Nanomagnetism

Scientific opportunities with soft X-ray microscopy

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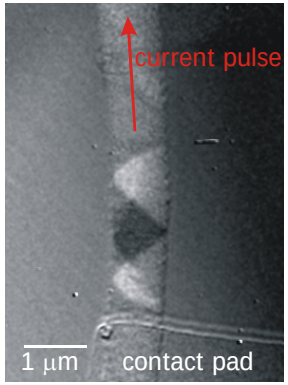
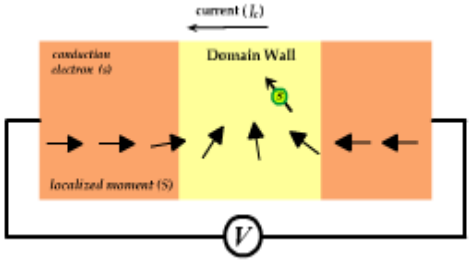
Nanomagnetism research



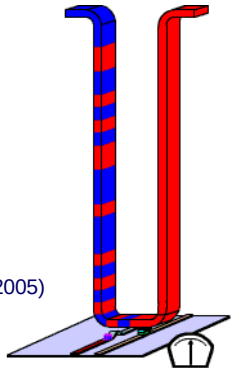
G. Meier et al. PRL (2007)

observation - experiment



courtesy S. Maekawa

understanding - theory

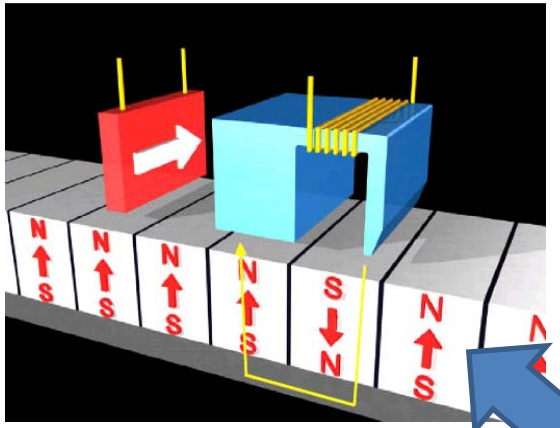


S. Parkin et al (2005)

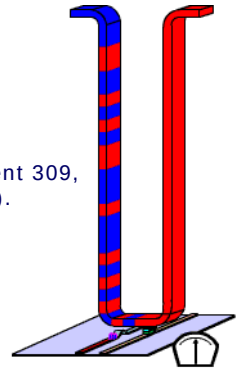
controlling - applications

Controlling spins on the nanoscale

magnetic (Oersted) field



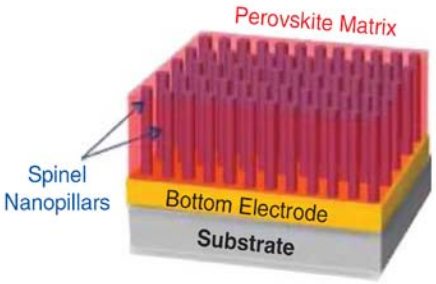
spin currents/ spin torque



S. Parkin US Patent 309, 6,834,005 (2004).

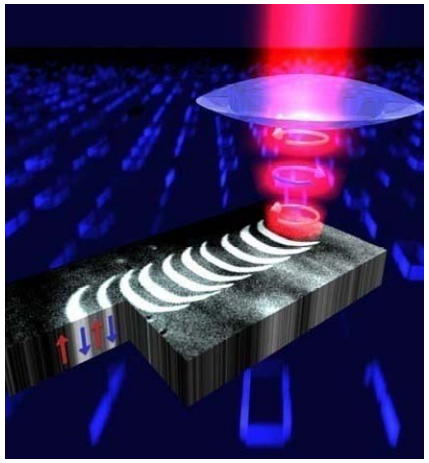
spintronics

electric fields e.g. multiferroics



Spaldin & Ramesh MRS Bull Nov 2008

photonic control

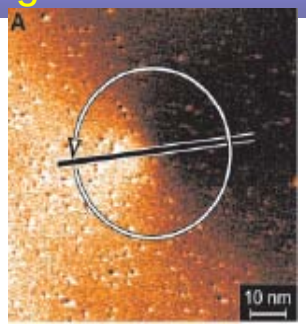


C.D. Stanciu et al., Phys Rev Lett 99 047601 (2007)

The Holy Grail for magnetic microscopy

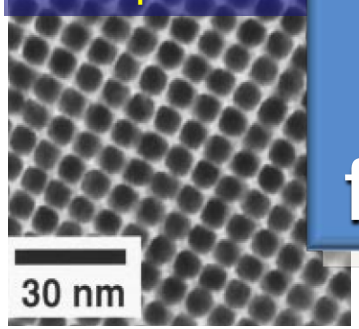
Imaging spin structur
nm spatial and
fsec (snapshot) time re

magnetic vortices



A. Wachowiak et al, Science (2002)

nanoparticles



S. Sun et al, Science (2000)

nm

µm

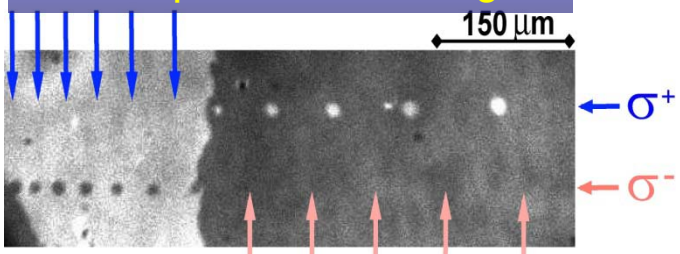
length scales
exchange length

$$l_K \sim \sqrt{A/K} \sim \text{sub} - 10\text{nm}$$

time scales
exchange interactions

$$t(fs) \sim 4/E_{ex}(eV) \sim 20 - 50fs$$

all optical switching

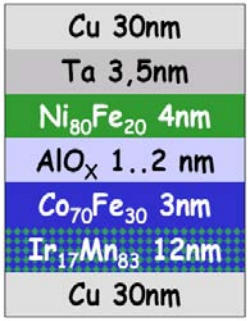


C.D. Stanciu et al., PRL 99,047601 (2007)

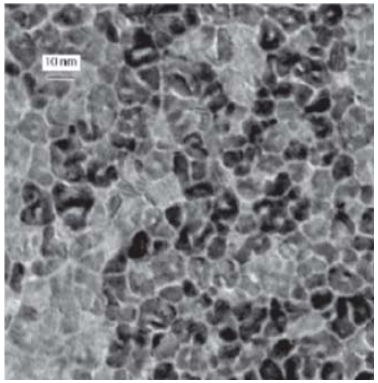
courtesy Th. Rasing

ns ps fs

... in multicomponent magnetic materials

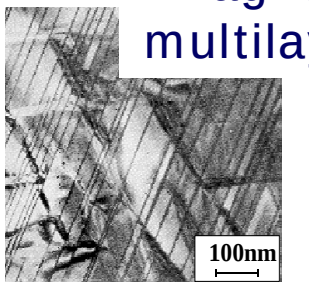


magnetic multilayers



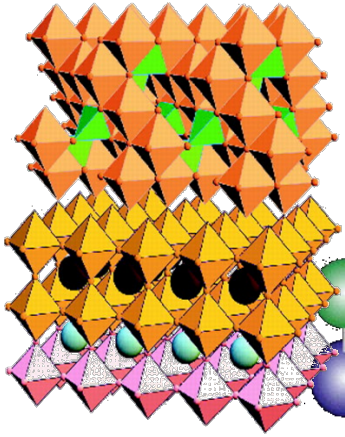
granular CoCrPtB

A. Moser et al. JPhysD (2002)



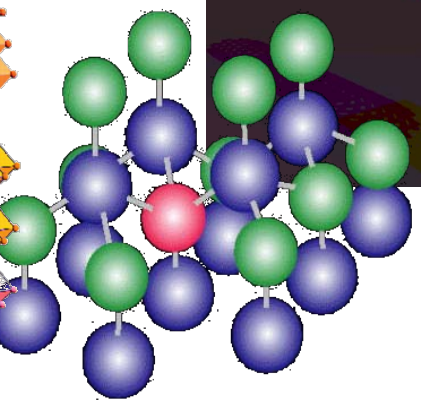
$Sm_2(Co,Cu,Fe,Zr)_{17}$

D. Goll, Z. Metallk. (2002)

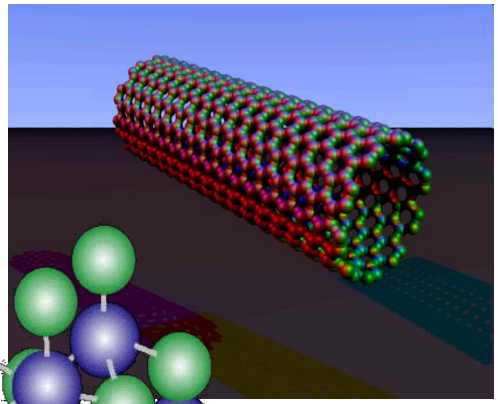


courtesy R. Ramesh

multiferroics



magnetic semiconductors



courtesy wikipedia.com

carbon nanotubes

length scales

exchange length

$$l_K \sim \sqrt{A/K} \sim \text{sub} - 10\text{nm}$$

+

time scales

exchange interactions

$$t(fs) \sim 4/E(eV) \sim 20 - 50fs$$

+

elemental specificity

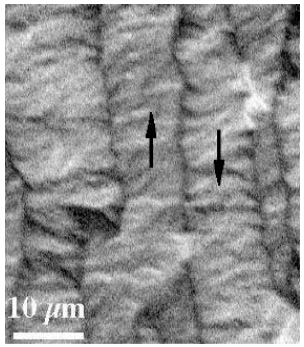
Fe, Co, Ni, ...
high sensitivity

Outline

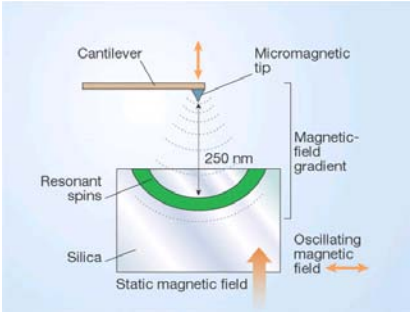
- What can we study today?
- What are the open questions?
- What needs to be done tomorrow?

Other magnetic microscopy techniques

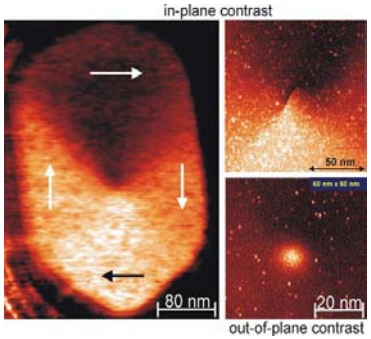
- Optical microscopies
  - Kerrmicroscopy
- Electron microscopies
  - Scanning Electron Microscopy with Polarization Analysis (SEMPA)
  - Lorentz (TEM) microscopy
  - Spin polarized SPLEEM
  - X-PEEM (X-ray-in/ Photoelectron-out)
  - Spin polarized SP-STM
- Scanning force microscopies
  - Magnetic Force Microscopy (MFM)
  - Magnetic Resonant Force Microscopy (MRFM)



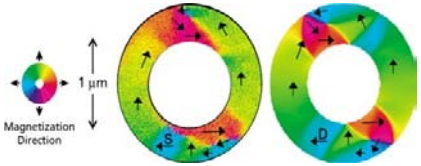
R. Schäfer, et al.IEEE TransMag 39 (2003)



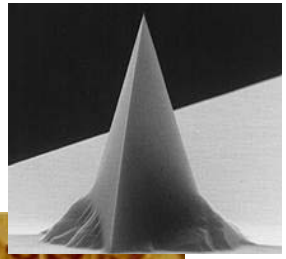
P.C. Hammel, Nature (2004)

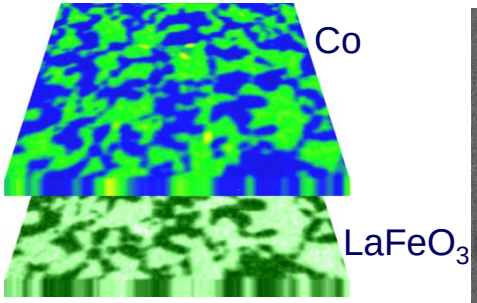


A. Wachowiak et al, Science 298 (2002)

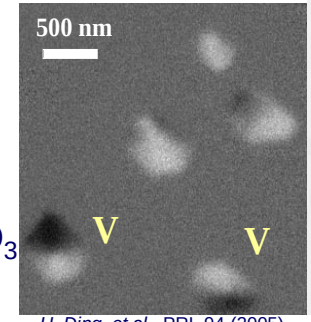


courtesy J. Unguris, NIST

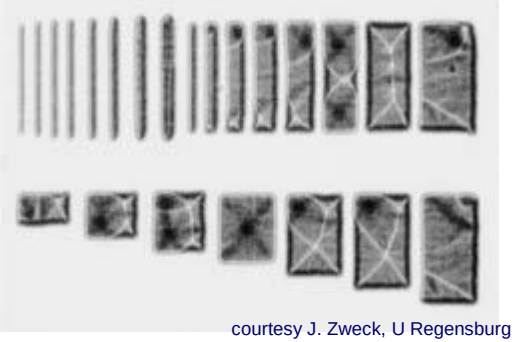




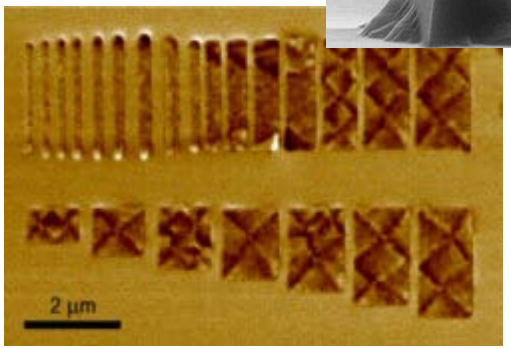
F. Nolting et al, Nature (2000)



