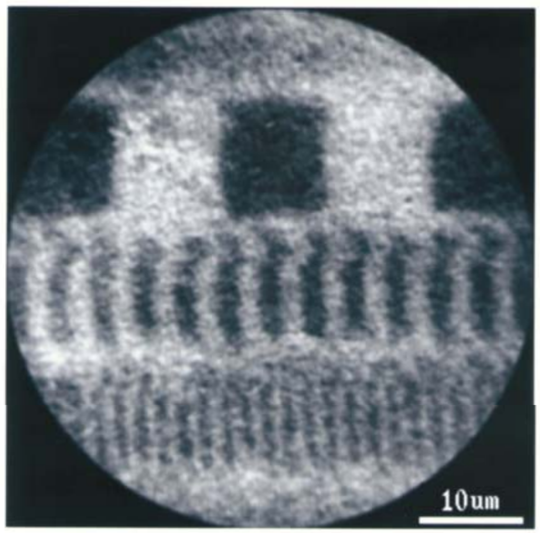
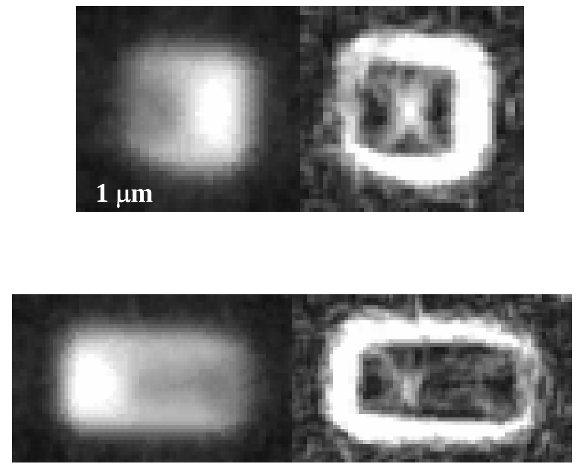
X-Ray Spectro-Microscopy

Application to Magnetic Systems

1895



1993



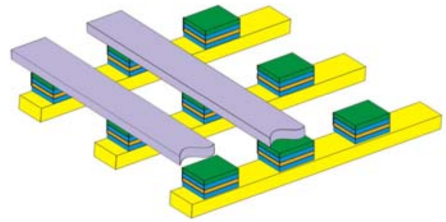
2003

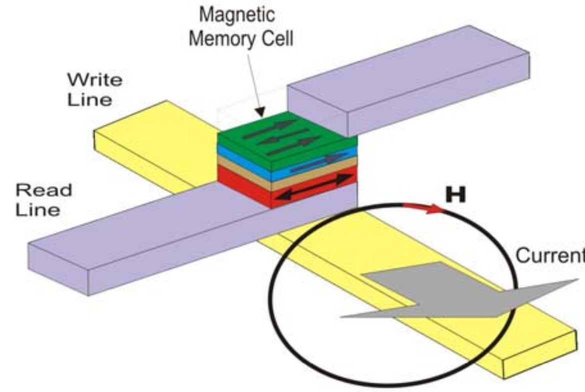
http://www-ssrl.slac.stanford.edu/stohr/index.htm

http://www-ssrl.slac.stanford.edu/stohrgroup/

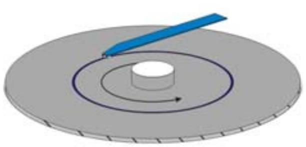
Magnetic Technologies in Computers

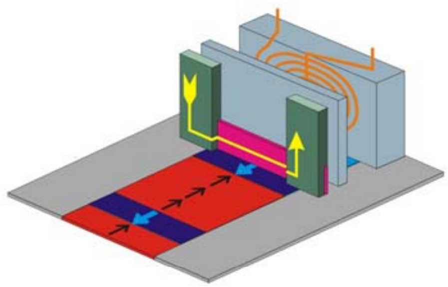
Memory



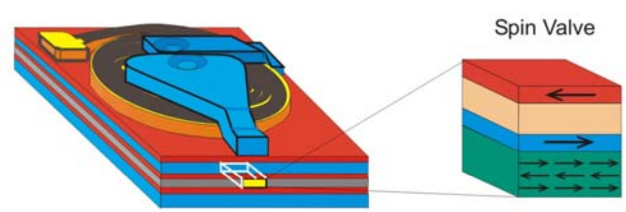


Storage





Head



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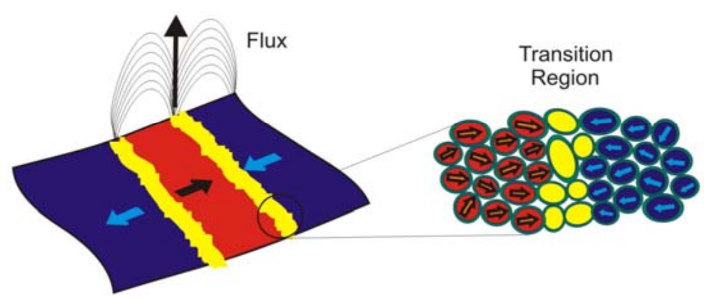
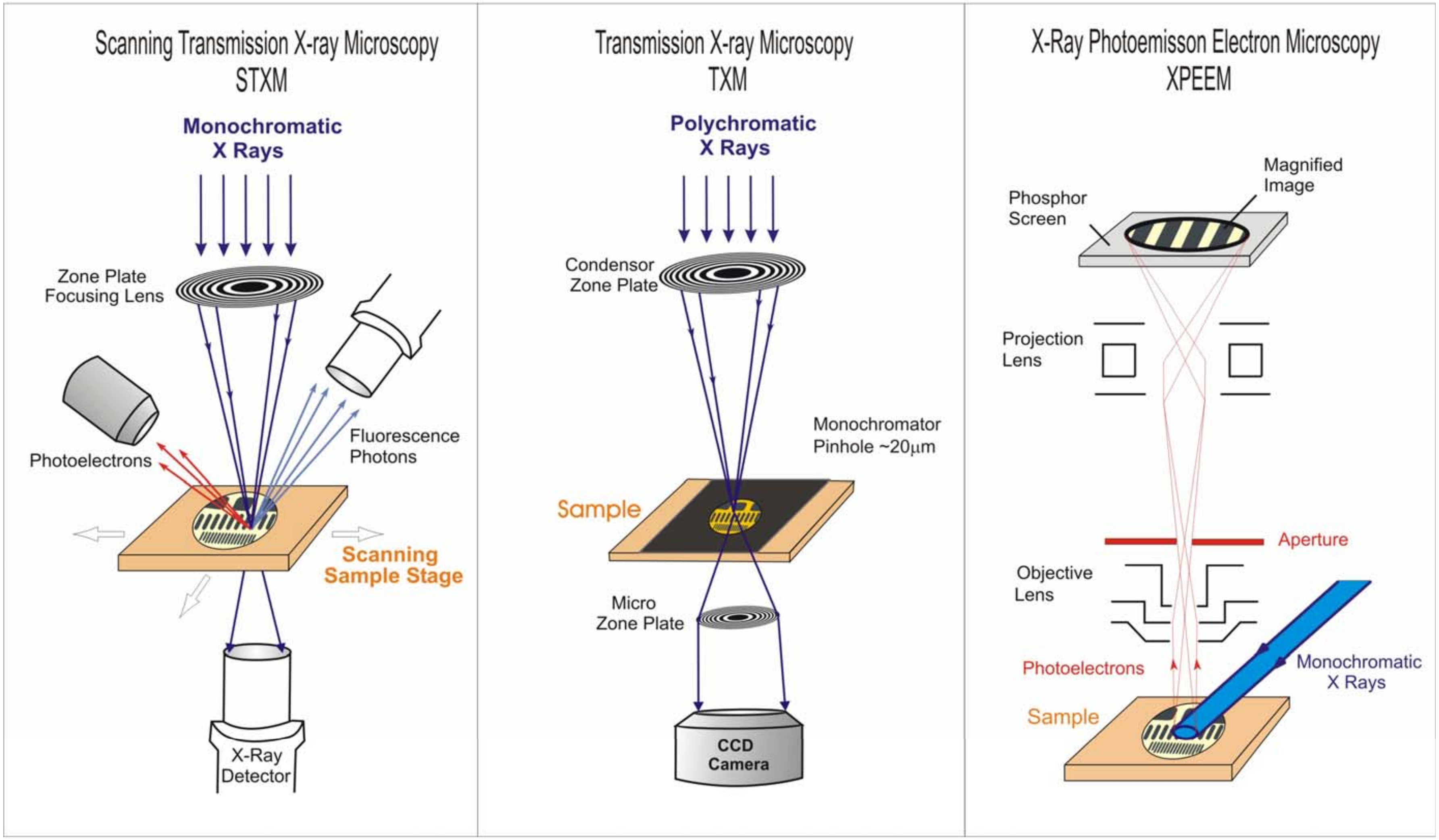


X-Ray Microscopy Methods - toward Nanometer Resolution

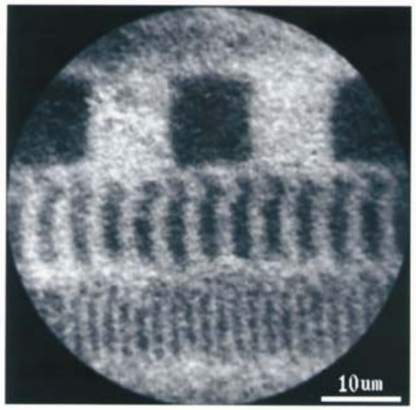


Present resolution in the 20 - 40 nm range

Polarization Dependent Imaging with X-Rays

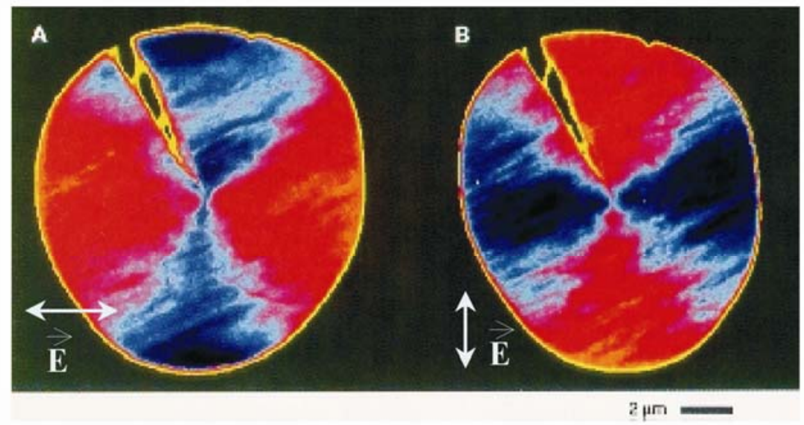
X-Ray Magnetic Circular Dichroism

Stöhr *et al*., Science **259**, 658 (1993)



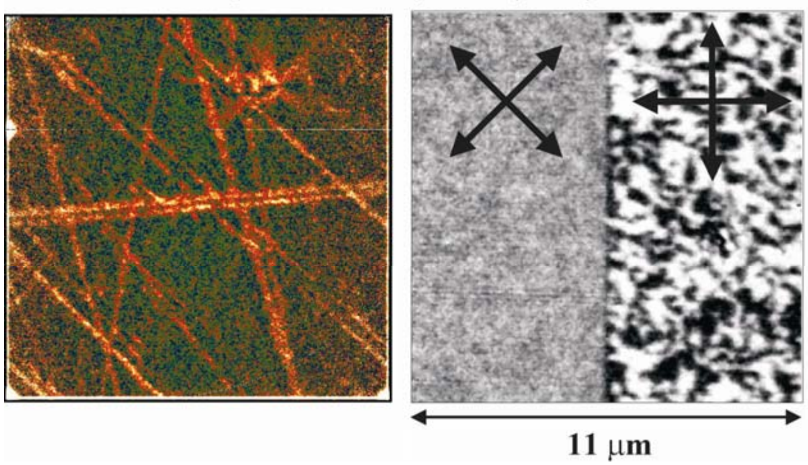
X-Ray Natural Linear Dichroism

Ade and Hsiao., Science **262**, 1427 (1993)



X-Ray Magnetic Linear Dichroism

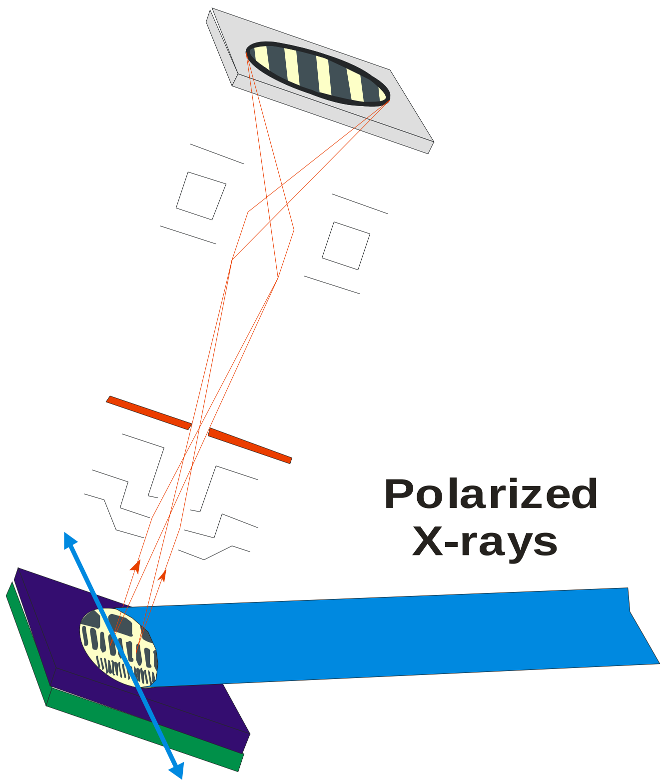
Stöhr *et al*., Phys. Rev. Lett. **83**, 1862 (1999)
Scholl *et al*., Science **287**, 1014 (2000)

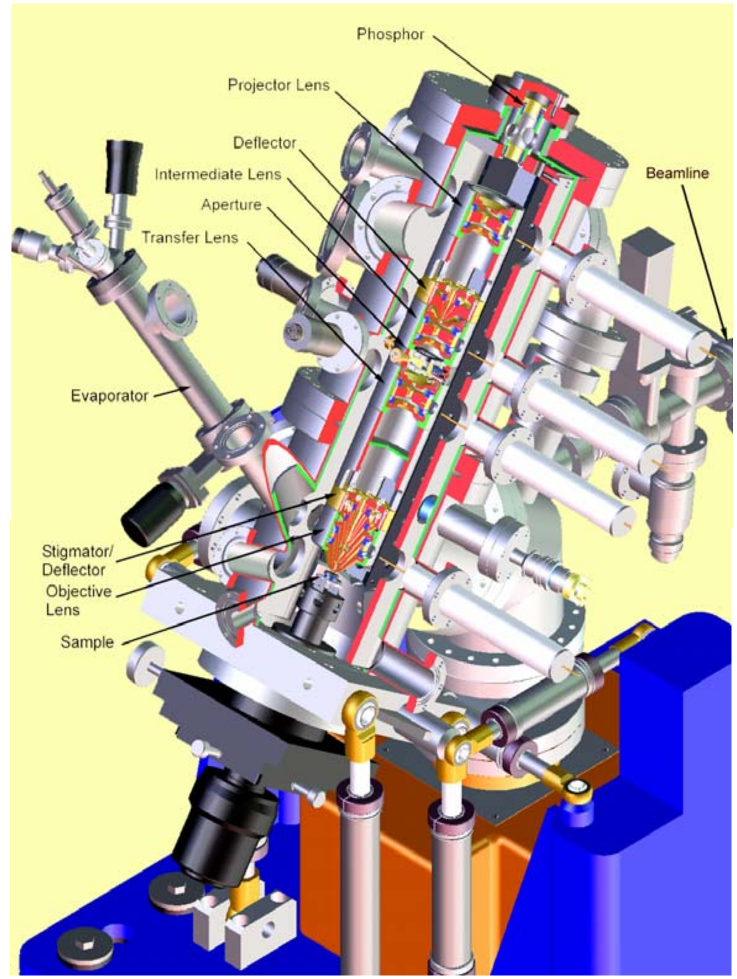


X-Ray Natural Circular Dichroism

?

