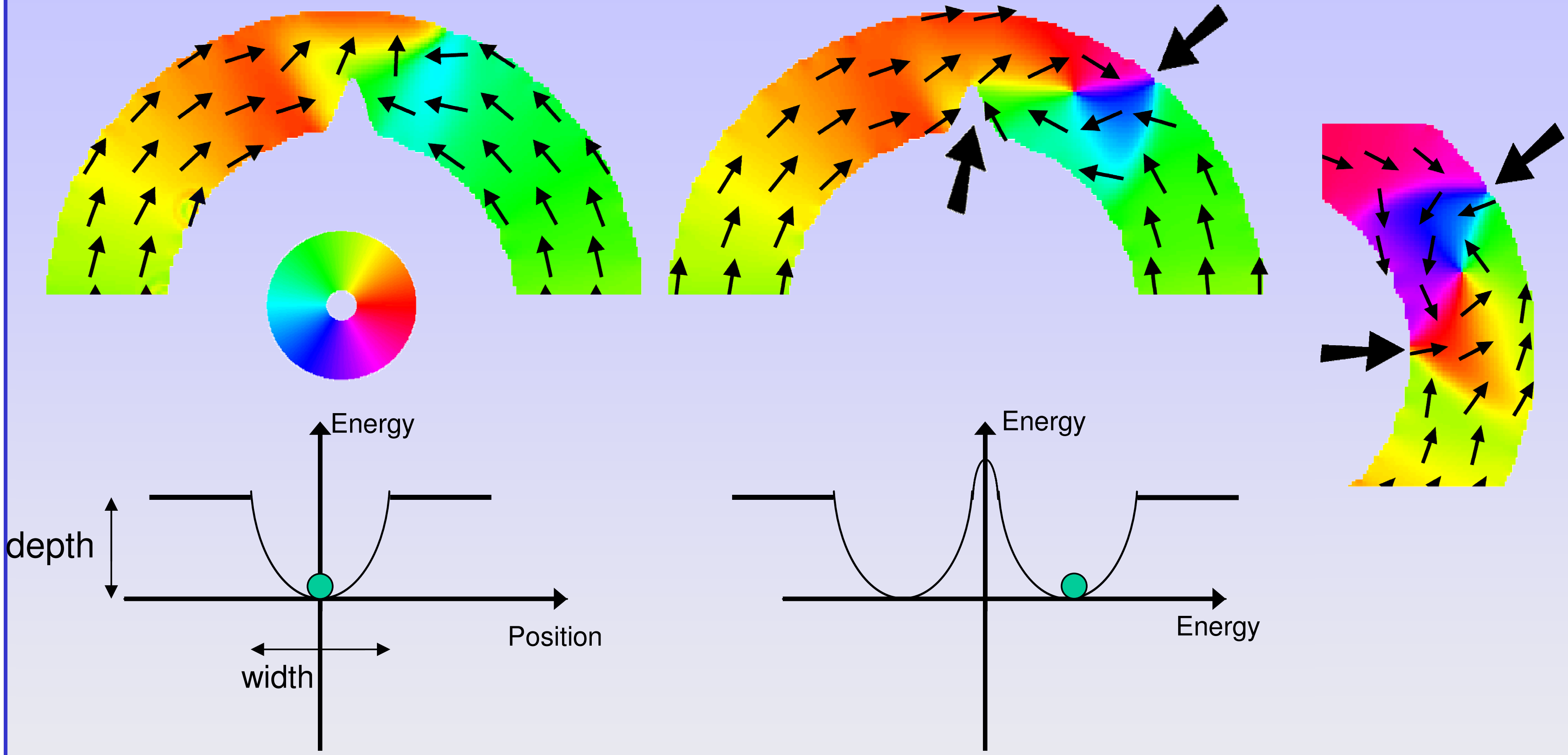


M. Eltschka, MK et al., Appl. Phys. Lett. **92**, 222508 (2008)

[1] M. Kläui et al., PRB **68**, 134426 (2003); PRL **86**, 1098 (2001), APL **84**, 951 (2004); APL **86**, 32504 (2005);

