Magnetic Soft X-Ray Microscopy
A path towards imaging magnetism down to fundamental length and time scales

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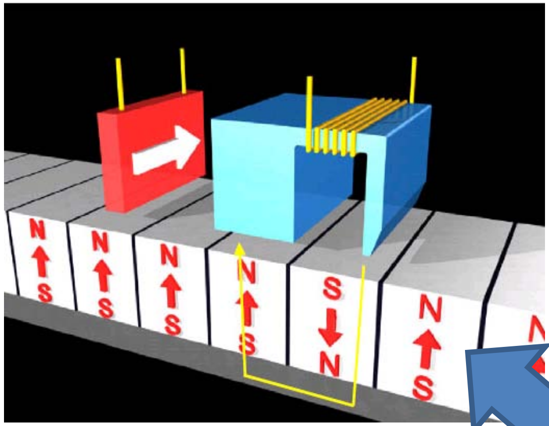
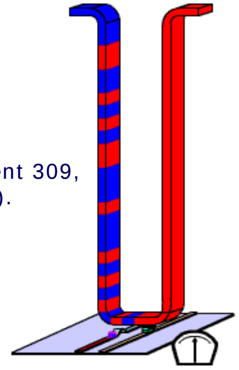
Controlling spins on the nanoscale

magnetic (Oersted) field



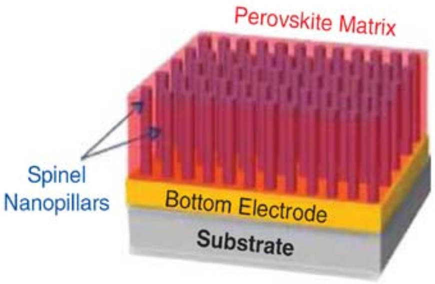
spin currents/ spin torque

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



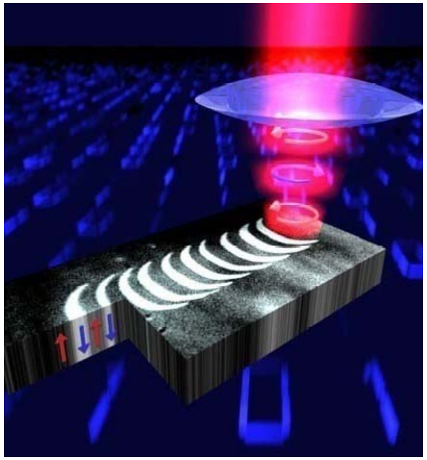
spintronics

electric fields
e.g. multiferroics



Spaldin & Ramesh MRS Bull Nov 2008

photonic control



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

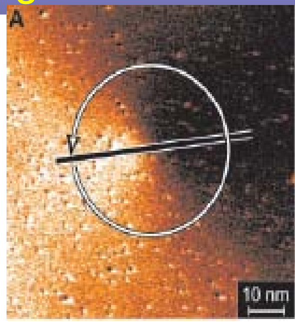
The Holy Grail for magnetic microscopy

Imaging spin structur[e]
nm spatial and
fsec (snapshot) time re[s]

nm

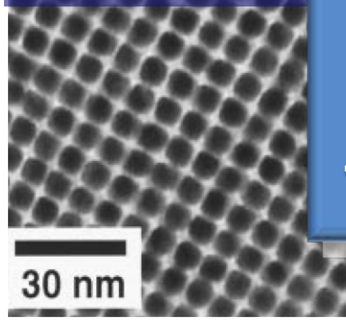
µm

magnetic vortices



A. Wachowiak et al, Science (2002)

nanoparticles



S. Sun et al, Science (2000)

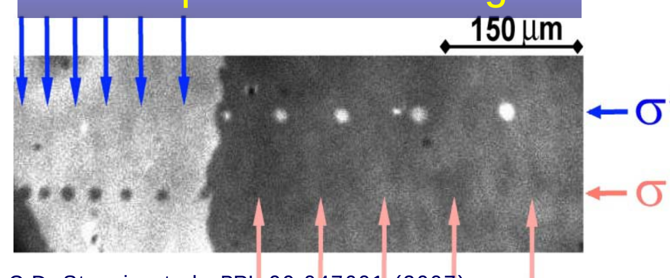
length scales
exchange length

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

time scales
exchange interactions

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

all optical switching

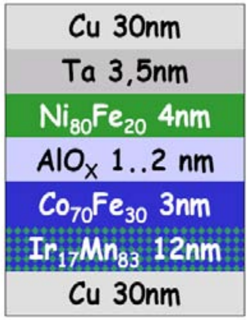


C.D. Stanciu et al., PRL 99,047601 (2007)

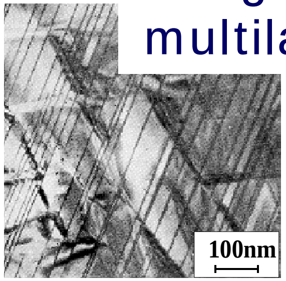
courtesy Th. Rasing

ns ps fs

... in multicomponent magnetic materials

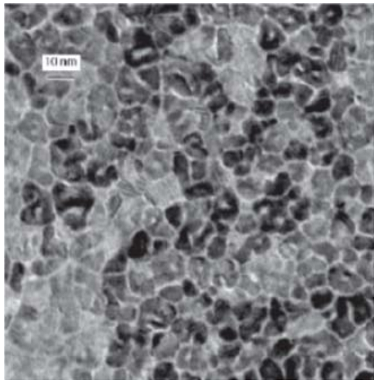


magnetic multilayers



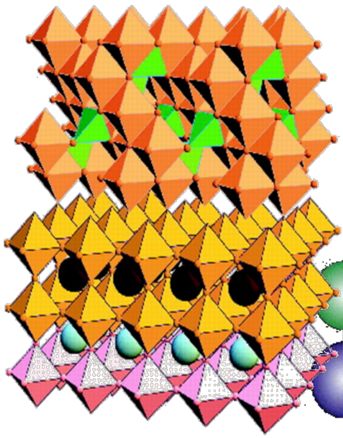
$Sm_2(Co,Cu,Fe,Zr)_{17}$

D. Goll, Z. Metallk. (2002)



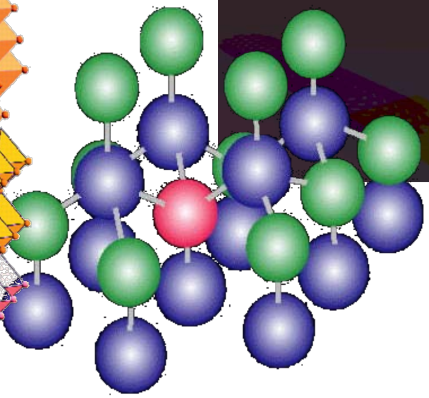
granular CoCrPtB

A. Moser et al. JPhysD (2002)

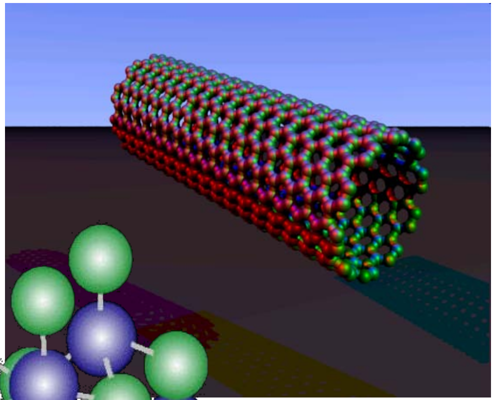


courtesy R. Ramesh

multiferroics



magnetic semiconductors



courtesy wikipedia.com

carbon nanotubes

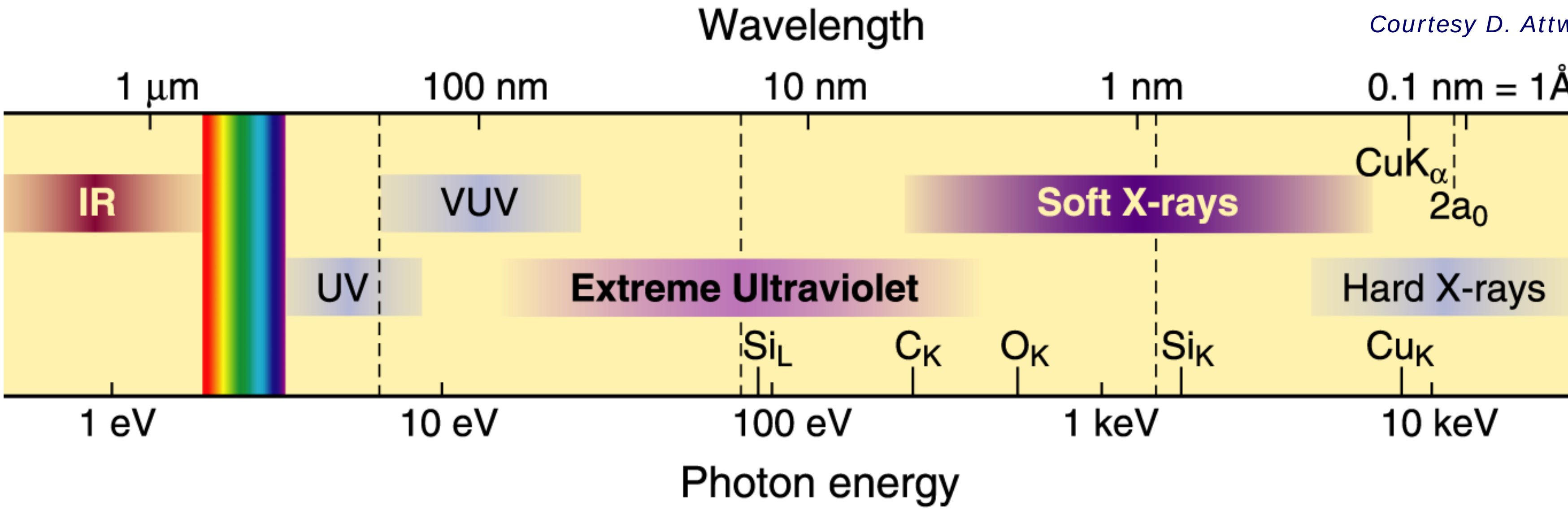
length scales	+	time scales	+	elemental specificity
exchange length $l_K \sim \sqrt{A/K} \sim \text{sub} - 10\text{nm}$		exchange interactions $t(fs) \sim 4/E(eV) \sim 20 - 50fs$		Fe, Co, Ni, … high sensitivity

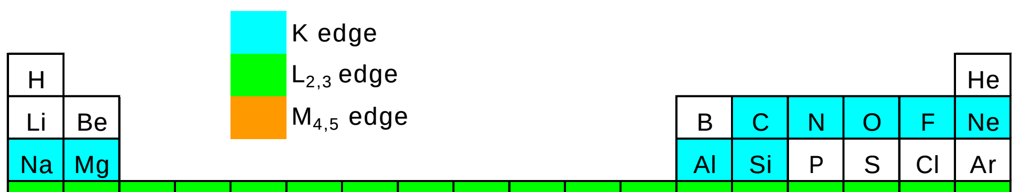
Outline

- soft X-ray microscopy and X-ray optics
- nanoscale magnetic structures
  - → *domain walls (DW)*
  - → *magnetic vortices (MV)*
- fast spin dynamics in MVs
  - → *combining sub-ns time and high spatial resolution*
- imaging spin currents
- future developments

Why soft X-rays?

Courtesy D. Attwood





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

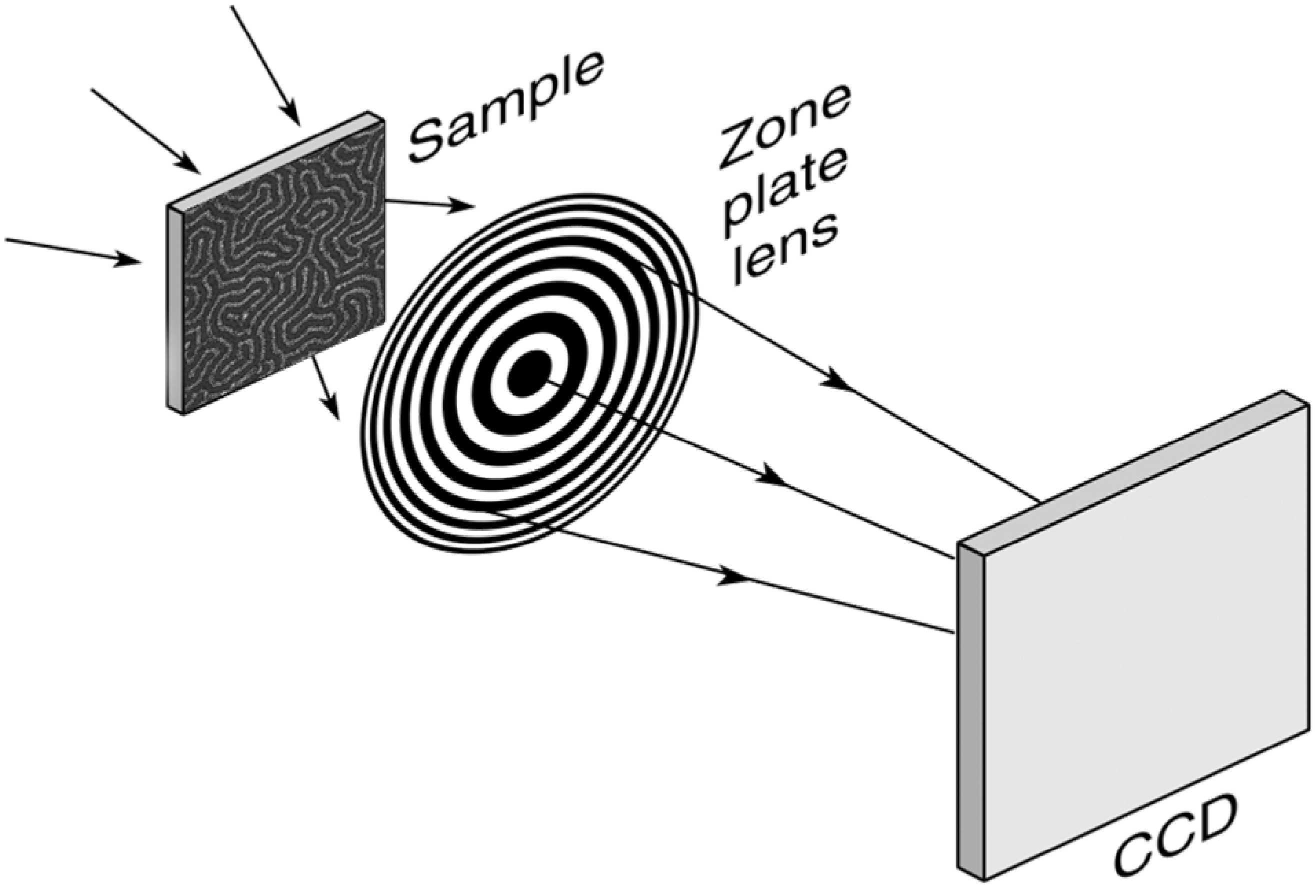
Imaging with soft X-rays ?

