Magnetic Multilayers

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Magnetic Multilayers

Outline

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

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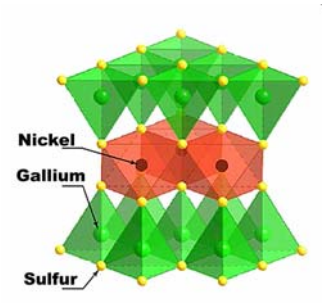
Magnetism

Atomic property



Collective response

applications

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

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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

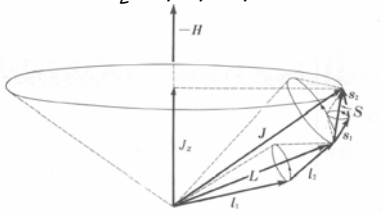
- **Spin magnetic dipole moment:** $\vec{\mu}_S = -e/m \vec{S}$

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*



Spin-Orbit Interaction

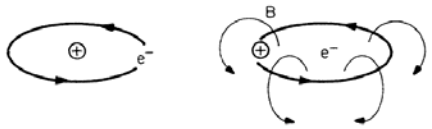


Figure 3.14 Diagram on left, depicts an electron orbiting about the nucleus. In the diagram on the right, from the electron's rest frame, the nucleus appears to be orbiting around the electron and hence producing a magnetic field in the sense indicated. The interaction of the electron spin with its orbitally induced magnetic field is the spin–orbit interaction.

Magnetic field experienced by electron due to motion relative to nucleus

$$\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{\vec{j} \times \vec{r}}{r^3} = -\frac{Ze\mu_0}{4\pi}\left(\frac{\vec{v} \times \vec{r}}{r^3}\right)$$

Spin-orbit interaction
- only for orbitals with L≠ 0
- atomic number Z implicit in V ⇒ stronger for heavier atoms

$$\Delta E_{SO} = \frac{1}{2m^2c^2} \cdot \frac{1}{r^3} \cdot \frac{\partial V}{\partial r} \vec{L} \cdot \vec{S}$$

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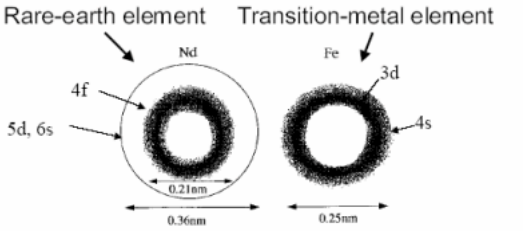
3d transition metals *vs*. 4-f rare-earth elements

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

results in different properties



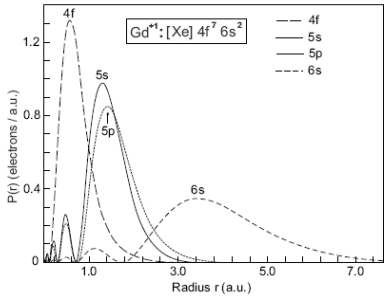


Fig. 7.4. Radial charge density for the Gd^{+1} ion ($4f^7\,6s^2$) calculated by Freeman and Watson [204] for the $4f$, $5s$, $5p$ and $6s$ orbitals. The figure shows that the $4f$ orbitals are actually located well inside the outer shells which screen them from the extra-atomic environment

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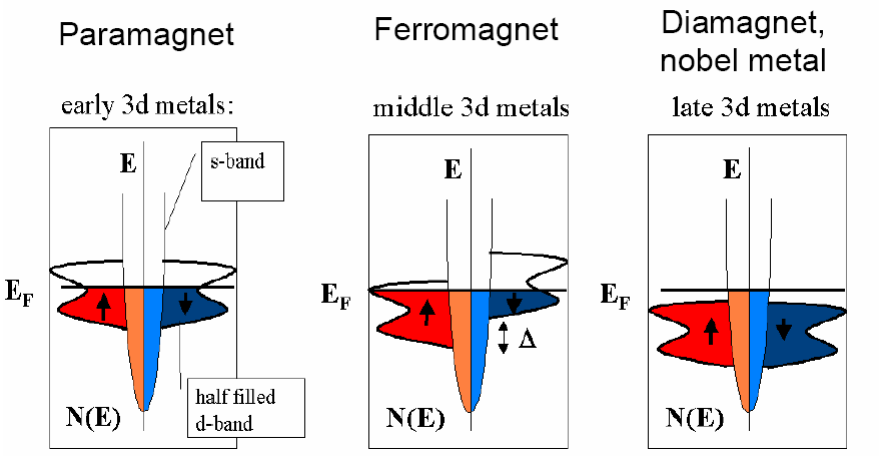
Band magnetism



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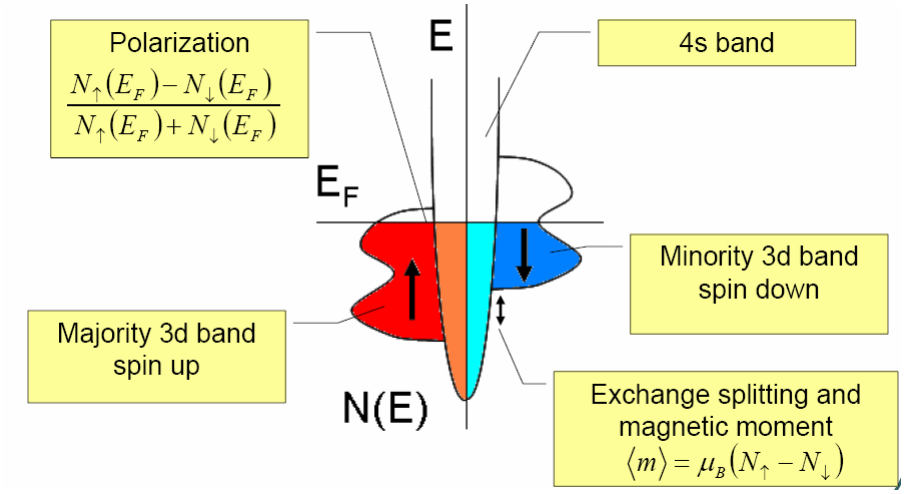
Band magnetism



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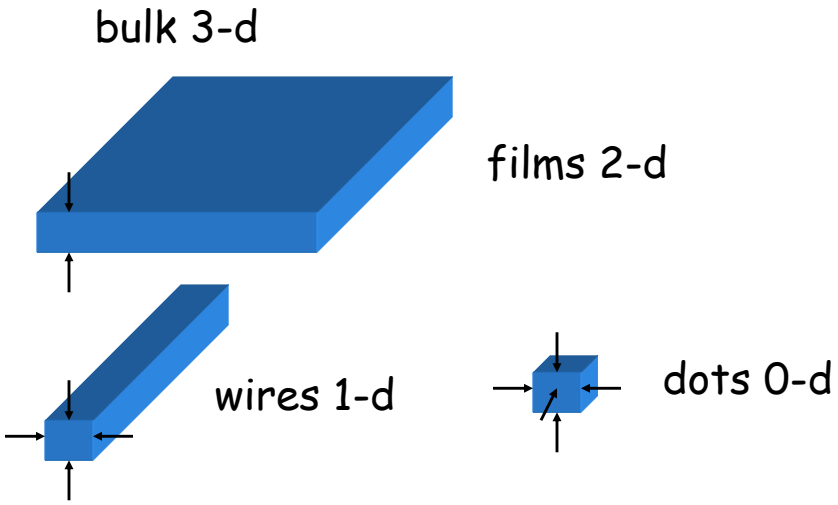
Nano-structures



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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

