Magnetic Spectroscopies

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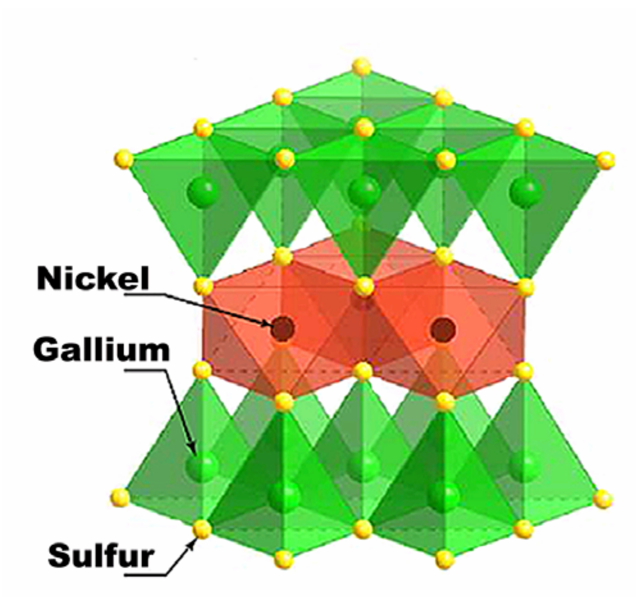
Magnetic spectroscopies

Outline

- Introduction to magnetism
- X-ray techniques
  - Spectroscopy
  - Imaging
  - Scattering

Magnetism

Atomic property



Collective response

applications

Model of compass used in China about 450 BC. The reference direction was south

Spin and orbital magnetic moment

$$\mu_B \equiv \frac{e\hbar}{2m} = 9.274 \cdot 10^{-24}\,\frac{J}{T} = 9.274 \cdot 10^{-24}\,emu$$

dipole moment created by electron on Bohr radius of the hydrogen atom, a_B=0.529Å

- **Spin magnetic dipole moment:** $\vec{\mu}_S = -\,{}^{e}\!/_{m}\,\vec{S}$

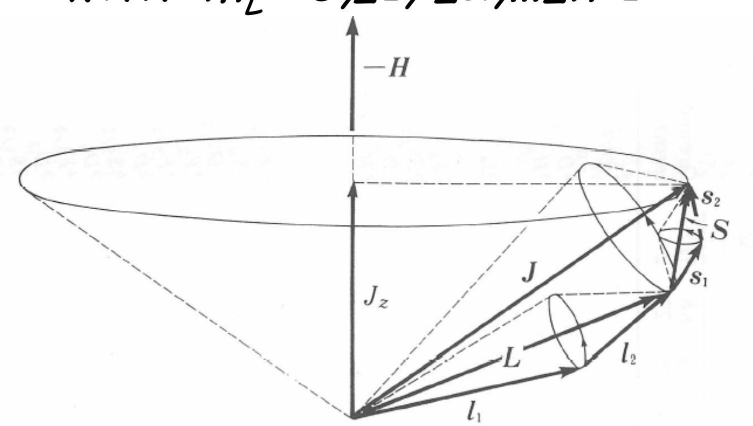
component of S is quantized, $S_z = m_S\, h/2\pi$ with *m_S=±1/2*

- **Orbital magnetic moment** $\vec{\mu}_{orb} = -\,{}^{e}\!/_{2m}\,\vec{L}_{orb}$

component of L is quantized, $L_{orb,z} = m_L\, h/2\pi$ with *m_L= 0,±1, ±2,…±n-1*

- **Total moment** $\vec{J} = \vec{L} + \vec{S}$

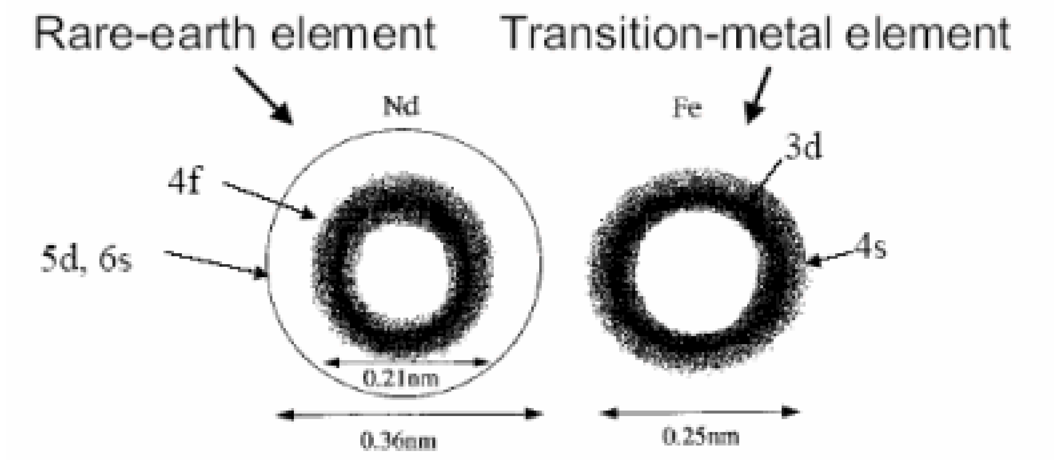
    - *Arrange electrons via Hund's rule*



3d transition metals *vs*. 4-f rare-earth elements

magnetism carried by
- 3d electrons: outer shell
- 4f electrons: inner shell

results in different properties



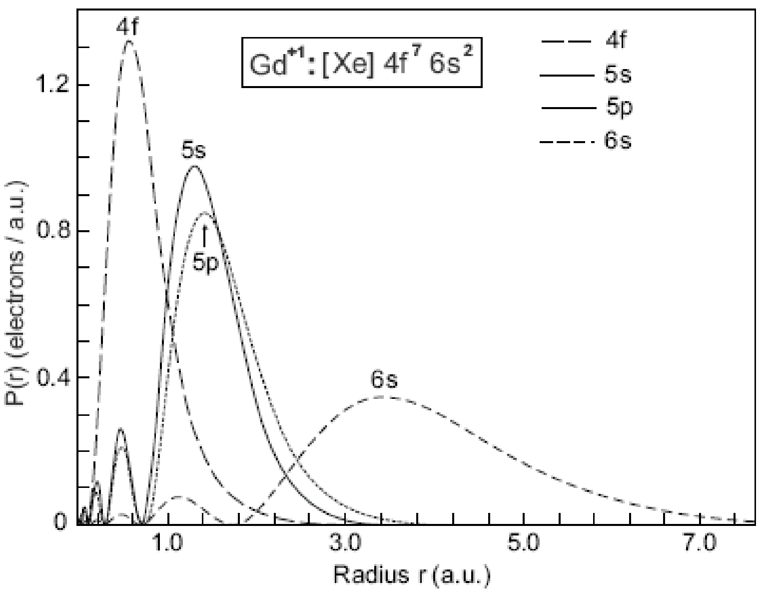
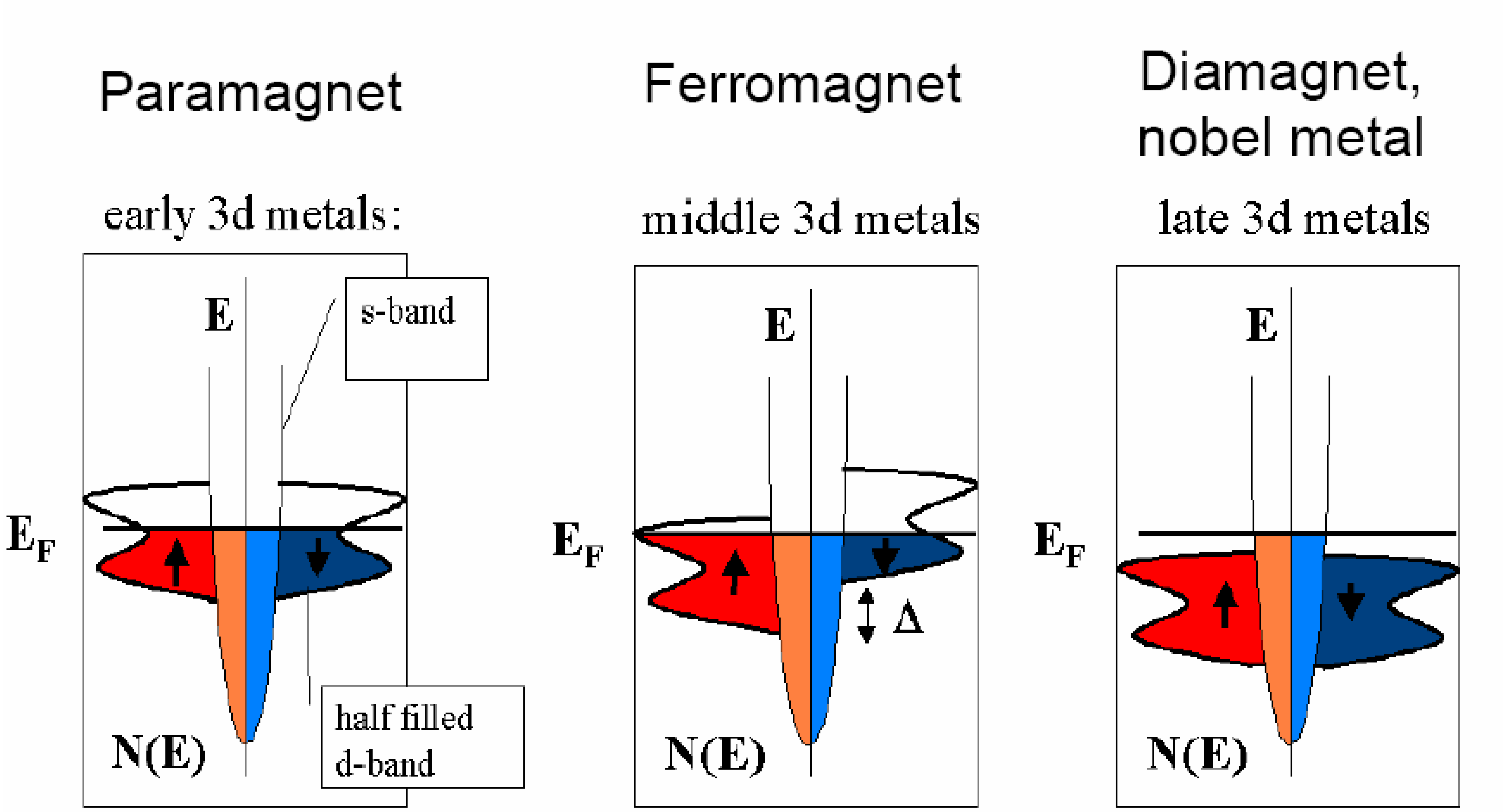


Fig. 7.4. Radial charge density for the Gd^{+1} ion ($4f^7\,6s^2$) calculated by Freeman and Watson [204] for the $4f$, $5s$, $5p$ and $6s$ orbitals. The figure shows that the $4f$ orbitals are actually located well inside the outer shells which screen them from the extra-atomic environment

Band magnetism



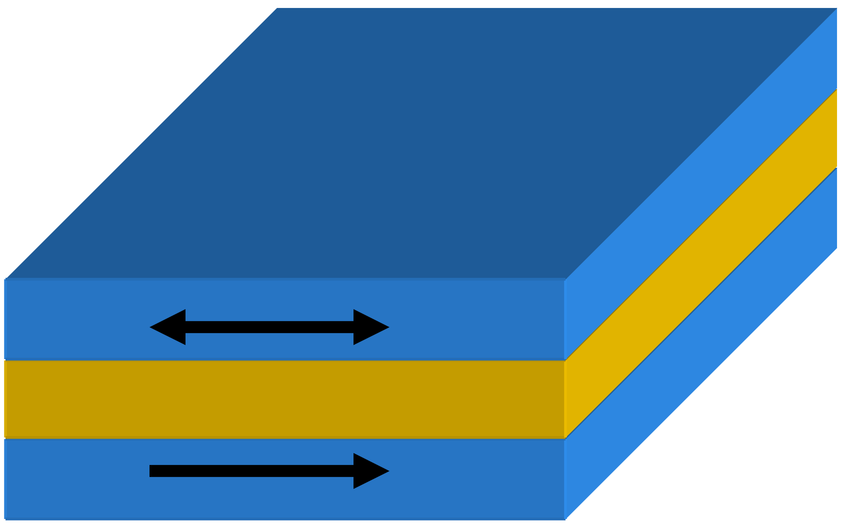
Nanomagnetism: length scales?

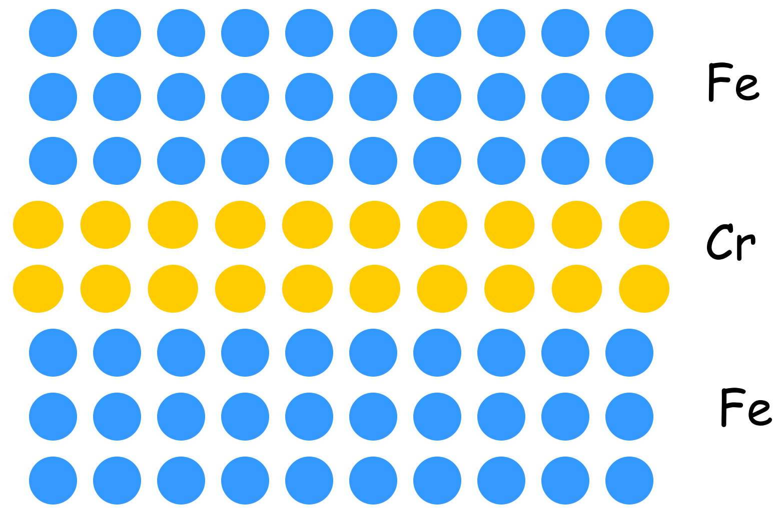
Characteristic length scales (metals)

- exchange and λ_F: <1 nm
  - (semiconductors λ_F ~100 nm)
- e^- mean free path: ~10 nm
- spin diffusion length: 1 – 1000 nm
- RKKY: 0.4 – 5 nm
- exchange length: 5 nm
- Dipolar: all length scales

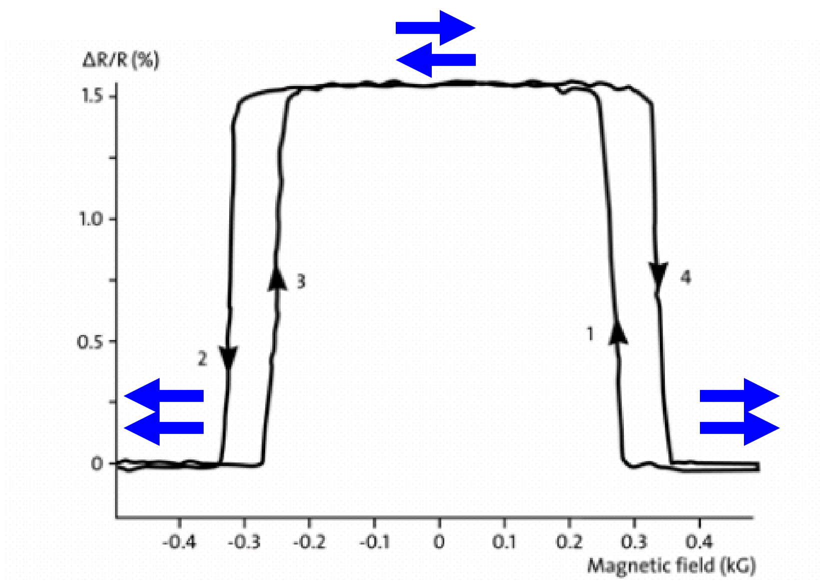
Nano-structures

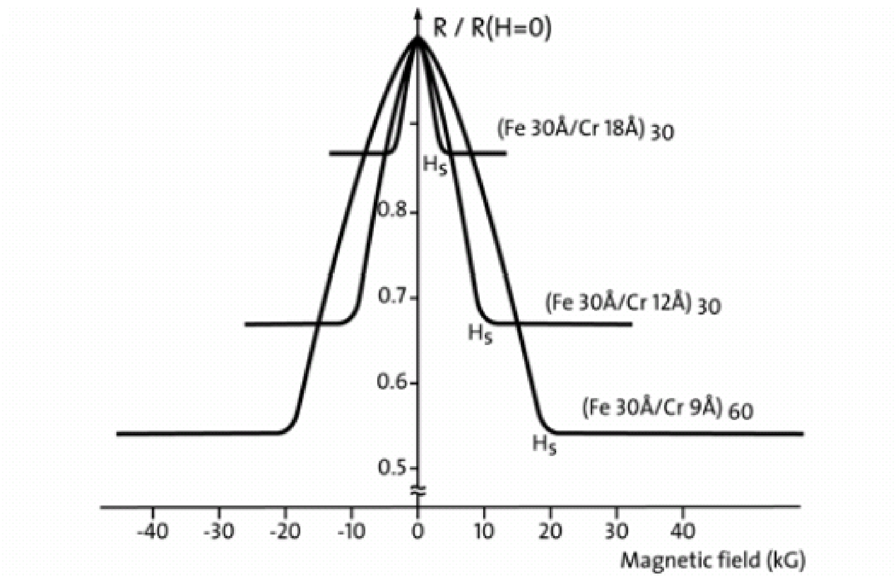
Indirect effects





Giant magnetoresistance (GMR)





VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff

PHYSICAL REVIEW B VOLUME 39, NUMBER 7 1 MARCH 1989

Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn

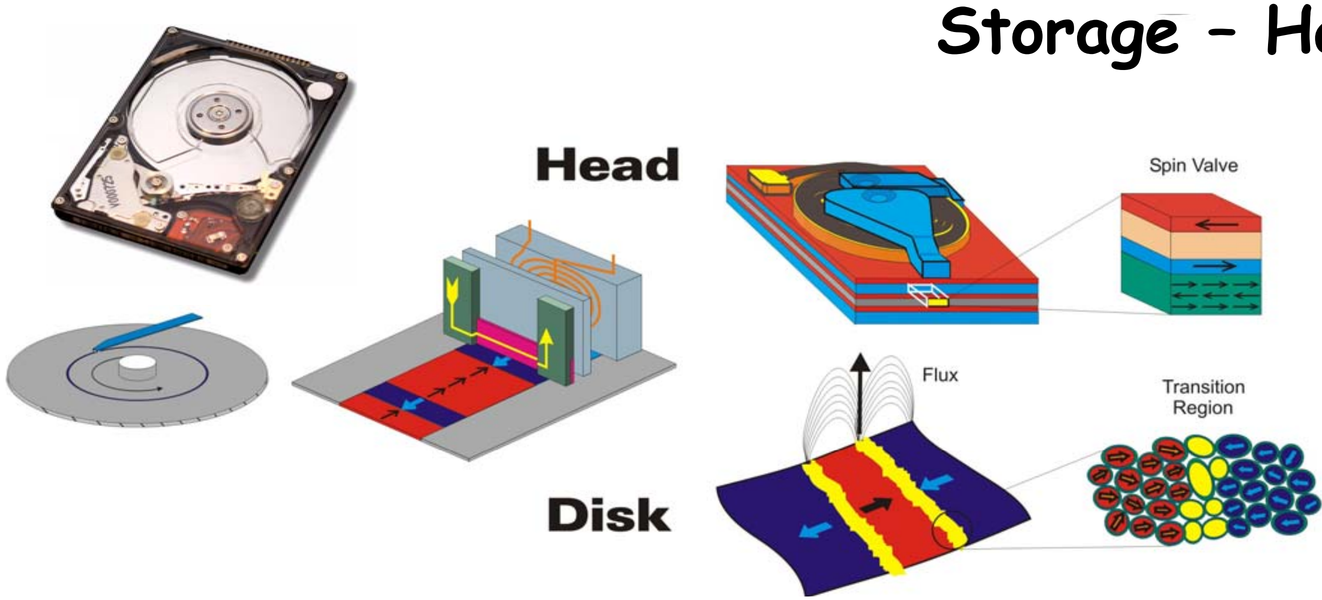
Nobel Prize in Physics 2007

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Peter Grunberg Albert Fert

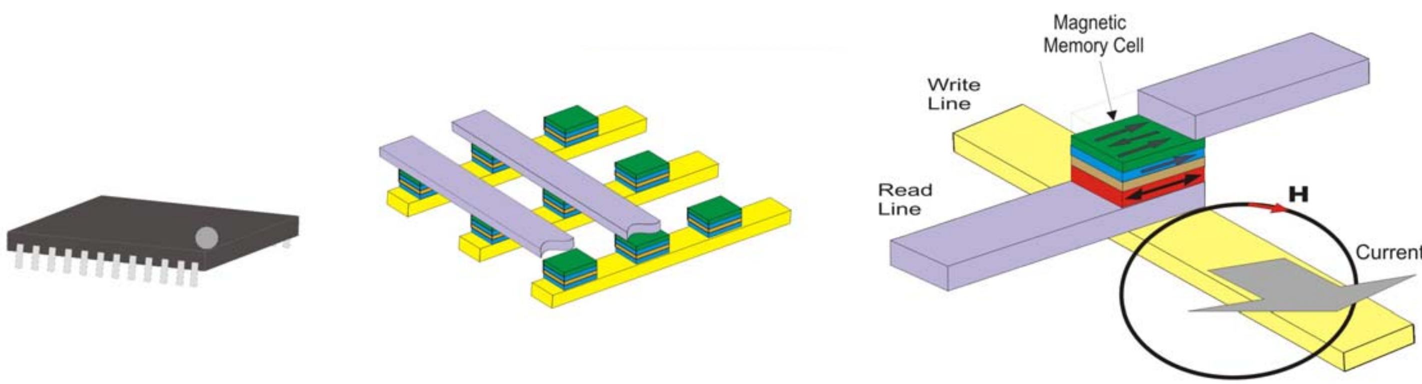
Magnetic Nanotechnologies

Storage – Hard Disk Drive



spatial resolution
σ = 2 nm
temporal resolution
GHz (1 ns)

