X-ray Magnetic Circular and Linear Dichroism (XMCD, XMLD)

and

X-ray Magnetic Imaging (PEEM, ...)

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- X-ray (Magnetic) Circular and Linear Dichroism in Absorption
- Sum rules: determination of orbital and spin moments
- XMCD and XMLD for element-selective magnetic imaging

Dichroism as contrast mechanism for magnetic imaging

- X-ray Photoemission Electron Microscopy (X-PEEM)

  Secondary electrons

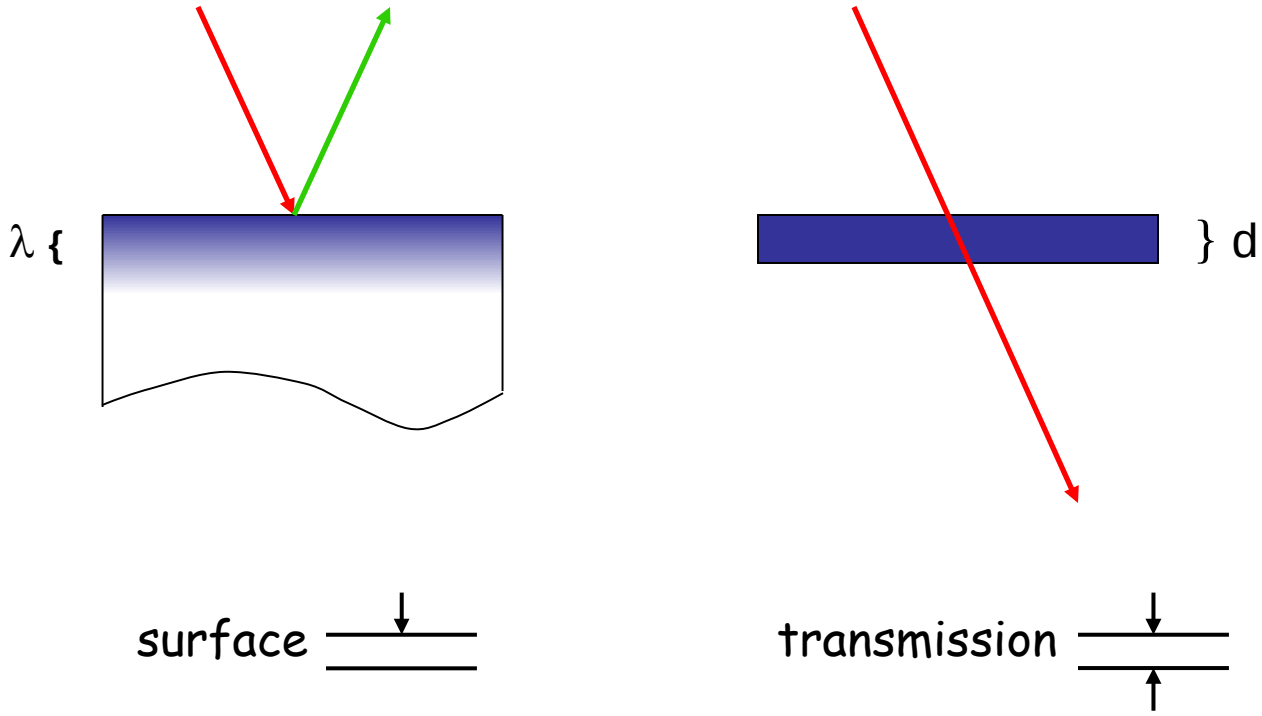
- Transmission X-ray Microscopy

  Transmitted x-ray photons

- Scanning x-ray microscope

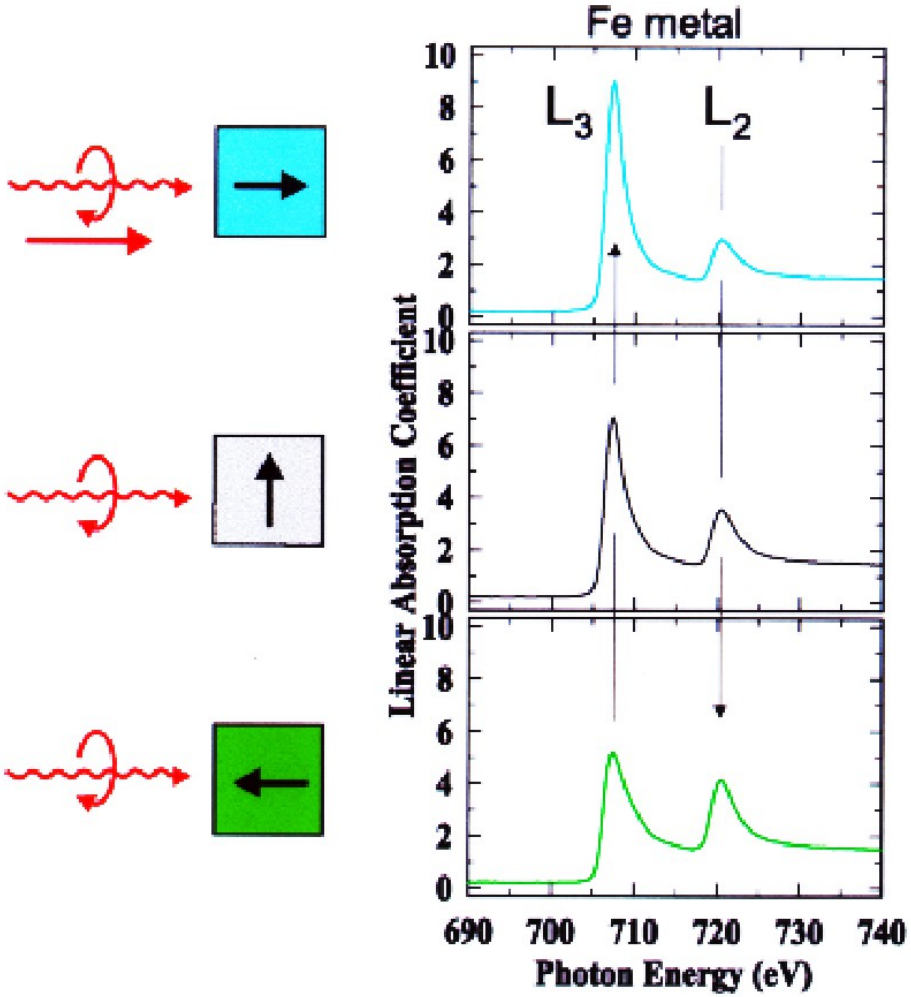
  Fluorescence, photoemission, secondary electrons, ...