„dass man mit Linsen die X-Strahlen nicht concentrieren kann“

(*„it is impossible to focus the X-rays with lenses“*)

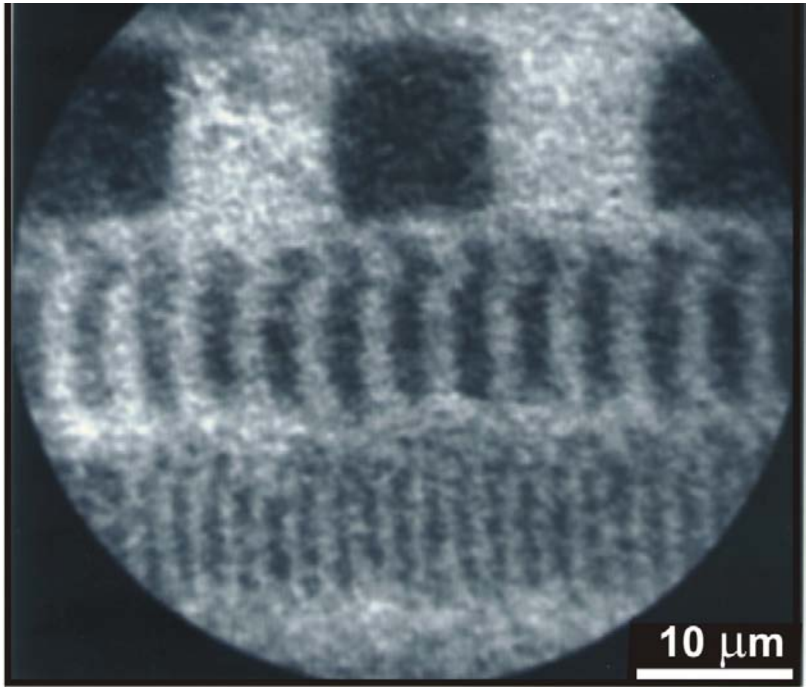
W. C. Röntgen, Sitzungsberichte der physikal.-medizin. Gesellschaft, 132 (1895)

Imaging with soft X-rays



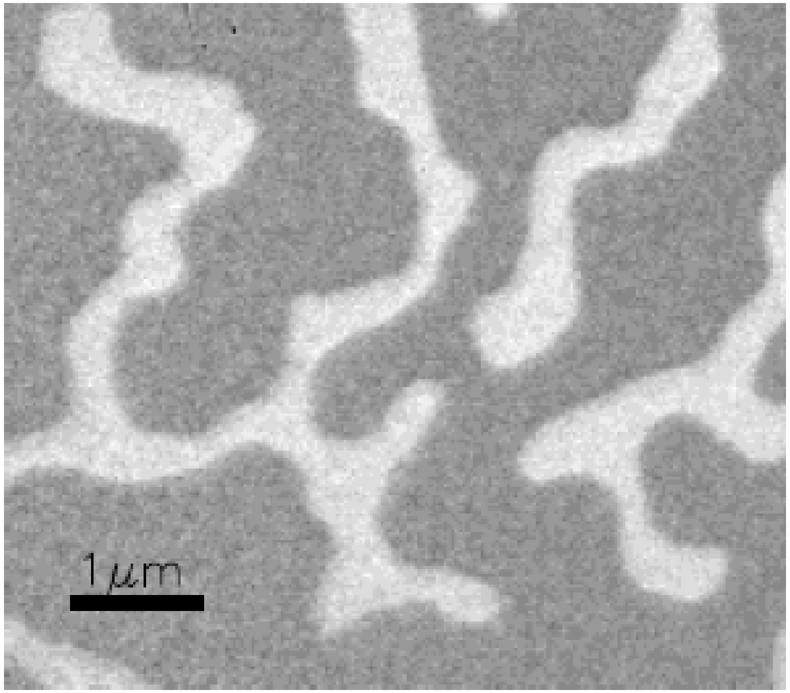
Magnetic imaging with soft X-rays

Photo**E**mission **E**lectron **M**icroscope
"photon in – electron out"



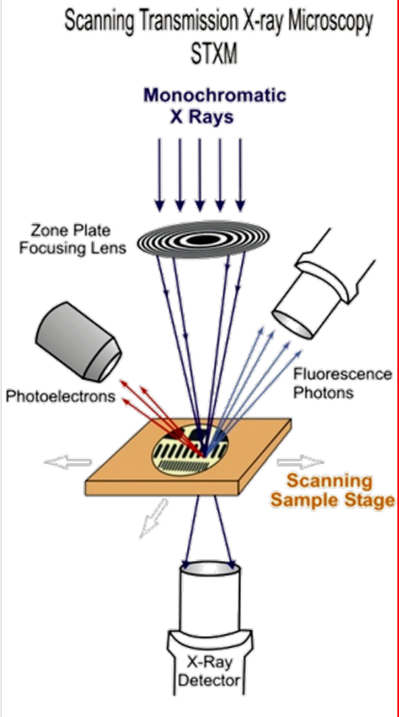
J. Stoehr, et al., *Science* **259** 658 (1993)

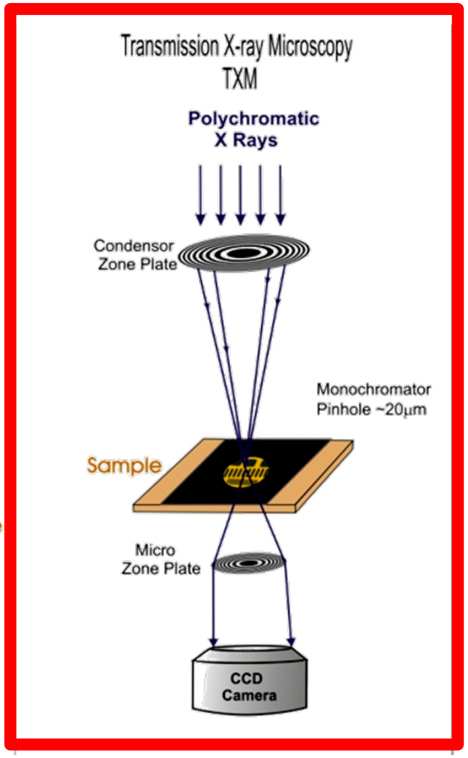
Full-field **T**ransmission **X**-ray **M**icroscope
"photon in – photon out"

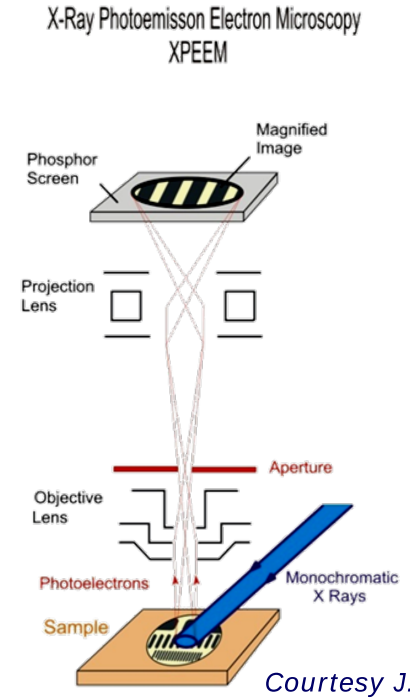


P. Fischer, et al., Z. f. Phys. **B101** 313 (1996)

Various X-ray imaging techniques







Courtesy J. Stöhr

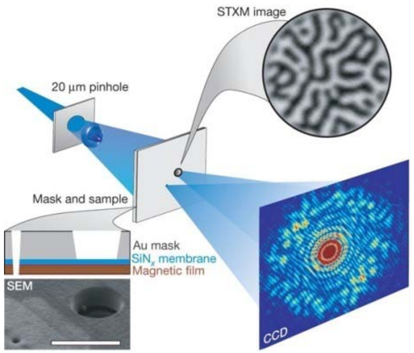
in real space

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

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

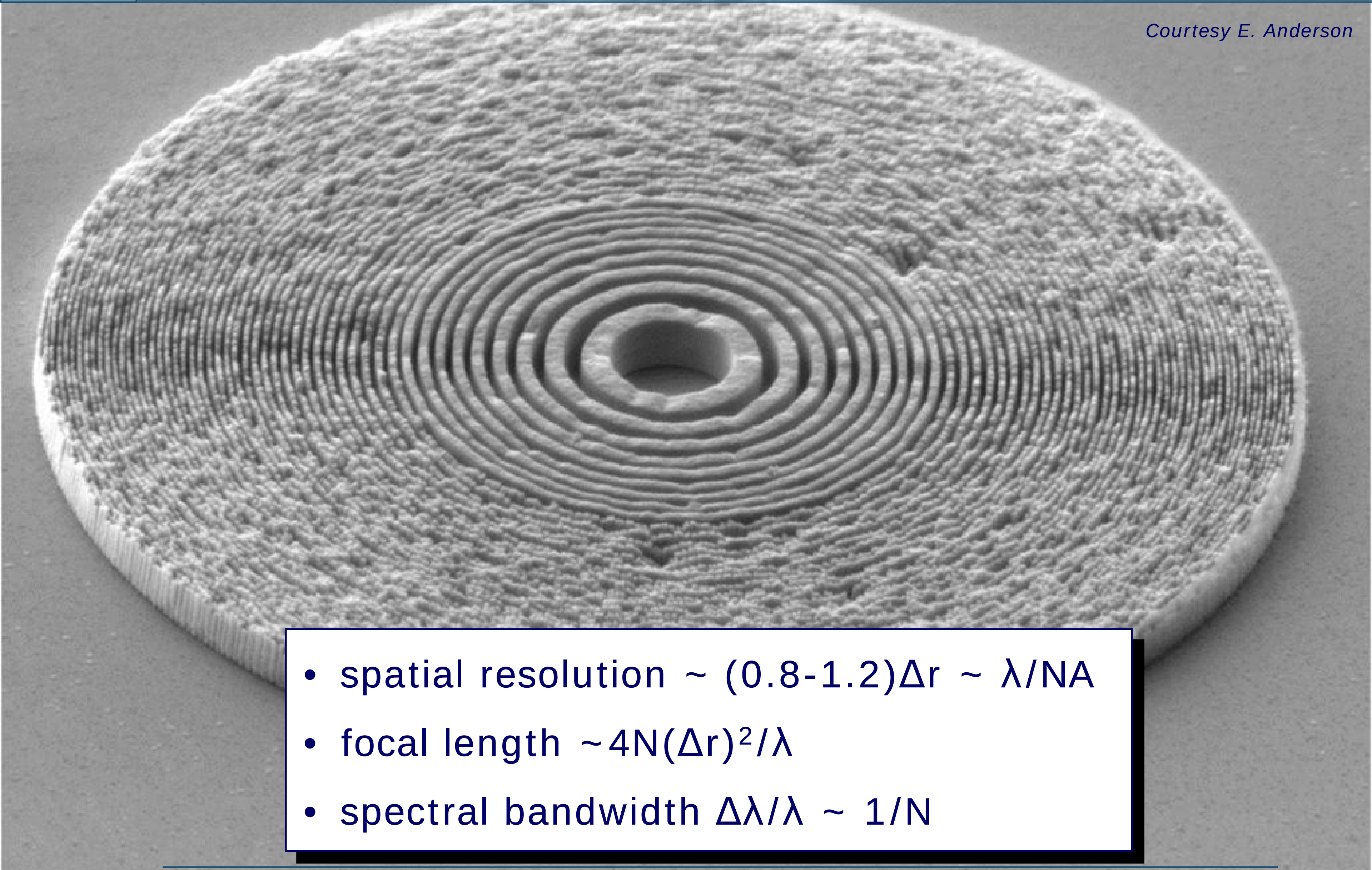
J. Stoehr, et al., *Science* **259** 658 (1993)