Memory – MRAM, FeRAM



Magnetic nanostructures

- Important new physics (e.g. Nobel Prize)

- Important technologies
  - Sensors (bio-magnetism, auto, …)
  - IT (storage, memory, processing)
  - Energy efficiency

Magnetic nanostructures

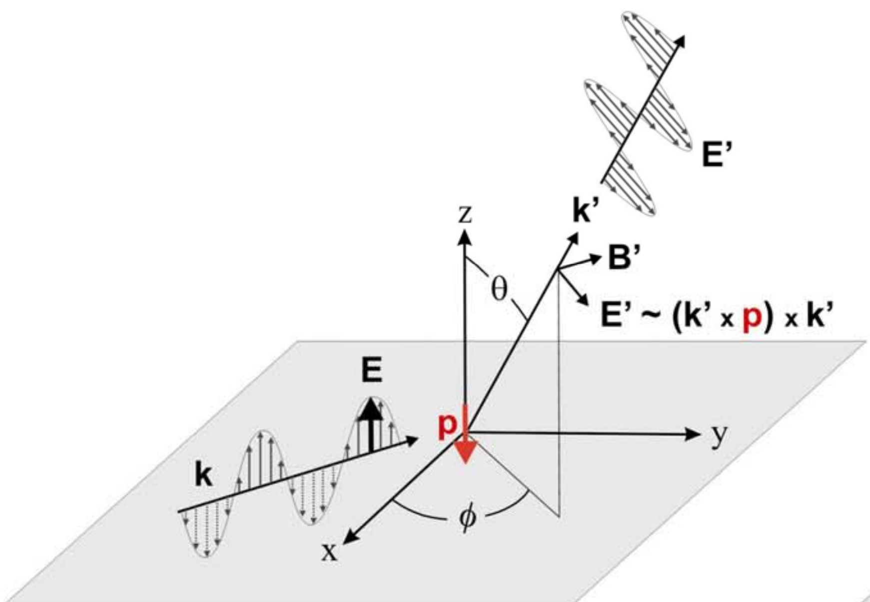
- Want to link structure and magnetism
  - atomic depth resolution
  - <10 nm lateral resolution
  - < 1 ns temporal resolution

- neutrons
- electrons
- scanning probe
- x-rays (and optical light)

(neutrons, electrons, scanning probe: have a spin)

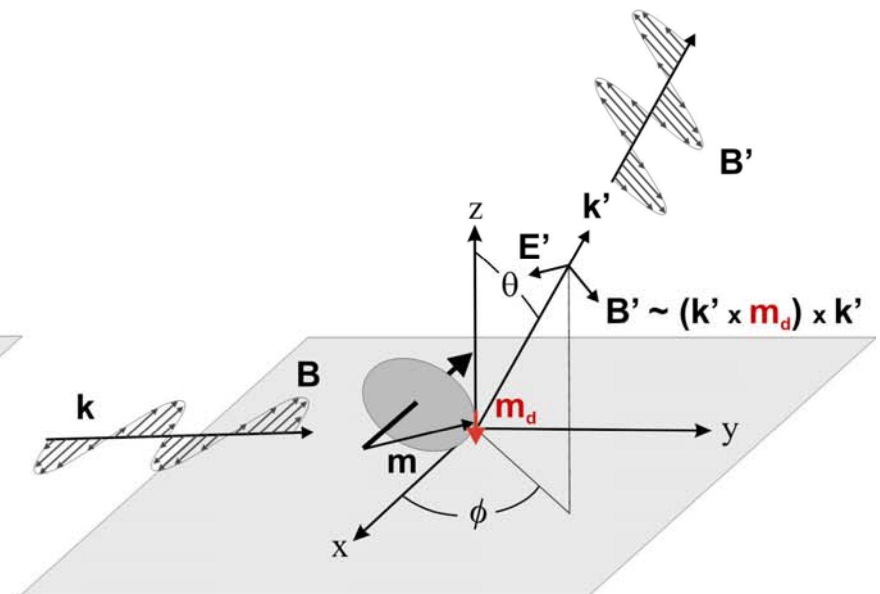
Non-resonant scattering

Electric Dipole Scattering



Relative Intensity: **1**

Magnetic Dipole Scattering

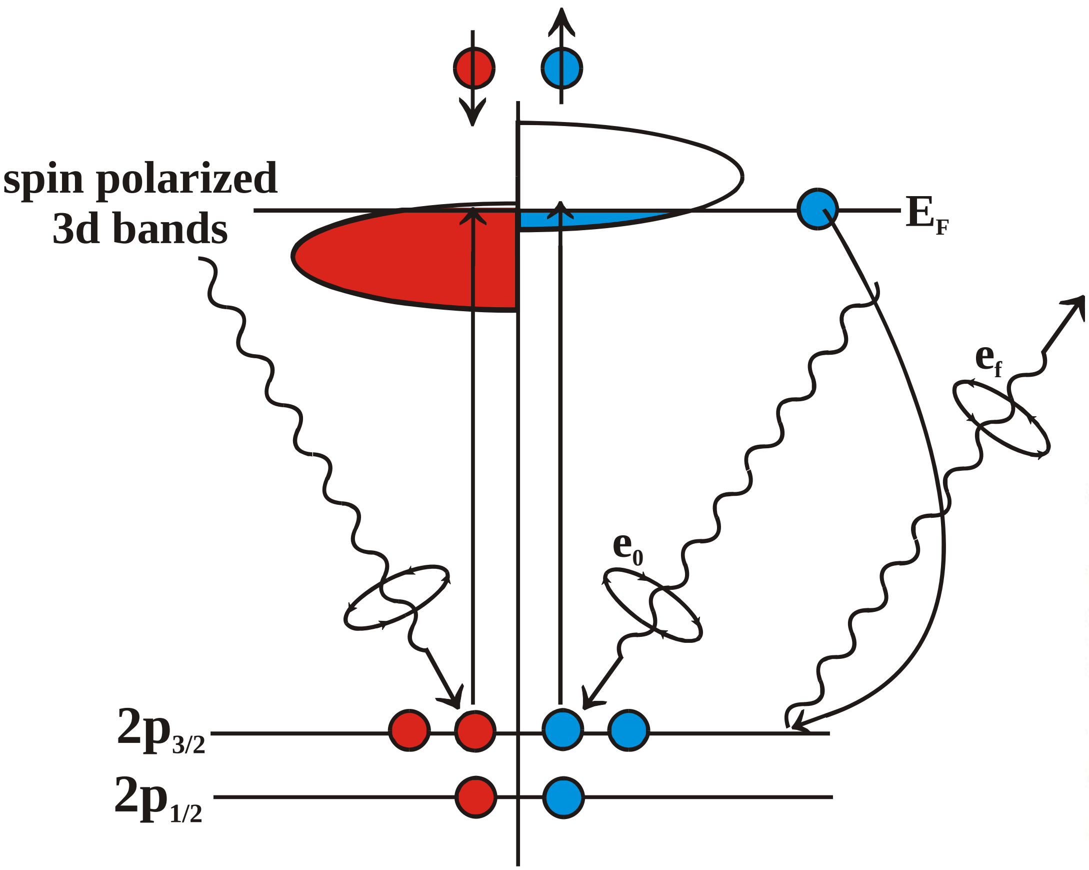


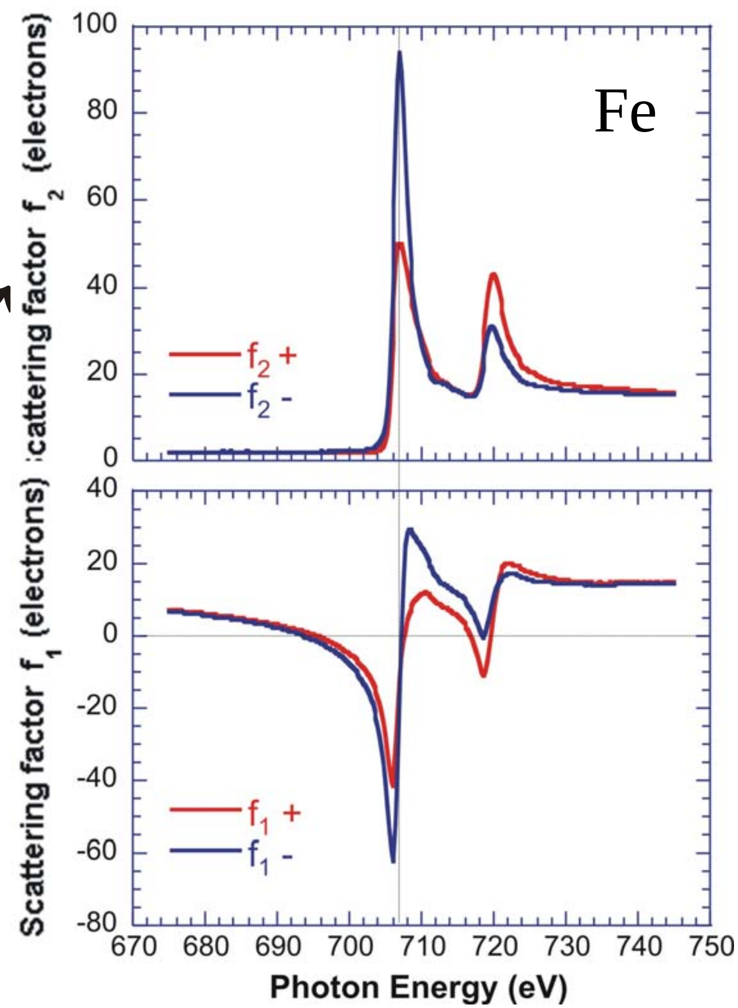
Relative Intensity: $\mathbf{(h\nu / mc^2)^2}$

$h\nu \sim 10$ keV, $mc^2 = 500$ keV

X-rays typically are not very sensitive to magnetism

Core level resonances





$$f = f_1 + if_2$$

Kortright *et al.*, Phys. Rev. B **65**, 12216 (2000)

Soft x-ray techniques

- 3d-transition metal L-edges 2p → 3d transitions (550-900 eV)
- rare-earth M-edges   3d → 4f transitions (800-1600 eV)

  $\lambda = 1 – 2$ nm

- tuning energy gives element specificity
- tuning polarization gives magnetic specificity

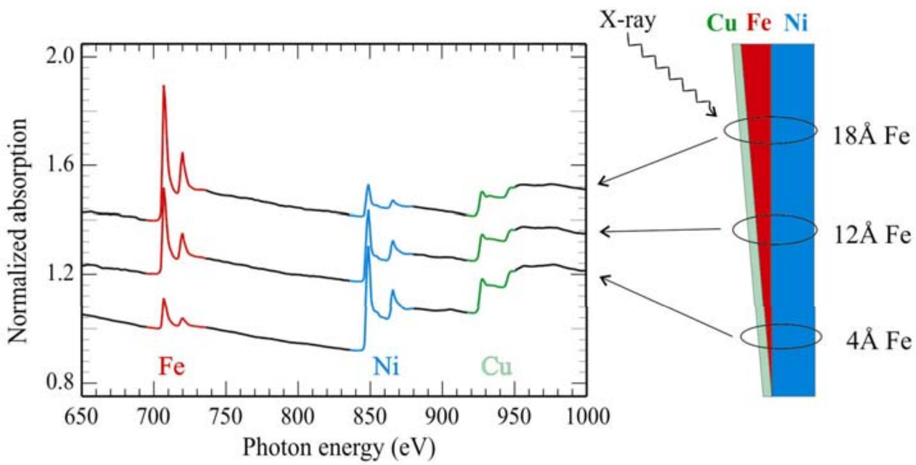
- Various spectroscopy, imaging, optical and scattering techniques with nm resolution

  For reviews see

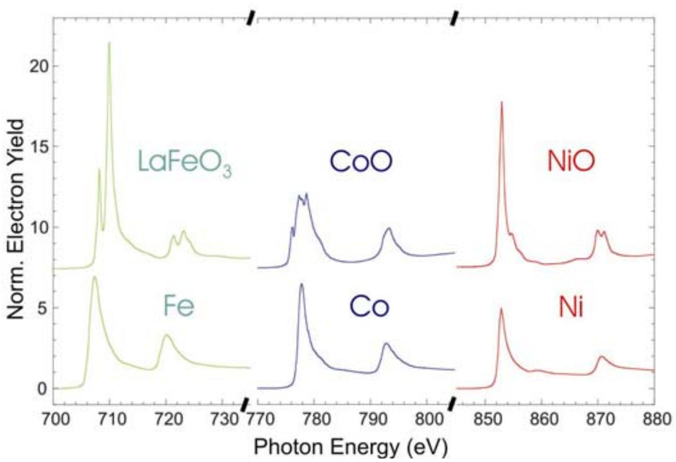
  - Kortright *et al*, J. Magn. Magn. Mater. **207**, 7 (1999).
  - Srajer *et al*, J. Magn. Magn. Mater. **307**, 1-36 (2006).

Elemental and chemical sensitivity

X-rays can pick materials apart: layer-by-layer



X-rays offer chemical sensitivity



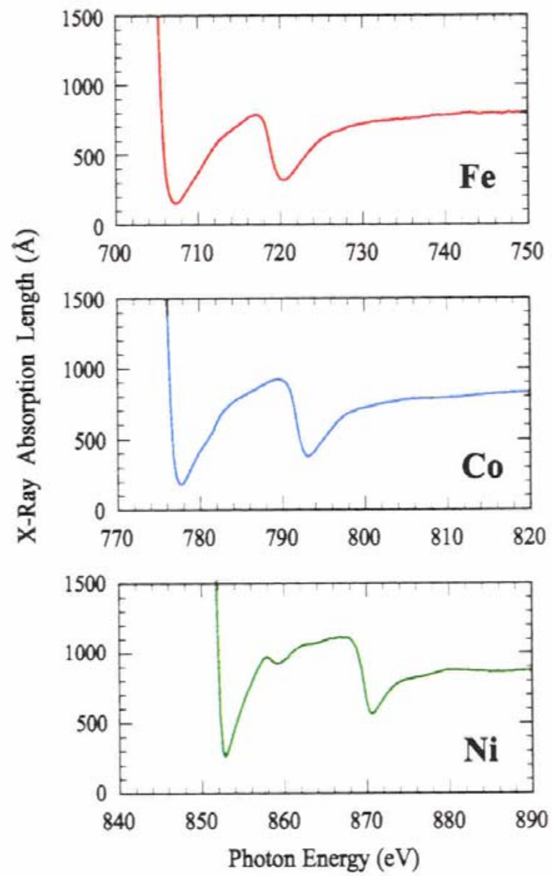


Fig. 8. X-ray absorption length ($1/e$ attenuation) for Fe, Co and Ni in the L edge region.[37] The absorption lengths in the pre-edge regions (not shown) are about 600 nm.

Stohr *et al.*, Surf. Rev. Lett. **5**, 1297 ('98).

Spectroscopy

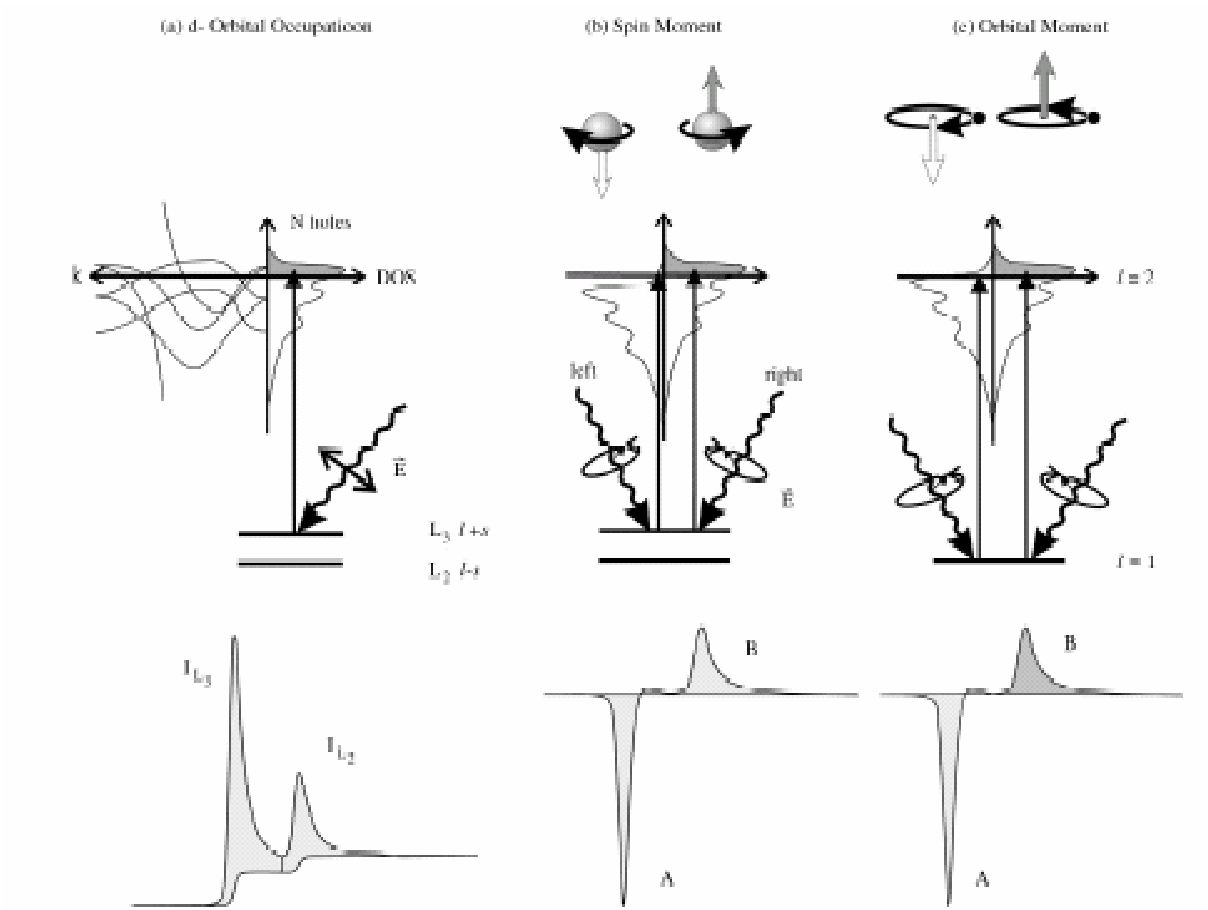


Fig. 1. (a) Electronic transitions in conventional L-edge X-ray absorption, (b) and (c) X-ray magnetic circular dichroism, illustrated in a one-electron model. The transitions occur from the spin–orbit split 2p core shell to empty conduction band states above the Fermi level. In conventional X-ray absorption the transition intensity measured as the white line intensity $I_{L_3} + I_{L_2}$ is proportional to the number of d holes, N. By use of circularly polarized X-rays the spin moment (b), and orbital moment (c), can be determined from the dichroic difference intensities A and B, as explained in the text.