3. Pinning of TW & VWs at constrictions - Theory

Permalloy (NiFe) Rings, D=1.6 µm, W=200 nm, t=32 nm, micromagnetic simulations

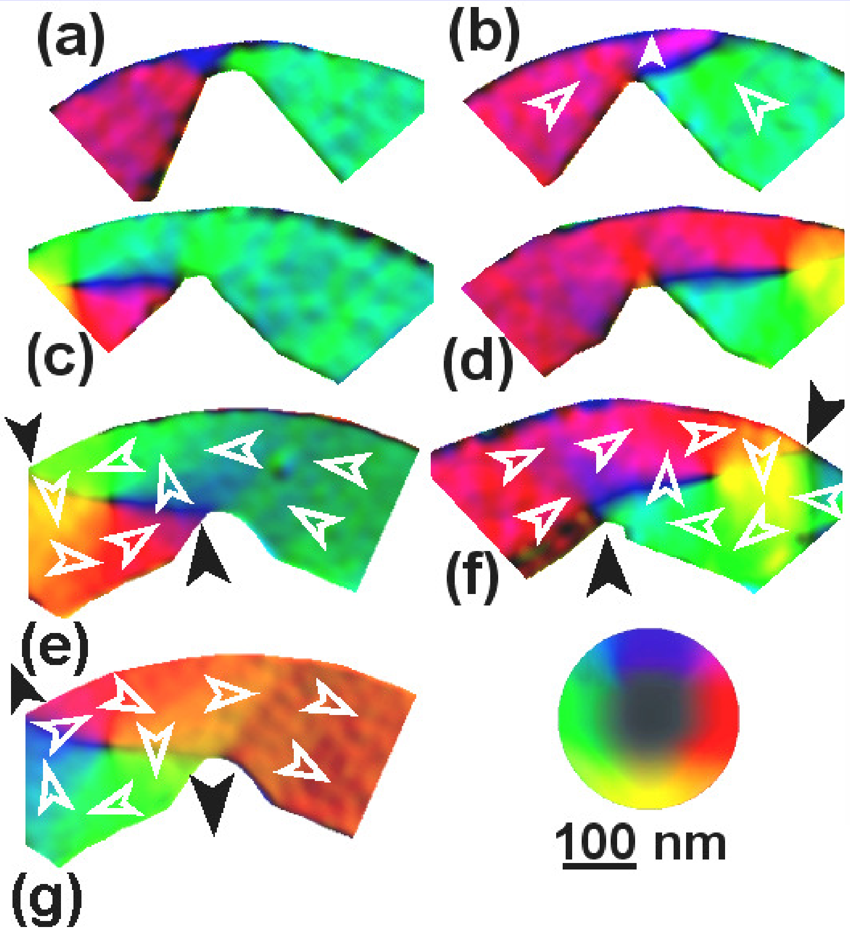


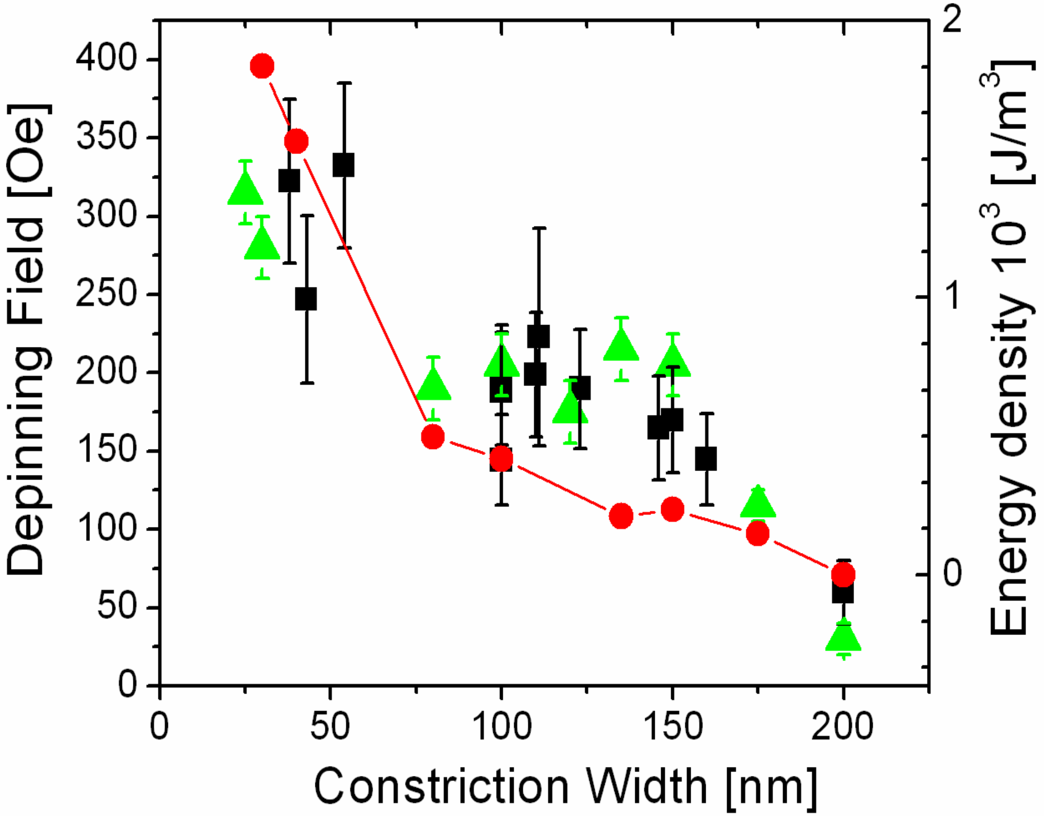
- Transverse walls are attracted into the notch (single attractive potential well).
- Vortex walls are repelled by the constriction but pinned adjacent to the constriction due to the reduced stray field (double potential well).
- There is a definite sense of rotation of the vortex wall depending on the position.

M. Kläui et al., PRL **90**, 97202 (2003); APL **87**, 102509 (2005)

3. Pinning of TW and VW at constrictions - Experiment

Permalloy Rings, W=200 nm; t=27 nm; Electron holography and magnetotransport



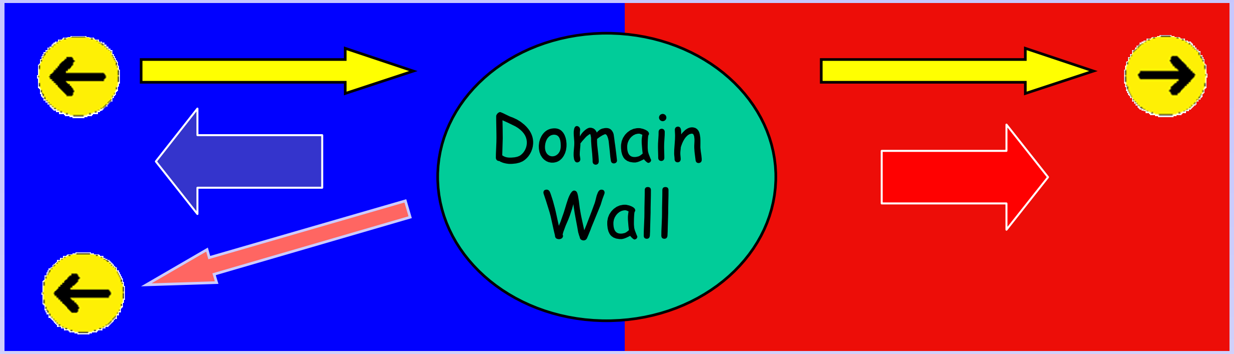


- (a),(b) show transverse walls (<50nm)
- (c)-(g) show vortex walls (>50nm).
- (e), (g) show a head-to-head and a tail-to-tail wall after reversing **H**.