Probing depth depends on detection technique

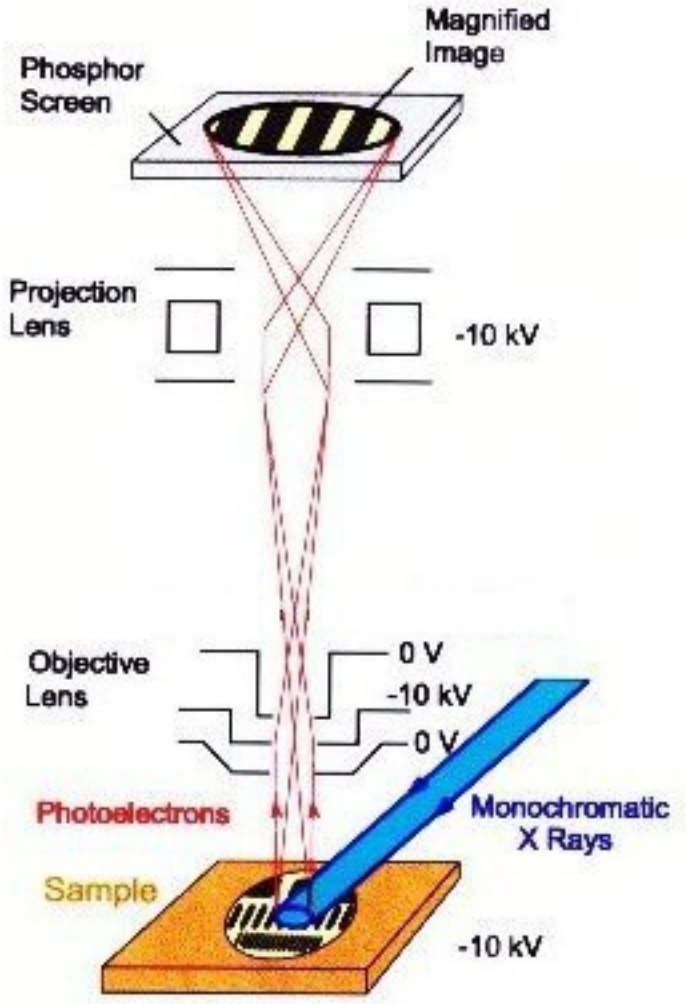


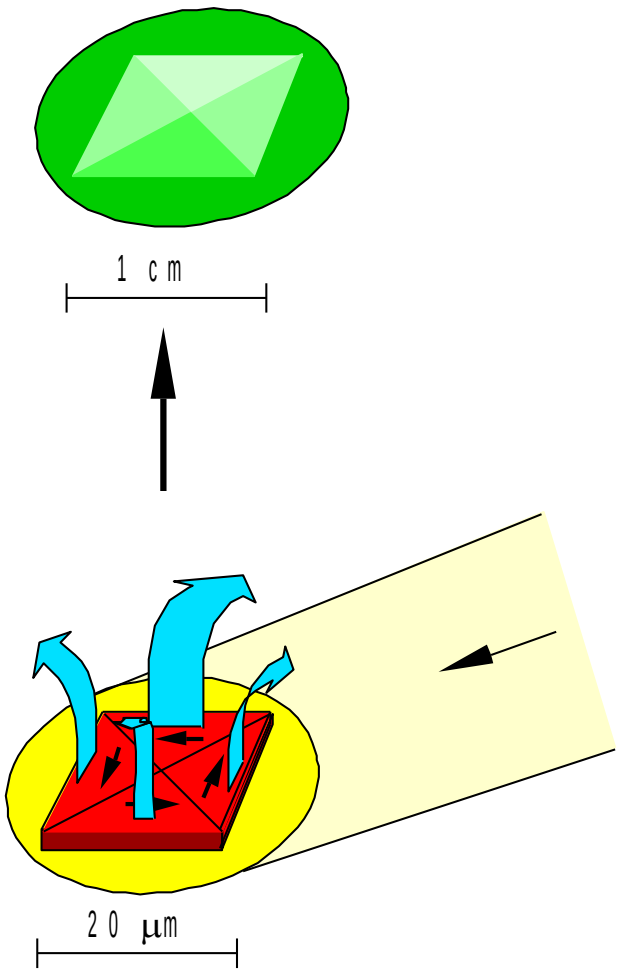
Courtesy W. Kuch

XMCD for magnetic contrast



X-ray Photoemission Electron Microscopy (X-PEEM)





J. Stöhr et al.: Surf. Rev. Lett. **5** (1998) 1297

X-PEEM : spatial resolution

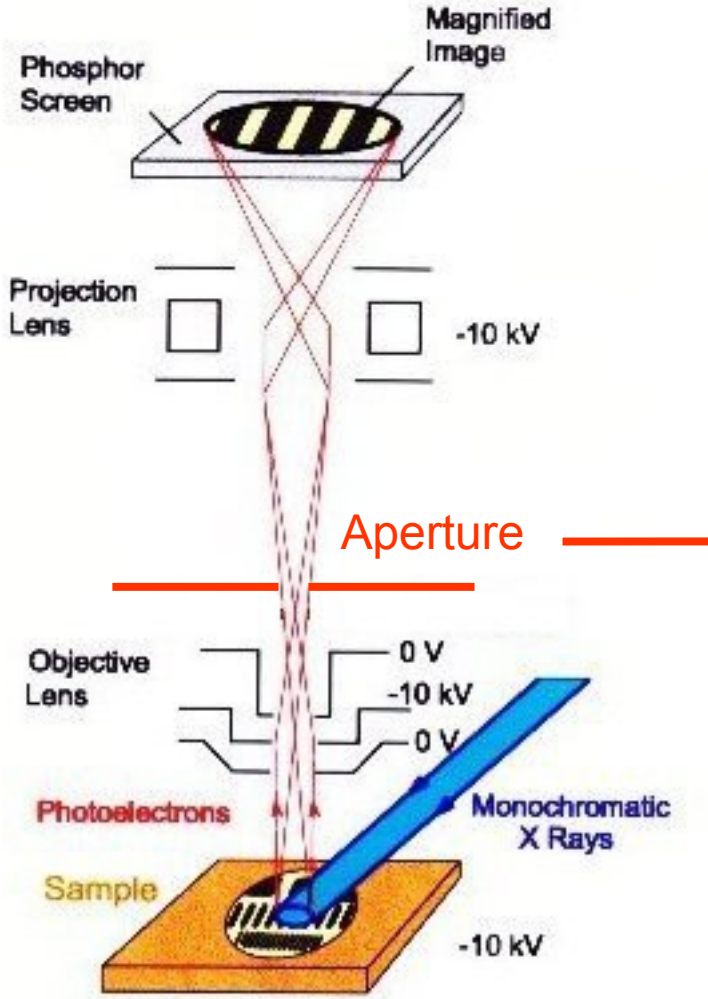
- **Chromatic aberrations**

  Secondary electrons with large energy spreadth

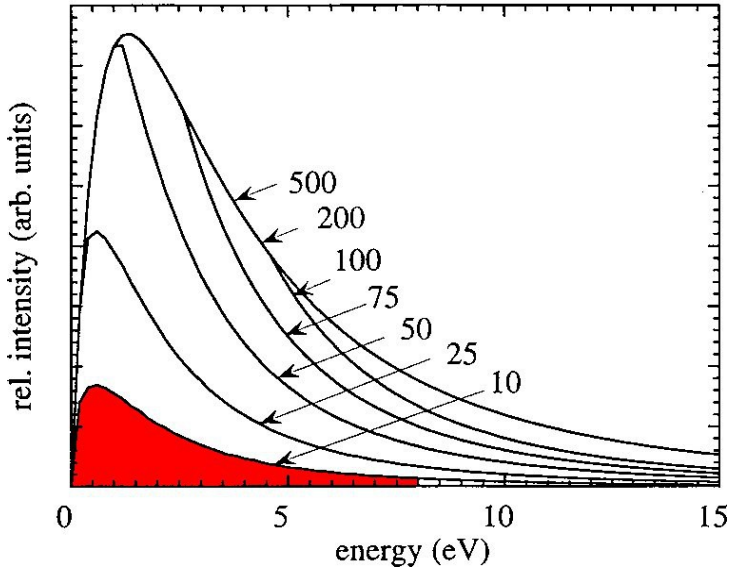
- **Spherical aberrations**

  Non-perfect lenses

X-ray Photoemission Electron Microscopy (X-PEEM)



J. Stöhr et al.: Surf. Rev. Lett. **5** (1998) 1297



S. Anders et al.: Rev. Sci. Instrum. **70** (1999) 3973

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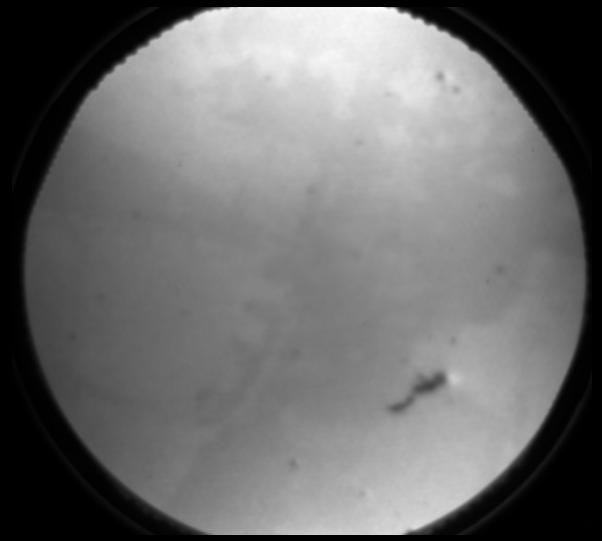
X-ray magnetic circular dichroism (XMCD)