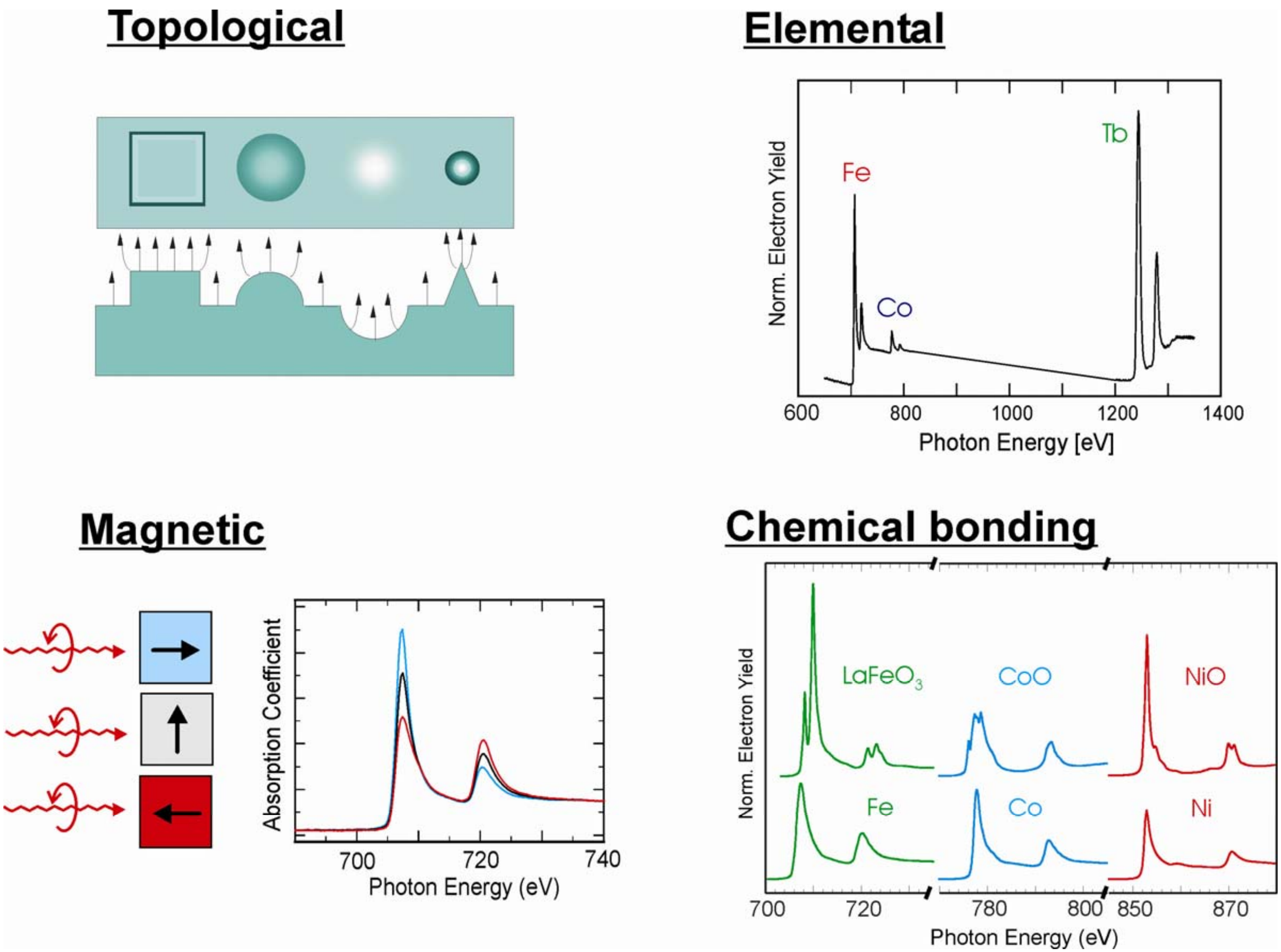
PEEM-II at ALS





- Full Field Imaging
- Electrostatic (30 kV)
- 20 - 50 nm Resolution
- Linear and circular polarization