in reciprocal space



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

Fresnel Zone Plate Lenses

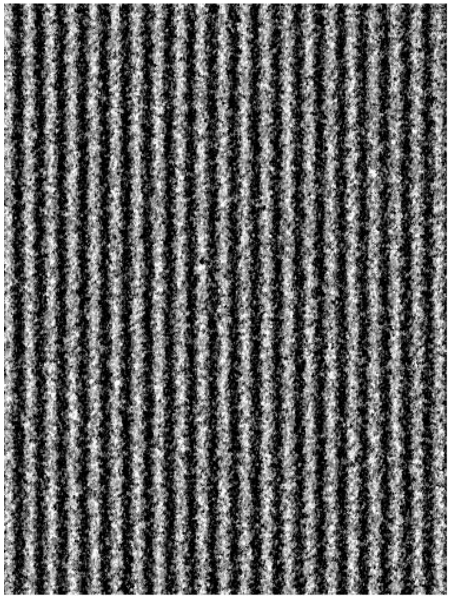


Courtesy E. Anderson

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

Progress in spatial resolution

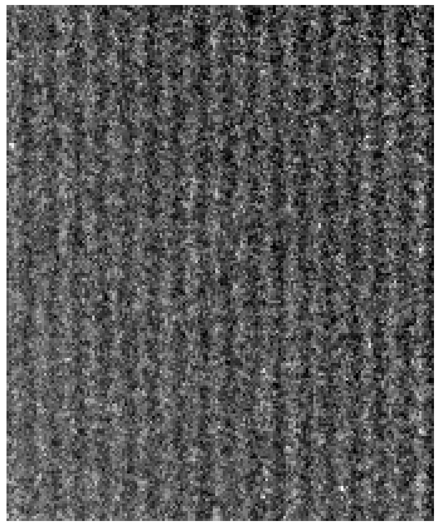
15 nm



2005

W. Chao, et al, Nature ***435*** 1210 (2005)

12 nm

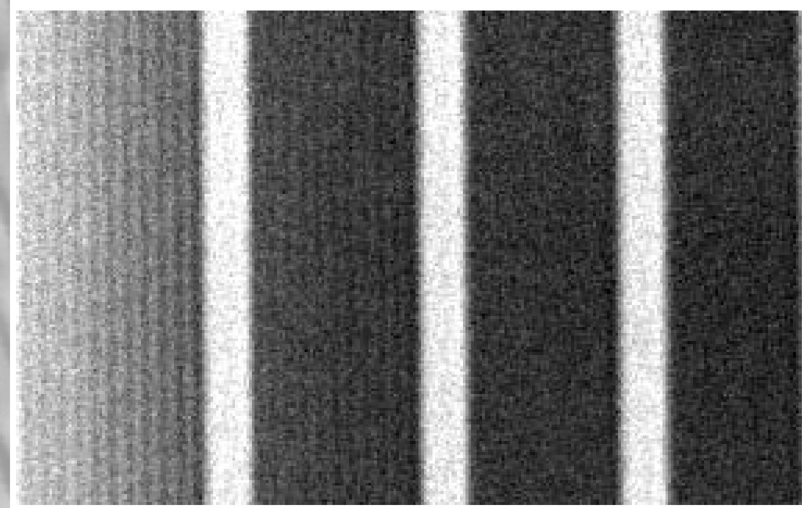


2009

W. Chao, et al, Optics Express, ***17****(20) 17669 (2009)*

10 nm

11 nm 10 nm 9 nm 8 nm



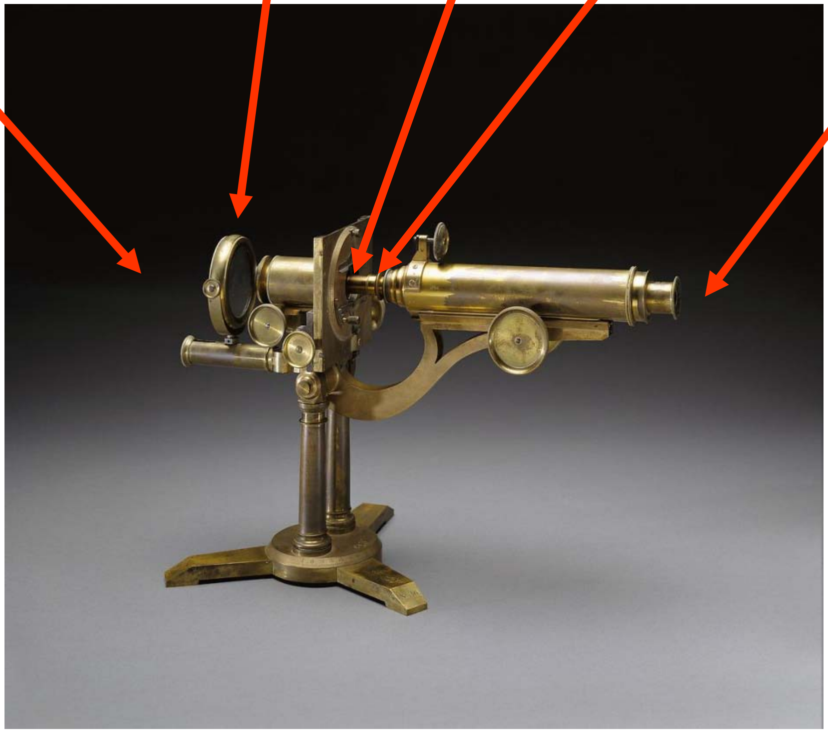
2010

W. Chao, et al, (2011) in preparation

A „Conventional“ Light Microscope

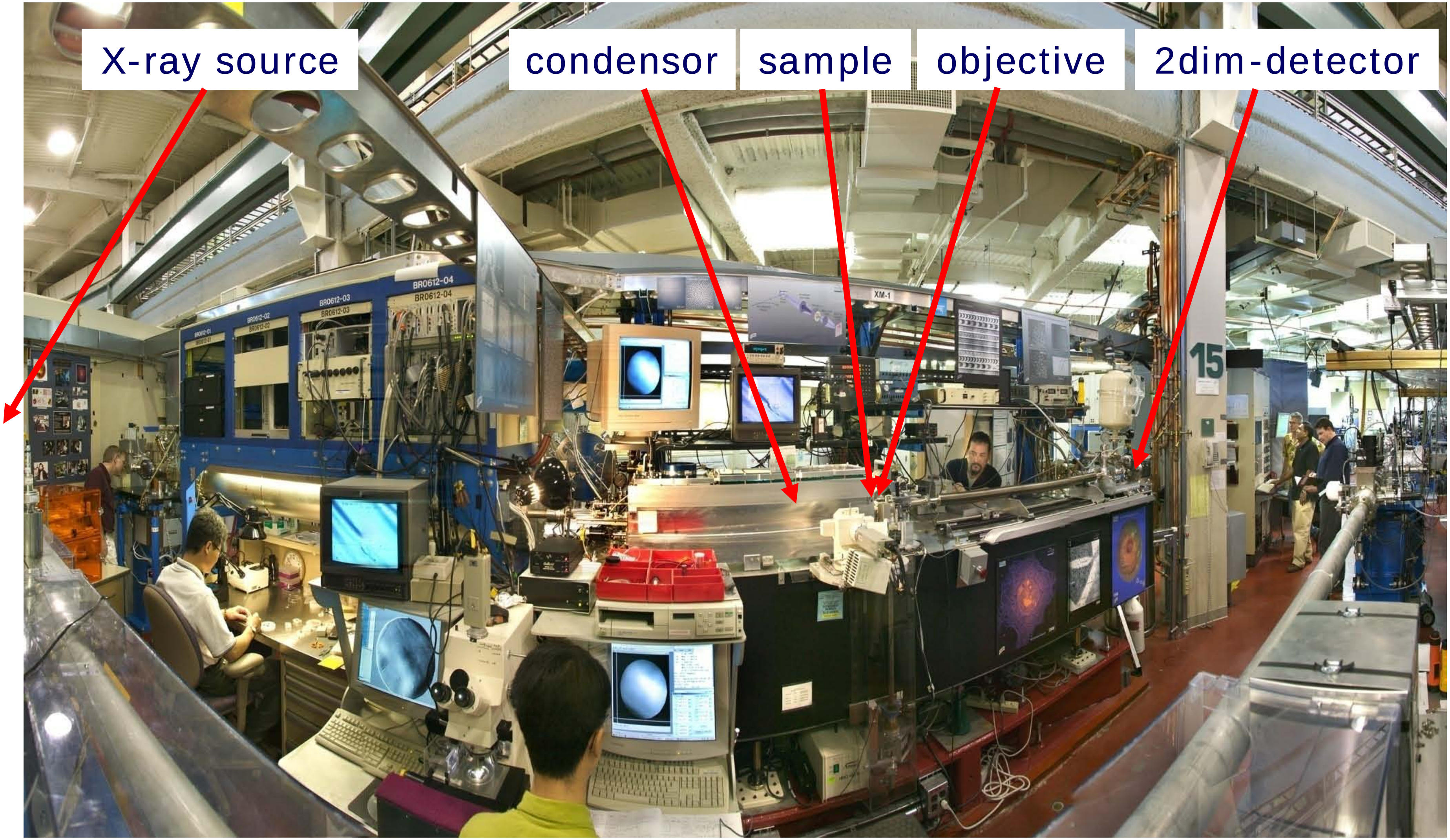
From: U.S. Natl Library of Medicine
http://www.nlm.nih.gov/visibleproofs/galleries/technologies/photomicrography_image_8.html

light source condensor sample objective lens 2dim-detector

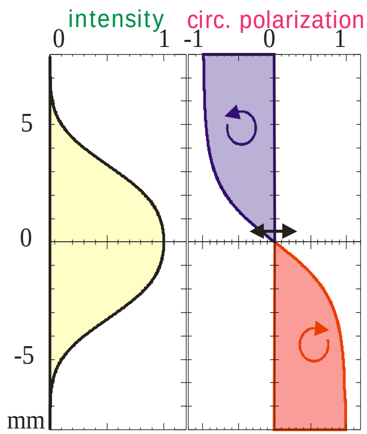


Soft X-ray Microscope XM-1 (BL 6.1.2@ALS)

