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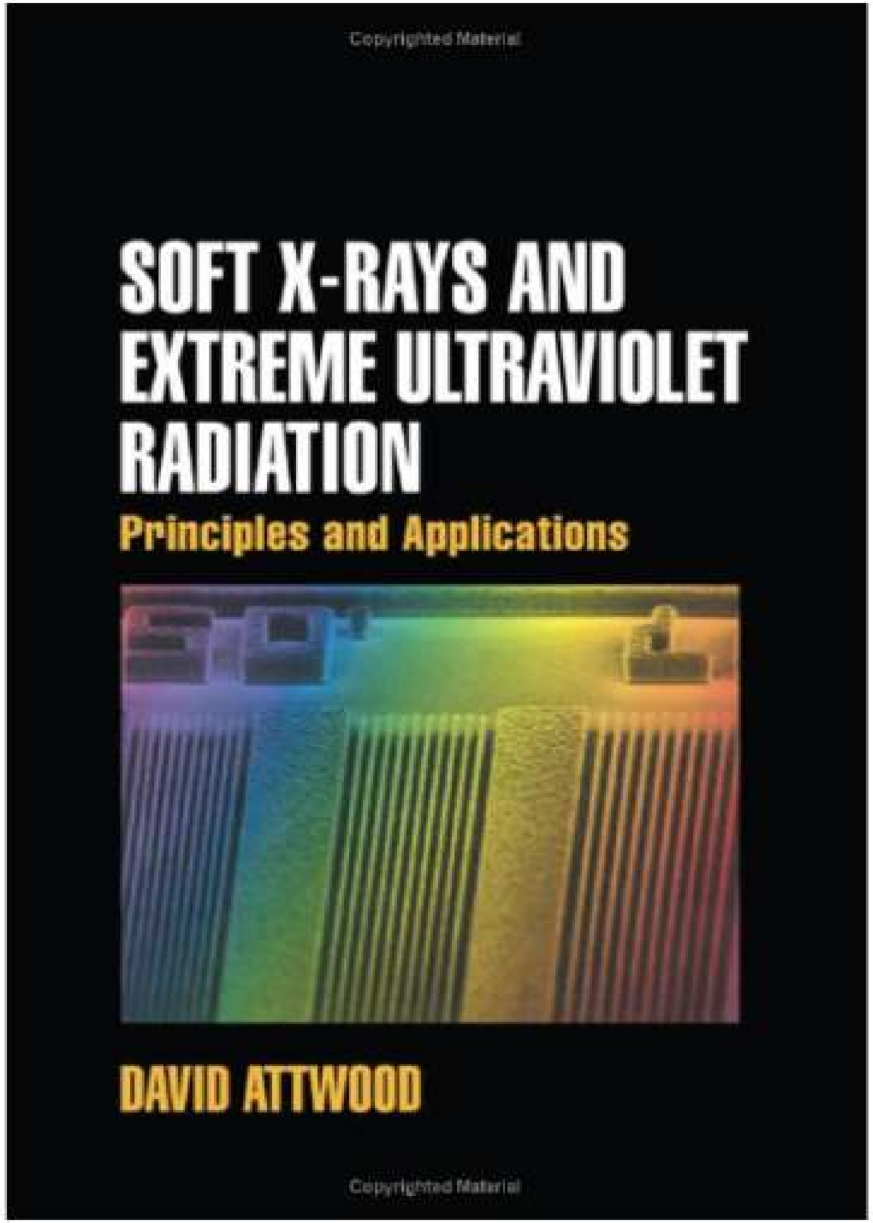
Lecture topics:

1) A brief introduction to X-rays
    - The basics of the interaction of X-rays with matter
    - Origin and properties of synchrotron radiation

2) X-ray based techniques
    - X-ray absorption spectroscopy
    - Types of magnetic dichroism
        - XMCD and Sum Rules
        - XMLD
    - Resonant magnetic scattering

3) X-ray microscopy
    - STXM
    - XPEEM
    - Lensless microscopy

Reference for synchrotron radiation



Discovery of X-rays

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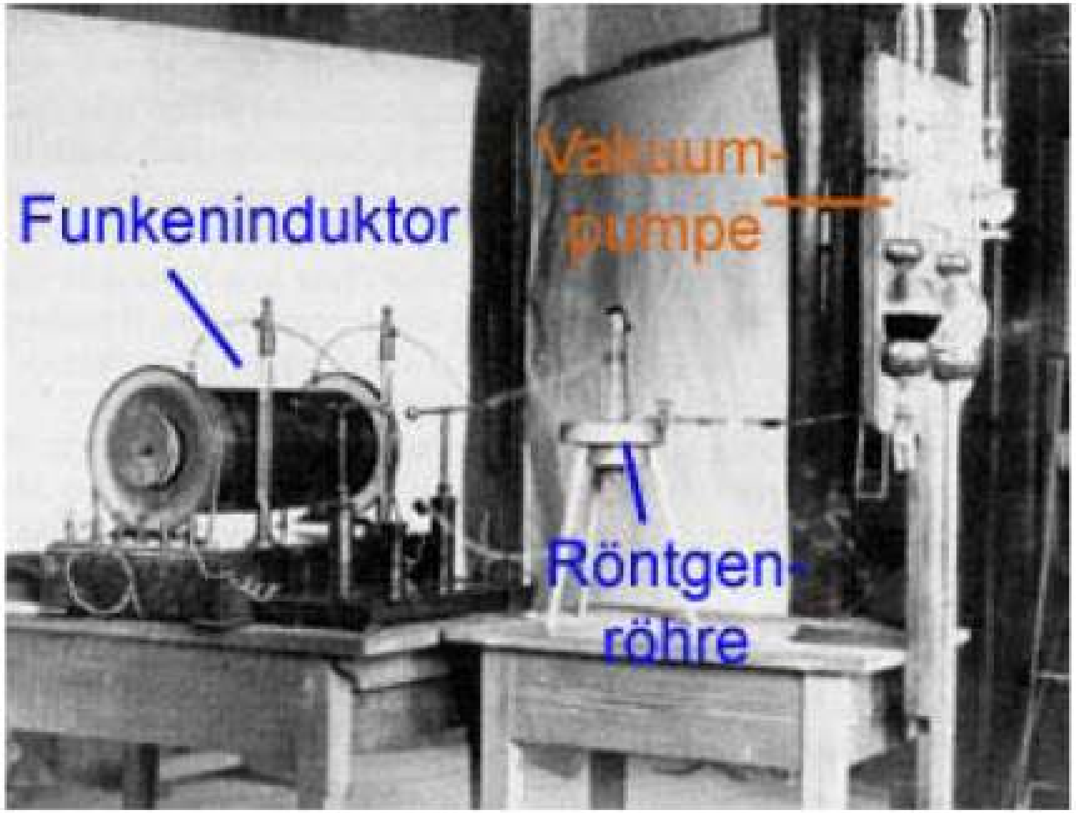
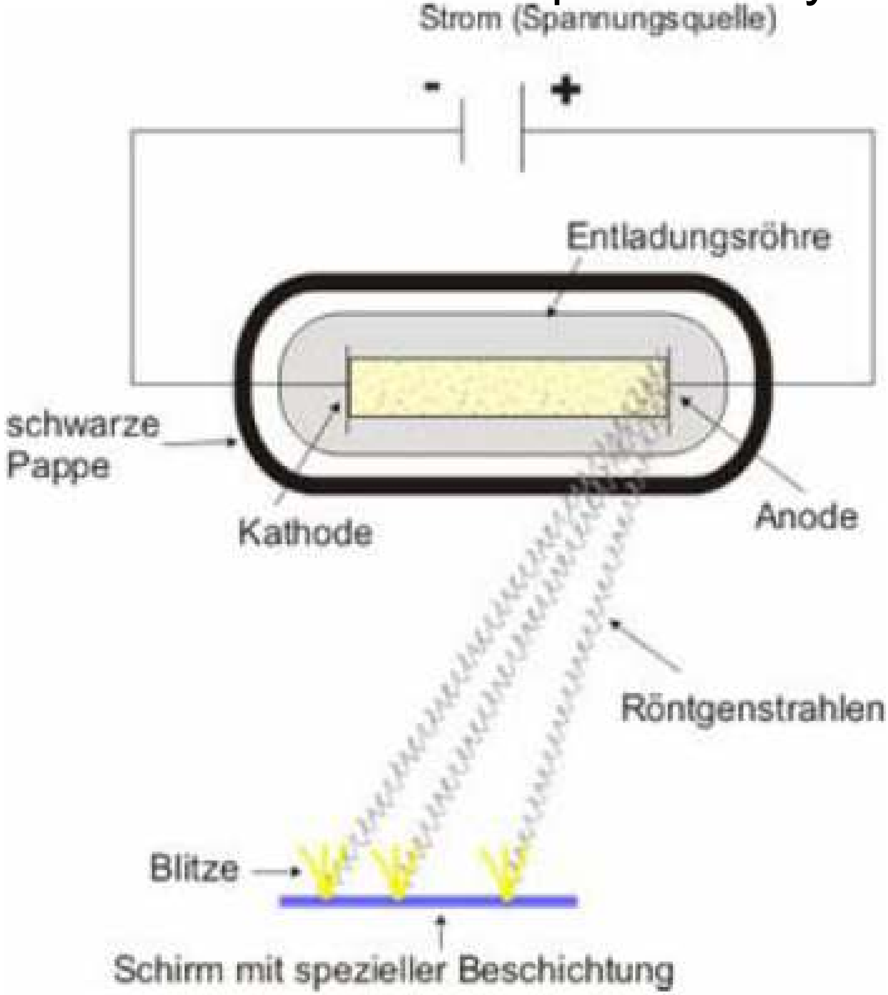
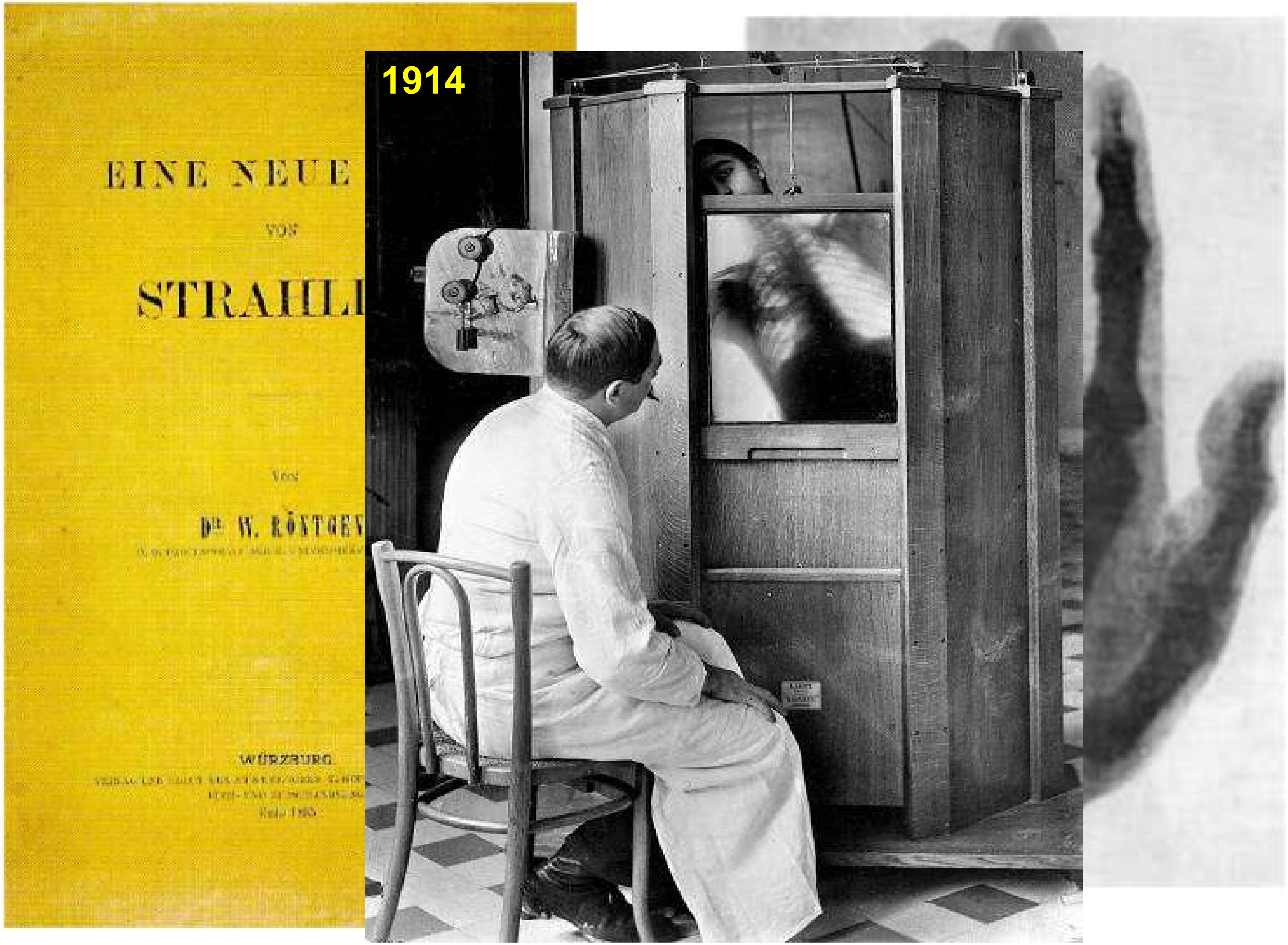
8 November 1895
(Würzburg, Germany)

1901 : Nobel price in Physics





First applications



A chest X-ray in progress at Professor Menard's radiology department at the Cochin hospital, Paris, 1914. (Jacques Boyer/Roger Viollet—Getty Images)

Why are X-rays so useful

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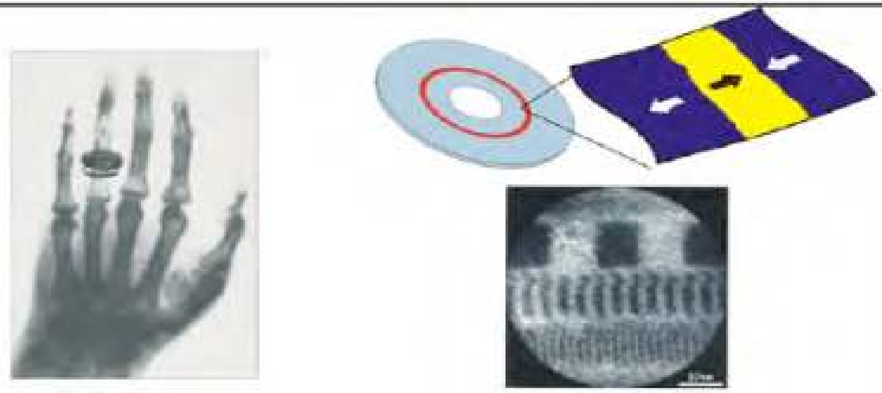
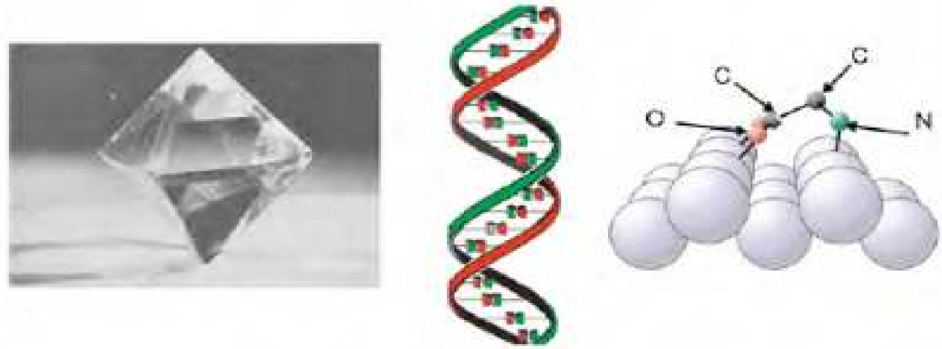
Imaging - Seeing the Invisible



1895 1993

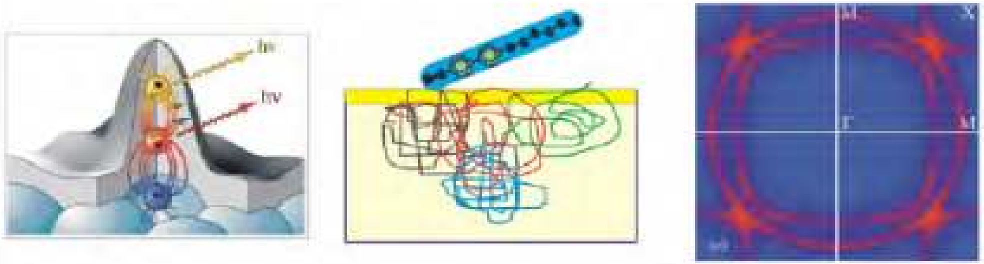
Atomic and Molecular Structure

- where are the atoms -



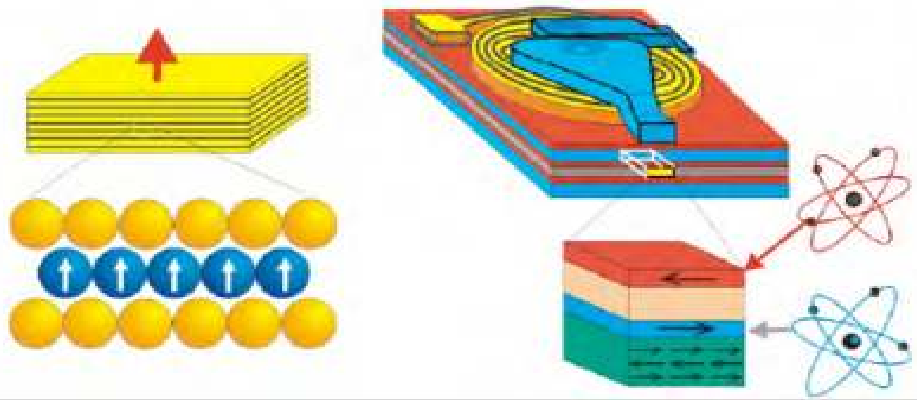
Electronic Structure and Bonding

- where are the electrons -



Magnetic Structure and Properties

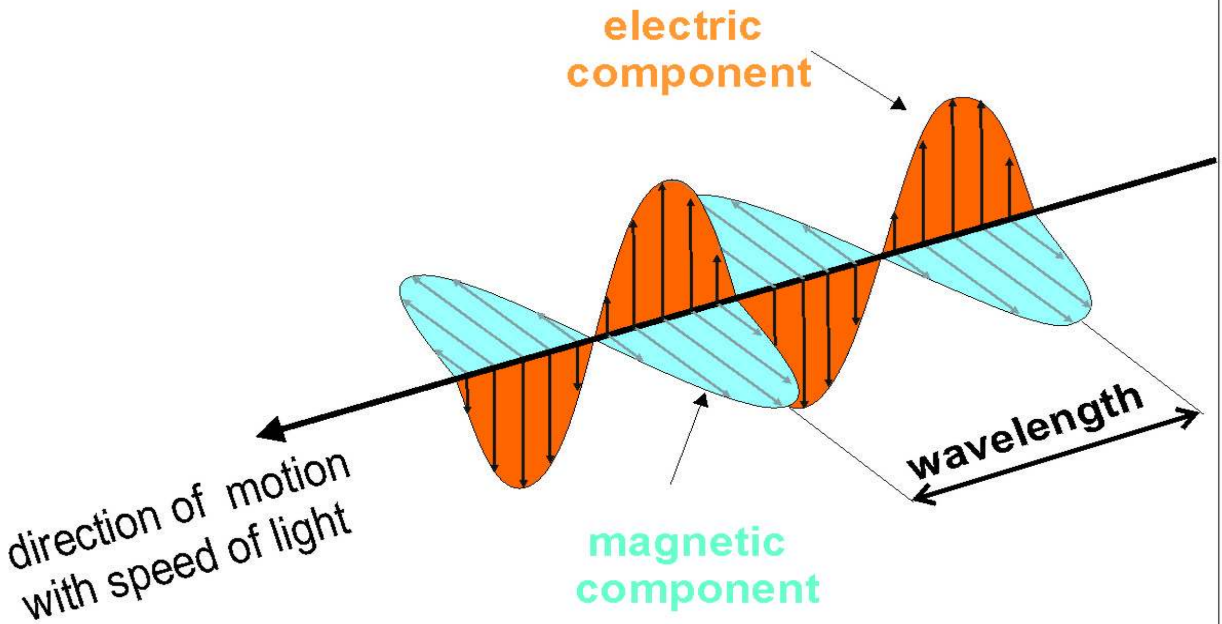
- where are the spins-

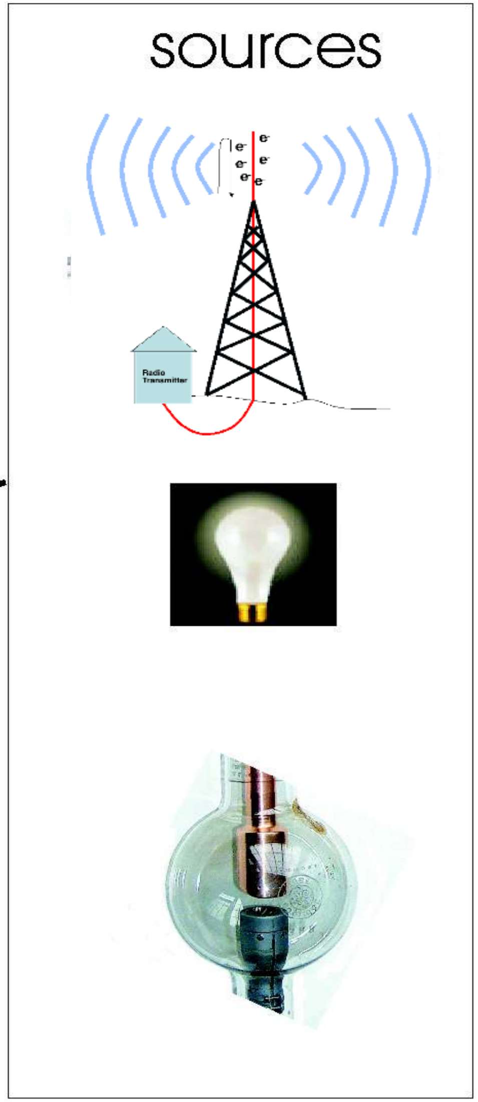


J. Stöhr

Electromagnetic Waves

Only difference: the wavelength!