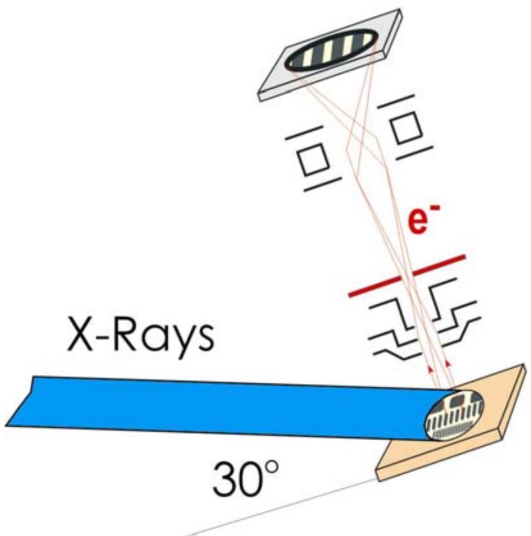
PEEM Contrast Mechanisms

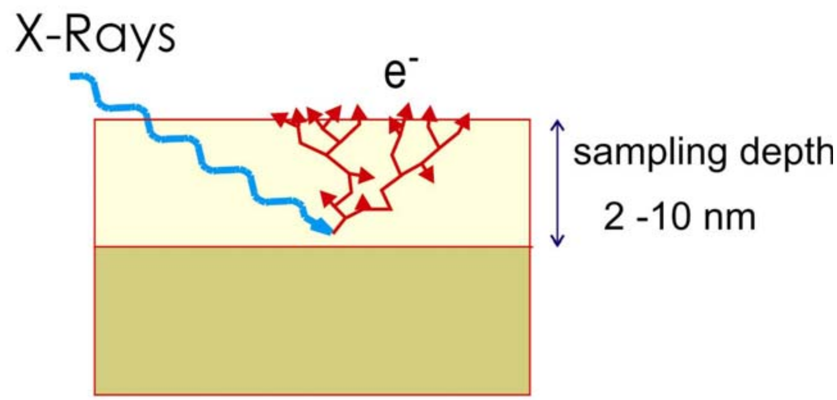


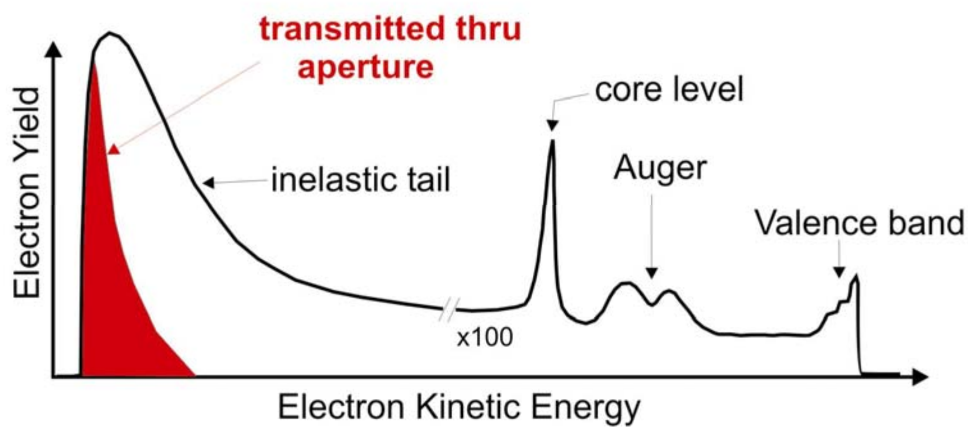
Use soft x-rays – L edges of Fe, Co, Ni

Photo Emission Electron Microscopy - PEEM

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

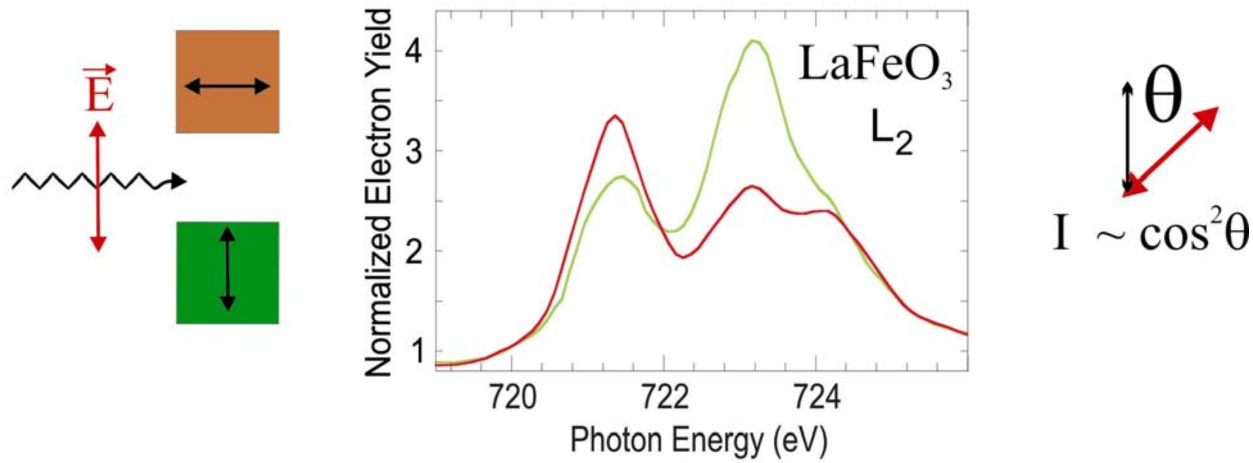




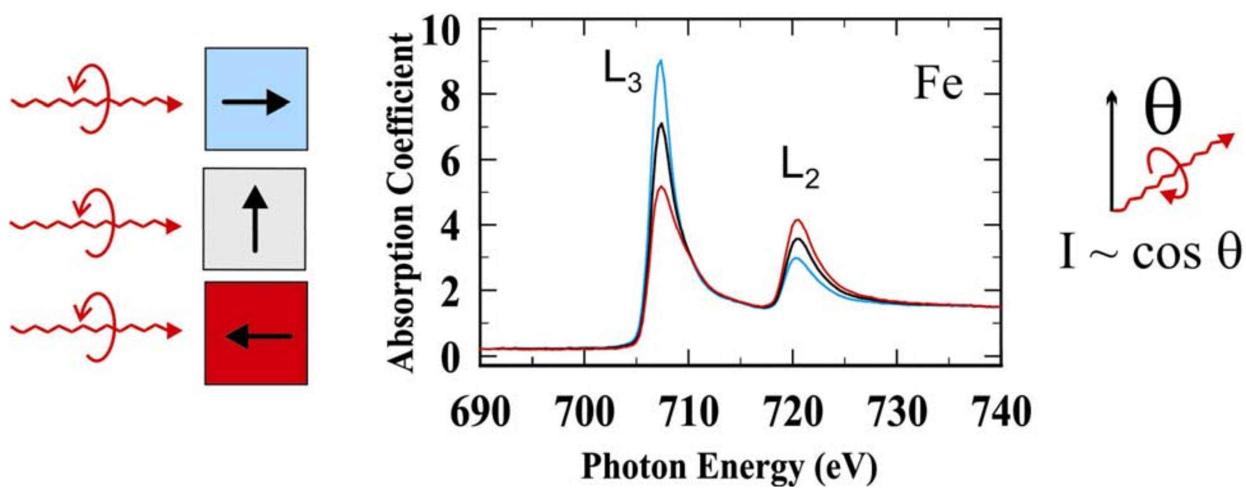


Magnetic Spectroscopy and Microscopy

X-ray Magnetic Linear Dichroism: Antiferromagnets

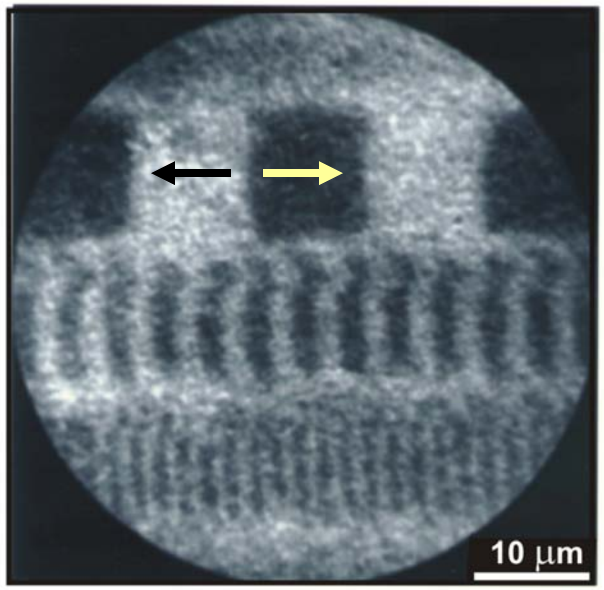


X-ray Magnetic Circular Dichroism: Ferromagnets

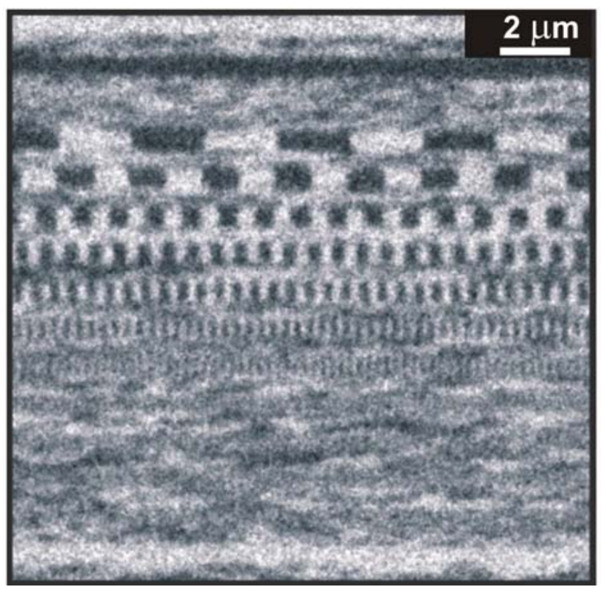


Magnetic Recording Bits imaged with PEEM

2μm



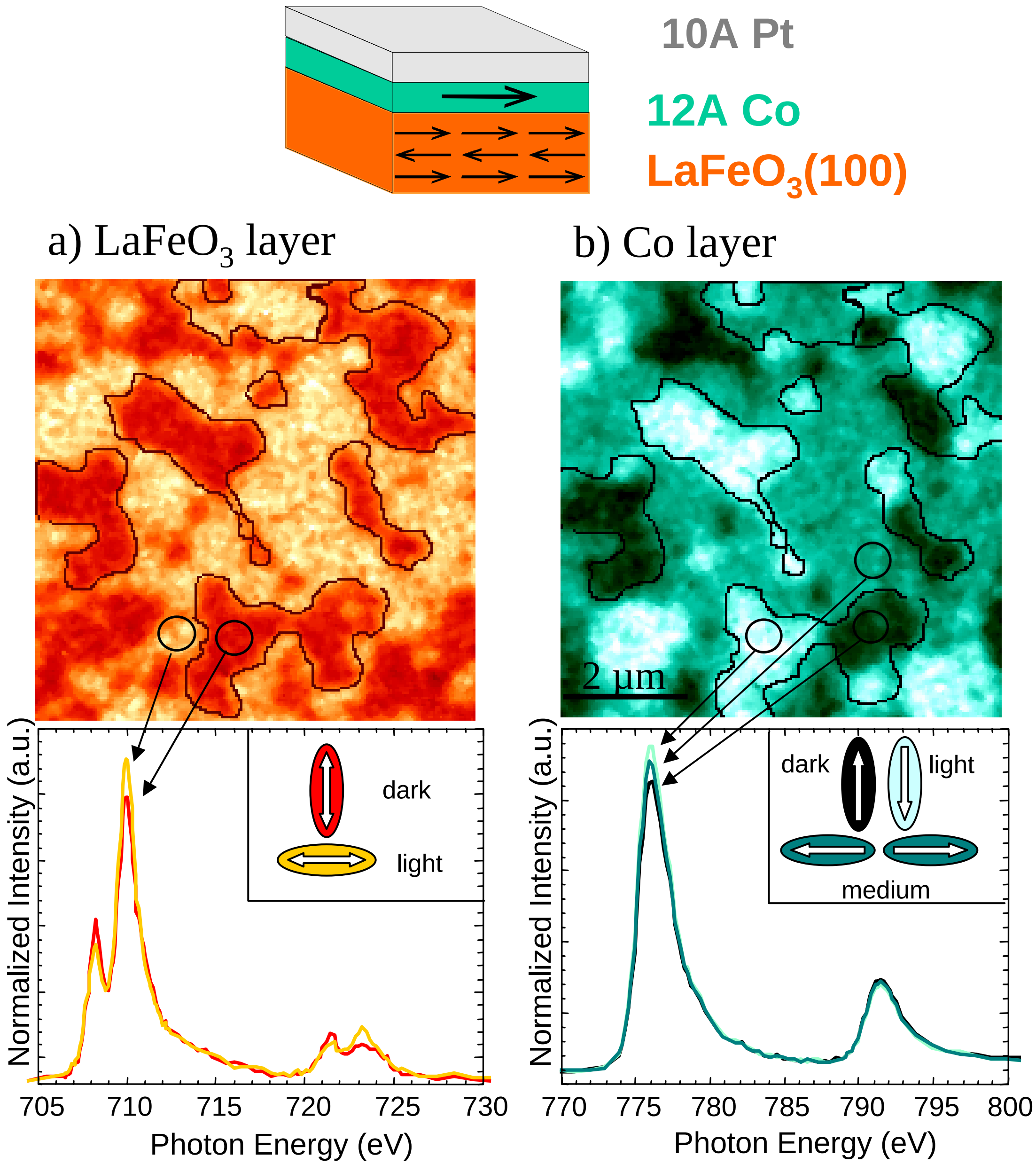
1993



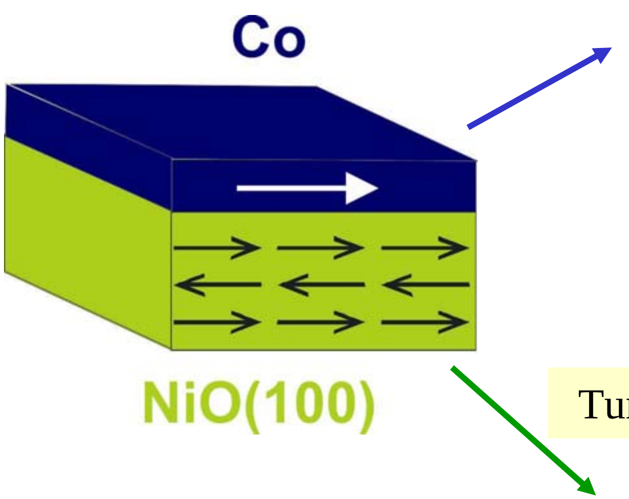
2002

Alignment of Ferromagnetic by Antiferromagnetic Domains

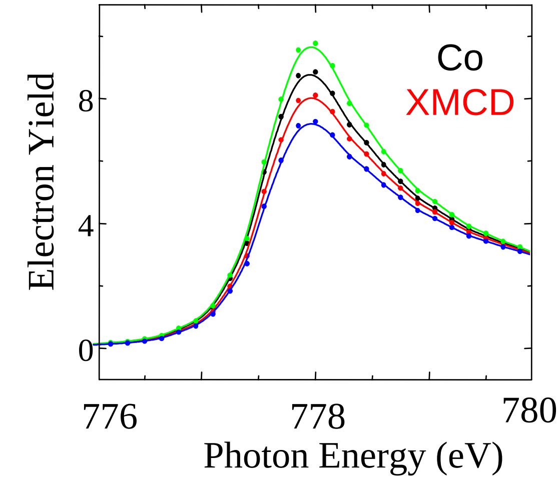
Nolting *et al.*, Nature **405**, 767 (2000)

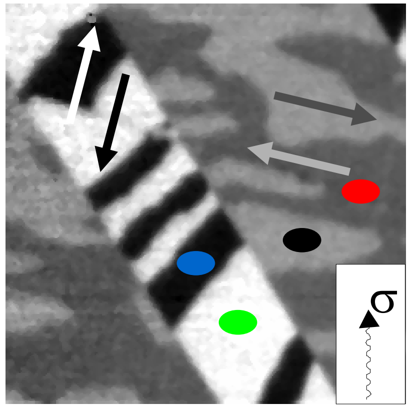


Spectro-Microscopy of Ferromagnets on Antiferromagnets

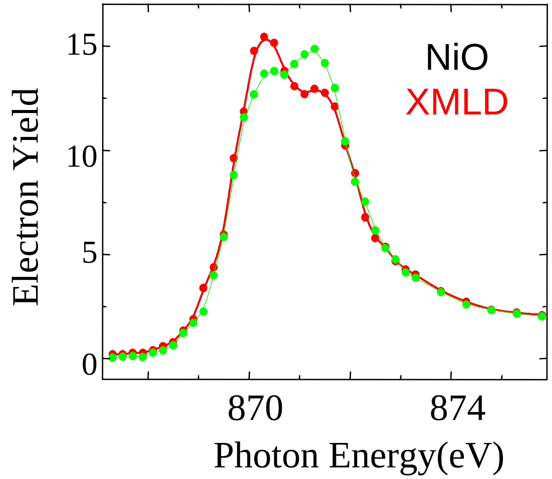


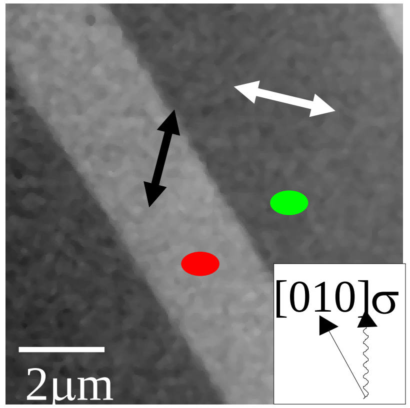
Tune to **Co** edge – use **circular** polarization – ferromagnetic domains





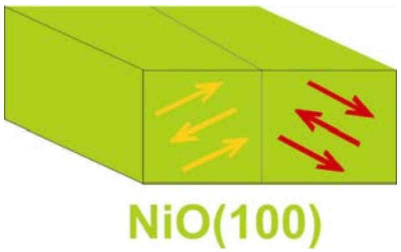
Tune to **Ni** edge – use **linear** polarization – antiferromagnetic domains

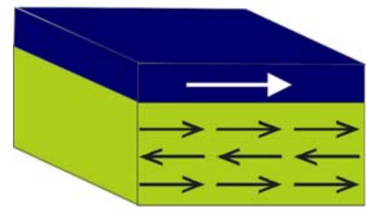


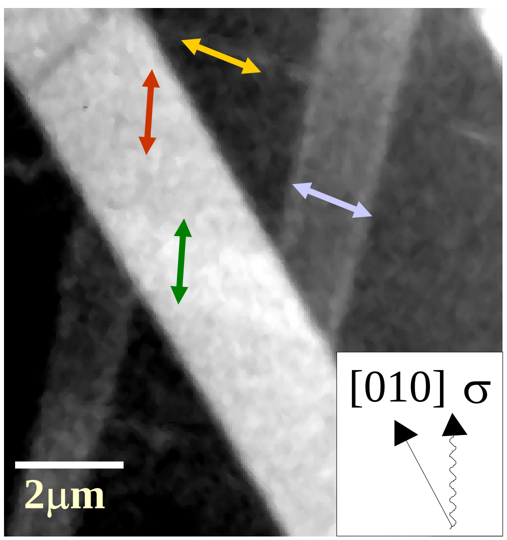


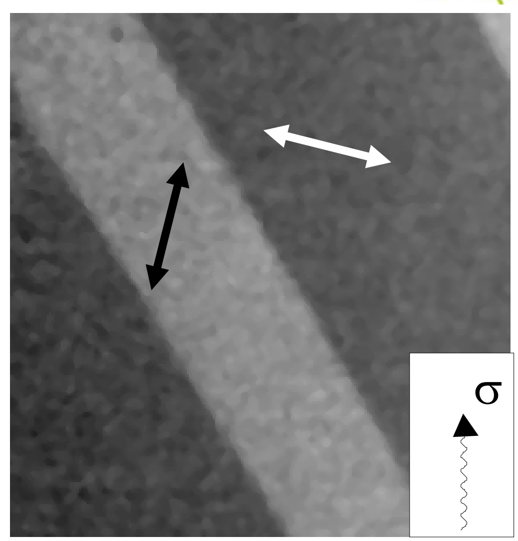
H. Ohldag *et al.*, PRL **86**, 2878 (2001).

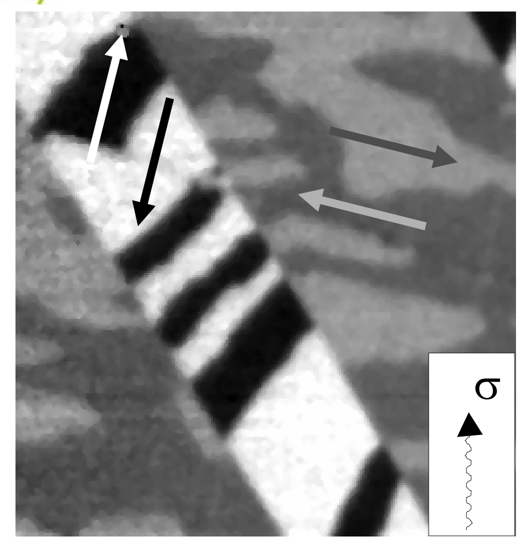
Co on NiO(001)











Bare NiO(001)

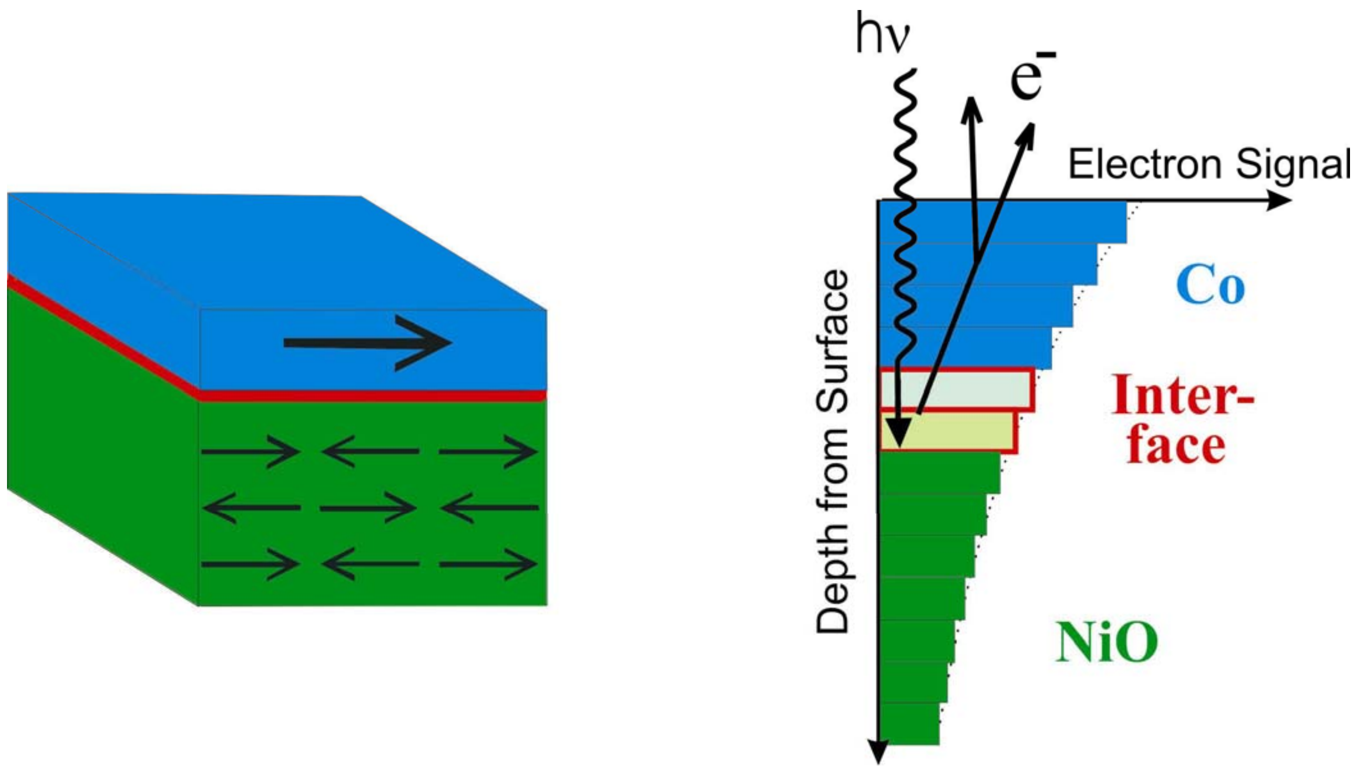
NiO after deposition

2nm Co on NiO(001)

Co causes Ni spins at NiO surface to rotate into plane

AFM and FM spins couple parallel

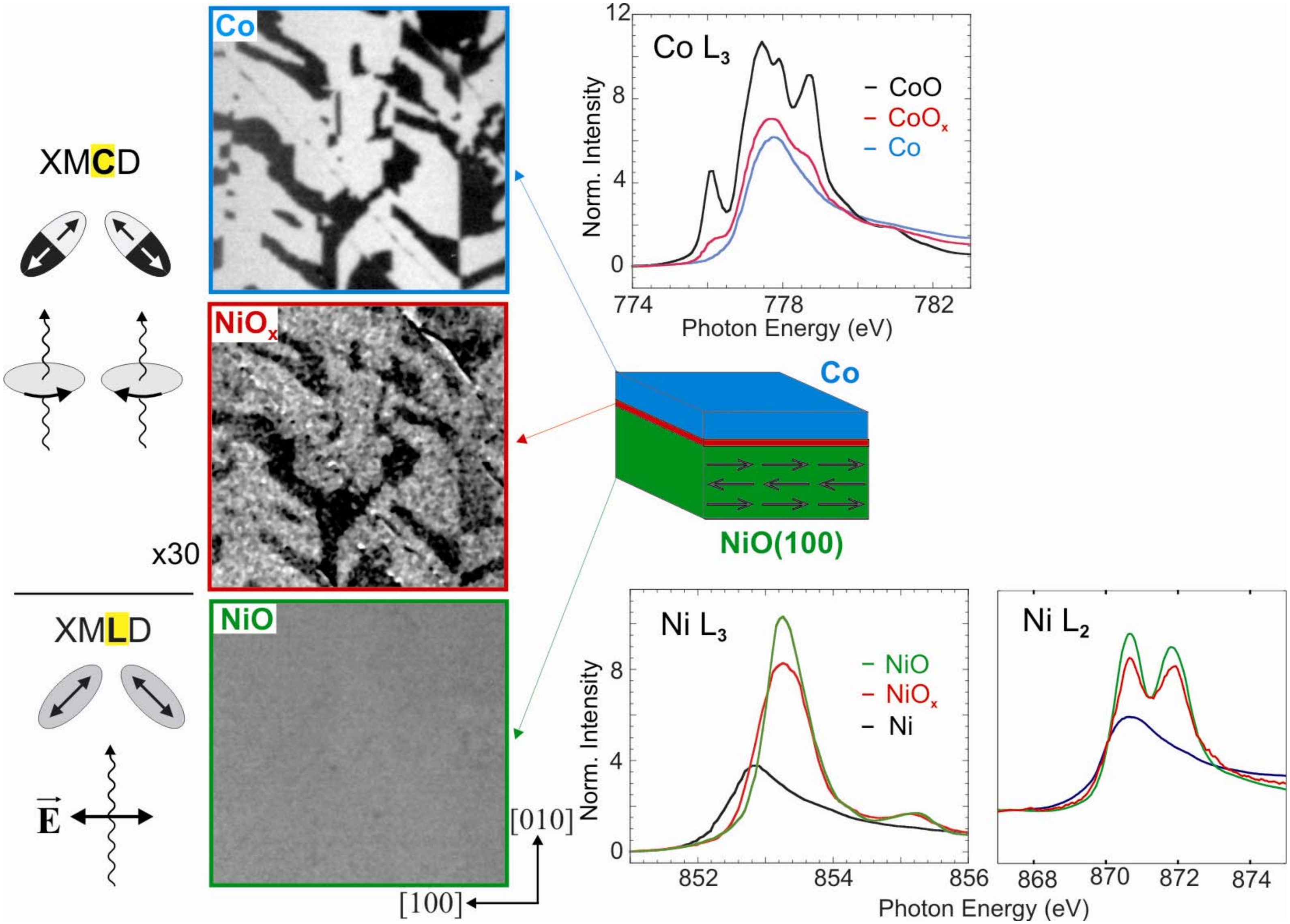
X-Rays-in / Electrons-out - A way to study Interfaces