- Depinning field (exp. black) increases as potential well **DEPTH** (red) with decreasing constriction width (factor 6).[1]
- The **WIDTH** of the potential well extends far beyond the physical size of the notch.[2]

[1] M. Kläui et al., APL **87**, 102509 (2005); [2] M. Kläui et al., PRL **90,** 97202 (2003)

4. Current induced domain wall propagation



Incoming Electron

1. Reflection

Domain Wall

2. Transmission Spin rotates

Two possible mechanisms:

1. Narrow wall: Linear momentum transfer   2. Wide wall: Angular momentum transfer

(non-adiabatic transport)   (adiabatic transport)

G. Tatara

- Description using the Landau – Lifshitz Gilbert equation:

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

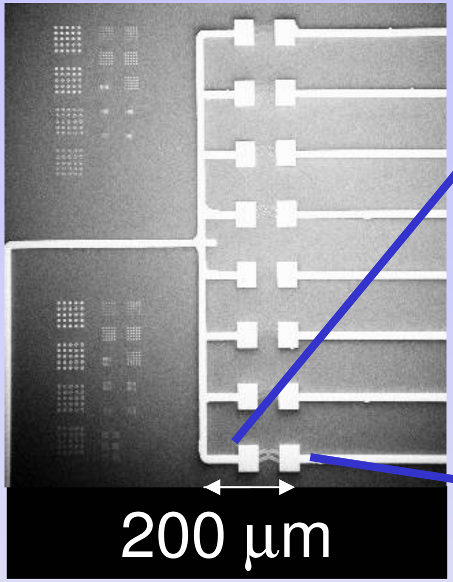
- Adiabatic spin torque: proportional to $\vec{u} = \vec{j} g P \mu_B / (2eM_s)$
- β-term torque (sources: spin relaxation and non-adiabatic transport): β = α?

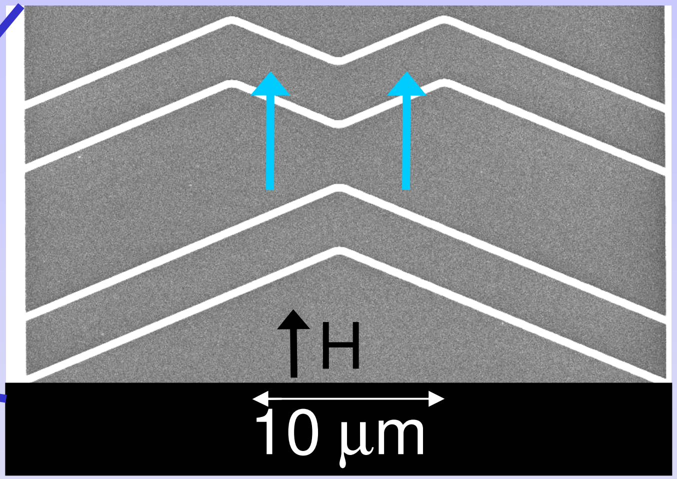
A. Thiaville et al., J. Appl. Phys. 95, 7049 (2004); G. Tatara et al., Phys. Rev. Lett. 92, 86601 (2004); C. Schieback, Eur. J. Phys. B 59, 429 ('07)

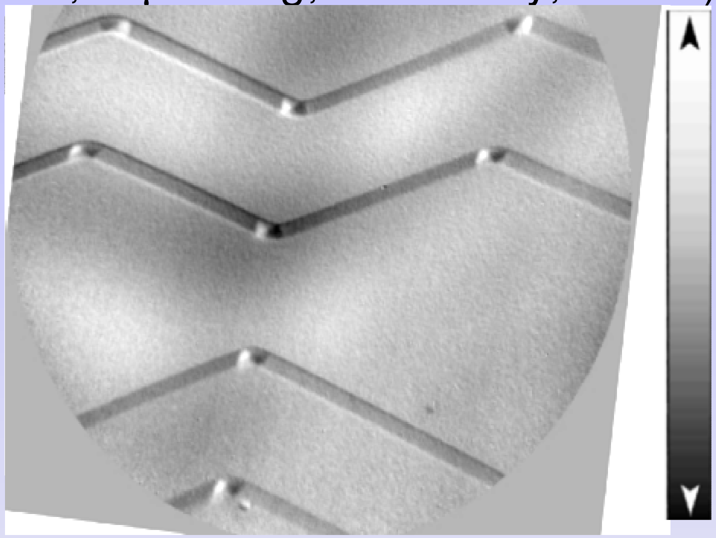
4. Current-induced domain wall motion – Experiment