TV

Radio

Radar

Microwaves

Light

X-Rays

Gamma-Rays

Soft & Hard X-rays as part of the electromagnetic spectrum

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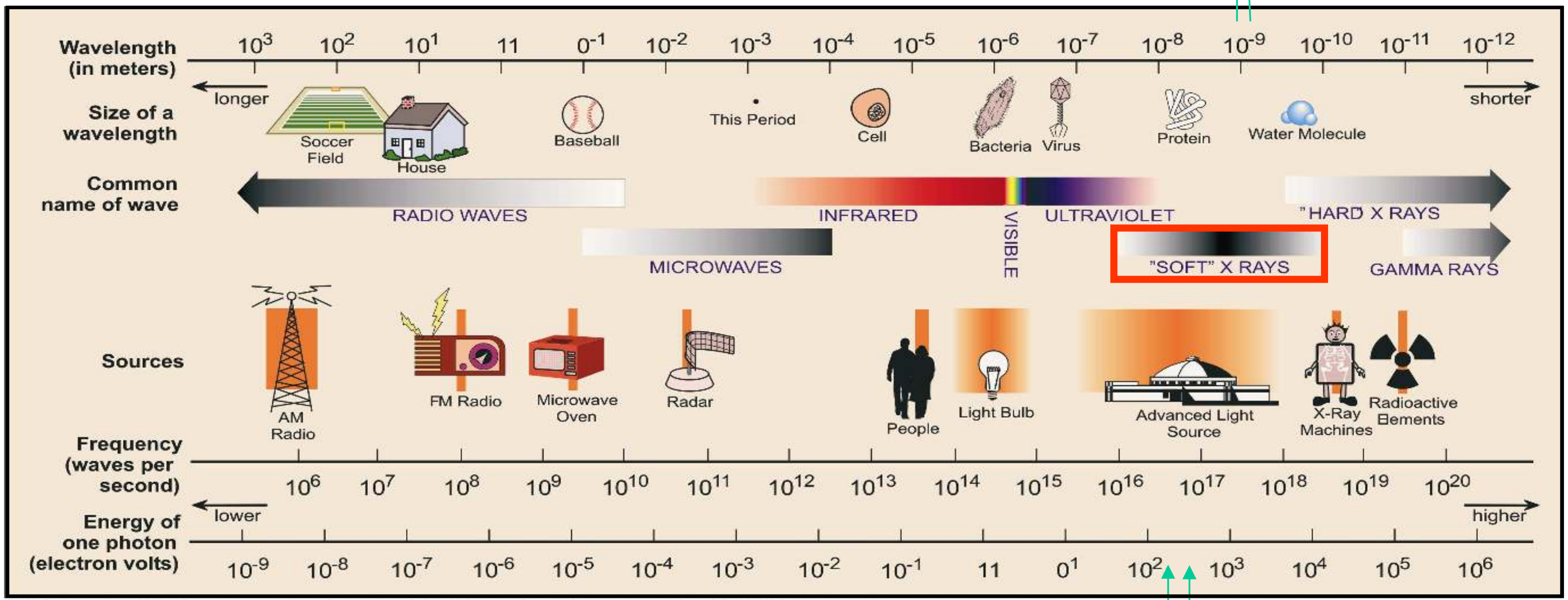
Three ‘common’ definitions:

Soft:	Grating	UHV	electronic structure
Hard:	Crystal	'Air'	crystal structure

Soft X ← → Hard X

nano atomic

Wavelength

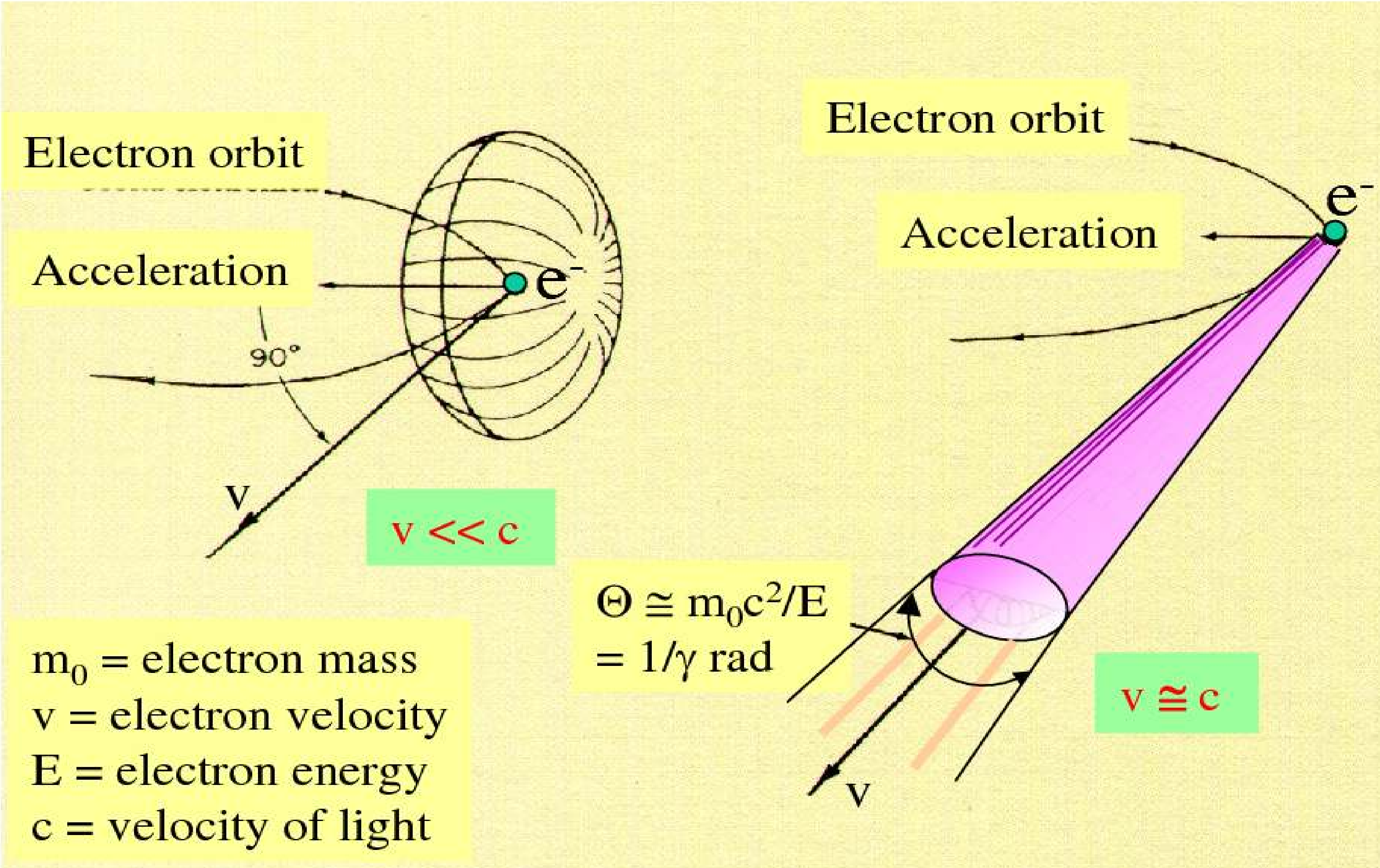


Energy

C, N, O K-edges

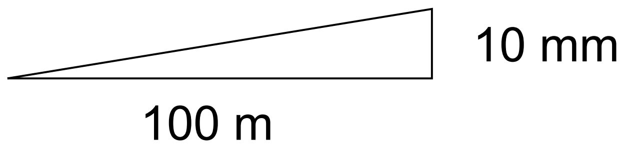
3d TM: strong magnetic L-edge resonances

Origin of synchrotron radiation

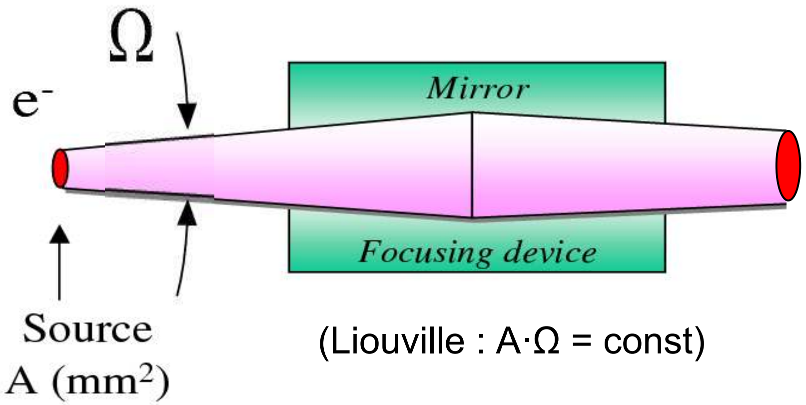


Emission angle Θ = 1/γ rad ~ 100 μrad

Small angle: tan (Θ [rad]) = Θ [rad]



UNE grandeur caractéristique pour évaluer la qualité d'une source est la luminance.

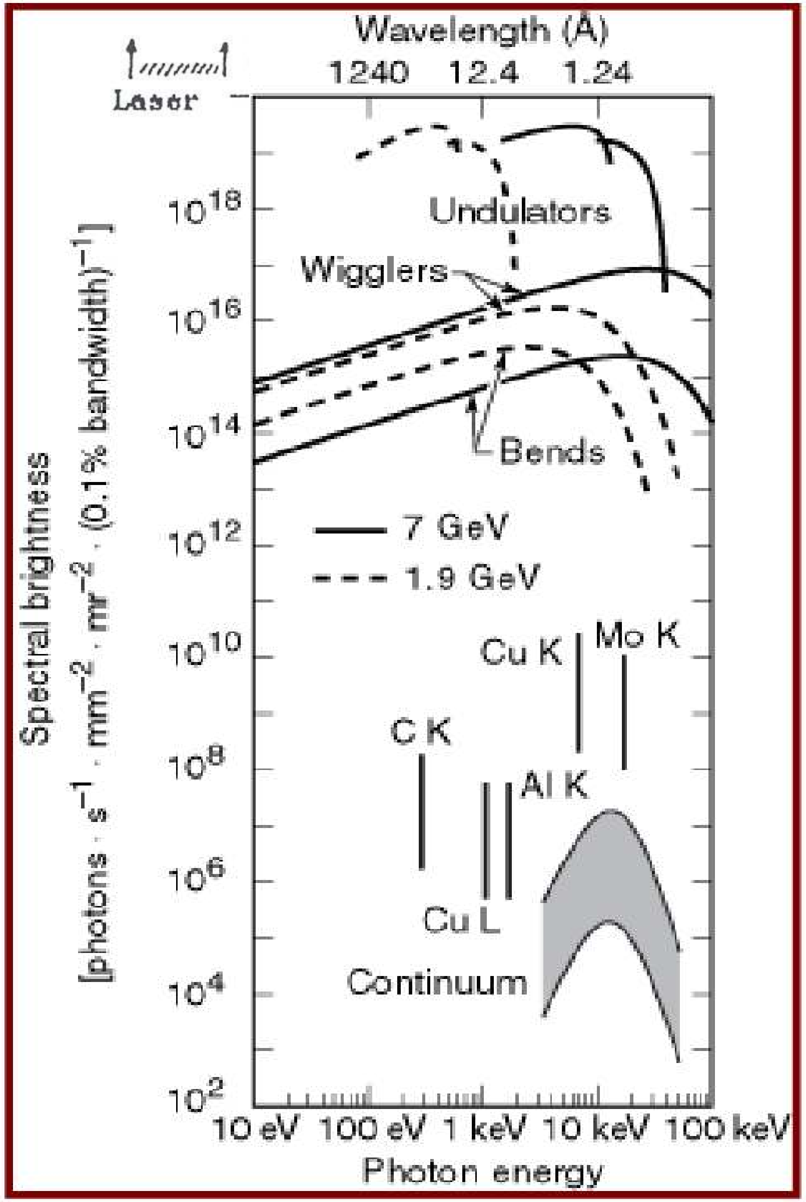


(Liouville : A·Ω = const)

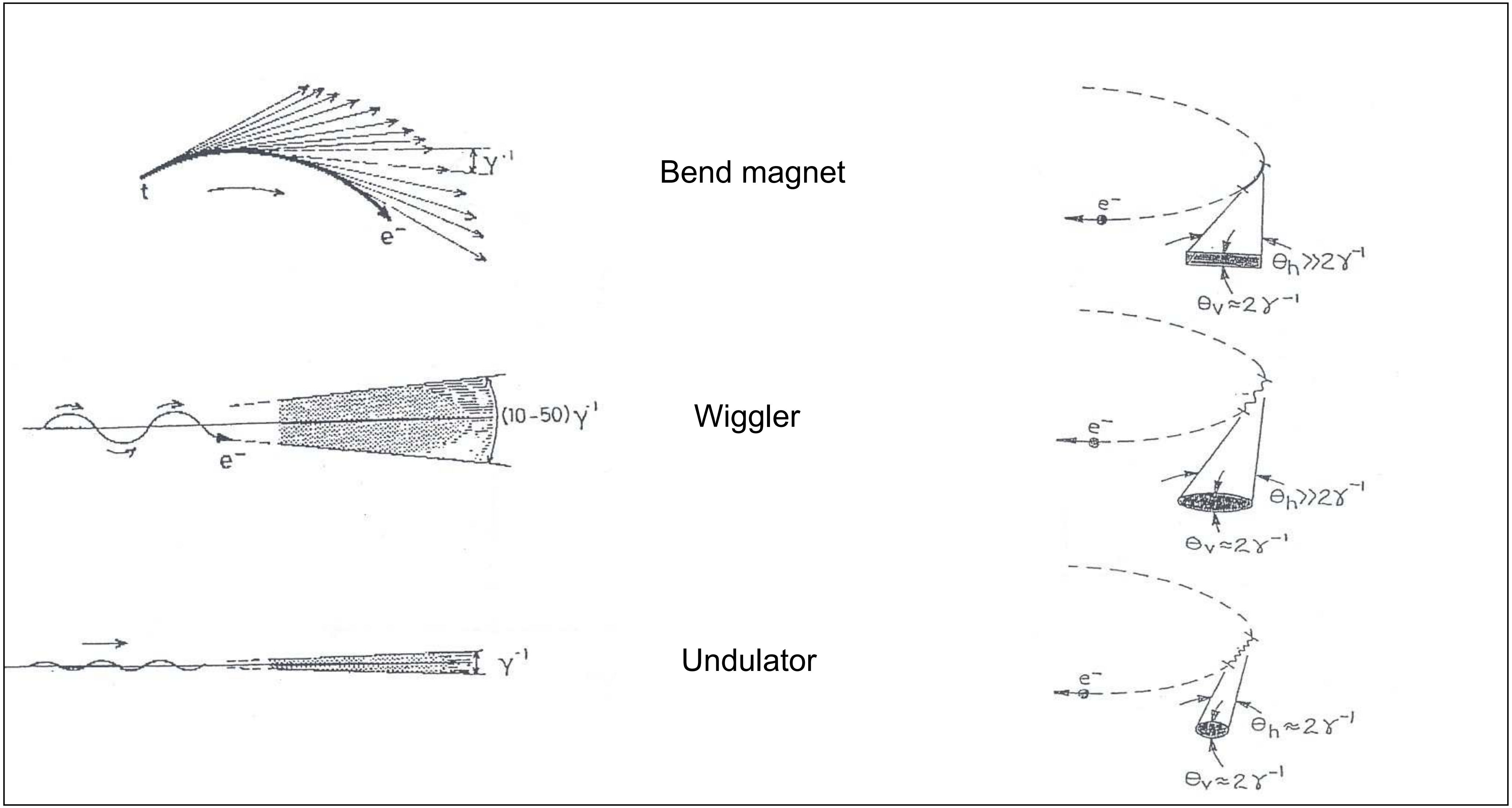
$$\text{Brilliance} = \frac{\text{Photons/second}}{\text{Source size x Divergence x }\Delta E}$$

$$\left(\frac{Photons\,/\,sec}{mm^2\,.(m\,rad)^2\,(0.1\%\,ban)}\right)$$

Note: The coherence of a source is proportional to its brilliance!



Bending magnet and insertion device radiation



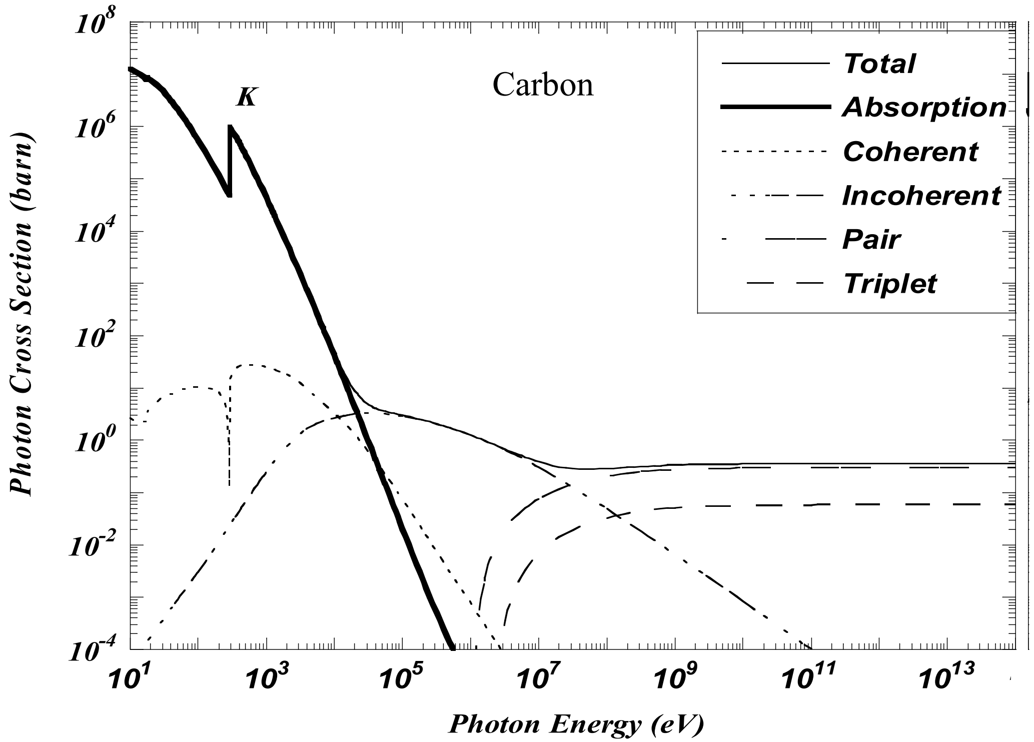
50+ SR sources world-wide

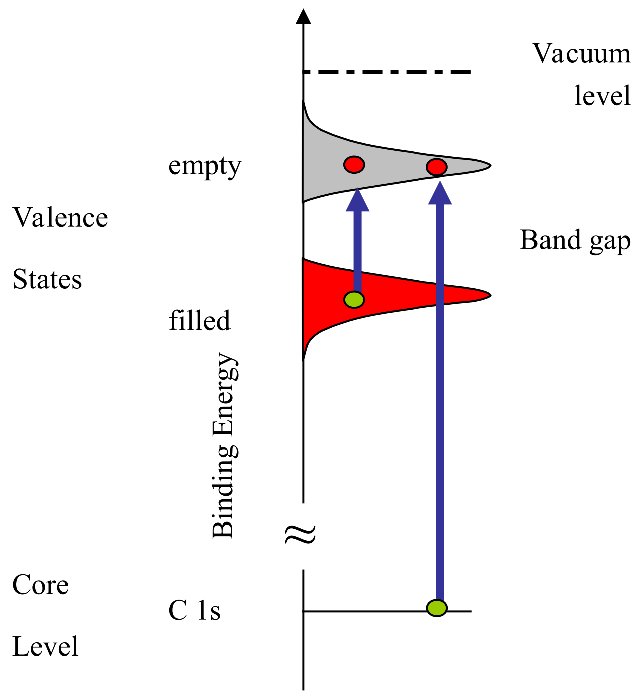
13 SR sources in Europe

… and 4 XUV/X-FELs

Photon – Matter Interaction

Photon – Matter Interactions





Absorption → dominates in X-ray photon energy range

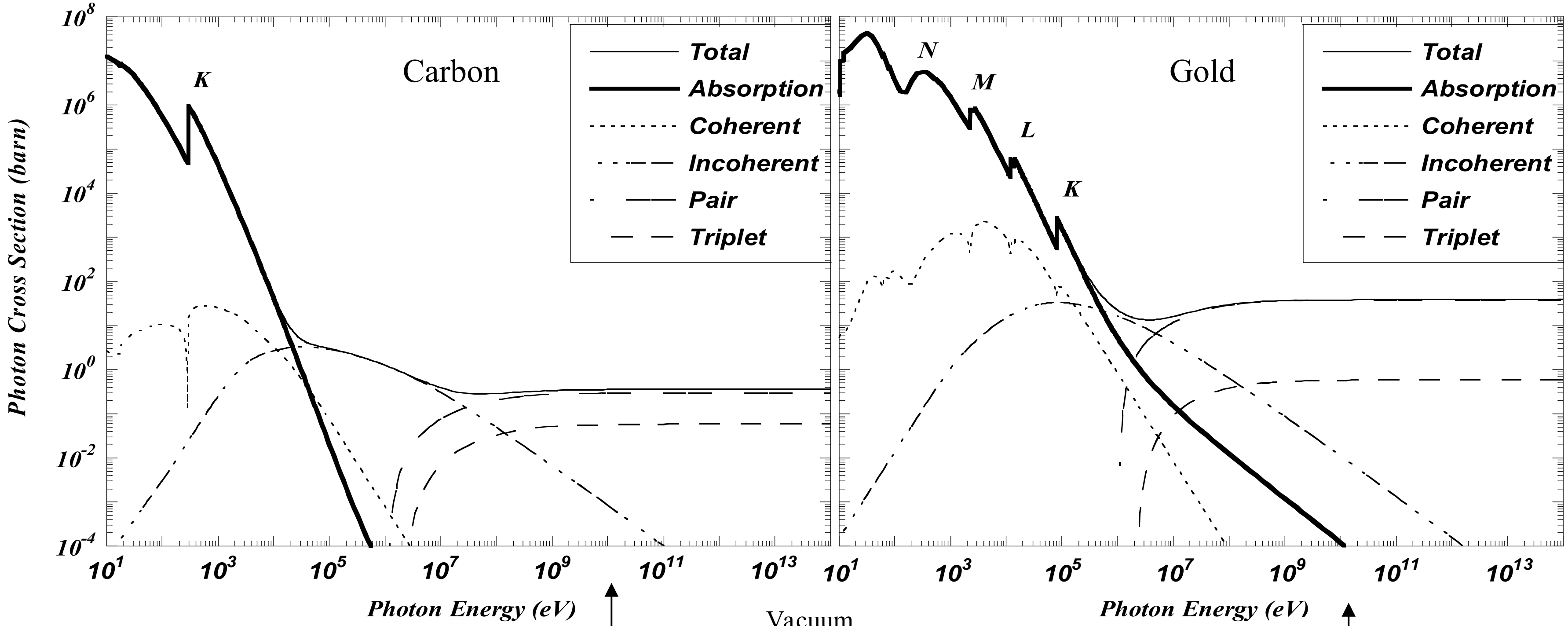
Coherent = Thomson scattering → X-ray scattering/diffraction
Incoherent = Compton scattering

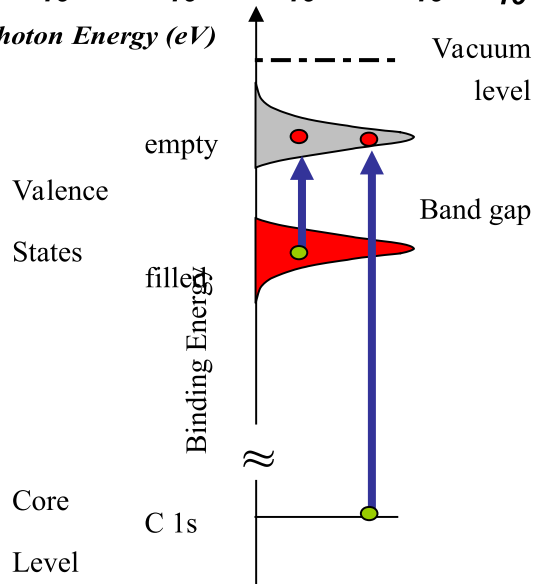
Photon Absorption Cross Section:

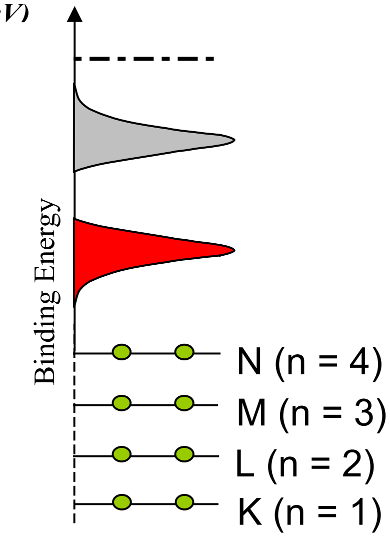
$$\sigma_X = \frac{\#\text{ of absorbed photons per second}}{\#\text{ of incident photons per second per area}}$$

$$[\sigma] = \text{barn} = 12^{-24}\,\text{cm}^2$$

Photon Matter Interactions

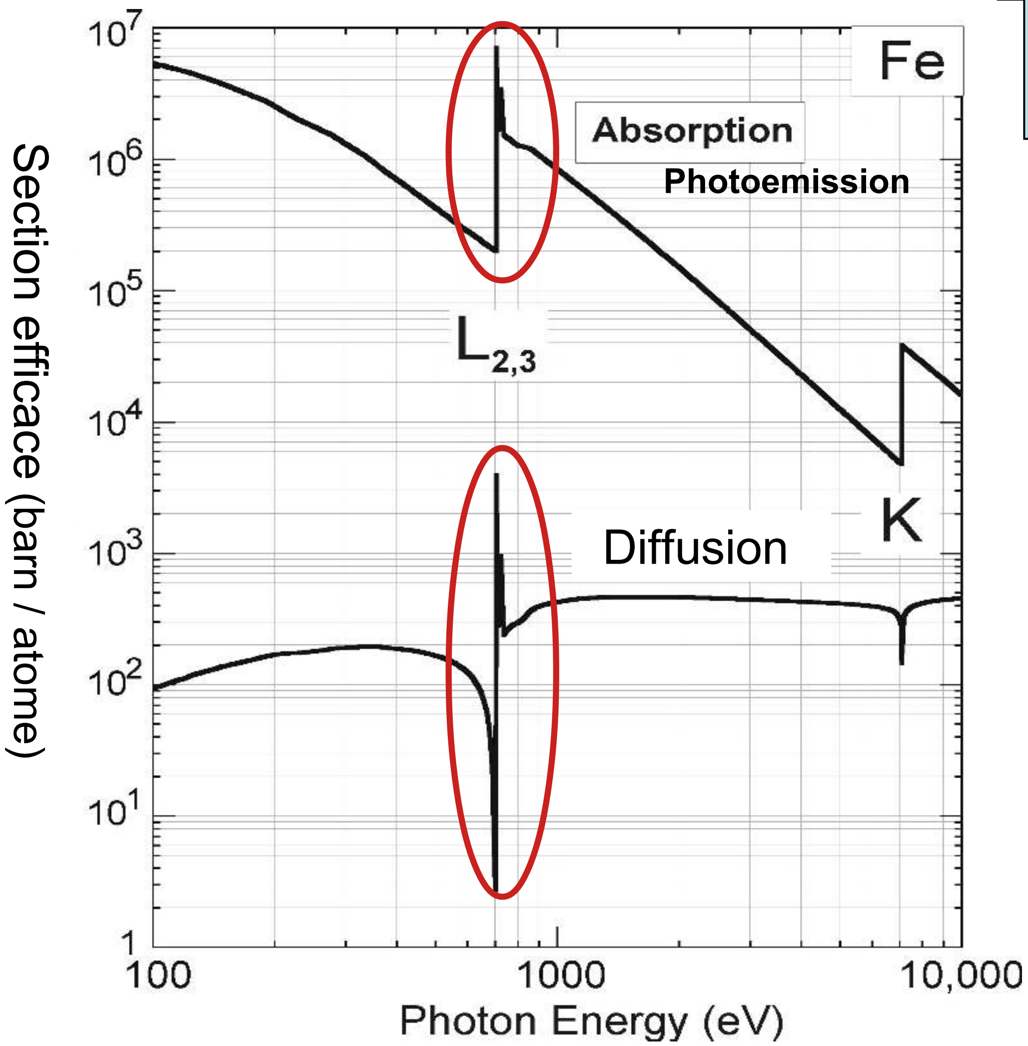






Interaction strengths of different probes

Visible light
(Metals)