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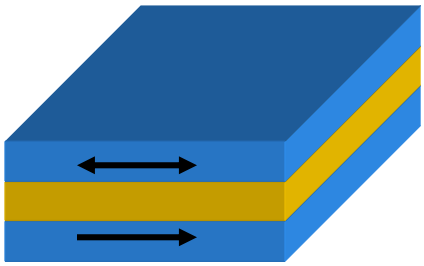
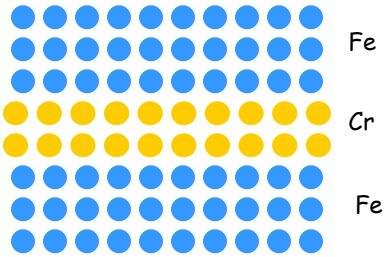
Nano-structures

Indirect effects





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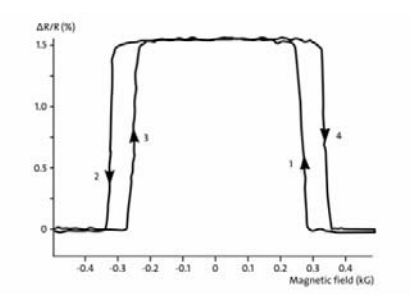
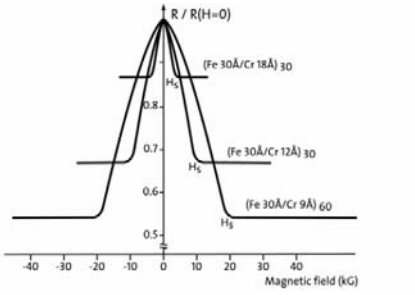
Giant magnetoresistance (GMR)





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

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Nobel Prize in Physics 2007

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Peter Grunberg Albert Fert

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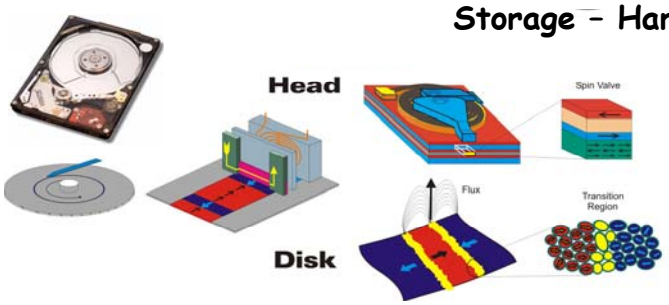
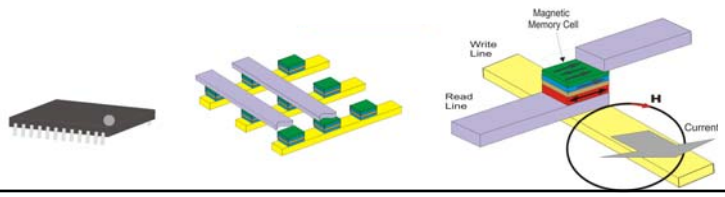
Magnetic Nanotechnologies

Storage – Hard Disk Drive



Memory – MRAM, FeRAM



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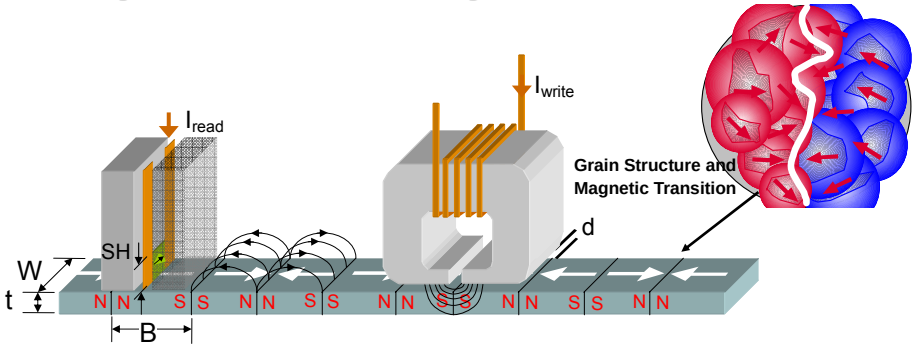
Magnetic recording components



B = 30 nm (σ<3 nm),
W=210 nm, t = 14 nm
Data rate: GHz

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Magnetic nanostructures

- Important new physics (e.g. Nobel Prize)
- Important technologies
  - Sensors (bio-magnetism, auto, …)
  - IT (storage, memory, processing)
  - Energy efficiency

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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

} have a spin

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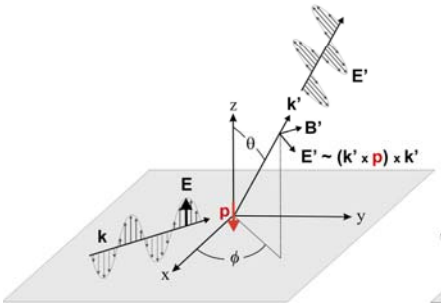
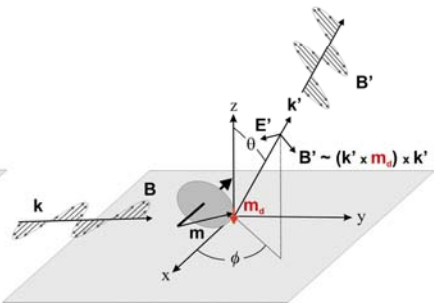
Non-resonant scattering

Electric Dipole Scattering



Relative Intensity: **1**

Magnetic Dipole Scattering



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

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

X-rays typically are not very sensitive to magnetism

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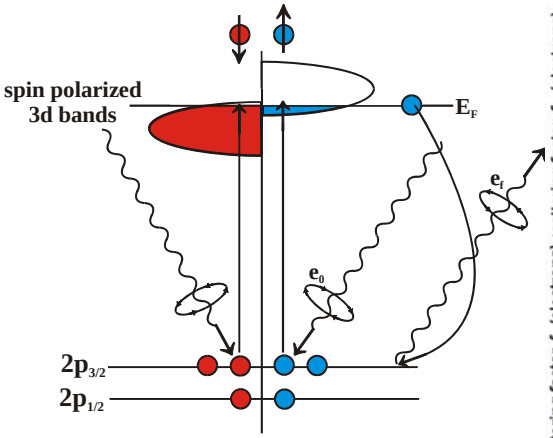
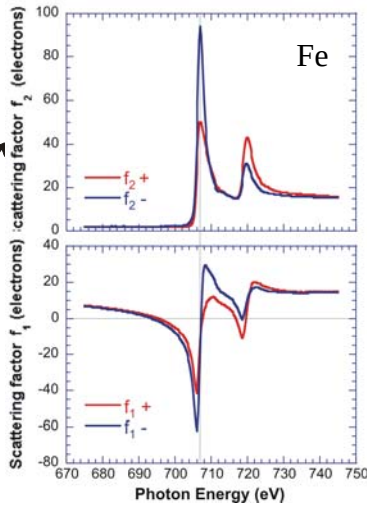
Core level resonances



$f = f_1 + if_2$



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

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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)

  λ = 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).

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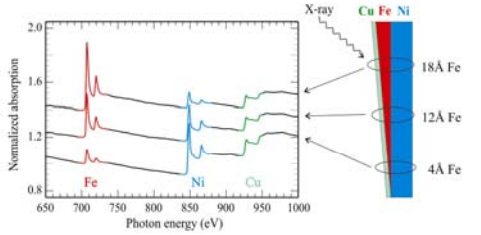
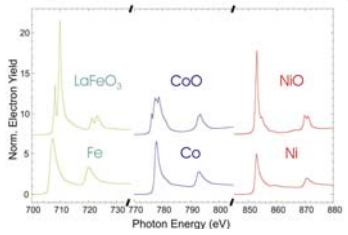
Elemental and chemical sensitivity

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



X-rays offer chemical sensitivity



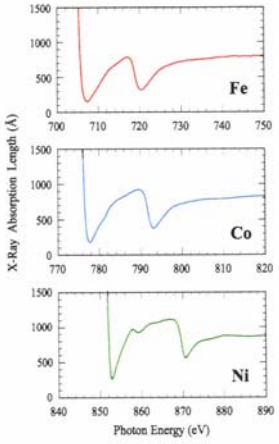


Fig. 8. X-ray absorption length ($1/e$ attenuation) for Fe, Co and Ni in the L edge region.[37] The absorption lengths in the pre-edge regions (not shown) are about 600 nm.