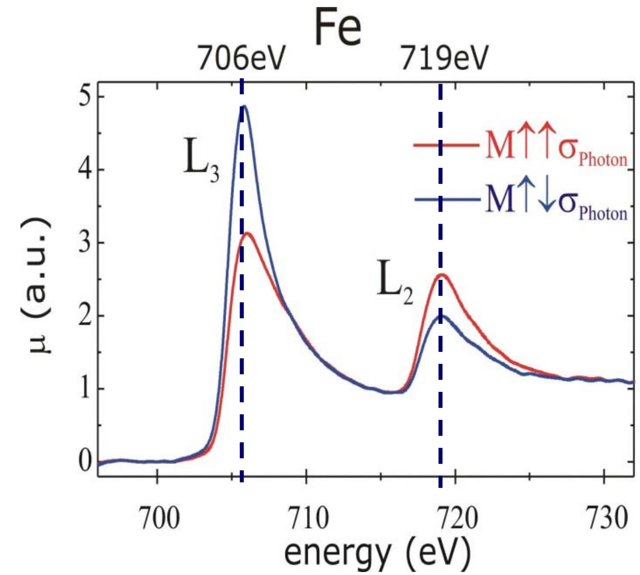
http://www.cxro.lbl.gov/BL612/



Magnetic full-field soft X-ray microscopy



XMCD contrast

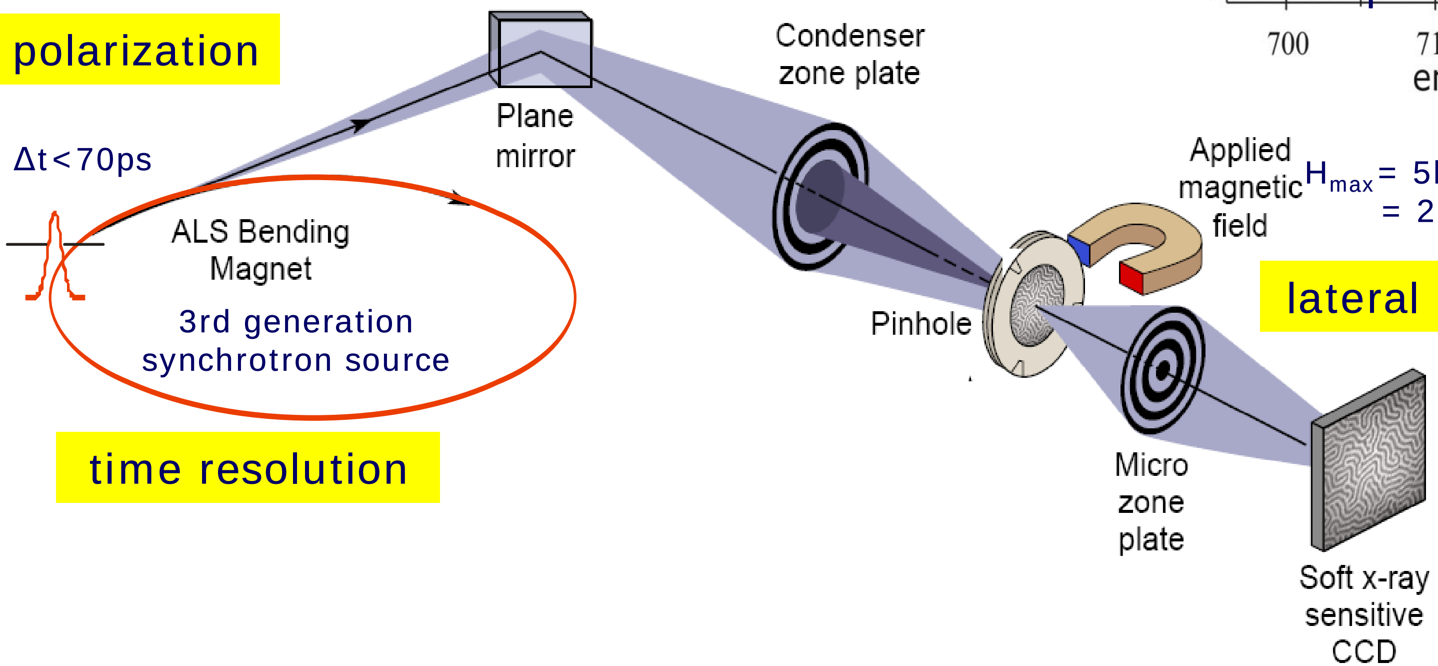


element specificity

E = 250eV - 1.8 keV
λ= 0.7 nm - 5 nm
ΔE/E=500

polarization

Δt<70ps



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

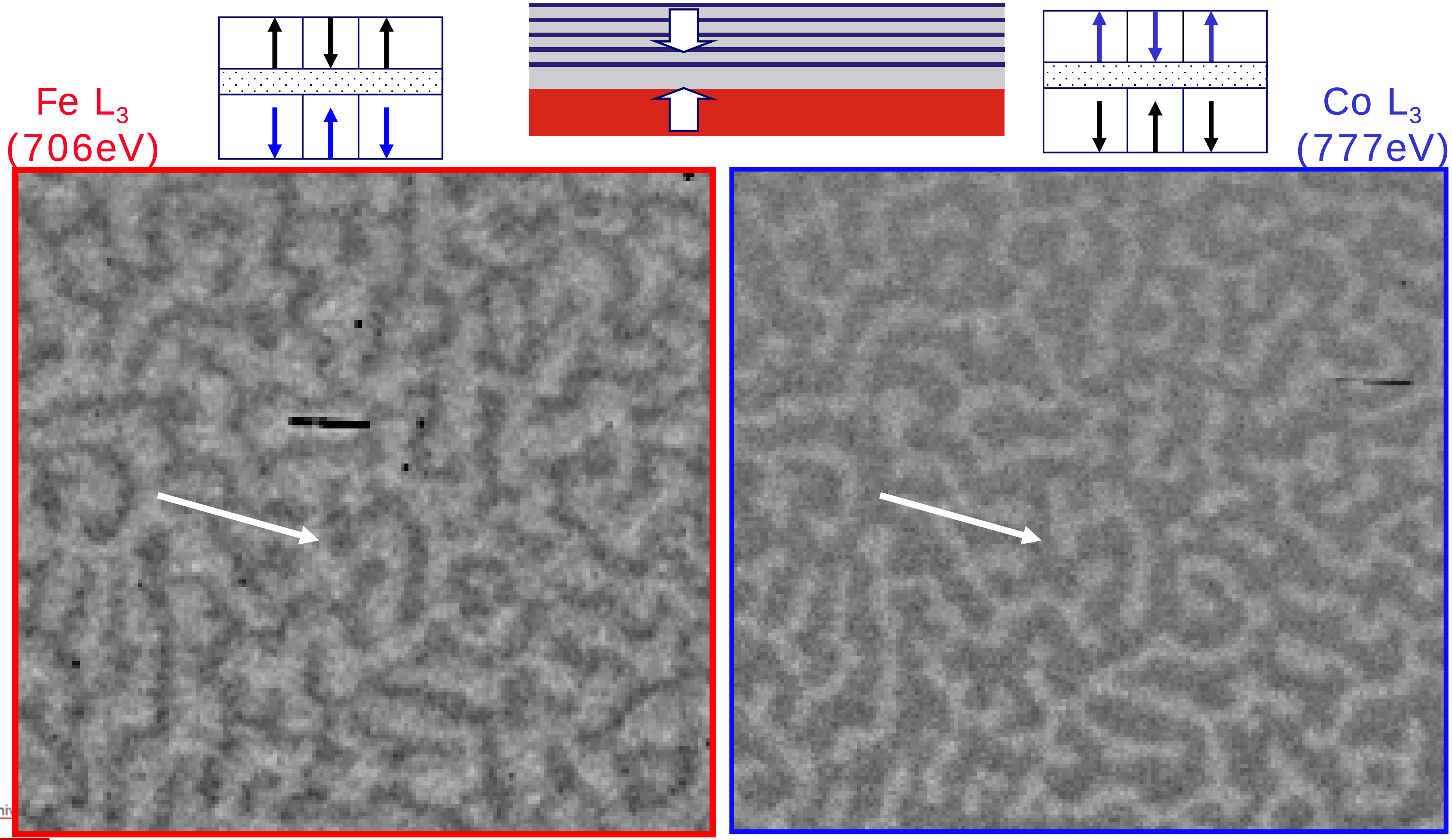
lateral resolution

time resolution

CCD 2048x2048 px^2
Mag ~ 2000
FOV ~ 10-15μm

Element specificity = layer resolving

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

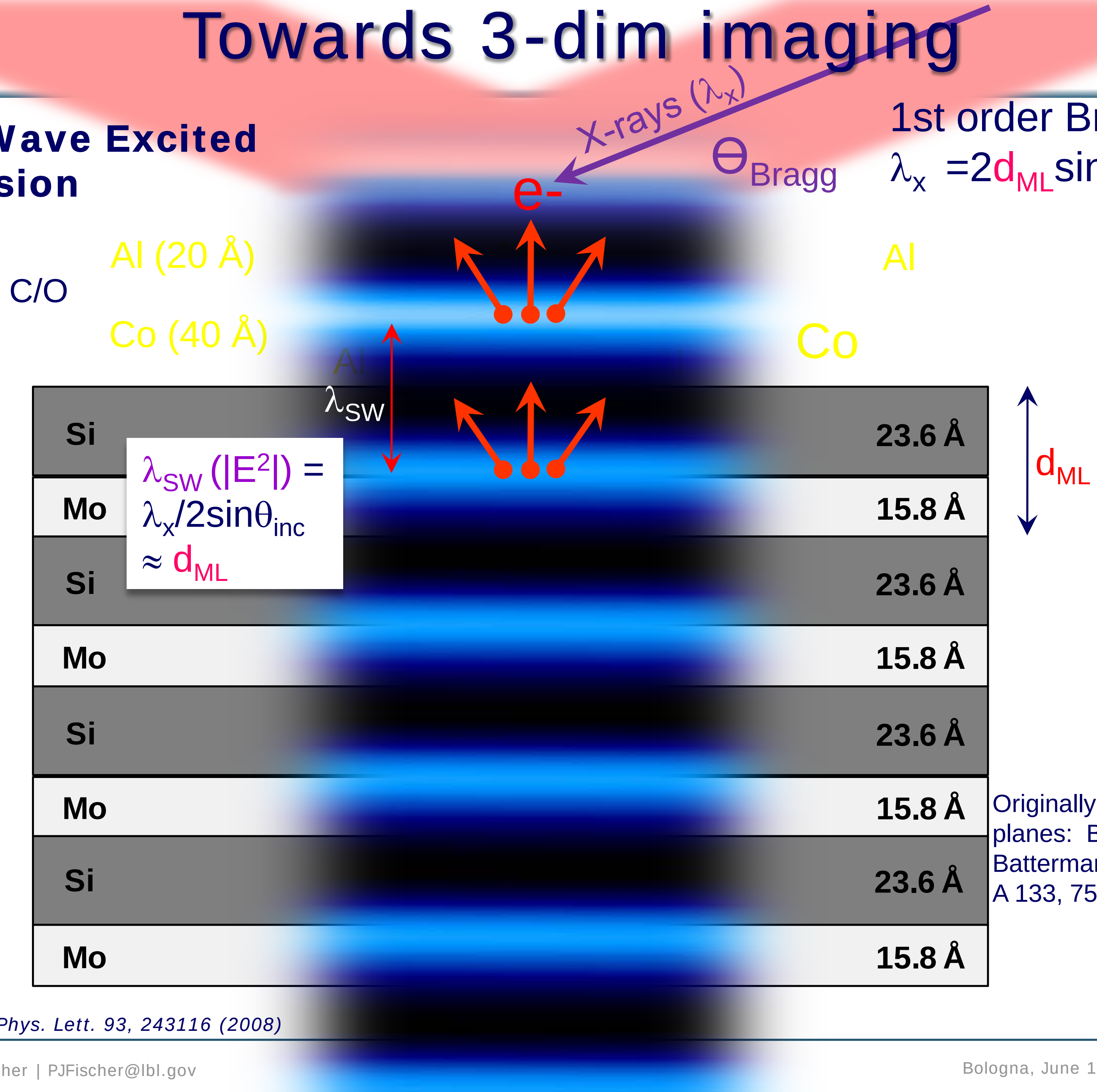


S. Mangin, T. Hauet, P. Fischer, D.H. Kim, J.B. Kortright, K. Chesnel, E. Arenholz, E.Fullerton, Phys Rev B 78 024424 (2008)

Towards 3-dim imaging

Standing-Wave Excited Photoemission

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

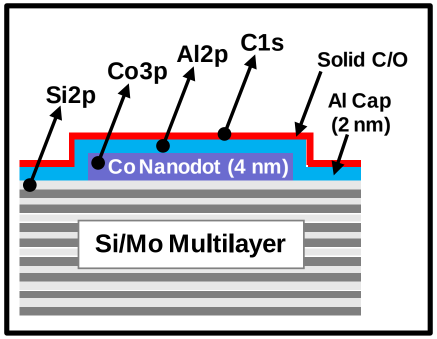


Originally from crystal planes: B.W. Batterman Phys. Rev. A 133, 759 (1964)

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

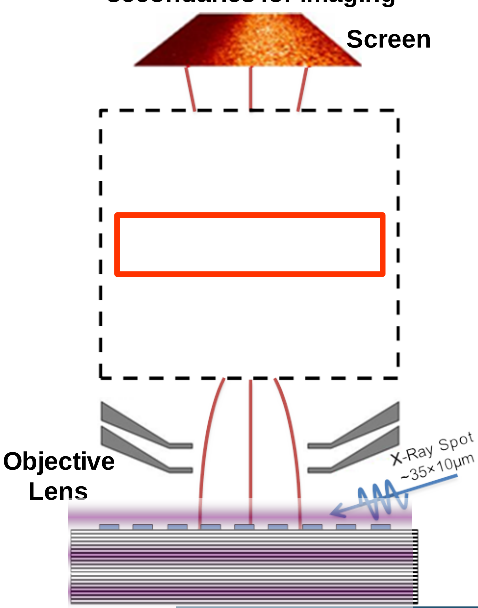
Element-Specific 3-dim Imaging

Measured Structure



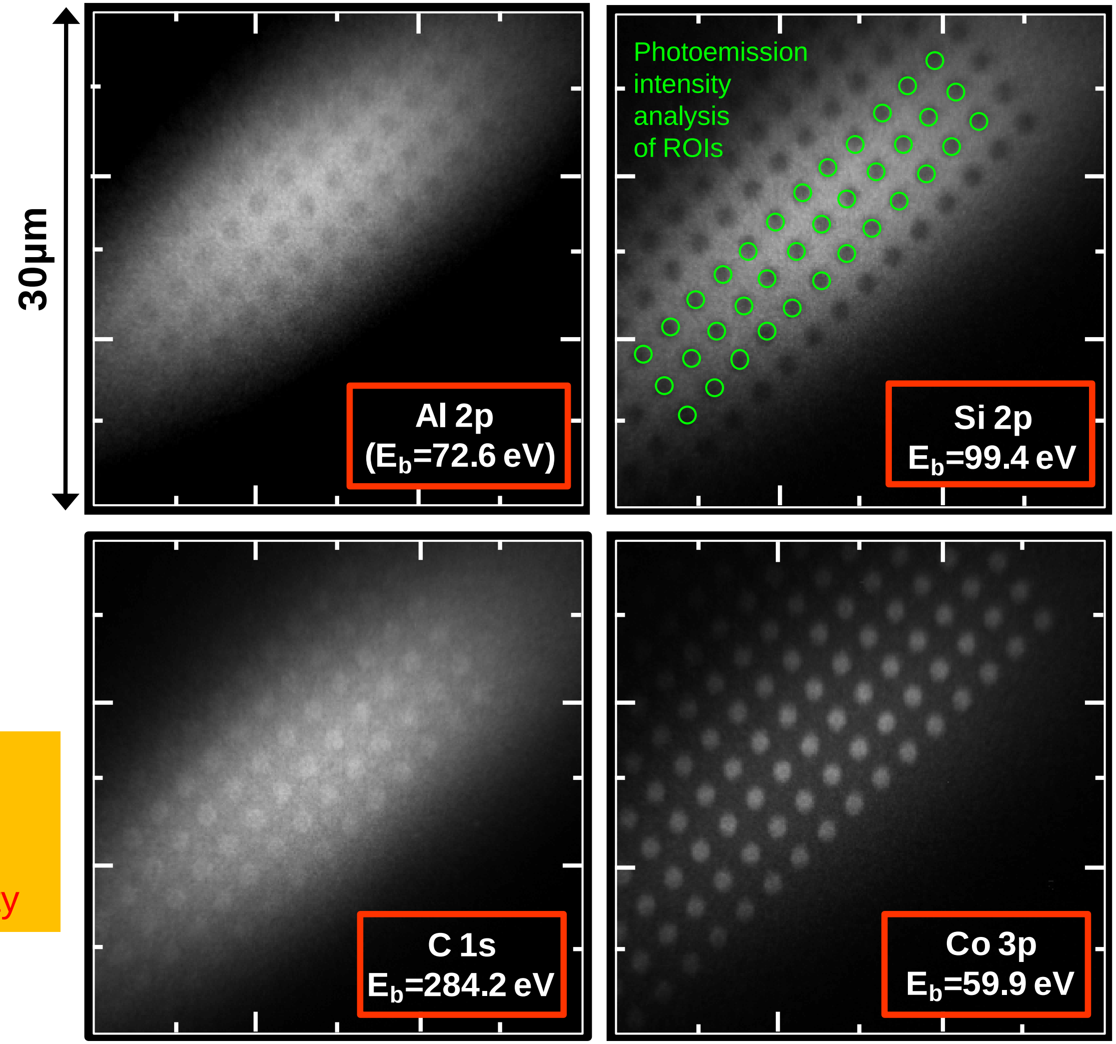
Measurement System (Elmitec PEEM II)

Si 2p, Co 3p, Al 2p, C 1s or secondaries for imaging



Scan *hv* to add depth sensitivity

Imaging via core-level photoelectron excitation



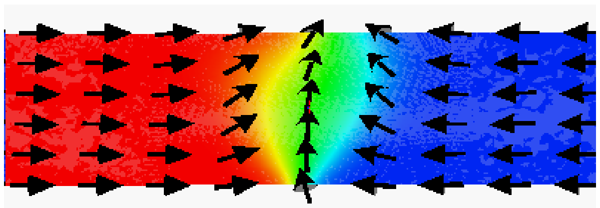
A. X. Gray , F. Kronast, C. Papp, S.-H. Yang, S. Cramm, I. Krug, F. Salmassi, E. Gullikson, D. Hilken, E. Anderson, P. Fischer, C.M. Schneider, C.S. Fadley, Appl. Phys. Lett. ***97****, 062503 (2010);*

Magnetic Domain Walls

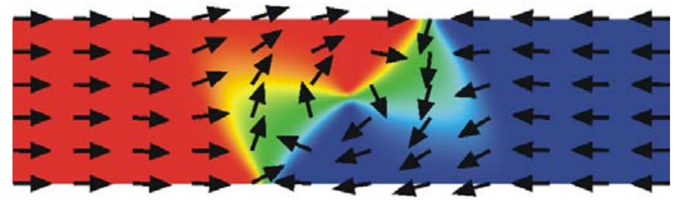
"How deterministic is the DW motion?"

Domain walls in nanowires

- Two main types of domain wall structure

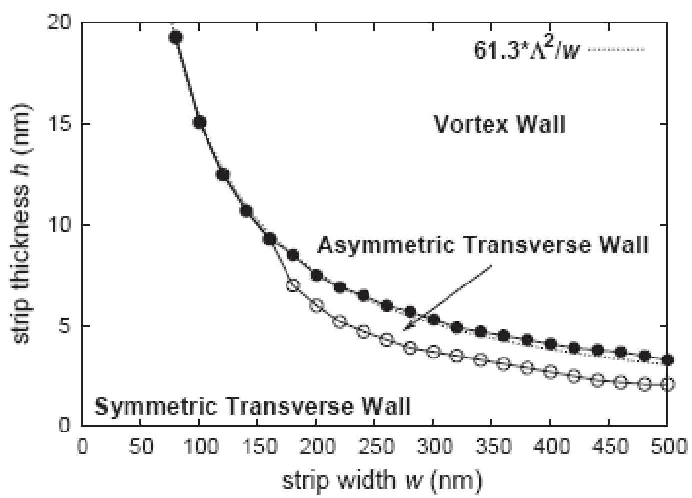


Transverse



Vortex

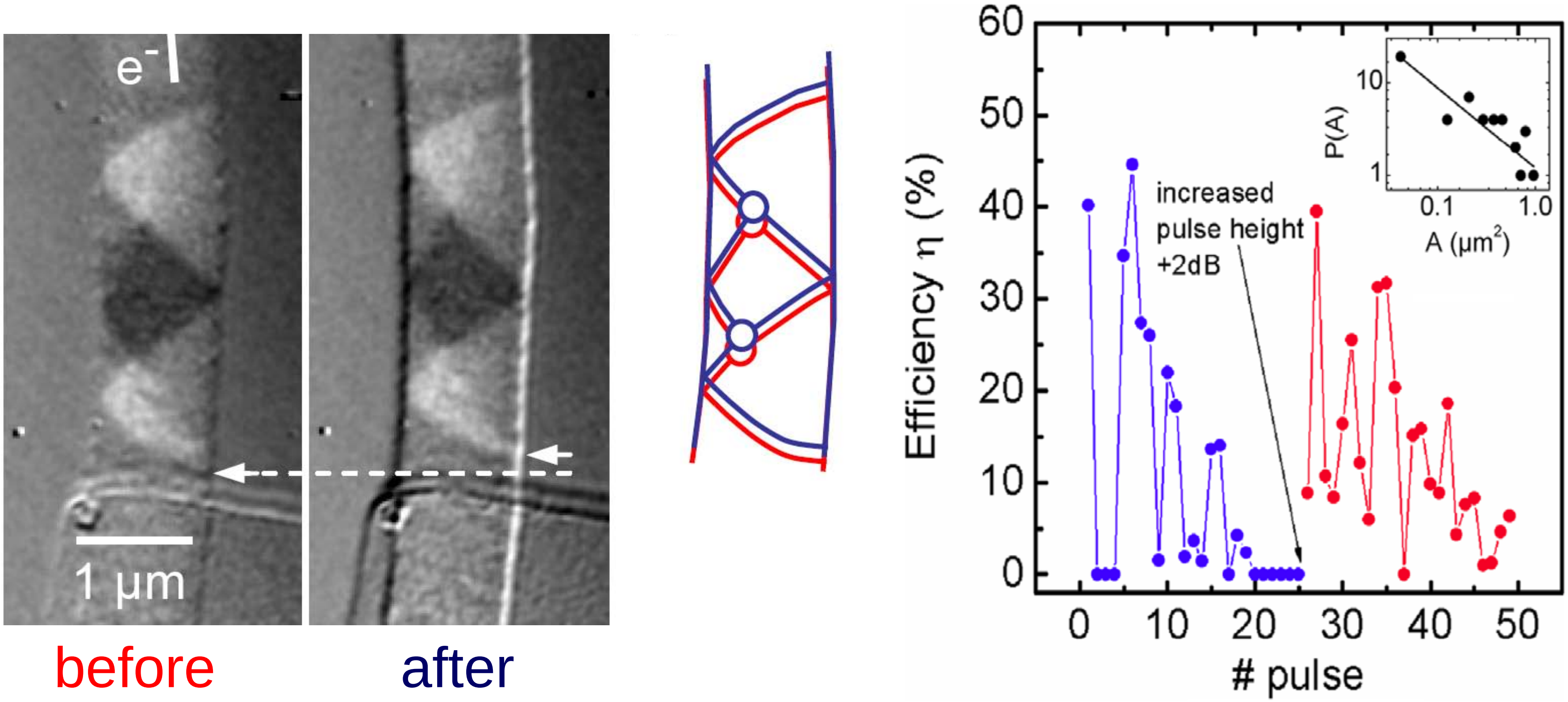
- Structure depends on nanowire geometry



Transverse walls in narrower, thinner wires

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

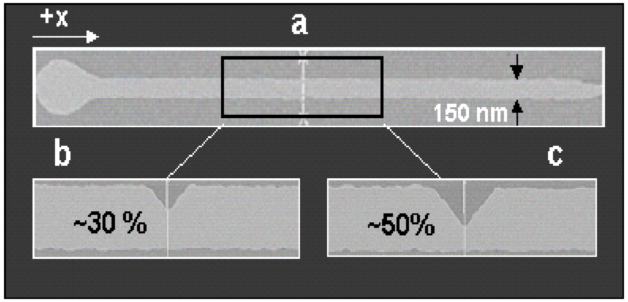
Spin current induced DW motion



- 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

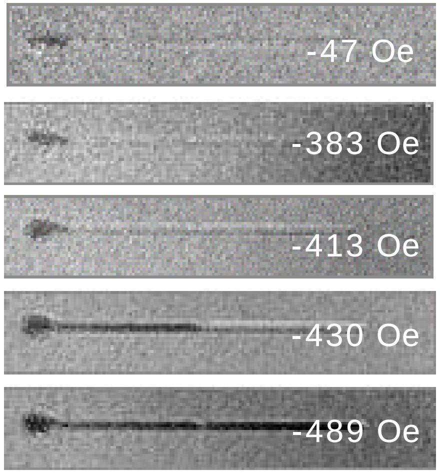
G. Meier, M. Bolte, R. Eiselt, B. Krüger, D.-H. Kim., P. Fischer, Physical Review Letters 98, 187202 (2007)