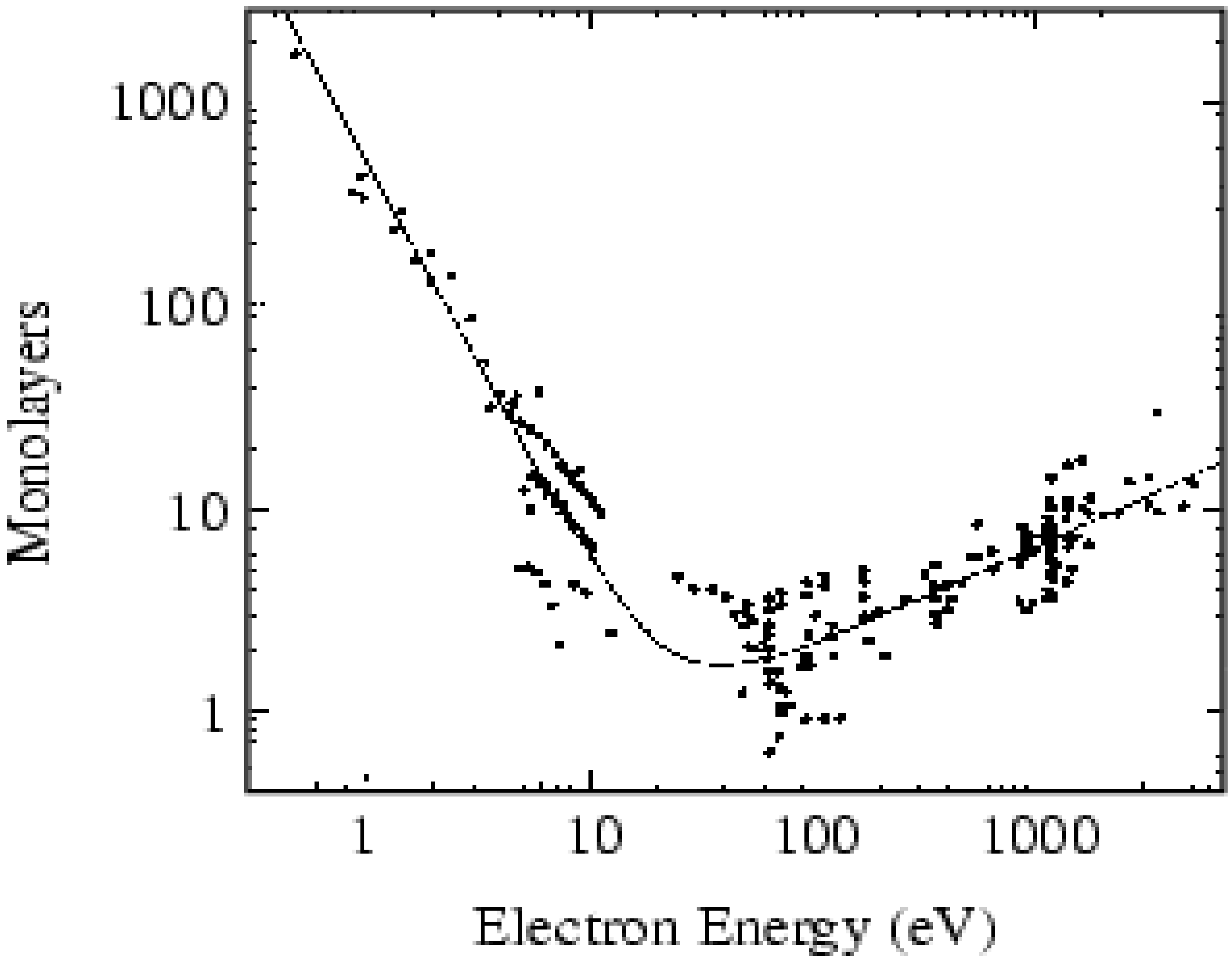


Electrons
Charged probe

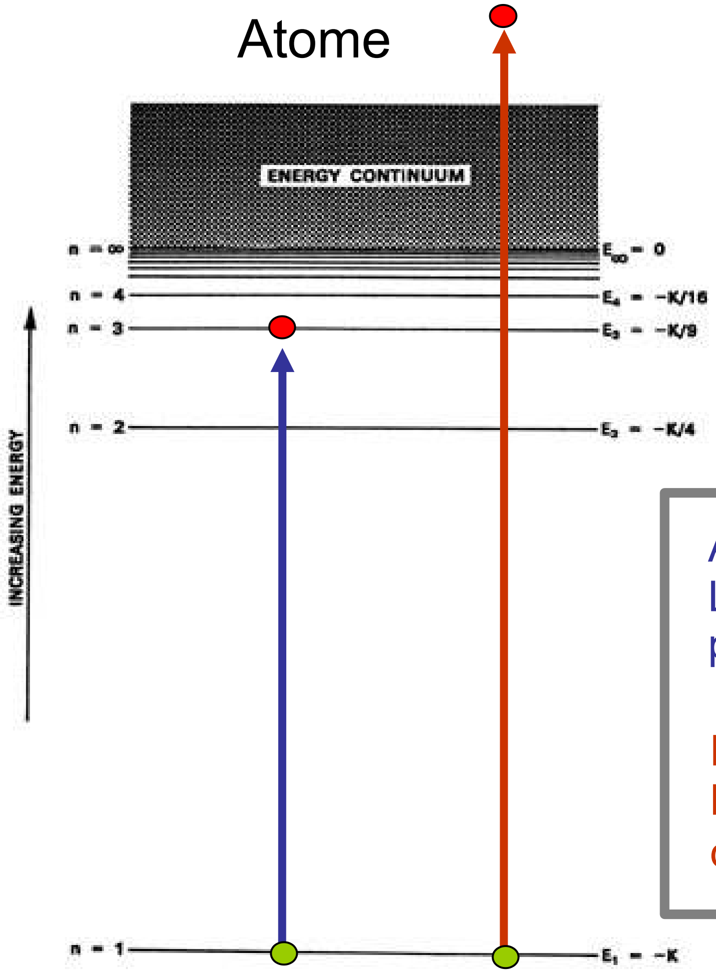
Visible light
(Insulators)

Neutrons
No charge, but a spin

Mean free path of electrons in materials

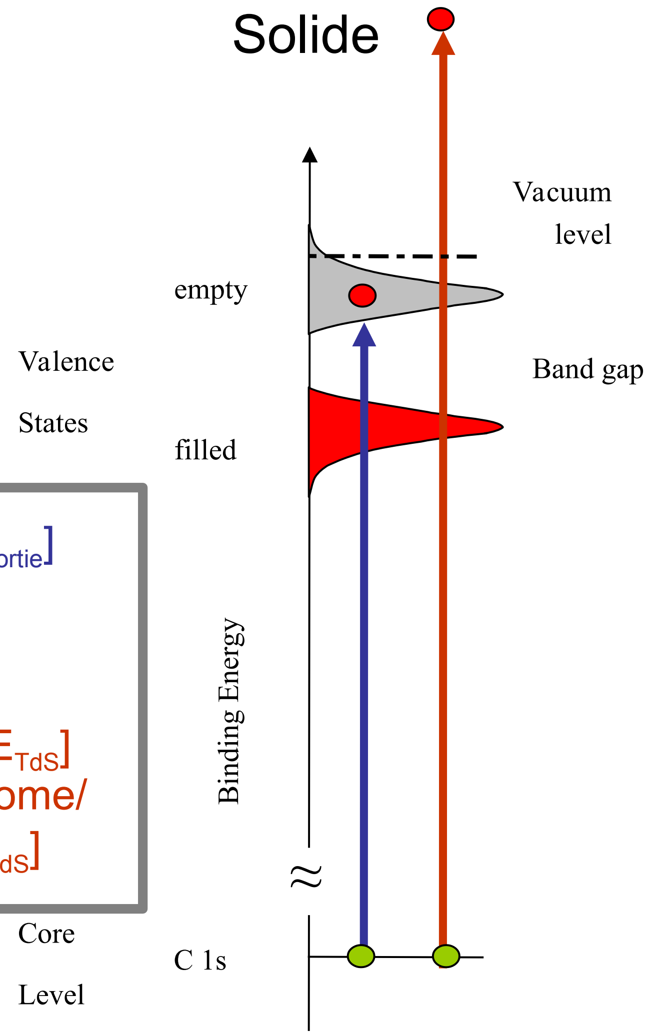


Absorption and Photoemission in atoms and solides



Absorption : hν < E_B [+ $E_{T.d.Sortie}$]
L'électron excité ne sort
pas de l'atome/du solide.

Photoémission : hν > E_B [+ E_{TdS}]
L'électron excité sort de l'atome/
du solide. E_{Kin} = hν - E_B [- E_{TdS}]



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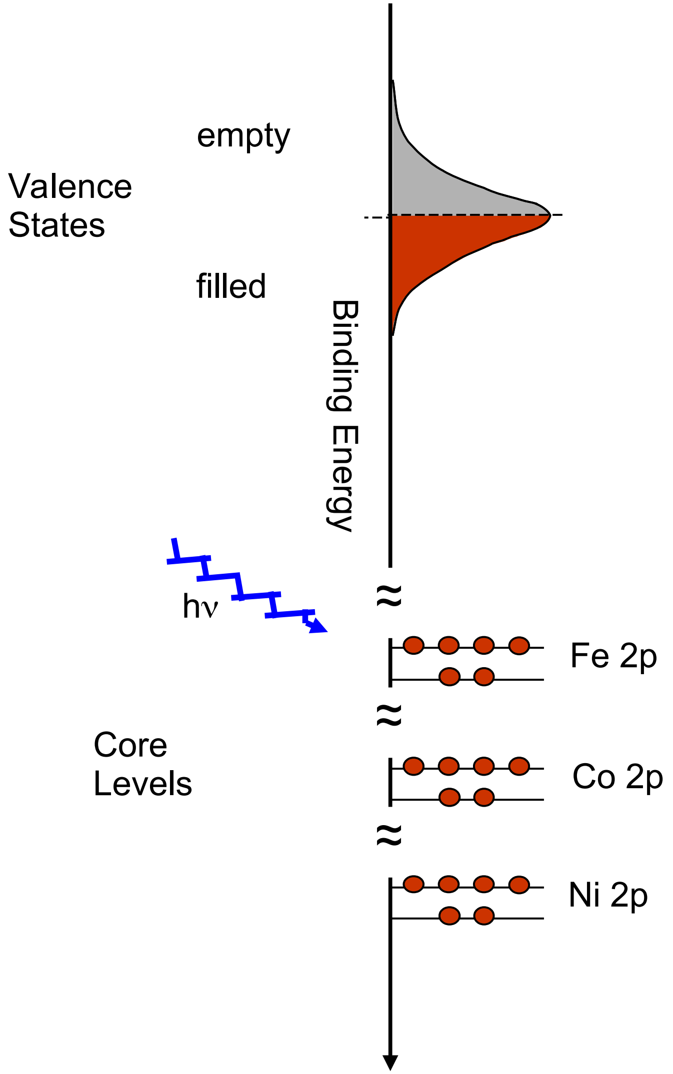
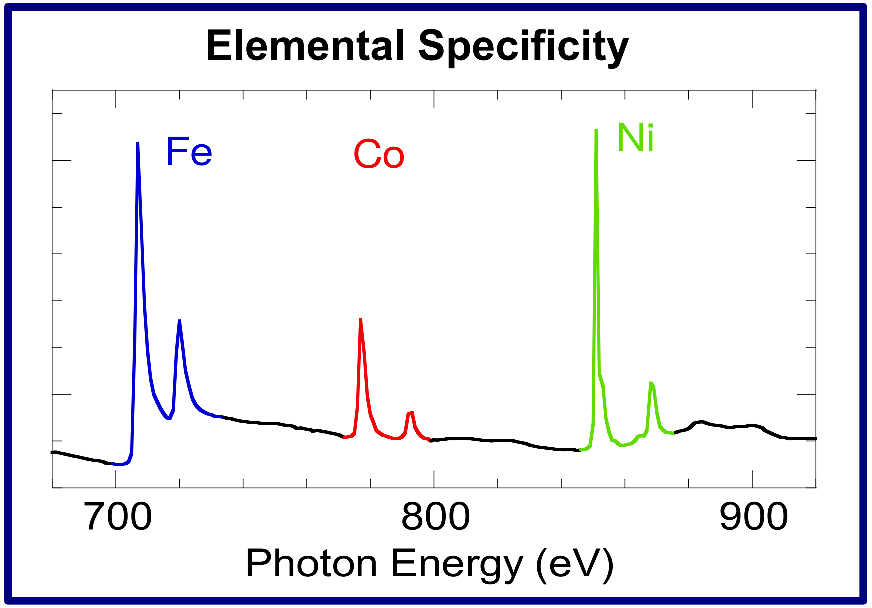
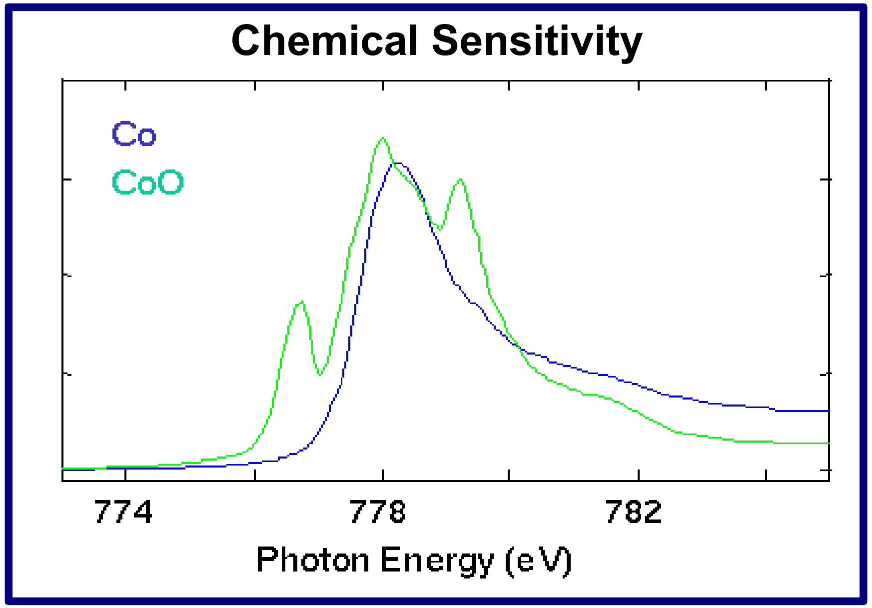
X-ray absorption spectroscopy

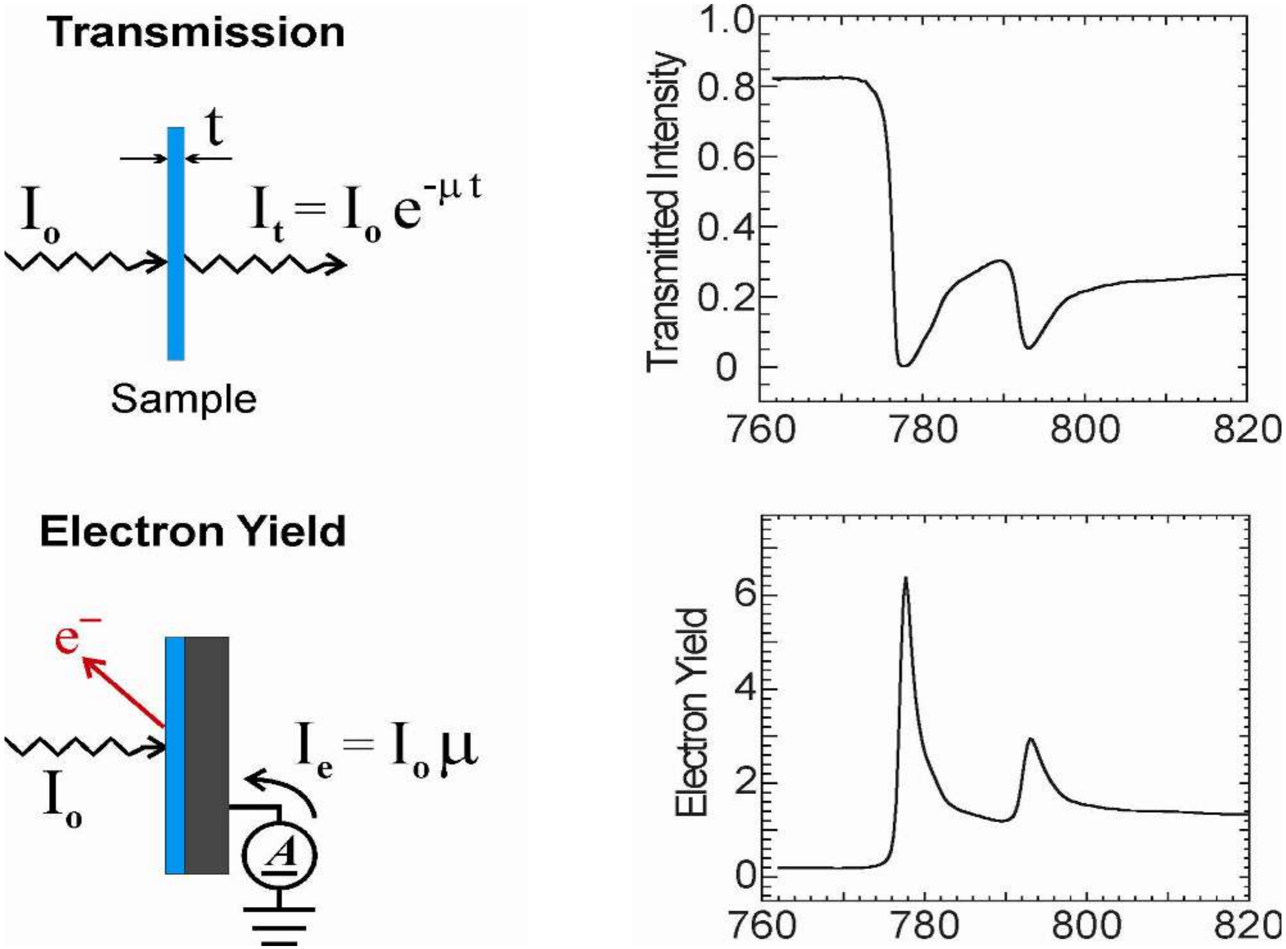
X-ray absorption resonances







X-ray absorption: Transmission versus Yield detection



"Photons lost"

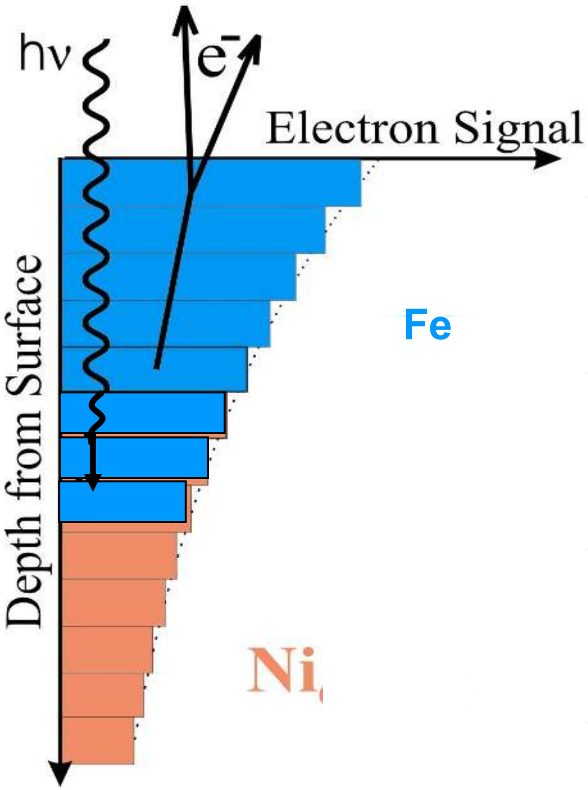
Volume
(< 1 - 10 microns)

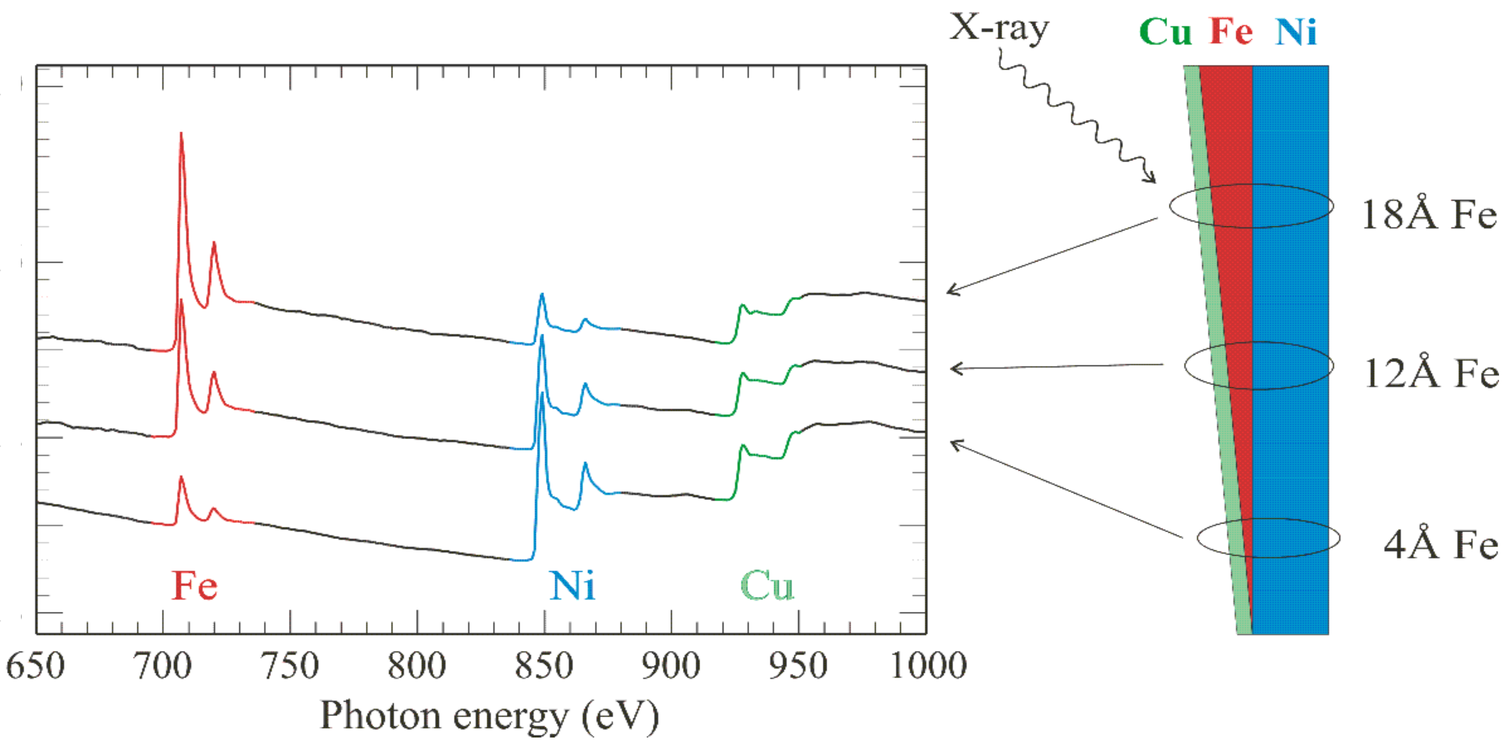
"Electrons generated"