J. Stohr, JMMM 200, 470 (97).

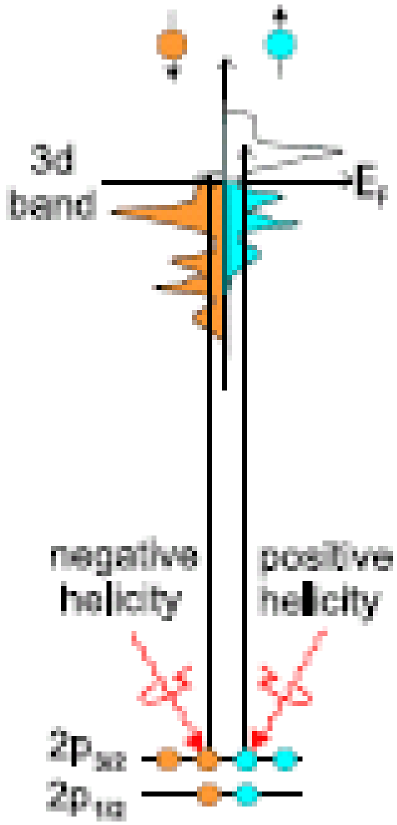
Measures average Properties

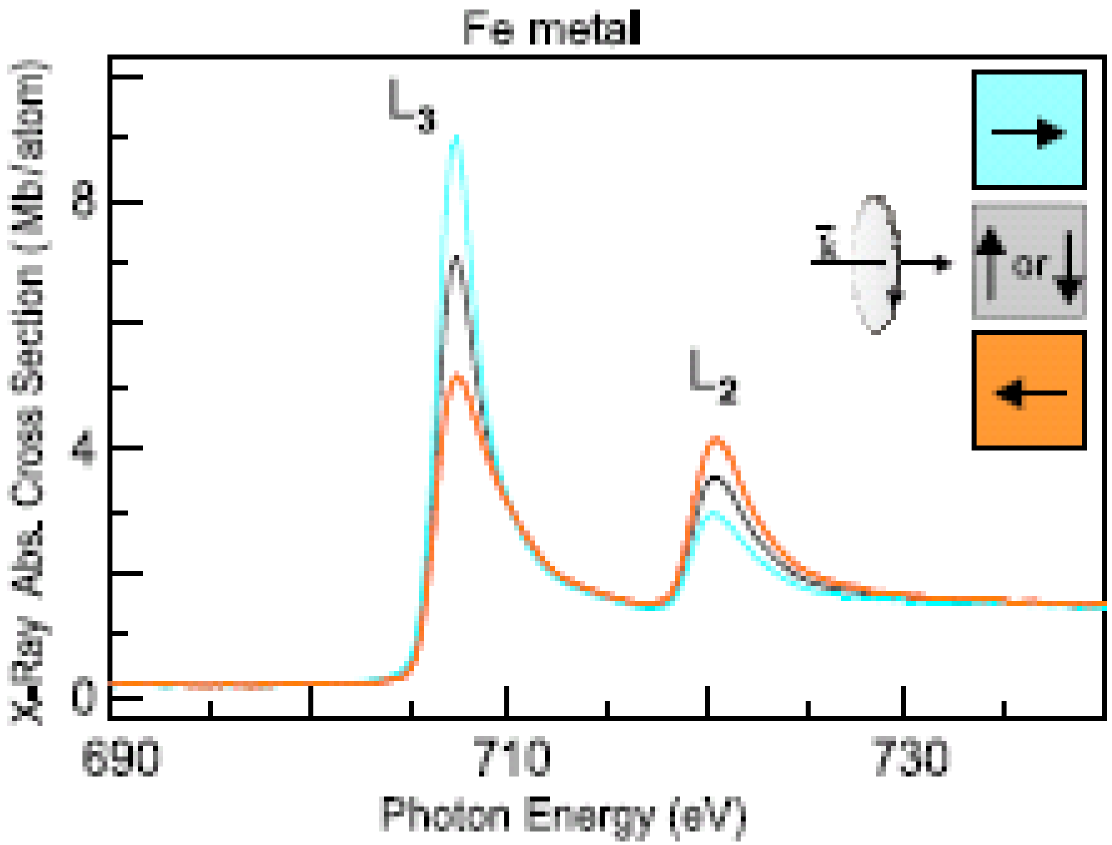
MCD (magnetic circular dichroism)

e.g.

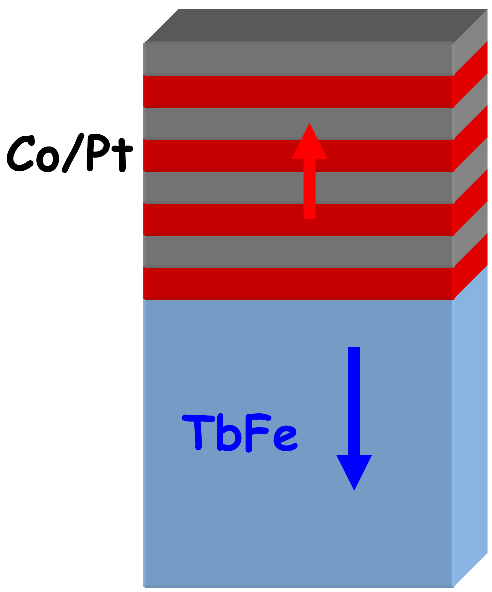
- d-band filling
- Moment
  - spin
  - orbital
- hysteresis loops

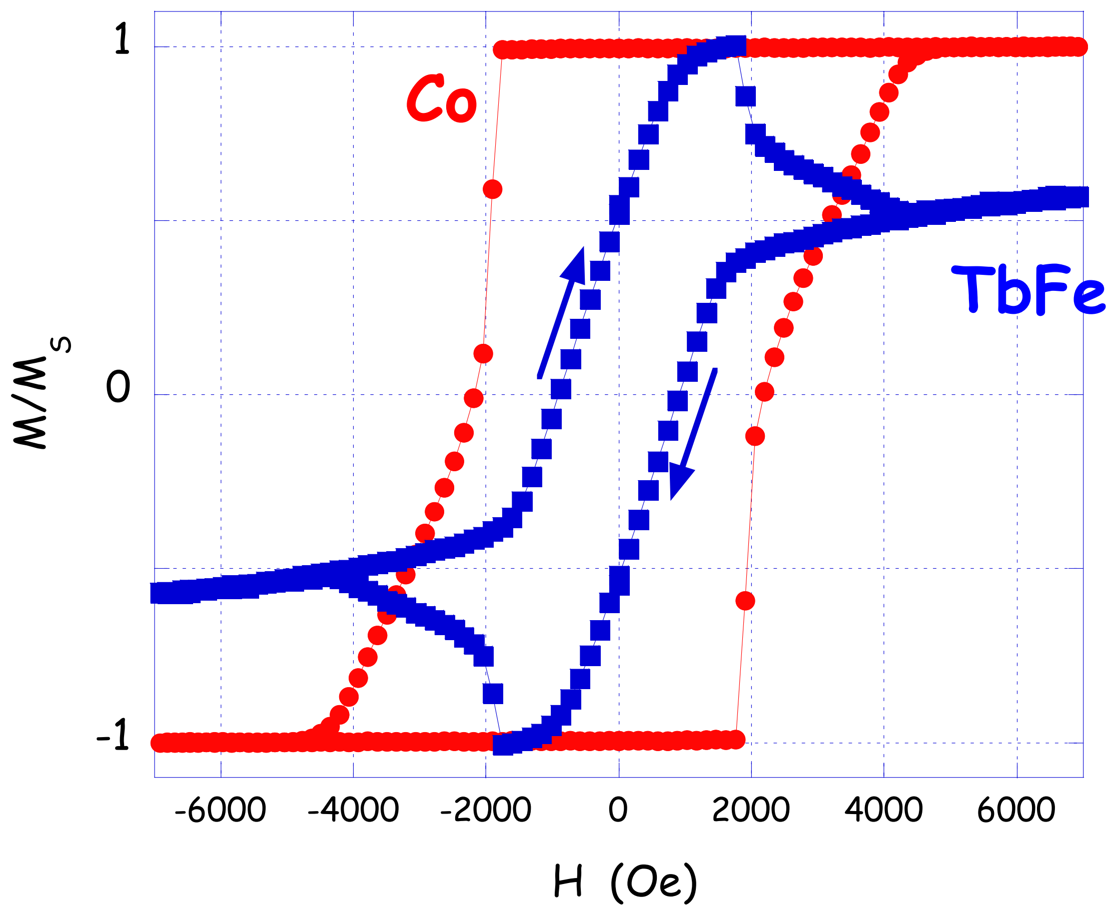
Element specific magnetometry





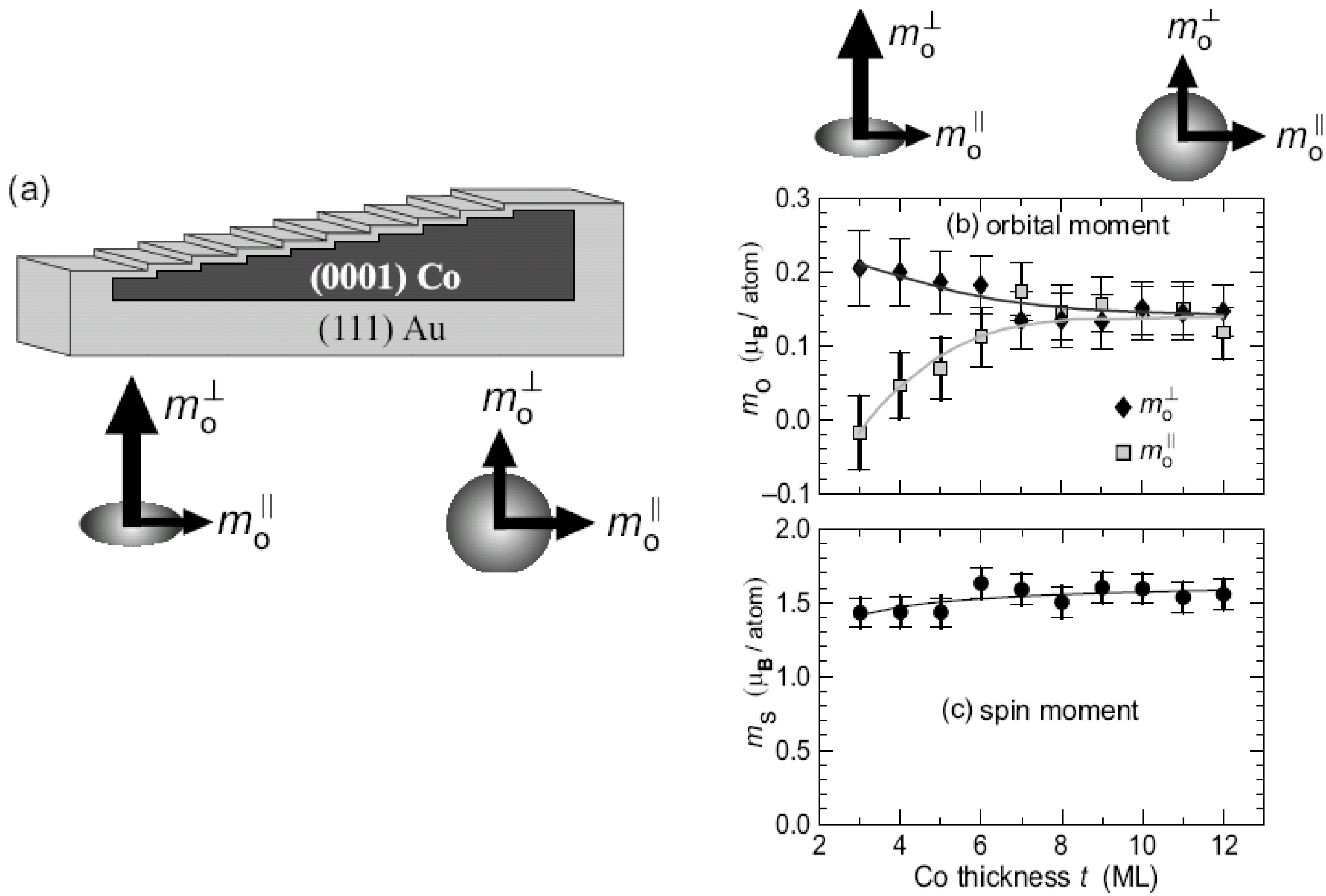
Elemental and chemical sensitivity





S. Mangin et al., Phys. Rev. B **78**, 024424 (2008)

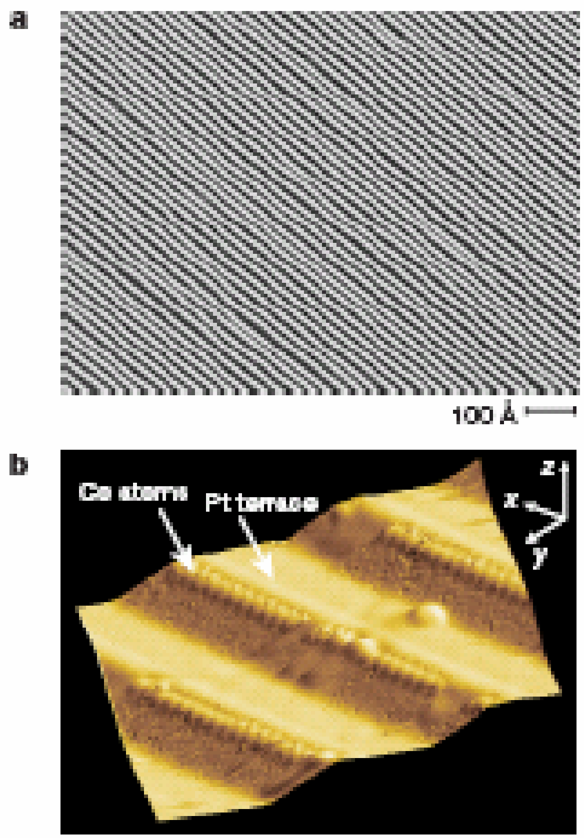
Spin and orbital moments



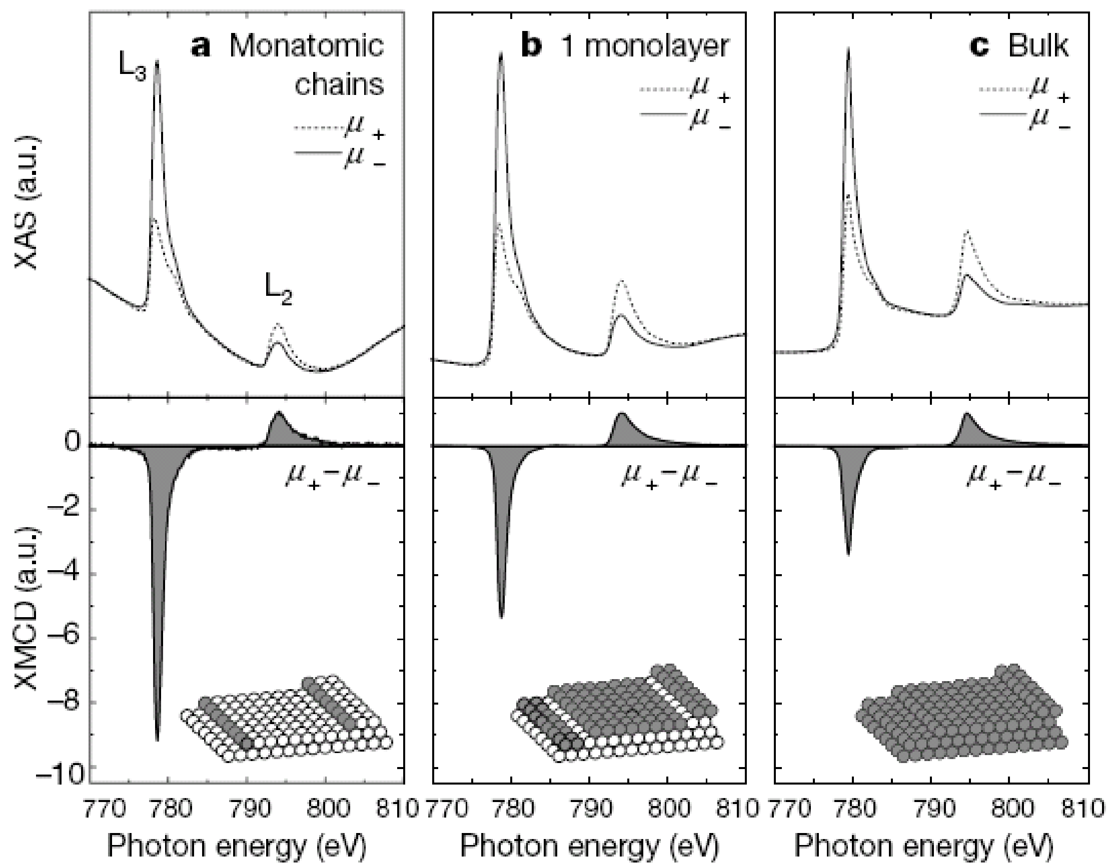
Spin and orbital moments

Ferromagnetism in one-dimensional monatomic metal chains

Gambardella, *et al.*, Nature **416**, 301 (2002)