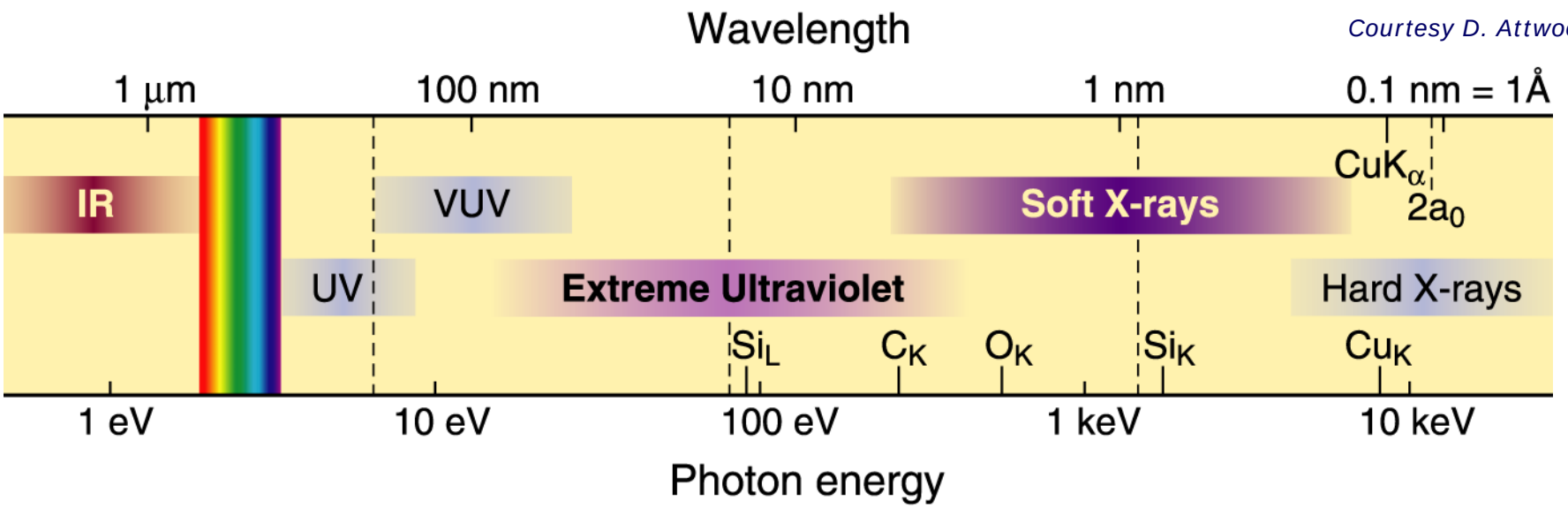
H. Ding, et al., PRL 94 (2005)



courtesy J. Zweck, U Regensburg



The power of soft X-rays

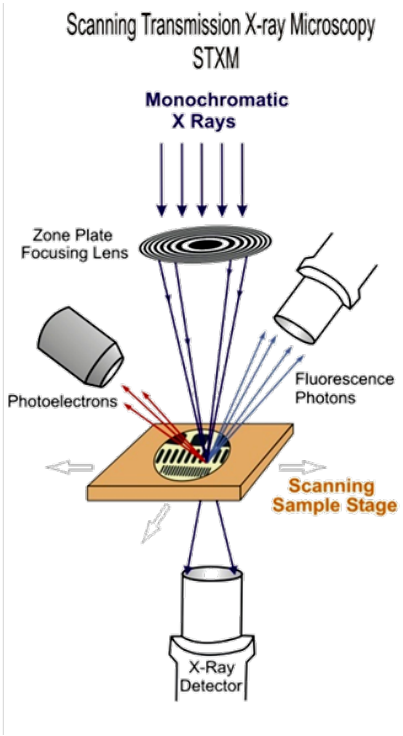


Courtesy D. Attwood

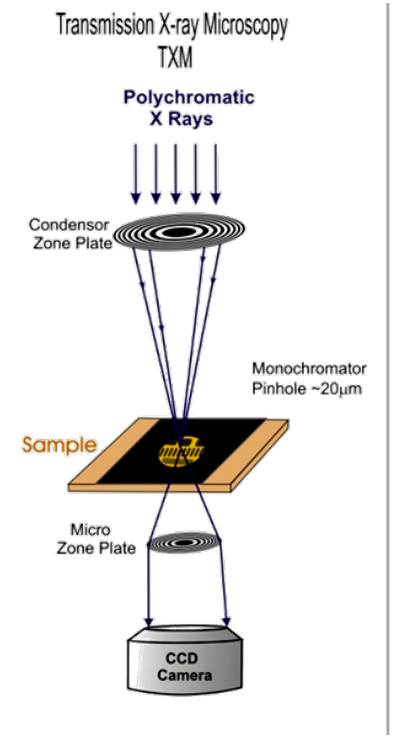
⇒ access to relevant magnetic elements down to fundamental magnetic length and time scales

Various X-ray imaging techniques

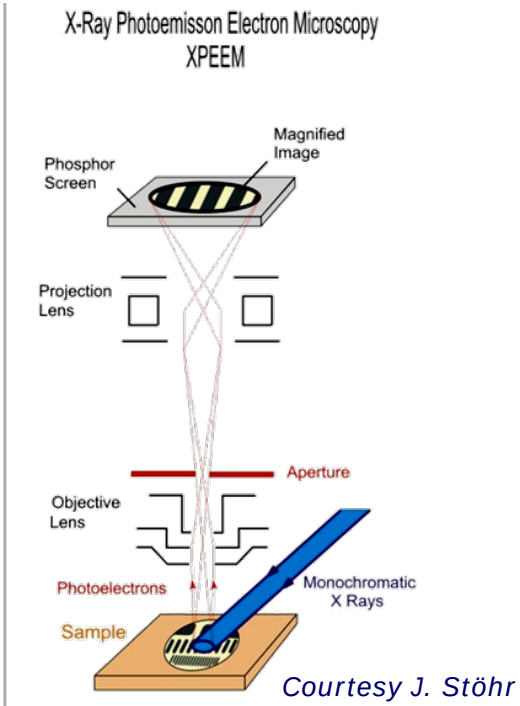
in real space



J.B. Kortright, et al., in: X-Ray Microscopy, AIP **507** 49 (2000)

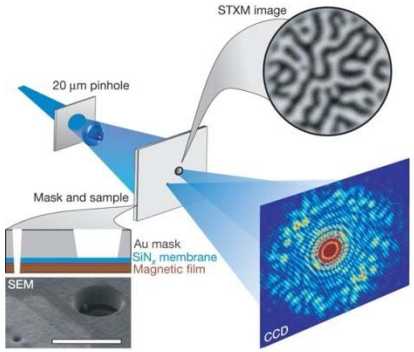


P. Fischer, et al., Z. f. Phys. **B101** 313 (1996)



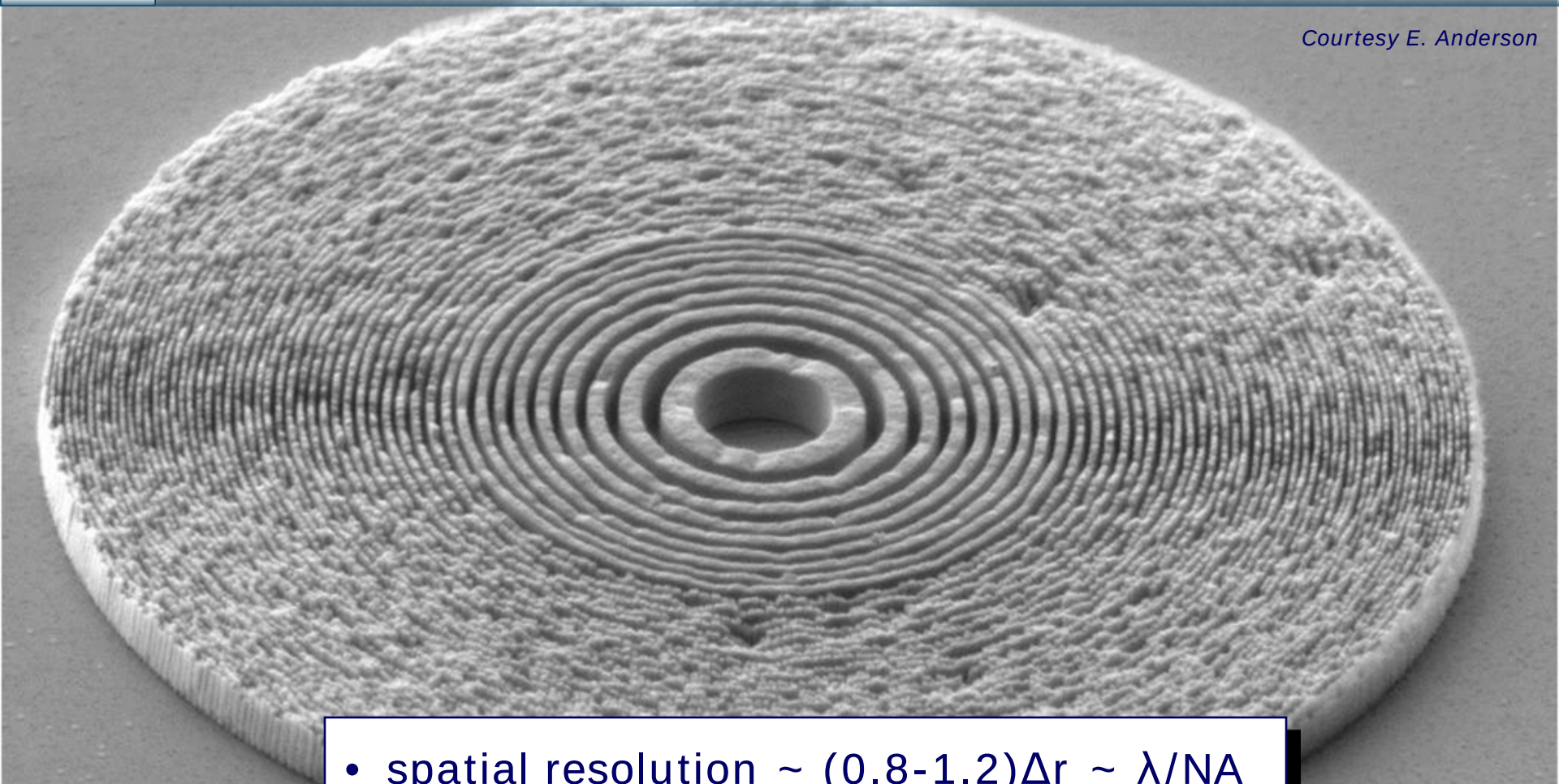
J. Stoehr, et al., *Science* **259** 658 (1993)

in reciprocal space



S. Eisebitt, et al. *Nature* **432**, 885 (2004)

Fresnel Zone Plate Lenses

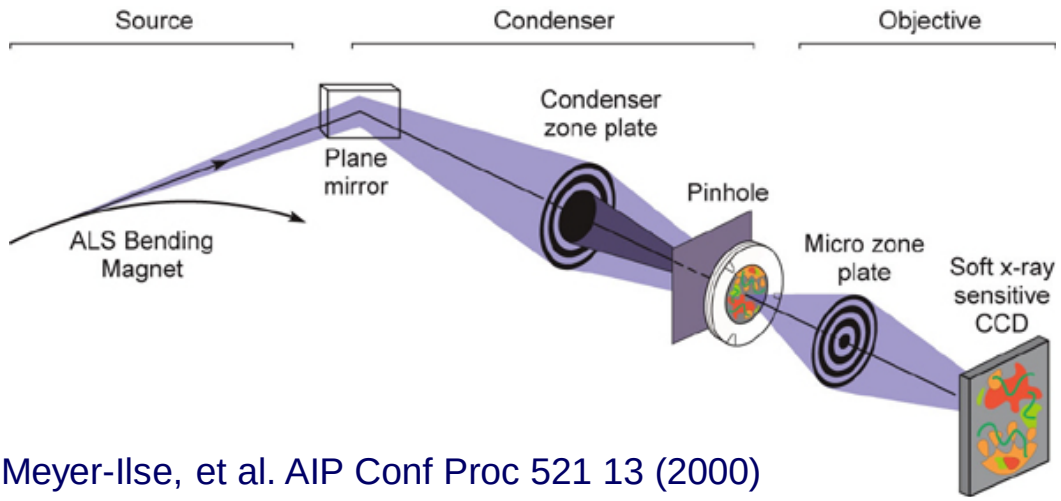


Courtesy E. Anderson

- spatial resolution ~ (0.8-1.2)Δr ~ λ/NA
- focal length ~$4N(\Delta r)^2/\lambda$
- spectral bandwidth $\Delta\lambda/\lambda$ ~ 1/N