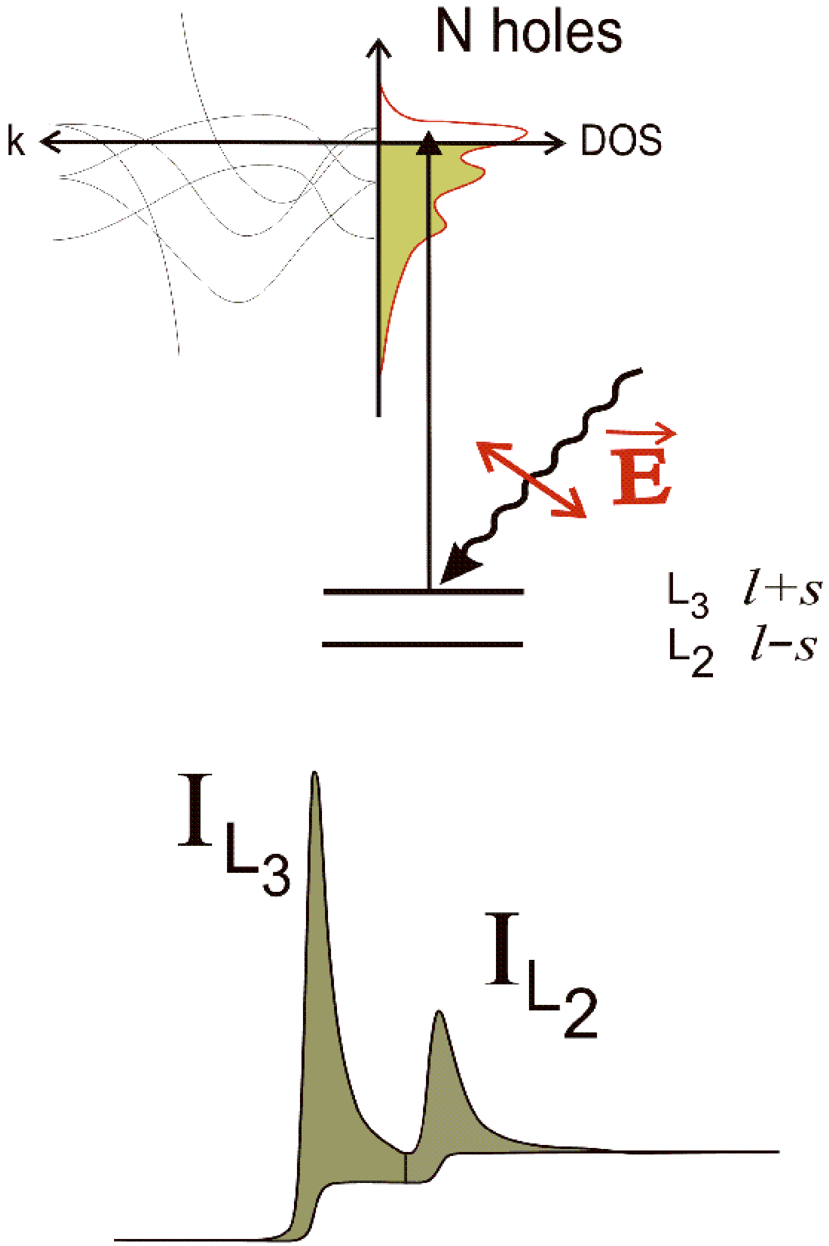
Surface
(1 – 2 nanometer)

Total electron yield detection to render

X-ray absorption spectroscopy surface sensitive

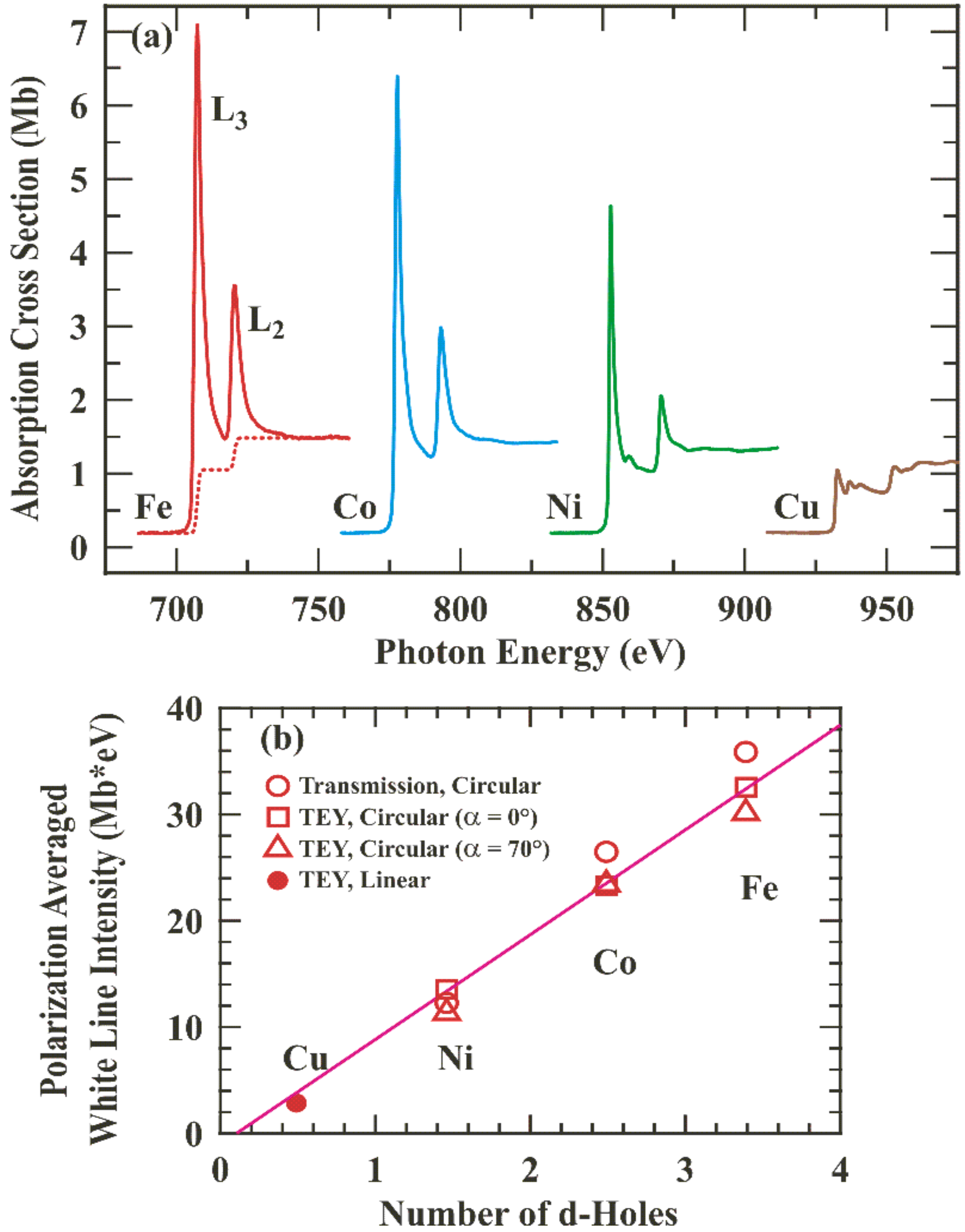






	holes
Fe	3.4
Co	2.5
Ni	1.5

L_{32} ‘white line’ intensity of transition metals (3d)



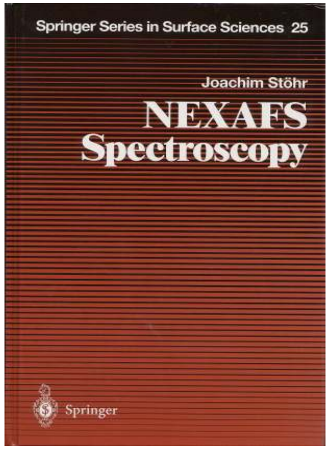
J. Stohr et al.

X-ray magnetic circular dichroism (XMCD)

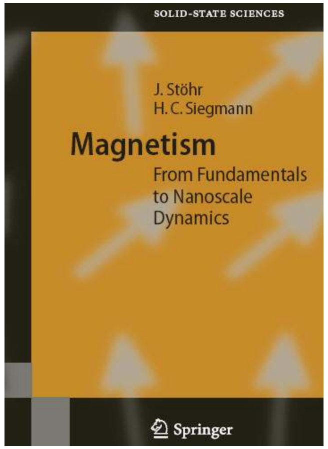
in X-ray absorption spectroscopy

More about X-rays and magnetism

J. Stöhr,
NEXAFS SPECTROSCOPY,
Springer Series in Surface Sciences 25,
Springer, Heidelberg, 1992.

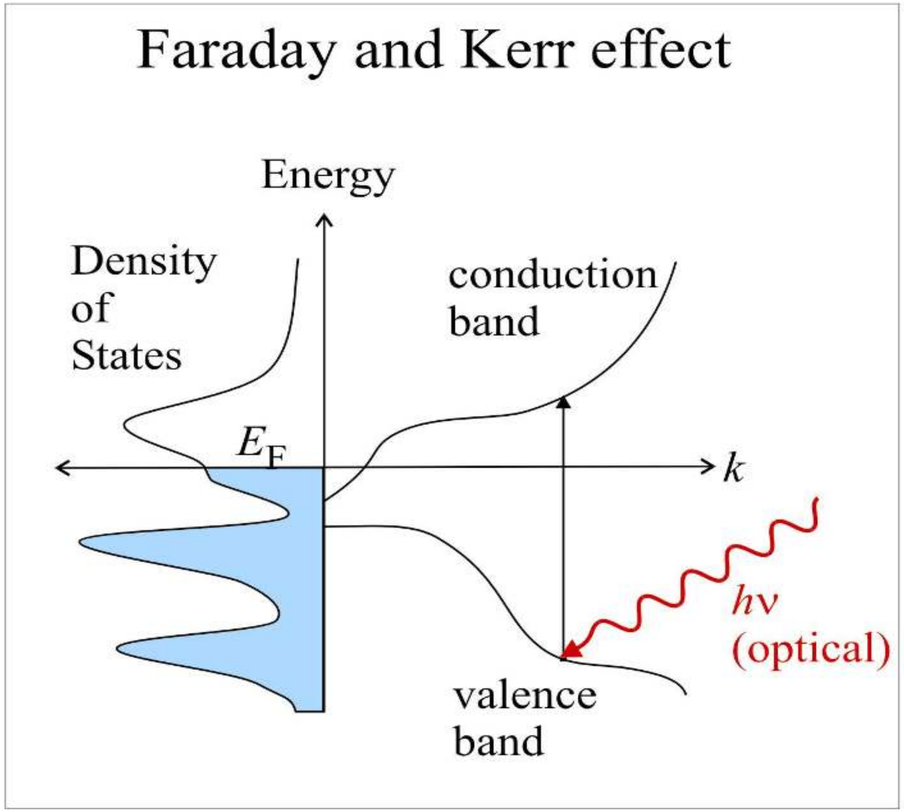


J. Stöhr and H. C. Siegmann
MAGNETISM: FROM FUNDAMENTALS TO NANOSCALE DYNAMICS,
Springer Series in Solid State Sciences 152,
Springer, Heidelberg, 2006

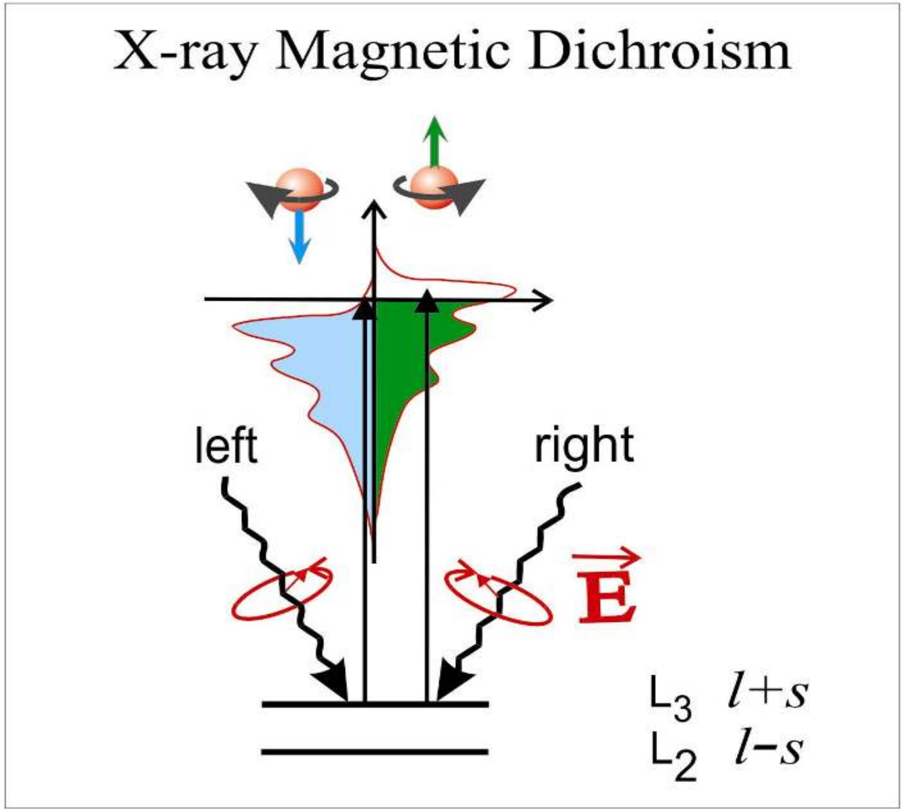


Many (!) transparencies are taken from Jo Stohr's 2007 presentation on 'X-rays and magnetism'

www-ssrl.slac.stanford.edu/stohr

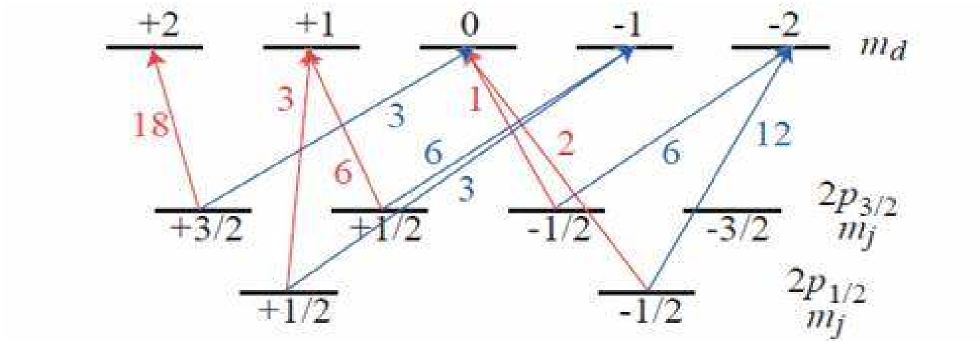


Magneto-optical response:
weak, *k*-dependent

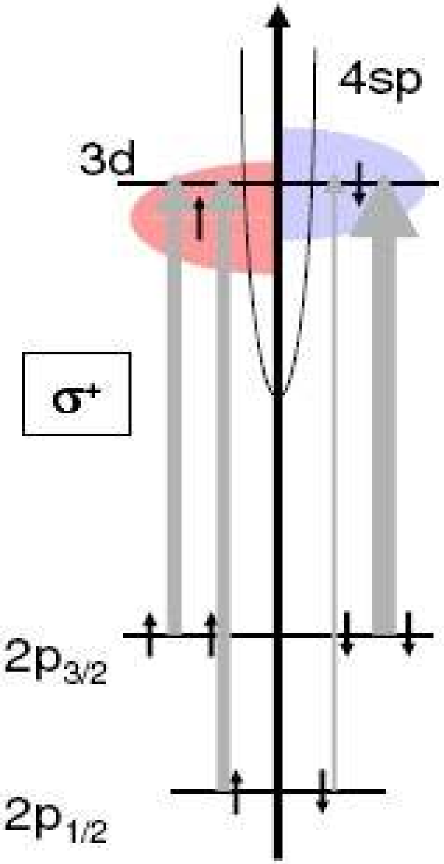


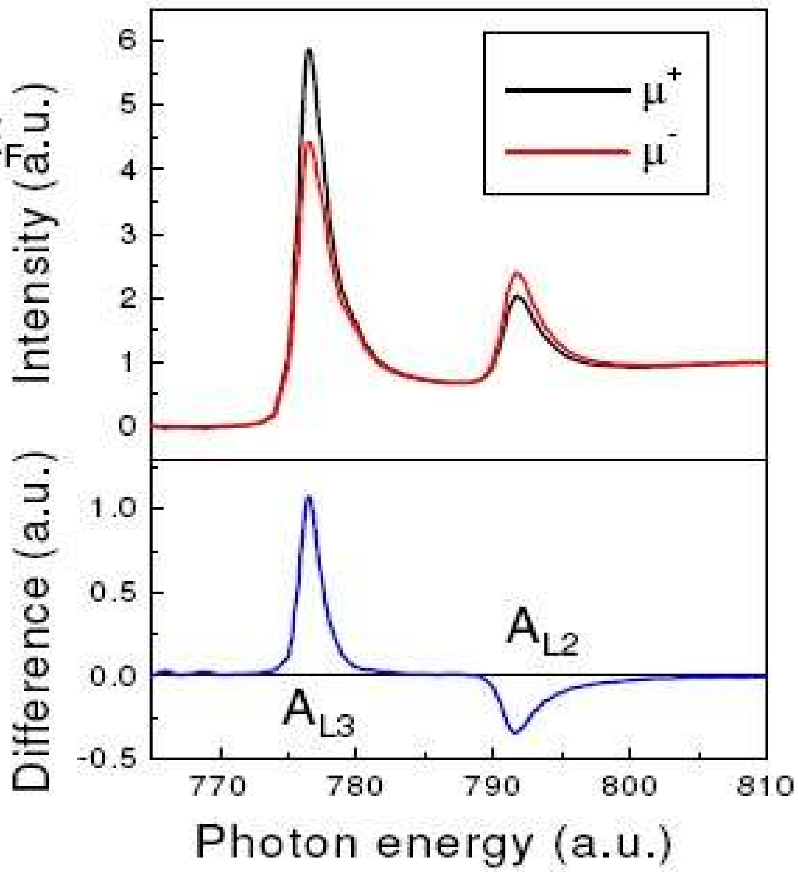
X-ray response:
strong, k-integrated quantities
number of holes, spin monent, orbital moment

Origin of the XMCD effect

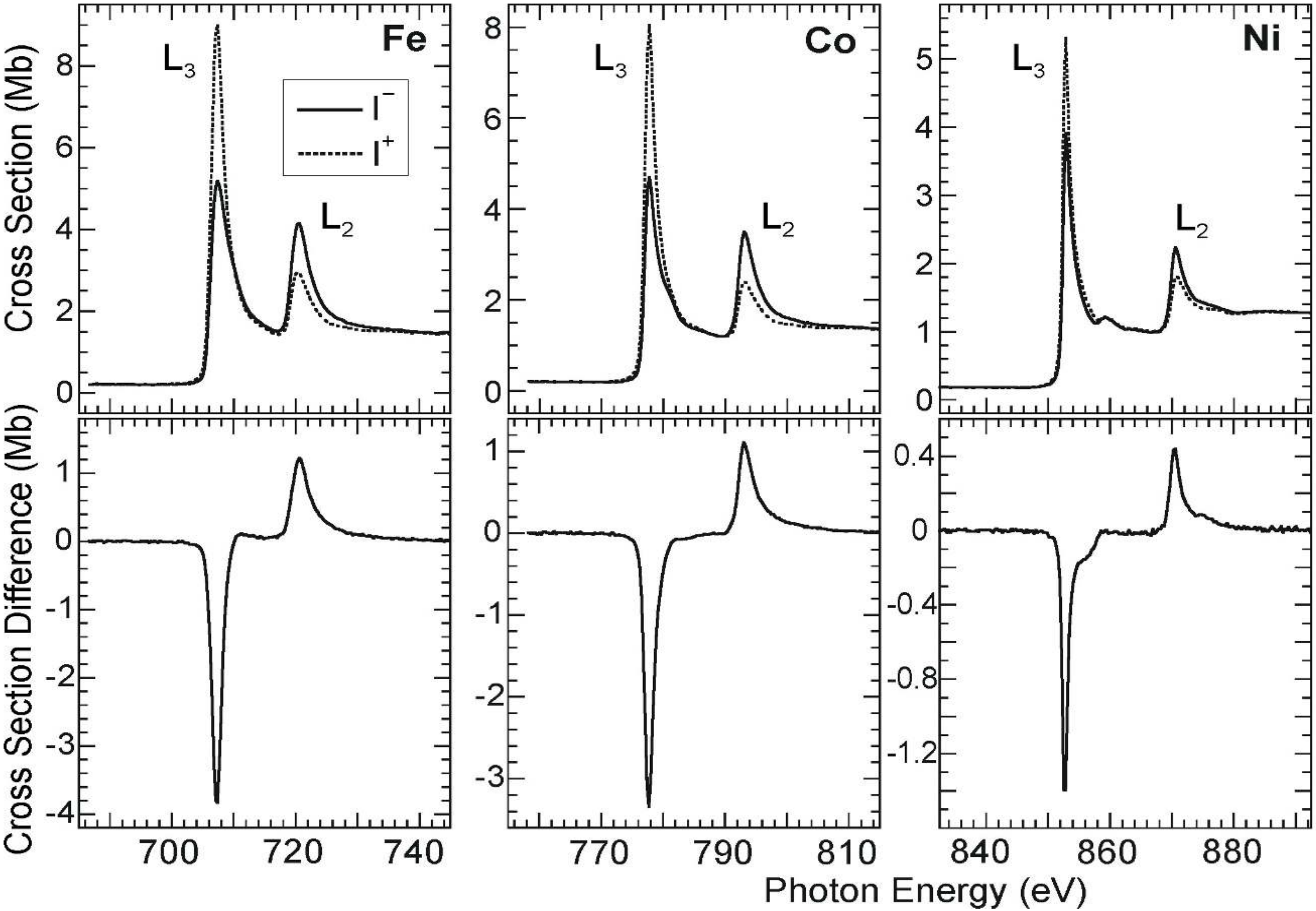


Relative transition amplitudes are given by the respective Clebsch Gordon coefficients