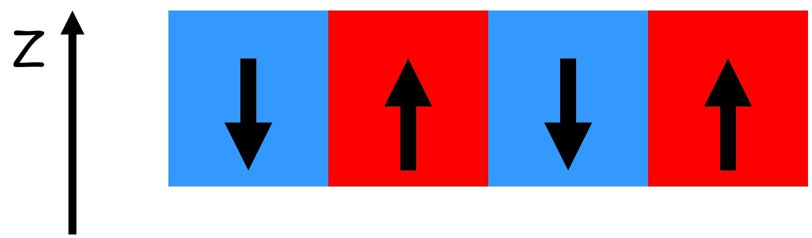


$m_L = 0.68\ \mu_B$ $0.31\ \mu_B$ $0.14\ \mu_B$



Spatial sensitivity

Spectroscopy gives you and average response of the atoms in systems

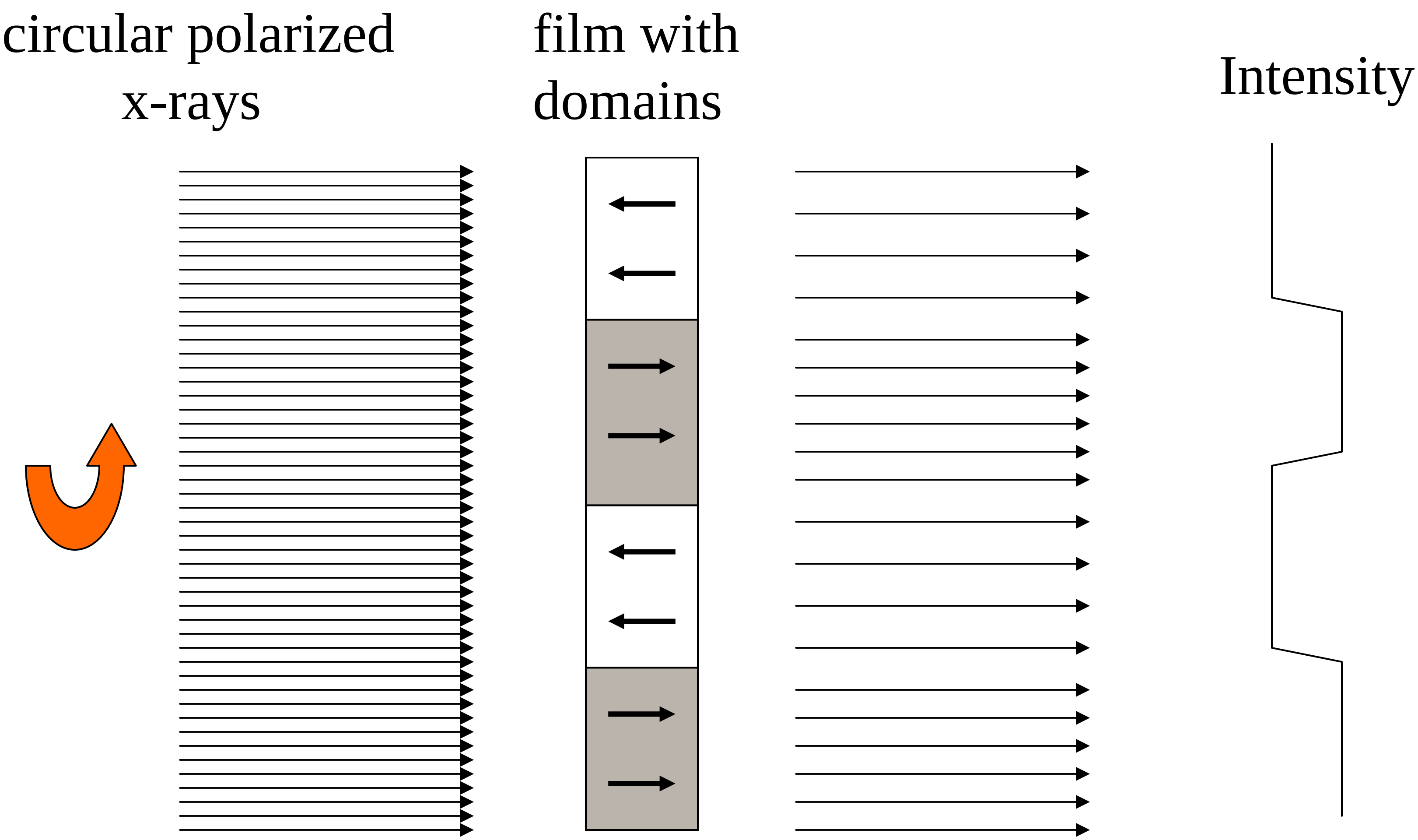


$M_Z = 0$

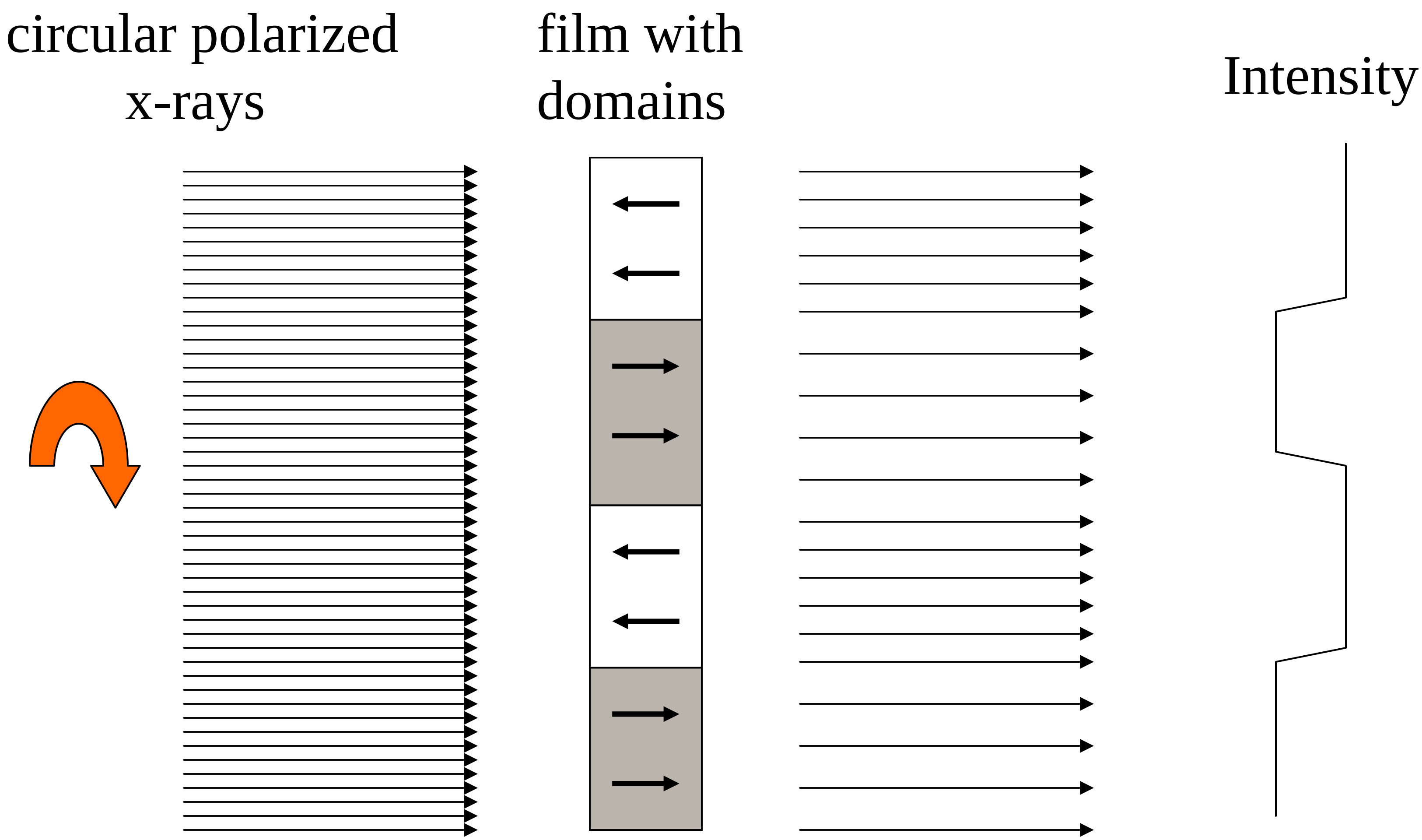
$M_Z = 0$

Spatial variations require either imaging or scattering

Magnetic Microscopy

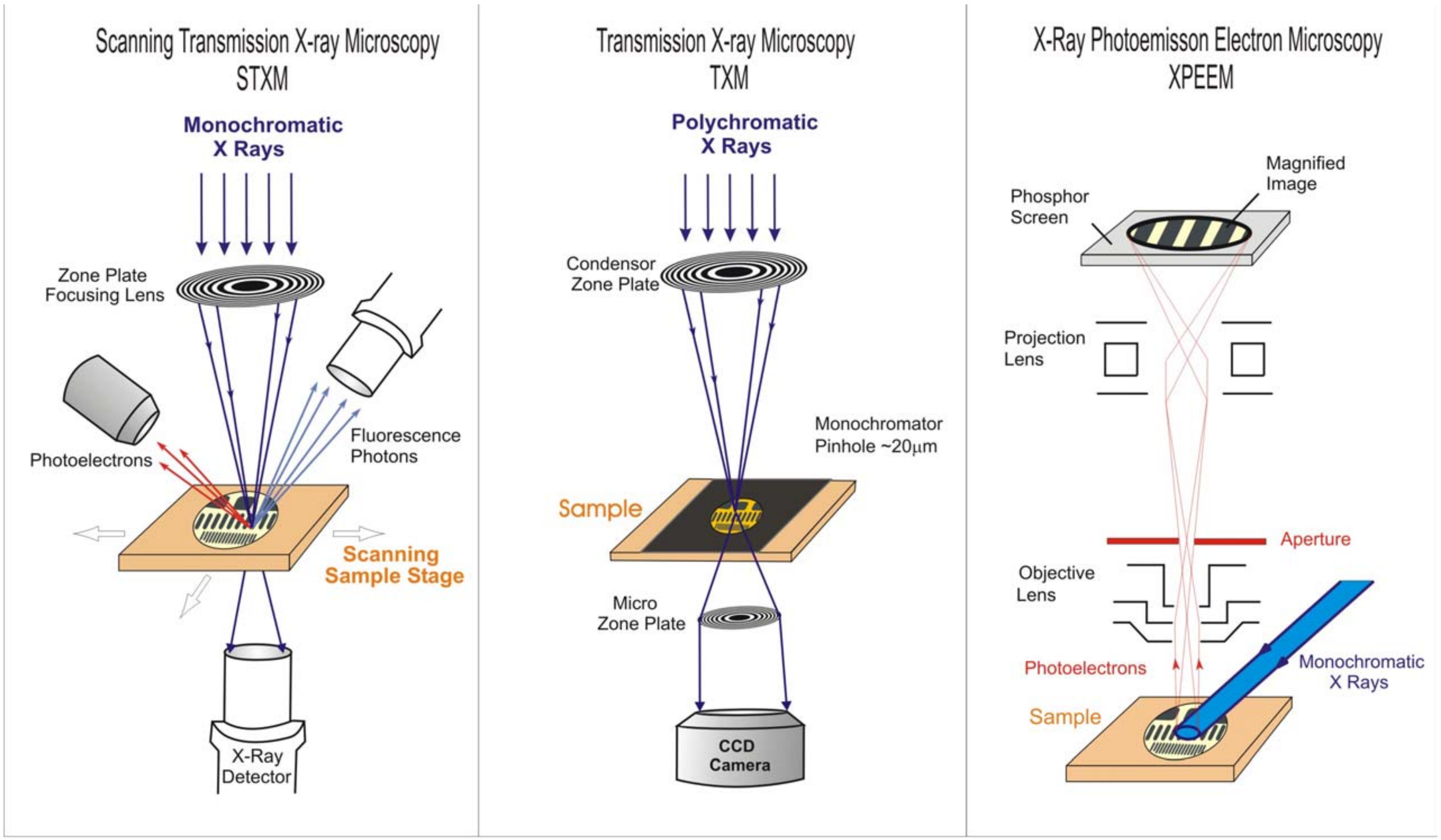


Magnetic Microscopy



Magnetic contrast is the difference of the left and right circular polarization

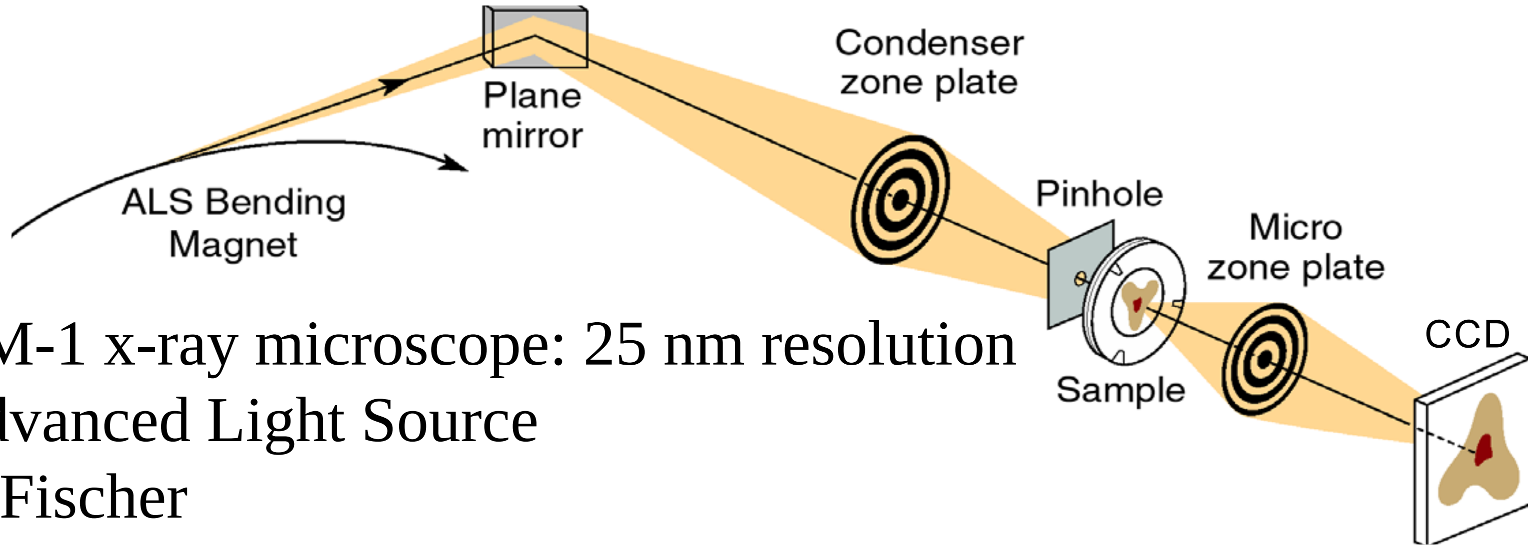
Microscopes at the ALS



Present resolution in the 20 - 40 nm range

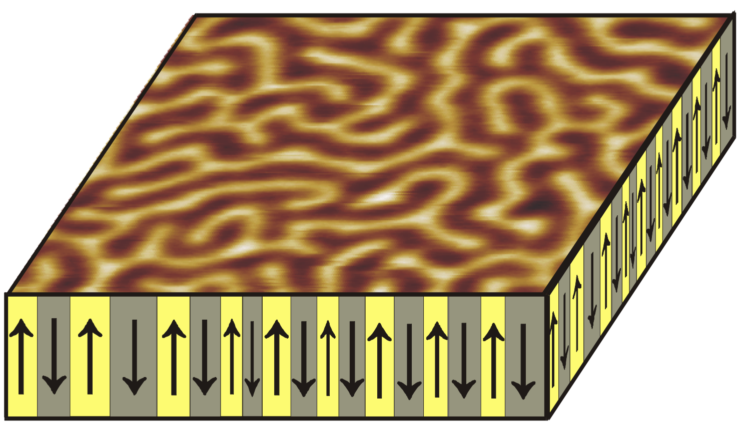
http://www-als.lbl.gov/als/microscopes/index.html

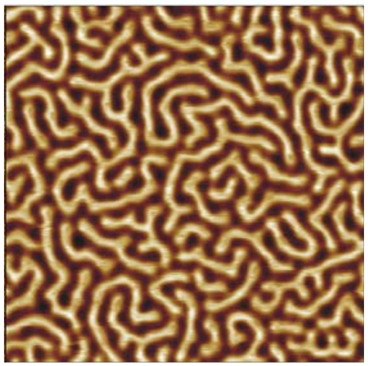
Domains in Co/Pt ML's



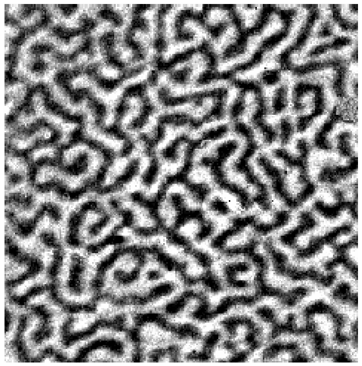
XM-1 x-ray microscope: 25 nm resolution
Advanced Light Source
P. Fischer

Co/Pt multilayer



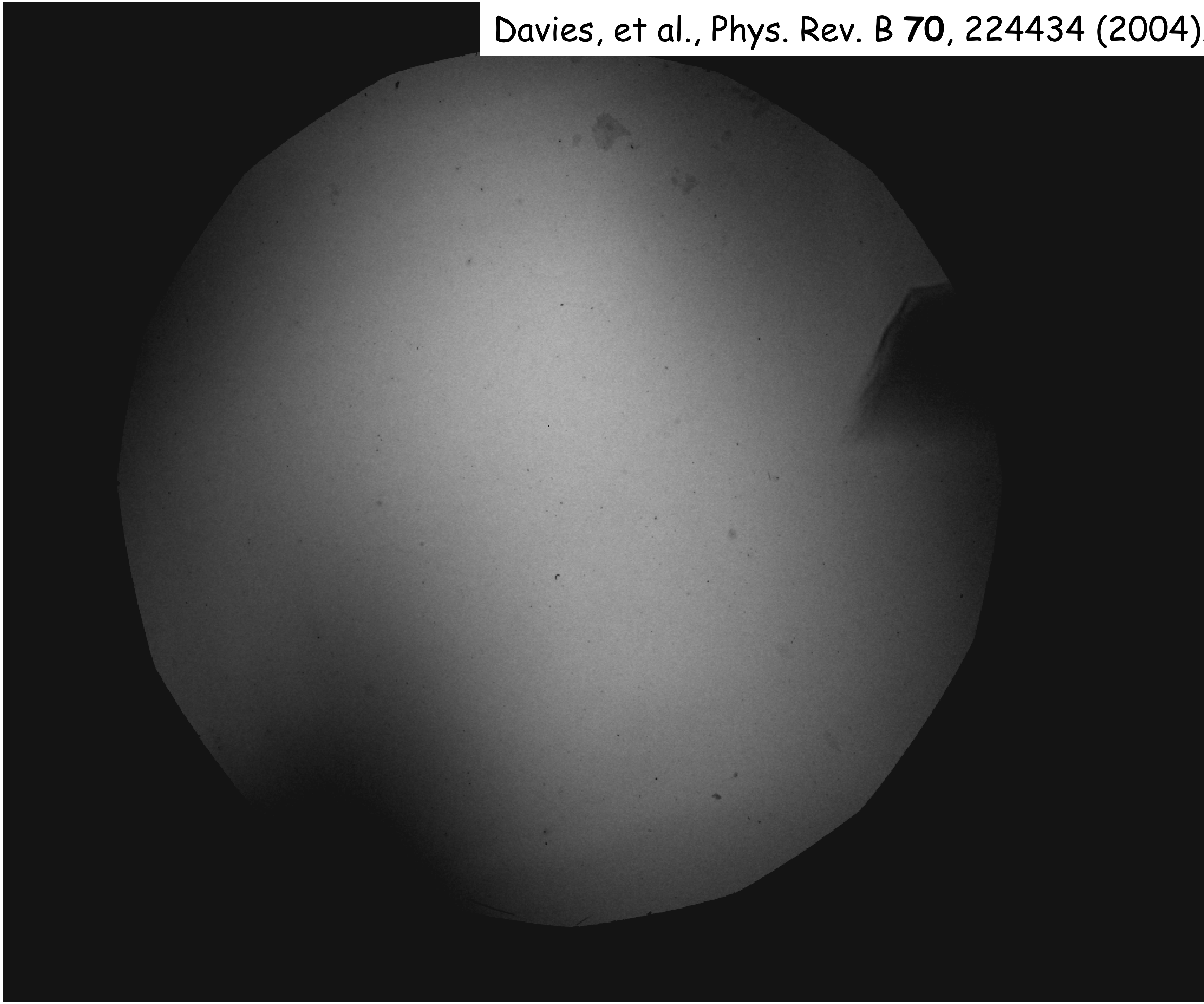


MFM
stray fields



XM-1
magnetization

Davies, et al., Phys. Rev. B **70**, 224434 (2004).