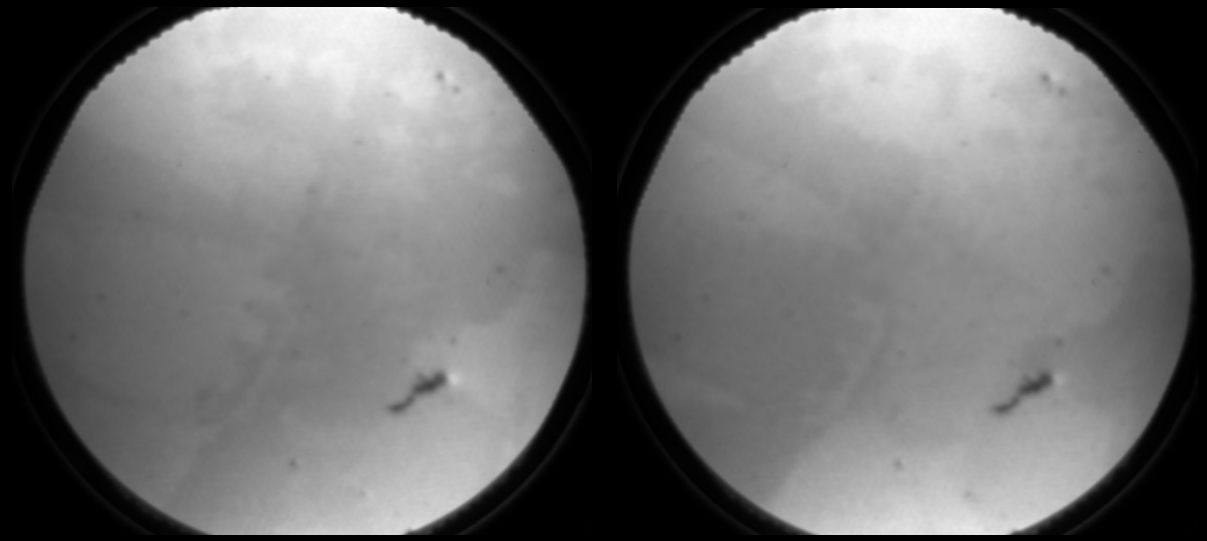
Magnetic contrast : Co/MgO/Fe/MgO(001),
Co L_3 -edge



Left circularly polarized

X-ray magnetic circular dichroism (XMCD)

Magnetic contrast : Co/MgO/Fe/MgO(001),
Co L_3 -edge

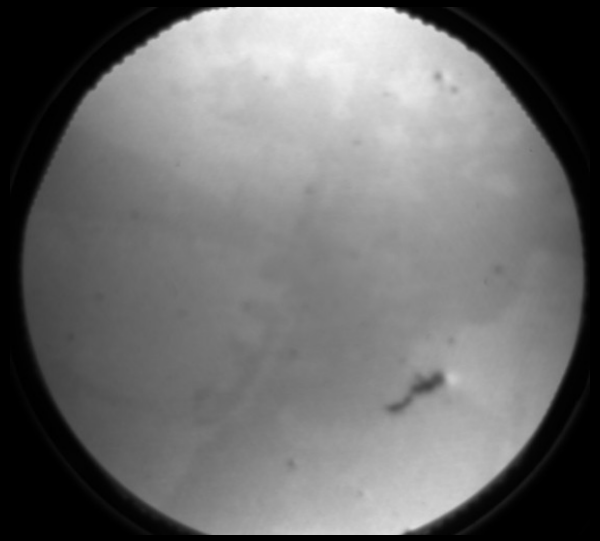


Left circularly polarized

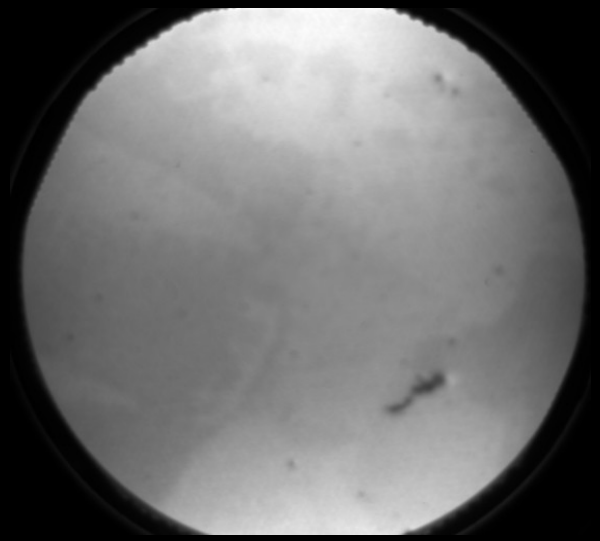
Right circularly polarized

X-ray magnetic circular dichroism (XMCD)

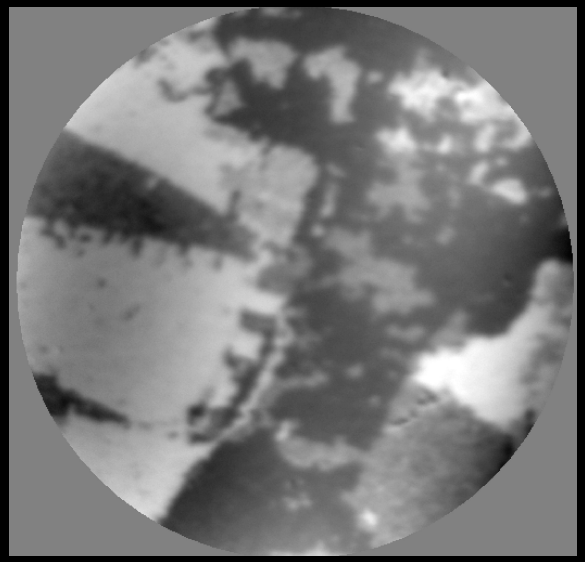
Magnetic contrast : Co/MgO/Fe/MgO(001),
Co L_3 -edge



Left circularly polarized



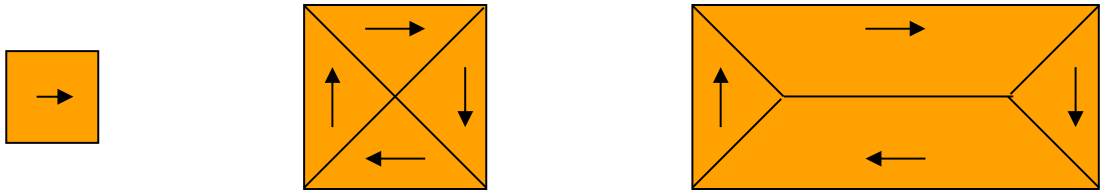
Right circularly polarized

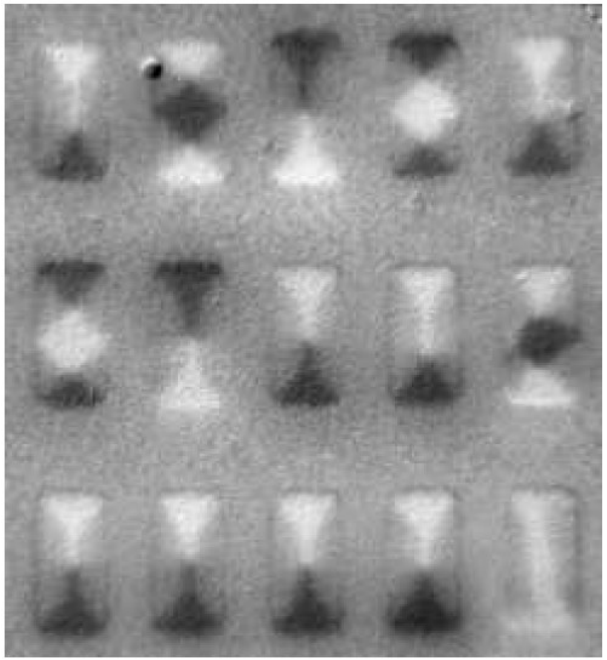


(L – R)/(L + R)