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

Spectroscopy

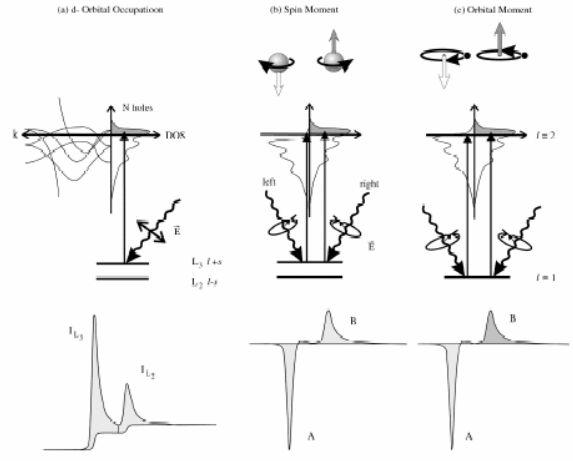


Fig. 1. (a) Electronic transitions in conventional L-edge X-ray absorption, (b) and (c) X-ray magnetic circular dichroism, illustrated in a one-electron model. The transitions occur from the spin–orbit split 2p core shell to empty conduction band states above the Fermi level. In conventional X-ray absorption 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.

Measures average Properties

MCD (magnetic circular dichroism)

e.g.
- d-band filling
- Moment
  - spin
  - orbital
- hysteresis loops

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

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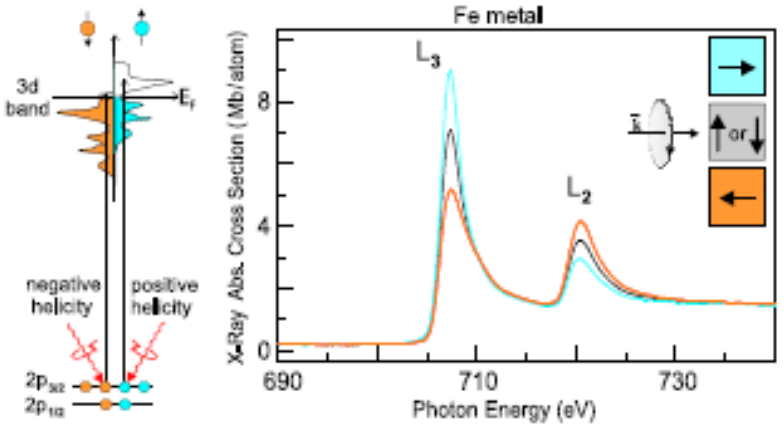
Element specific magnetometry



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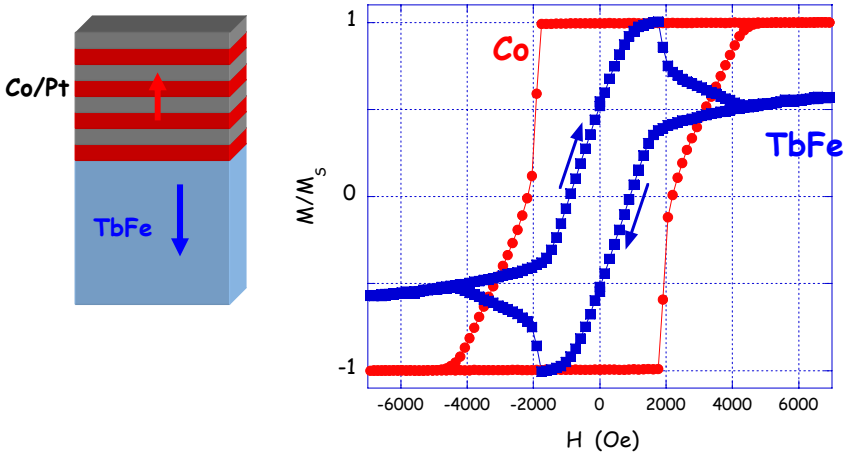
Elemental and chemical sensitivity



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

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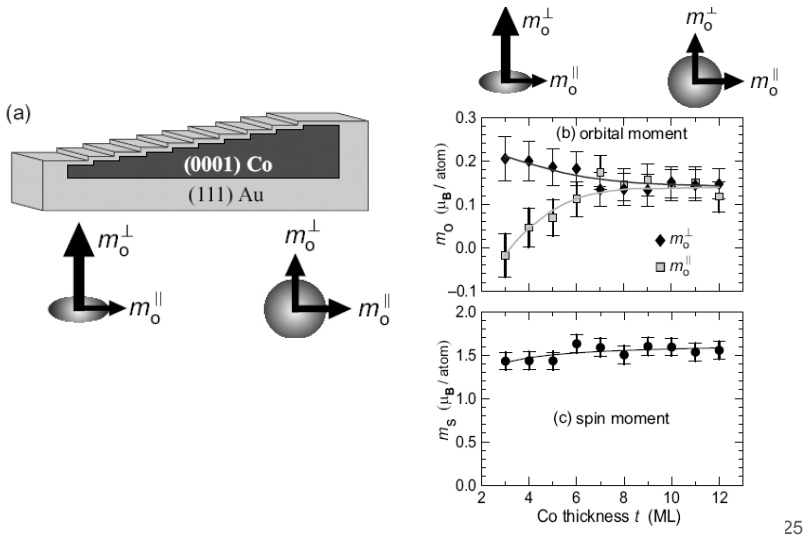
Spin and orbital moments



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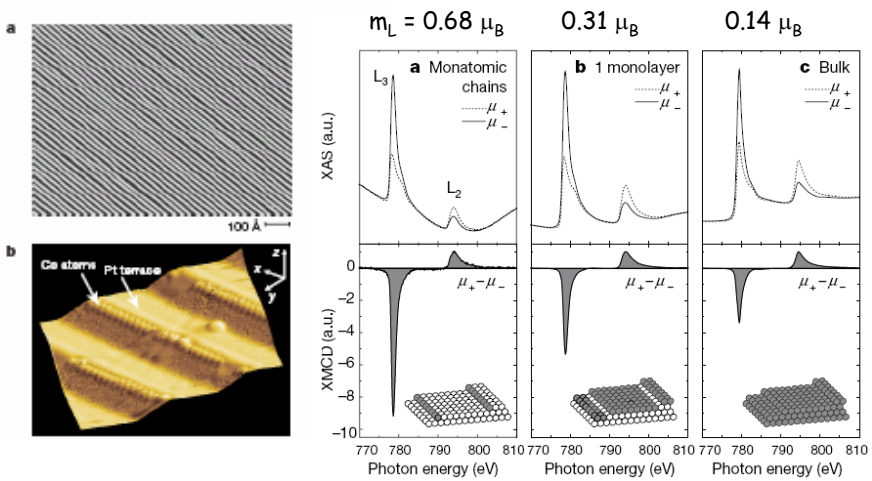
Spin and orbital moments

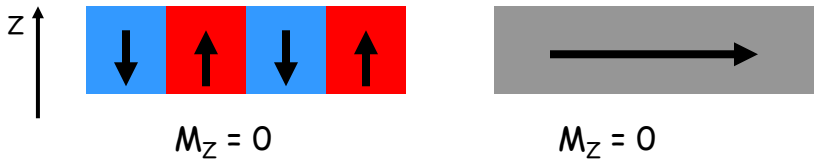
Ferromagnetism in one-dimensional monatomic metal chains