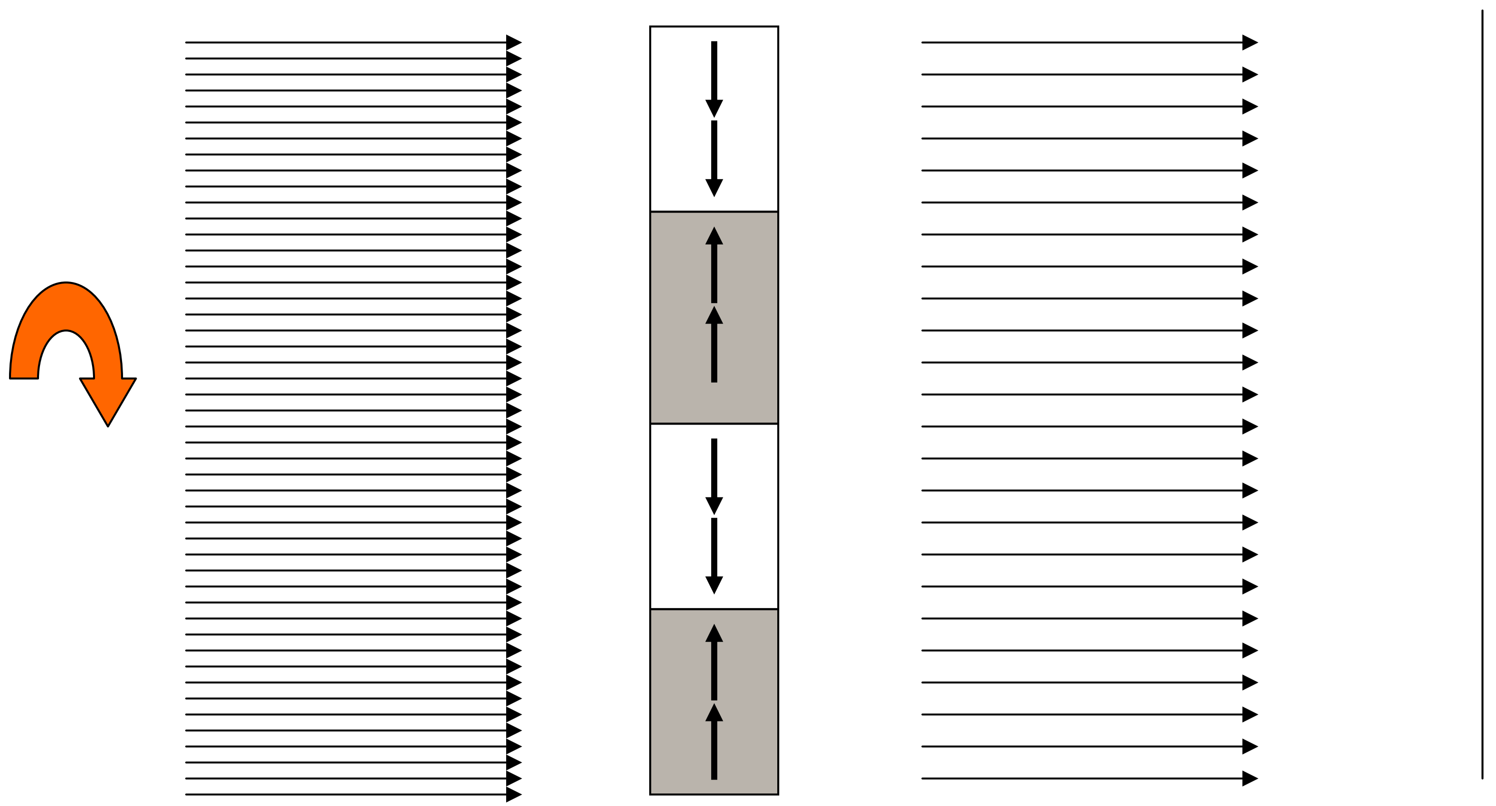


Vector magnetic microscopy

circular polarized x-rays

film with domains

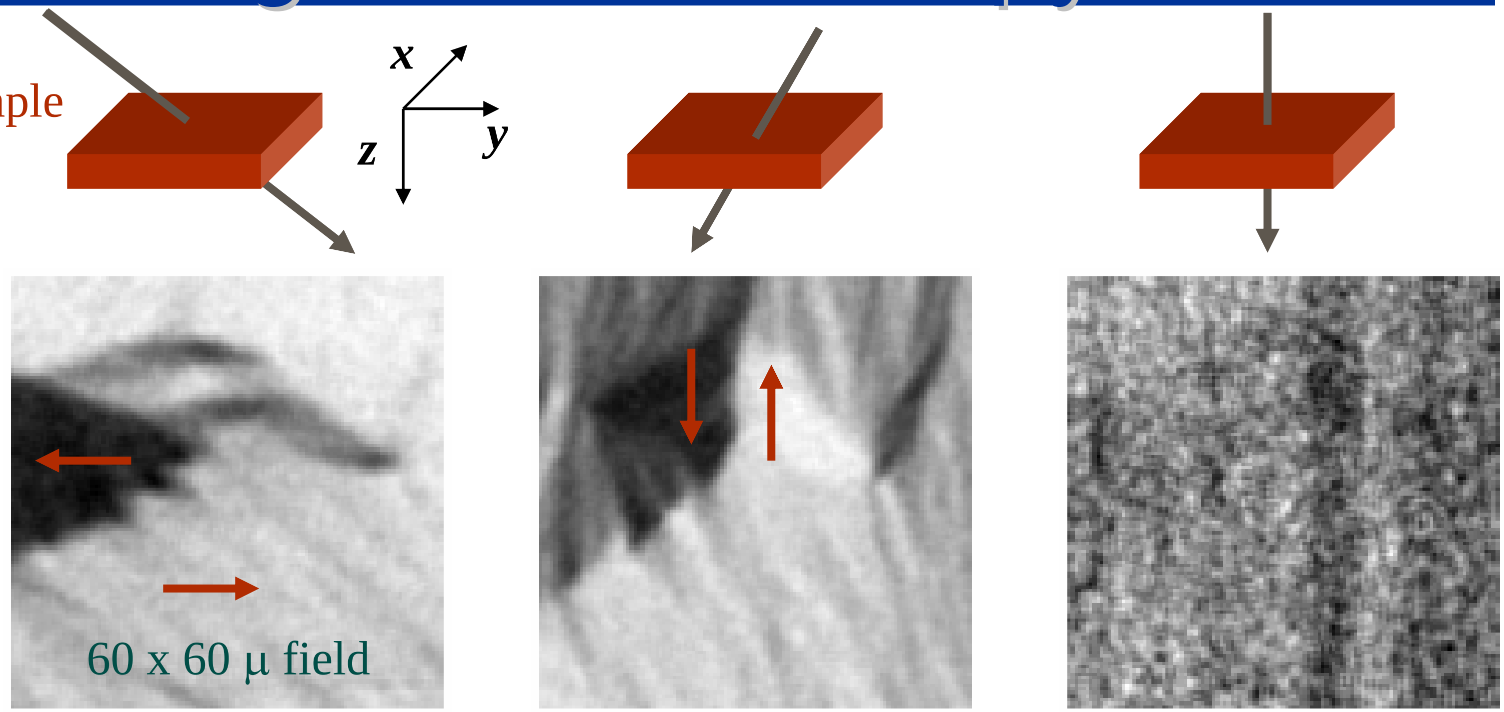
Intensity



Vector magnetic microscopy

33 nm Fe sample

Difference Images Δμ/<μ>



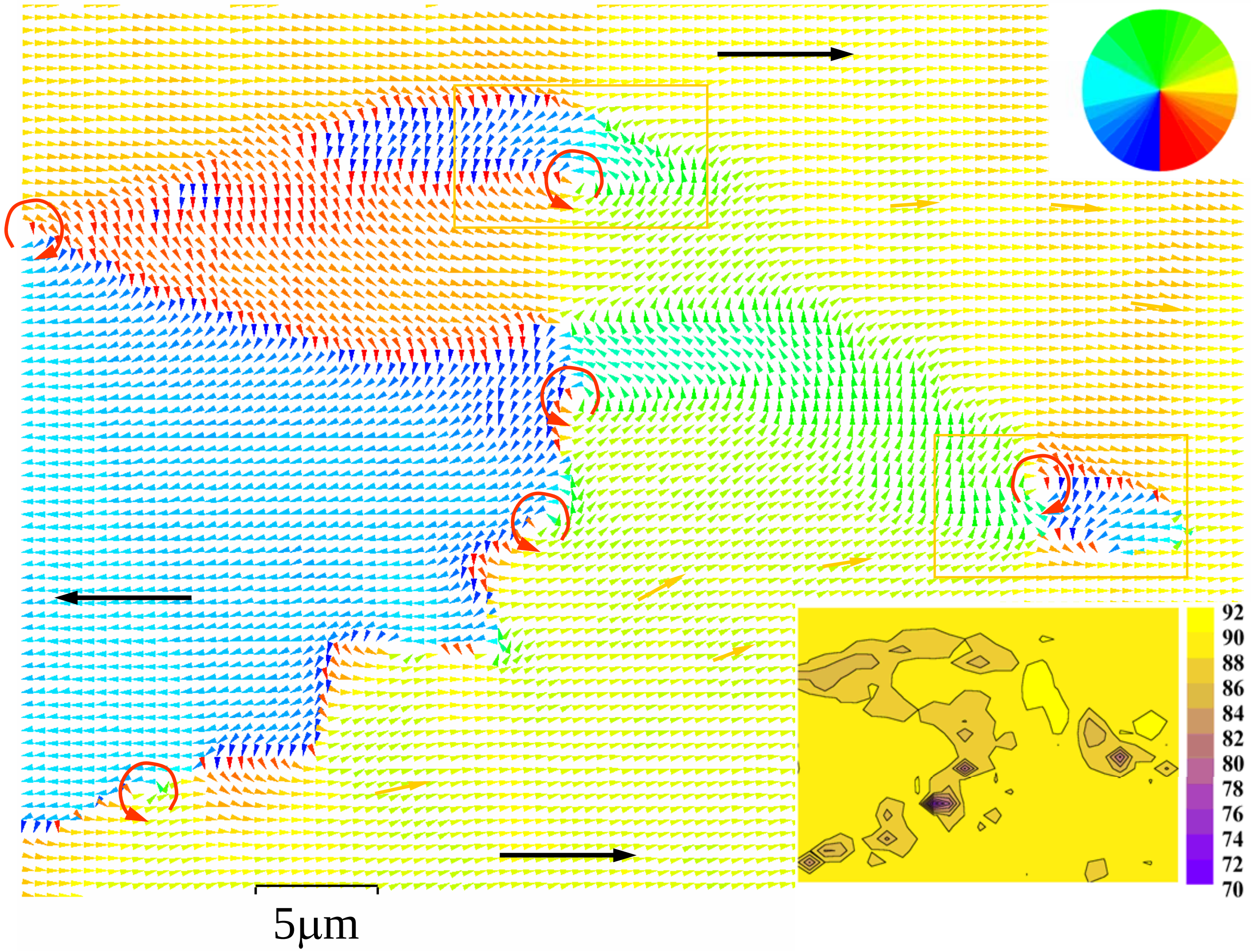
$$\begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = \begin{pmatrix} k_{1x} & k_{1y} & k_{1z} \\ k_{2x} & k_{2y} & k_{2z} \\ k_{3x} & k_{3y} & k_{3z} \end{pmatrix}^{-1} \begin{pmatrix} \Delta\mu_1 \\ \Delta\mu_2 \\ \Delta\mu_3 \end{pmatrix}$$

$$|\mathbf{M}| = (M_x{}^2 + M_y{}^2 + M_z{}^2)^{1/2}$$

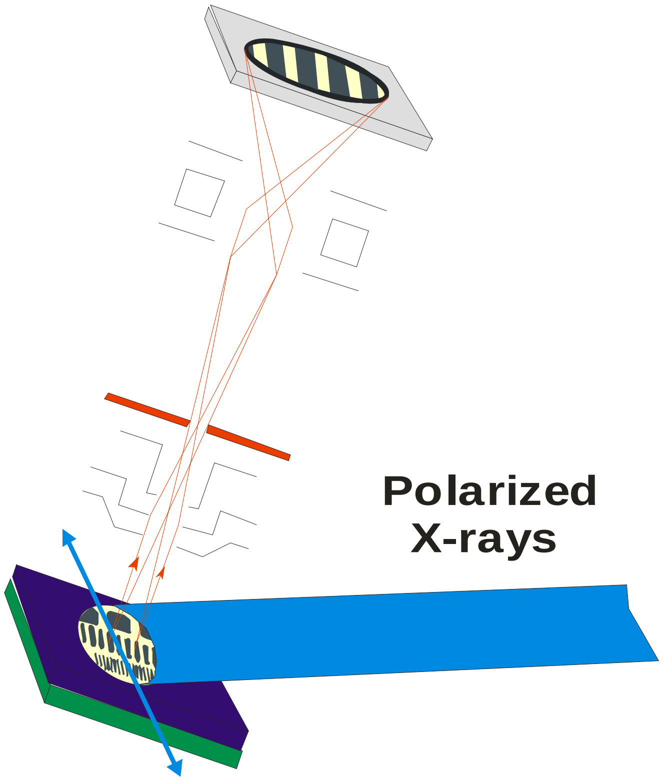
S. K. Kim and J. B. Kortright, Appl. Phys. Lett. 78, 2742 (2001)

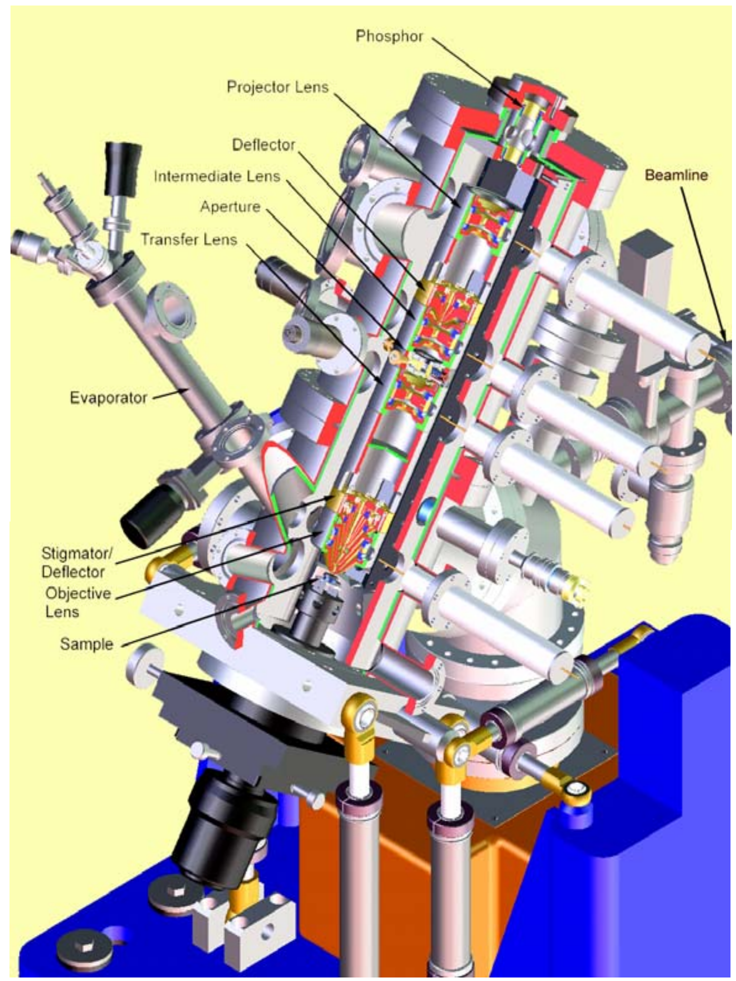
Vector magnetic microscopy

S. K. Kim and J. B. Kortright, Appl. Phys. Lett. 78, 2742 (2001)



Domains in $LaFeO_3$/Co films

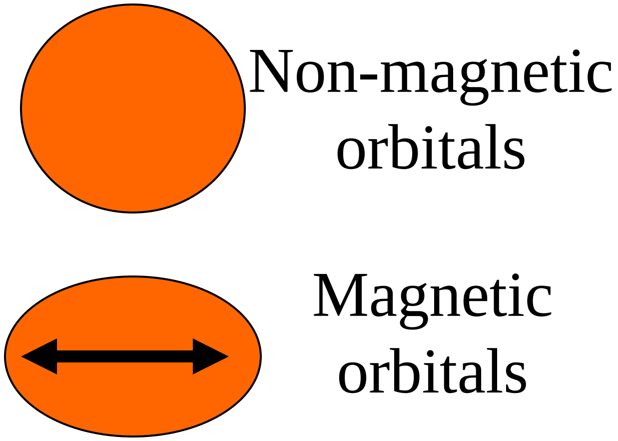


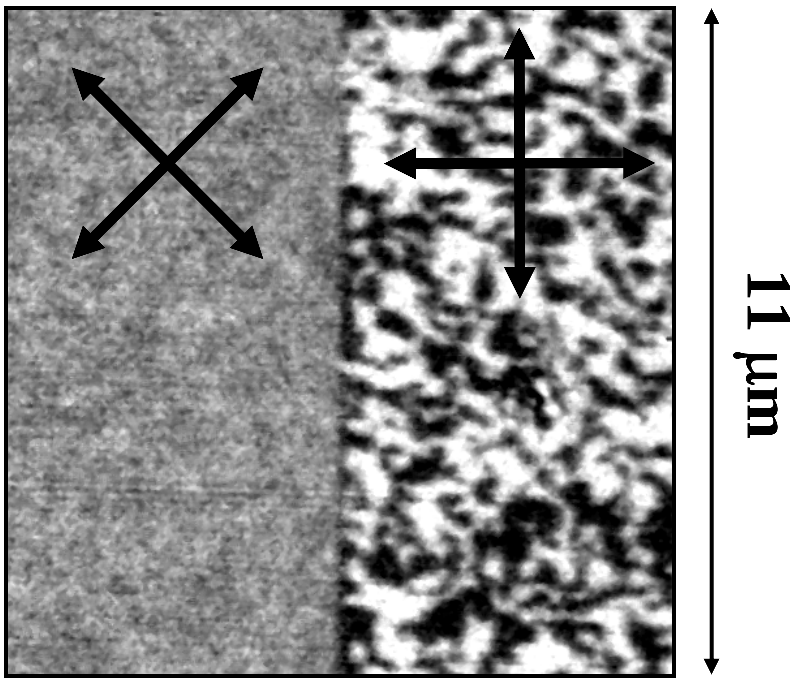


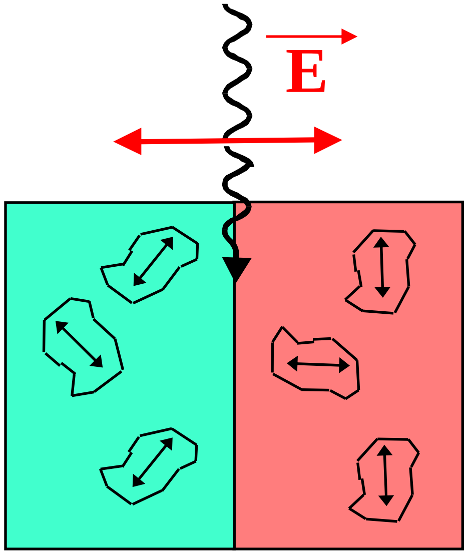
- Full Field Imaging
- Electrostatic (30 kV)
- 20 - 50 nm Resolution
- Linear and circular polarization

Domains in $LaFeO_3$ films

$LaFeO_3$ is an antiferromagnetic material





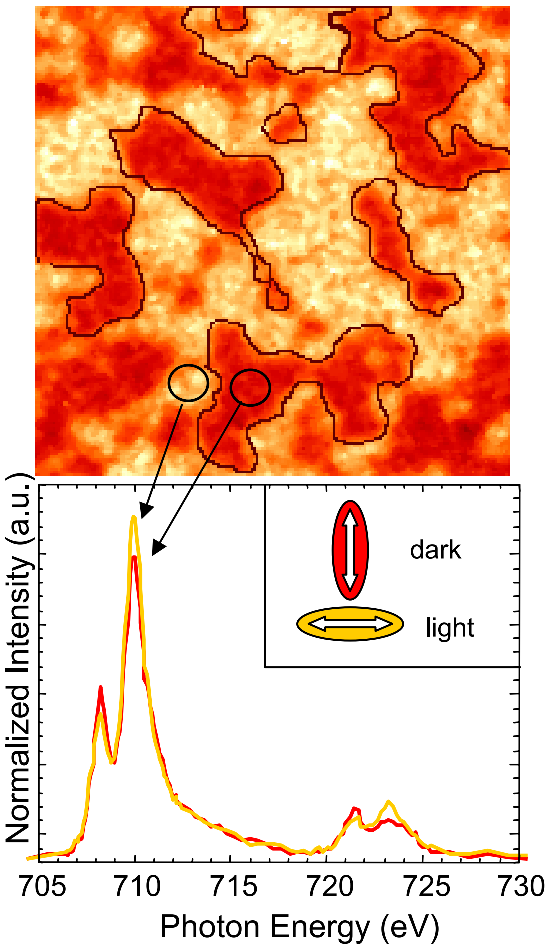


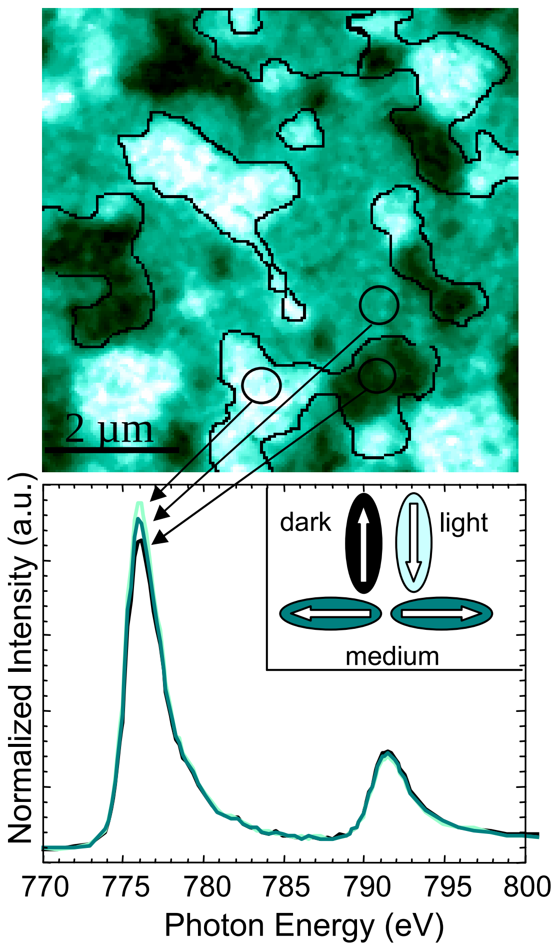
Scholl *et al.*, Science **287**, 1014 (2000)