FM Co – tune to Co edge – circular polarization

AFM NiO – tune to Ni edge – linear polarization

FM Ni(O) – tune to Ni edge – circular polarization


XMCD
x30
XMLD
E
Co
NiOx
NiO
[010]
[100]
Co L3
Norm. Intensity
CoO
CoOx
Co
Photon Energy (eV)
Co
NiO(100)
Ni L3
Ni L2
NiO
NiOx
Ni
Photon Energy (eV)

X-Ray Picture of Exchange Bias

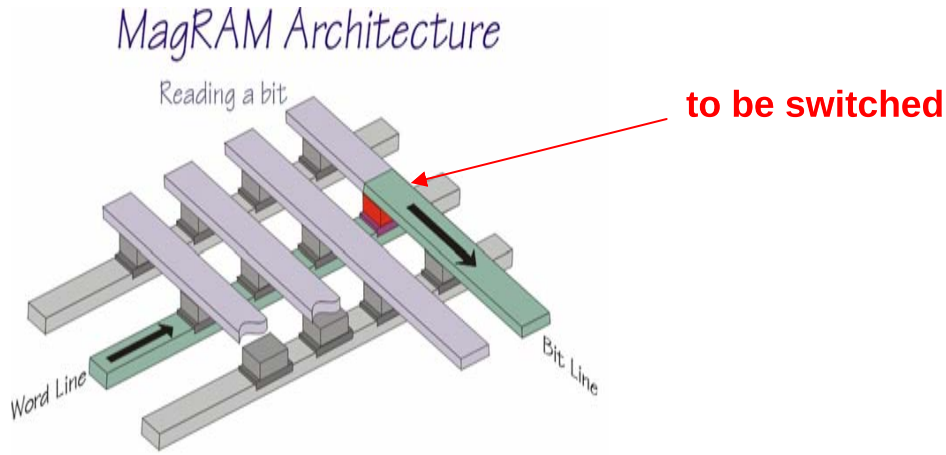
Co/NiO

Co

NiO

- The interface is not sharp
- AFM axis is rotated at interface
- Parallel coupling FM-AFM
- 1 ML of uncompensated “AFM” spins

A new way of magnetic switching: spin injection

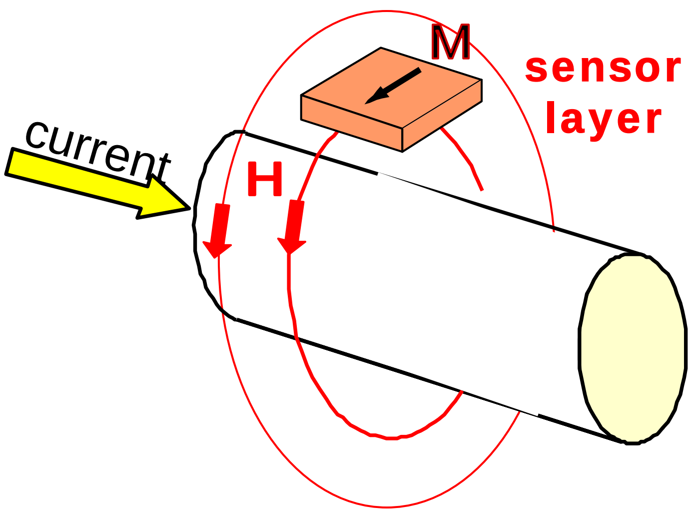


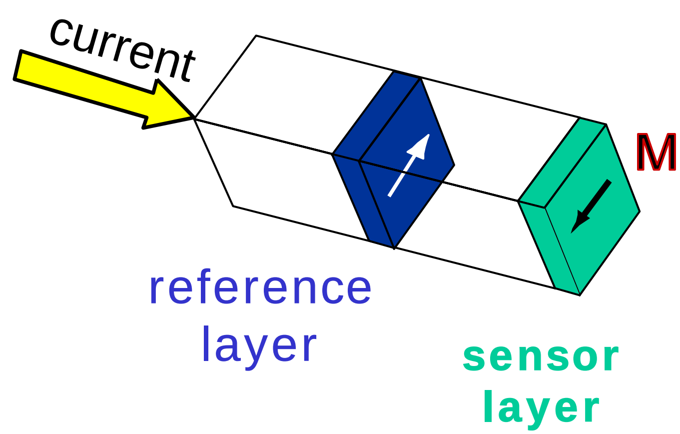
electric current creates magnetic field

"Oersted field"

spin current acts like an

"Exchange field"

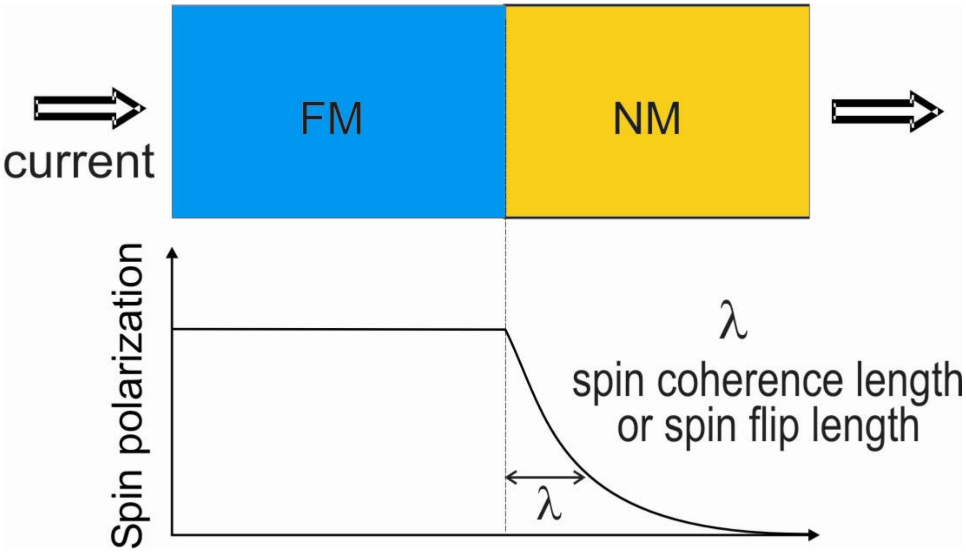




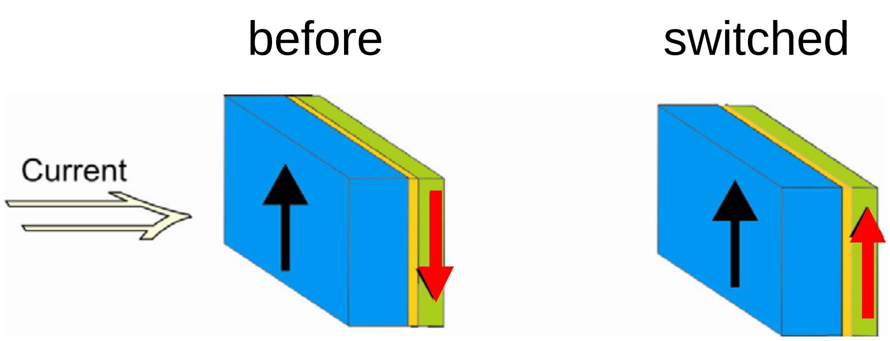
Weak, long range

Strong, short range

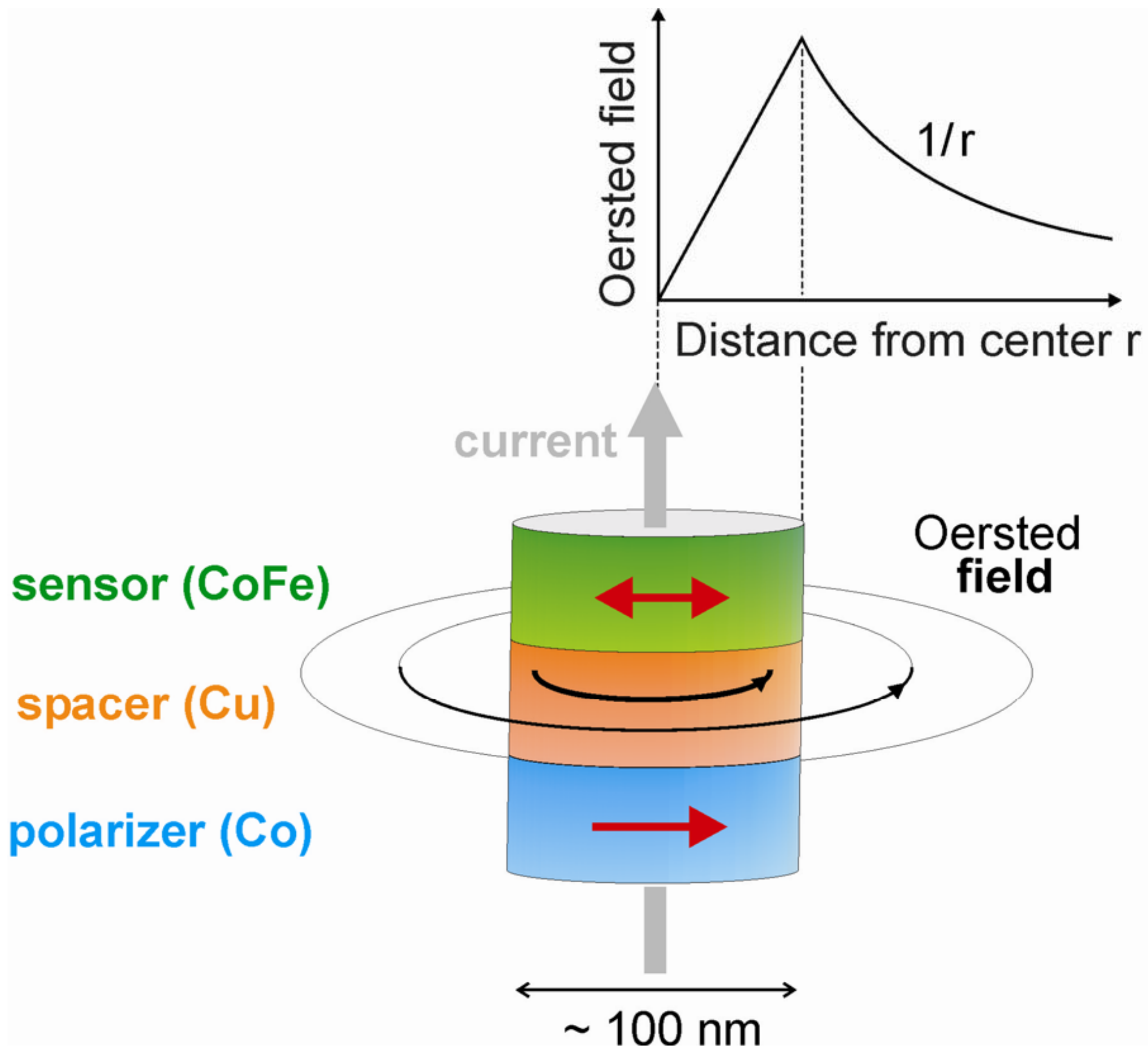
Spin injection from a ferromagnet



λ ~ 1 nm for ferromagnets (or 10 fs)
λ ~ 1 μm for noble metals (or 10 ps)
λ ~ 100 μm for semiconductors (or 1 ns)