Full-field TXMs

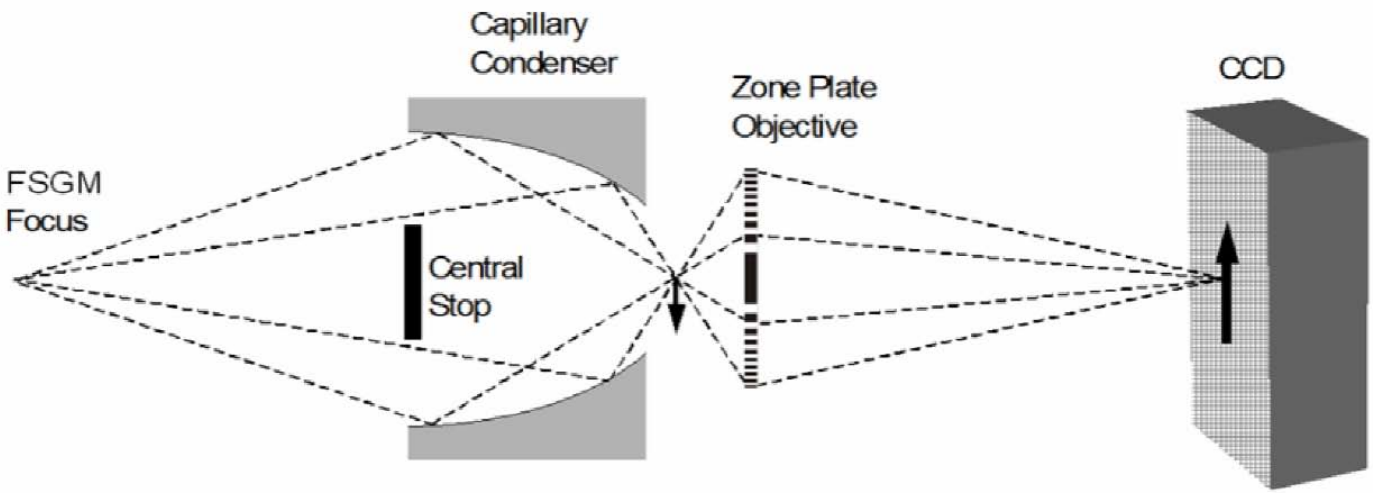
ALS



W. Meyer-Ilse, et al. AIP Conf Proc 521 13 (2000)

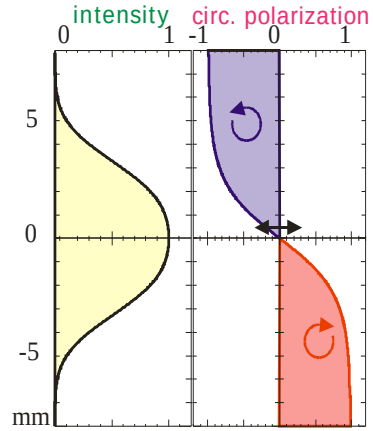
BESSY II

U41



P. Guttmann et al, JOP Conf Ser. 186 012064 (2009)

Schematics of XM-1

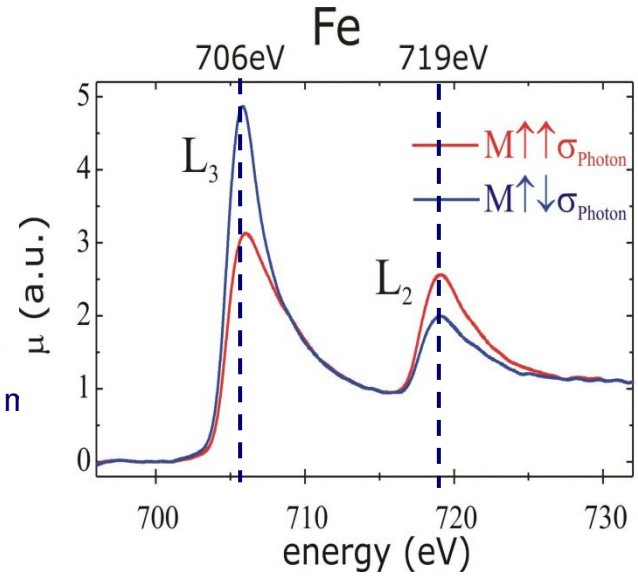


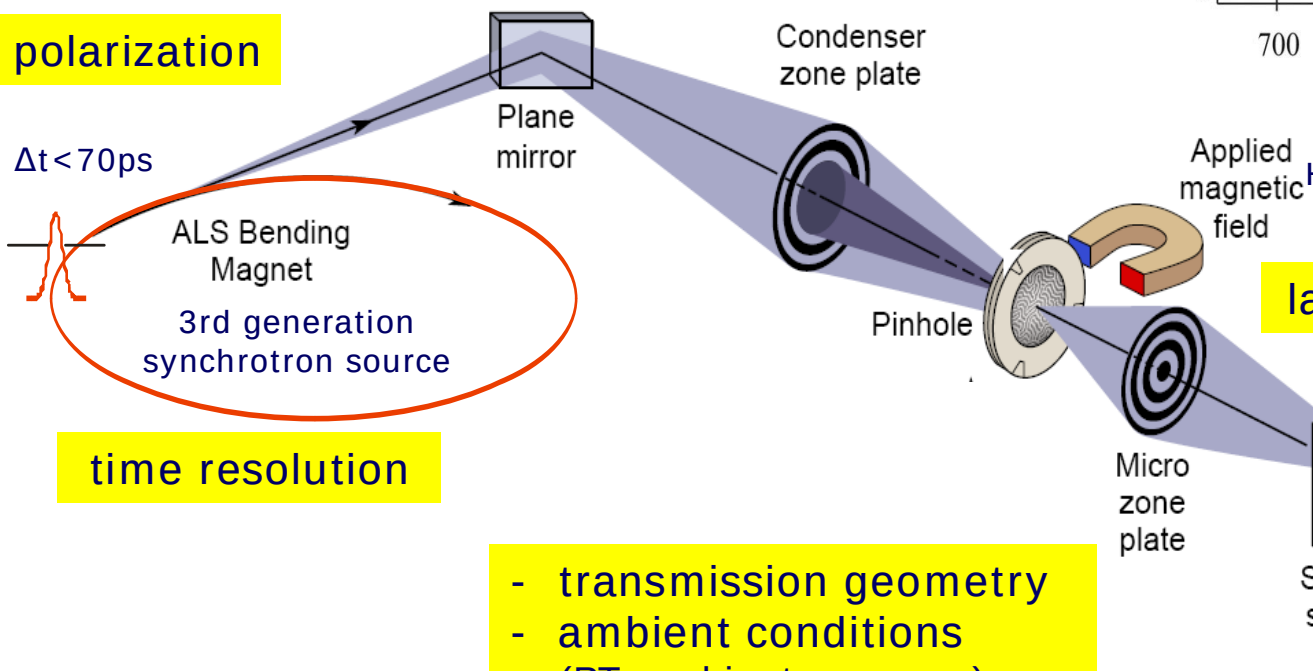
polarization

XMCD contrast

element specificity

E = 500eV – 1.0 keV
λ= 1.24 nm – 2.48 nn
ΔE/E=300-500





Δt<70ps

H_{max} = 5kOe (perp.)
= 2kOe (long.)

lateral resolution

CCD 2048x2048 px²
Mag ~ 2000
FOV ~ 10-15μm

time resolution

- transmission geometry
- ambient conditions
  (RT, ambient pressure)

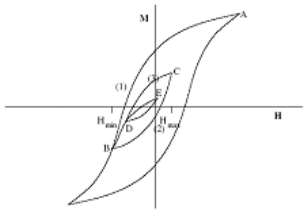
Is nanoscale magnetic behavior deterministic?

Deterministic vs. stochastic

scientifically interesting

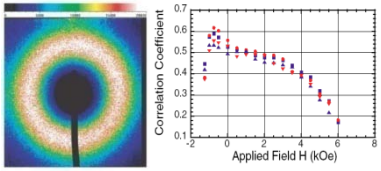
Are magnetic processes reproducible on the nanoscale?

Reproducible behavior



J. M. Deutsche et al., Phys. Rev. Lett. 227203(2004)

Irreproducible Behavior



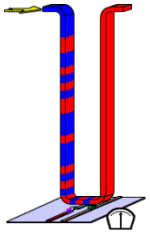
M. S. Pierce et al., Phys. Rev. Lett. 175502 (2003)

Controversial Discussion

technologically relevant

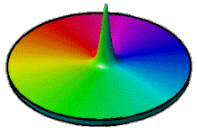
Can we control magnetic processes on the nanoscale ?

Domain Wall Motion



S. Parkin, US Patent 309, 6,834,005 (2004)

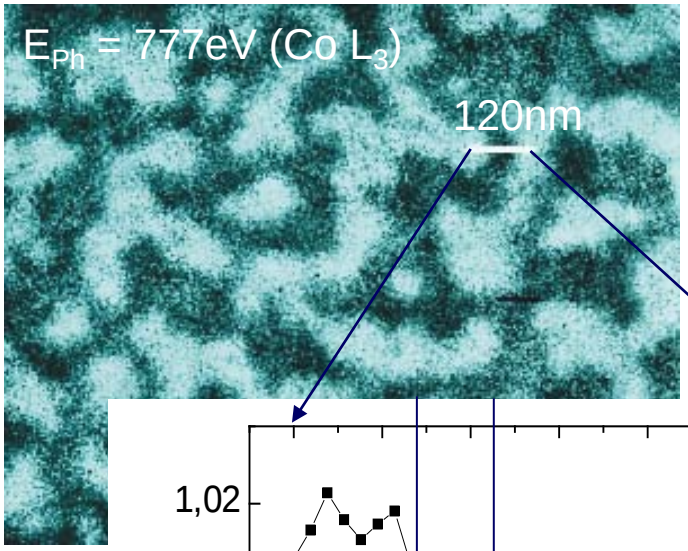
Vortex Core Switching

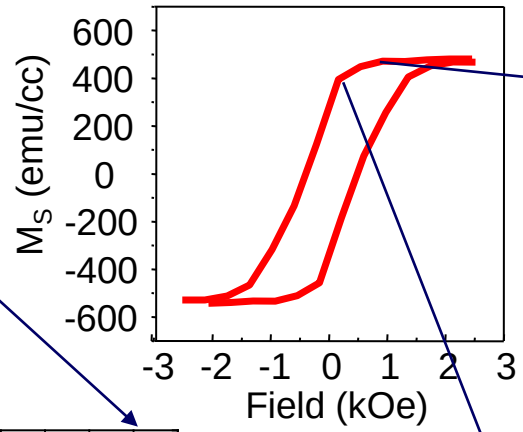


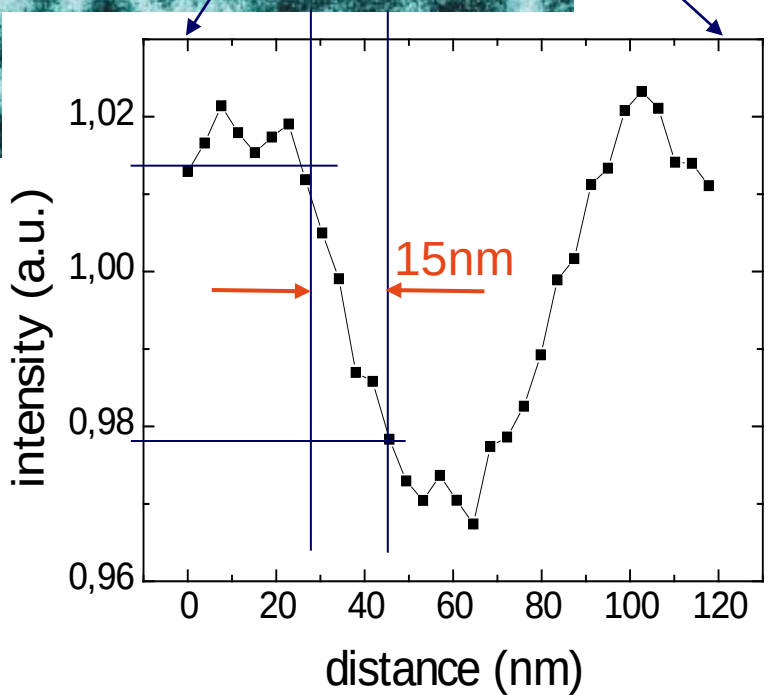
K.- S. Lee et al., Phys. Rev. Lett. 267206 (2008)

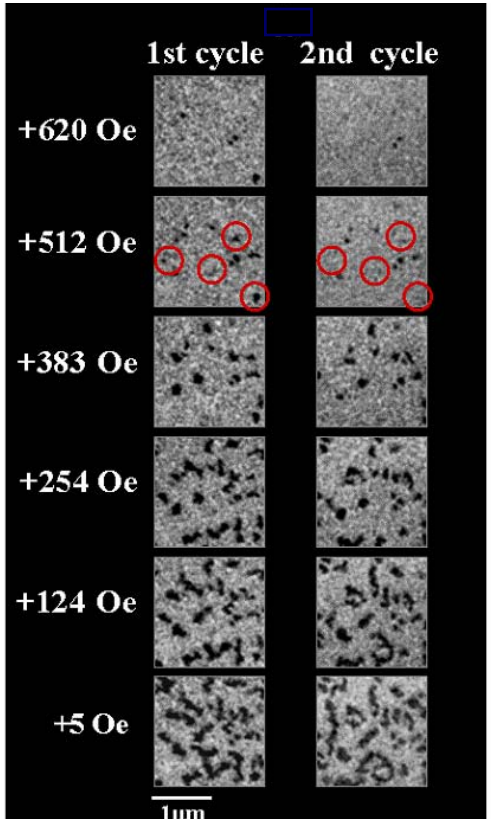
Essential Factor

X-ray imaging of domain nucleation





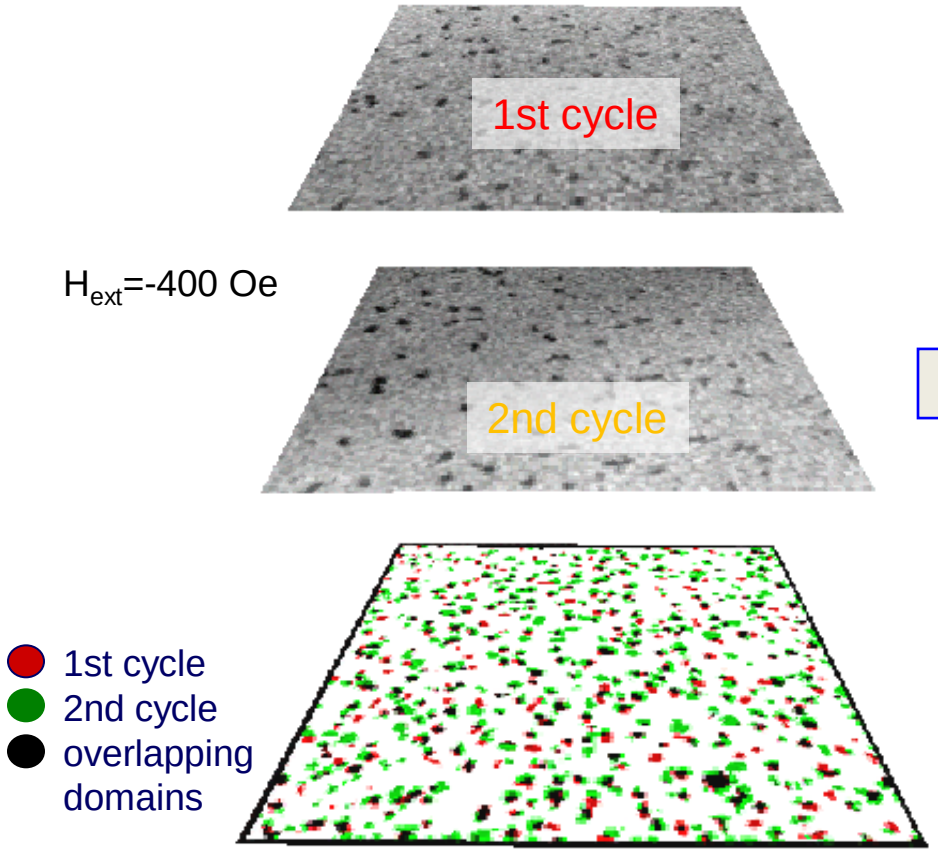


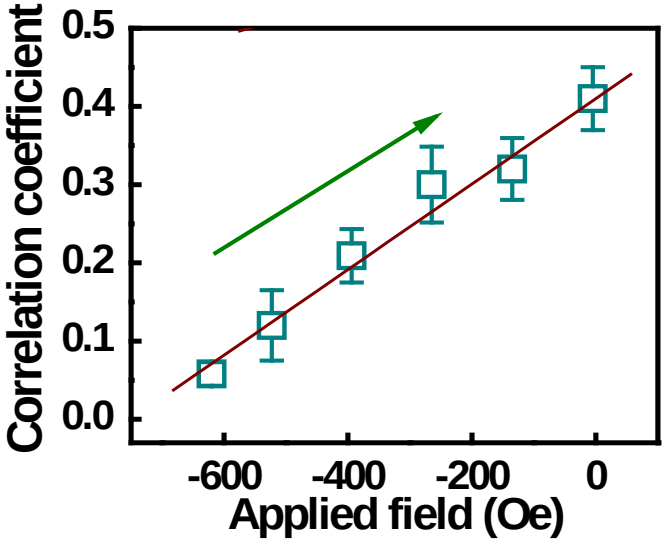


- 50nm $(Co_{84}Cr_{16})_{87}Pt_{13}$ nanogranular film
- perpendicular magn. anisotropy
- avg. grain size ~20nm
- nucleation mediated single grain reversal
- repeated hysteresis cycles

M.-Y. Im, D.-H. Kim, K.-D. Lee, S.H. Lee, P. Fischer, and S.-C. Shin, Adv. Mater 20 1750 (2008)