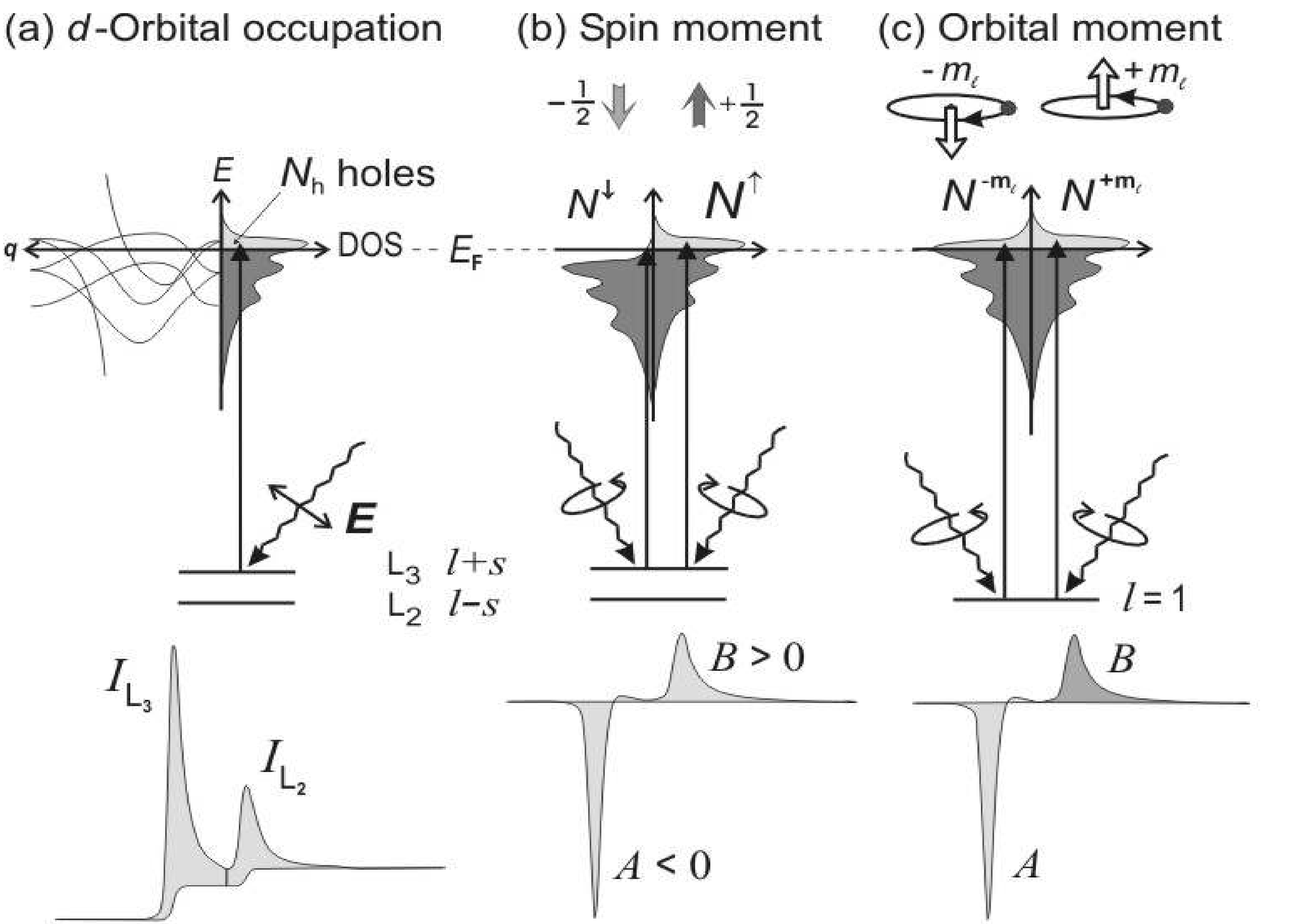




XMCD spectra of ferromagnetic 3d metals Fe, Co and Ni



XAS / XMCD sum rules

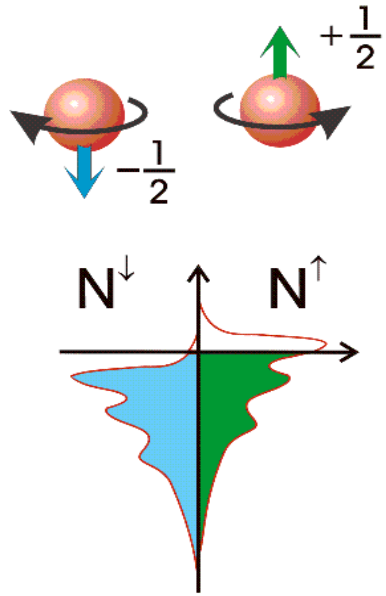


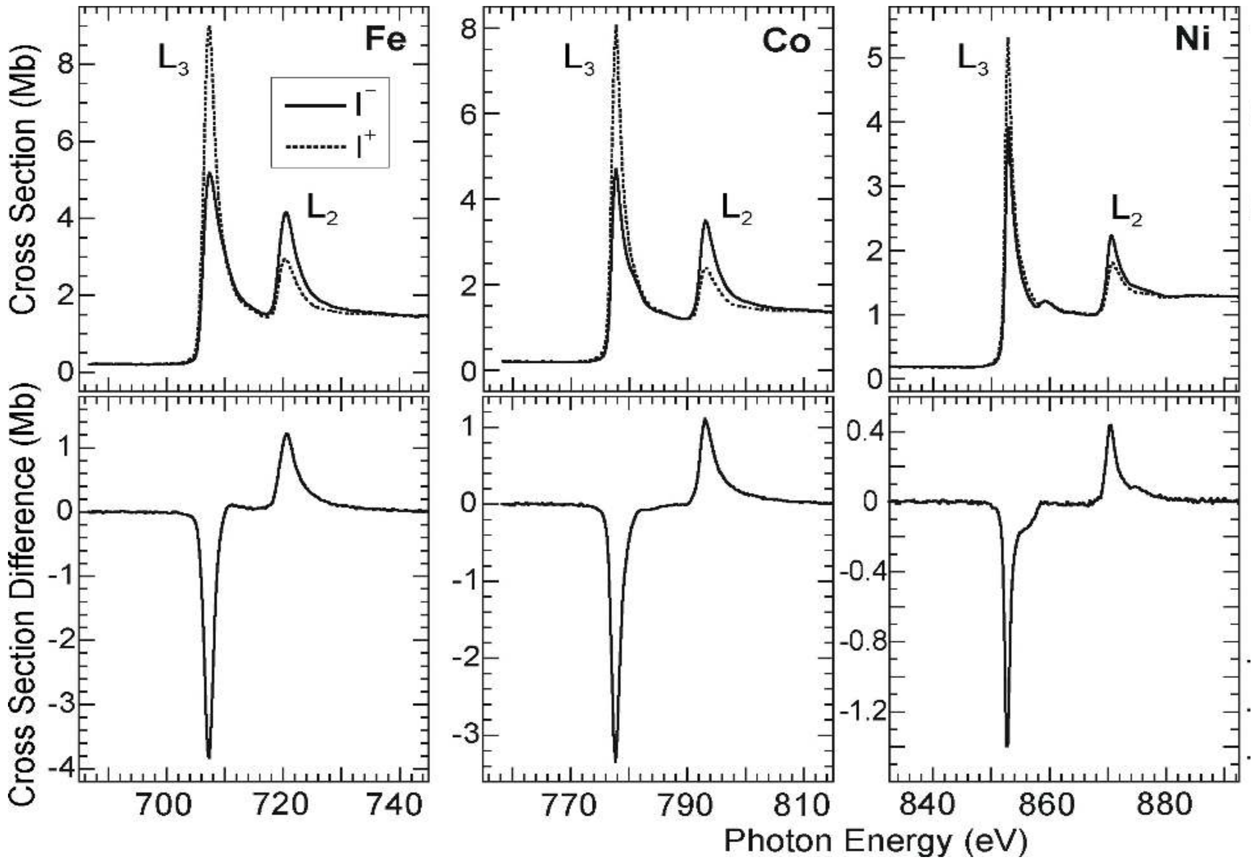
$N_h = \langle I_{L_3} + I_{L_2} \rangle / C$

$m_s = \mu_B \langle -A + 2B \rangle / C$

$m_o = -2\mu_B \langle A + B \rangle / 3C$

Magnetic moment of 3d transition metals Fe, Co and Ni





	m_{spin}^{tot}	m_{spin}^{d}	m_{spin}^{sp}
Fe	**2.19**	**2.26**	**−0.07**
Co	**1.57**	**1.64**	**−0.07**
Ni	**0.62**	**0.64**	**−0.02**

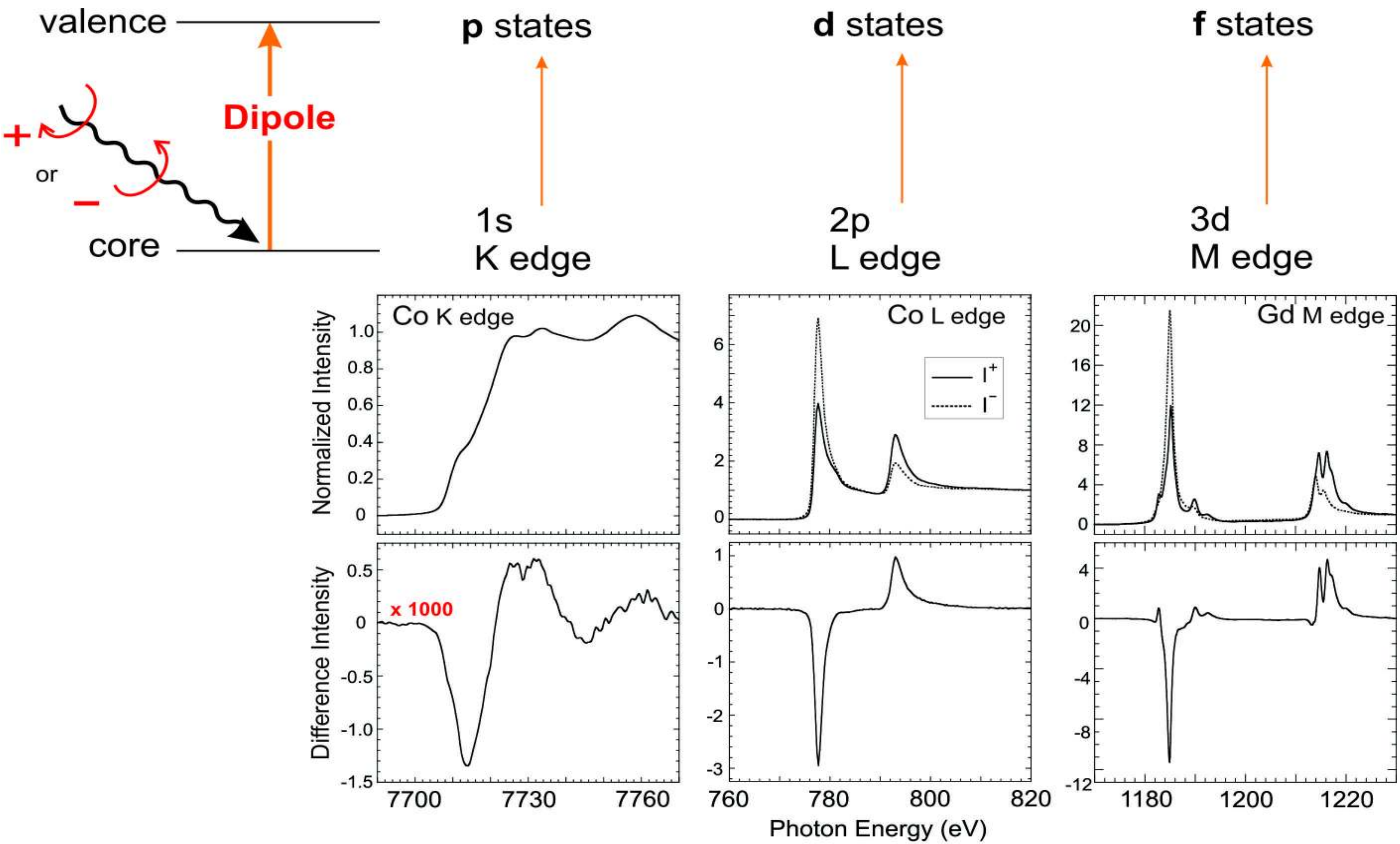
(b) Spin moment

$$m_s = \mu_B \langle -A + 2B \rangle / C$$

(c) Orbital moment

$$m_o = -2\mu_B \langle A + B \rangle / 3C$$

Spin polarization of valence band states



XMCD of transition metal $M_{2,3}$ and $L_{2,3}$ edges

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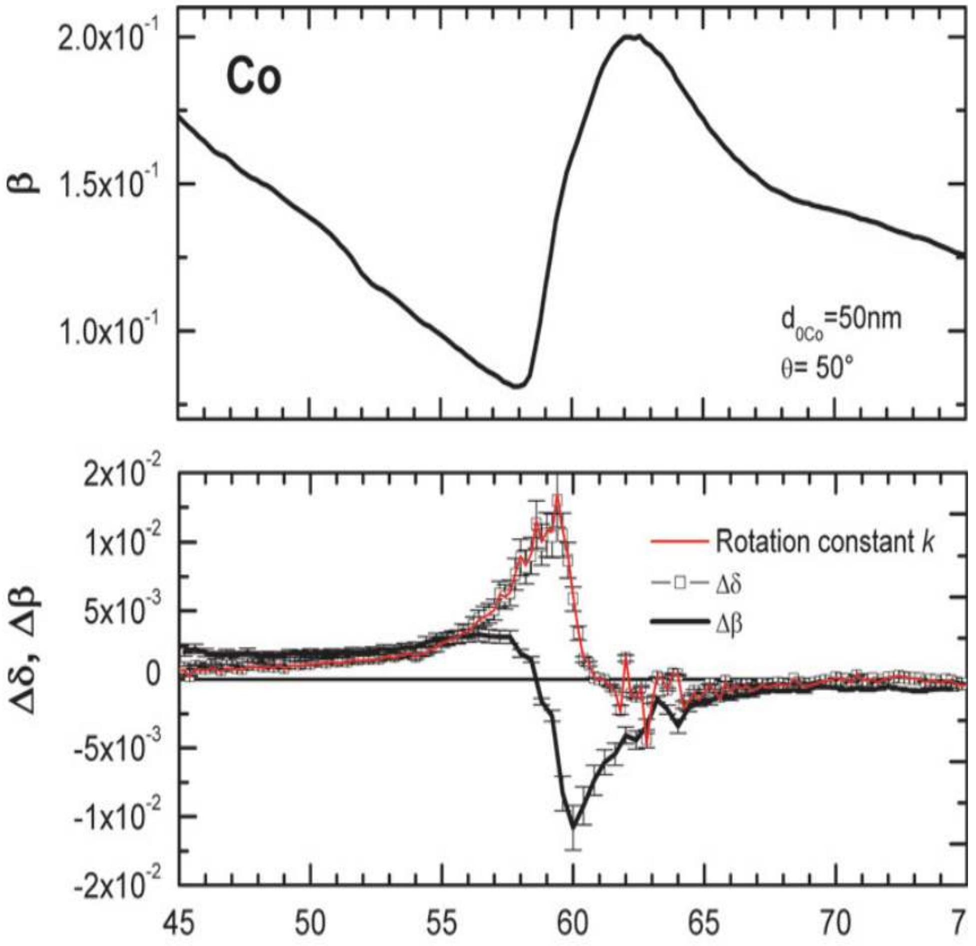
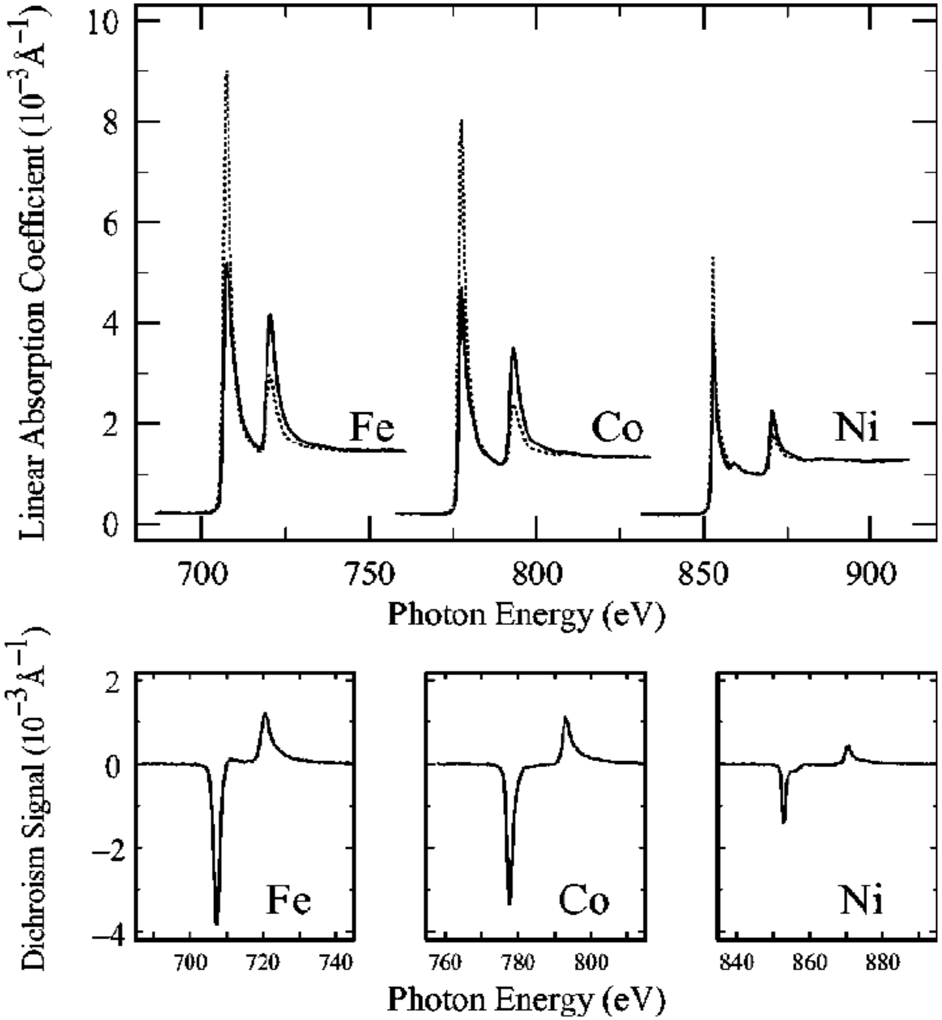
$M_{2,3}$ $3p_{1/2,\,3/2} \rightarrow 3d$



S. Valencia et al., New J. Phys. 8, 254 (2006)

$L_{2,3}$ $2p_{1/2,\,3/2} \rightarrow 3d$

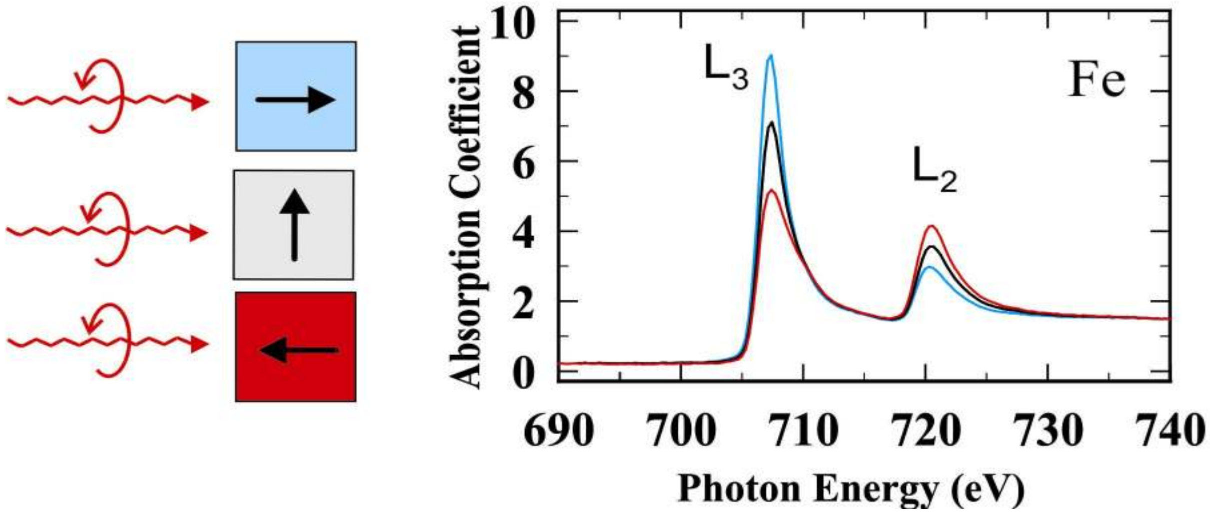


R. Nakajima et al., Phys. Rev. B 59, 6421 (1999)

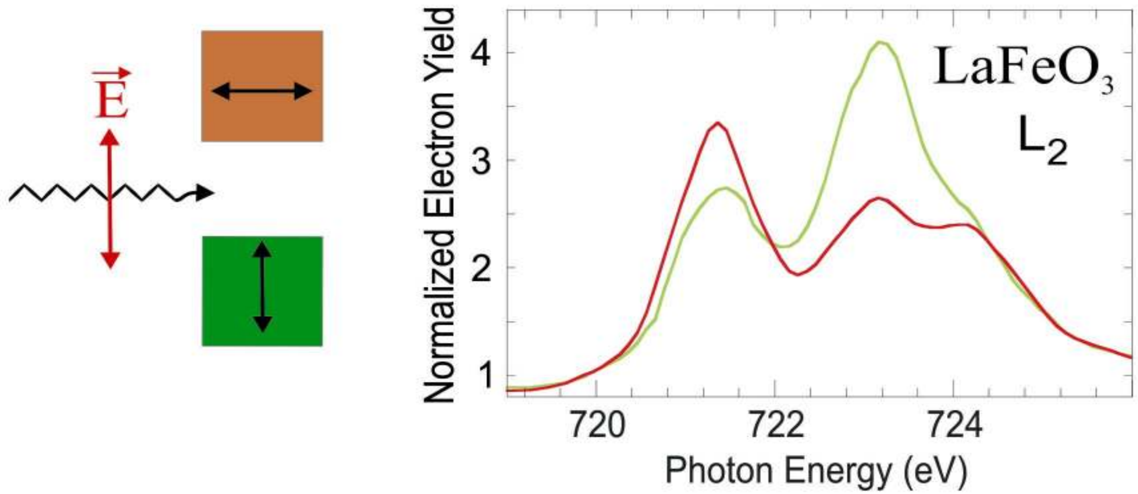
X-ray magnetic LINEAR dichroism (XM**L**D)

in X-ray absorption spectroscopy

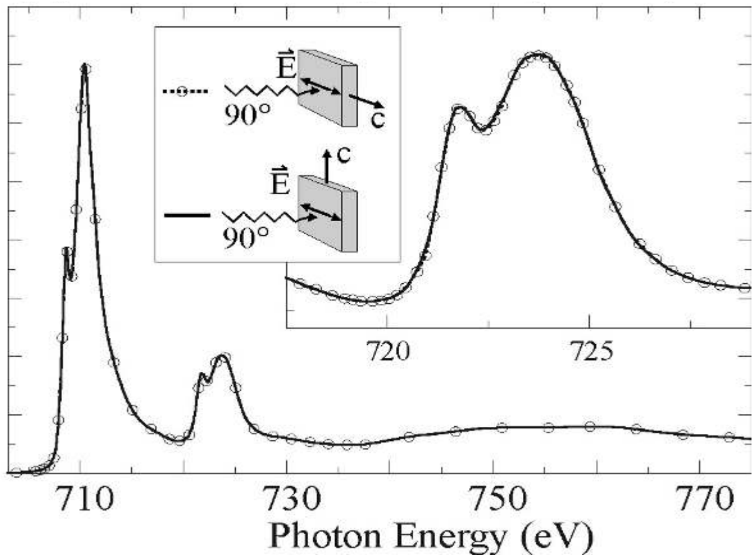
XMCD : X-ray Magnetic Circular Dichroism: Ferromagnets



XMLD : X-ray Magnetic Linear Dichroism: Antiferromagnets



XMLD: Linear dichroism and presence of AFM order



$La_{0.6}Sr_{0.4}FeO_3$ / $SrTiO_3$ (110)

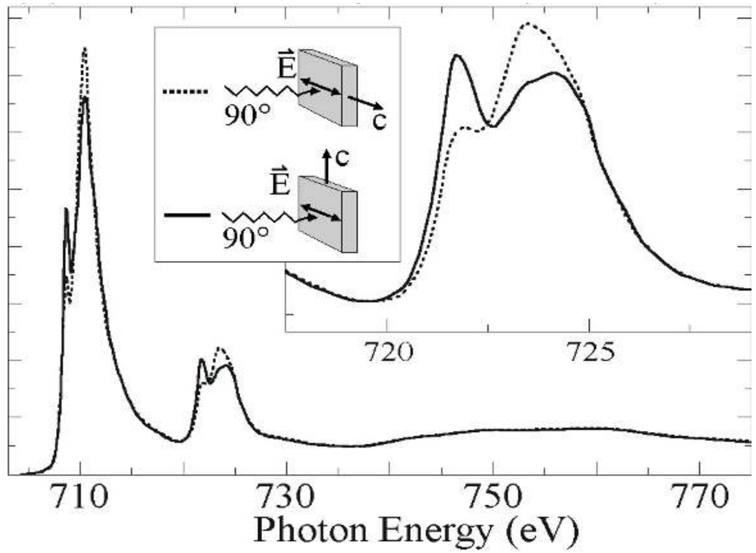
Above Néel temperature

No linear dichroism

Warnings:

Crystal fields can cause linear dichroism

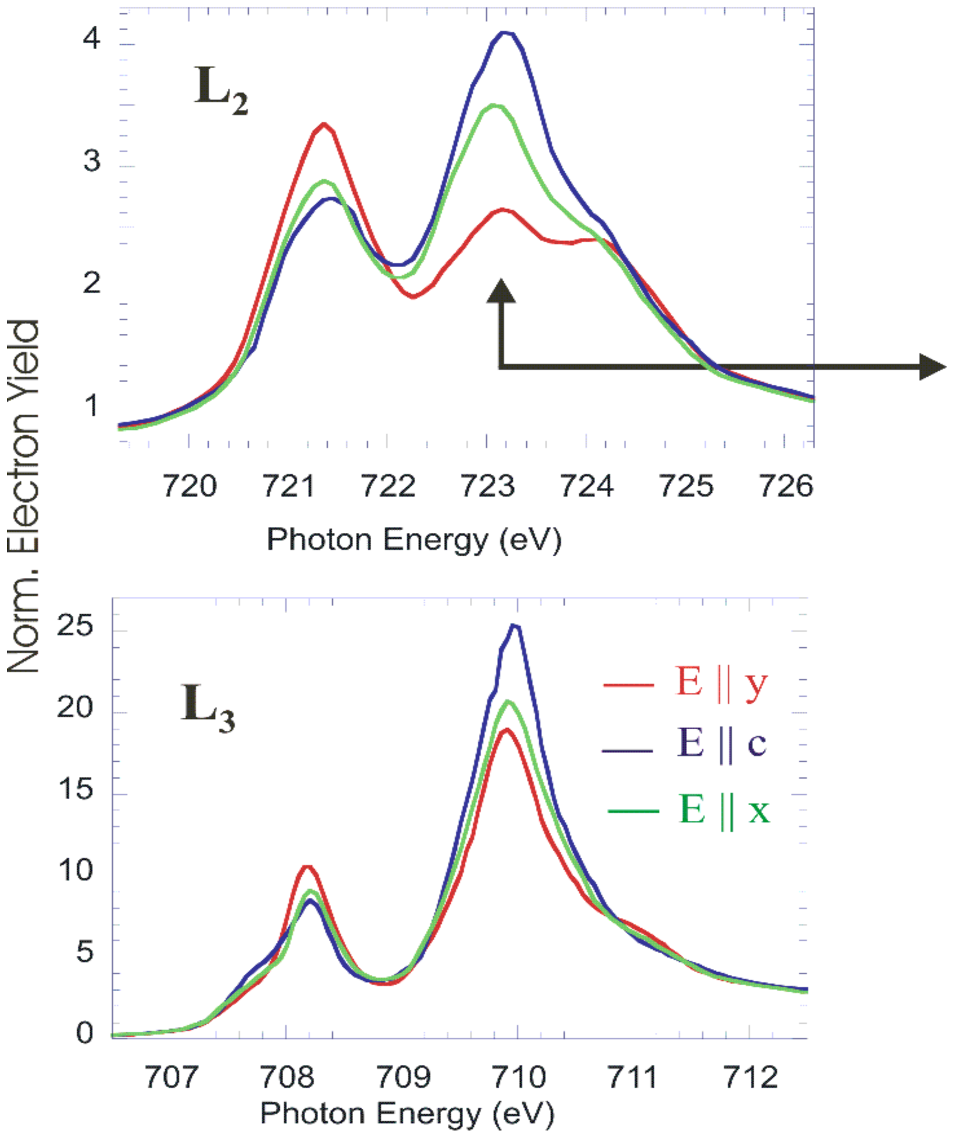
Relationship between orientation of AFM axis and dichroic ratio can depend on crystal orientation