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



Spatial sensitivity

Spectroscopy gives you and average response of the atoms in systems



Spatial variations require either imaging or scattering

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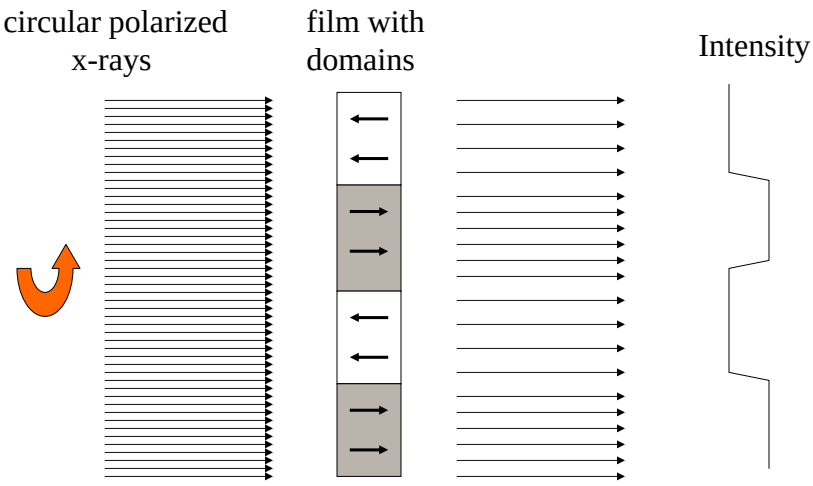
Magnetic Microscopy



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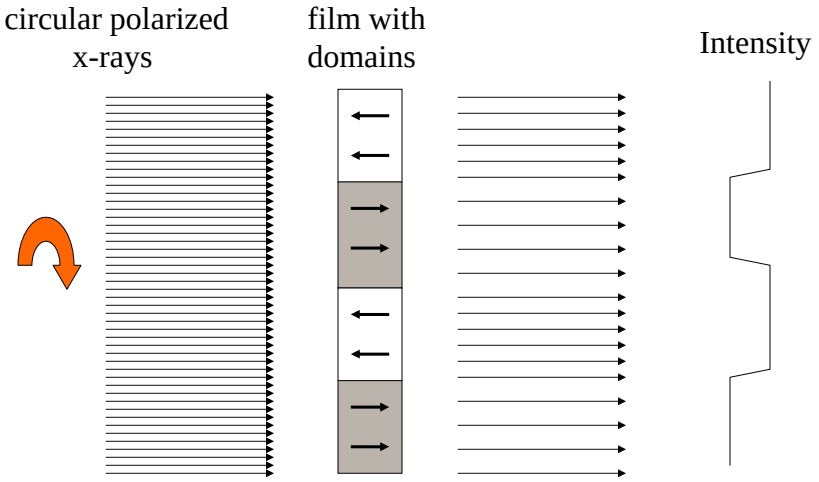
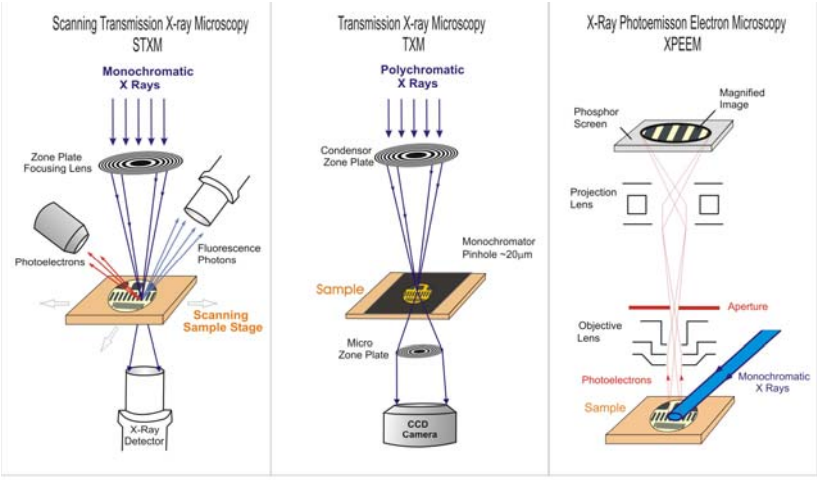
Magnetic Microscopy



Magnetic contrast is the difference of the left and right circular polarization 29

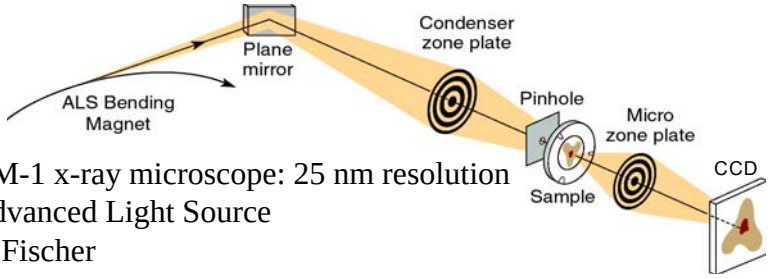
Microscopes at the ALS



Present resolution in the 20 - 40 nm range

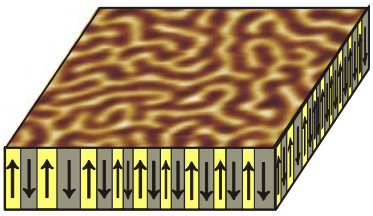
http://www-als.lbl.gov/als/microscopes/index.html 30

Domains in Co/Pt ML's

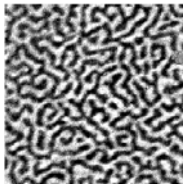


XM-1 x-ray microscope: 25 nm resolution
Advanced Light Source
P. Fischer

Co/Pt multilayer



MFM
stray fields



XM-1
magnetization

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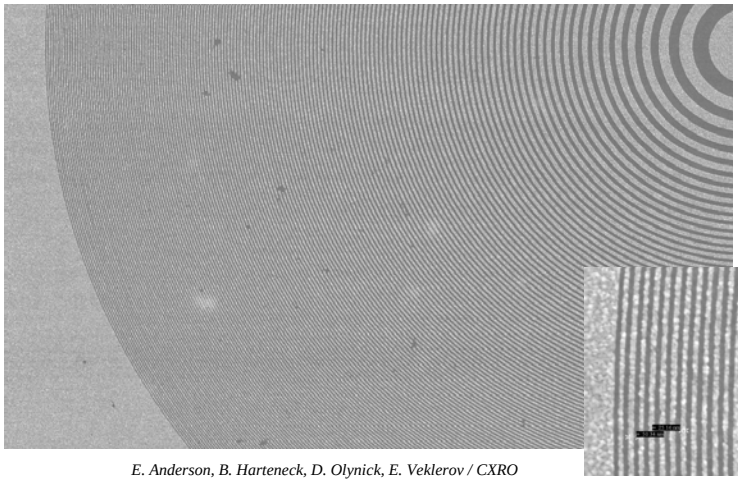
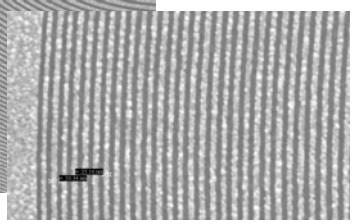
Zone plates



- **Δr = 25 nm**
- **D = 63 μm**
- **N = 618 zones**



E. Anderson, B. Harteneck, D. Olynick, E. Veklerov / CXRO

- **Zone plate manufacturability limits spatial resolution**
- **State of the art resolution is 20-30nm**