DW depinning in notched nanowires

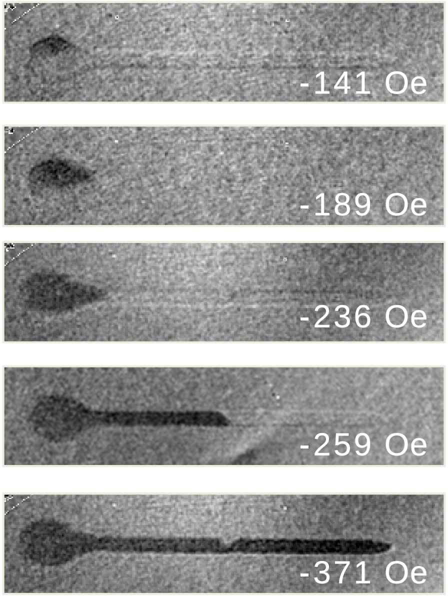


Permalloy ($Ni_{80}Fe_{20}$) wires with varying wire width (w), notch depth (N_d) and film thickness (t)

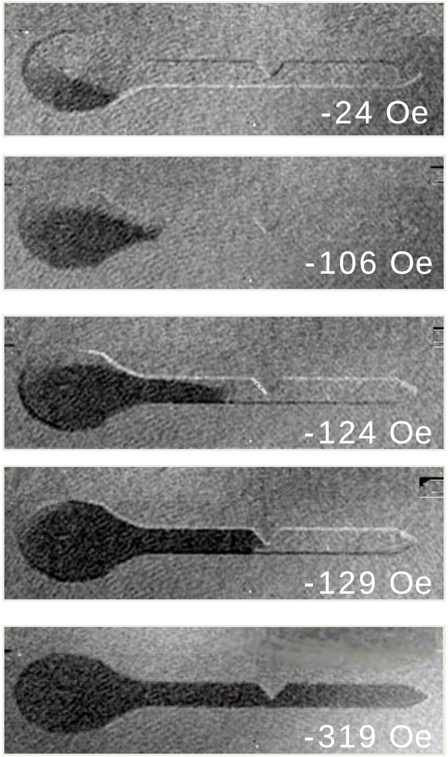
w= 150 nm



w= 250 nm



w= 450 nm

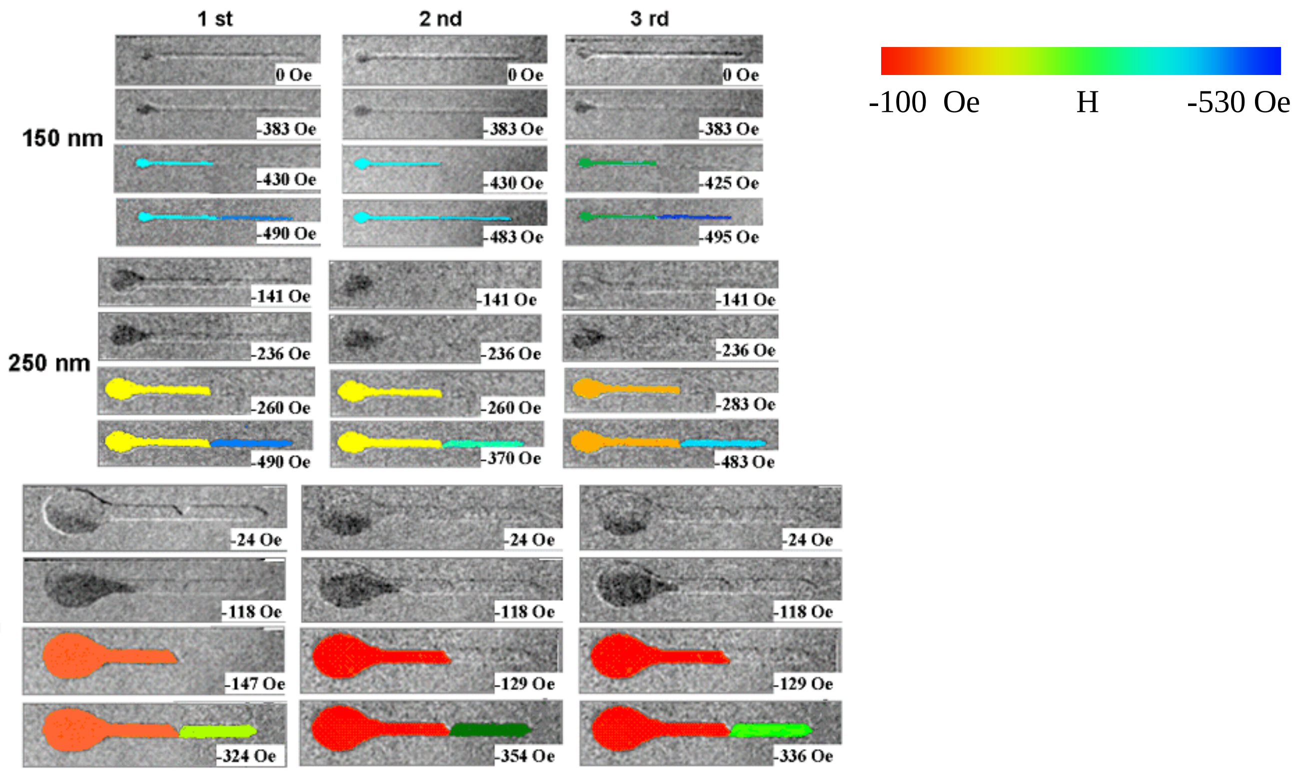


N_d=50 %
t=50 nm

$\Rightarrow$ 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



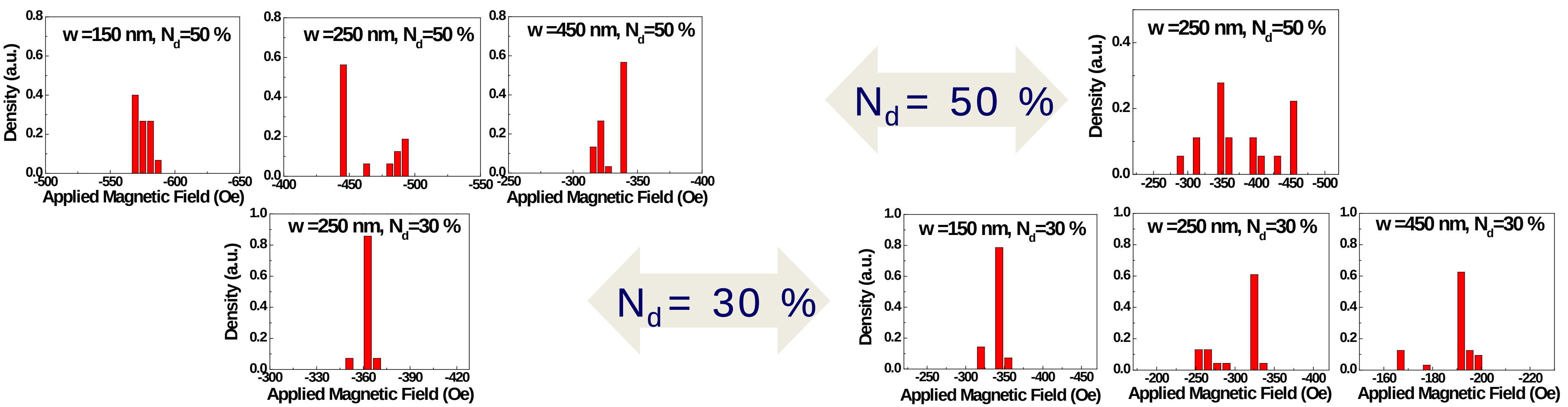
- Pinning probability decreases with wire width w
- Repeated measurements indicate stochastic behavior (generation of different DW types at the notch)
- DW depinning process is independent from the DW pinning process

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



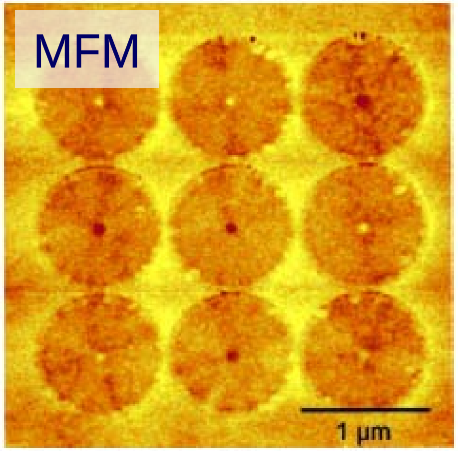
Distribution depends considerably on notch depth and wire width
$\Rightarrow$ reproducible DW depinning process can be achieved by a proper selection of the wire and the notch geometry

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

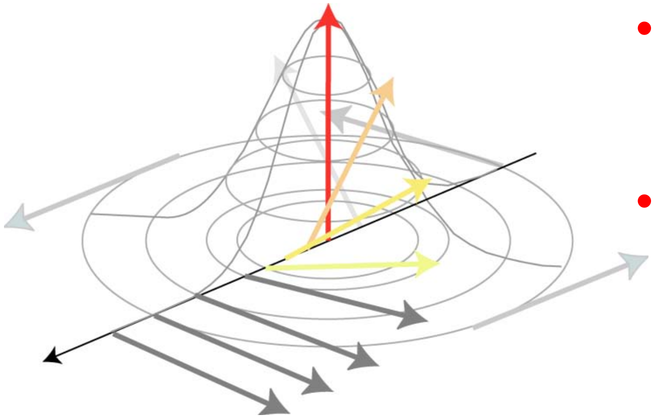
Spin dynamics of vortices and domain walls

Magnetic vortices

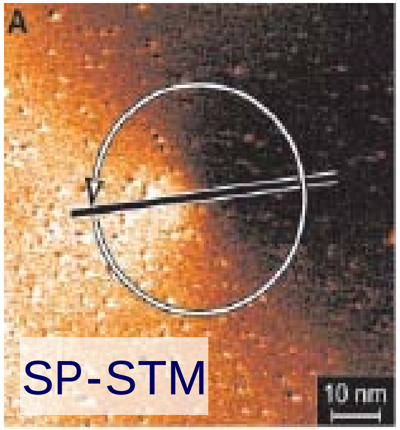
static imaging



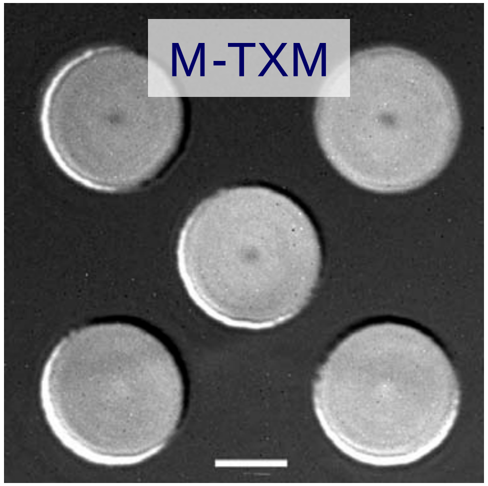
T. Shinjo *et al*,
Science 268, 314 (2000)



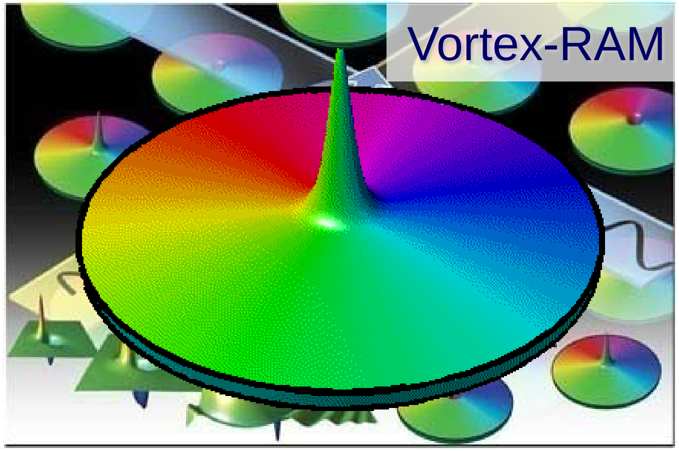
- Chirality
  in-plane circular domain structure
- Polarity
  out-of-plane component of magnetization



A. Wachowiak et al,
Science 298 577 (2002)



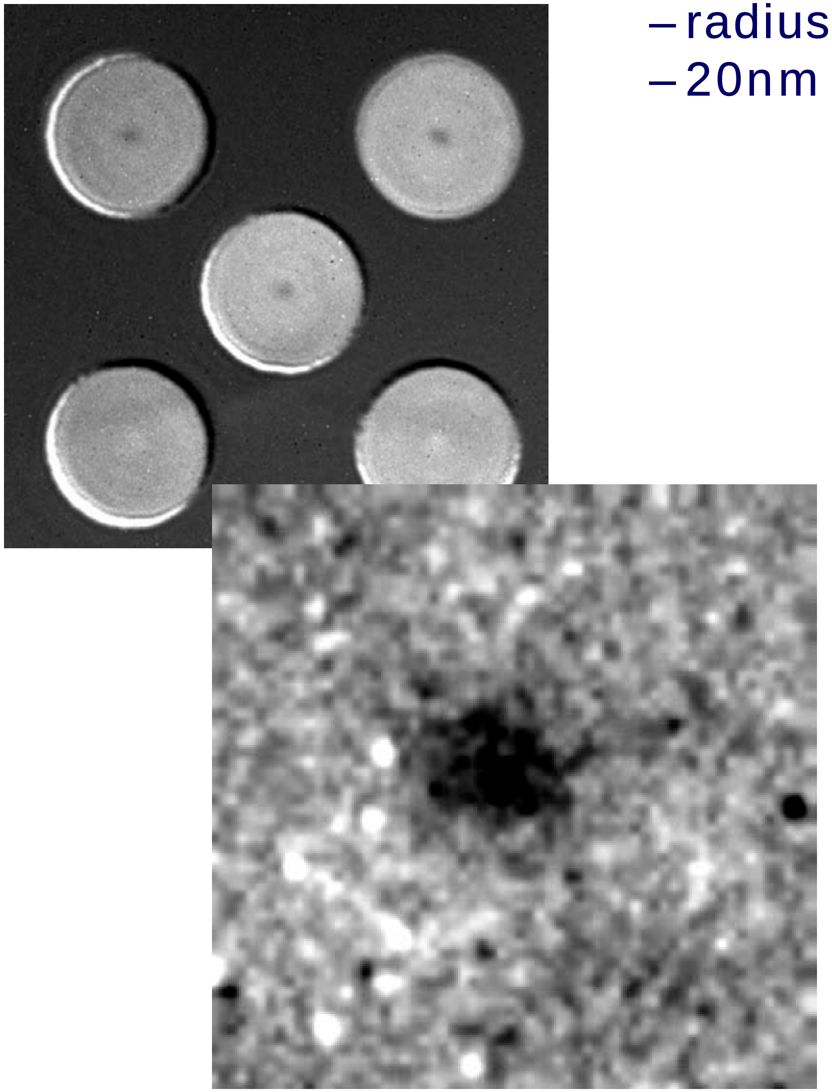
P. Fischer, S. Kasai, K. Yamada, T. Ono,
A. Thiaville, PRB (2011) in press