Permalloy (NiFe) Wires W=50-500nm, t=5-50 nm, Spin-SEM and XMCDPEEM

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





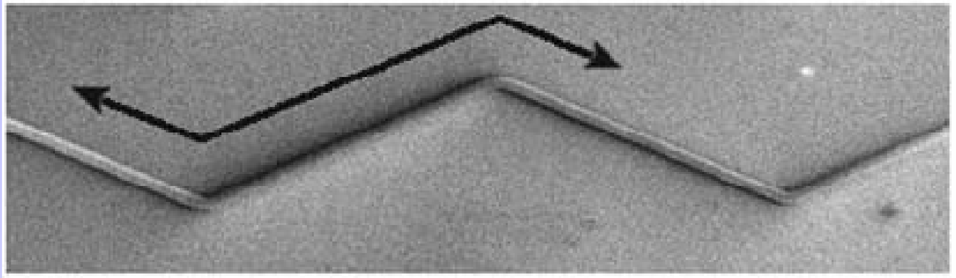


- Zig-zag permalloy ($Ni_{80}Fe_{20}$) wires with variable geometries are used.
- Depending on the geometry, vortex or transverse walls are present
- Zig-zag wires allow one to generate head-to-head domain walls at the kinks by applying the field in the direction indicated by the arrow.
- The magnetization is pointing in opposite directions in adjacent branches of the wire.
- The kinks are ¼ ring elements with a radius >> wire width (wires magnetically smooth).

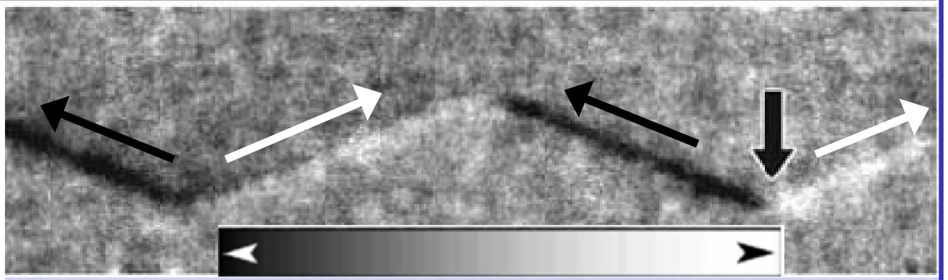
M. Kläui et al., APL **88**, 232507 (2006); PRL **94**, 106601 (2005)

4. Current-induced domain wall motion – Experiment

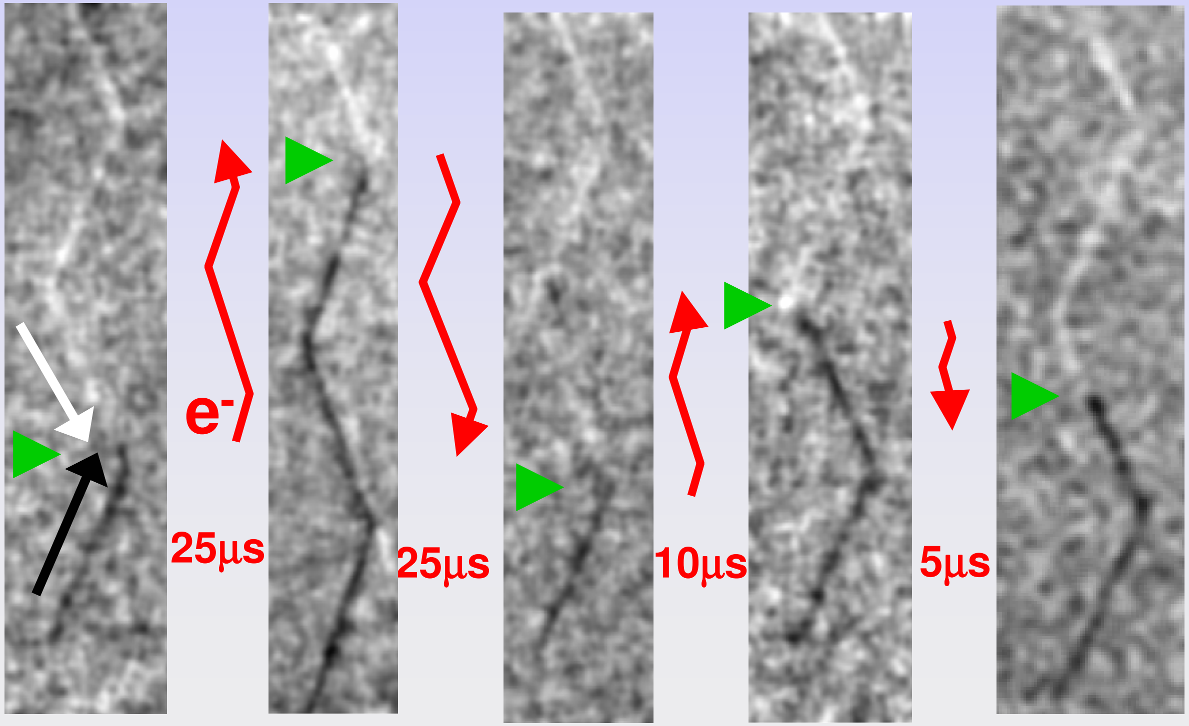
Permalloy (NiFe) Wires W=50-500nm, t=5-50 nm, Spin-SEM und XMCDPEEM