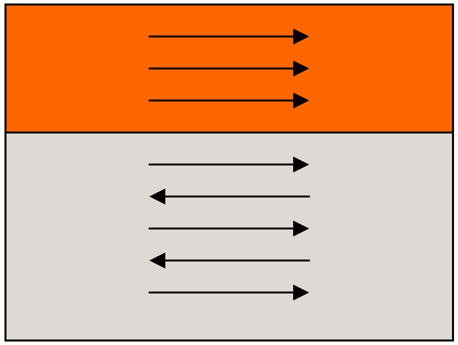
Domains in $LaFeO_3$/Co films

a) $LaFeO_3$ layer

b) Co layer

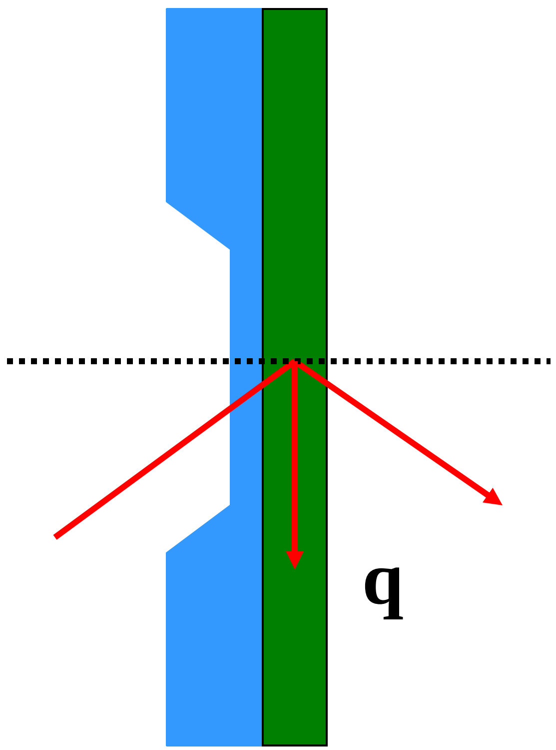






Nolting *et al*., Nature **405**, 767 (2000)

Small-angle scattering (SAS)

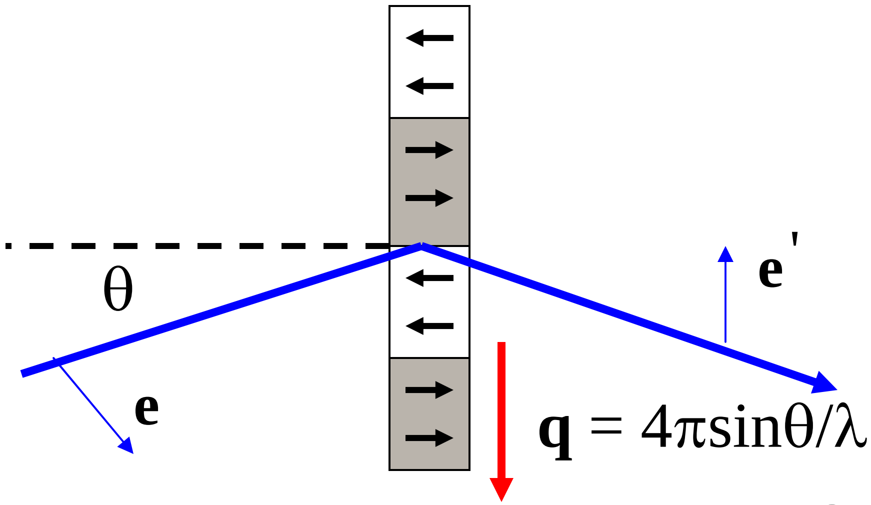


scattering arises from in-plane inhomogeneities (2-300 nm)

- Microstructure
  - Grains
  - Chemical segregation
  - lithography
- Magnetic disorder (*e.g.* domains)

Kortright et al., Phys. Rev. B **64**, 092401 (2001)

Magnetic domain scattering



charge magnetic -XMCD

$$f_n = \mathbf{e}\cdot\mathbf{e}\,F_n^{(0)} - i(\mathbf{e}'\times\mathbf{e})\cdot\mathbf{M}_n F_n^{(1)}$$

$$\mathrm{I} = \left|\sum_n f_n \exp(i\mathbf{q}\cdot\mathbf{r}_n)\right|^2$$

magnetic scattering

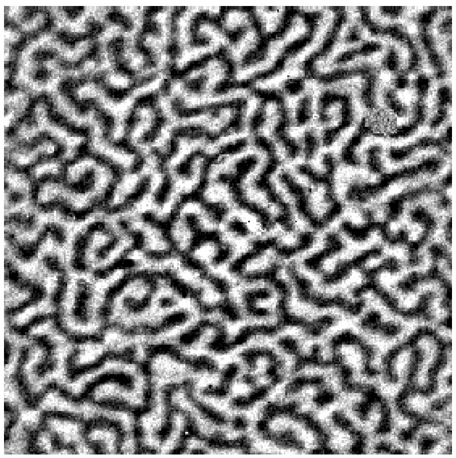
$$f_n \sim \mathbf{M}_n$$

Scattering ~ |Fourier Transform|^2 of the domains

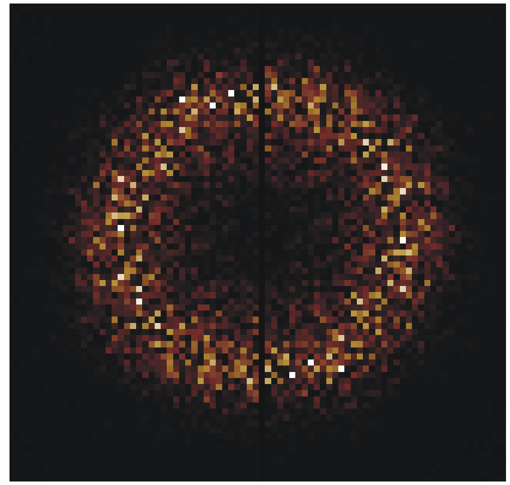
Real vs. reciprocal space

Domains in a Co/Pt ML

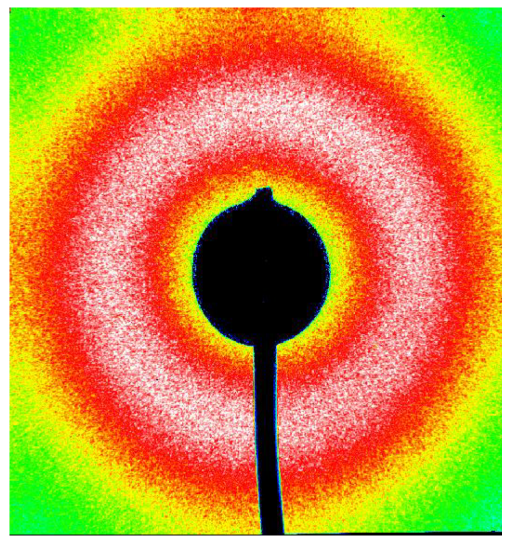
5 x 5 μm^2



XM-1
Imaging x-ray microscope

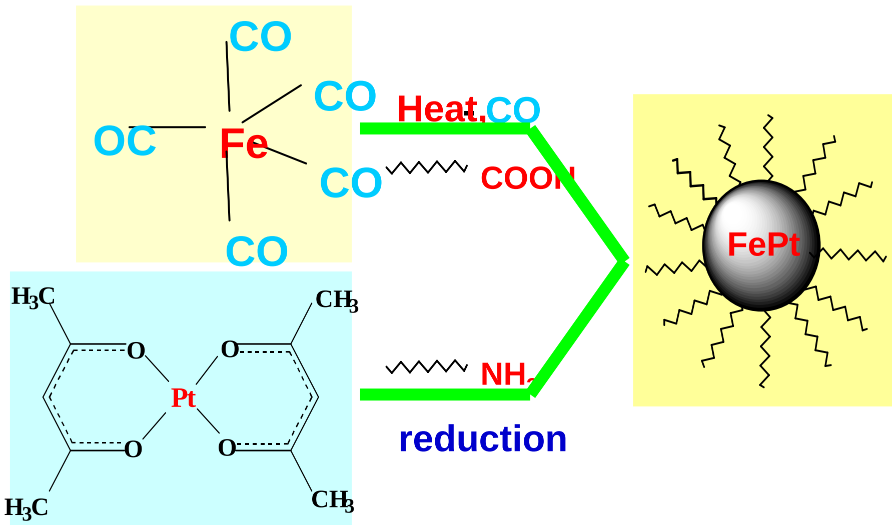


FT

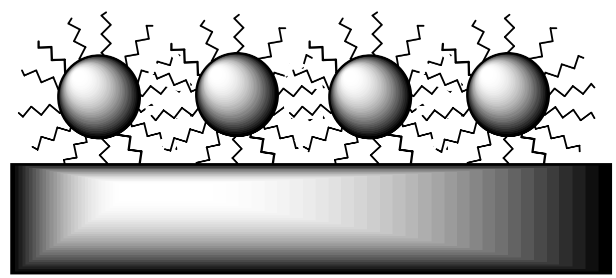


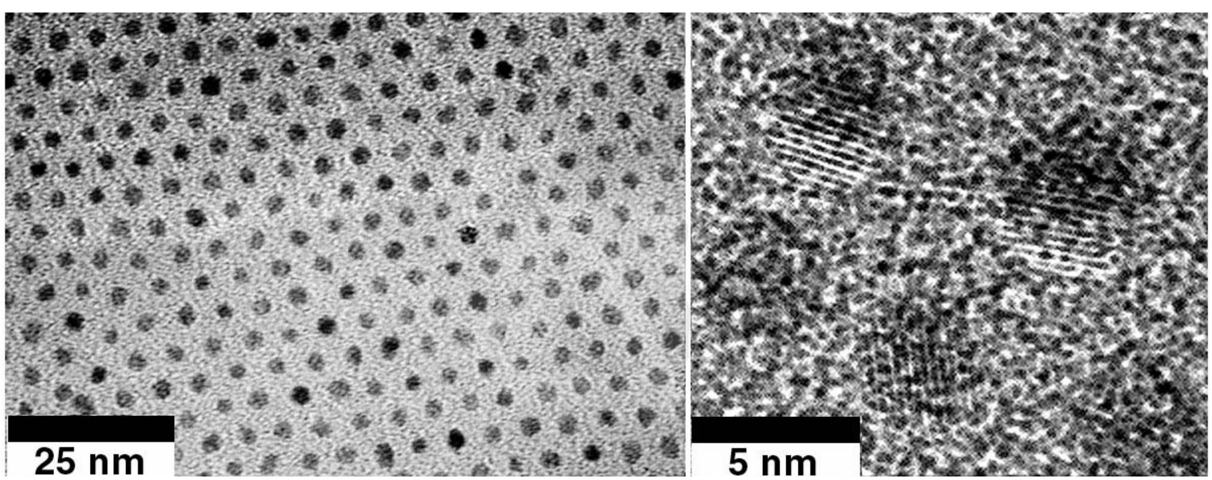
Magnetic SAS
$\sim |FT|^2$

Example: nanoparticle arrays



particles are coated with Oleic acid and oleyl amine

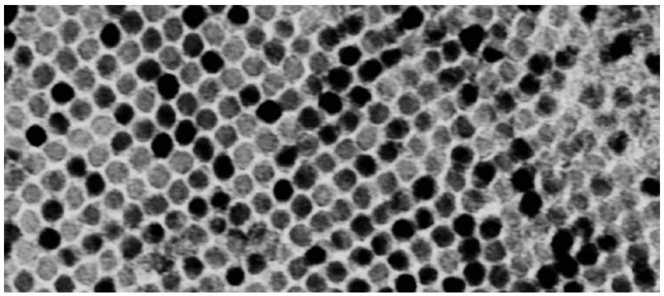


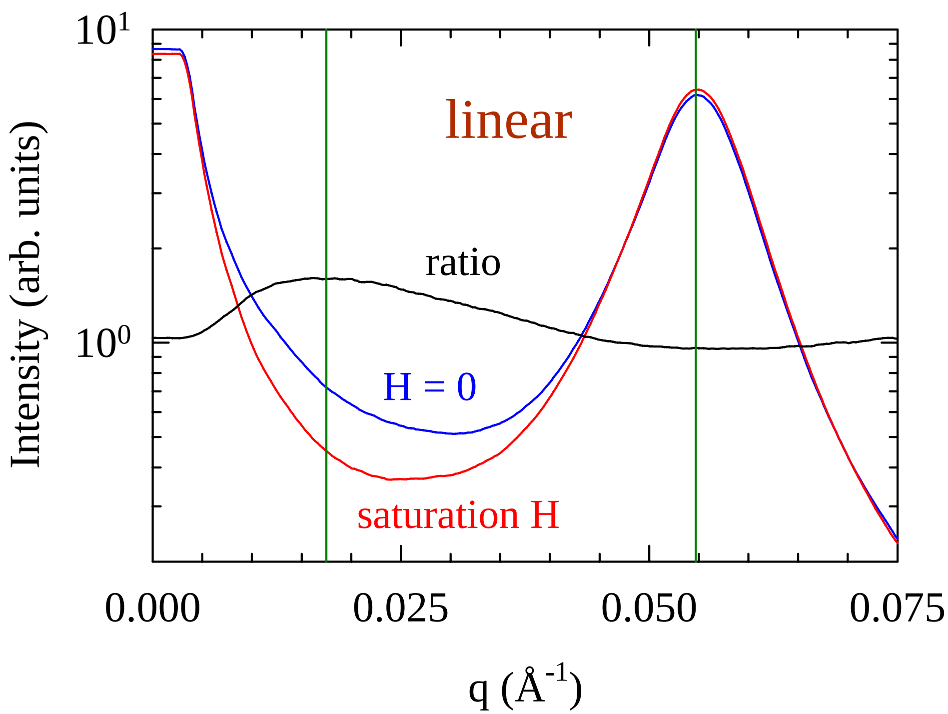


Tune: particle size and separation

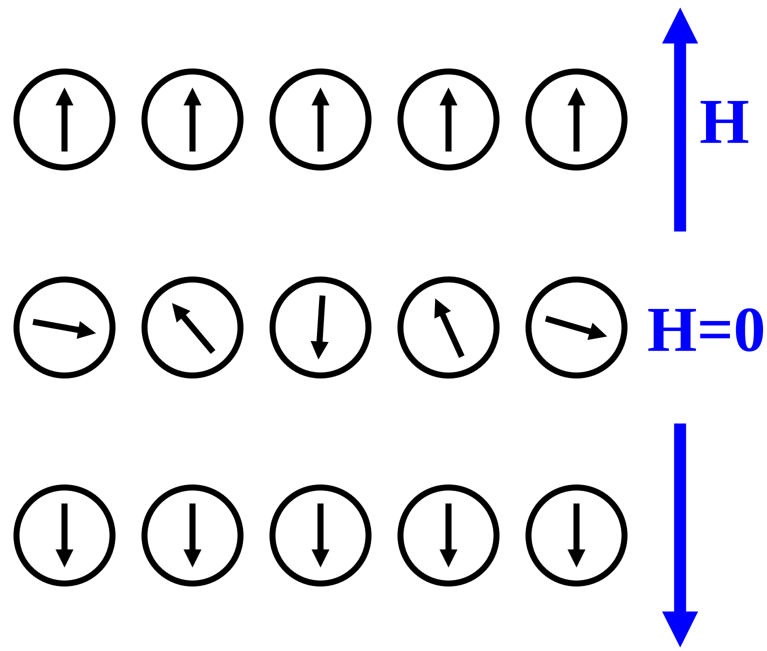
S. Sun
IBM

9-nm Co particle arrays





Superparamagnetic at room temperature

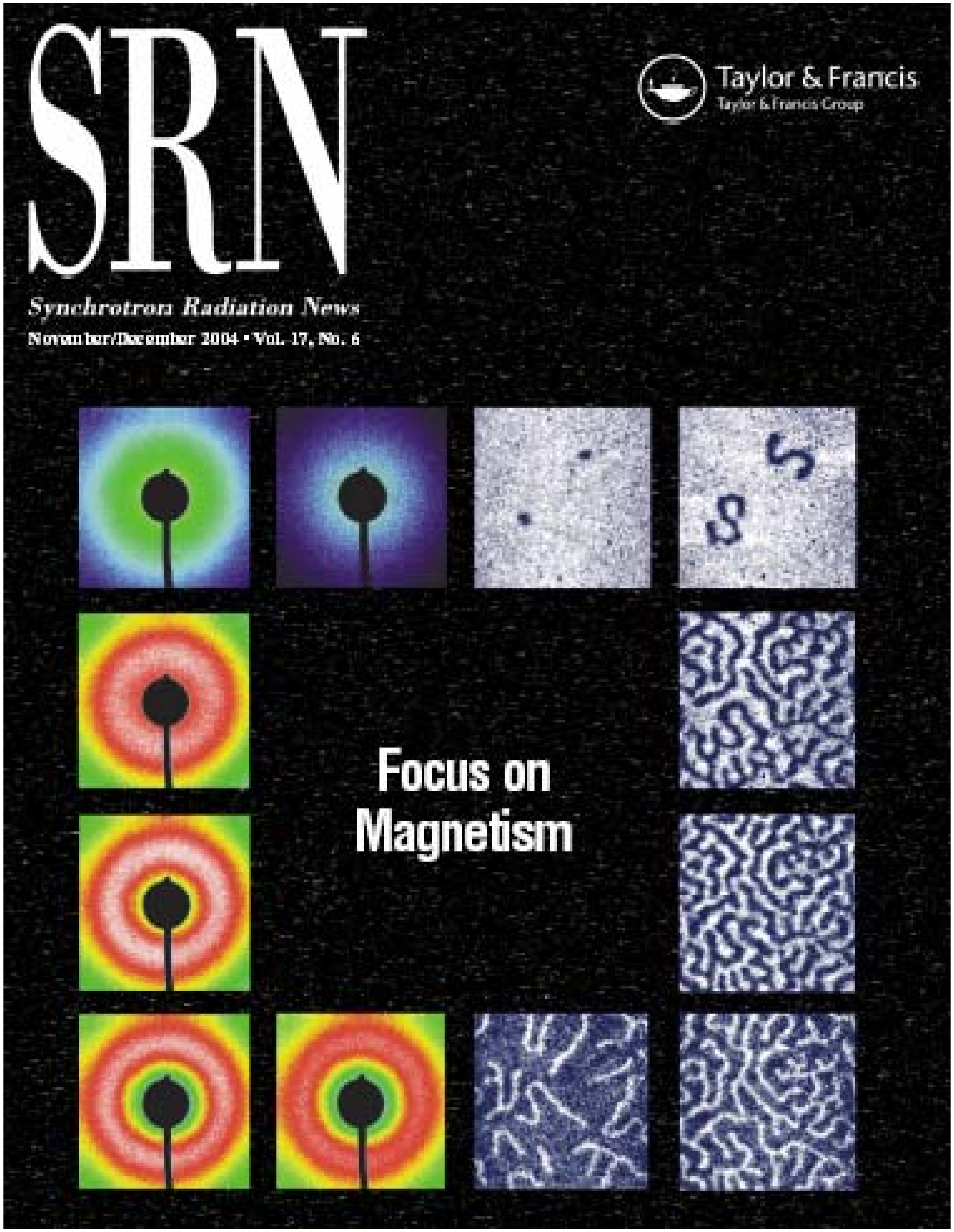


Magnetic structure at H=0?