S.-K. Kim et al. APL
92, 022509 (2008)

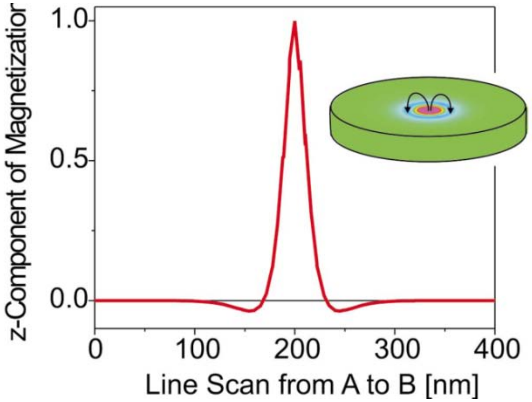
Courtesy S.-K. Kim

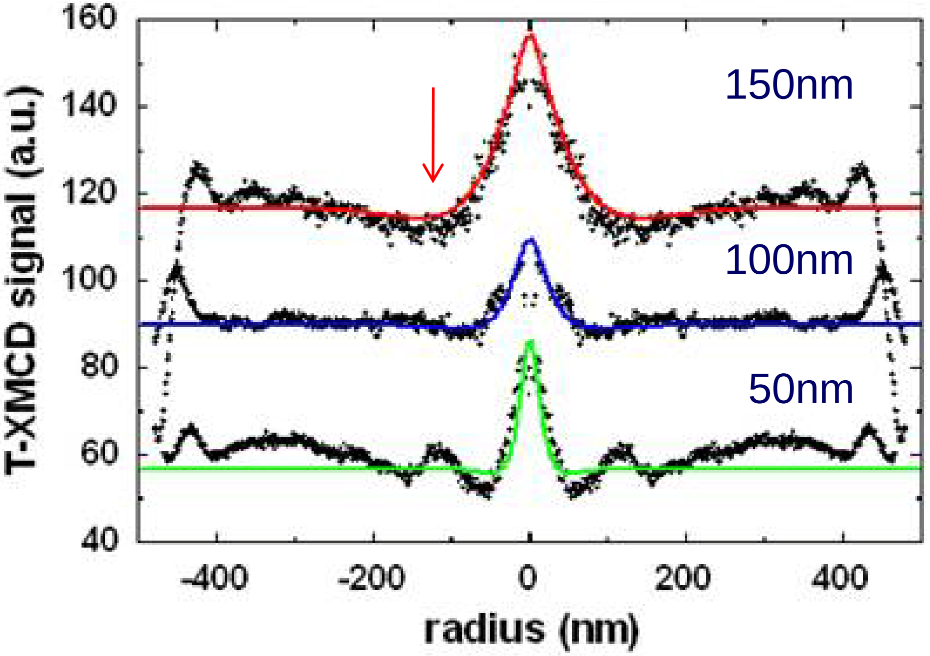
X-ray imaging of MV in PY dots



- radius 500nm
- 20nm spatial res

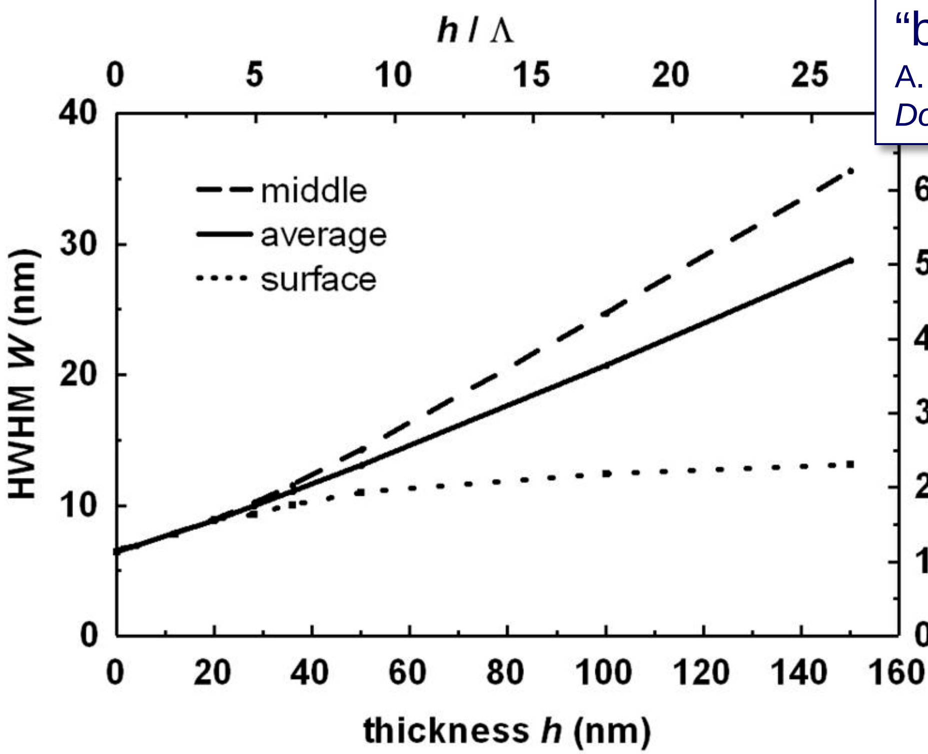
J. K. Ha et al, PRB 67, 224432 (2003)



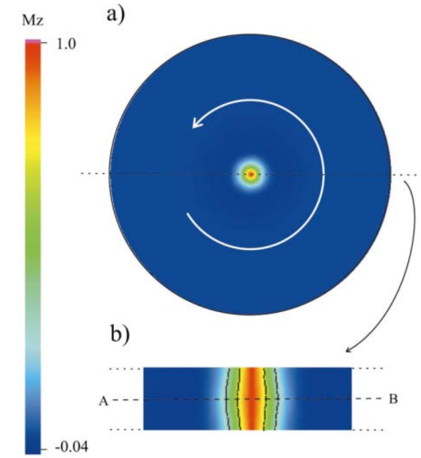


P. Fischer, M.-Y. Im, S. Kasai, K. Yamada, T. Ono, A. Thiaville, PRB Brief Rep (2011) in press

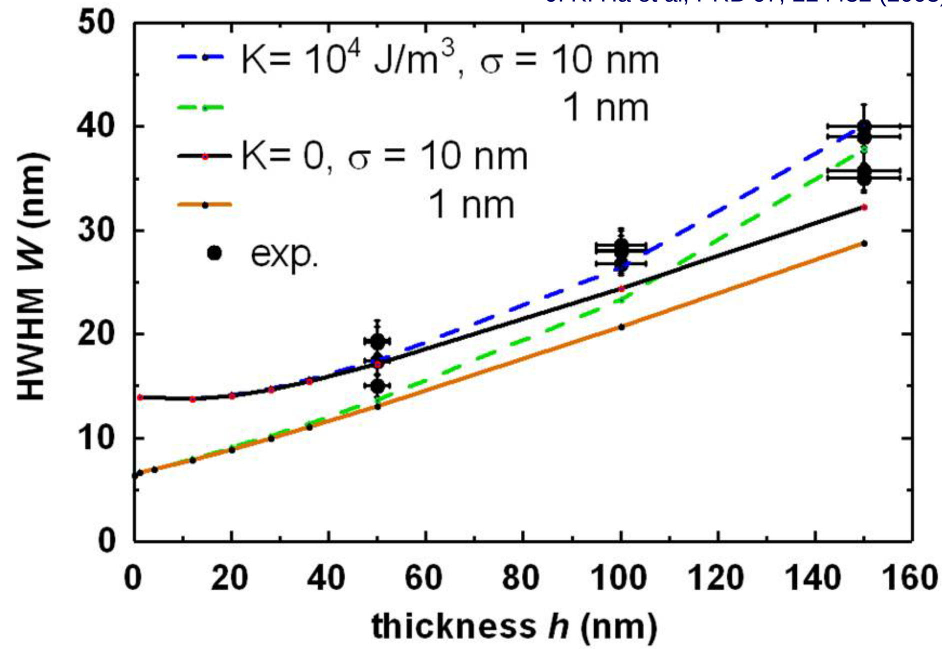
3D micromagnetic calculations



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



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

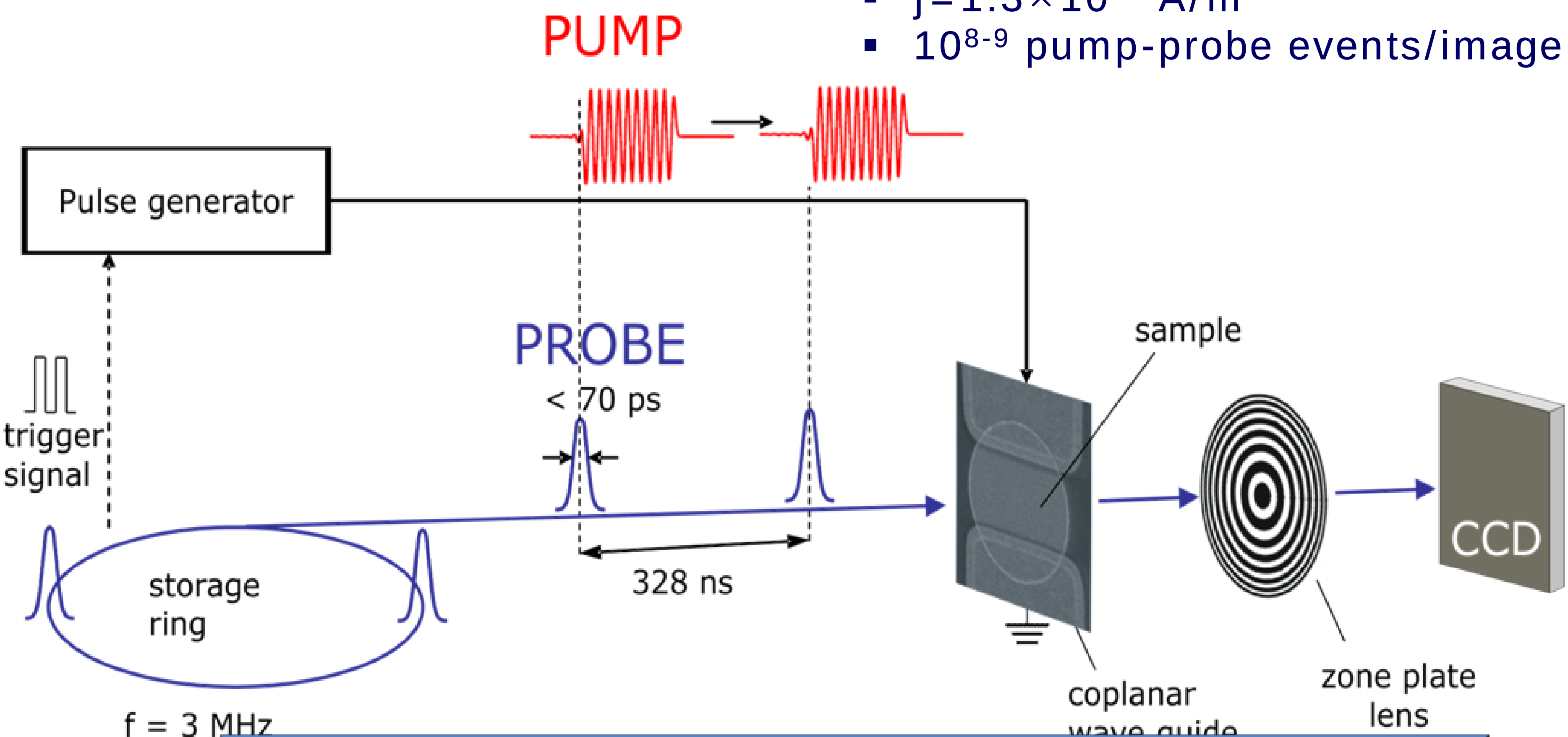


- perfect agreement of full 3d micromagnetic simul. with expt. for $K=10^4$ J/m^3 and $\sigma=10$nm
- fine details can be observed

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

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

- $j=1.3\times10^{11}$ A/m^2
- 10^{8-9} pump-probe events/image

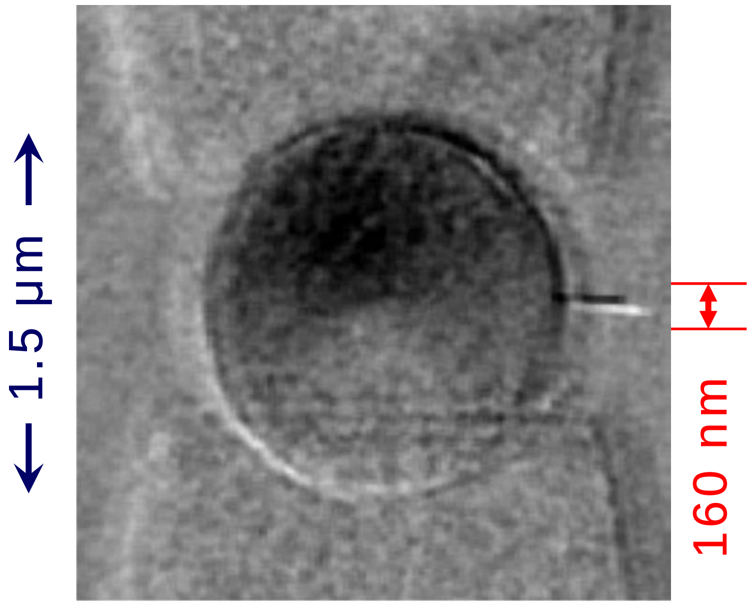


- perfect repeatability of the dynamics required
- no access to non-deterministic components e.g. spin fluctuations