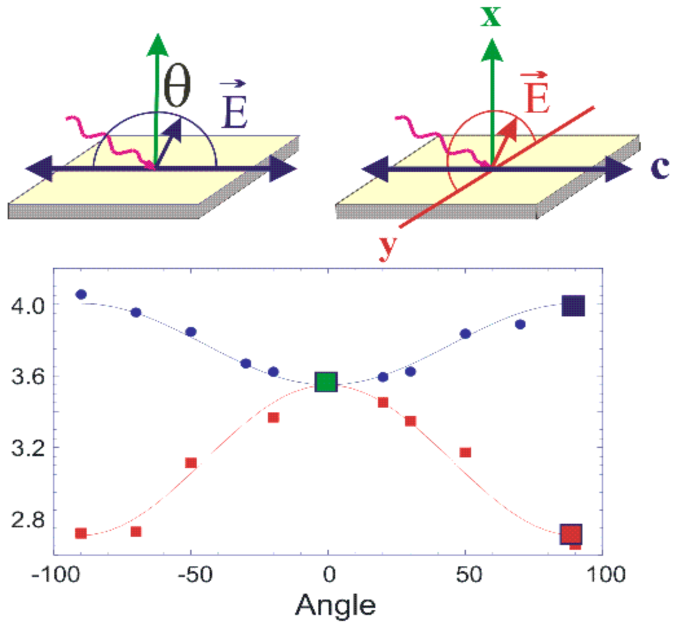


Below Néel temperature

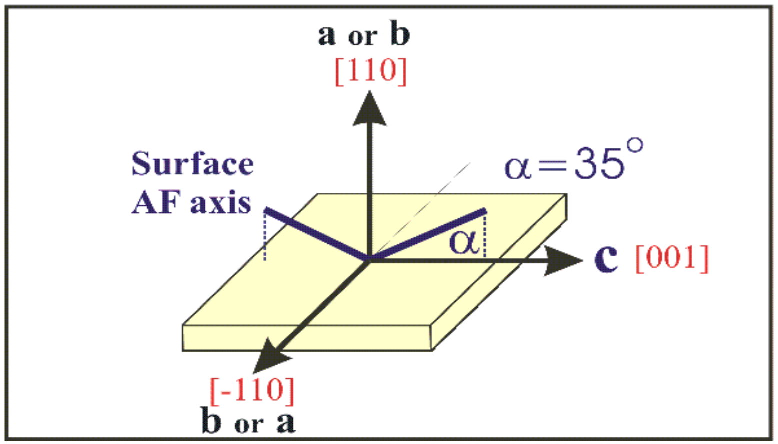
Strong linear dichroism

Orientation of AFM axis in a thin film of $LaFeO_3$ / $SrTiO_3$ (110)





AF axis is rotated from bulk



Adding spatial resolution to x-ray spectroscopy

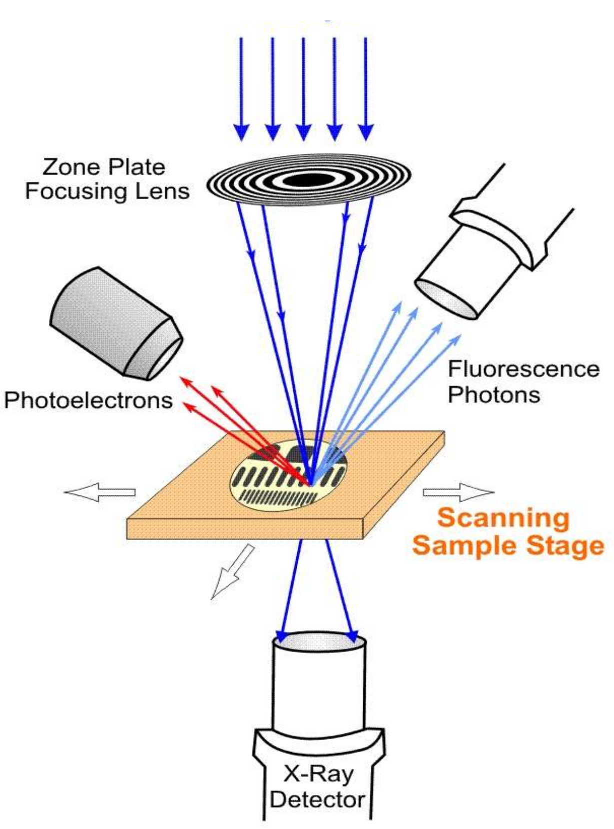
X-ray spectro-microscopy

Application: Co / NiO

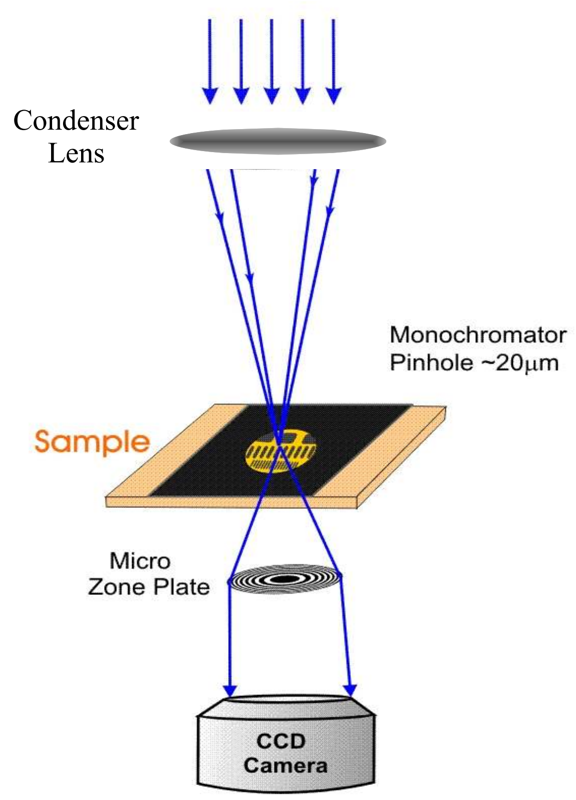
The interface between a ferromagnetic metal
and an antiferromagnetic metal oxide

Quantitative imaging with sensitivity to
elemental and chemical distribution and charge/spin ordering

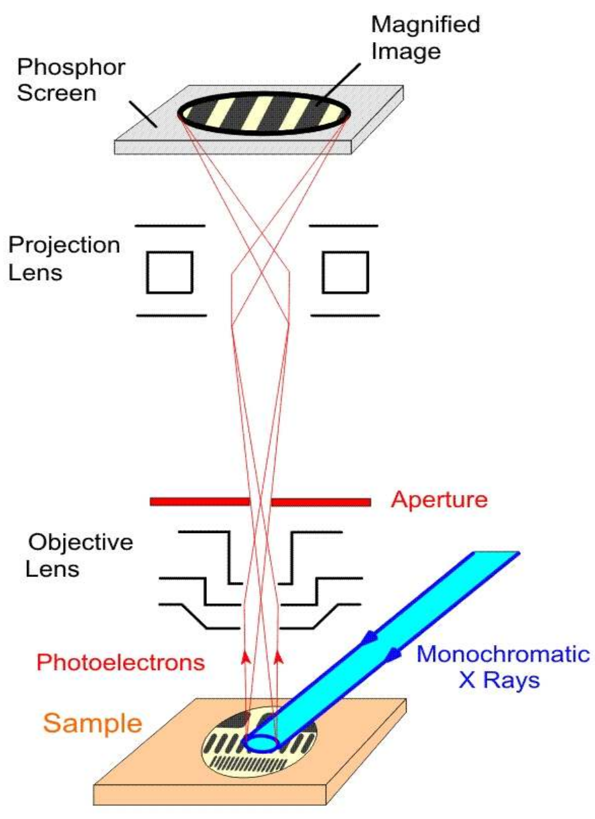
Scanning Transmission X-ray Microscopy STXM



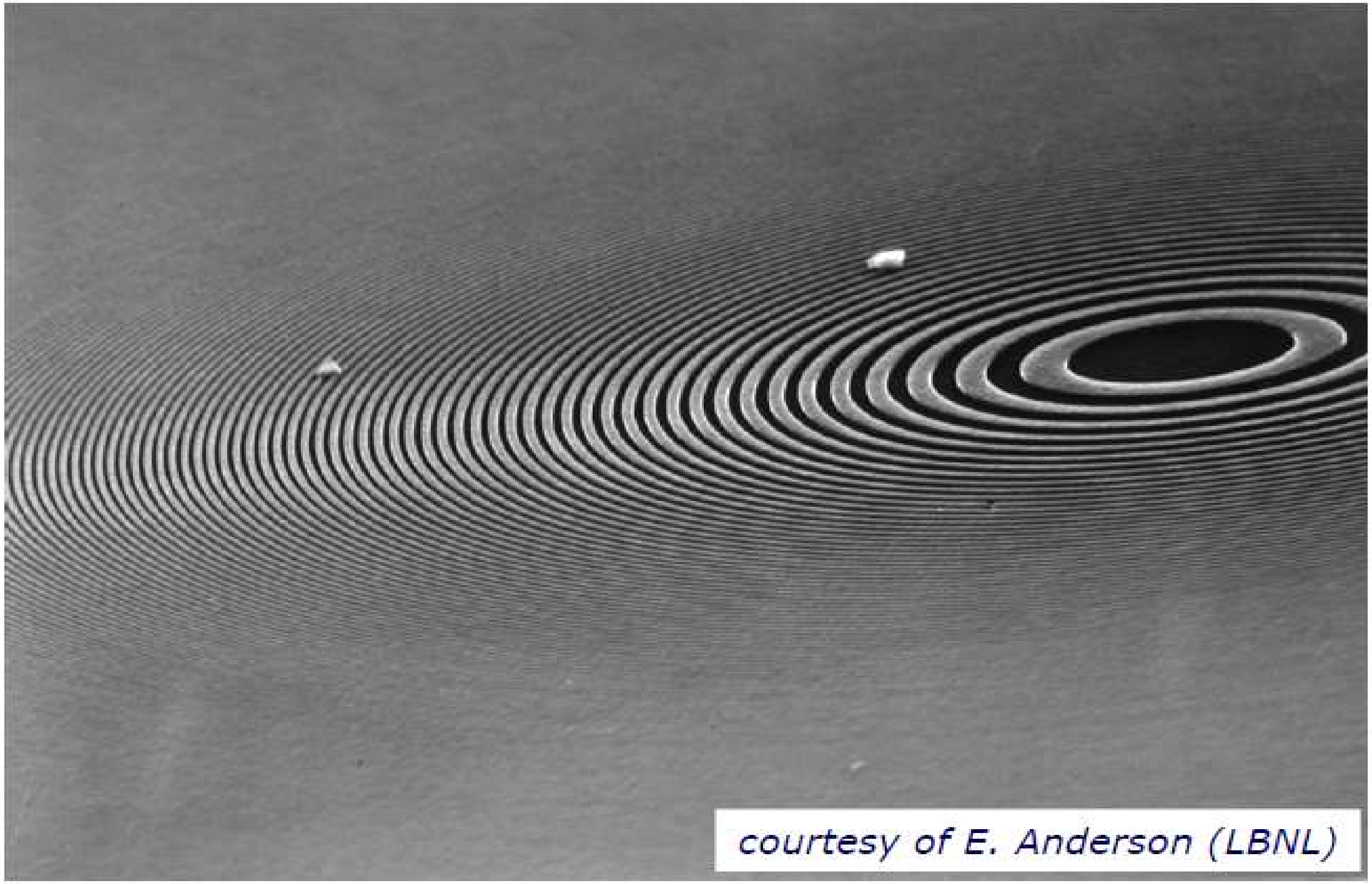
Transmission X-ray Microscopy TXM



X-Ray Photoemisson Electron Microscopy XPEEM

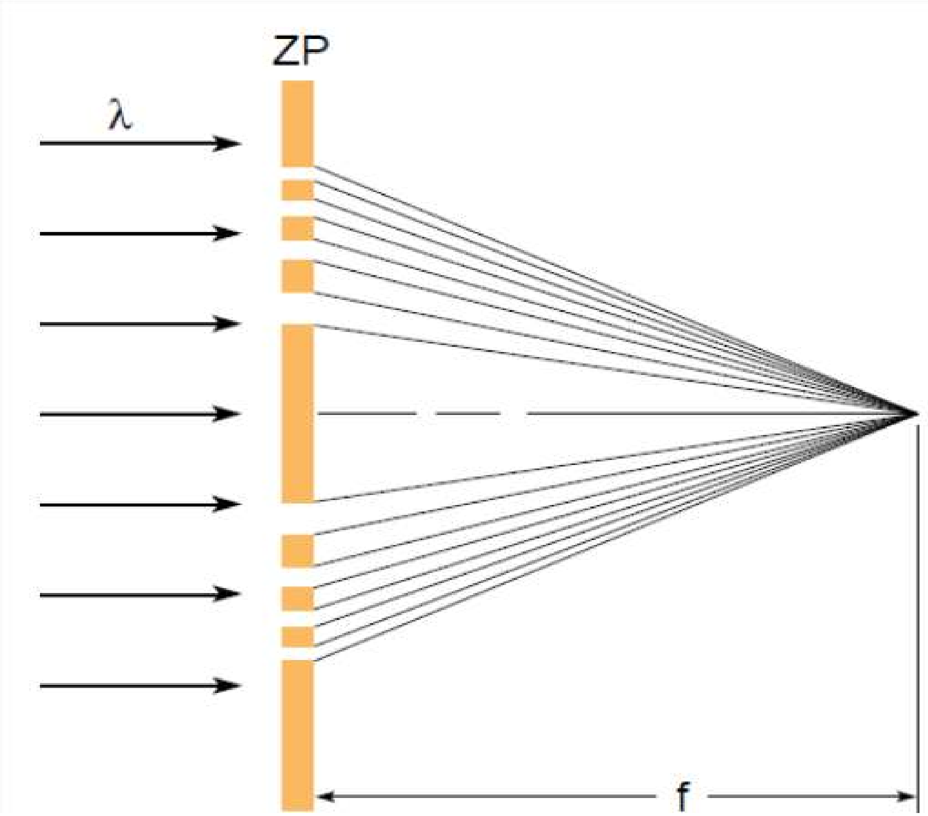


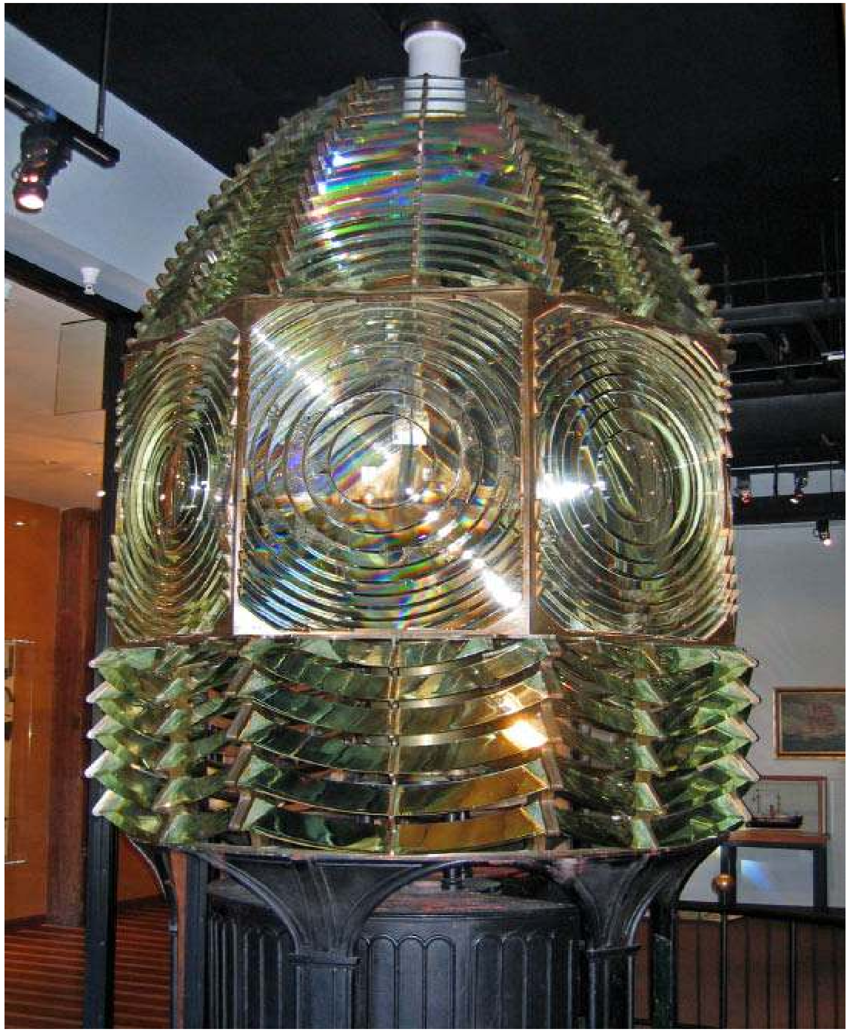
Fresnel Zone Plate Lenses



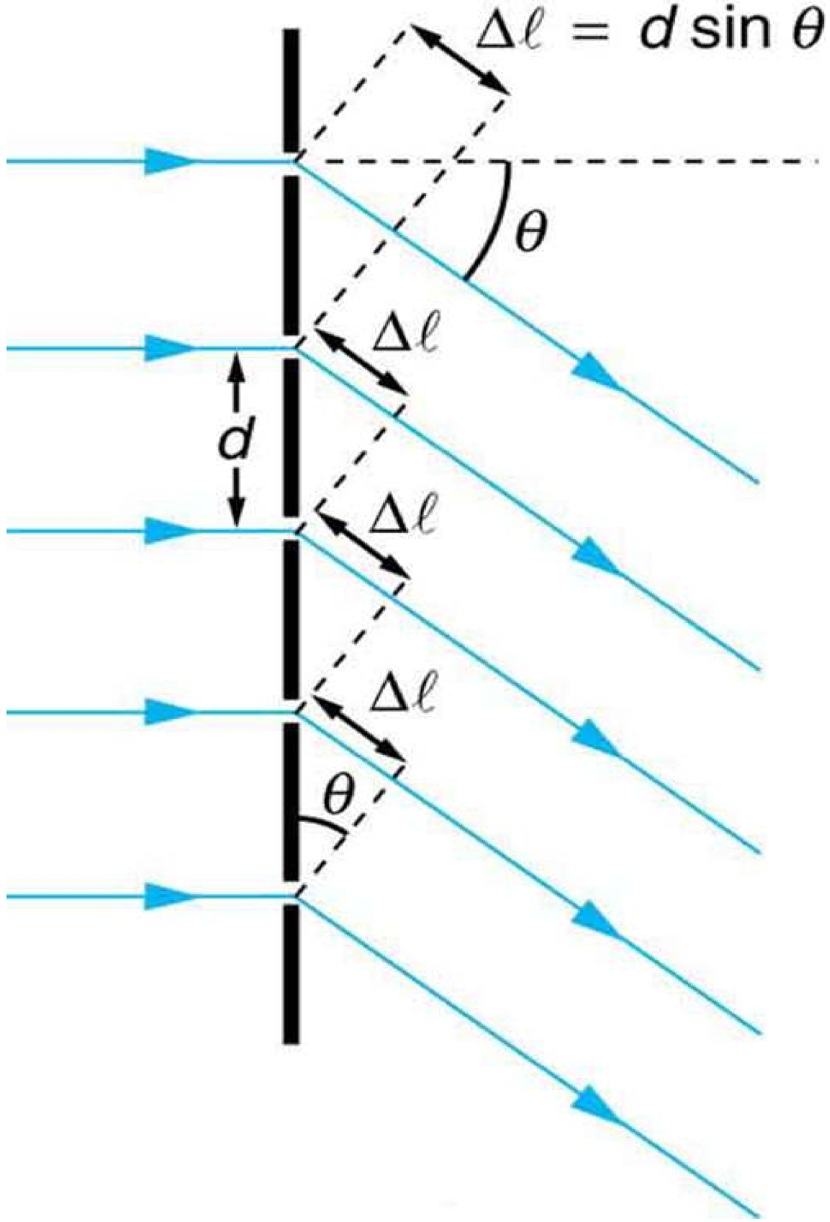
- spatial resolution ~ Δr
- focal length ~$N(\Delta r)^2/\lambda$
- spectral bandwidth $\Delta\lambda/\lambda$ ~ $1/N$