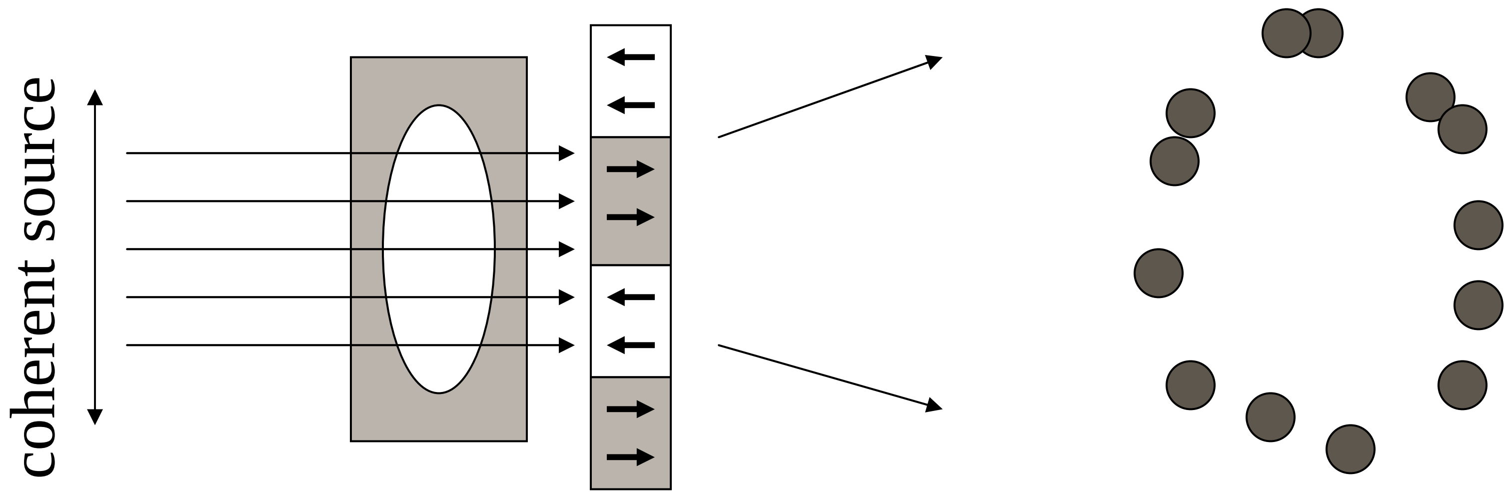
X-rays
&
Magnetism

Imaging: specific patterns w/ relatively poor resolution

Scattering: statistical information w/ good resolution



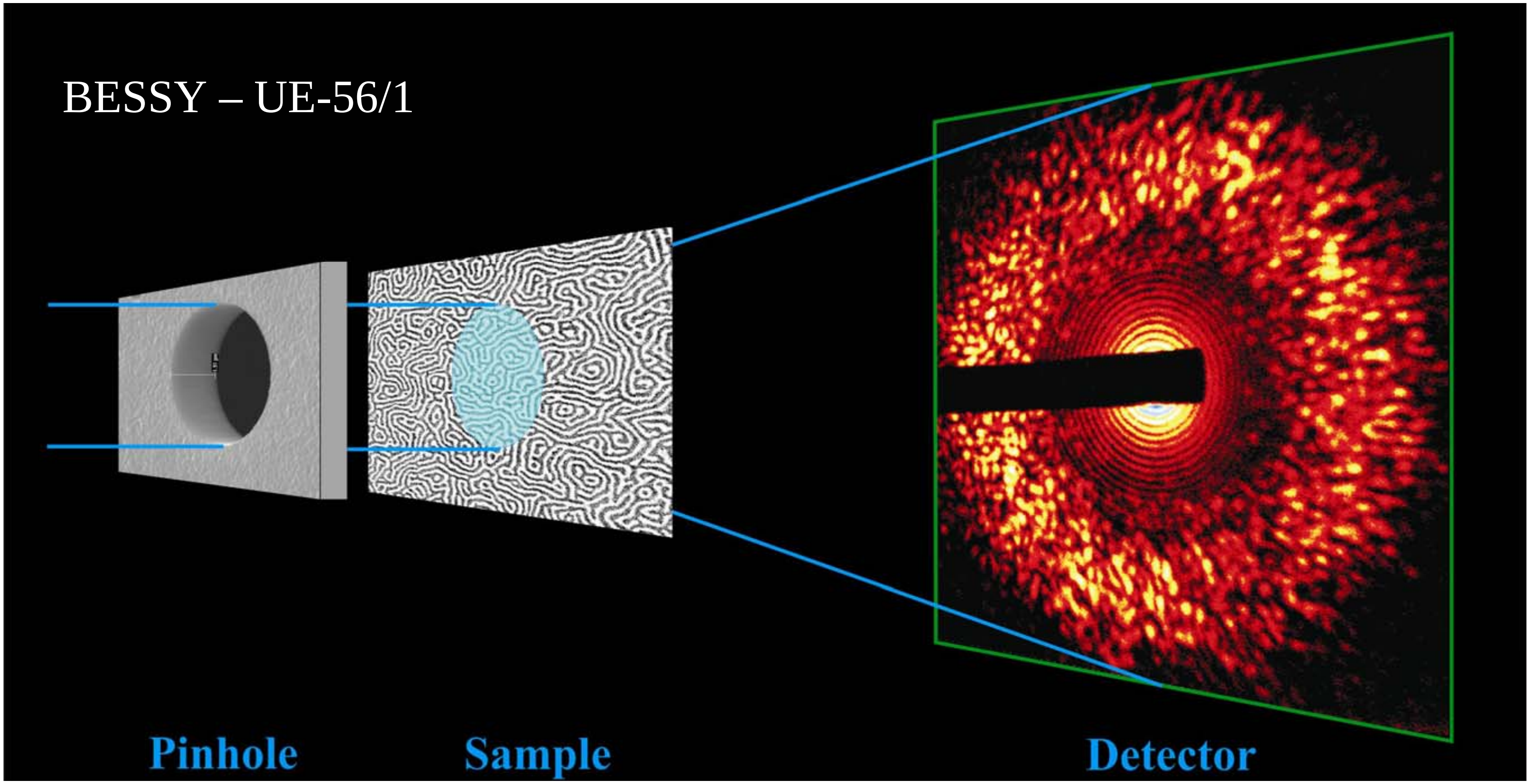
Coherent scattering (speckle)



	Undulator ALS
Wavelength	**16 Å**
T correlation length	**~ 40 μm (19,000 λ)**
L correlation length	**> 13,000 Å (800 λ)**
Coherent flux	**~ 10^{12} photons/second**

Pattern encodes the spatial distribution of the domain.

Coherent scattering



S. Eisebitt et al., Phys. Rev. B **68**, 104419 (2003).

Speckle

Metrology

configurational changes (H, T etc.)

Pierce *et al.*, Phys. Rev. Lett., **90**, 175502 (2003).

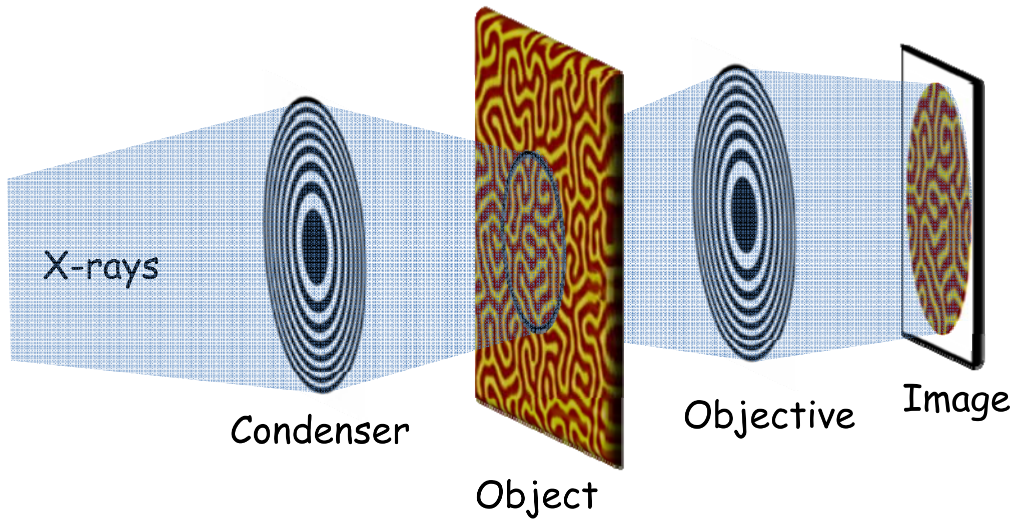
Dynamics

configurational changes (time)

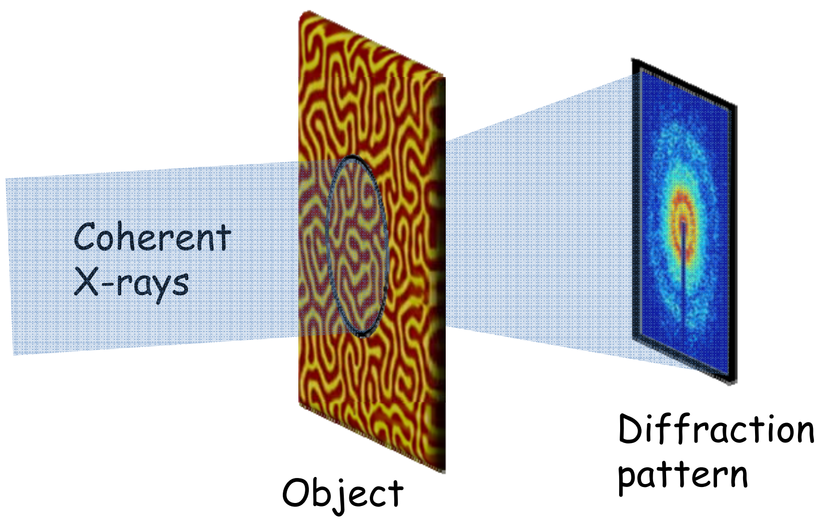
Shpyrko et al., Nature **447**, 68-71 (2007)

Data Inversion to real space

Data inversion



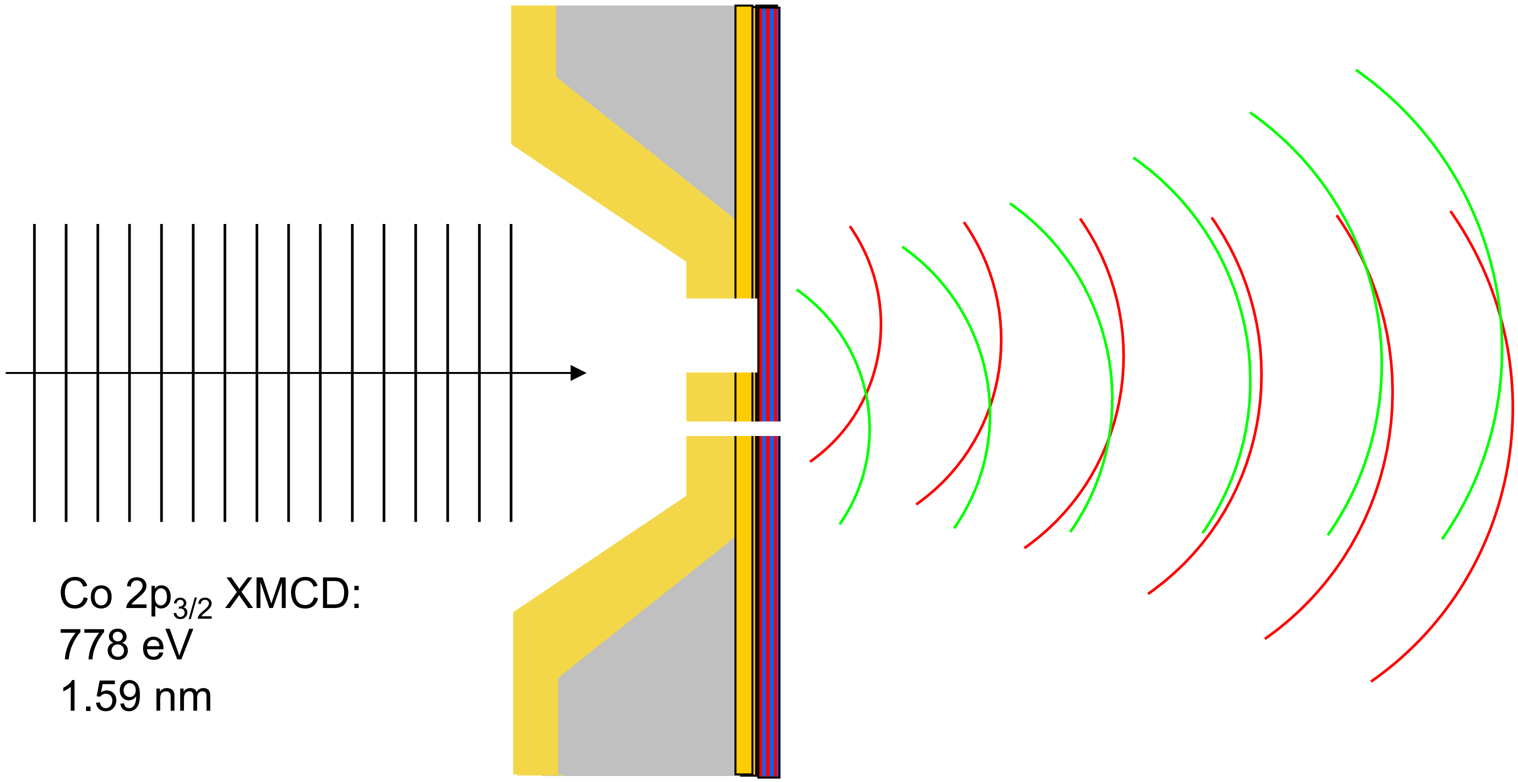
Scanning Transmission
X-ray Microscopy



Coherent X-ray Diffractive
Imaging?

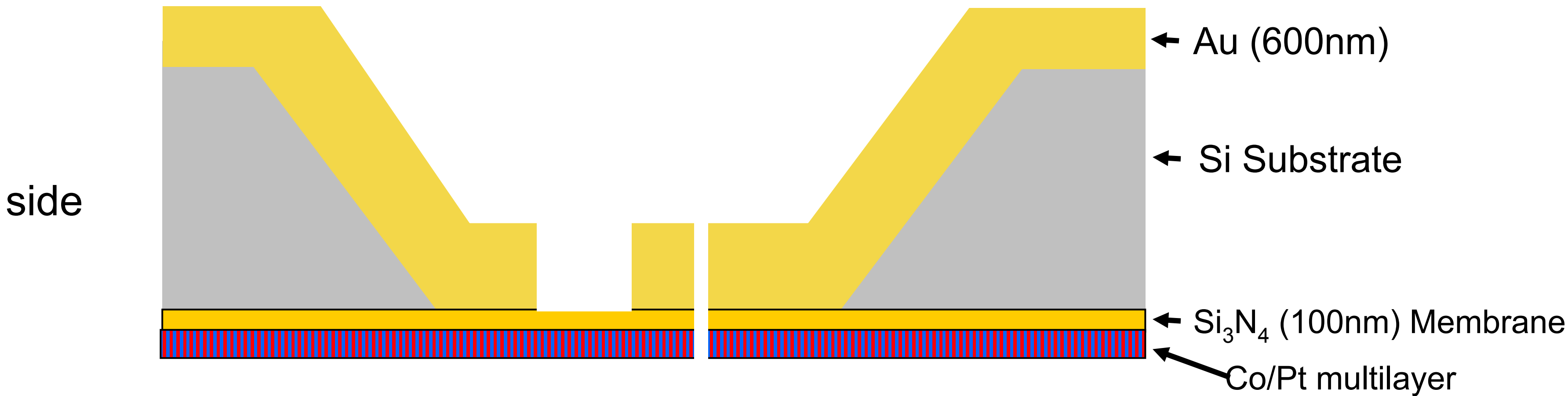
Yes, but requires some
knowledge to perform the
reconstruction e.g. sample that
is smaller than the beam