Stochastic character of domain nucleation





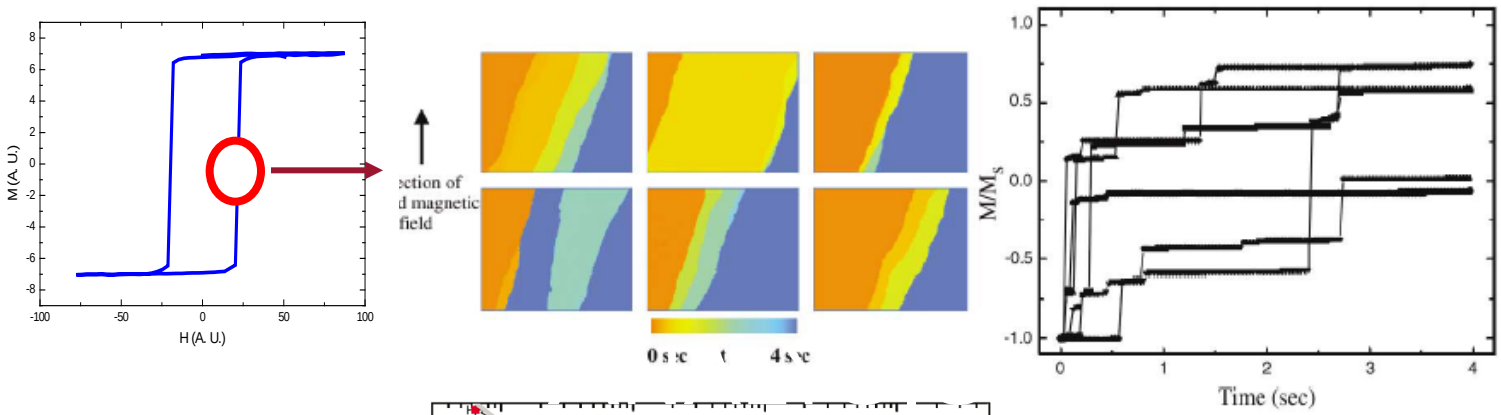
- Deterministic vs stochastic behavior on the nanoscale?
- Thermal fluctuations in the orientation of magnetic moment determine largely the stochastic behavior

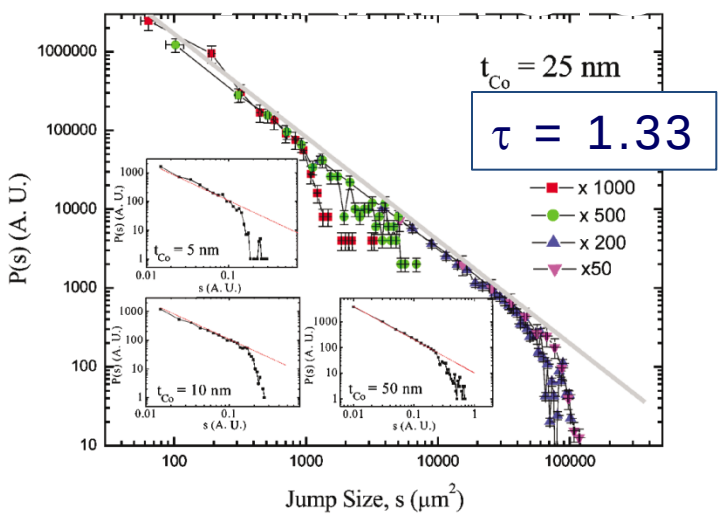
M.-Y. Im, D.-H. Kim, K.-D. Lee, S.H. Lee, P. Fischer, and S.-C. Shin, Adv. Mater 20 1750 (2008)

Barkhausen Avalanches (B.A.)

D.-H Kim et al., Phys. Rev. Lett. 90, 87230 (2002)

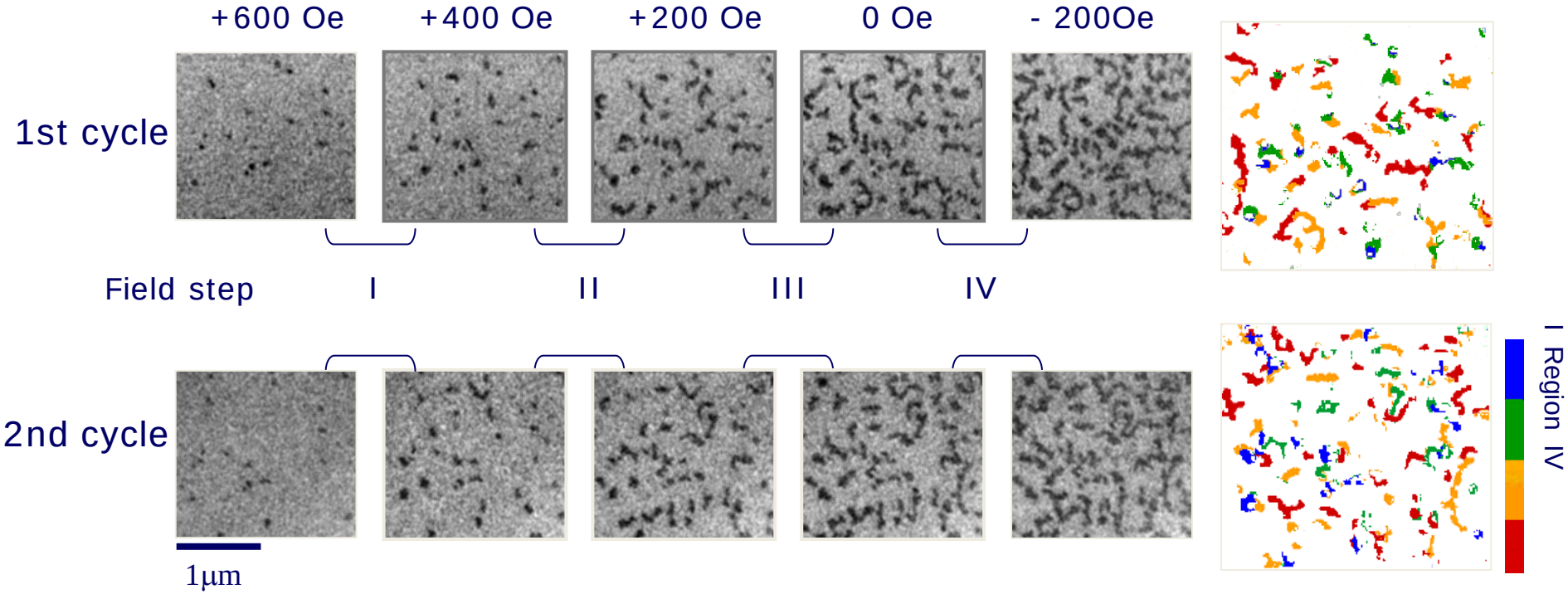
Domain-wall mediated magnetization reversal process





⇒ power law scaling behavior

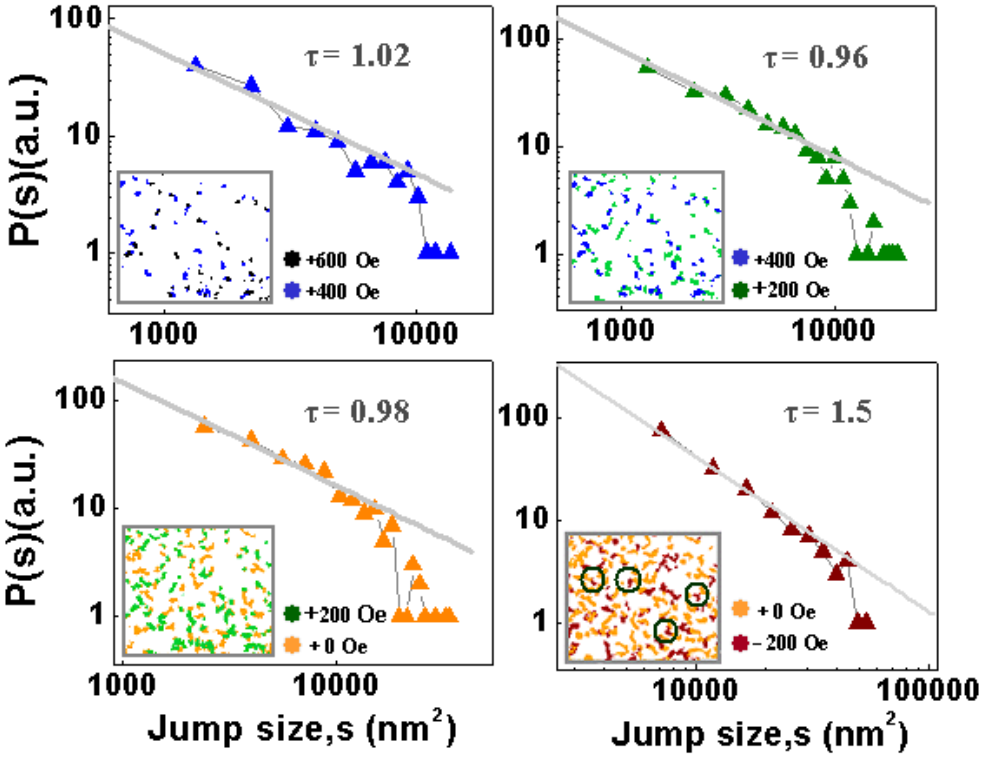
M-TXM study of Barkhausen Avalanches



- 50nm $(Co_{84}Cr_{16})_{87}Pt_{13}$ nanogranular film w/ perpendicular magn. anisotropy
- study of B.A. in nucleation mediated reversal processes
- domain nucleation of individual grains (I) to domain wall propagation (IV)
- stochastic character of B.A. processes in repeated hysteresis cycles

*M.-Y. Im, P. Fischer, D.-H. Kim, S.-C. Shin, APL **95** 182504 (2009)*

Scaling Behavior

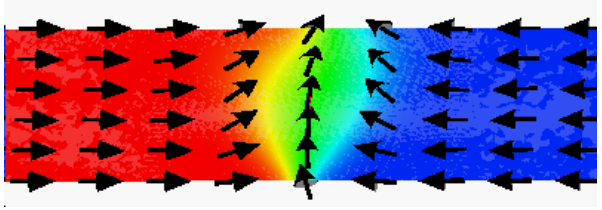


- Power-law scaling behavior at all field steps along the hysteresis loop
- sudden change of scaling exponent τ around coercivity from 1.0 – 1.5
- proximity between grains reponsible for the increased exponent

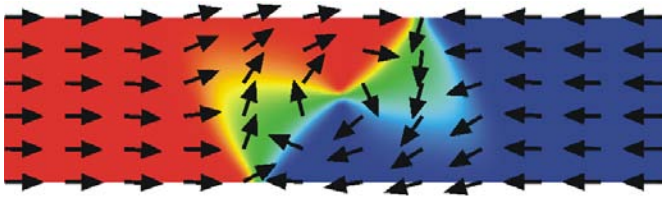
*M.-Y. Im, P. Fischer, D.-H. Kim, S.-C. Shin, APL **95** 182504 (2009)*

Domain walls in nanowires

- Two main types of domain wall structure

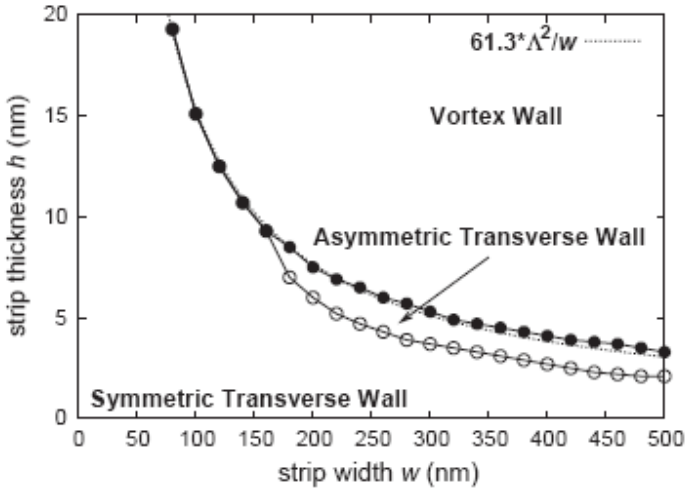


Transverse



Vortex

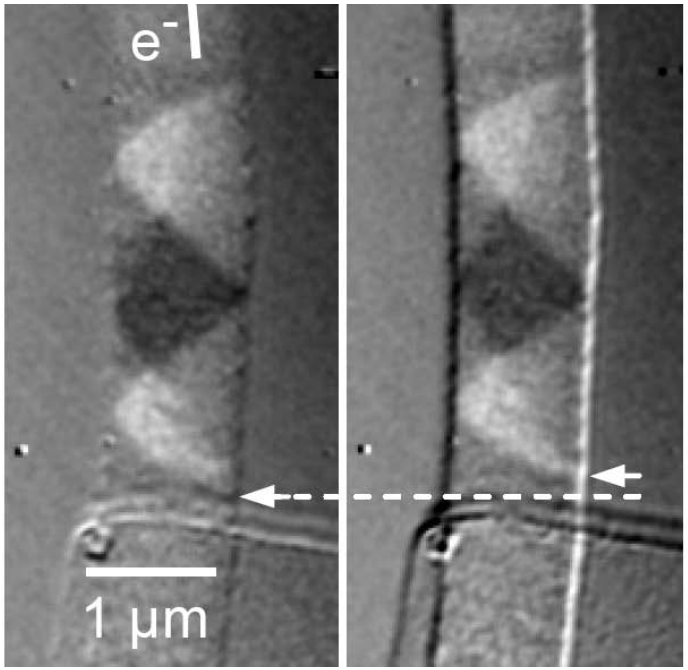
- Structure depends on nanowire geometry



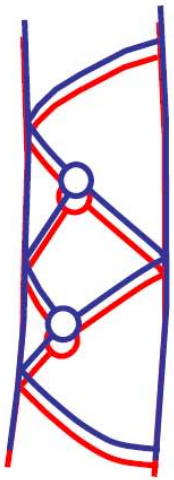
Transverse walls in narrower, thinner wires

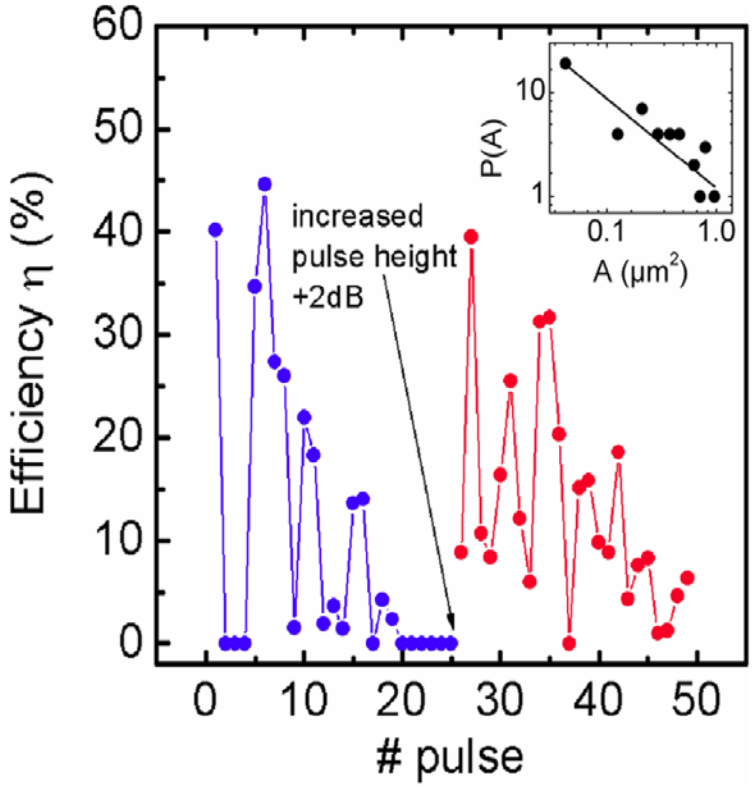
Y. Nakatani et al, JMMM ***290-291*** *(2005) 750*