Spherical Grating with varying line density

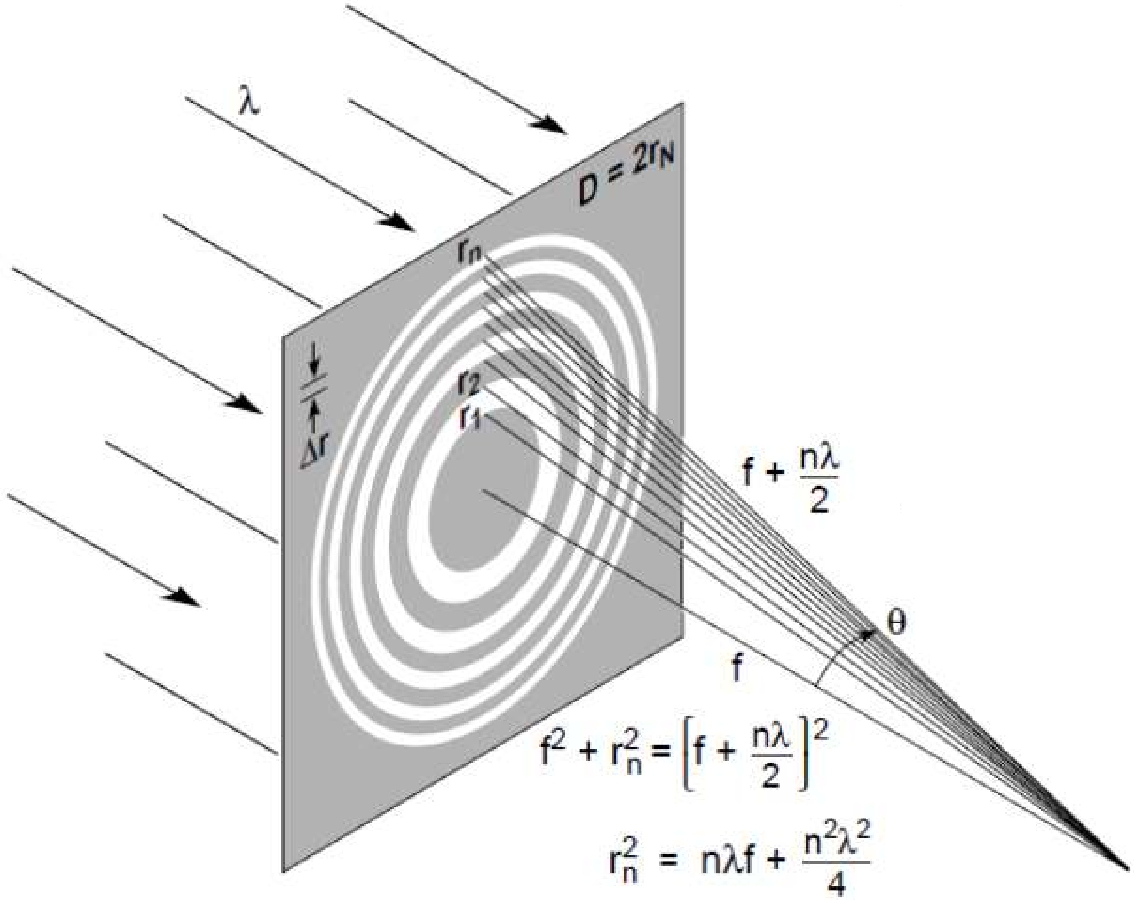


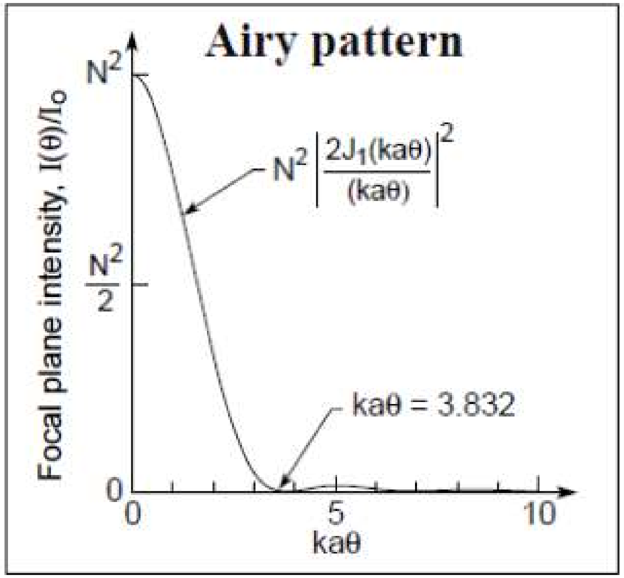


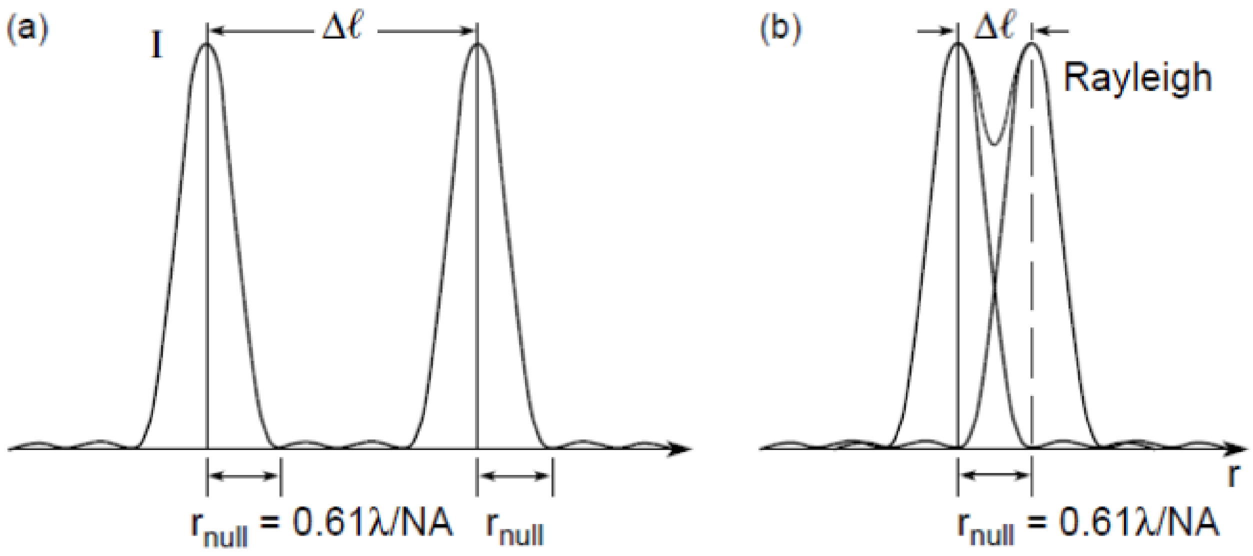
Principle of a diffraction grating



Focussing with a Fresnel zone plate





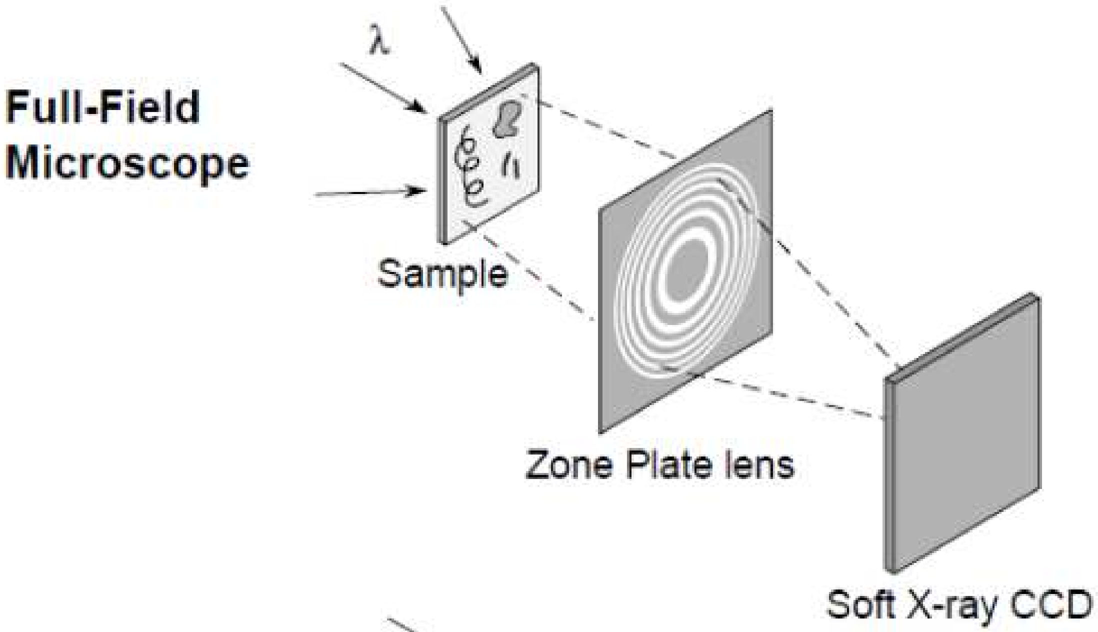


- Point sources are spatially coherent
- Mutually incoherent
- Intensities add
- Rayleigh criterion (26.5% dip)

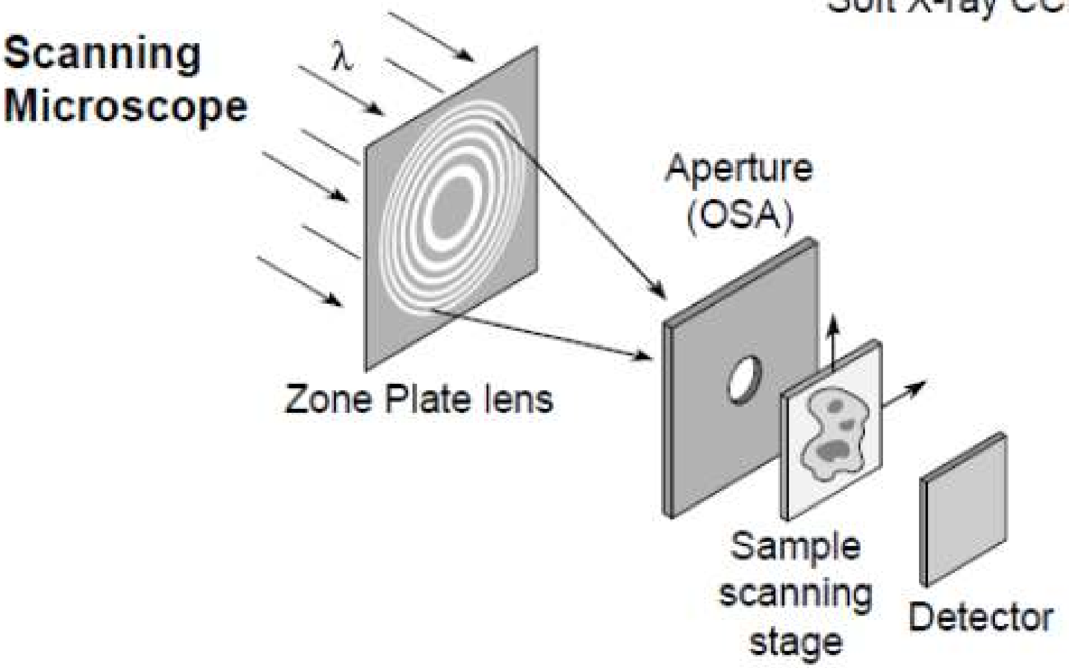
Conclusion: With spatially coherent illumination, objects are "just resolvable" when

$$Res|_{coh} = \frac{0.61\ \lambda}{NA} = 1.22\ \Delta r$$

Scanning (STXM) vs fulf field (TXM) X-ray microscopy

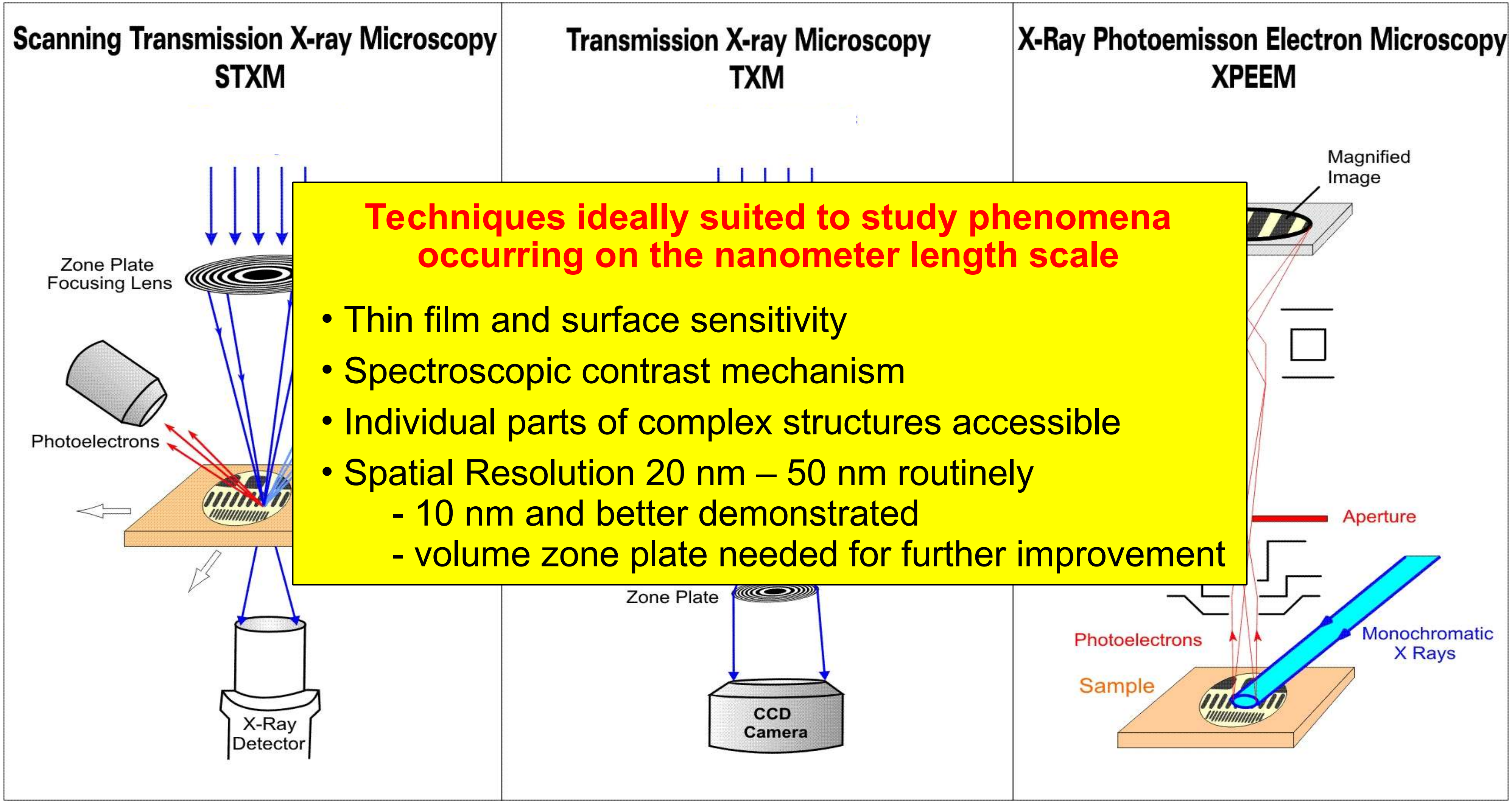


- Best spatial resolution
- Modest spectral resolution
- Shortest exposure time
- Bending magnet radiation
- Higher radiation dose
- Flexible sample environment (wet, cryo, labeled magnetic fields, electric fields, cement, ...)



- Least radiation dose
- Next best spatial resolution
- Best spectral resolution
- Requires spatially coherent radiation
- Long exposure time
- Flexible sample environment
- Photoemission (restricted magnetic fields), fluorescence imaging

Quantitative imaging with sensitivity to
elemental and chemical distribution and charge/spin ordering

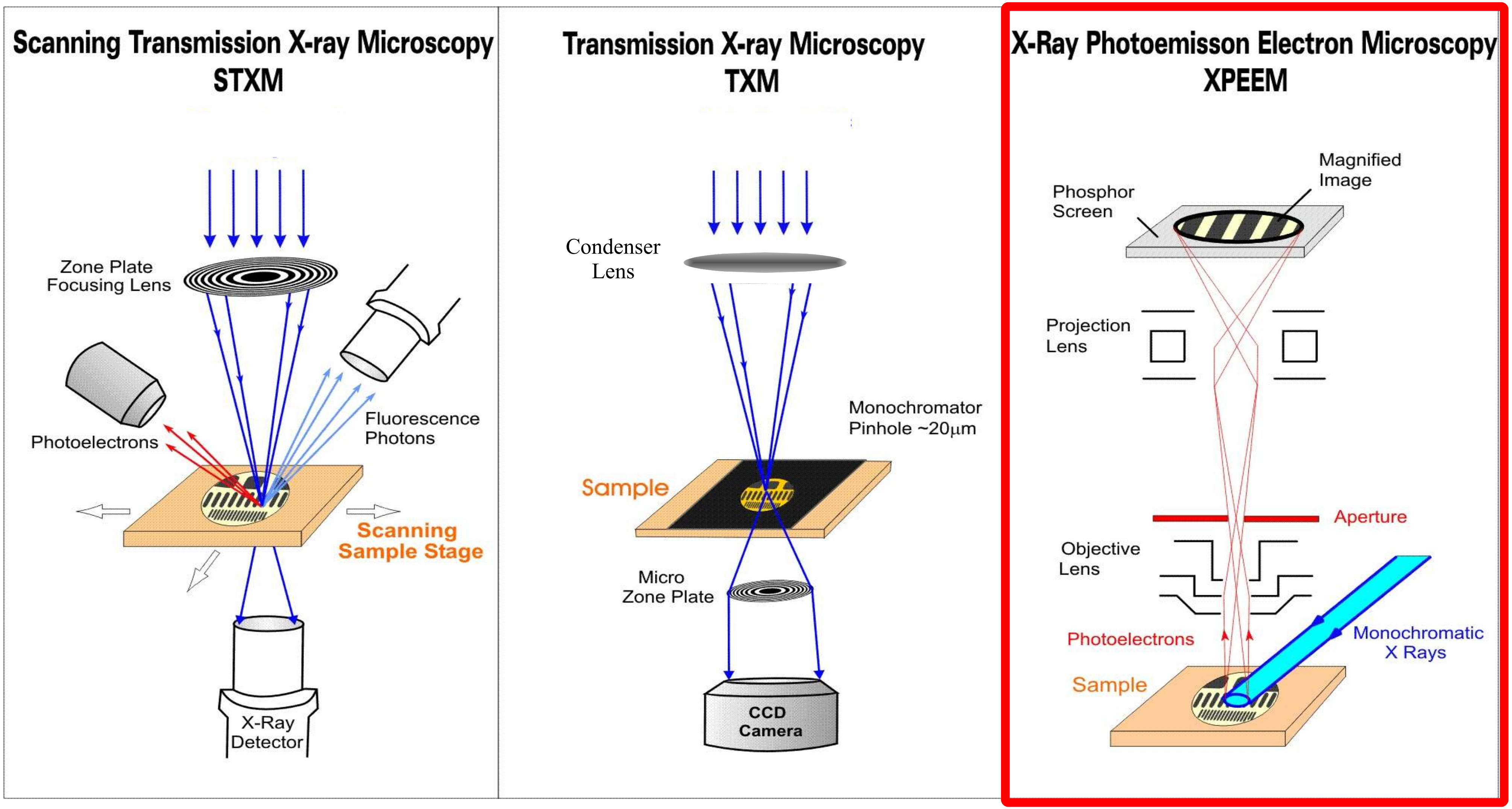


Techniques ideally suited to study phenomena occurring on the nanometer length scale

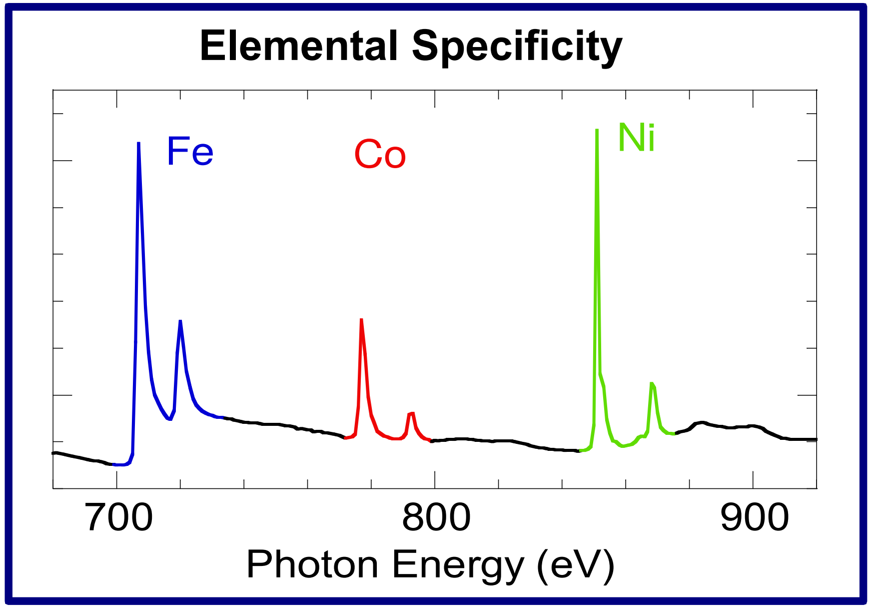
- Thin film and surface sensitivity
- Spectroscopic contrast mechanism
- Individual parts of complex structures accessible
- Spatial Resolution 20 nm – 50 nm routinely
  - 10 nm and better demonstrated
  - volume zone plate needed for further improvement

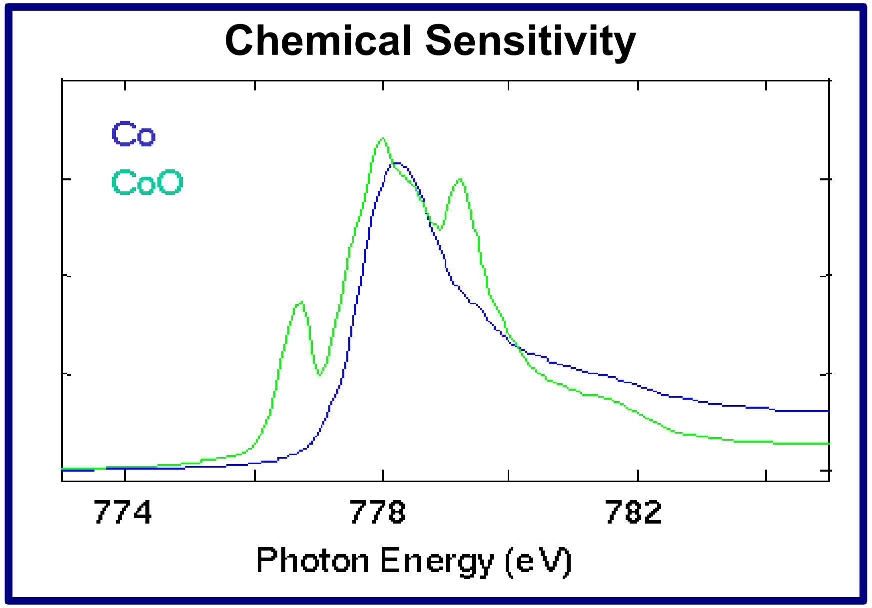
X-ray spectromicroscopy techniques

Quantitative imaging with sensitivity to
elemental and chemical distribution and charge/spin ordering

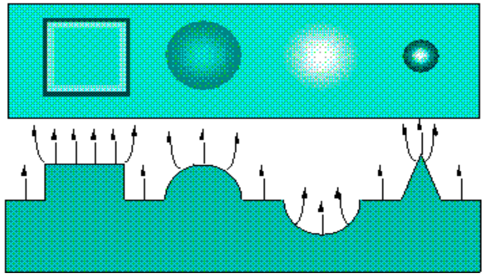


Photoemission Electron Microscopy

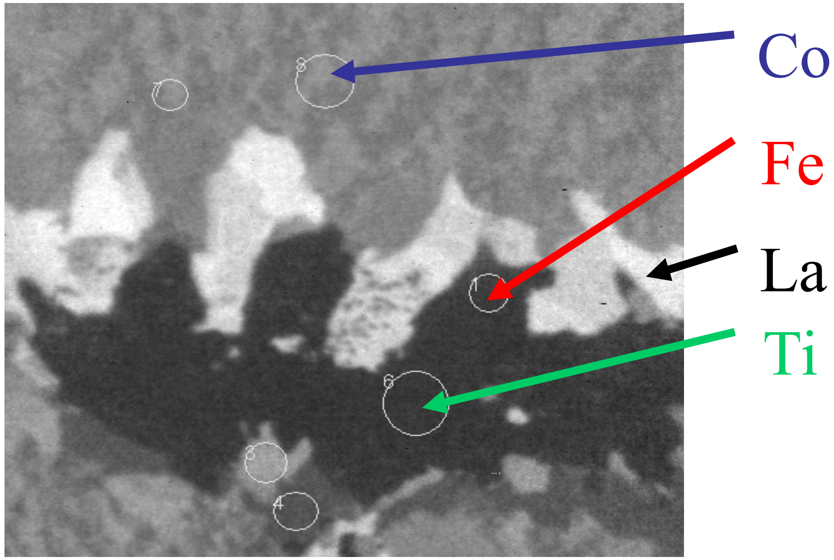




Topographical Contrast

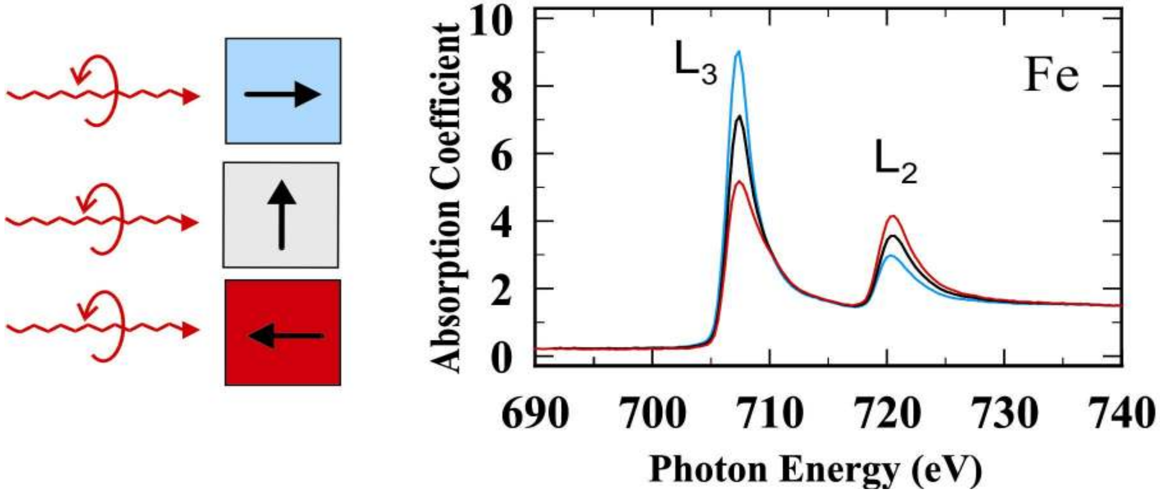


Elemental Contrast

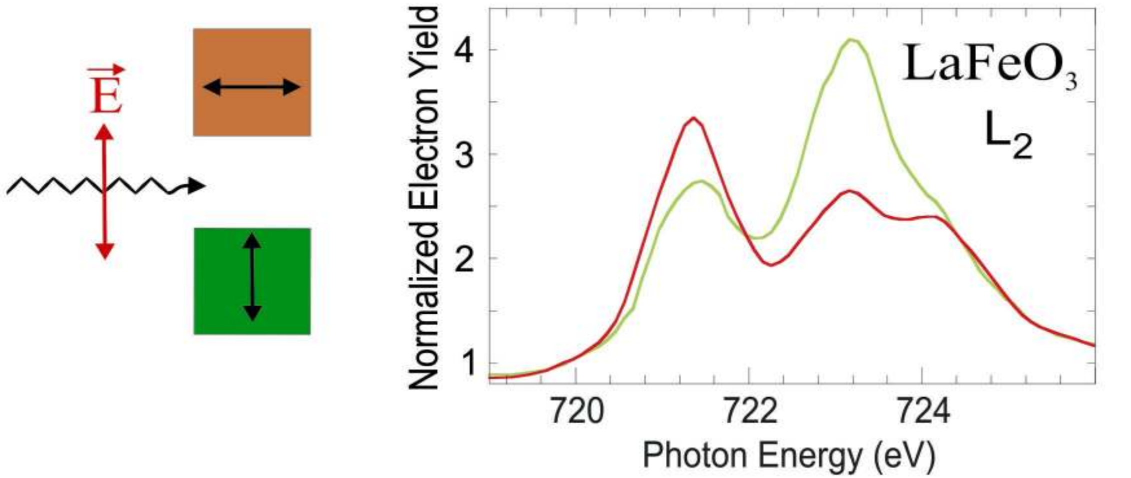


Photoemission Electron Microscopy

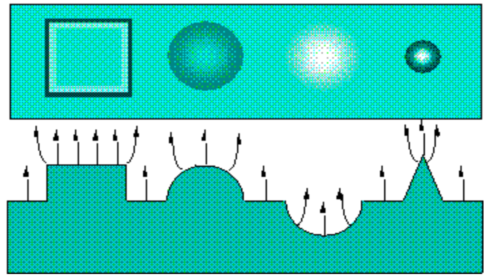
X-ray Magnetic Circular Dichroism: Ferromagnets