Fourier Transform Holography

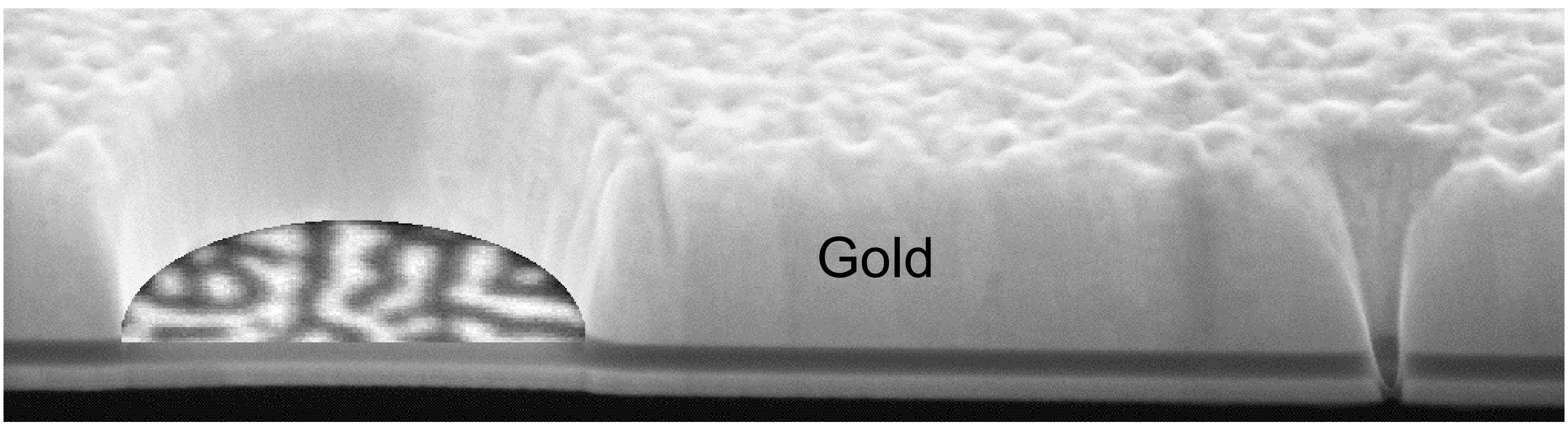


Co $2p_{3/2}$ XMCD:
778 eV
1.59 nm

Fourier Transform Holography

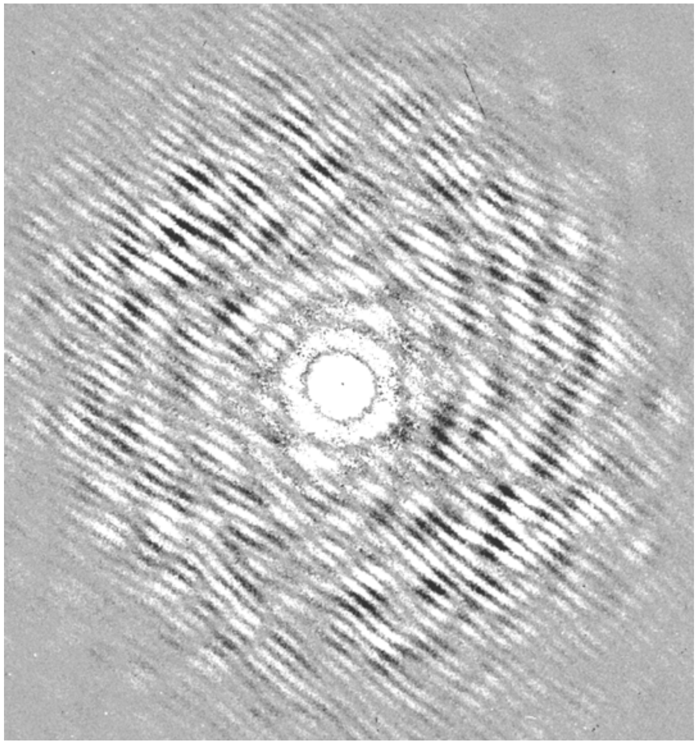


W.F. Schlotter



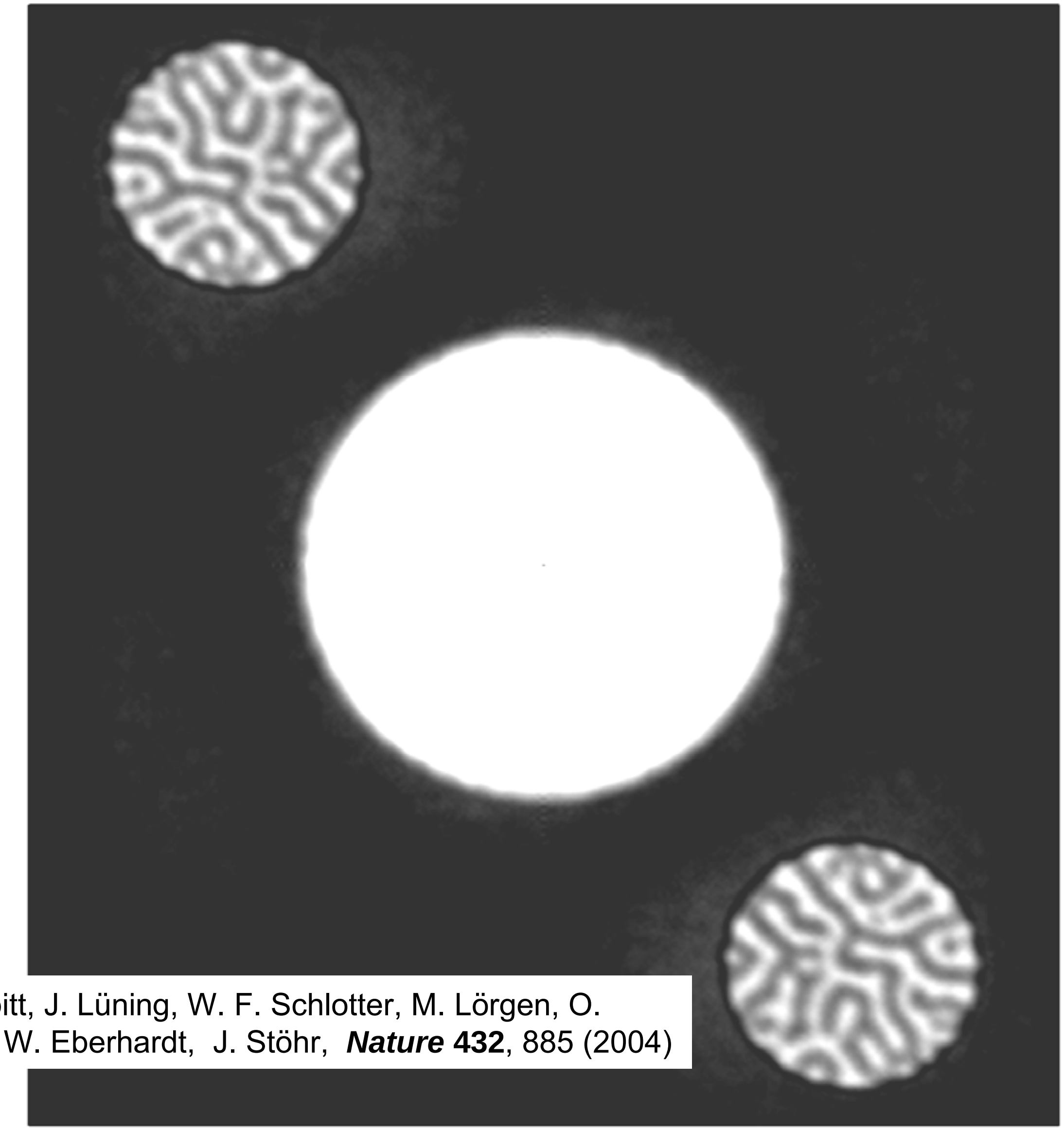
Microscope on a chip

… the real space image



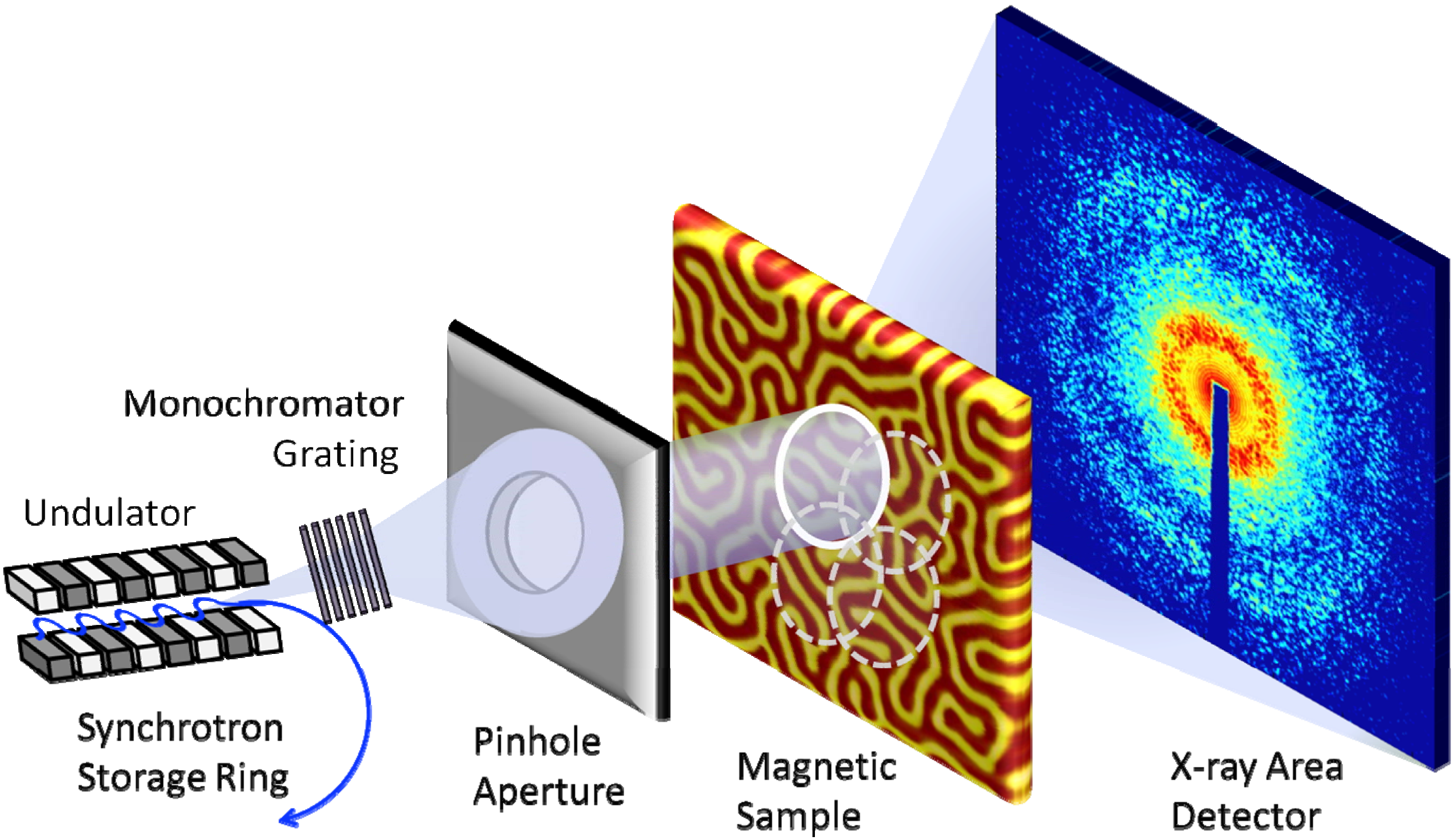
$I^+ - I^-$

charge-magnetic interference

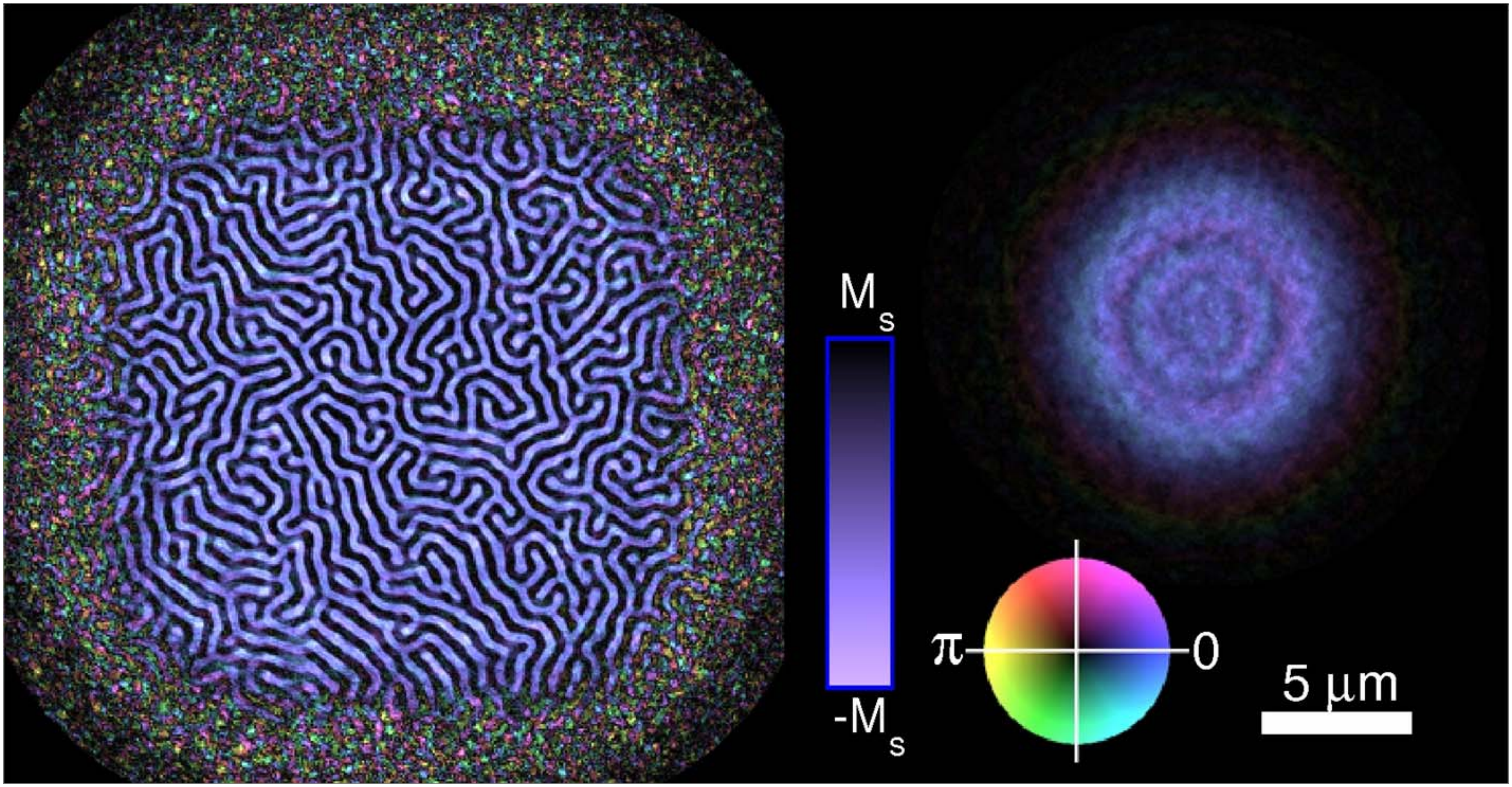


S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt, J. Stöhr, ***Nature* 432**, 885 (2004)

Ptychography



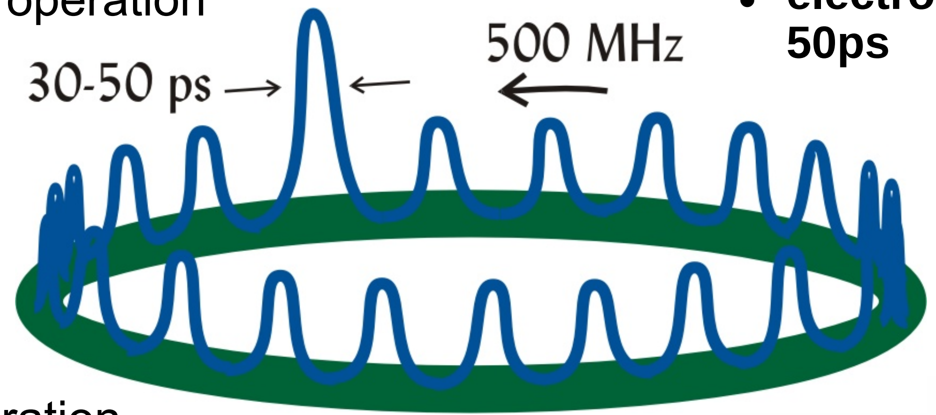
To real space



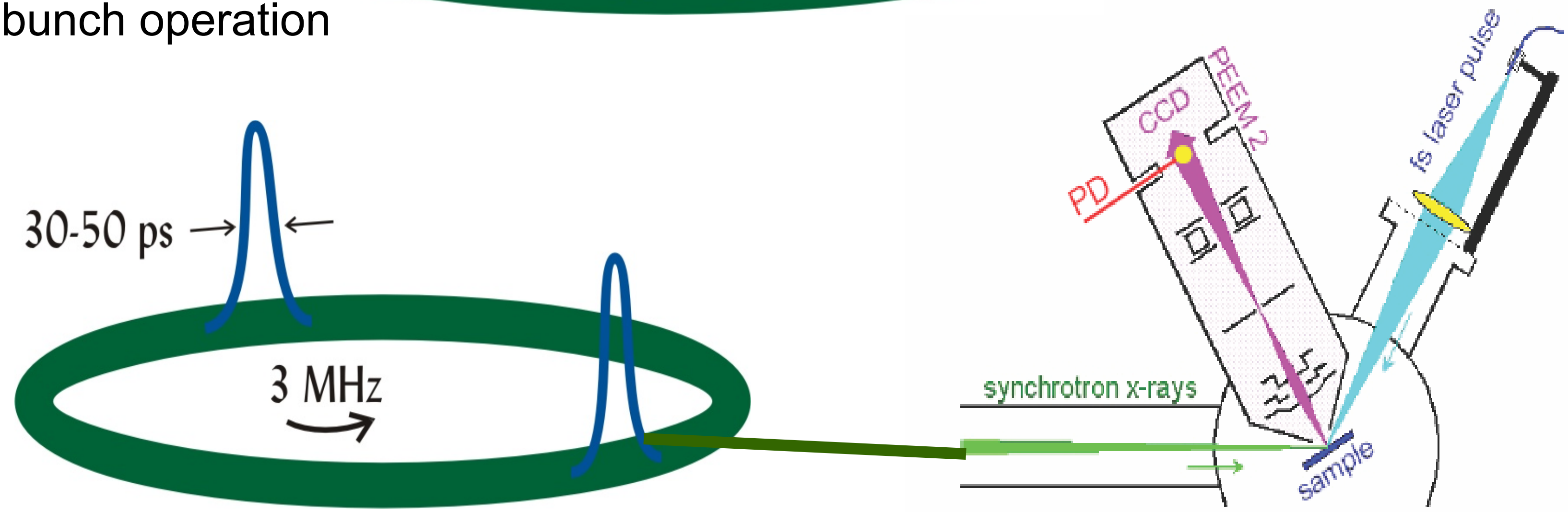
A. Tripathi, J. Mohanty, S. Dietze, O. G. Shpyrko, E. Shipton, E. E. Fullerton, S.S. Kim and I. McNulty , submitted.

Time-resolved measurements

multi-bunch operation

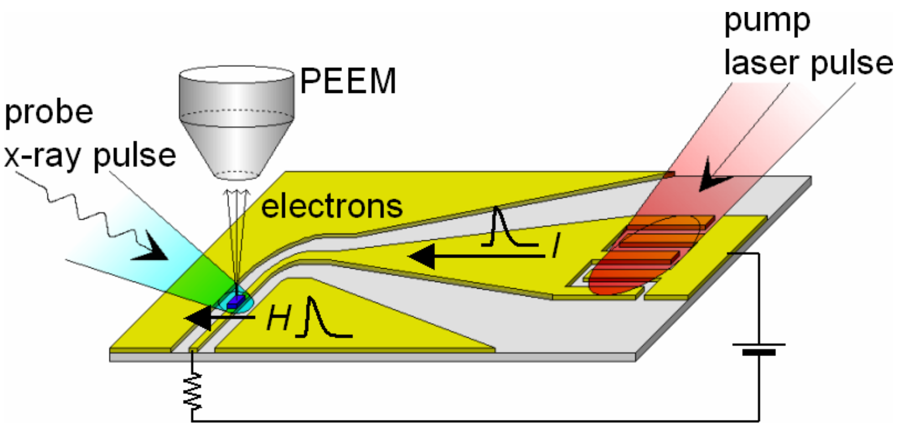


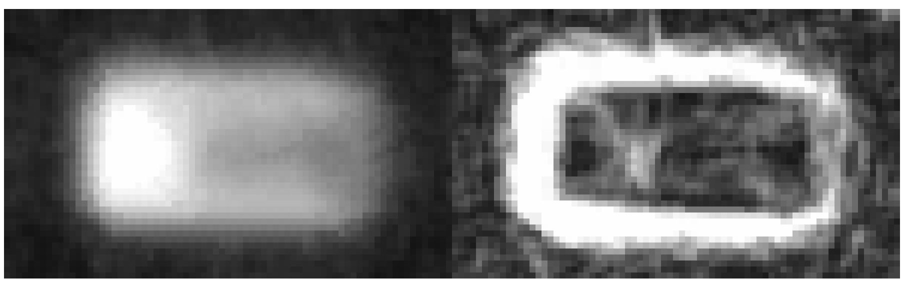
2-bunch operation



- **electron-bunches typically 30-50ps**

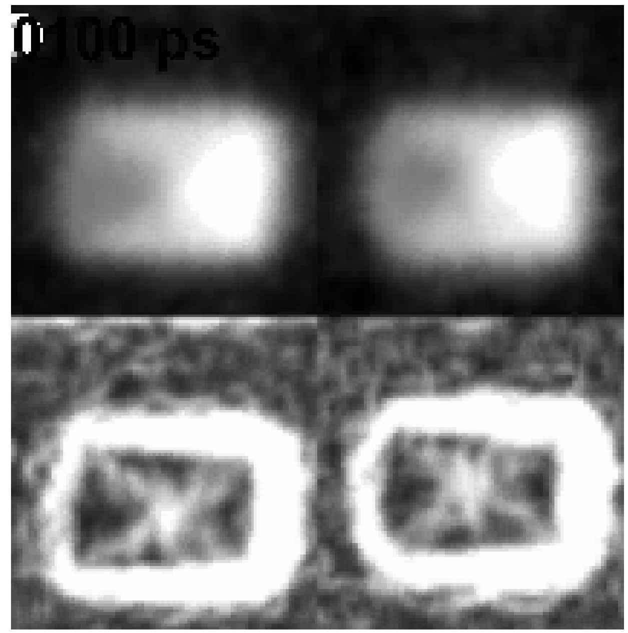
Synchrotron x-ray techniques





S.-B. Choe, et al., Science **304**, 430 (2004)

CoFe patterns



Measures only deterministic processes

Summary: X-rays and magnet nanostructures

- Resonant soft x-ray techniques provides nm-resolved magnetic and chemical information of heterogeneous films
- Spectroscopy: spin/orbital moments, DOS, etc.
- Imaging: real space (20 nm resolution)
- Scattering: reciprocal space (< 10 nm res.)
- Coherent scattering provides new opportunities.
- Pump-probe techniques give time resolved measurements