SEM topography image



Spin-SEM magnetization image



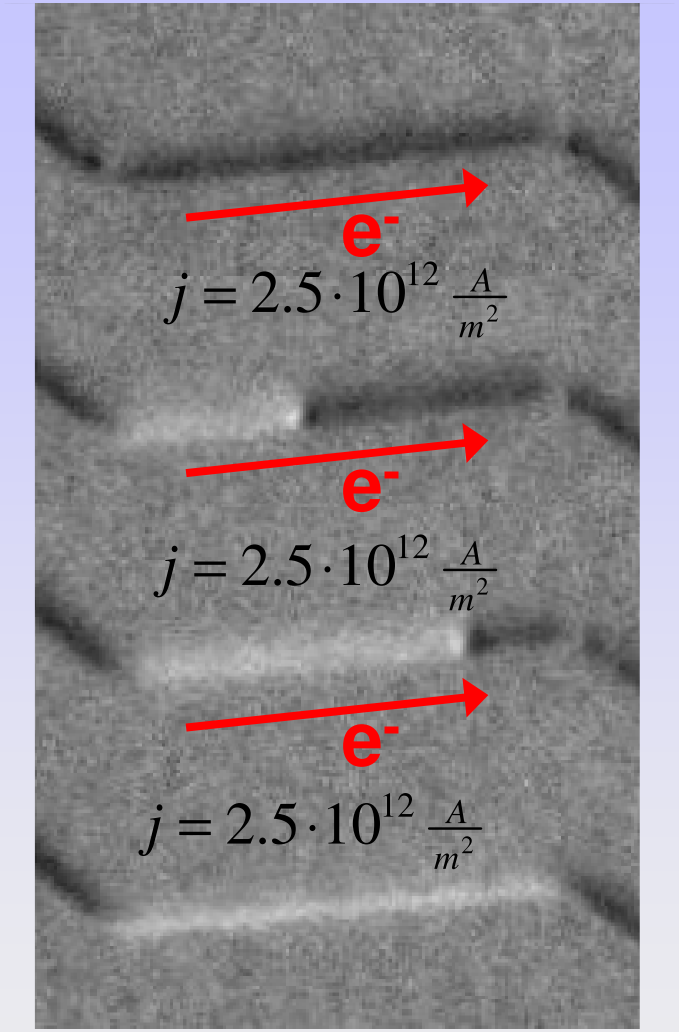
- Head-to-head vortex walls are formed at kinks.
- $j_{crit}=2,3\times10^{12}$ A/m^2
- Walls move in the direction of the electron flow.
- Pulse length Δt is varied.
- Velocity is independent of the pulse length: 1 m/s
- Walls move beyond kinks.
- Head-to-head and tail-to-tail walls move in the same direction → no field effect.

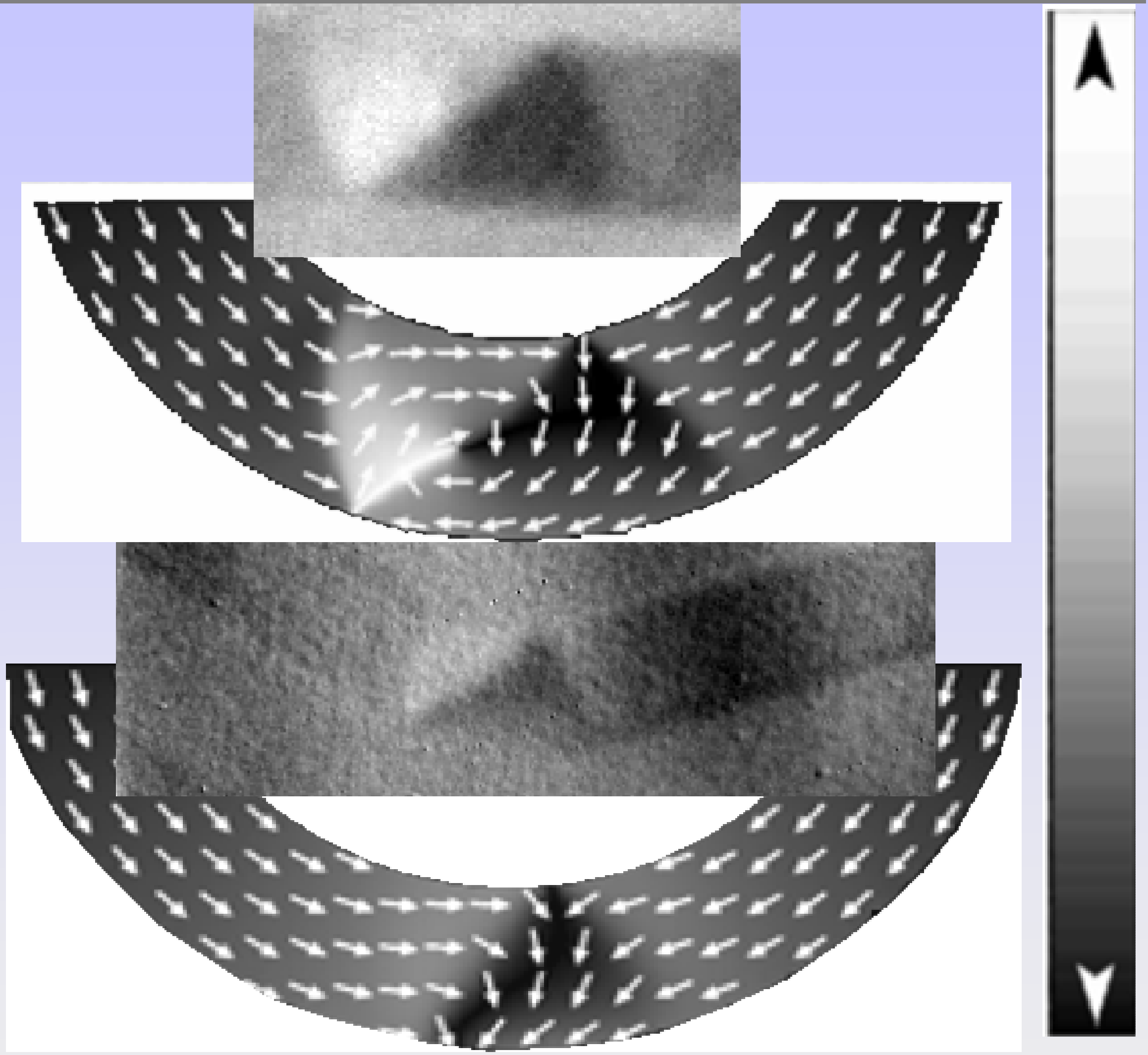
W=300nm; 60µm long; t=27nm Py, Spin-SEM measurement