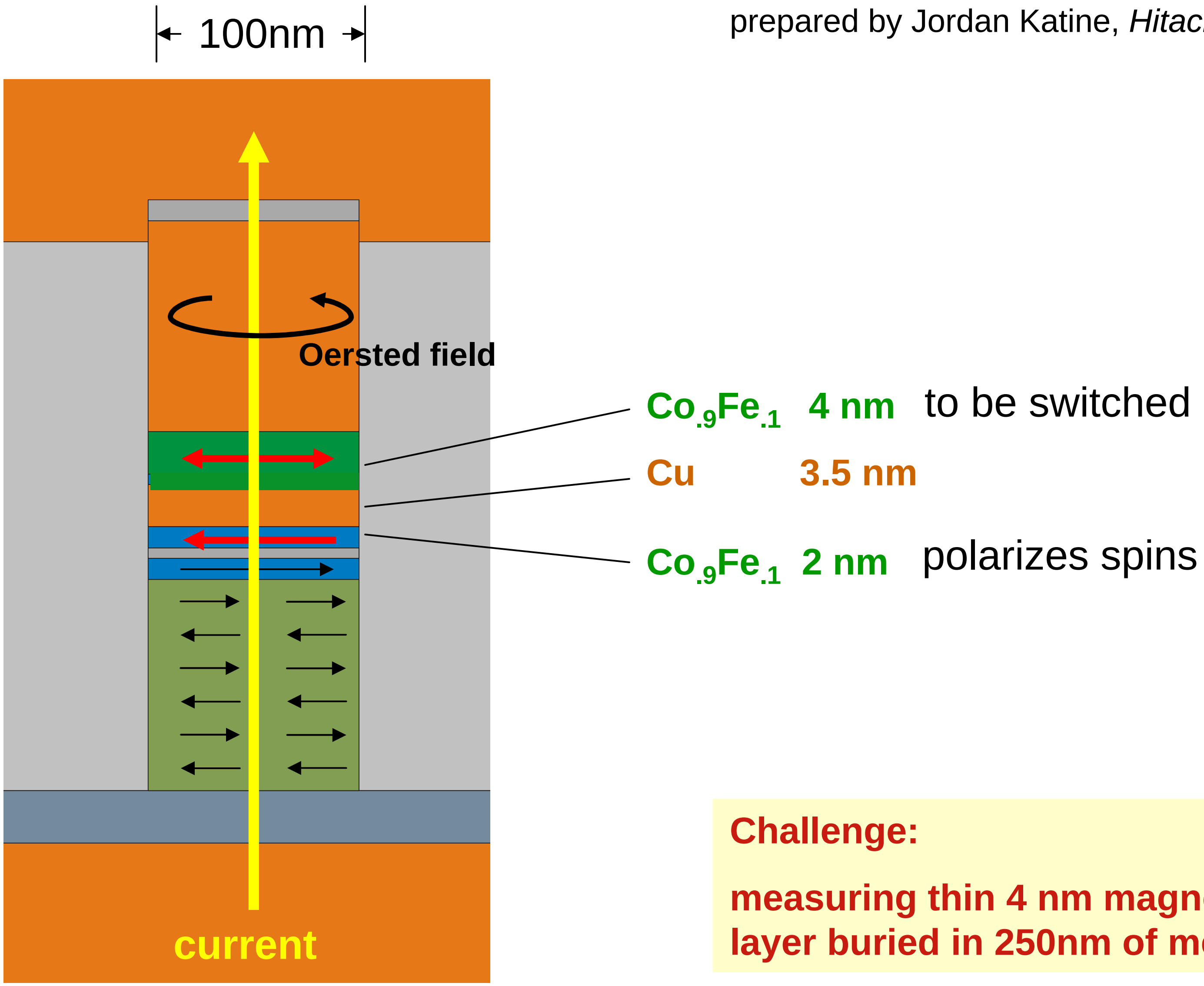


Principle of Magnetic Structure



Real samples for spin-injection studies

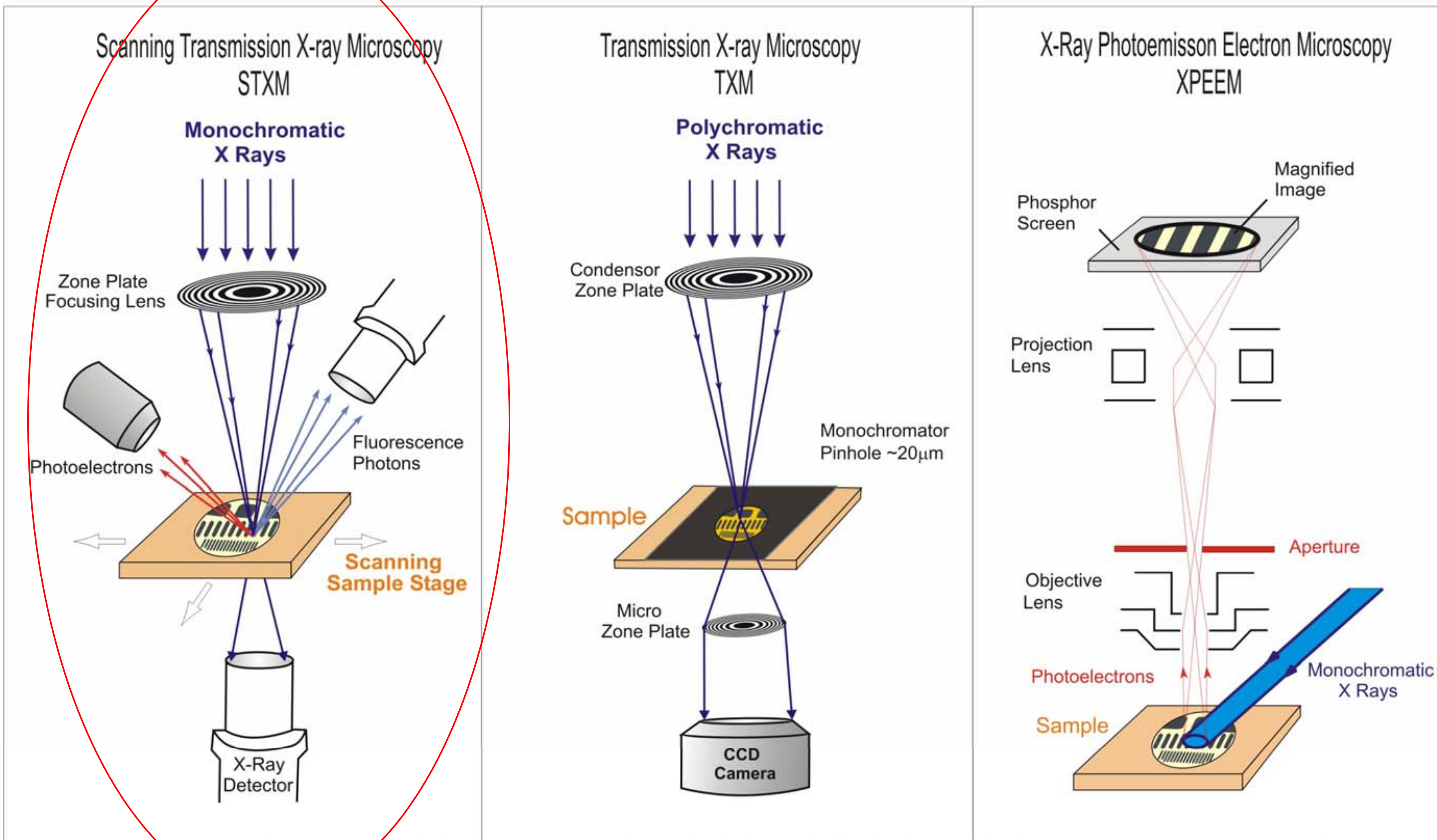
prepared by Jordan Katine, *Hitachi Global Storage*



Challenge:

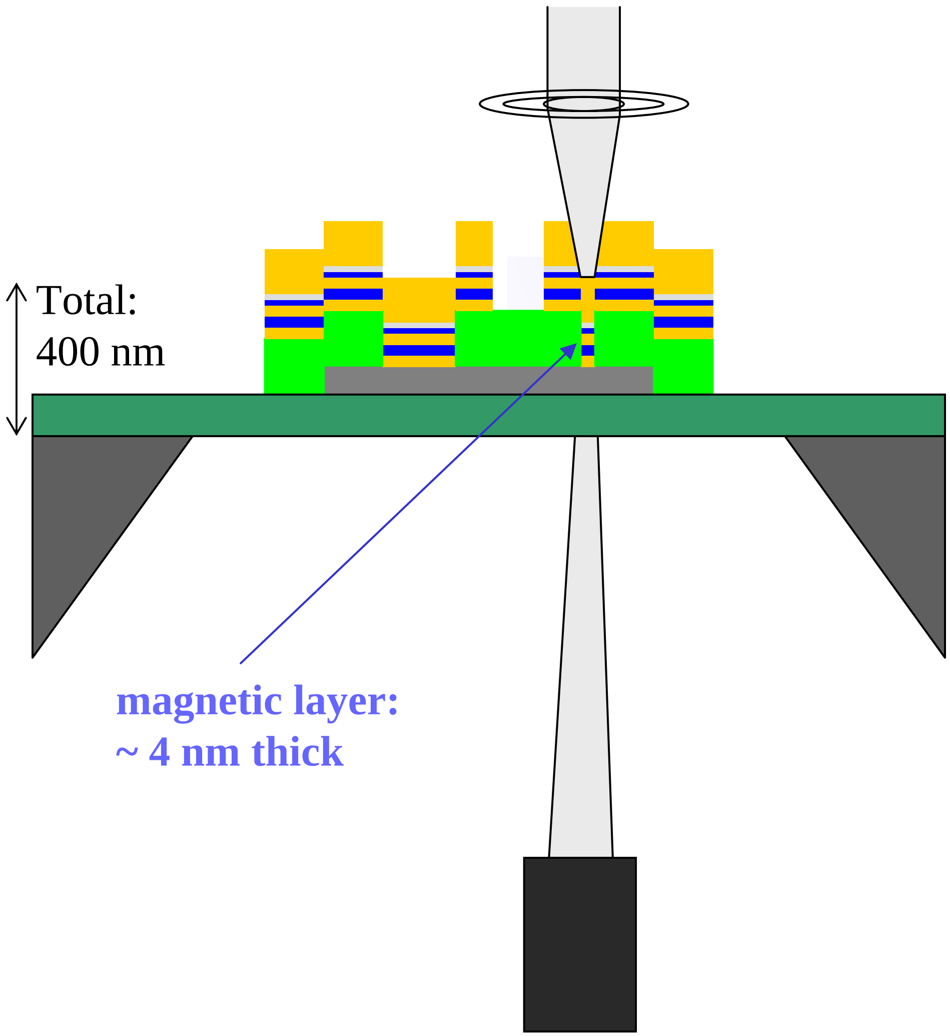
measuring thin 4 nm magnetic layer buried in 250nm of metals !

X-Ray Microscopy Methods - toward Nanometer Resolution



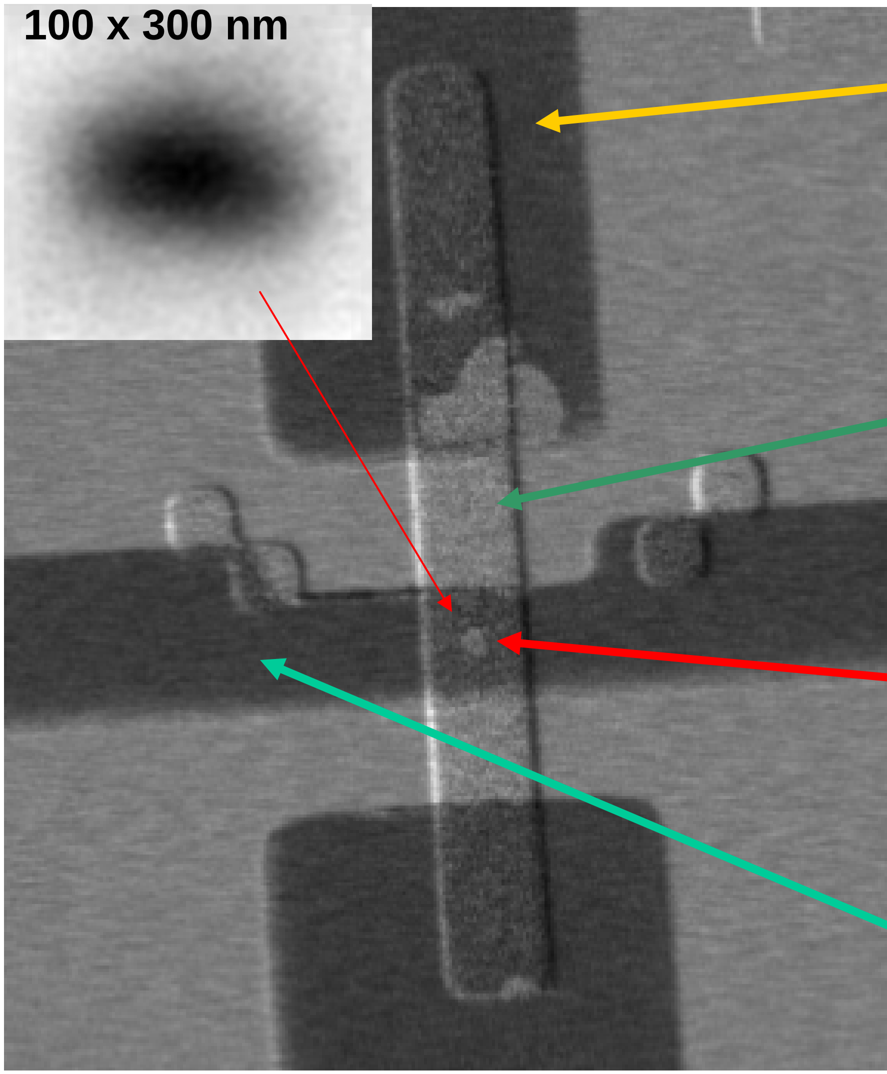
Present resolution in the 20 - 40 nm range

Scanning transmission x-ray microscopy of samples



- Spatial resolution ~35 nm
- Polarized x-rays give magnetic contrast (XMCD)
- Transmission experiment through all layers in device
- X-rays can distinguish layers: elemental (Fe,Co,Ni,Cu) and chemical (e.g. Cu, CuO_X) contrast

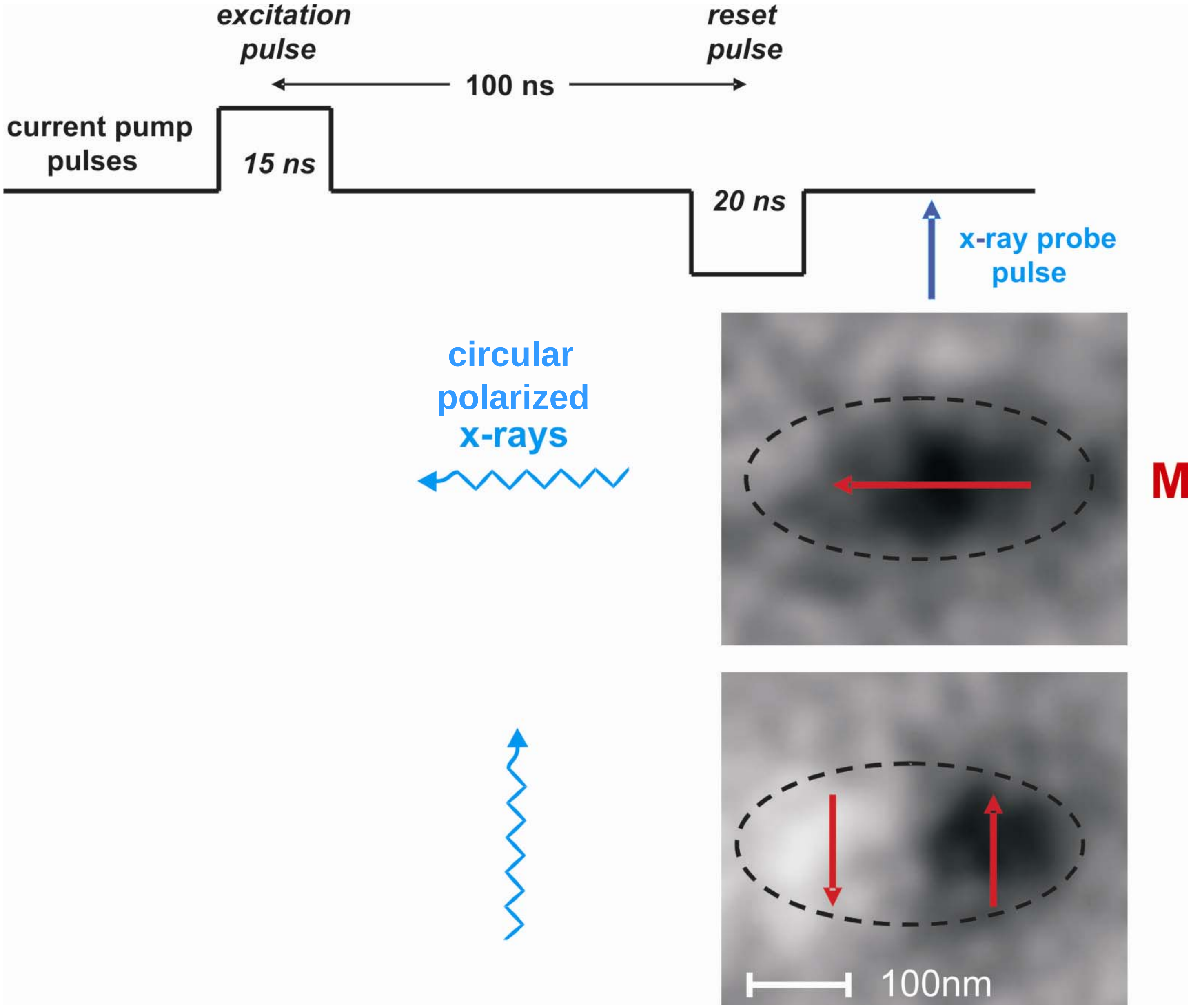
STXM image of spin injection structure



1. **Cu** lead - current in
2. **Pt** lead - current to bottom of spin injection pillar
3. Current flows through **pillar**, switching second ferromagnet
4. **Cu** lead - current out

Challenge is nanoscale sample production – pillar diameter is ~ 100 nm

Images of the magnetization in nanopillar after spin-injection

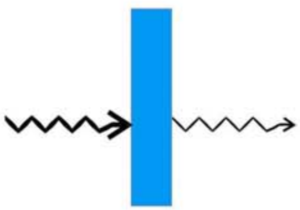


Another way of imaging

-- **reciprocal space**

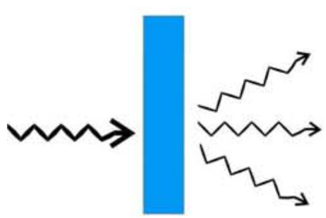
X-Ray Dichroism in Absorption and Scattering