Domain structures in Co rectangles

single domain vs. Landau or Kittel pattern

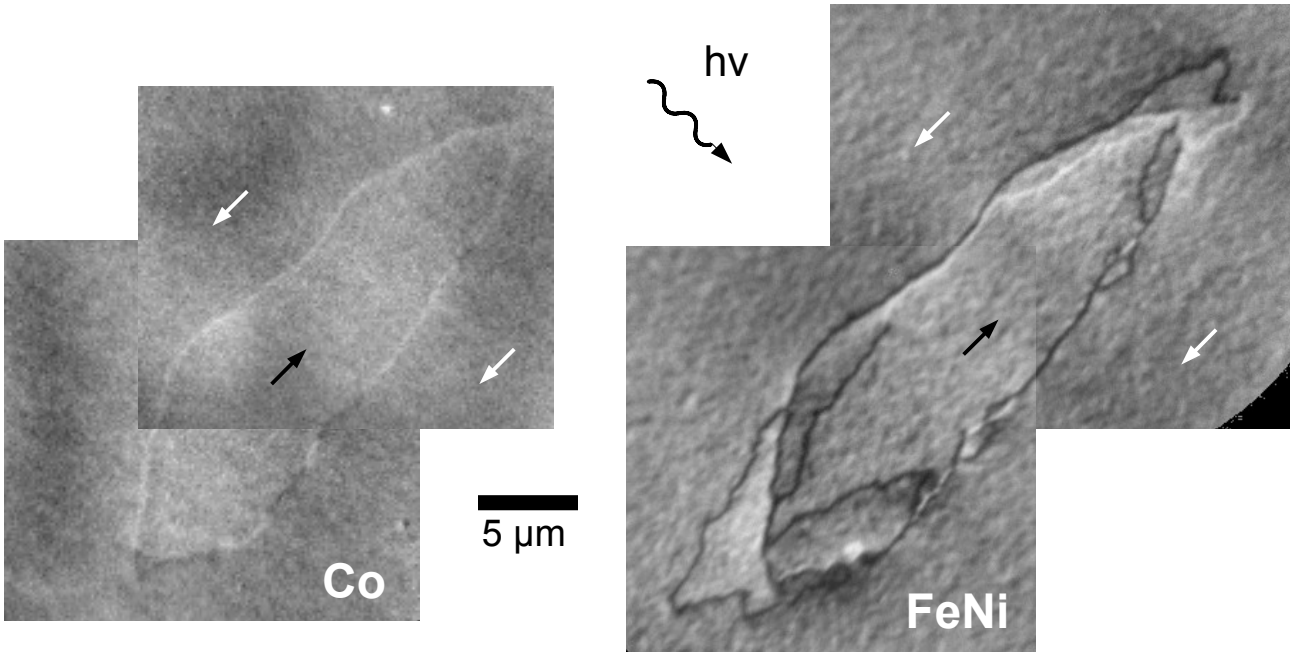




Lithographied Co (20nm)/SiO_2, 0.6 x 1.2 µm, as deposited

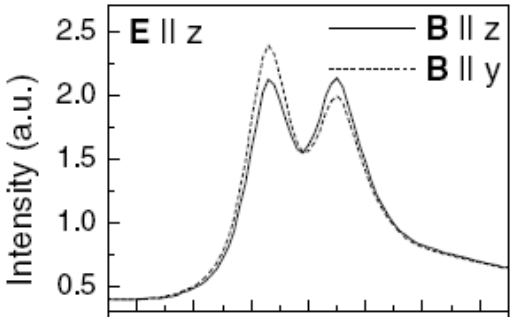
Courtesy S. Cherifi

Domain wall interactions in $FeNi/Al_2O_3/Co$ trilayers



J. Vogel, S. Cherifi, F. Romanens, S. Pizzini, J. Camarero,
F. Petroff, S. Heun, A. Locatelli, J. Phys. Condensed Matt. 2007

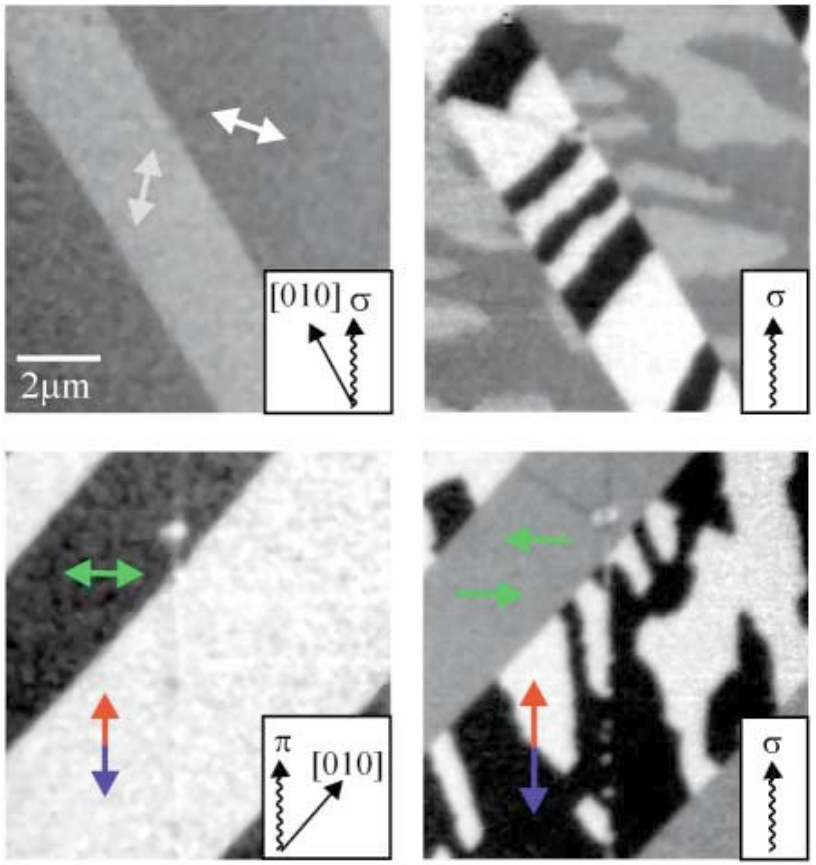
X-PEEM for anti-ferromagnetic domain imaging