Spin current induced DW motion



before after

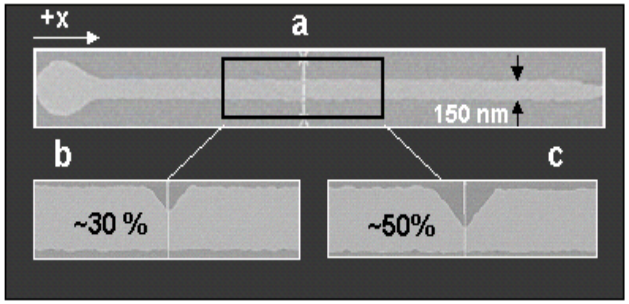




- creation of a domain wall and moving the DW by spin injection
- 1ns pulses, current density $<10^{12}$ A/m^2
- v_{DW}= 110m/s in agreement with micromagnetic simulations
- strong indications for a stochastic character of the DW motion

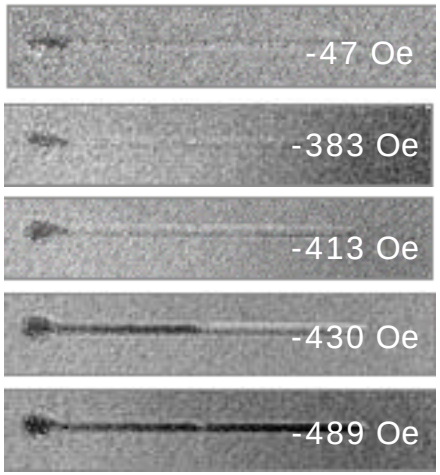
G. Meier, M. Bolte, R. Eiselt, B. Krüger, D.-H. Kim., P. Fischer, Physical Review Letters 98, 187202 (2007)

DW depinning in notched nanowires

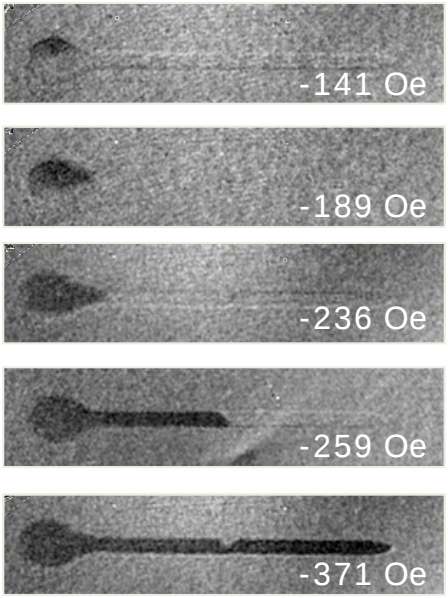


Permalloy ($Ni_{80}Fe_{20}$) wires with varying wire width (w), notch depth (N_d) and film thickness (t)

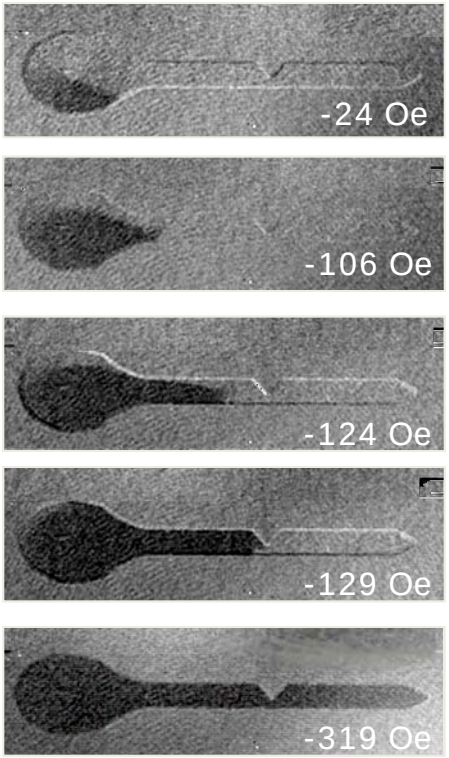
w= 150 nm



w= 250 nm



w= 450 nm

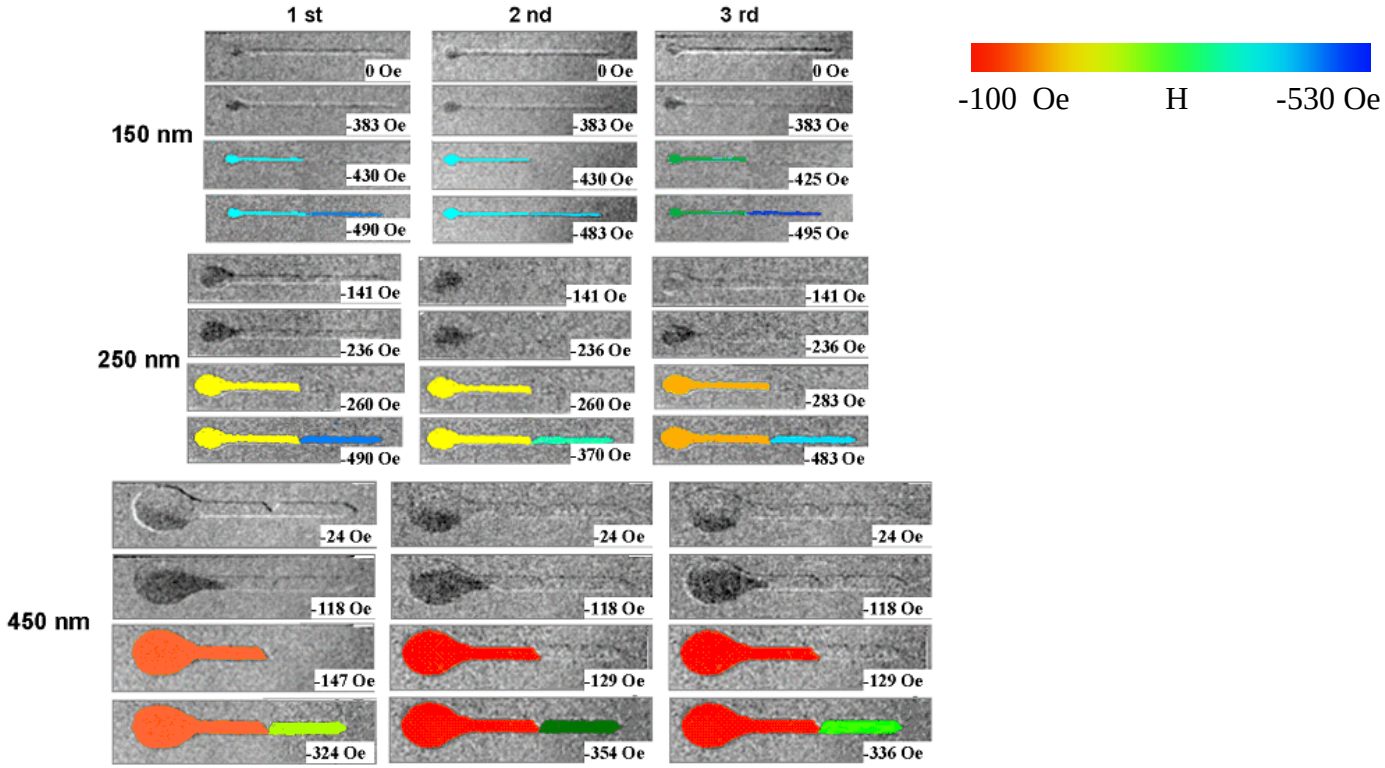


N_d=50 %
t=50 nm

⇒ Pinning/depinning field decreases as wire widens

M.-Y. Im, L. Bocklage, P. Fischer, G. Meier, Phys Rev Lett 102 147204 (2009)

Stochastic nature of DW depinning field



- Pinning probability decreases with wire width w
- Repeated measurements indicate stochastic behavior (generation of different DW types at the notch)
- DW depinning process is independent from the DW pinning process

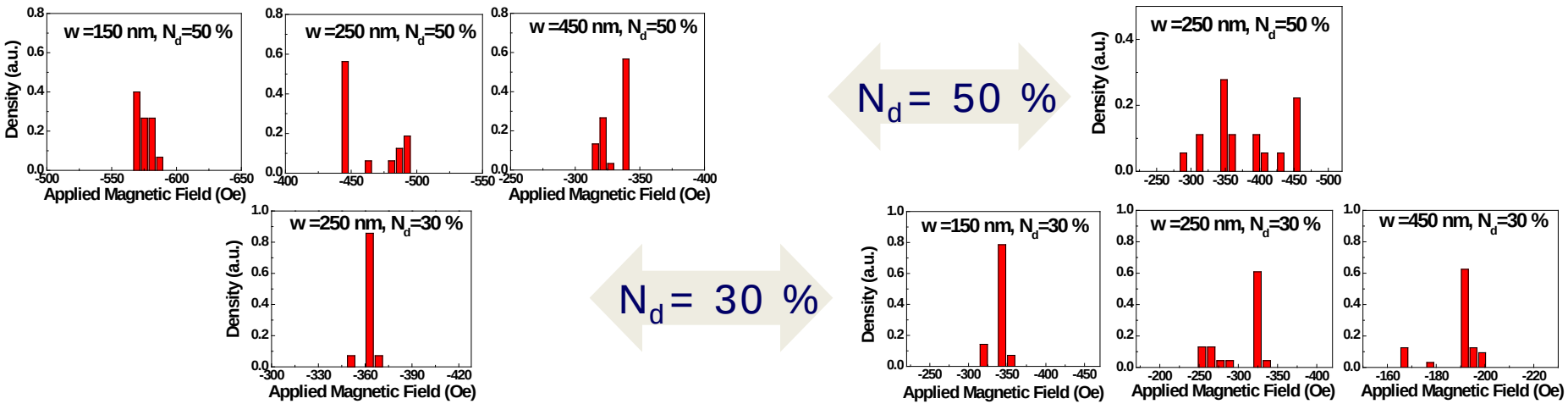
M.-Y. Im, L. Bocklage, P. Fischer, G. Meier, Phys Rev Lett 102 147204 (2009)

Degree of Stochastic Nature

Distribution of DW depinning field

t= 50 nm

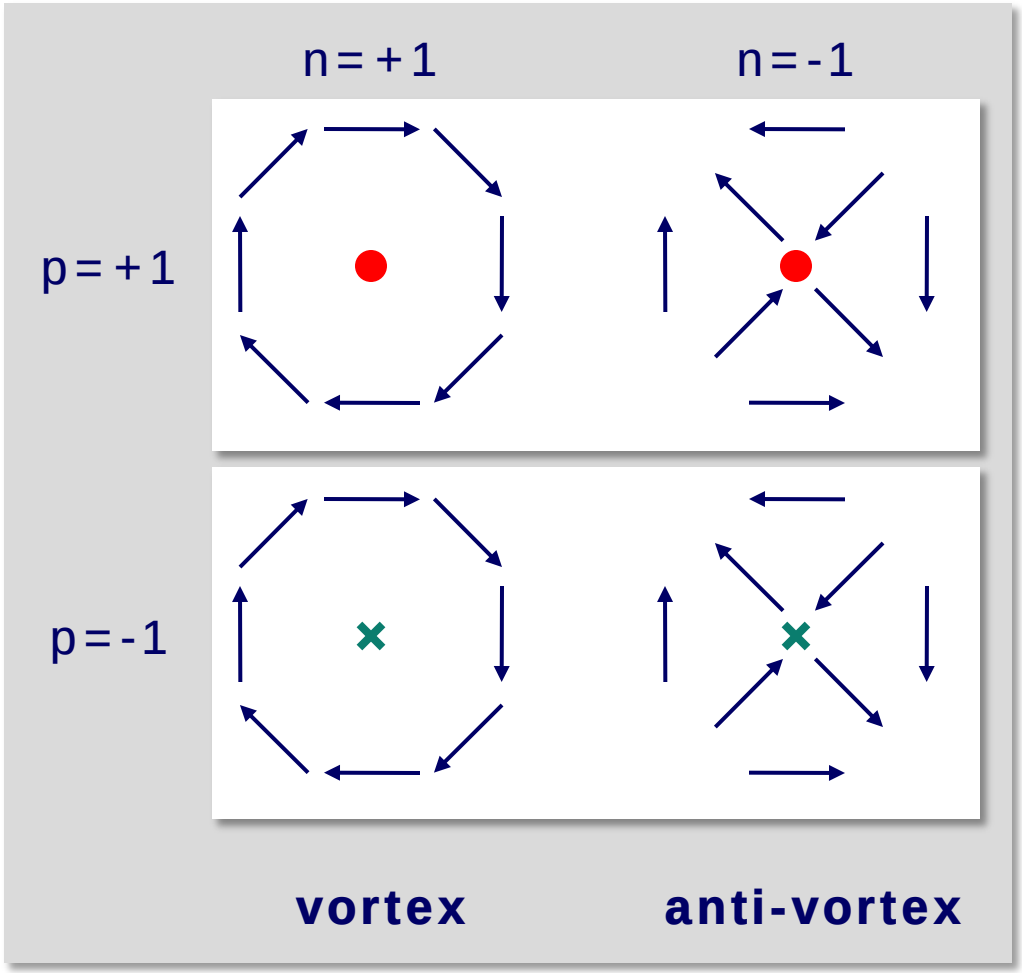
t= 30 nm

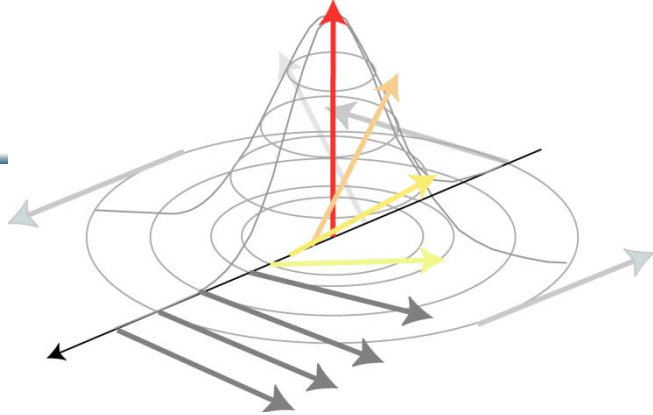


Distribution depends considerably on notch depth and wire width
$\Rightarrow$ reproducible DW depinning process can be achieved by a proper selection of the wire and the notch geometry

M.-Y. Im, L. Bocklage, P. Fischer, G. Meier, Phys Rev Lett 102 147204 (2009)

Magnetic vortices





polarity $p = \pm 1$
winding number $n = \pm 1$

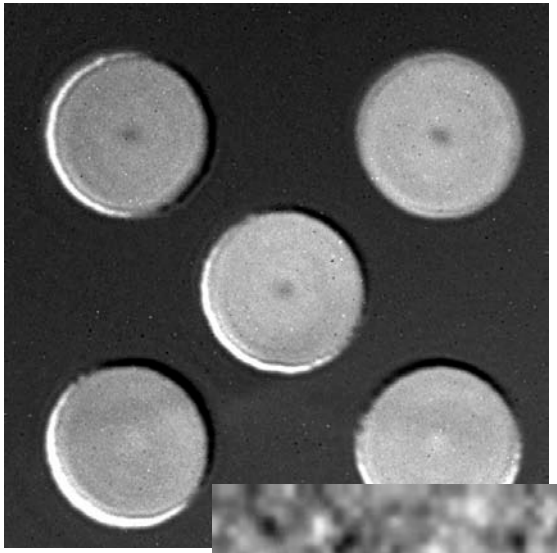
Skyrmion number q

$$q = \frac{1}{2}\int \frac{d^2\vec{r}}{4\pi}\varepsilon_{ij}\vec{n}\cdot\left(\partial_i\vec{n}\times\partial_j\vec{n}\right) = \frac{pn}{2}$$

$\Rightarrow$A vortex is a half skyrmion, a meron.