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

4. High resolution imaging of wall spin structures

Permalloy Wires, W=1.5µm, t=7 nm, XMCDPEEM



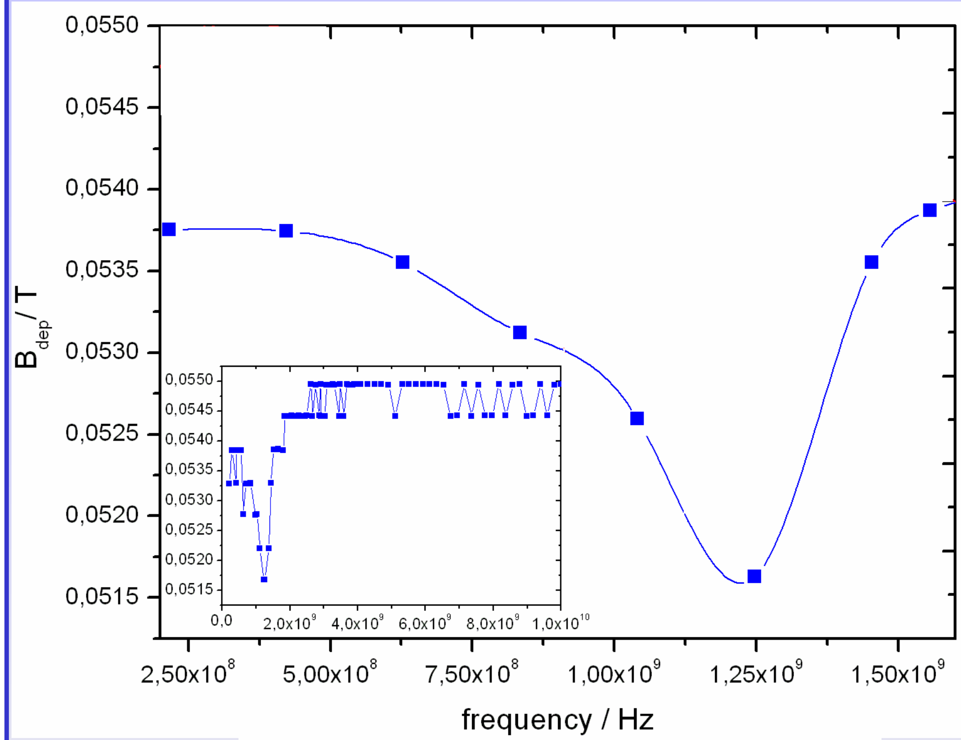


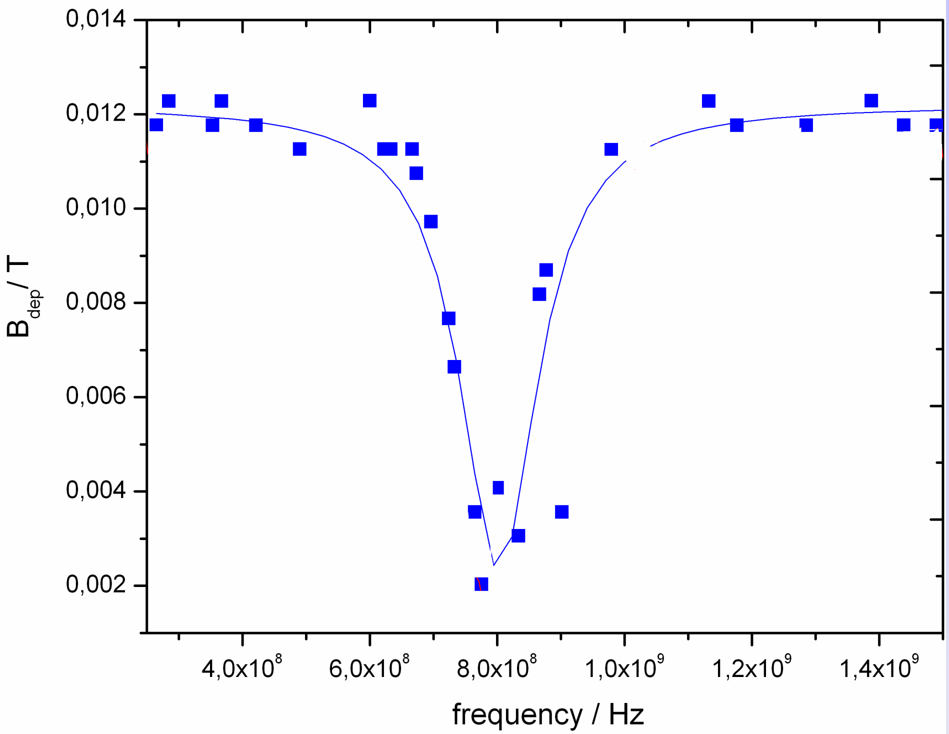
- Domain walls move in the direction of the electron flow and high-resolution imaging reveals the domain wall spin structures (vortex, transverse, etc.).