Absorption



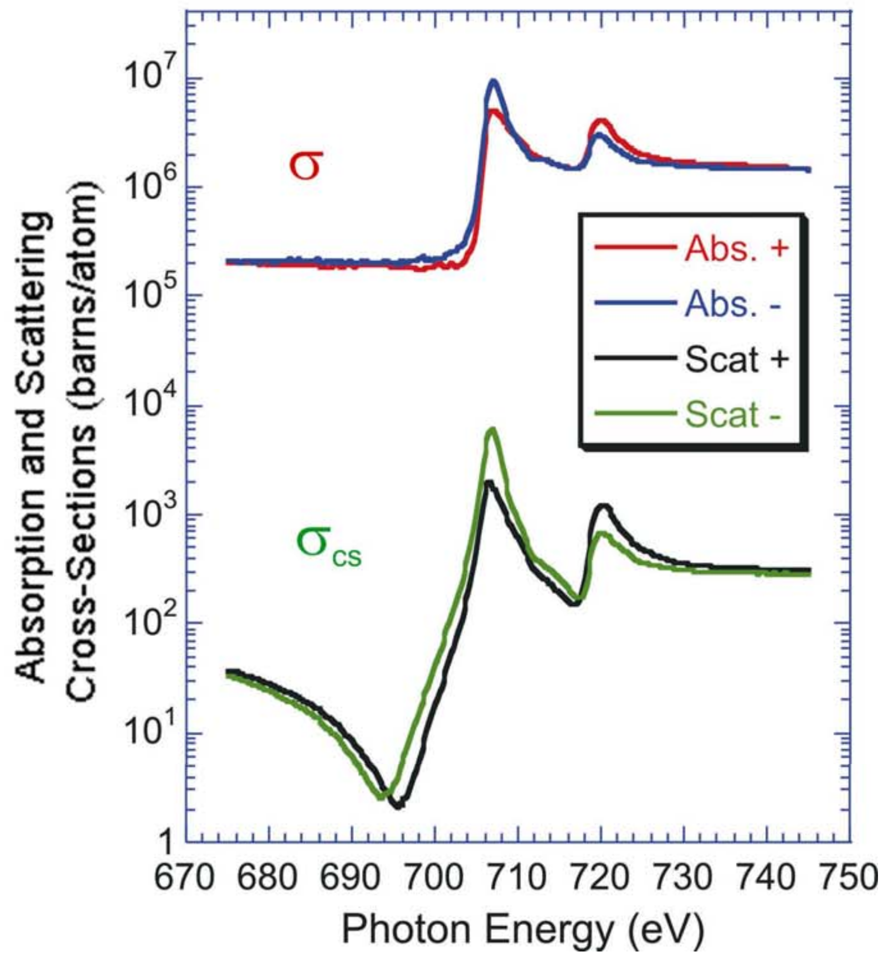
$\sigma_{abs} \propto f_2$

Resonant Elastic Scattering



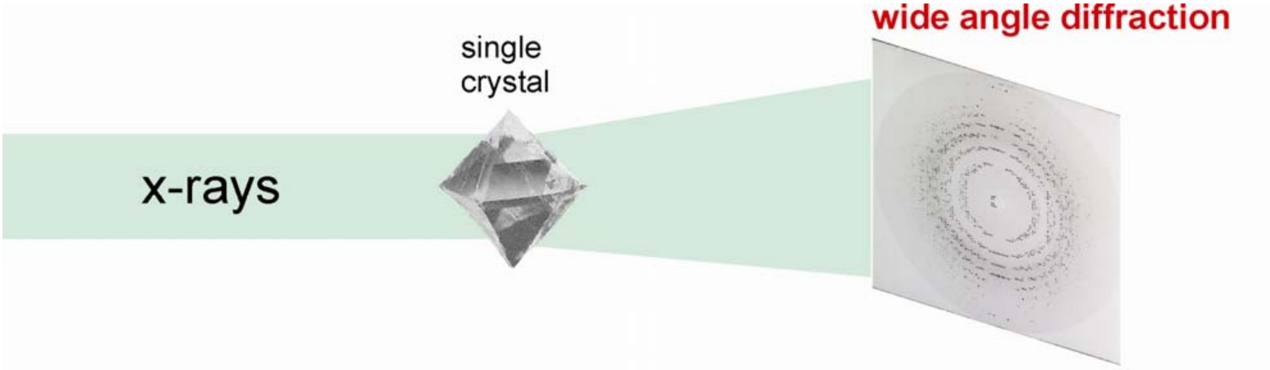
$\sigma_{scat} \propto | f_1 + i f_2 |^2$

Fe metal – L edge

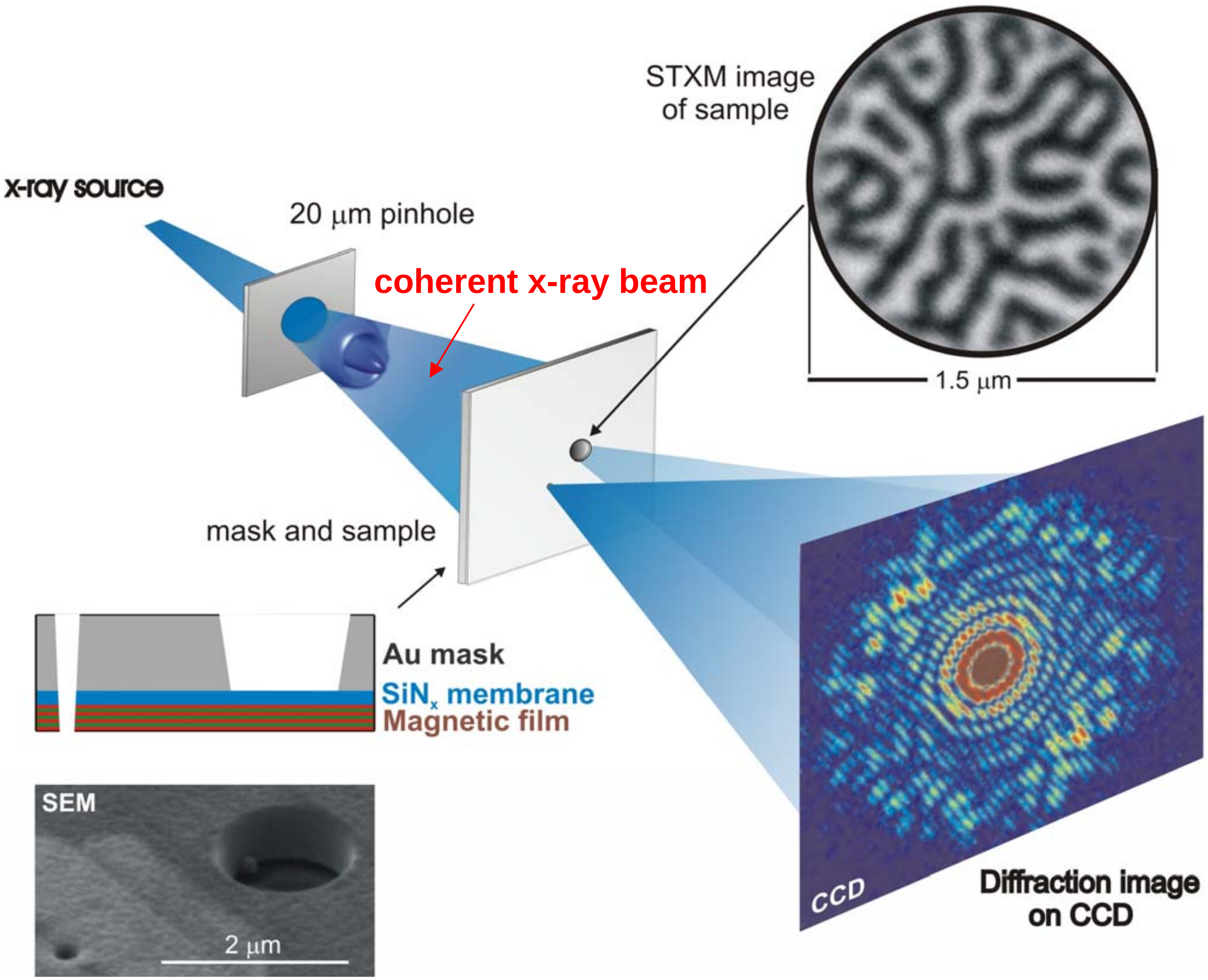


Kortright and Kim, Phys. Rev. B **62**, 12216 (2000)

X-ray diffraction and scattering



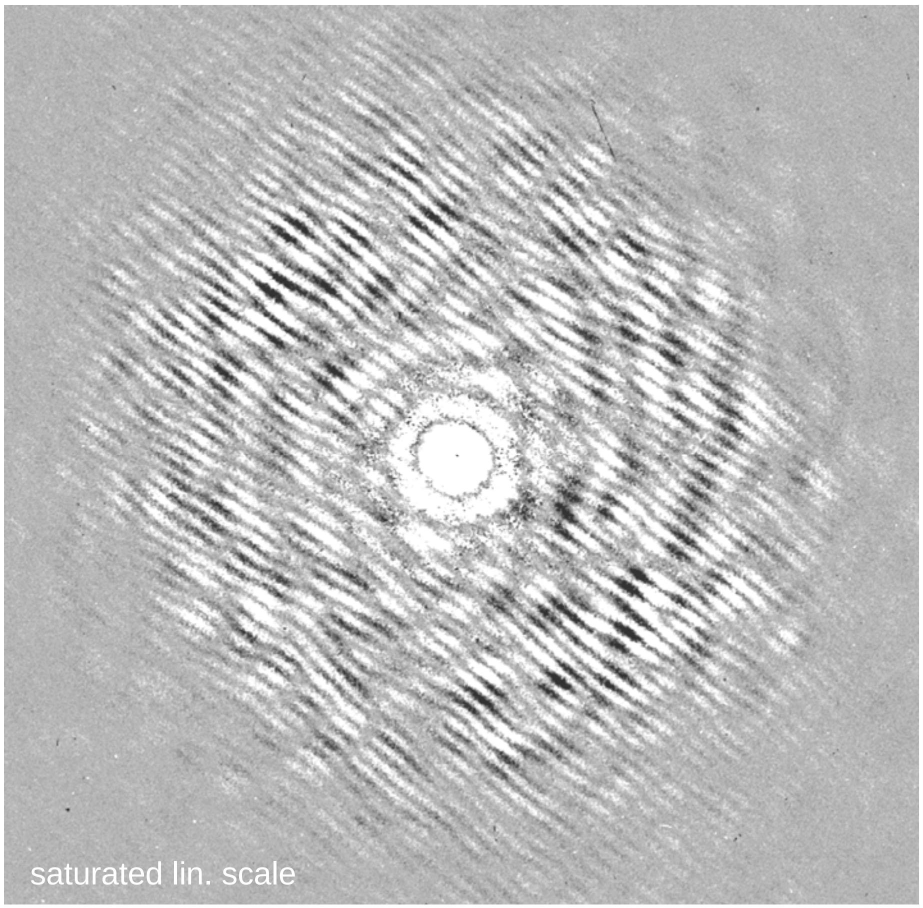
Yes - soft x-ray spectro-holography



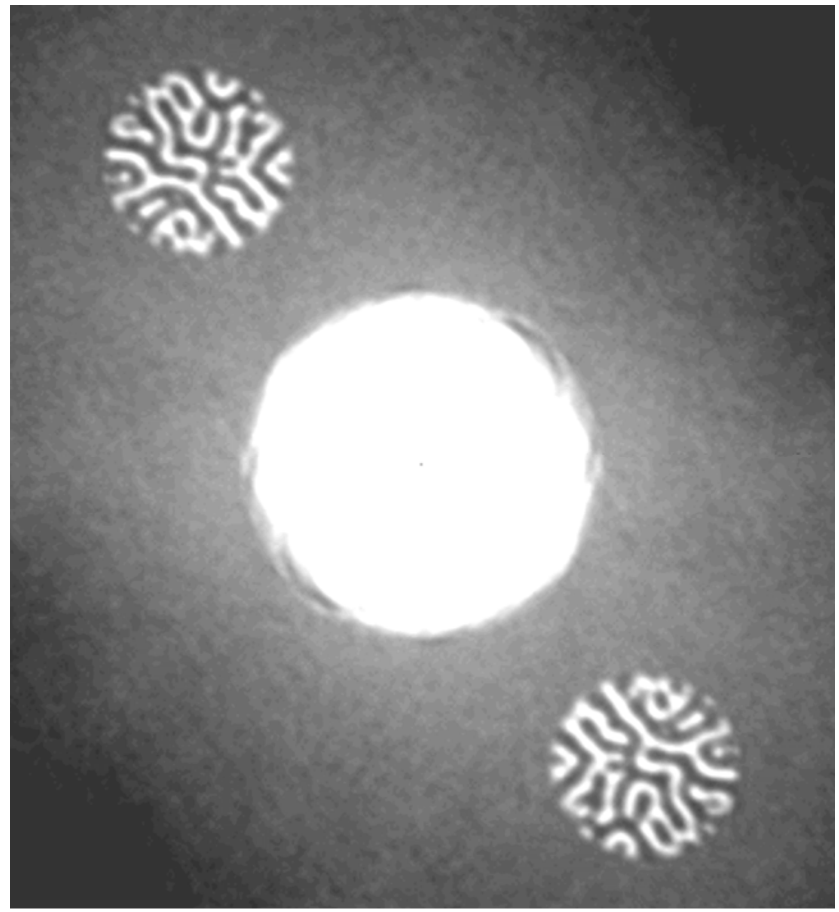
Eisebitt, Lüning, Schlotter, Lörgen, Hellwig, Eberhardt and Stöhr, *Nature* ***432****, 885 (2004)*

Digital Image Reconstruction

Difference (RCP – LCP)



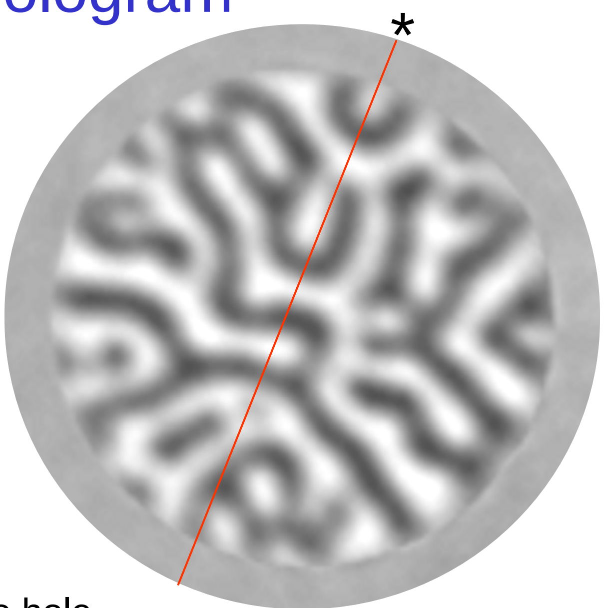
FFT (Difference)



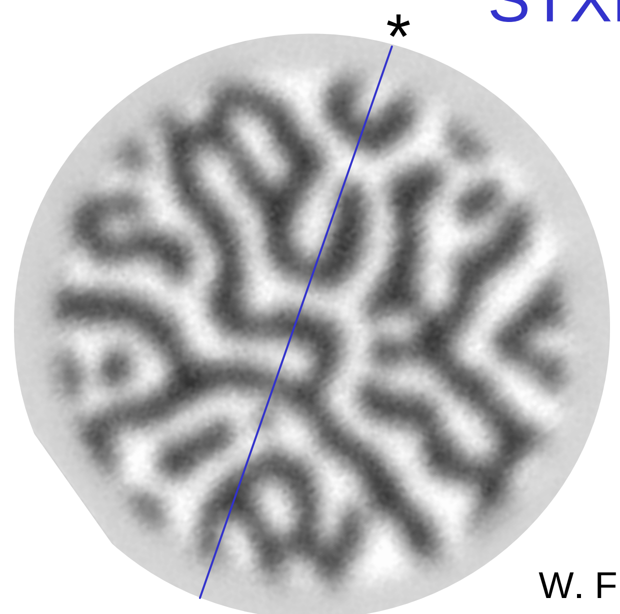
Convolution theorem applied to diffraction: FT(diffraction) = Autocorrelation (Object)

Is it real?