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

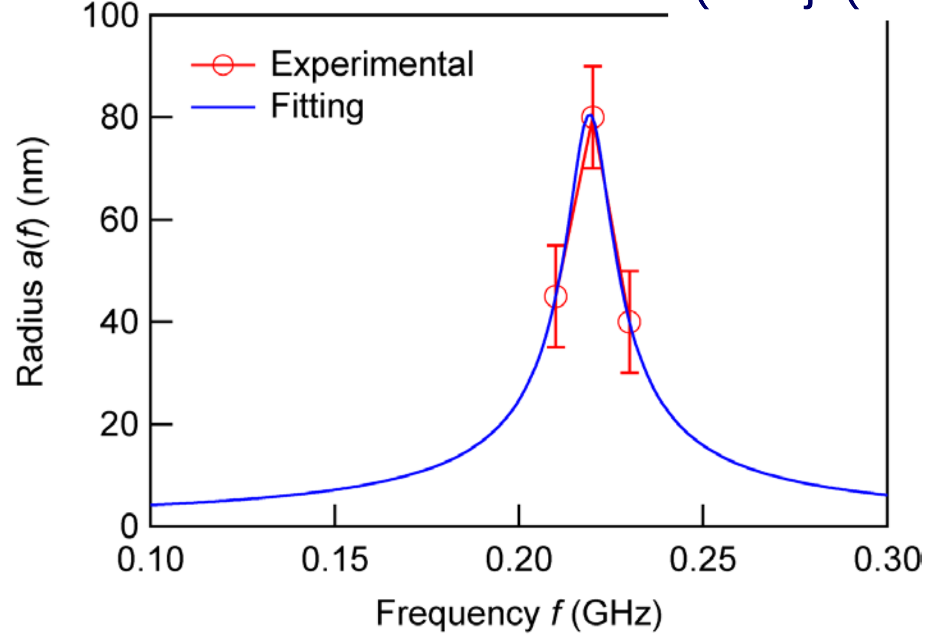


- CW rotation ⇒ polarity = -1
- gyration radius R~80 nm

Solving Thiele eqn with STT for u

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

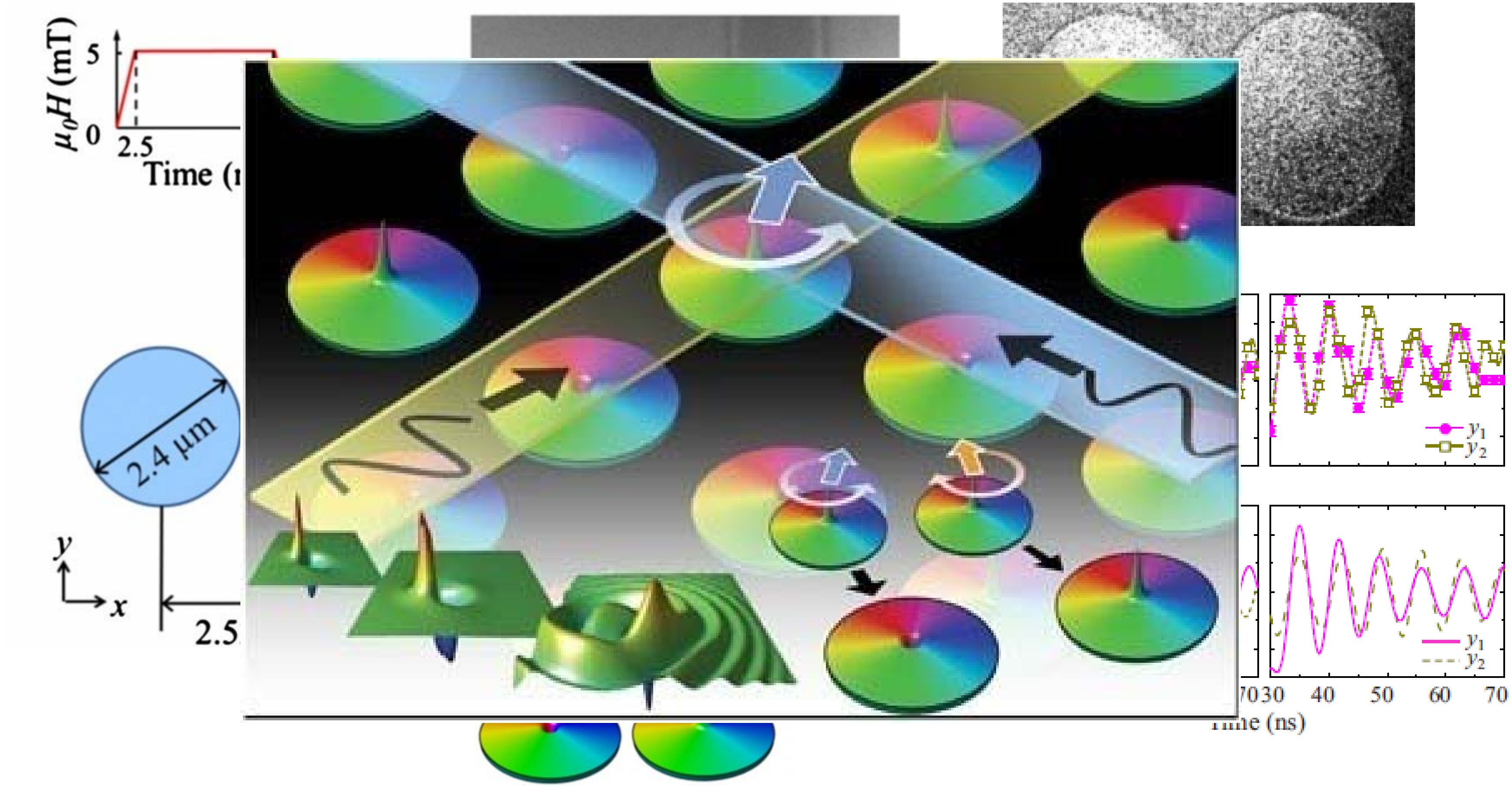
drift velocity
($\sim -Pj/(2eM_s)$)



measuring R(ω) ⇒ $P=0.67\pm0.15$

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

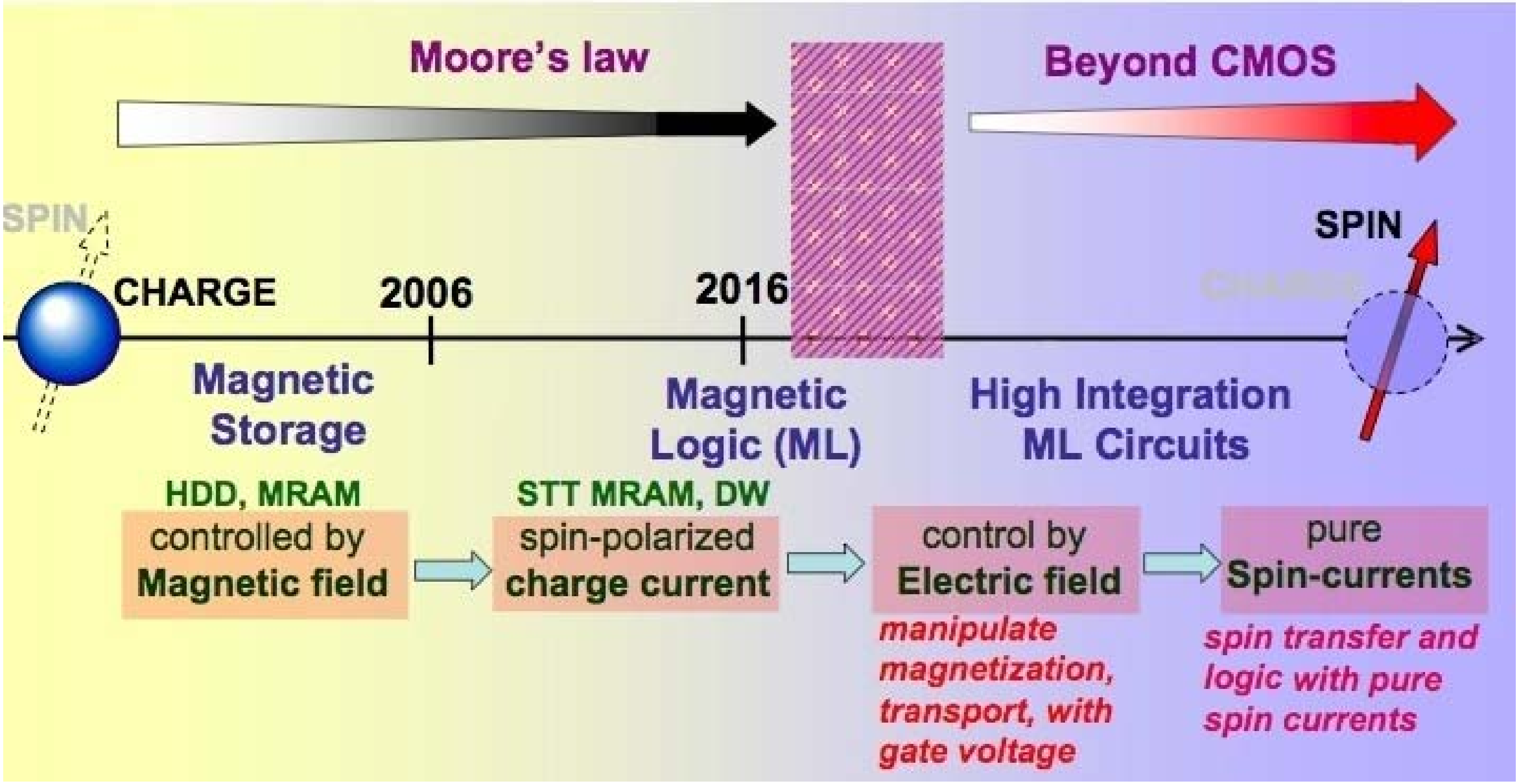
Coupled vortex gyration



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

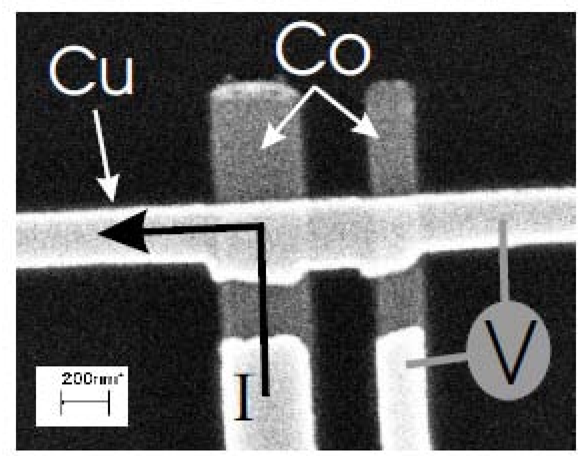
*H. Jung, Y.-S. Yu, K.-S. Lee, M.-Y. Im, P. Fischer, L. Bocklage, A. Vogel, M. Bolte, G. Meier, S.-K. Kim, APL, **97**, 222502 (2010)*

The road to spin currents

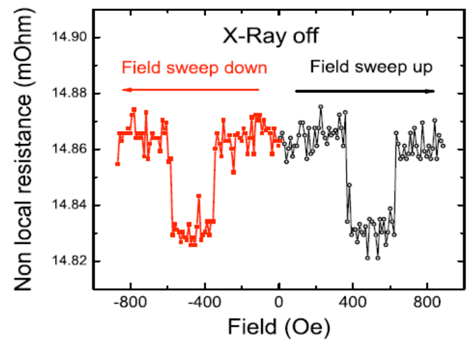


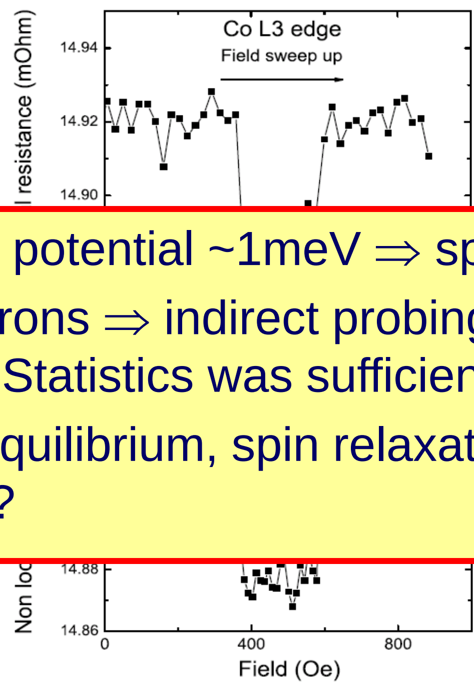
Courtesy C. Chappert

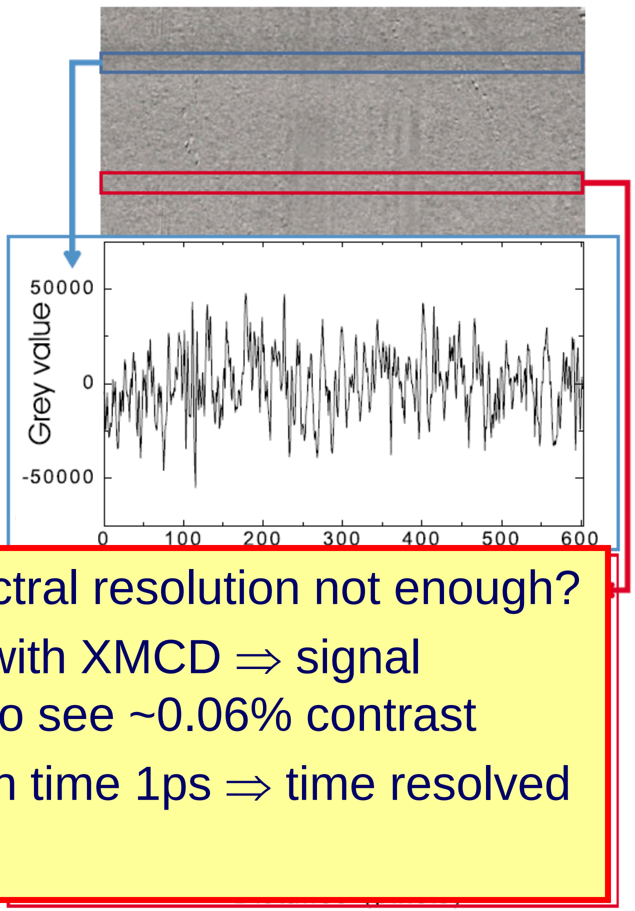
X-ray imaging of lateral spin valves



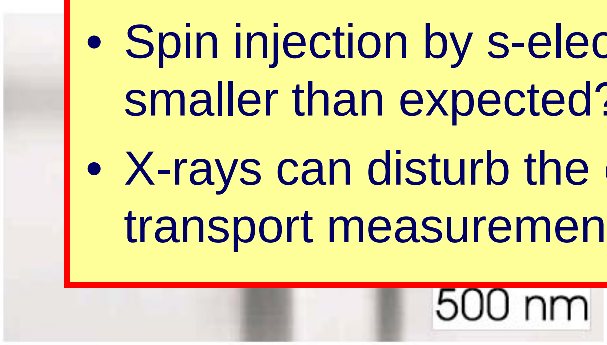
SEM image







- Splitting of the chemical potential ~1meV ⇒ spectral resolution not enough?
- Spin injection by s-electrons ⇒ indirect probing with XMCD ⇒ signal smaller than expected? Statistics was sufficient to see ~0.06% contrast
- X-rays can disturb the equilibrium, spin relaxation time 1ps ⇒ time resolved transport measurement?