M. Kläui et al., PRL **94**, 106601 (2005); PRL **95**, 026601 (2005); PRL **100**, 66603 (2008)

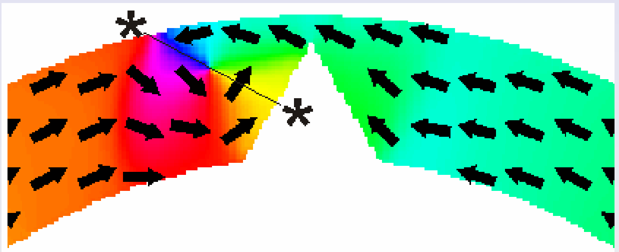
5. Resonant Domain Wall Dynamics

Permalloy (NiFe) Rings, W=200 nm; t=30 nm; Magnetotransport and Simulations





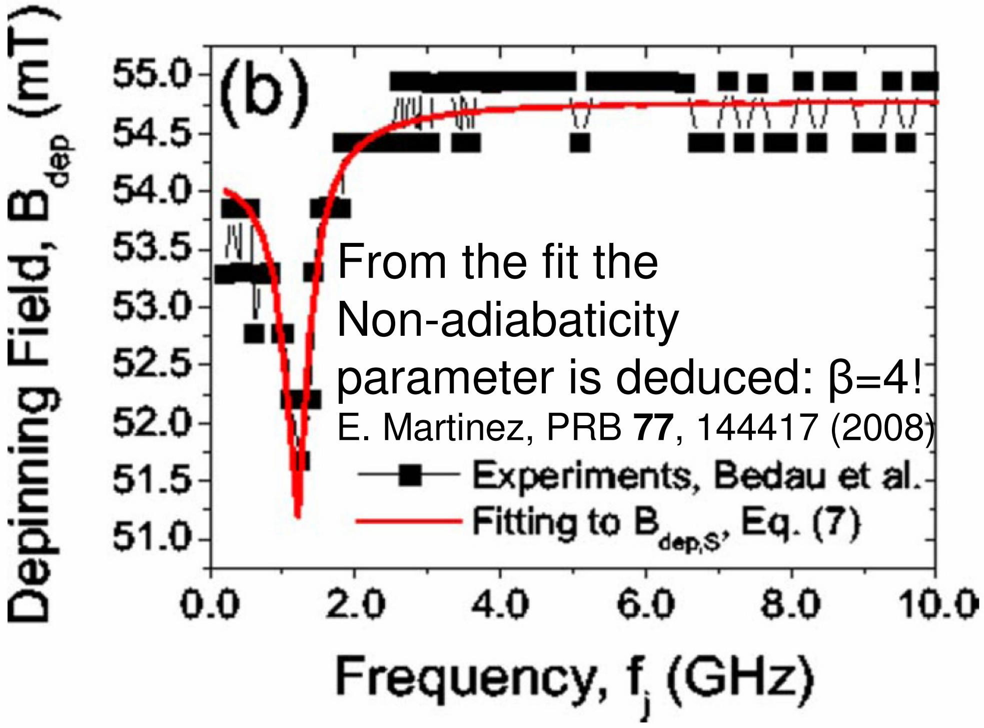
D. Bedau, M. Kläui et al., PRL **99**, 146601 (2007)



- Measurement of the depinning field as a function of µ-wave frequency .
- Depinning field is strongly reduced for certain µ-wave frequencies (resonance).
- TW has higher resonance frequency than VW; Narrow dip → high Q-factor.

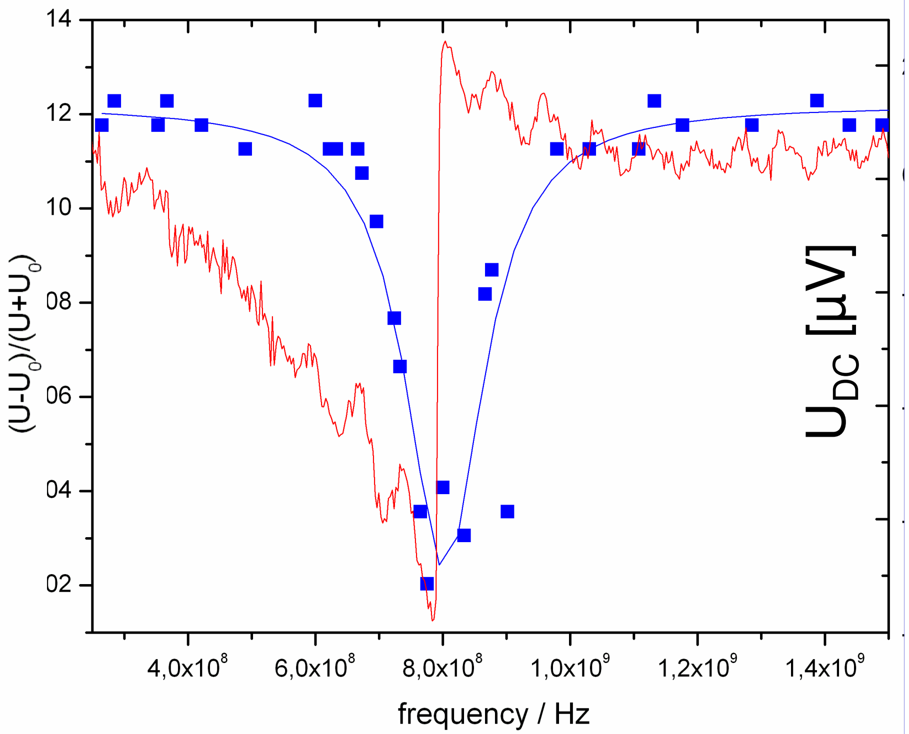
5. Electrical detection of domain wall oscillations

Py rings, W=200 nm, D=1.5 µm, t=30 nm, Magnetotransport



From the fit the Non-adiabaticity parameter is deduced: β=4!