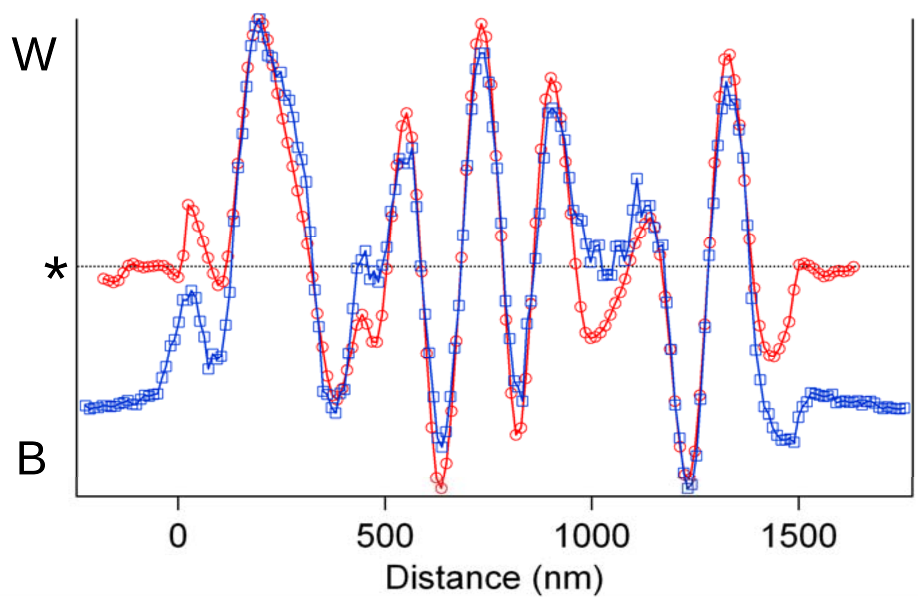
FT Hologram



STXM



Reference hole
∅ 100 nm

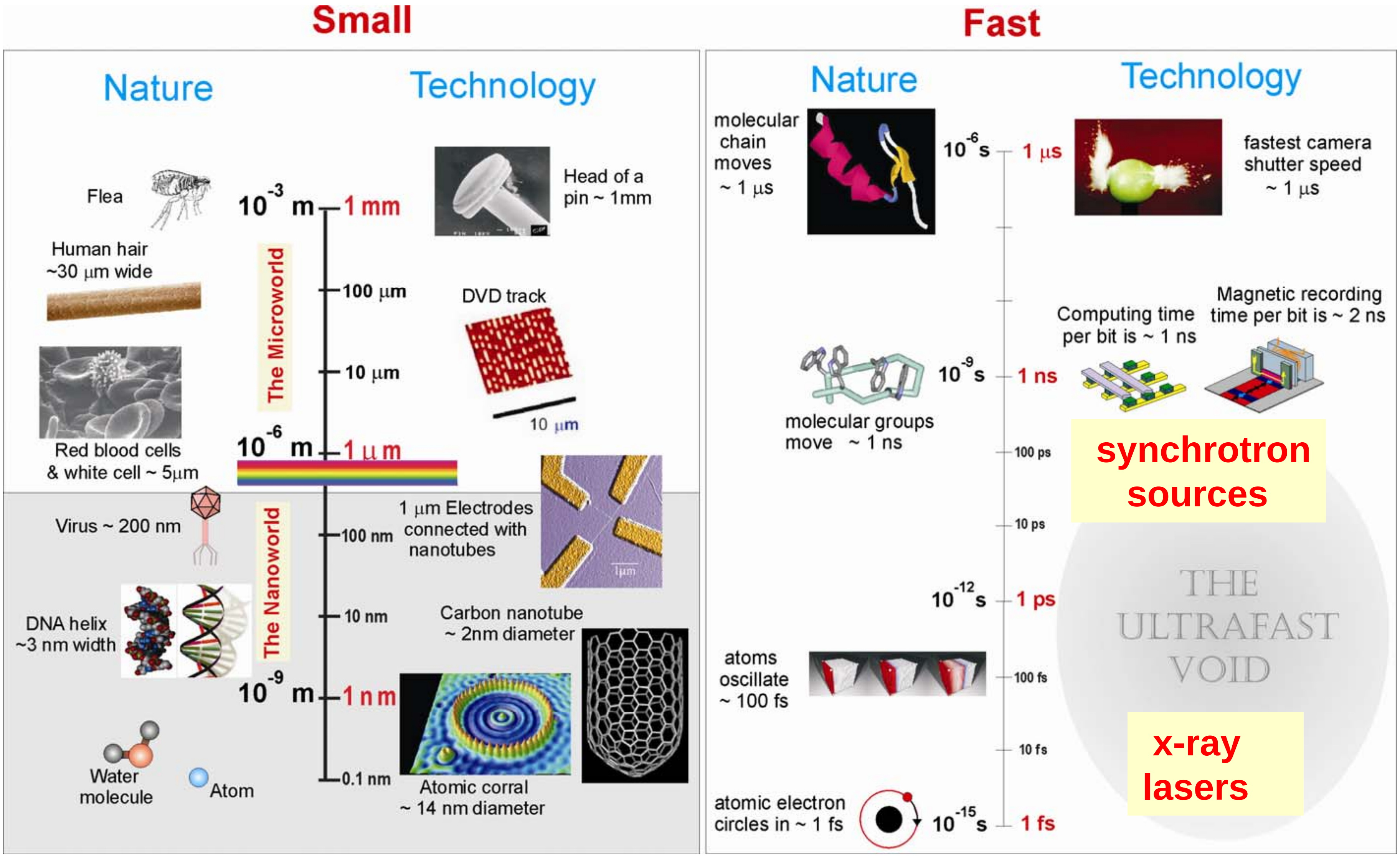


W. F. Schlotter
Y. Acremann

Resolution
30 - 40 nm

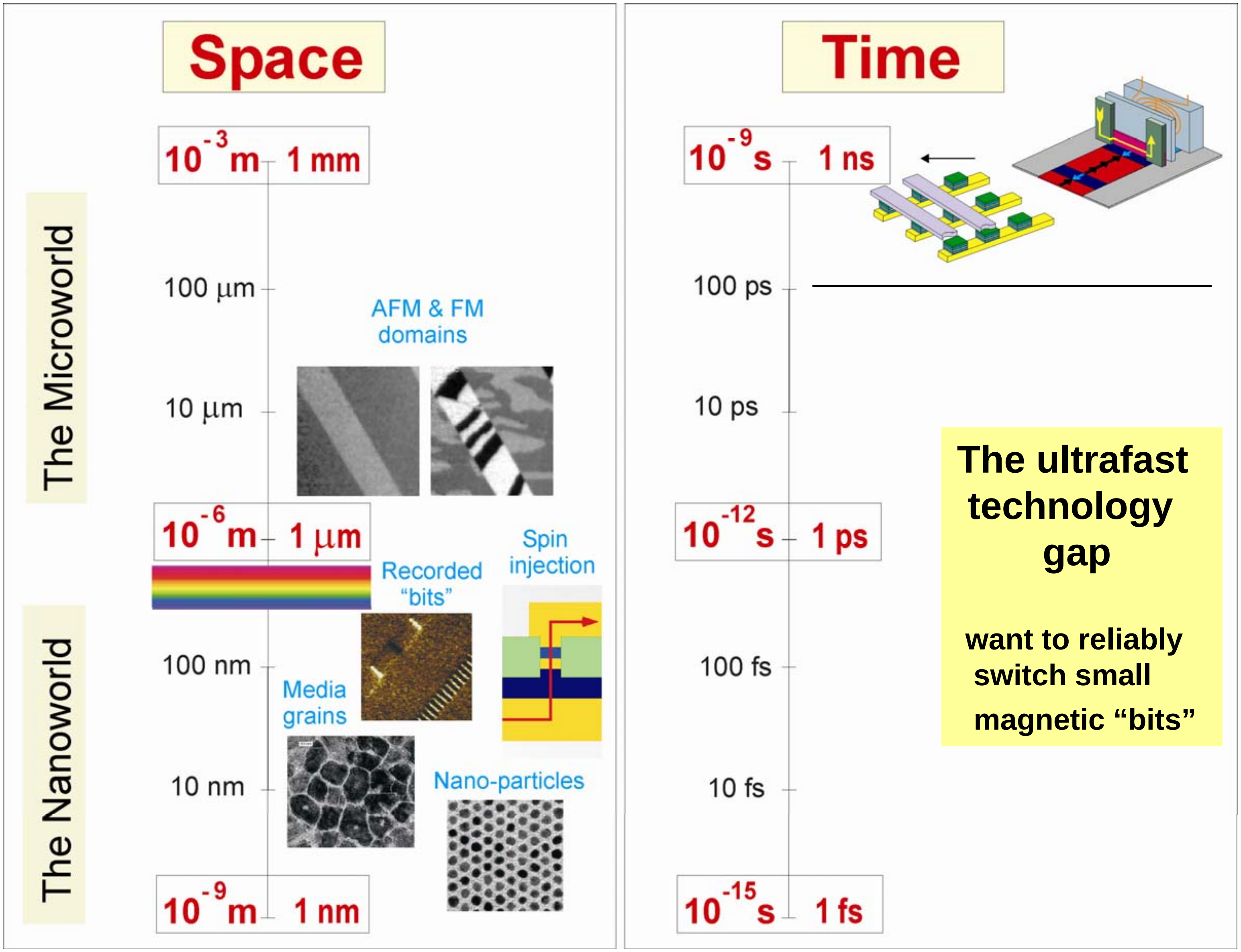
Smaller and faster …..

Space and Time: Toward seeing the ultra-fast nanoworld



Rule of thumb: the smaller the faster!

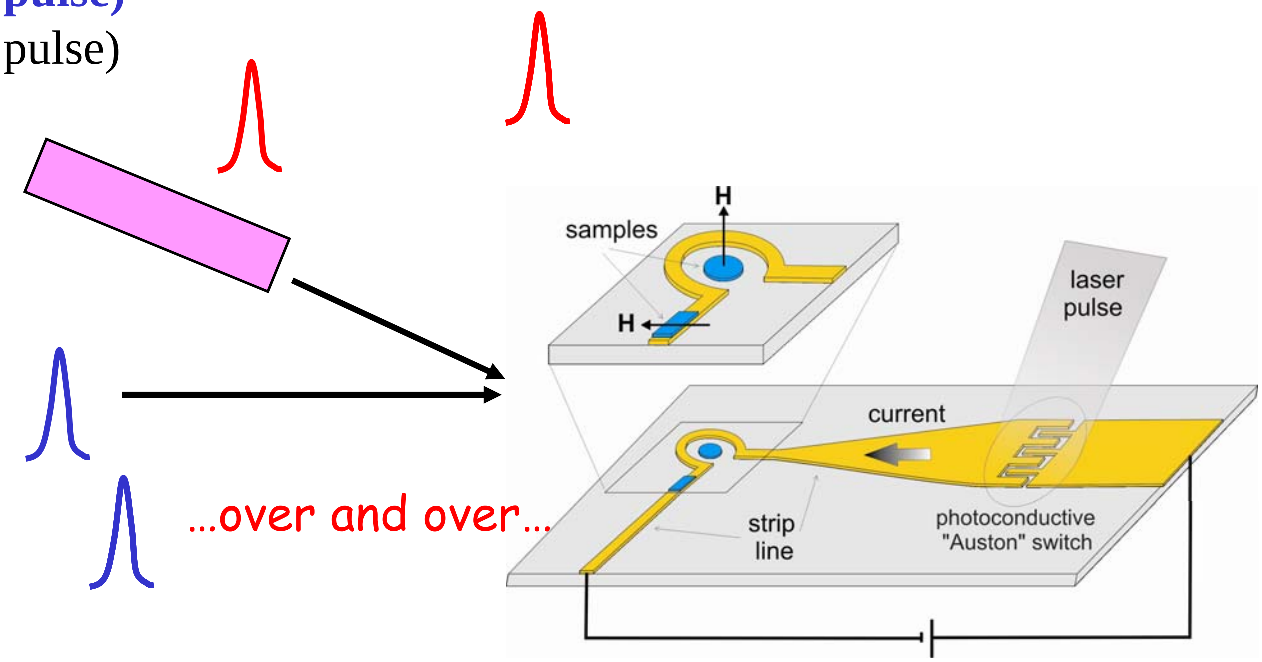
The Technology Problem: Smaller and Faster



Present: Pump/Probe Experiments

Pump pulses:
- **heat electrons (optical pulse)**
- **kick magnetization (field pulse)**
- heat lattice (pressure or IR pulse)

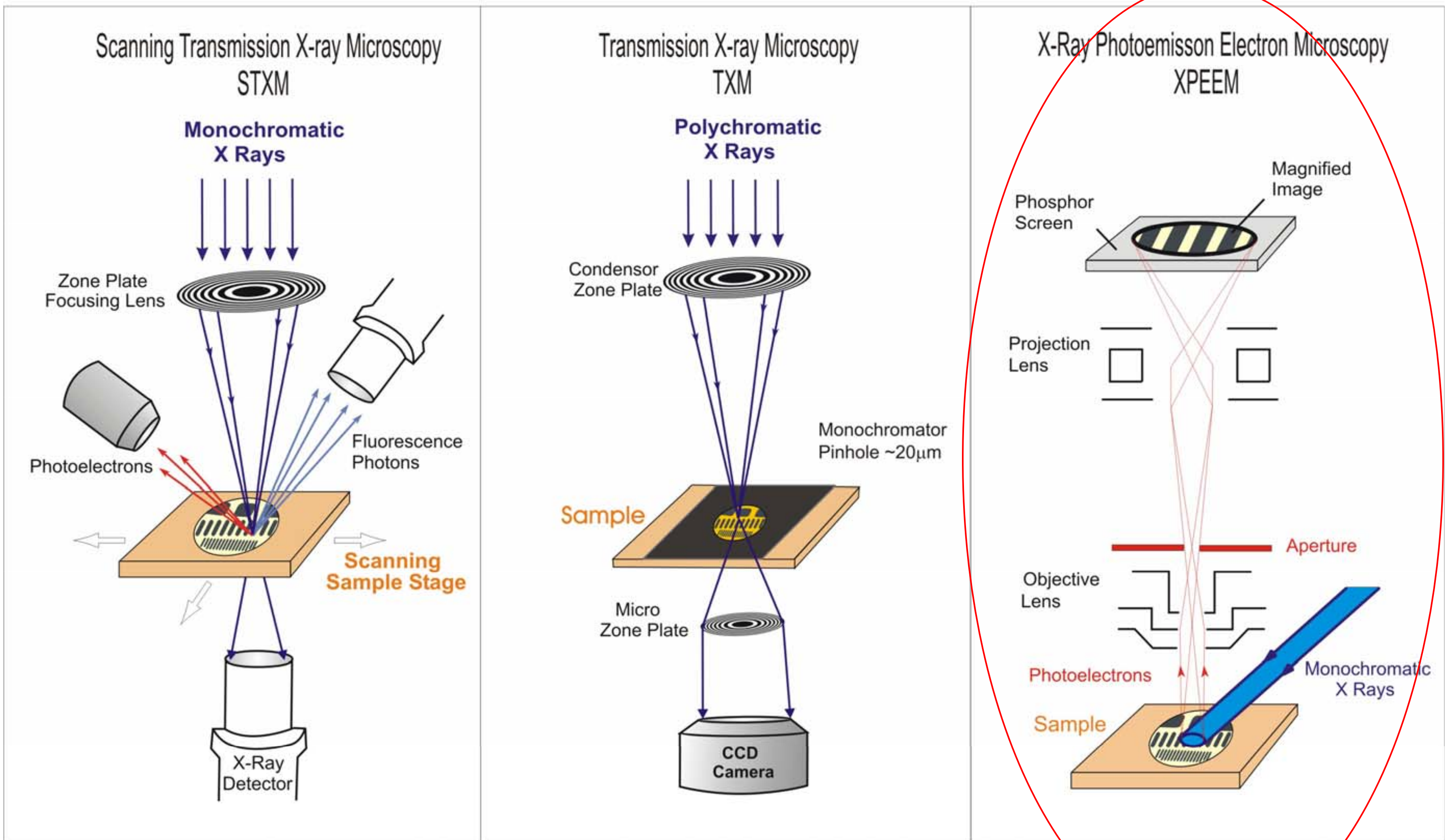
Probe pulse:
- **lasers**
  MO-Kerr, photoemission
- **(soft) x-rays**
  dichroism