Ni L_2-edge

Ni XMLD

Co XMCD



8 ML Co/NiO(001)

H. Ohldag et al., PRL 86 (2001) 2878

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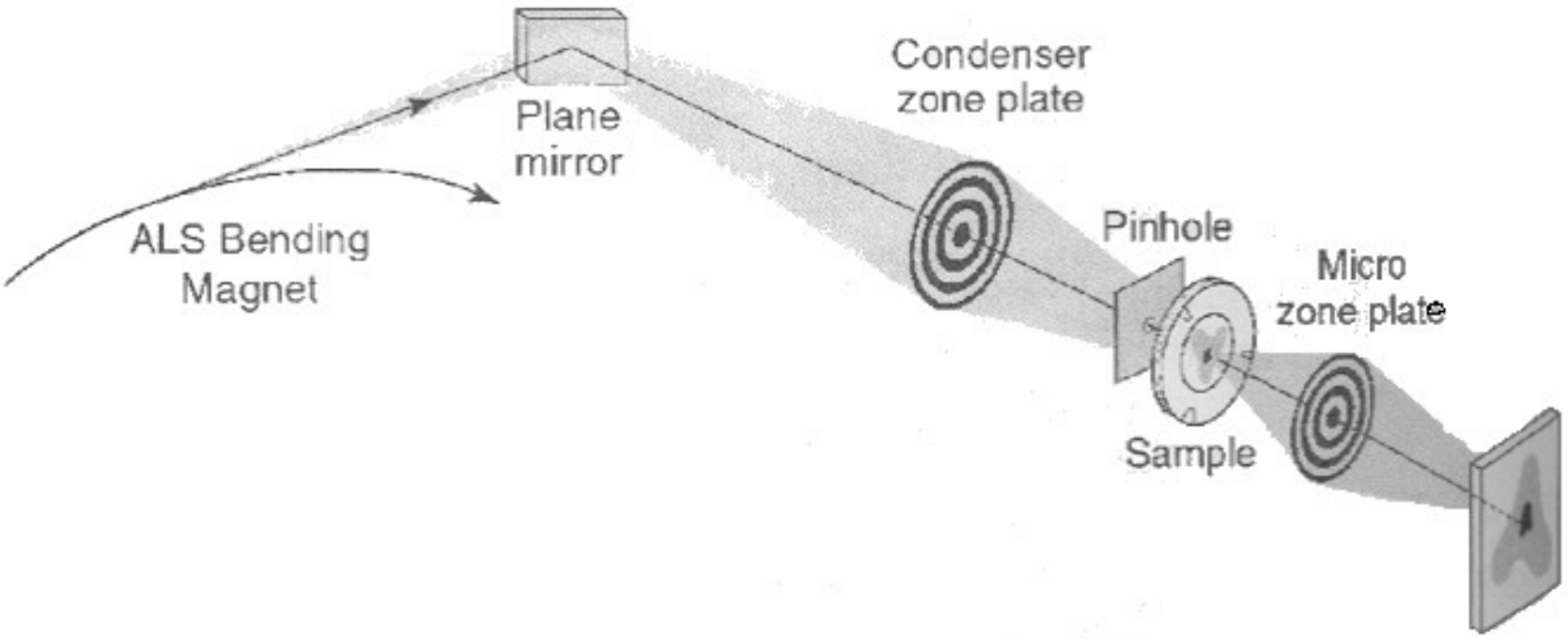
X-PEEM summary

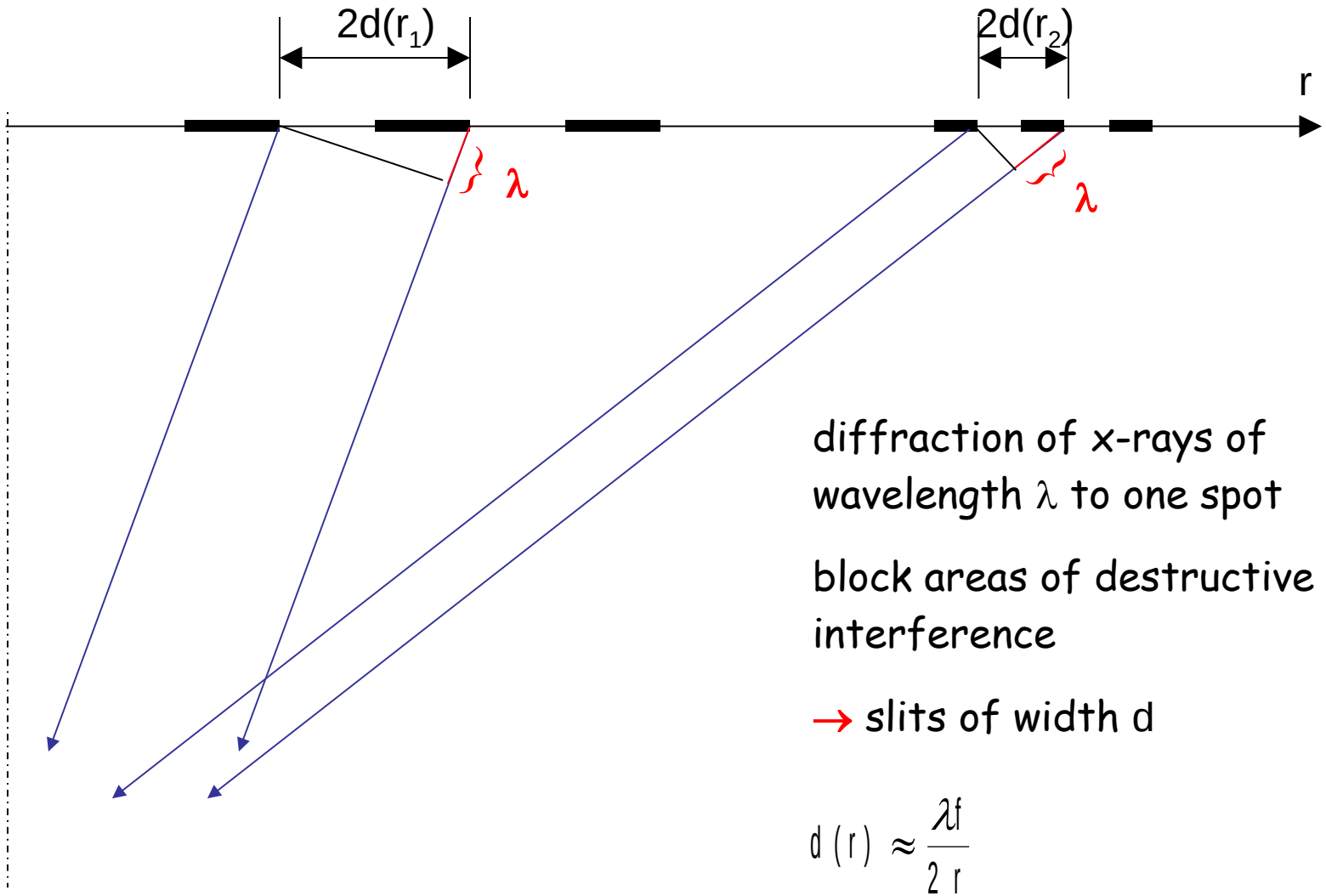
- element specific, can be used for layer-specificity
- good resolution
- parallel imaging
- moderately surface sensitive (≈ 2...10 nm)
- sensitive to external magnetic fields
- in vacuum
- vectorial information by rotating sample
- quantitative spectroscopic information available ("sum-rule microscopy")

Transmission x-ray microscopy (TXM)