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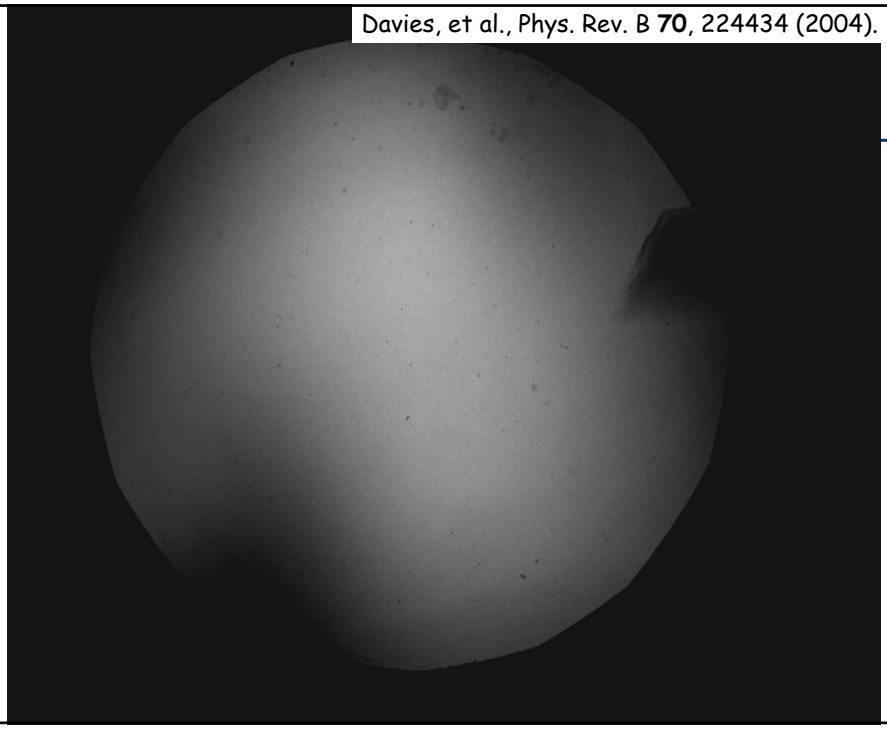
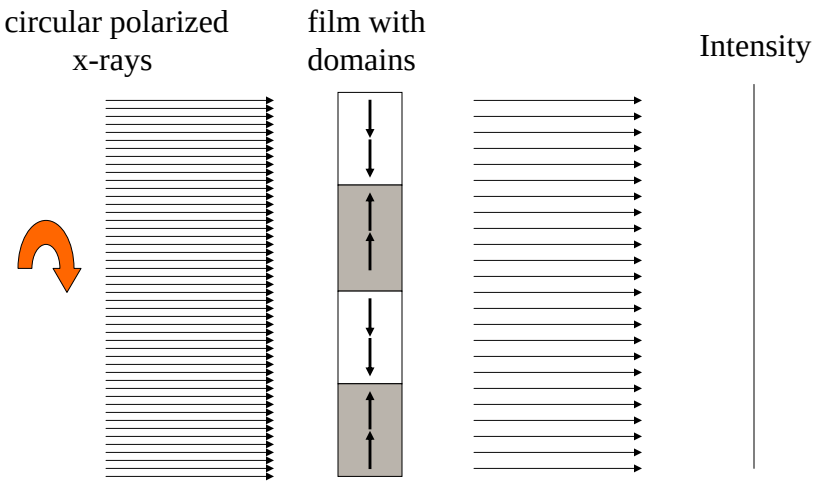


Davies, et al., Phys. Rev. B **70**, 224434 (2004).

Vector magnetic microscopy



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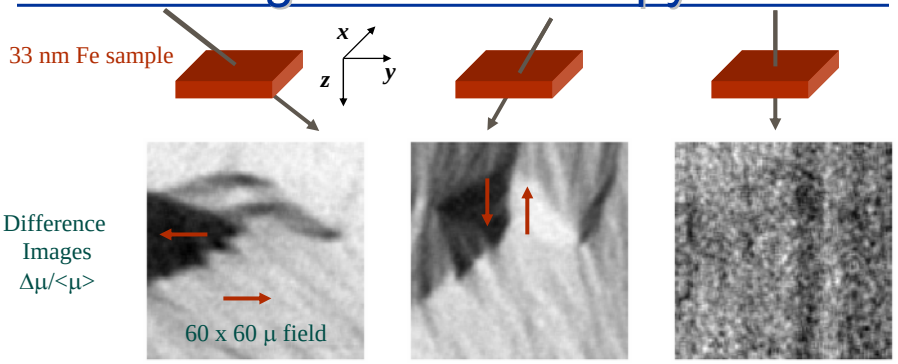
Vector magnetic microscopy



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

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

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

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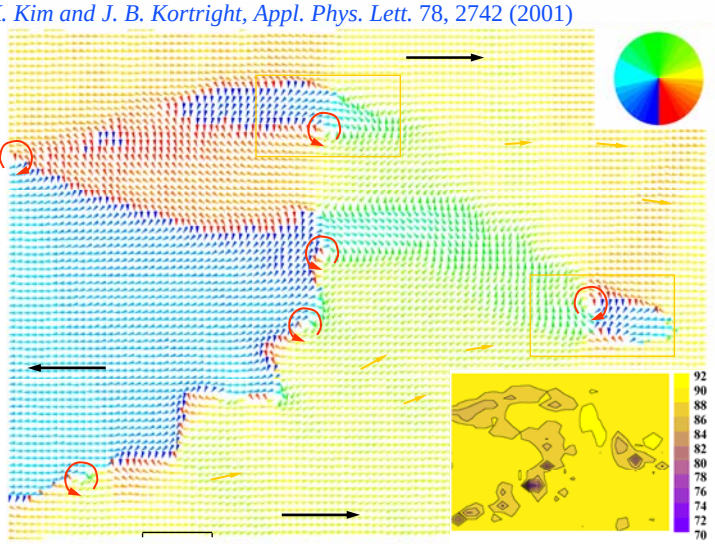
Vector magnetic microscopy

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



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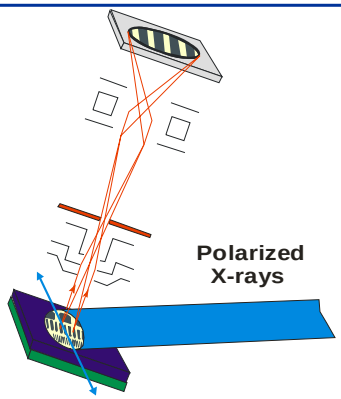
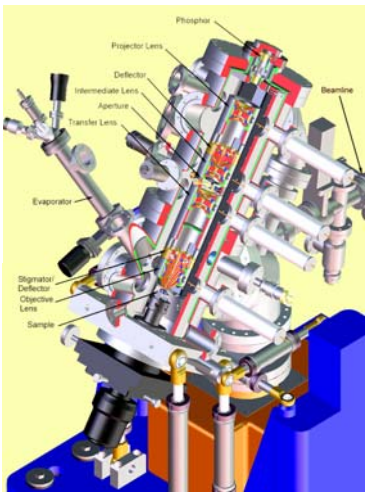
Domains in $LaFeO_3$/Co films



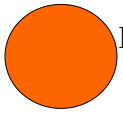


- Full Field Imaging
- Electrostatic (30 kV)
- 20 - 50 nm Resolution
- Linear and circular polarization

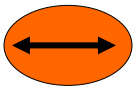
37

Domains in $LaFeO_3$ films

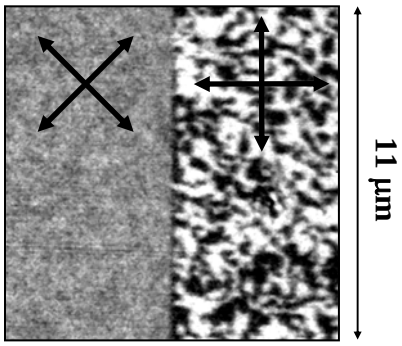
$LaFeO_3$ is an antiferromagnetic material