Process has to be repeatable:

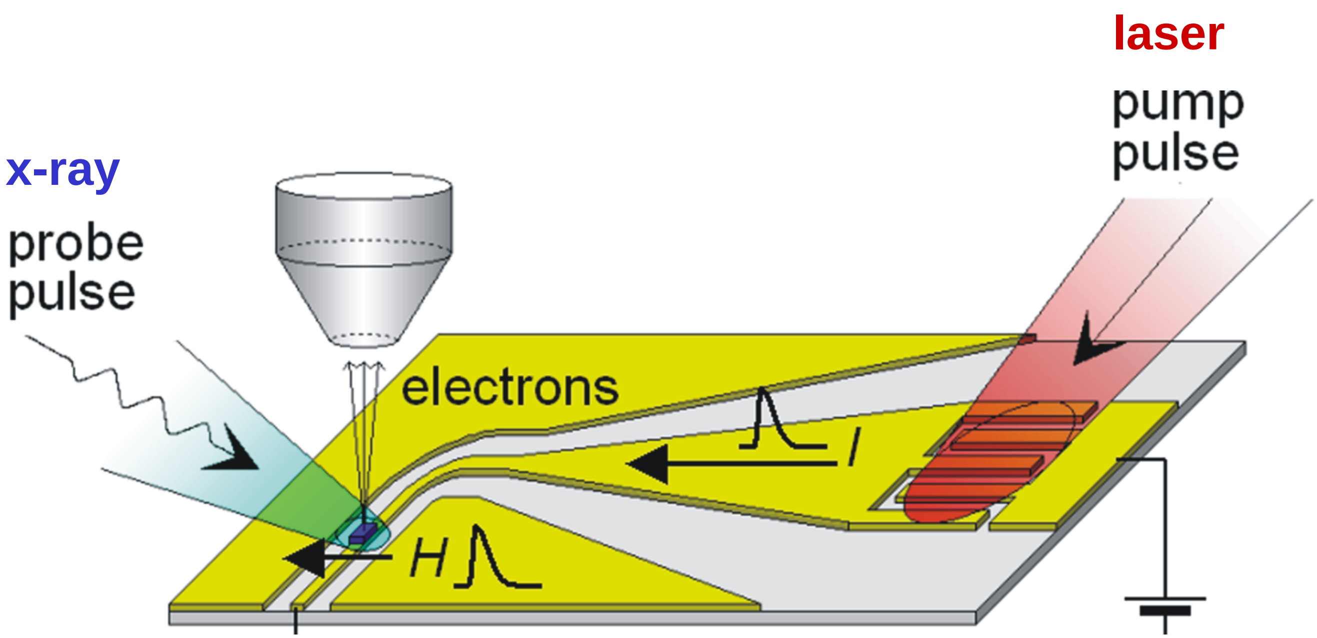
Not enough intensity for single shot experiments

X-Ray Microscopy Methods - toward Nanometer Resolution



Present resolution in the 20 - 40 nm range

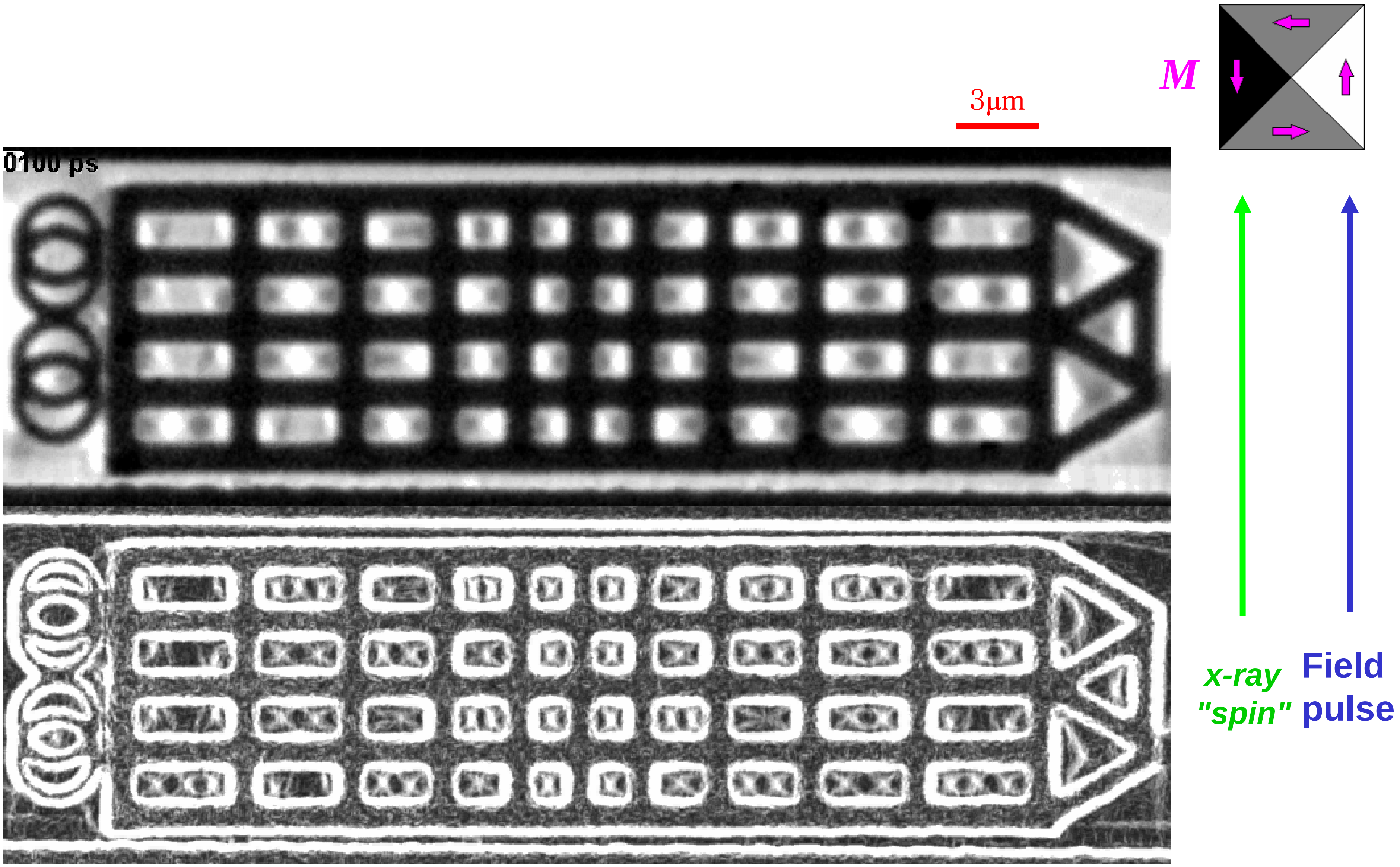
Imaging of Nanoscale Magnetization Dynamics with PEEM - ALS



Pump / probe requires reversibility of excitation process

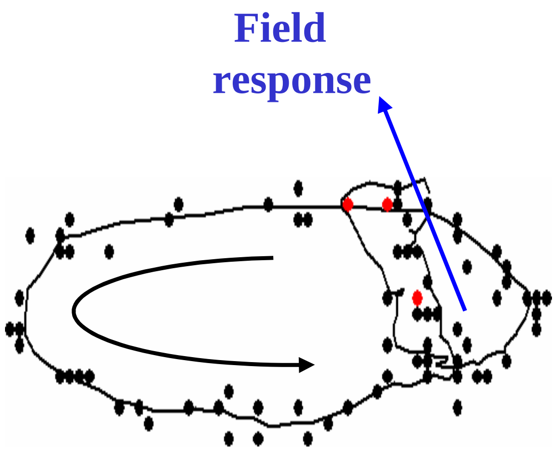
- not enough intensity to obtain single shot images

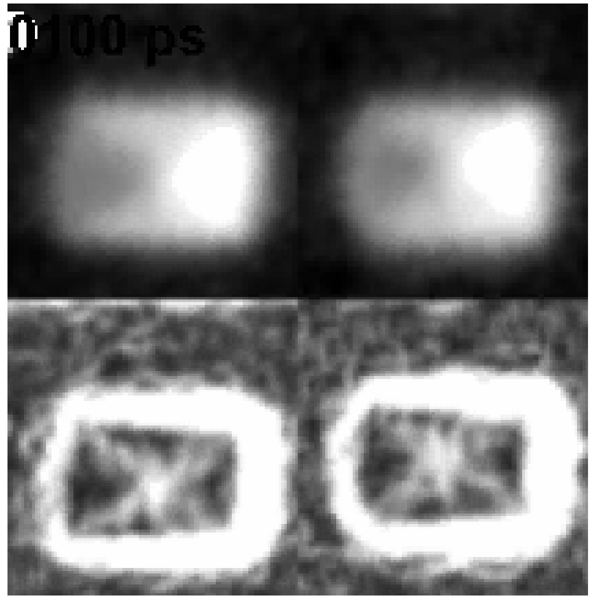
Magnetic Patterns in 20 nm $Co_{90}Fe_{10}$ films on waveguide

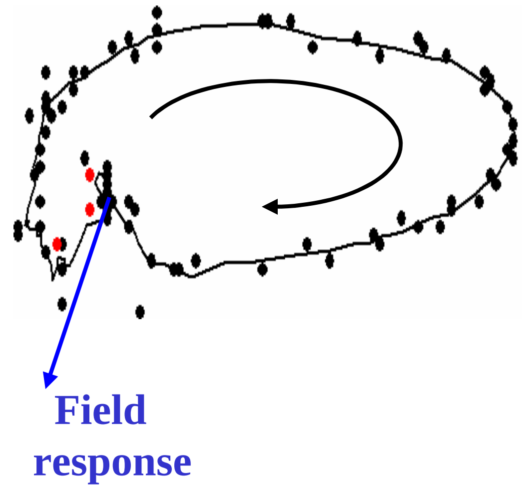


S.-B. Choe, Y. Acremann, A. Scholl, A. Bauer, A. Doran, J. Stöhr, H.A. Padmore, Science **304**, 430 (2004)

Two pattern with same static structure, but …..

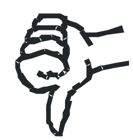


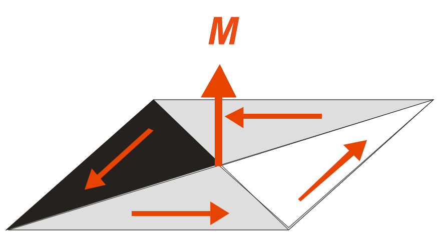


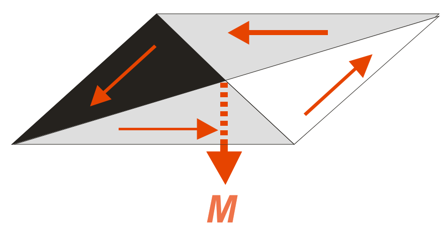


Opposite rotation is caused by direction of vortex core magnetization, i.e. chirality

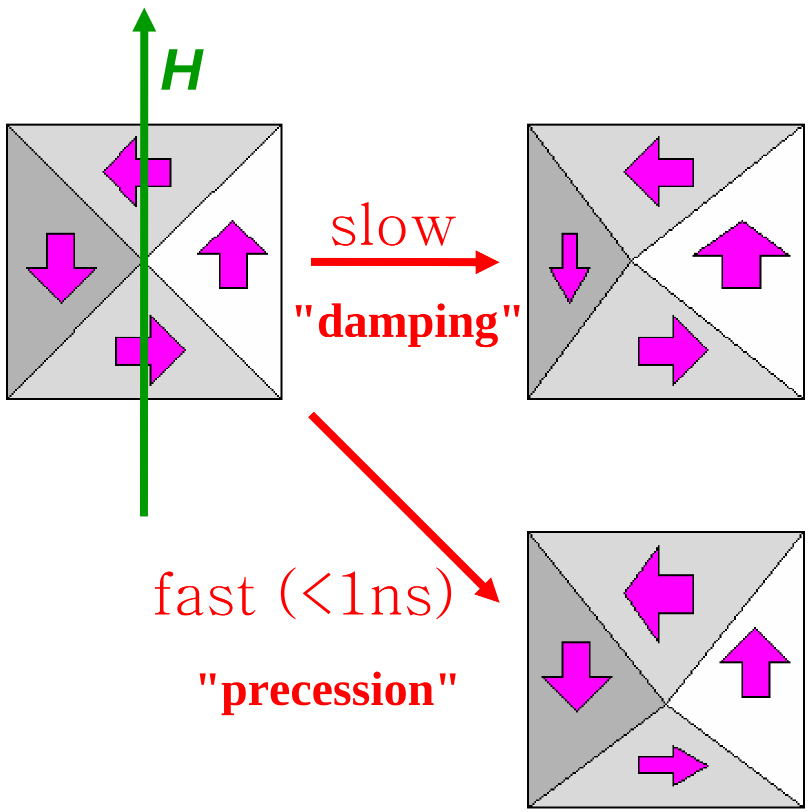
right handed 

left handed 



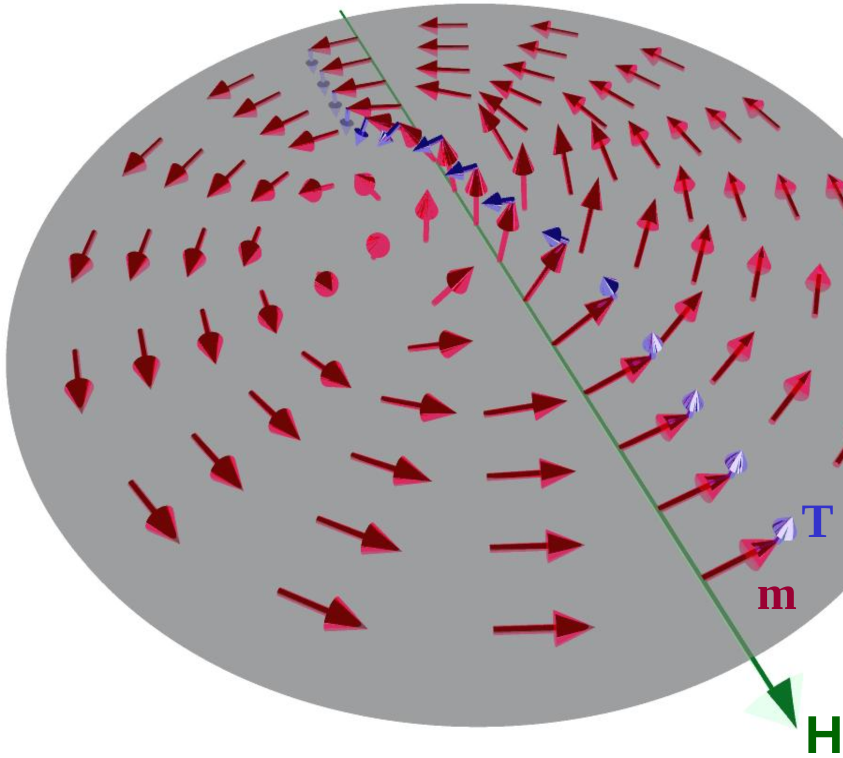


Response to a fast field pulse



Instantaneous precession determined by torque:

T = **H** x **m**



Tiny vortex core determines fast dynamics of the whole domain structure!