G. Denbeaux et al., IEEE Trans. Mag. 37 (2001) 2764

Zone plates as x-ray lenses



diffraction of x-rays of wavelength λ to one spot

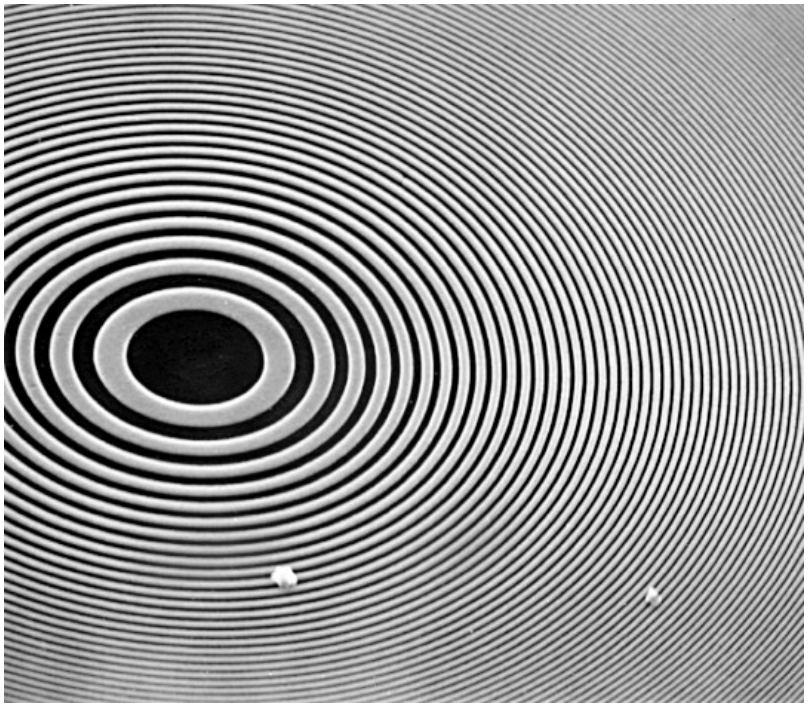
block areas of destructive interference

→ slits of width d

$$d(r) \approx \frac{\lambda f}{2r}$$

Courtesy W. Kuch

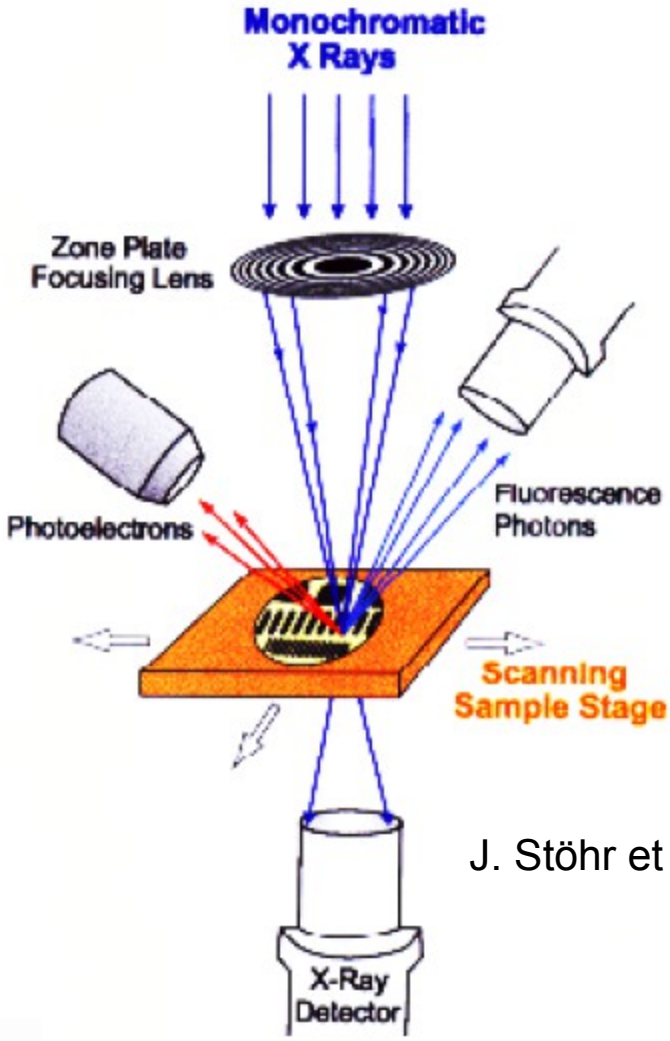
Zone plates as x-ray lenses



inner part of a zone plate lens.
diameter: 45 μm,
outermost zone: 35 nm wide.

from: homepage of Center for X-ray Optics,
Lawrence Berkeley National Laboratory

Scanning X-ray Microscopy



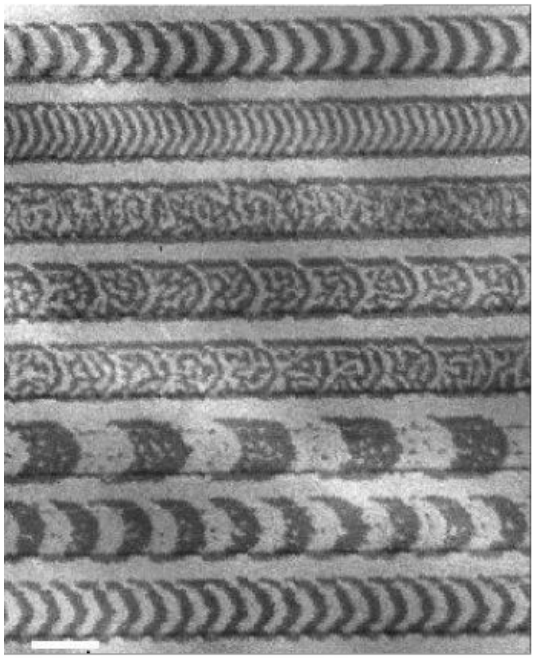
- Spatial resolution: spot size
- Detection:
  - Secondary electrons
  - Photoemission
  - Fluorescence
  - Transmission

J. Stöhr et al.: Surf. Rev. Lett. **5** (1998) 1297

Magnetic imaging with TXM

magneto-optical storage media

50 nm $Tb_{25}Fe_{56}Co_{19}$



P. Fischer et al., Rev. Sci. Instrum. 72 (2001) 2322

X-ray magnetic imaging : summary

All:

- element (layer) specific
- high resolution (20 nm), < 10nm in near future
- parallel imaging → magnetization dynamics

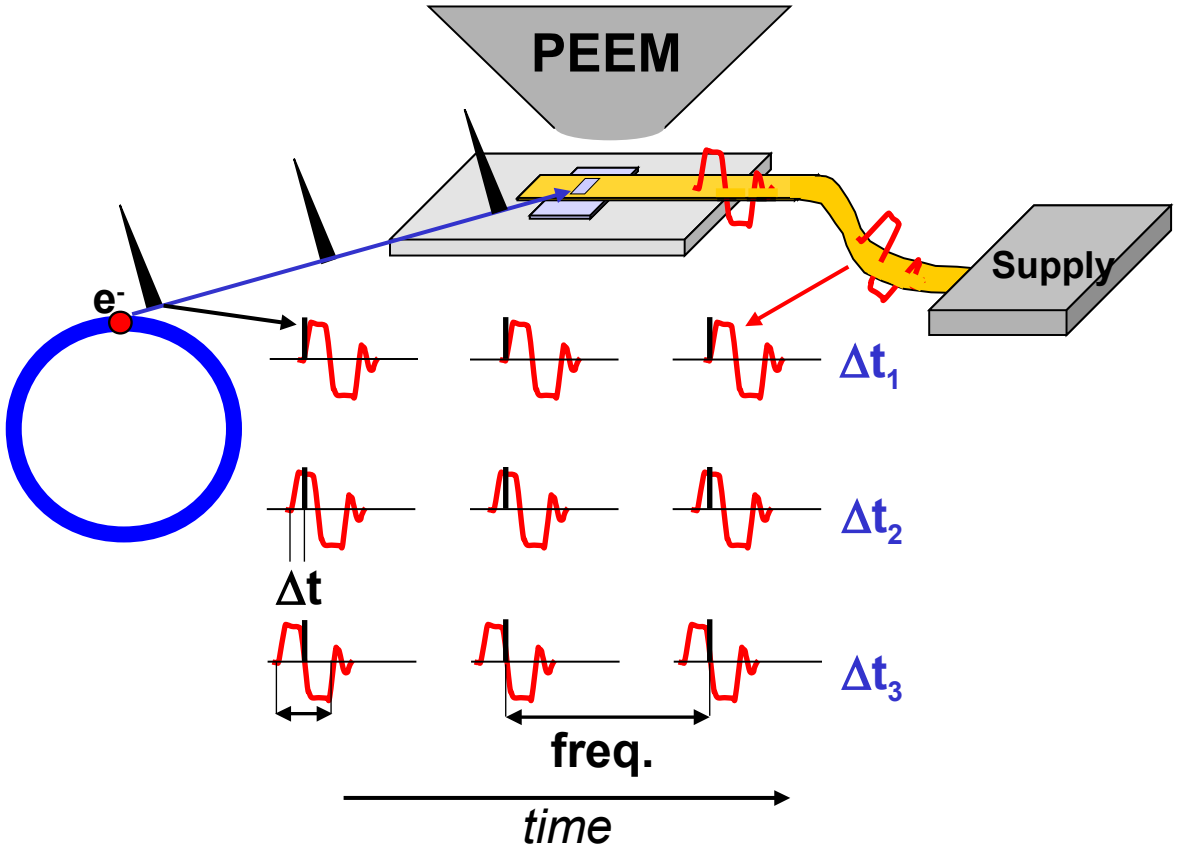
XPEEM:

- vectorial information (in-plane, out-of-plane)
- Thick substrates no problem
- sensitive to magnetic fields

TXM

- only in transmission
- special sample preparation
- Insensitive to magnetic fields