E. Martinez, PRB **77**, 144417 (2008)



- Mixing of AC current (with frequency f=ω) and resistance change ΔR (with f=ω): → DC signal (and 2ω).
- Homodyne detection (DC signal): **$U_{DC}= I_{AC} * \Delta R * \cos(\varphi)$** with φ the phase shift.[1]
- For an undamped oscillation φ(ω)=90° at resonance → dispersion-like signal.
- For TW asymmetric dip (φ≠90° at $\omega=\omega_{res}$ due to asymmetric potential or damping). → Independent check of the resonant frequencies possible (at variable fields!)

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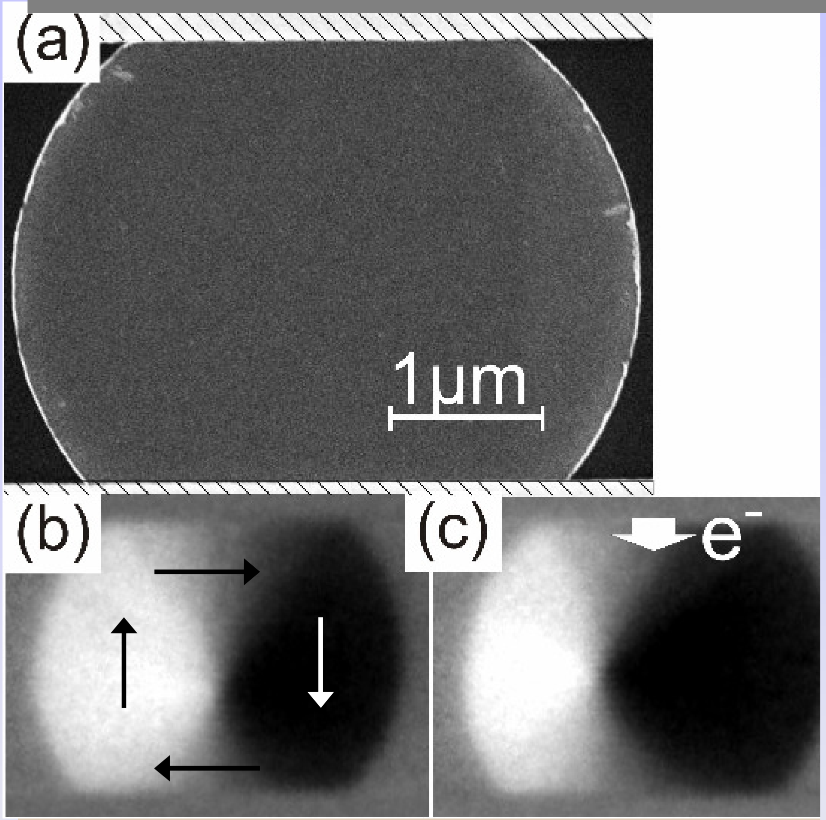
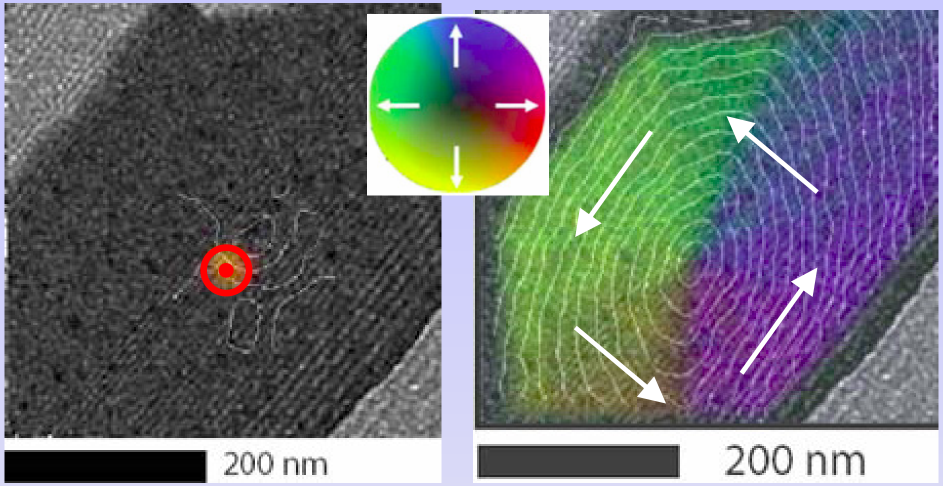
[1] D. Bedau, M. Kläui et al., PRL **99**, 146601 (2007); R. Moriya et al., Nature Phys. **5**, 368 (2008)

5. Current-induced vortex core displacement

Permalloy Discs, W=4µm, t=25 nm, High resolution MFM, holography & XMCDPEEM



Imaging with high resolution electron holography[3]



Out-of-plane vortex core In-plane magnetization

- Using TEM electron holography, the size and the polarity (out-of-plane component) of the vortex core is determined.[3]
- Using current pulses with alternating polarity, the vortex core can be moved **perpendicular** to the current reproducibly between two positions.[2]
- The direction depends on the vortex core polarity.
- The displacement direction and the total displacement is in agreement with theoretical predictions.[1]

[1] H. Kohno et al., JMMM **310**, 2020 ('07); [2] L. Heyne, MK et al., PRL **100**, 66603 ('08); [3] APL **92**, 112502 ('08)