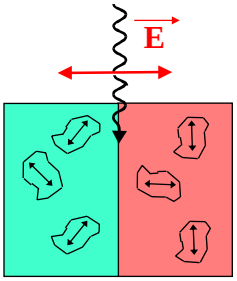


Non-magnetic orbitals



Magnetic orbitals

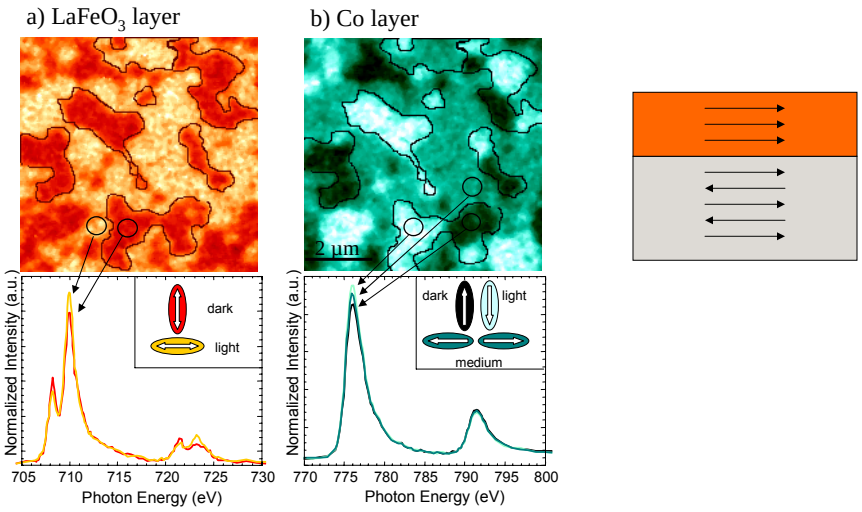




Scholl *et al.*, Science **287**, 1014 (2000)

38

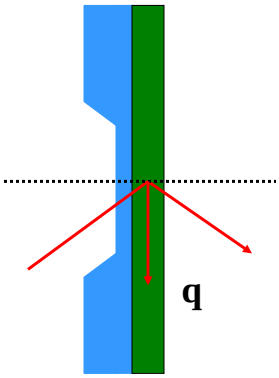
Domains in $LaFeO_3$/Co films



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

39

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)

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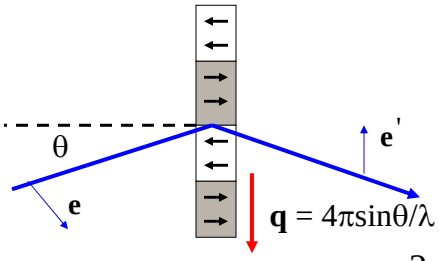
Magnetic domain scattering



charge magnetic -XMCD

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

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

magnetic scattering

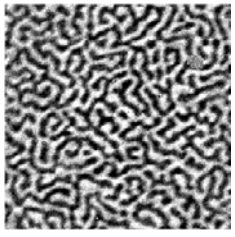
$$f_n \sim \mathbf{M}_n$$

Scattering ~ |Fourier Transform|^2 of the domains

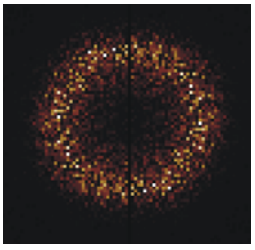
Real vs. reciprocal space

Domains in a Co/Pt ML

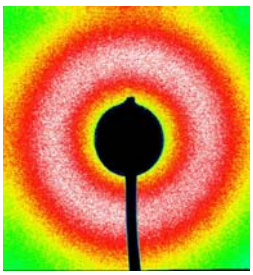
5 x 5 μm^2



XM-1
Imaging x-ray microscope

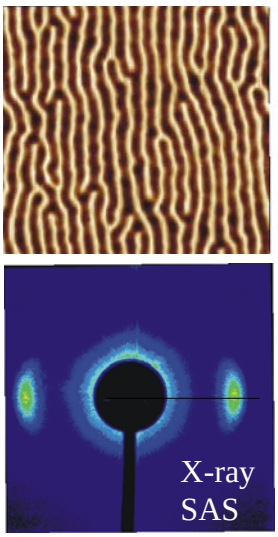


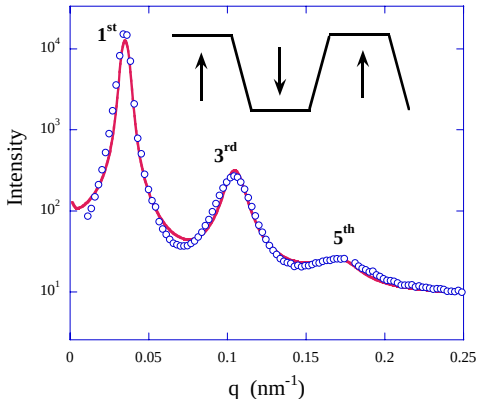
FT



Magnetic SAS
~ |FT|^2

Aligned domains





Hellwig *et al*., Physica B **336**, 136 (2003).

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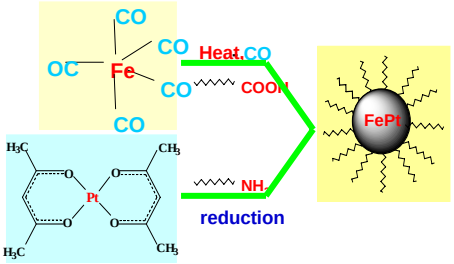
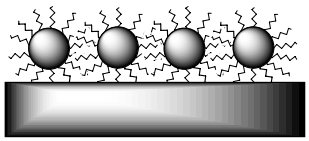
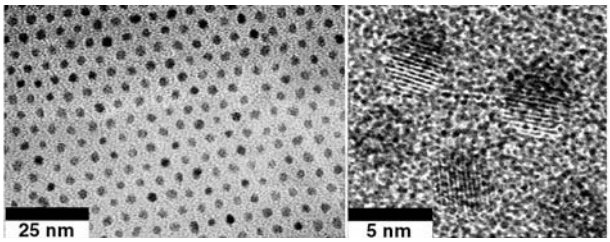
Example 2: nanoparticle arrays



particles are coated with Oleic acid and oleyl amine





Tune: particle size and separation

S. Sun
IBM

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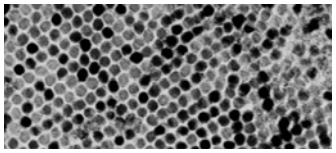
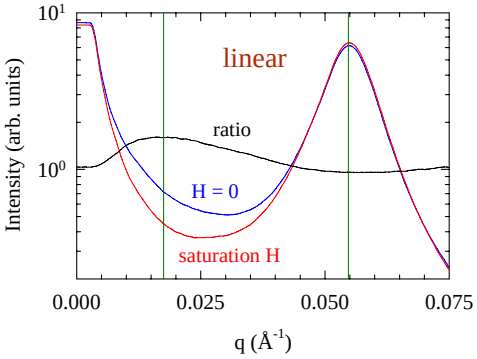
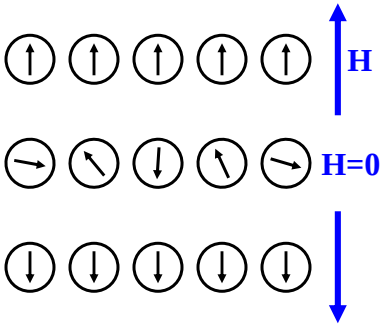
9-nm Co particle arrays



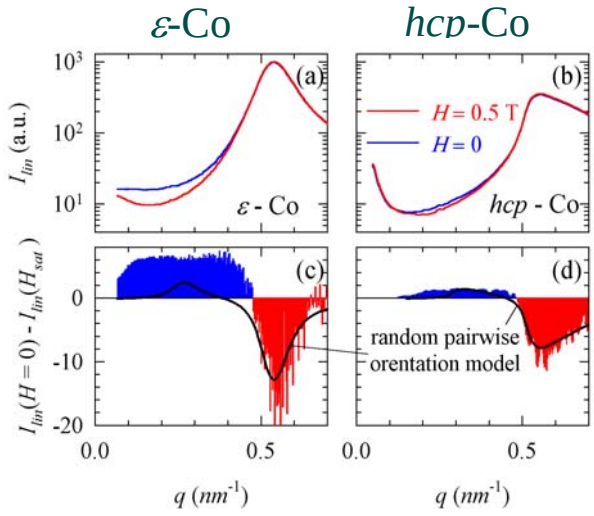


Superparamagnetic at room temperature



Magnetic structure at H=0?