Time and layer resolved magnetic microscopy

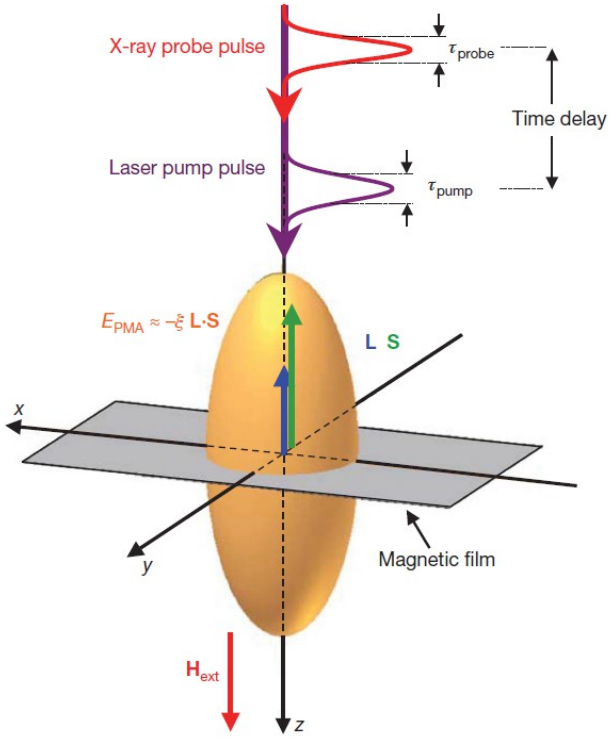


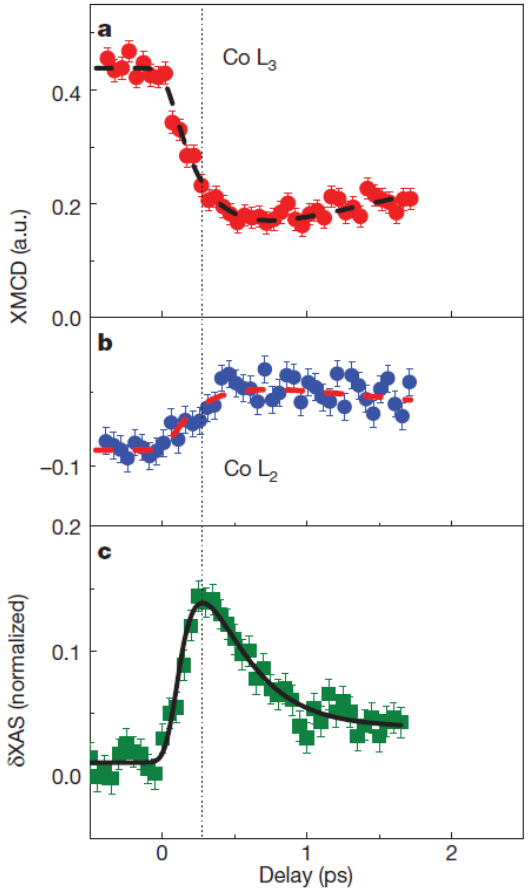
Pump-probe (stroboscopic) measurements

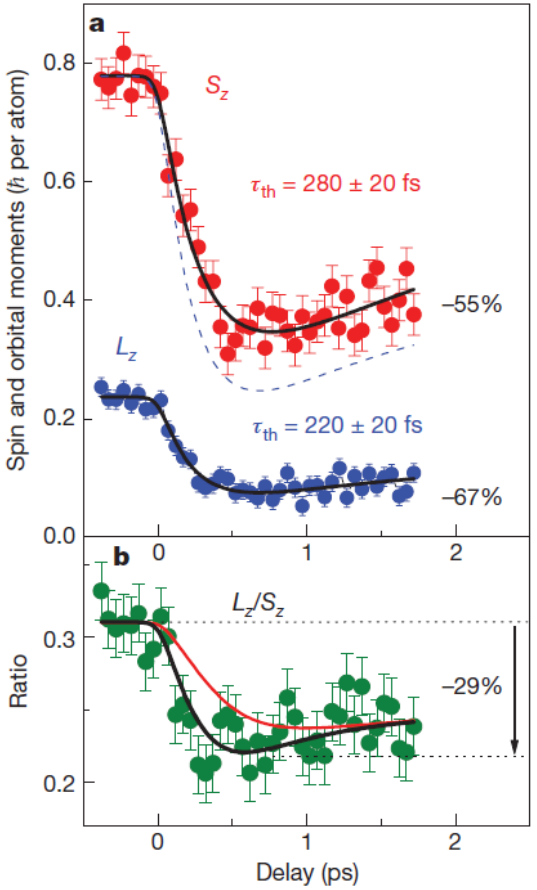
- M. Bonfim et al., Phys. Rev. Lett. 86, 3646 (2001)
- J. Vogel et al., Appl.Phys.Lett. 83, 2299 (2003)

Distinguishing the ultrafast dynamics of spin and orbital moments in solids

C. Boeglin[1], E. Beaurepaire[1], V. Halté[1], V. López-Flores[1], C. Stamm[2], N. Pontius[2], H. A. Dürr[2]† & J.-Y. Bigot[1]



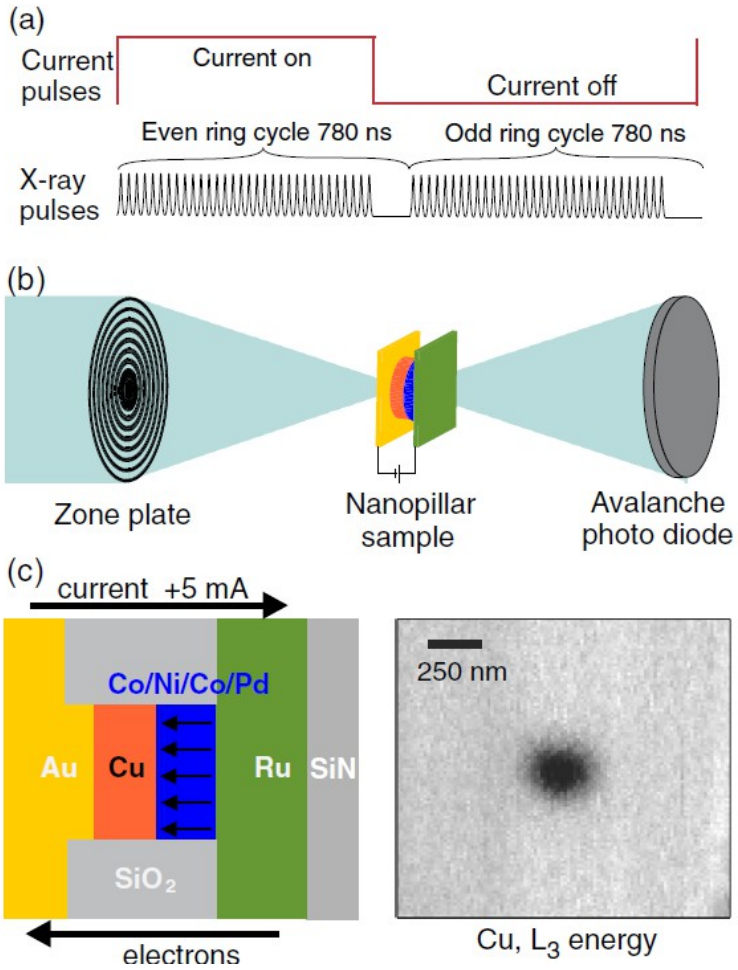


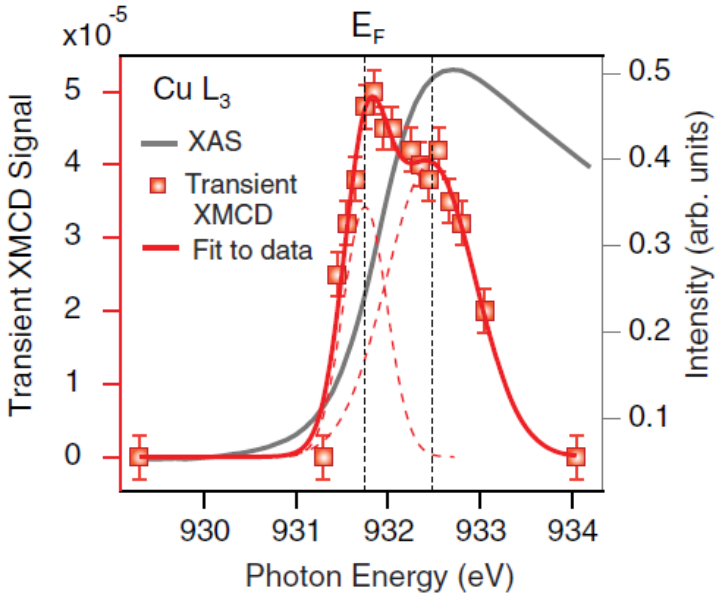


PRL 115, 096601 (2015) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

X-ray Detection of Transient Magnetic Moments Induced by a Spin Current in Cu

R. Kukreja,[1,2,*] S. Bonetti,[1,3] Z. Chen,[1,3] D. Backes,[4] Y. Acremann,[5] J. A. Katine,[6] A. D. Kent,[4] H. A. Dürr,[1] H. Ohldag,[7] and J. Stöhr[1,†]