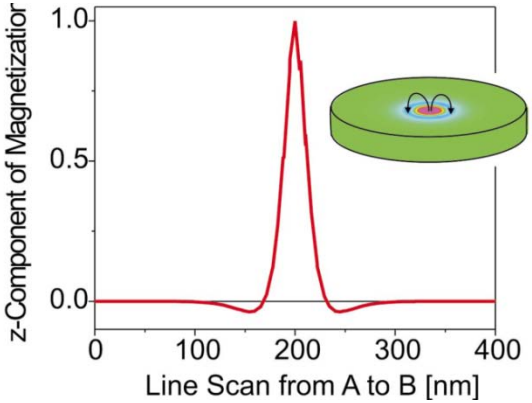
M. Ezawa, PRB 83, 100408(R) (2011)
R. Hertel, C.M. Schneider, PRL 97, 177202 (2006)
O.A. Tretiakov, O. Tchernyshyov, PRB 75, 012408 (2007)

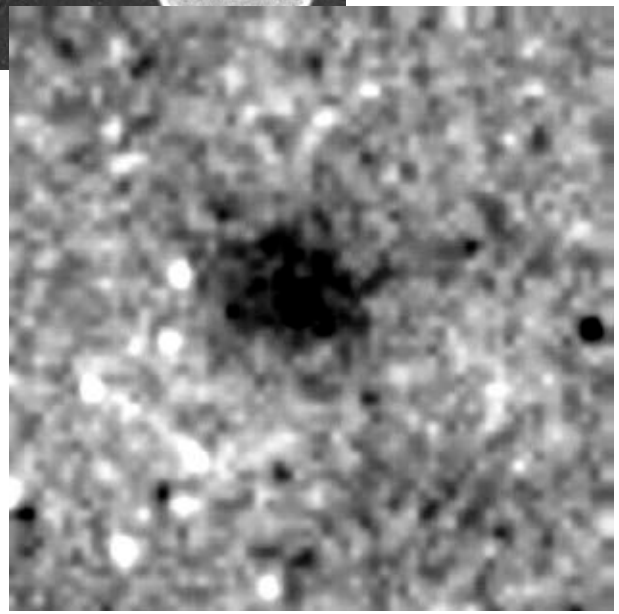
X-ray imaging of MV in PY dots

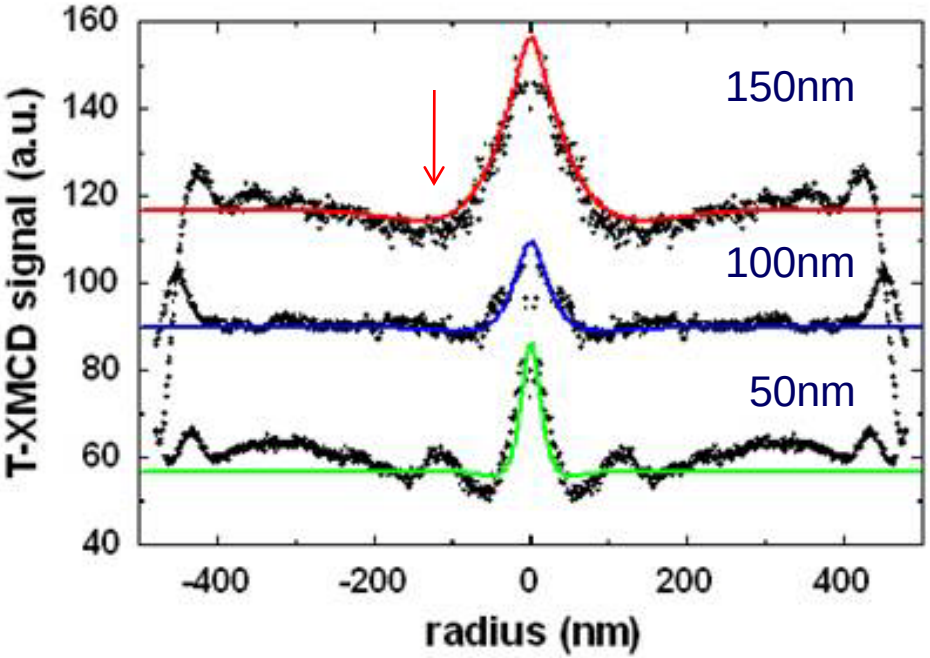


– radius 500nm
– 20nm spatial res

J. K. Ha et al, PRB 67, 224432 (2003)

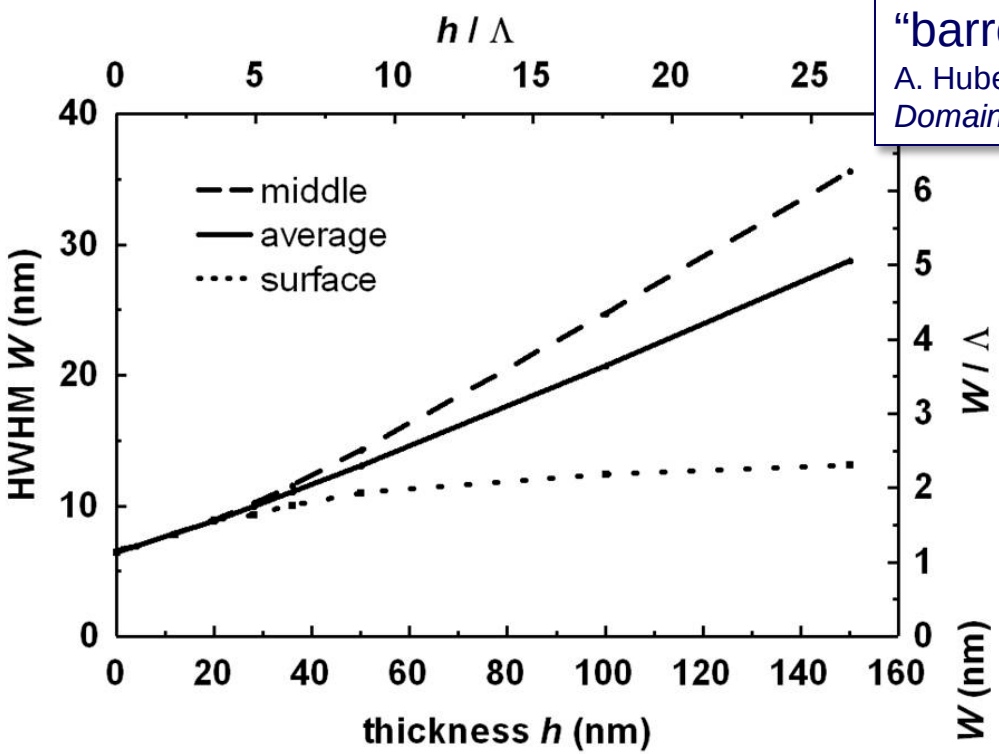






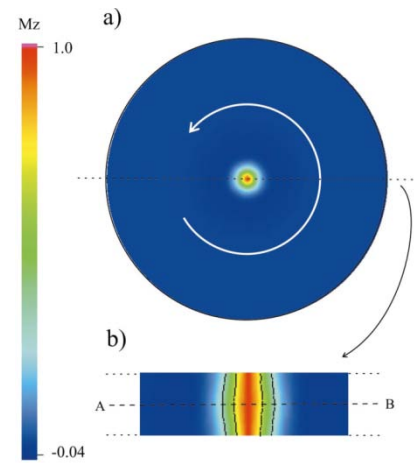
P. Fischer, M.-Y. Im, S. Kasai, K. Yamada, T. Ono, A. Thiaville, PRB Brief Rep (2011) in press

3D micromagnetic calculations

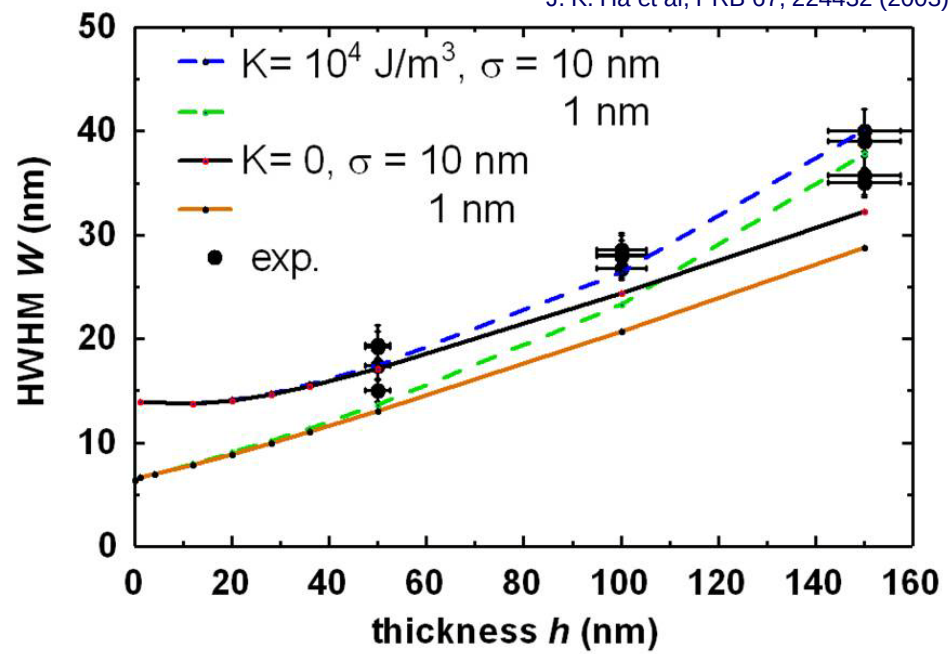


"barrel model"

A. Hubert and R. Schäfer, *Magnetic Domains* (Springer, Berlin, 1998)



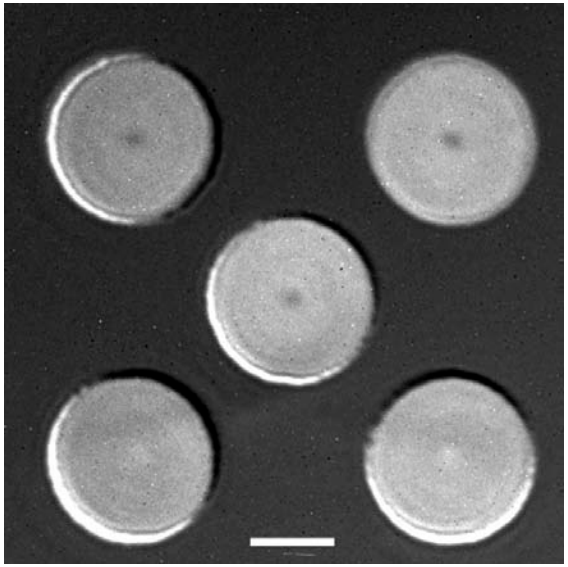
J. K. Ha et al, PRB 67, 224432 (2003)



- perfect agreement of full 3d micromagnetic simul. with expt. for $K=10^4$ J/m^3 and $\sigma=10$nm
- fine details can be observed

P. Fischer, M.-Y. Im, S. Kasai, K. Yamada, T. Ono, A. Thiaville, PRB Brief Rep (2011) in press

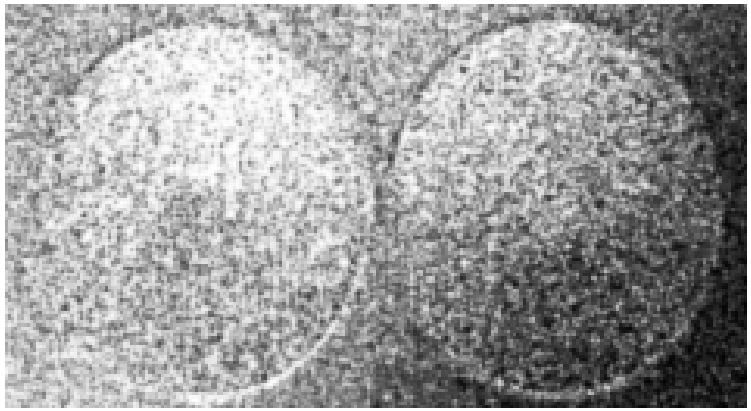
Imaging with spatial AND time resolution



P. Fischer, M.-Y. Im, S. Kasai, K. Yamada, T. Ono, A. Thiaville, PRB Brief Rep (2011) in press

statics = structures

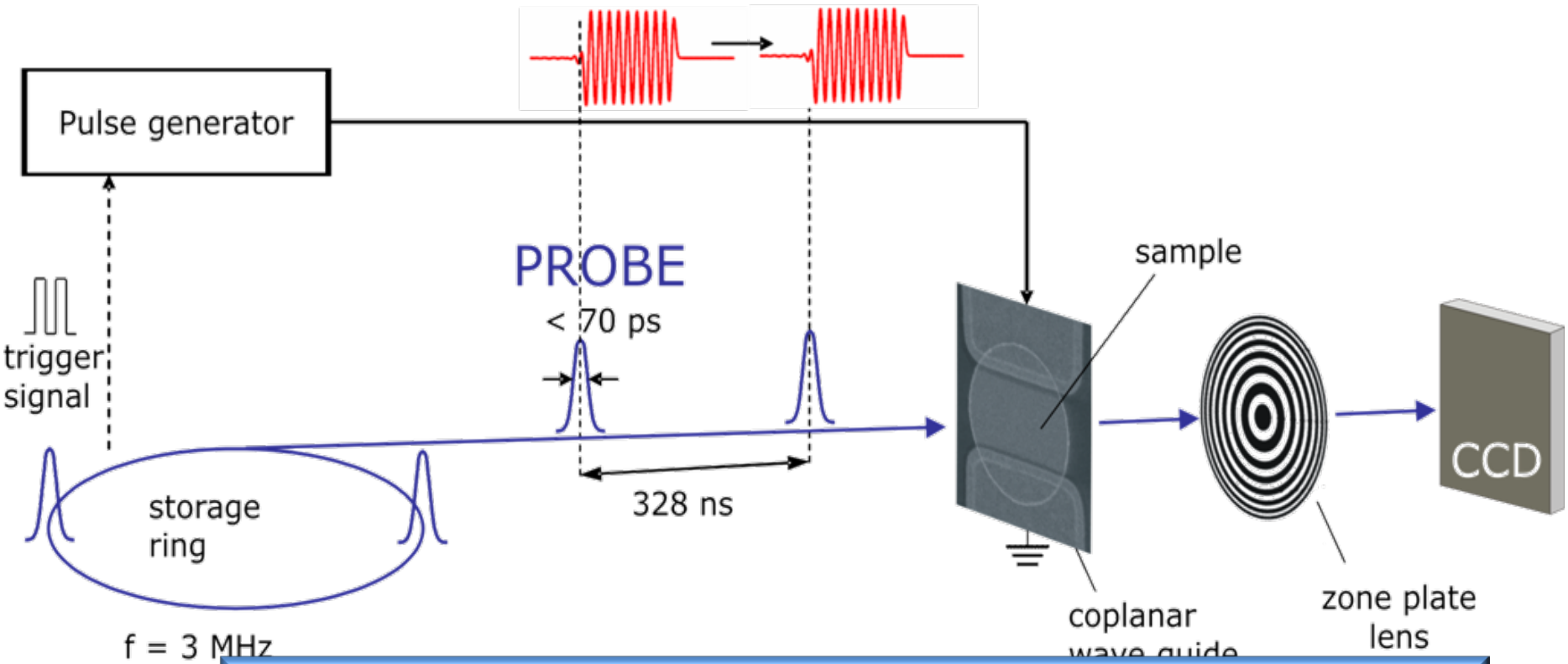
dynamics = functionality



H. Jung, Y.-S. Yu, K.-S. Lee, M.-Y. Im, P. Fischer, L. Bocklage, A. Vogel, M. Bolte, G. Meier, S.-K. Kim, APL, **97**, 222502 (2010)