Magnetic scattering

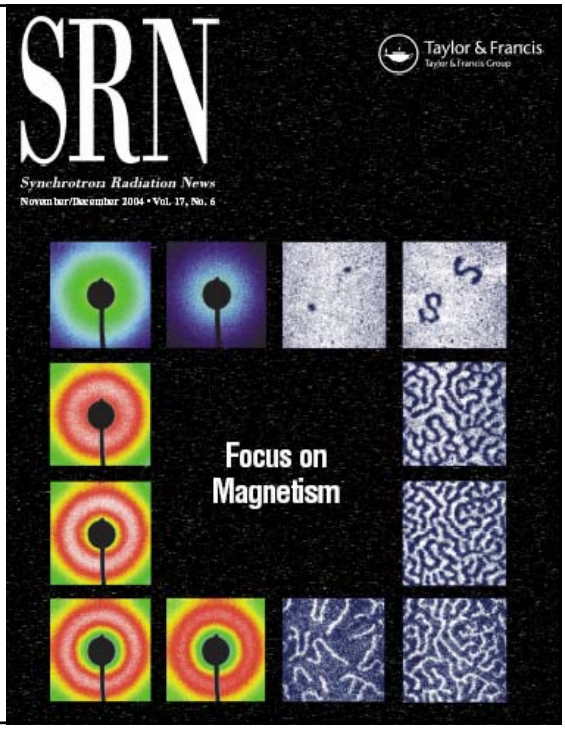


Kortright et al., Phys. Rev. B **71** 012402 (2005)

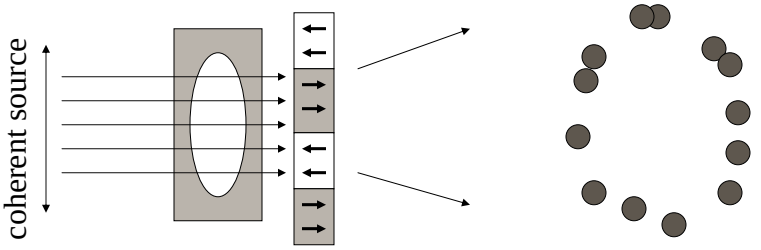
X-rays & Magnetism

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.

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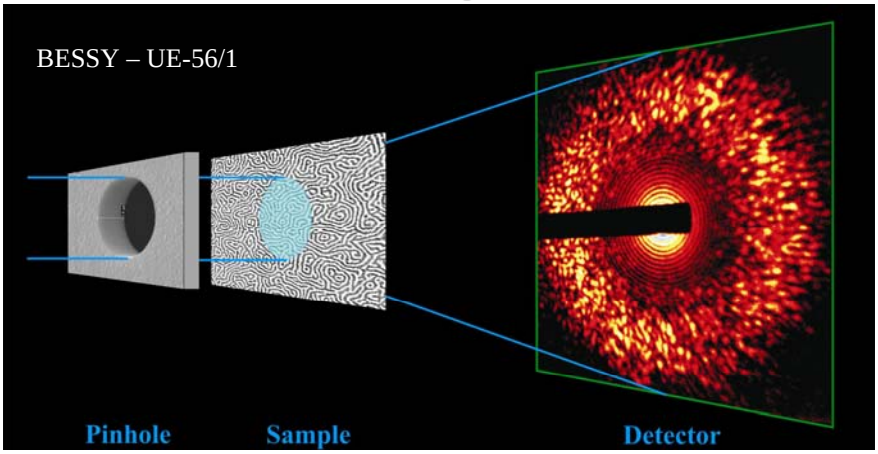
Coherent scattering



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

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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

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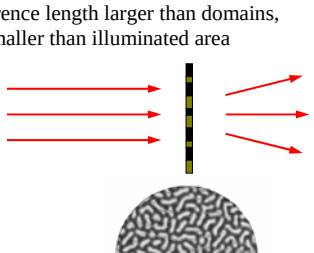
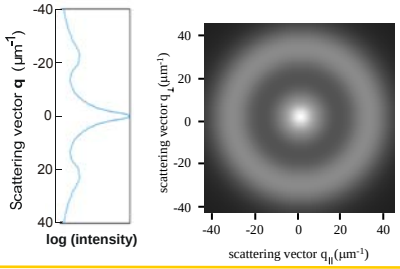
Incoherent vs. coherent scattering

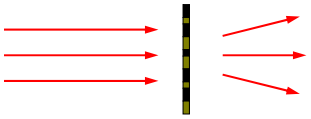
Coherence length larger than domains,
but smaller than illuminated area

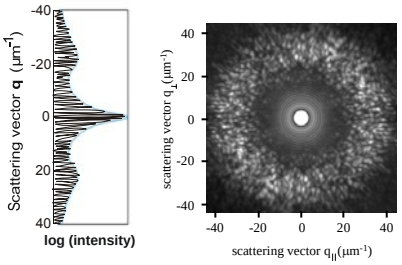




information about domain statistics

Speckle
Coherence length
larger than illuminated area





true information about domain structure

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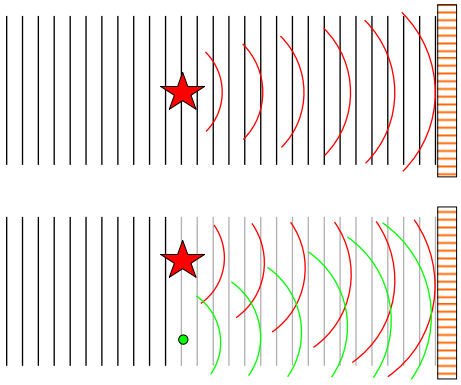
Fourier Transform Holography



J.T. Winthrop, C.R. Worrington, Phys. Lett. 15, 124 (1965)
G.W. Stroke, *Lensless Fourier-transform method for optical holography*, APL **6**, 201-203 (1965)

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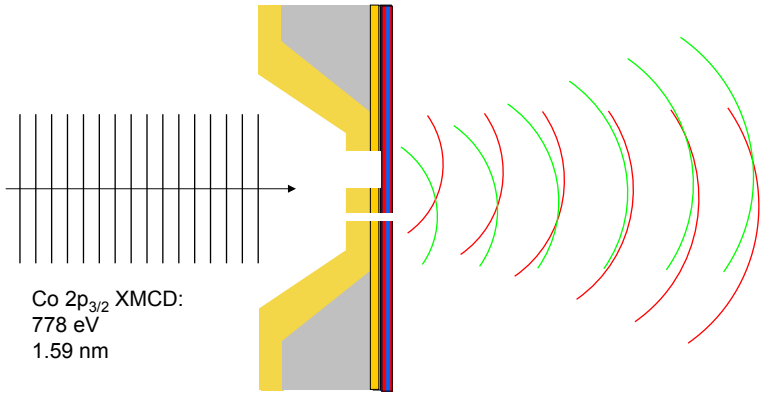
Fourier Transform Holography