Transient moments :

$m_{Cu} = 3 \times 10^{-5}\ \mu_B$ (bulk)

$m_{Cu} = 4 \times 10^{-3}\ \mu_B$ (interface)

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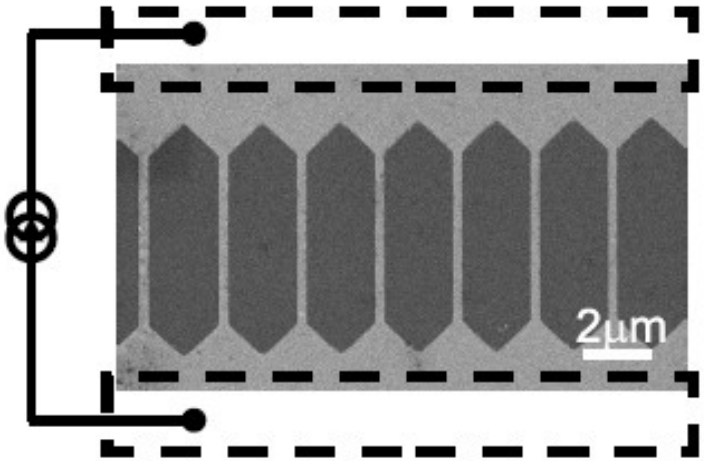
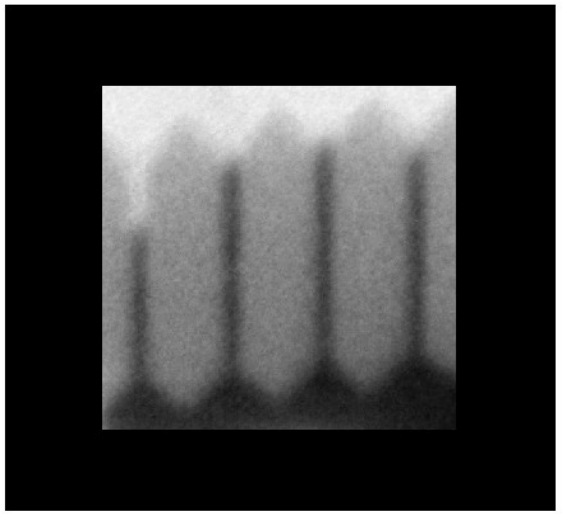
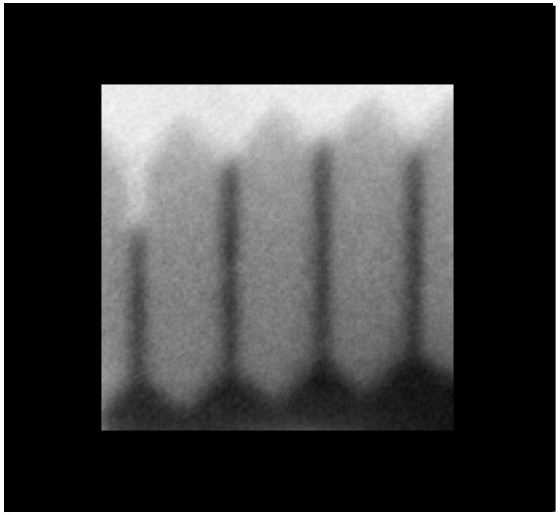
Current-induced domain wall motion in Pt/Co/AlOx

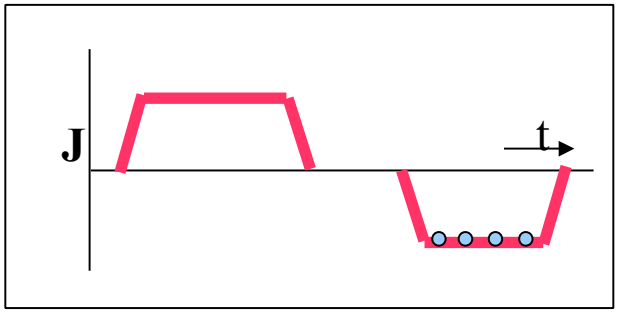




J. Vogel, M. Bonfim, N. Rougemaille, O. Boulle, I.M. Miron, S. Auffret, B. Rodmacq, G. Gaudin, J.C. Cezar, F. Sirotti, and S. Pizzini, Phys. Rev. Lett. 108, 247202 (2012)

Current-induced domain wall motion in Pt/Co/AlOx





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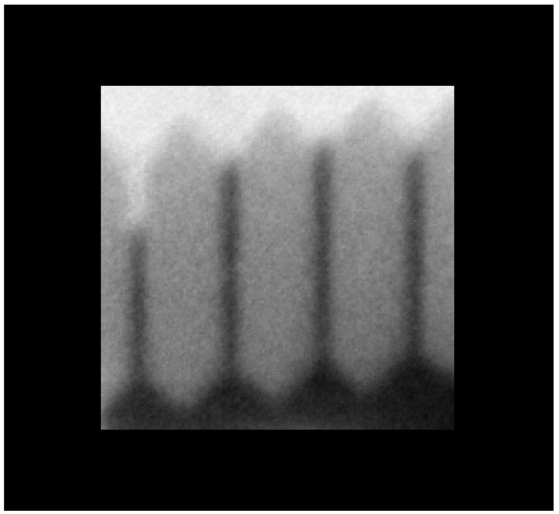

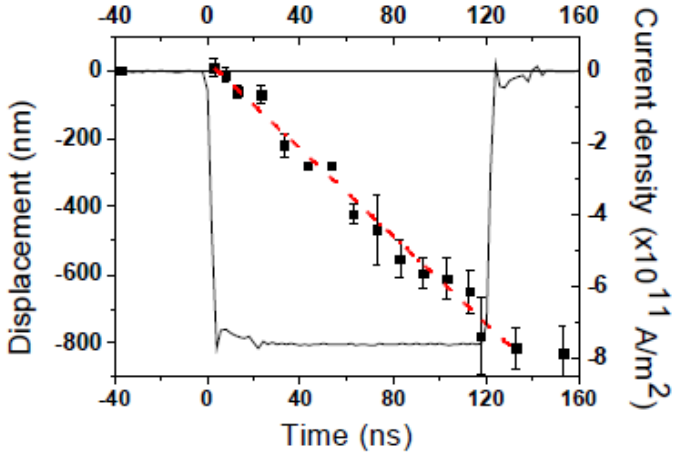

- DW speed is constant during the current pulse
- domain walls start moving as soon as the current pulse starts and stop when the pulse ends : no detectable inertia (< 2-3 ns, < 20 nm)
- DW motion reproducible over many billions of current pulses

J. Vogel, M. Bonfim, N. Rougemaille, O. Boulle, I.M. Miron, S. Auffret, B. Rodmacq, G. Gaudin, J.C. Cezar, F. Sirotti, and S. Pizzini, Phys. Rev. Lett. 108, 247202 (2012)

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Conclusions

- XMCD: element selective magnetic moments

  separation spin- and orbital components

- XMLD: also anti-ferromagnetic order

- XMCD for element selective magnetic contrast

  - Hysteresis loops

  - Magnetization dynamics (using time-structure of synchrotron x-rays)

  - High resolution magnetic imaging (PEEM, TXM)