Stroboscopic pump-probe setup for time resolved soft X-ray microscopy

- $j = 1.3 \times 10^{11}$ A/m^2
- $10^{8\text{-}9}$ pump-probe events/image

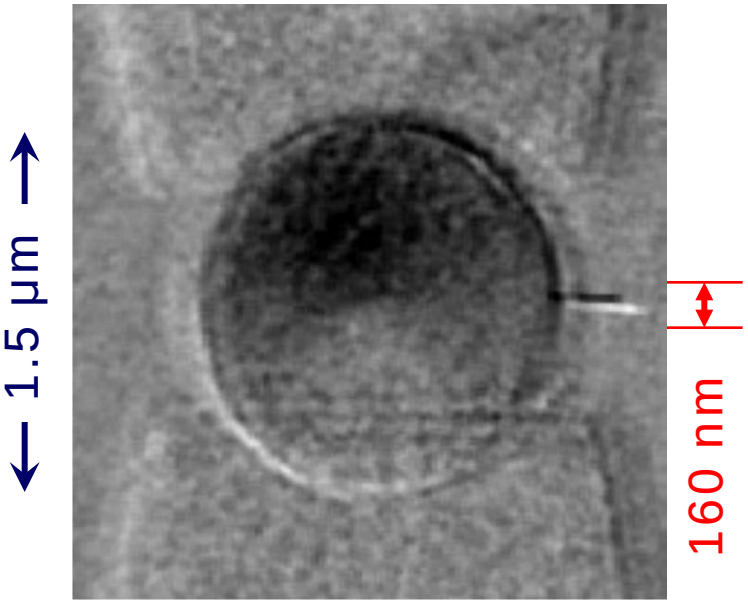


- perfect repeatability of the dynamics required
- no access to non-deterministic components e.g. spin fluctuations

S. Kasai, P. Fischer, M.-Y. Im, K. Yamada, Y. Nakatani, K. Kobayashi, H. Kohno, T. Ono, Phys Rev Lett 101, 237203 (2008)

Deriving spin polarisation of currents P

Permalloy ($Fe_{80}Ni_{20}$)
t=40 nm
f=220 MHz
Δt=0...9ns

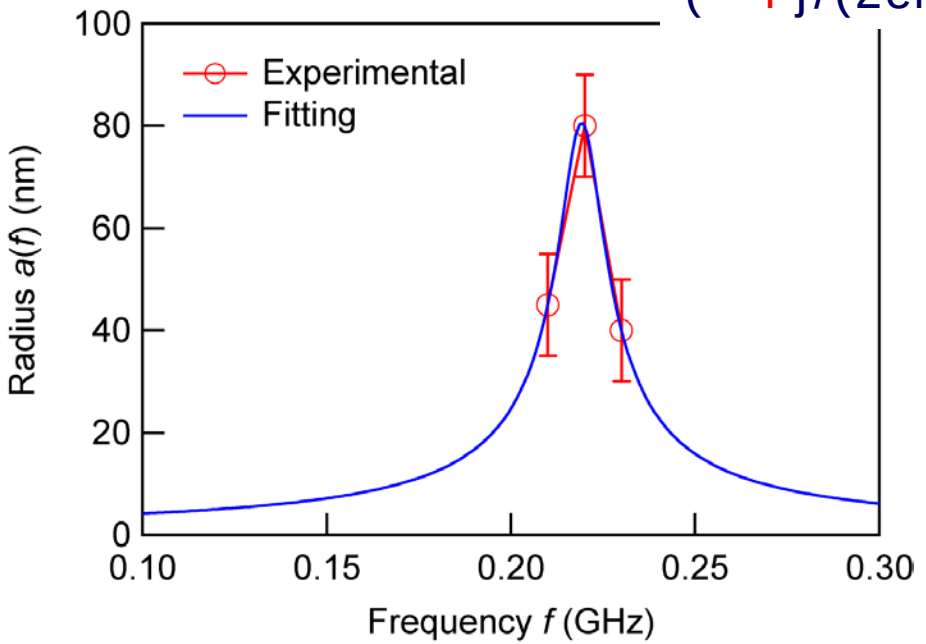


- CW rotation ⇒ polarity = -1
- gyration radius R~80 nm

Solving Thiele eqn with STT for u

$$\vec{G} \times \vec{v} + \alpha D \vec{v} + k\vec{X} - \vec{G} \times \vec{u} = 0$$

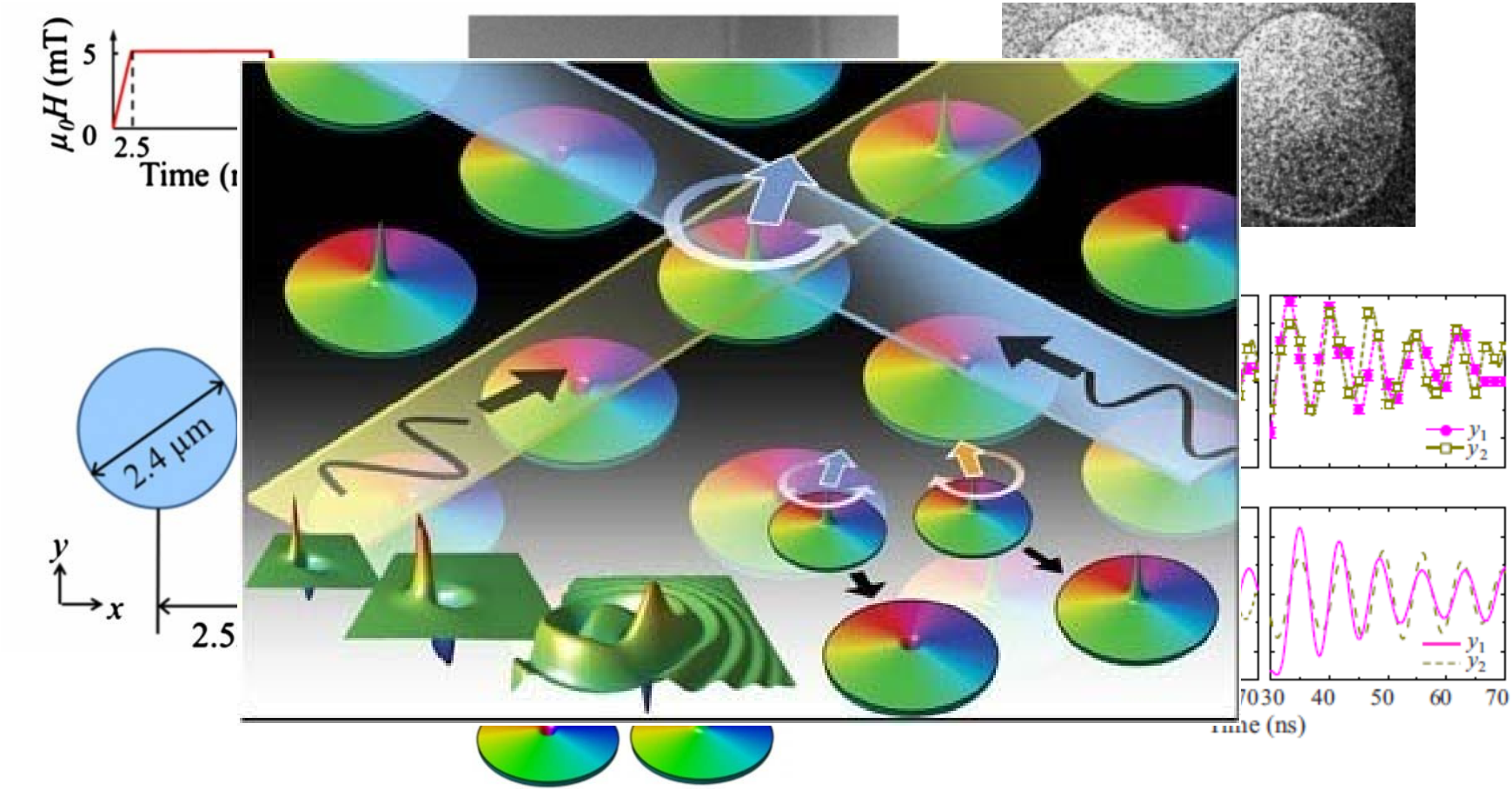
drift velocity
(~-Pj/(2eM$_s$))



measuring R(ω) ⇒ P=0.67±0.15

S. Kasai, P. Fischer, M.-Y. Im, K. Yamada, Y. Nakatani, K. Kobayashi, H. Kohno, T. Ono, Phys Rev Lett 101, 237203 (2008)

Coupled vortex gyration



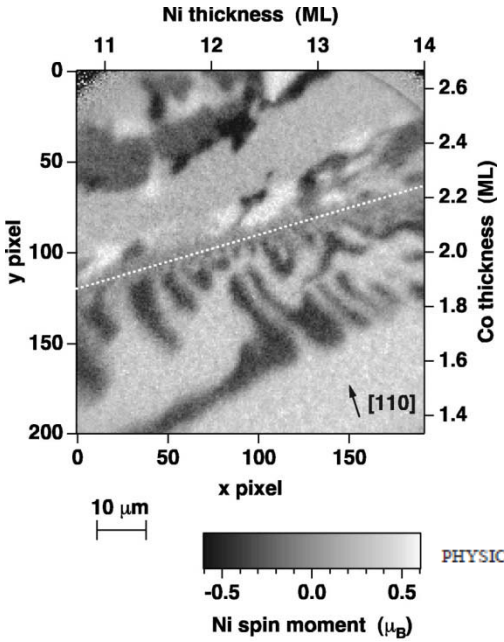
⇒ vortex gyration of one disk affects the other through dipolar interaction

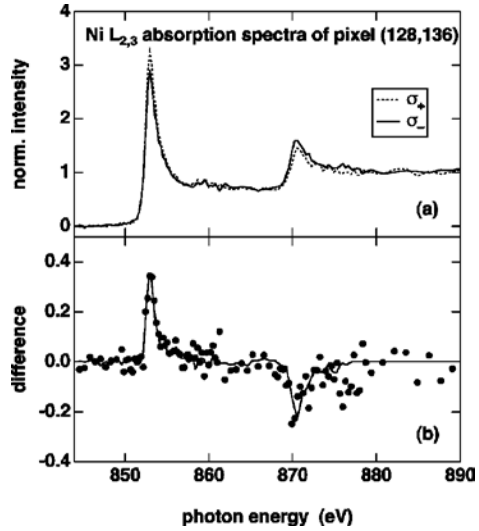
*H. Jung, Y.-S. Yu, K.-S. Lee, M.-Y. Im, P. Fischer, L. Bocklage, A. Vogel, M. Bolte, G. Meier, S.-K. Kim, APL, **97**, 222502 (2010)*

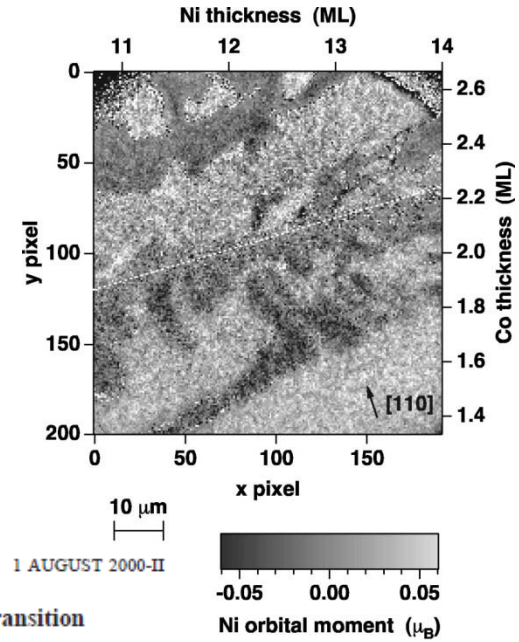
What are we missing?