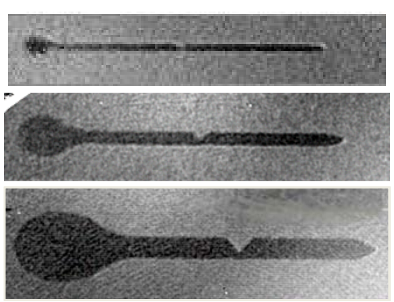


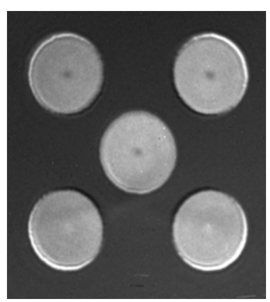
X-ray image @ Cu L_3 edge

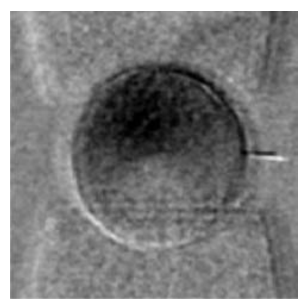
O. Mosendz, G. Mihajlović, J. E. Pearson, P. Fischer, M.-Y. Im, S. D. Bader, A. Hoffmann, Phys Rev B 80 104439 (2009)

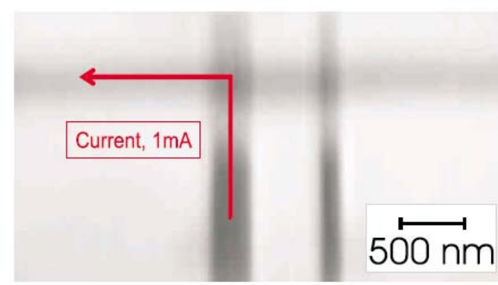
Summary

- Magnetic soft X-ray microscopy combines high lateral resolution (approaching<10nm) with time resolution in the sub-100ps regime and inherent elemental specificity
- Observation of nanoscale magnetism processes
  - Stochastic behavior in DW depinning processes in nanowires
  - magnetic vortex cores
- Fast spin dynamics
  - CI resonant magnetic vortex core motion provides a direct measure of P
- Spin injection in lateral spin valves



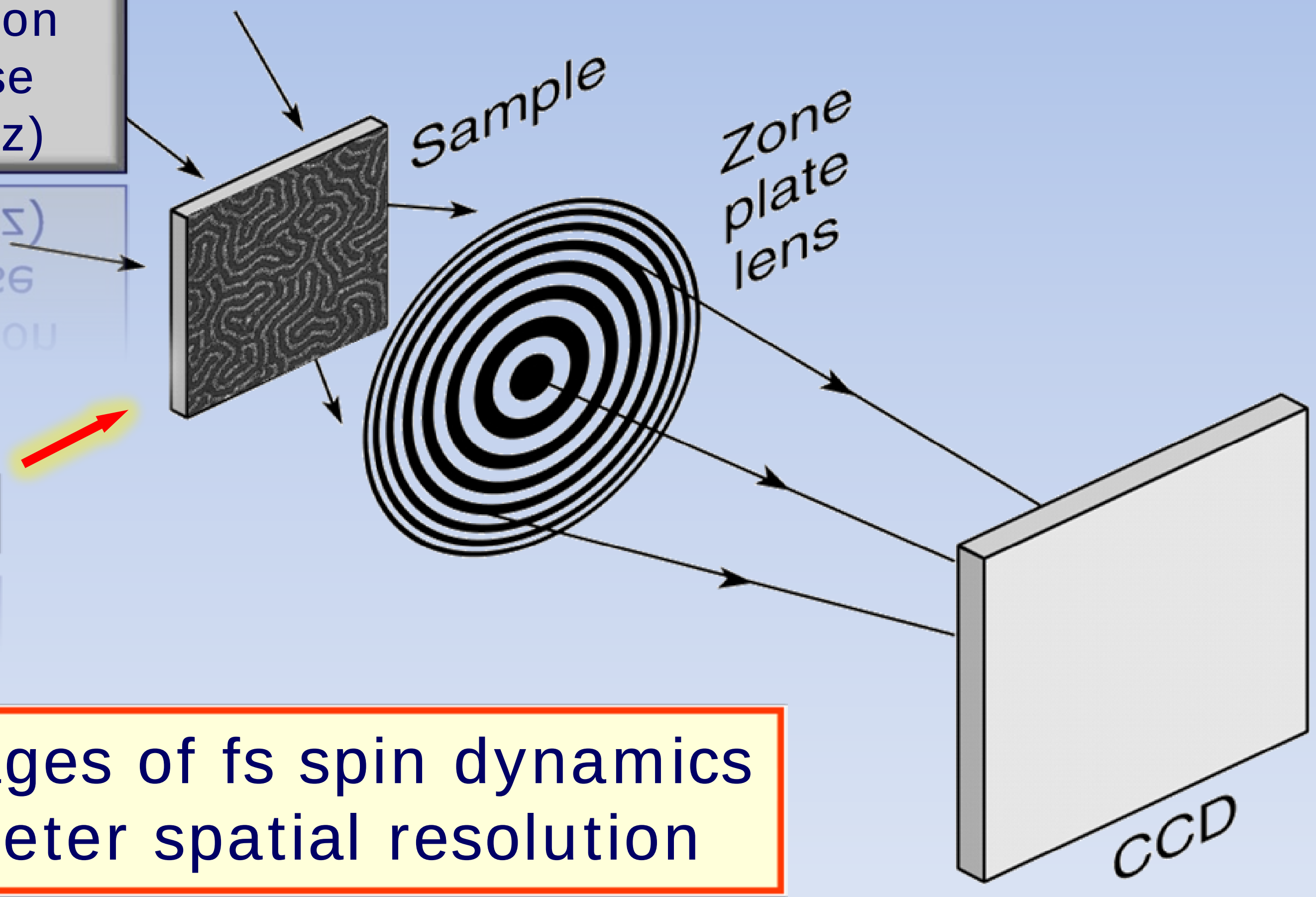






Future goal: imaging at the fsec scale

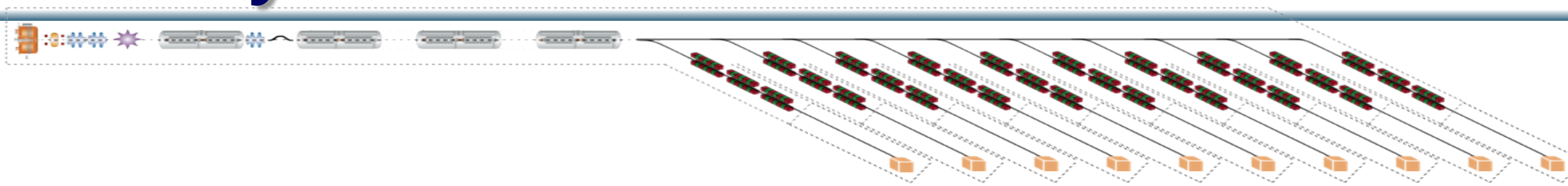
soft X-ray source
- fsec pulse length
- variable polarization
- high photons/pulse
- high rep rate (MHz)



pump stimulus

snapshot images of fs spin dynamics with nanometer spatial resolution

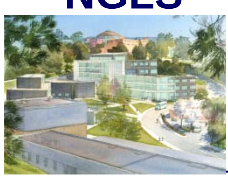
X-ray lasers – current and future

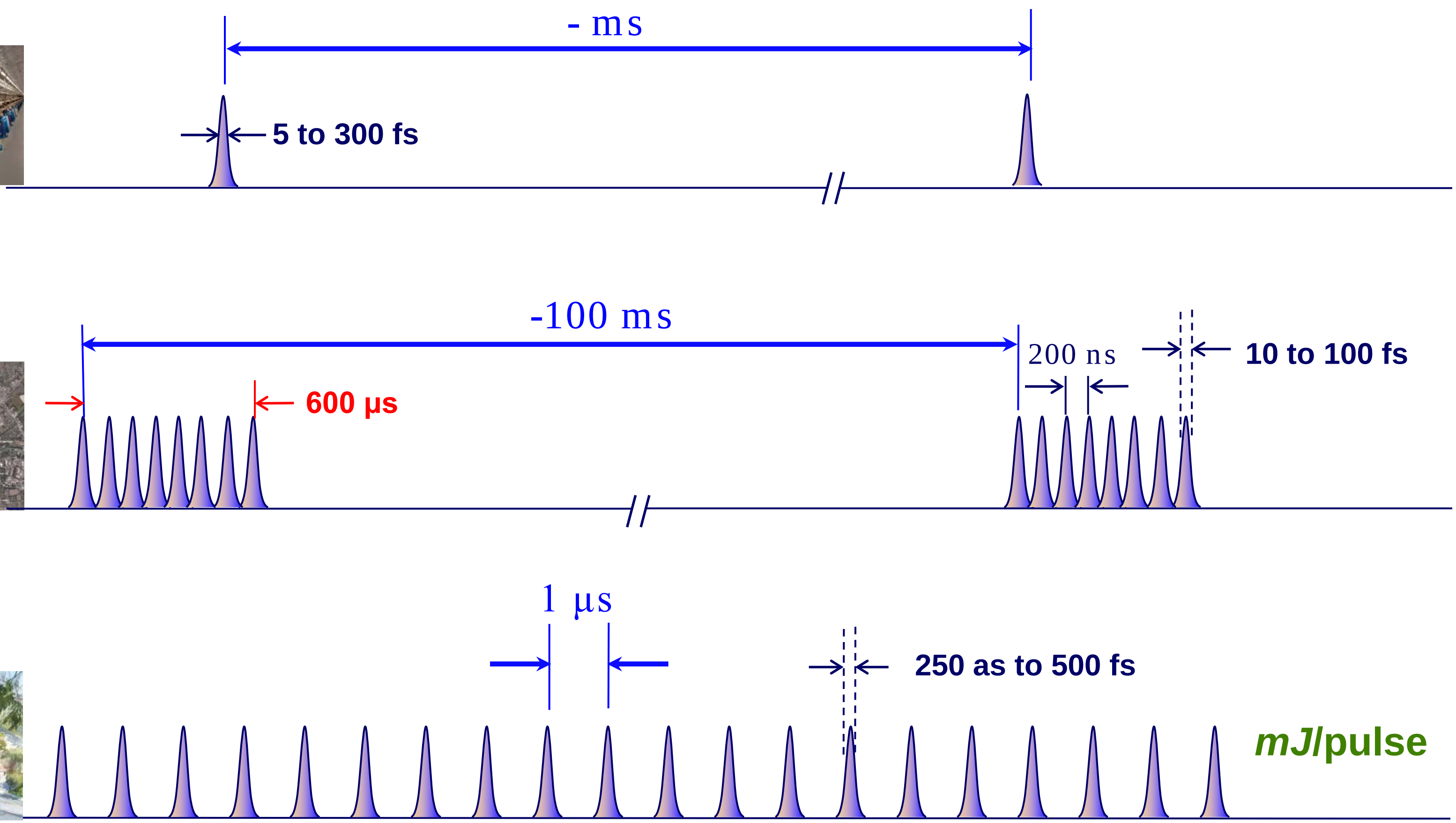


LCLS-II

XFEL

NGLS





>100x average power

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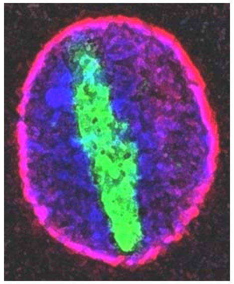
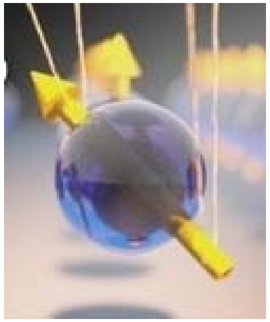
NGLS will have a broad science impact

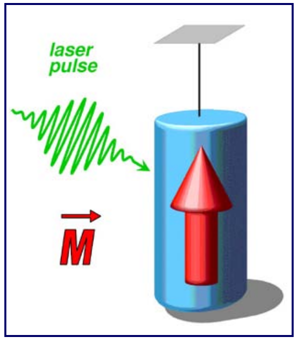
topological insulators



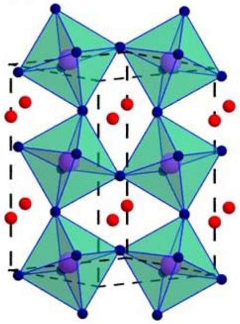
cellular imaging



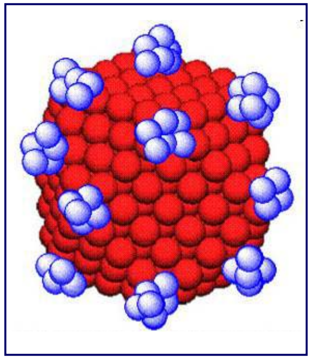
spin dynamics



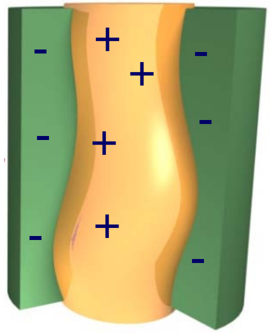
magnetization dynamics



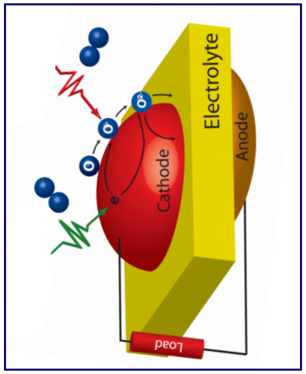
complex materials



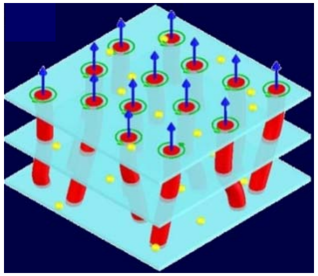
nano-synthesis and catalysis



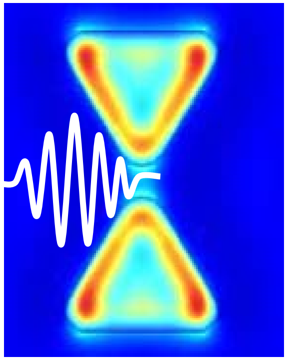
PV charge migration



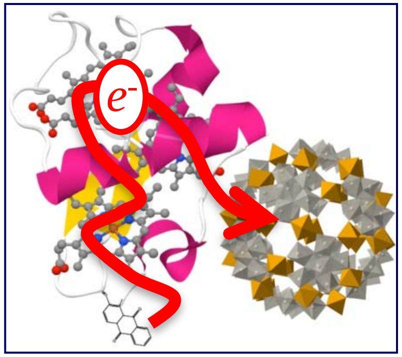
fuel cells



HTSC flux pinning



attosecond plasmonics



bio-geo electrochemistry

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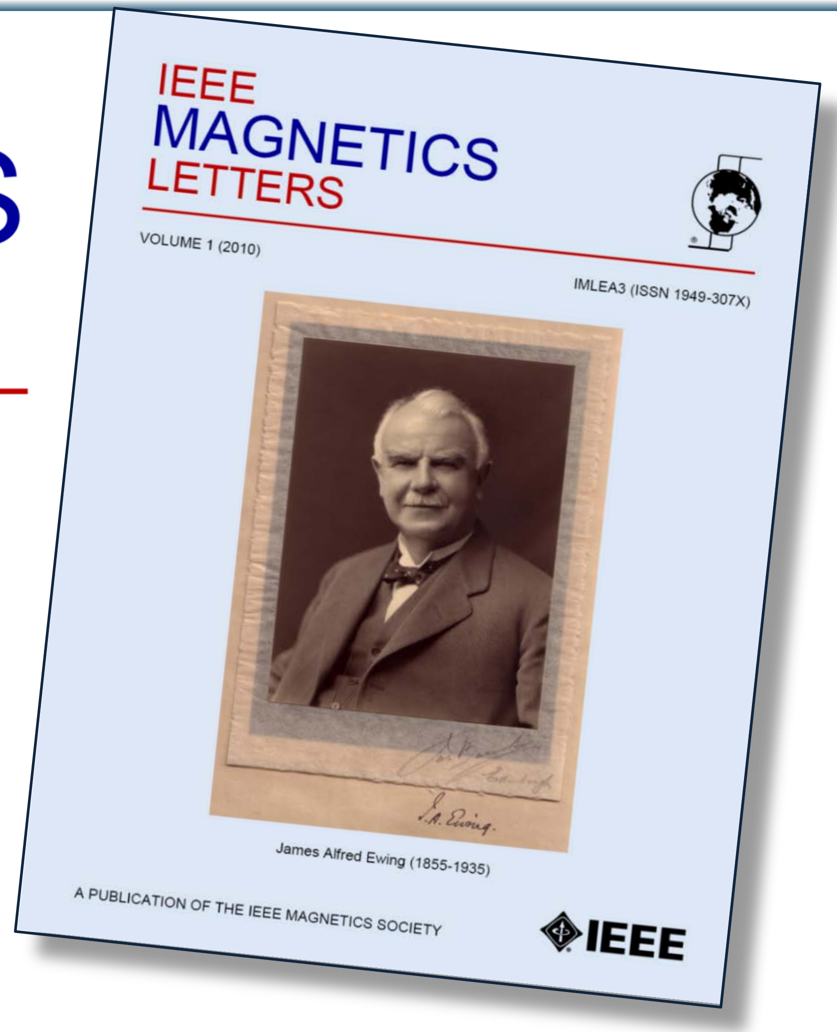

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