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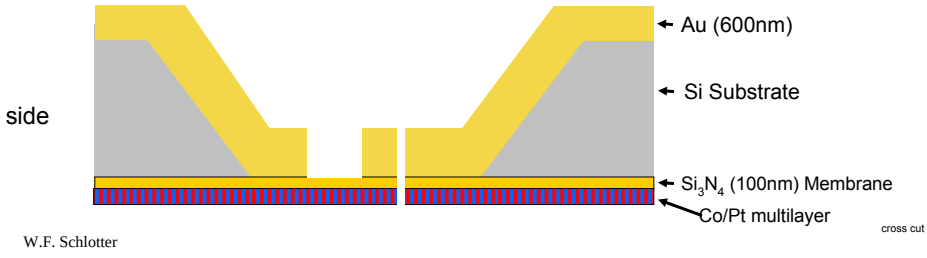
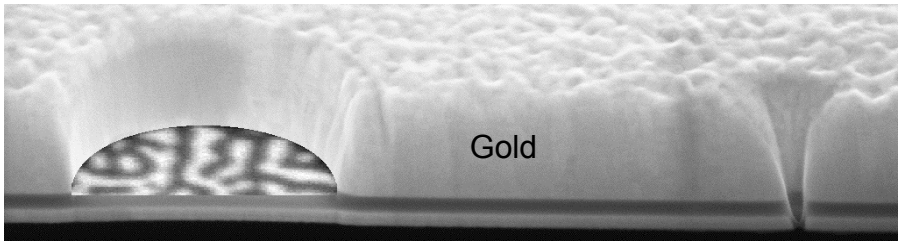
Fourier Transform Holography



W.F. Schlotter



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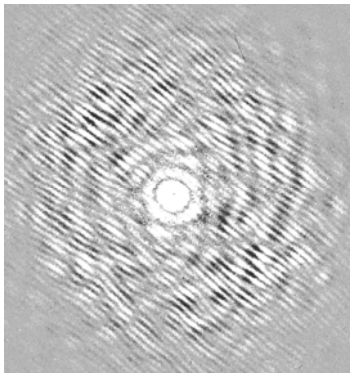
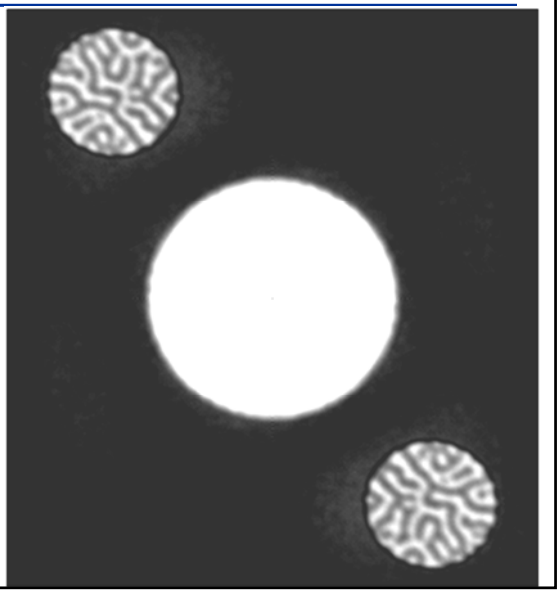
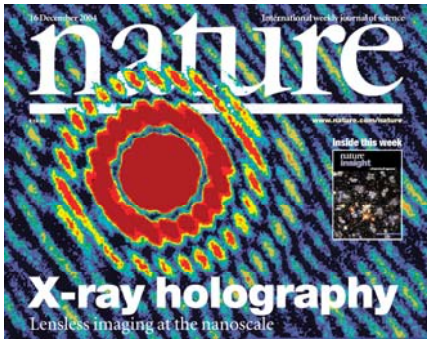
… the real space image



$I^+ - I^-$
charge-magnetic interference



Microscope on a chip



'Microscope on a chip'
- **stable image area**
- **high fields/low temperature**

Apply to a range of materials science problems

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

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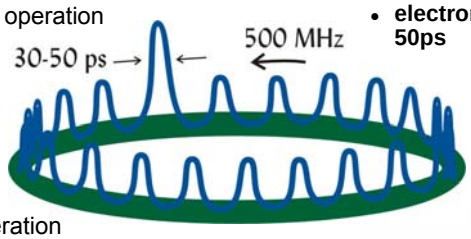
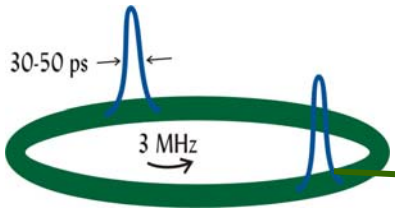
Time-resolved measurements

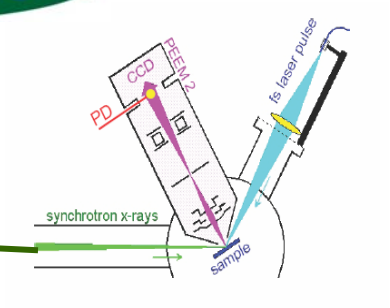
multi-bunch operation



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

2-bunch operation





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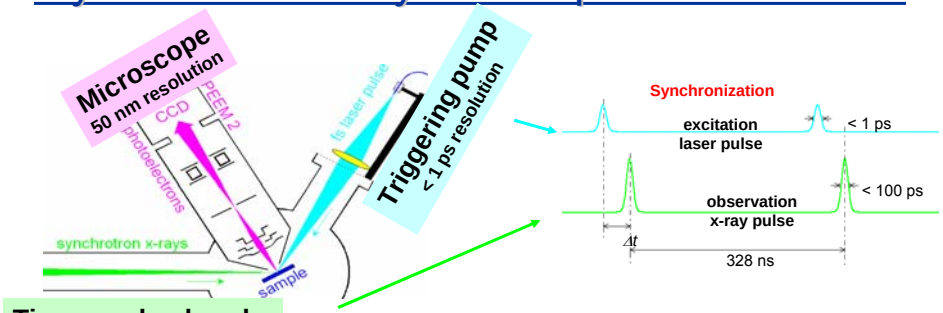
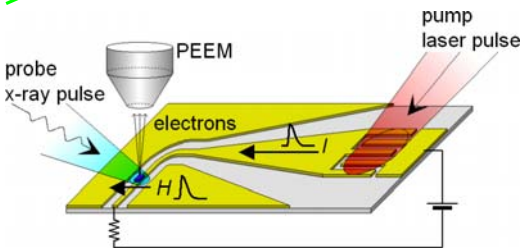
Synchrotron x-ray techniques



Time resolved probe
<100 ps resolution



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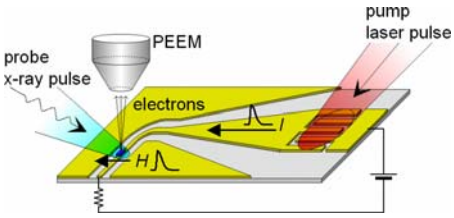
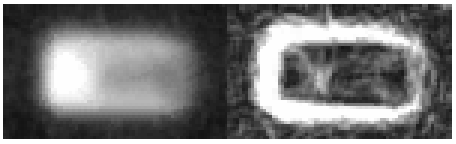
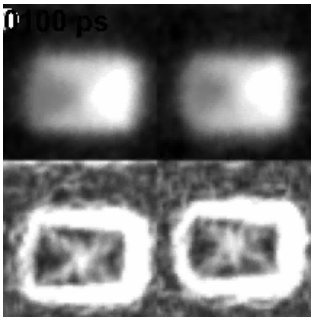
Synchrotron x-ray techniques





CoFe patterns



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

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