- Magnetic microspectroscopy
- Magnetic 3d imaging
- Magnetic interfaces
- AF domain imaging

Mapping spin and orbital moments







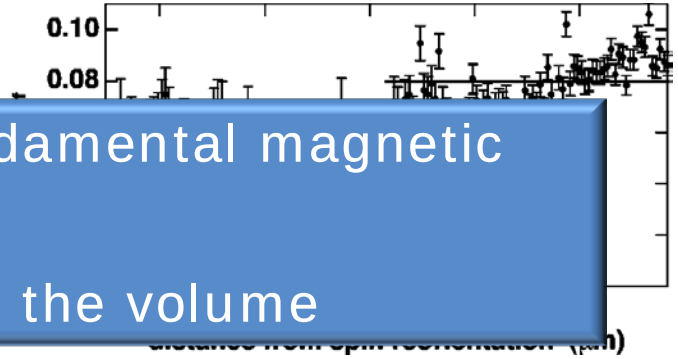
PHYSICAL REVIEW B VOLUME 62, NUMBER 6 1 AUGUST 2000-II

Magnetic-circular-dichroism microspectroscopy at the spin reorientation transition in Ni(001) films

W. Kuch, J. Gilles, and S. S. Kang
Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

S. Imada and S. Suga
Osaka University, Graduate School of Engineering Science, 1–3 Machikaneyama, Toyonaka 560-8531, Japan

J. Kirschner
Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle
(Received 10 November 1999)

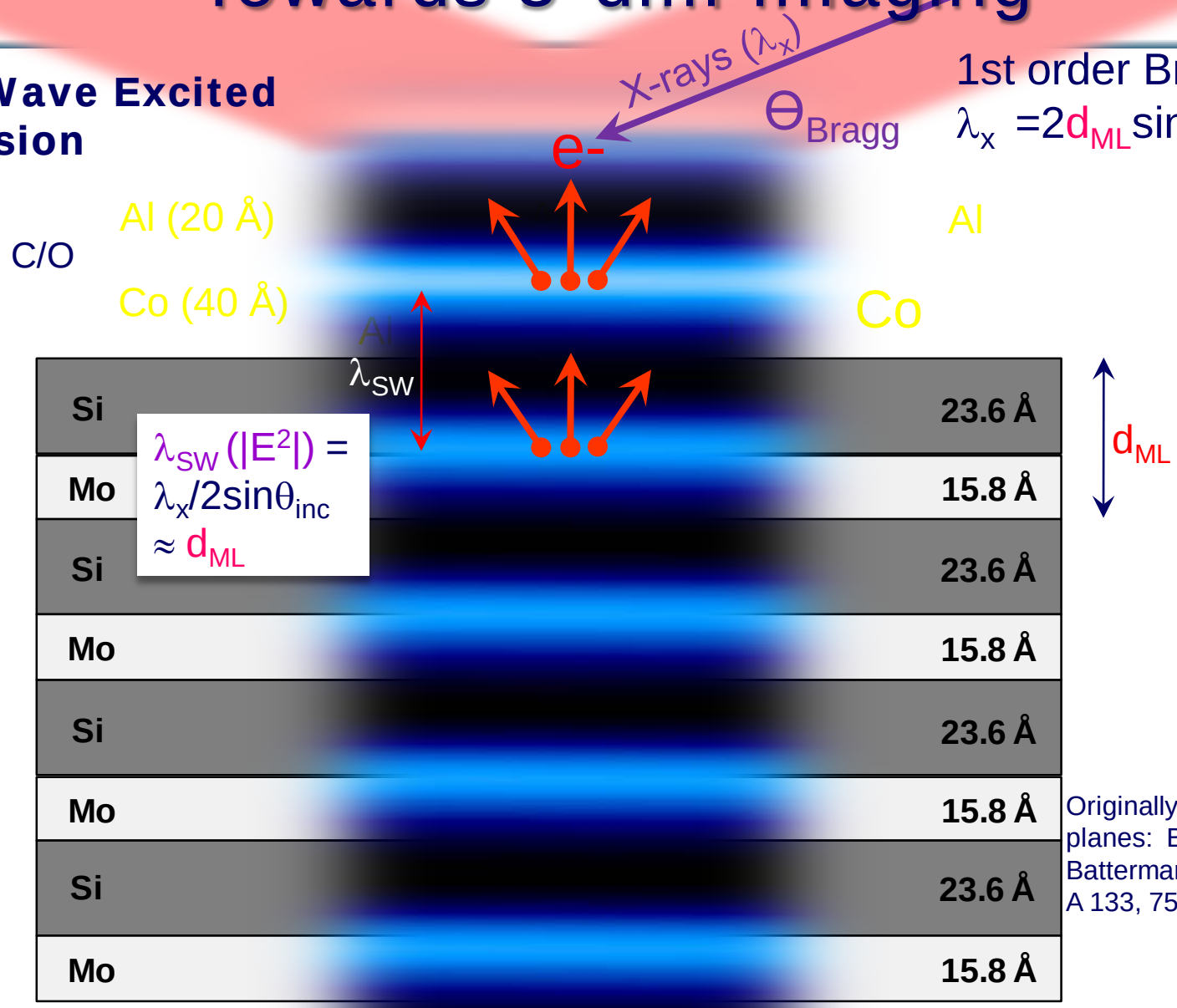


- better spatial resolution (close to fundamental magnetic length scales)
- PEEM is surface sensitive, MTXM sees the volume

Towards 3-dim imaging

Standing-Wave Excited Photoemission

1st order Bragg:
$\lambda_x = 2 d_{ML} \sin\theta_{Bragg}$



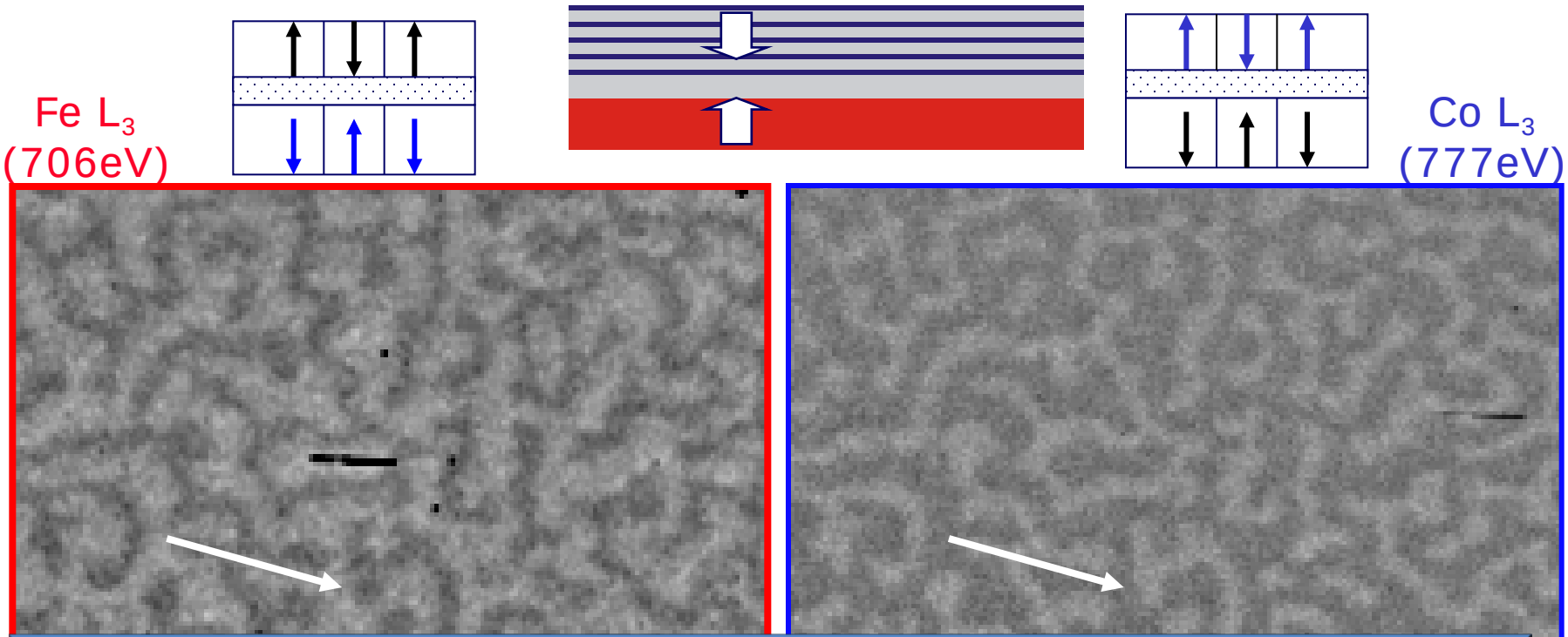
$\lambda_{SW}(|E^2|) = \lambda_x / 2\sin\theta_{inc} \approx d_{ML}$

Originally from crystal planes: B.W. Batterman Phys. Rev. A 133, 759 (1964)

F. Kronast, et al., Appl. Phys. Lett. 93, 243116 (2008)

Element specificity = layer resolving

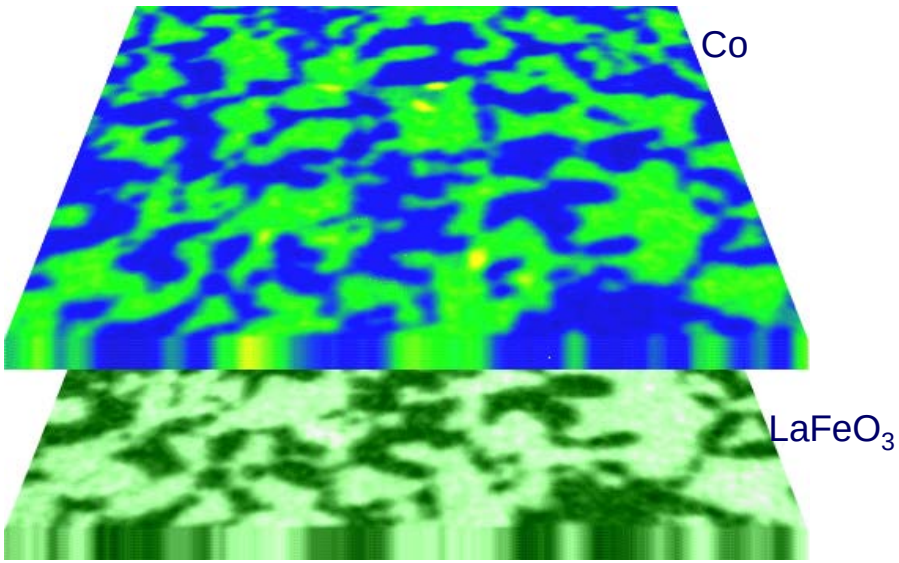
(Pt/[Pt 0.75nm/**Co** 0.35nm]*50/Pt 3nm/Tb_{45}**Fe_{55}** 25nm)/Pt 5nm)



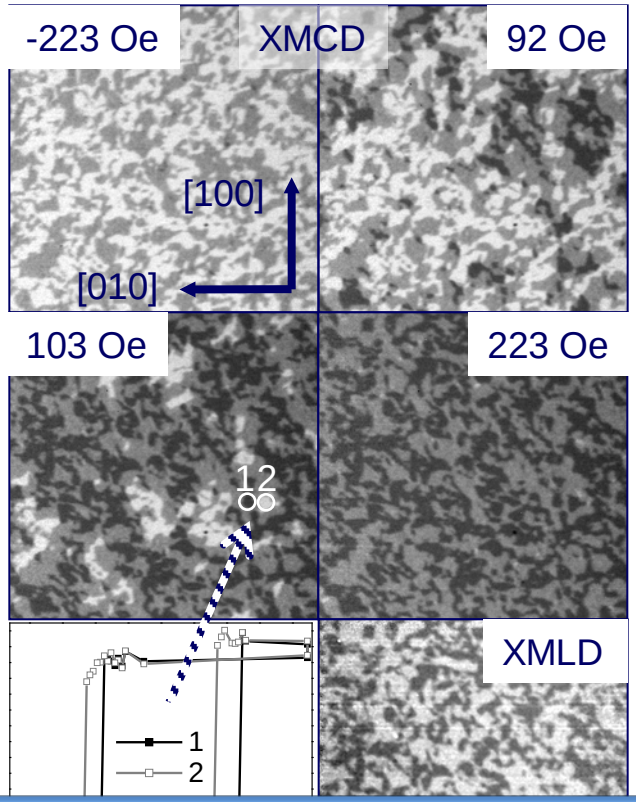
- How does the system accommodate the change in H_c?
- Structure of interfacial DW?

S. Mangin, T. Hauet, P. Fischer, D.H. Kim, J.B. Kortright, K. Chesnel, E. Arenholz, E.Fullerton, Phys Rev B 78 024424 (2008)

Co/$LaFeO_3$ Exchange Coupling



Co domain switching



- AF domain observation in applied magnetic fields (switching)?

F. Nolting et al., Nature 2000

Courtesy J. Stöhr/A. Scholl

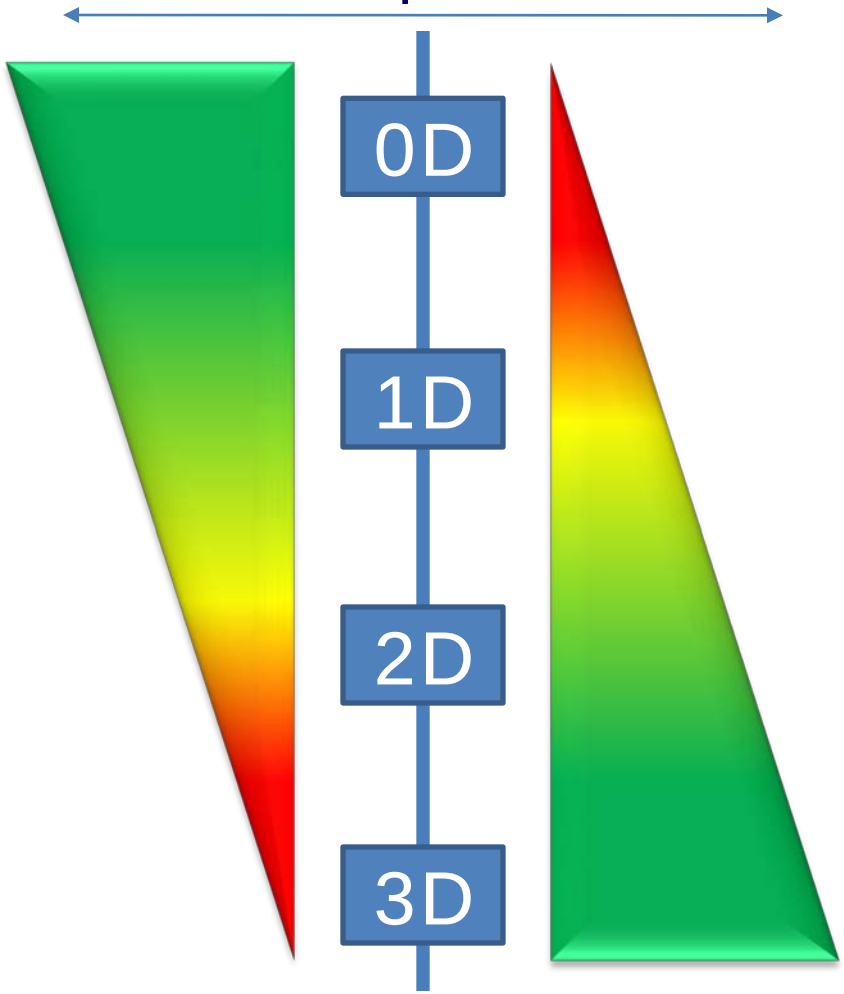
Shopping list for nanomagnetism…

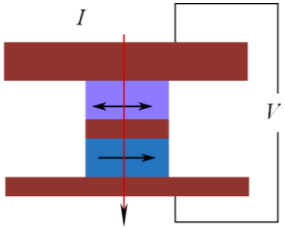
1) Wide photon energy range
2) High spectral resolution (~10-50 meV)
3) High spatial resolution
4) 3d resolution/tomography at high spatial resolution
5) Full polarization control
6) Large magnetic fields (T) in all directions
7) Variable temperature range (cooling/heating)
8) High throughput

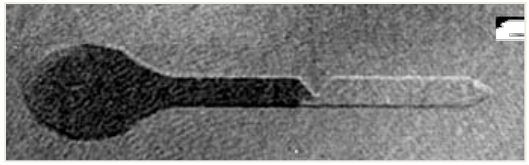
TXM vs. STXM

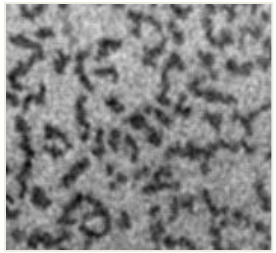
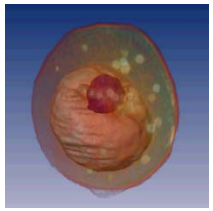
impact

STXM









TXM