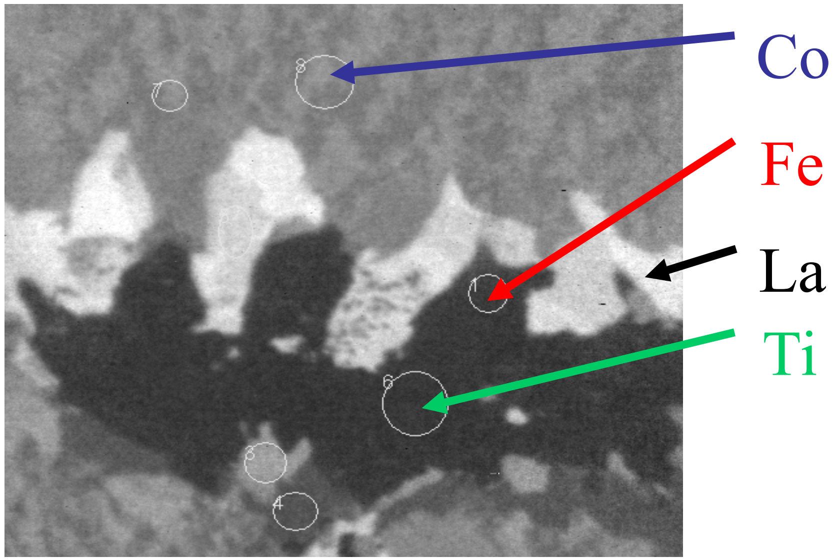
X-ray Magnetic Linear Dichroism: Antiferromagnets



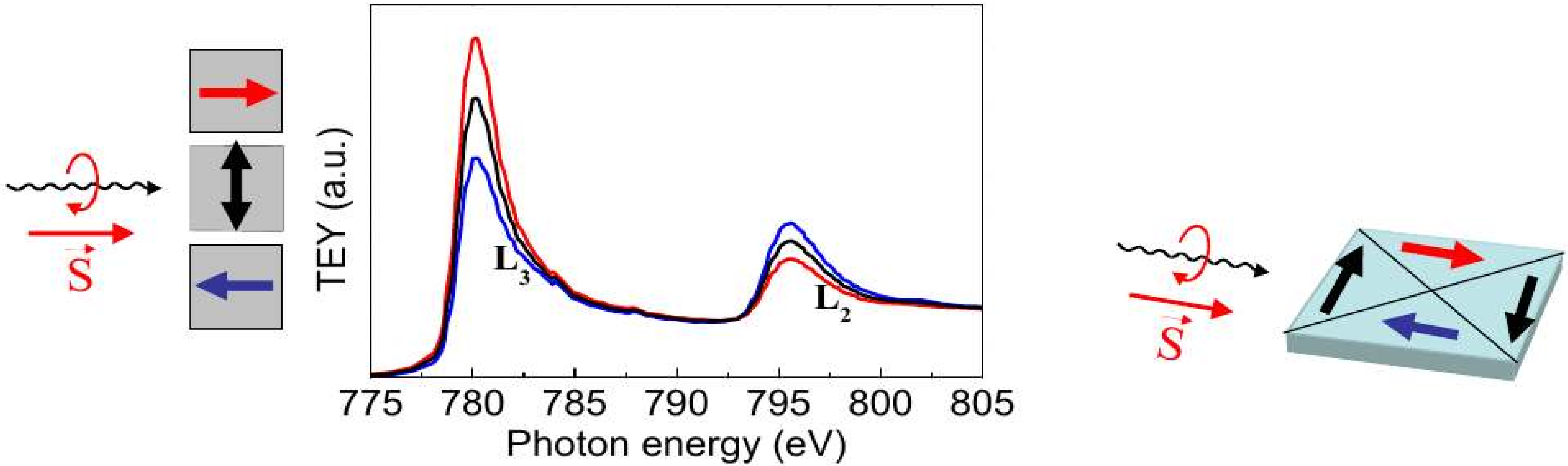
Topographical Contrast

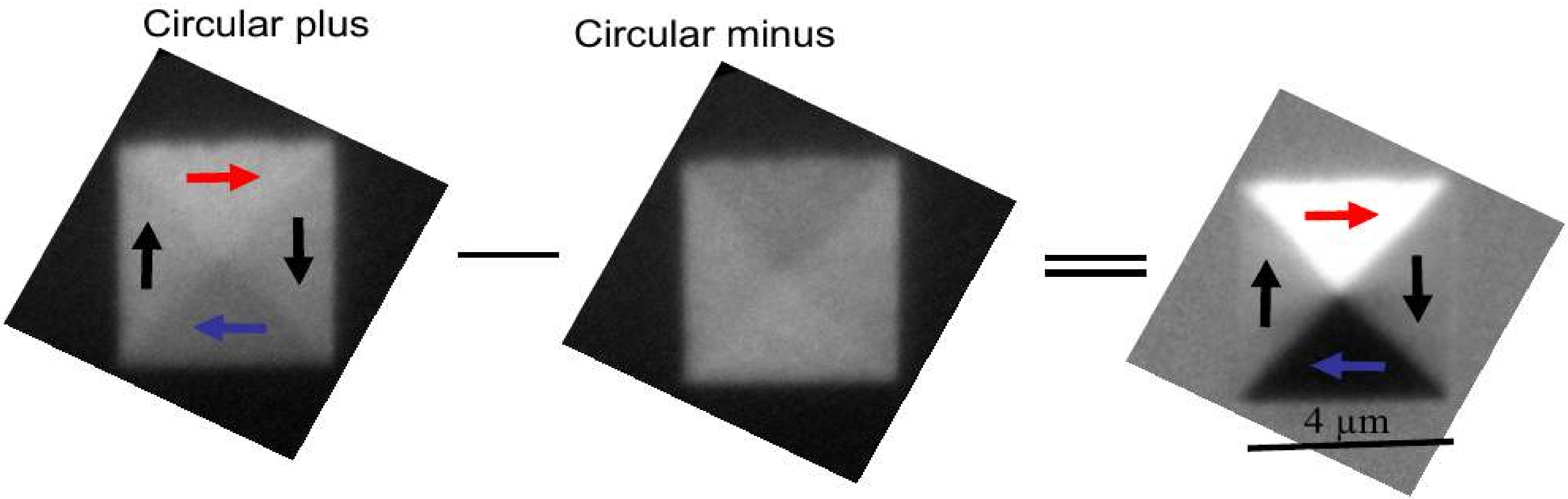


Elemental Contrast

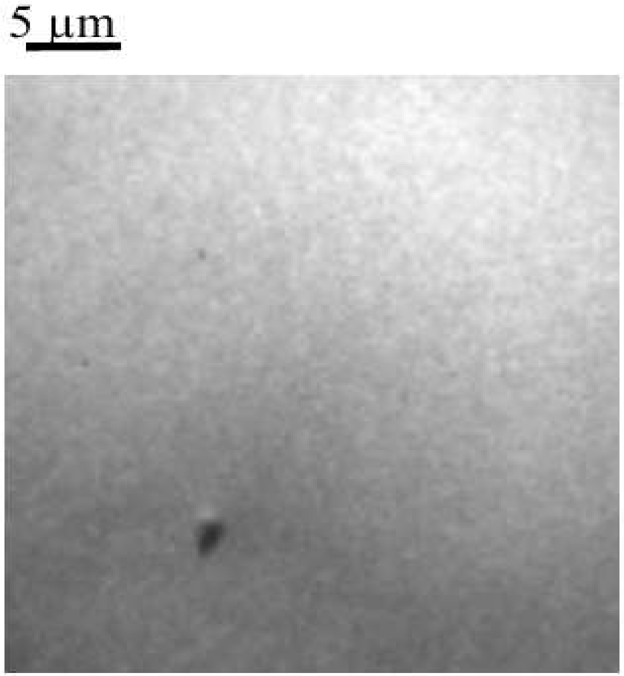


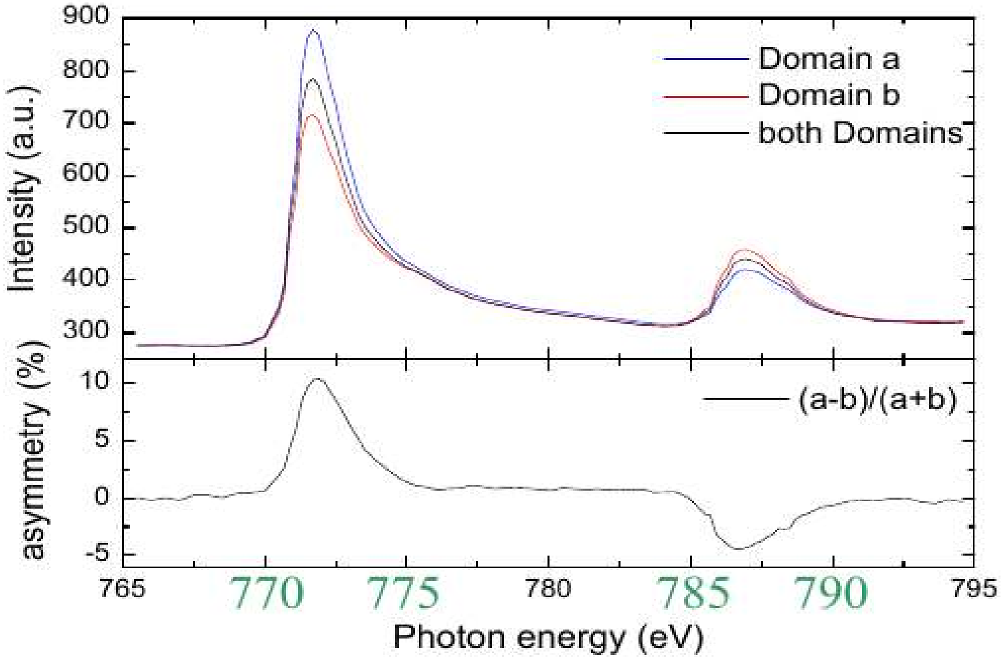
XMCD as contrast mechanism in X-ray spectroscopy

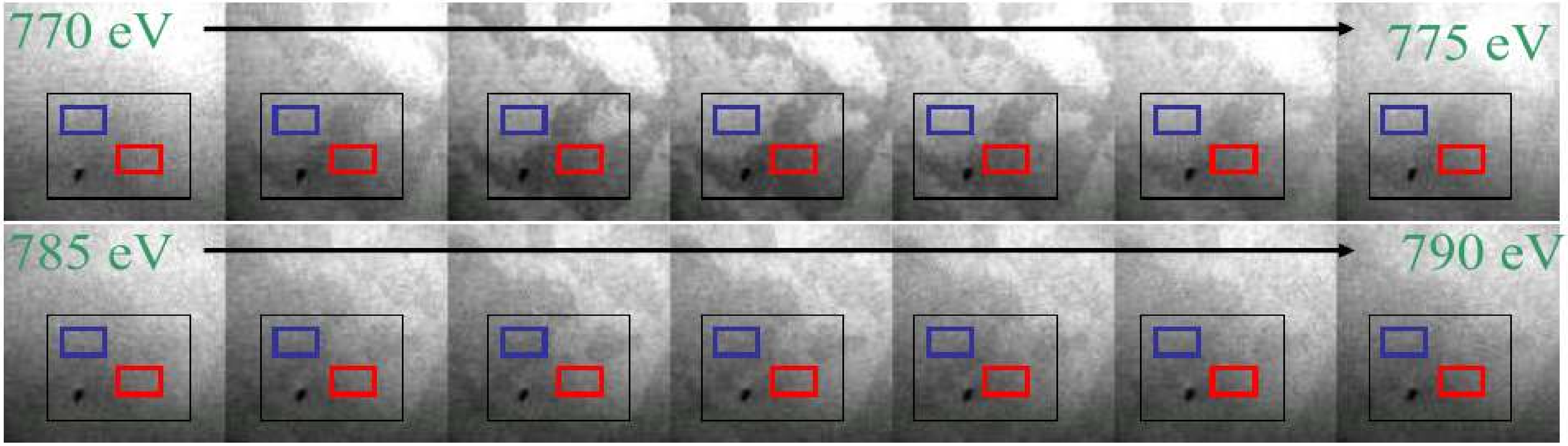




X-ray microscopy for ***local*** X-ray spectroscopy







Resolving the spin structure of a magnetic multilayer

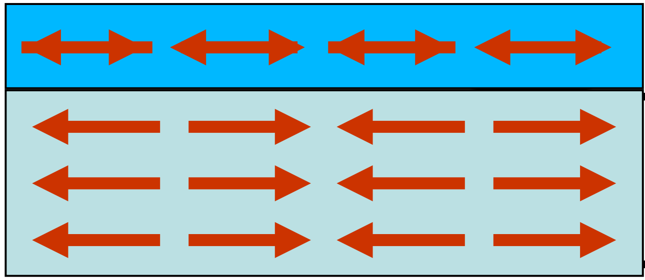
Magnetic domain structure in:

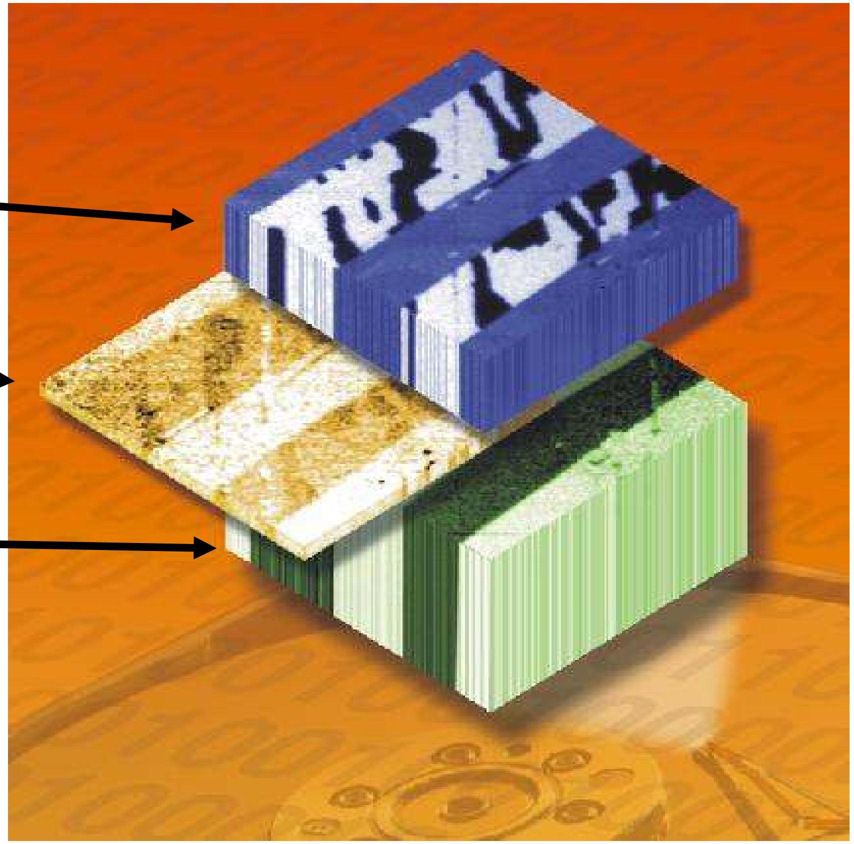
“Exchange bias” magnetic multilayer

ferromagnetic metal

FM

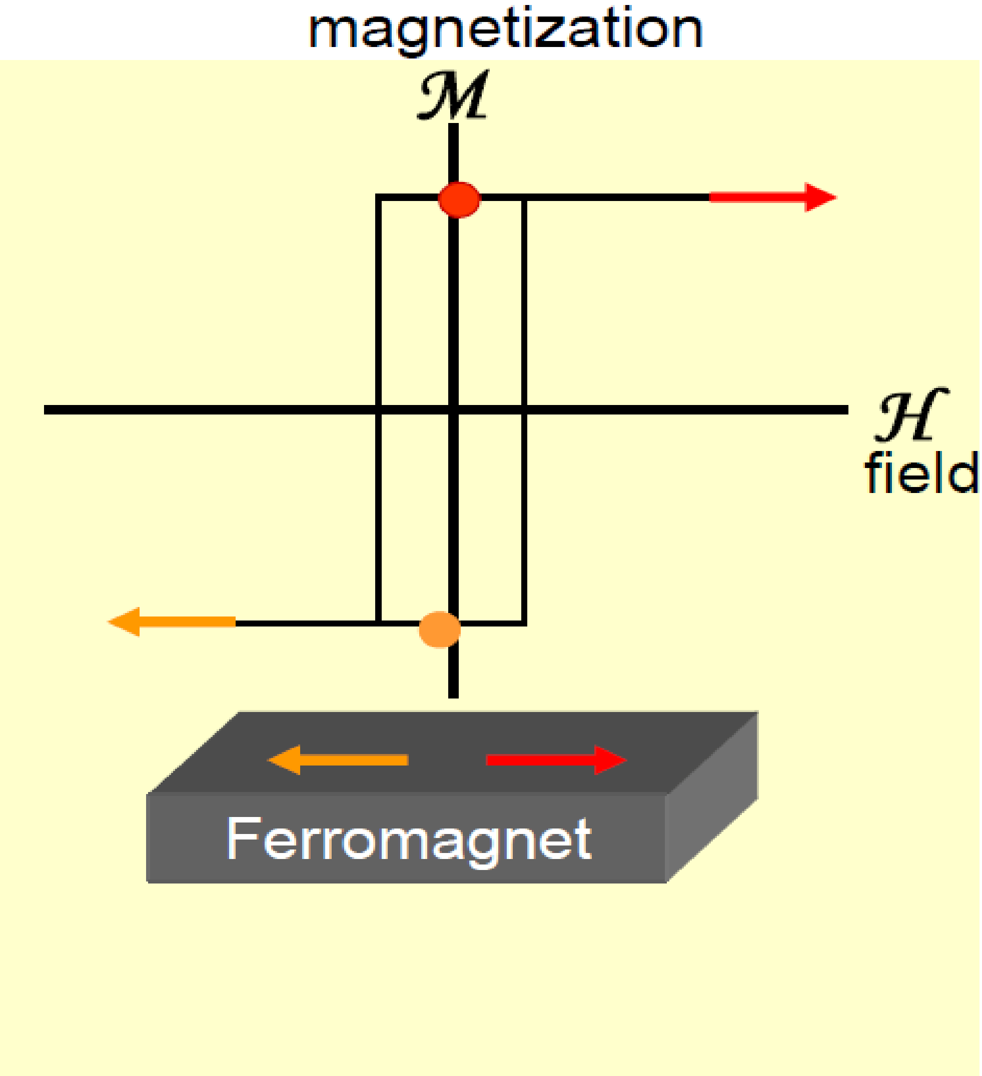
AFM

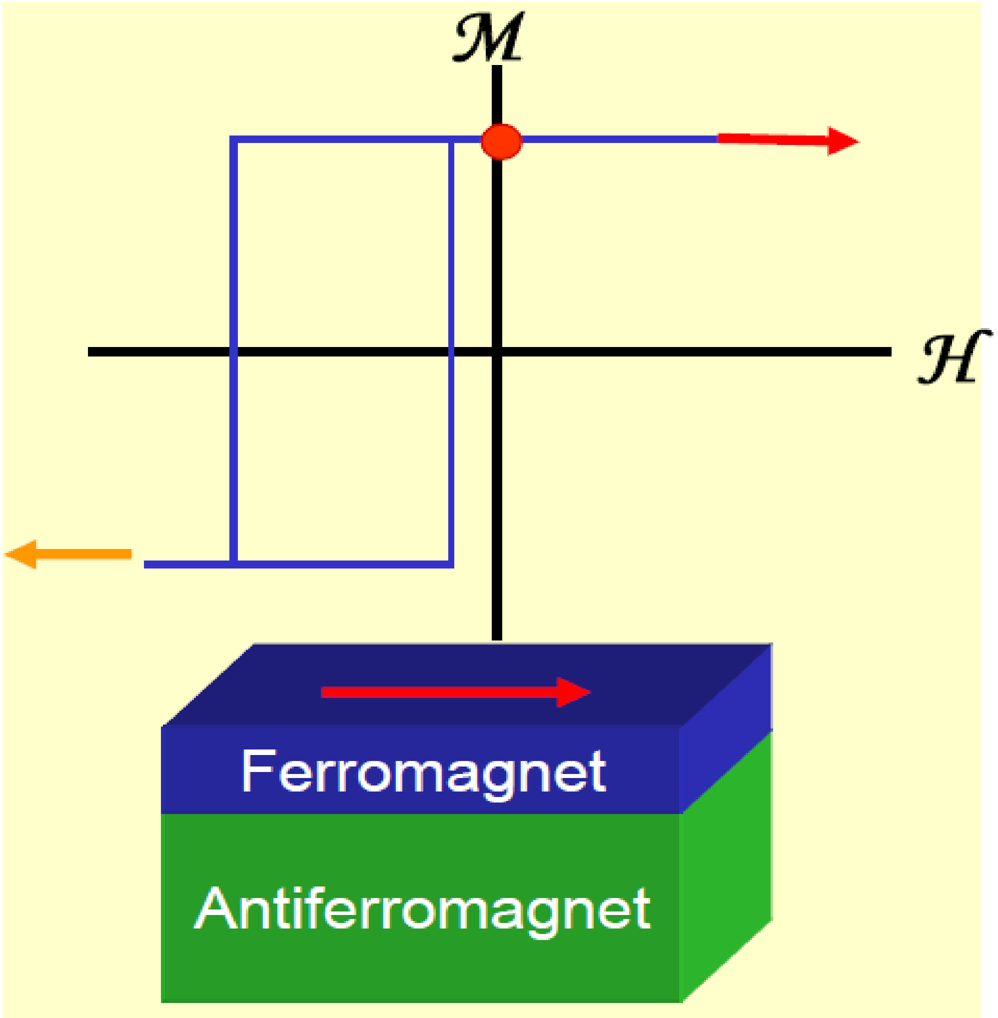




Spectroscopic Identification and Direct Imaging of Interfacial Magnetic Spins
H. Ohldag et al., Phys. Rev. Lett **87**, 247201 (2001).

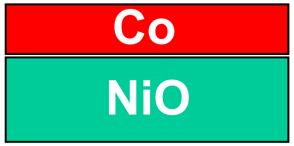
Exchange Bias Phenomenon



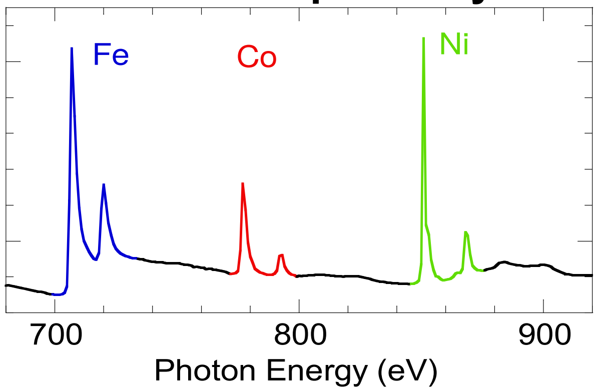


$\mathcal{M}$ of blue layer is "pinned"
or "exchange biased"

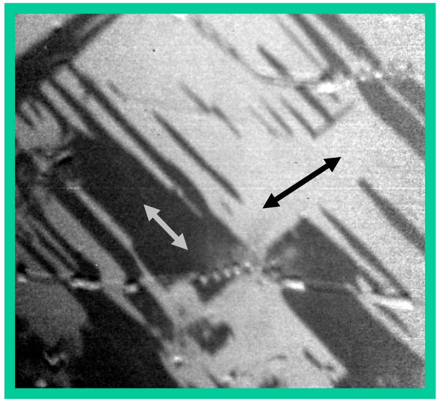
Spin structure in a magnetic multilayer



Elemental Specificity

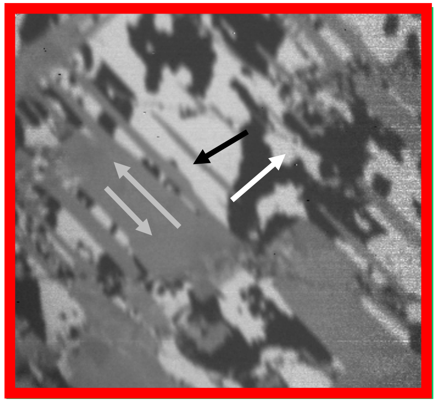


NiO XMLD



XMLD for imaging of **antiferromagnetic** spin order in NiO substrate

Co XMCD



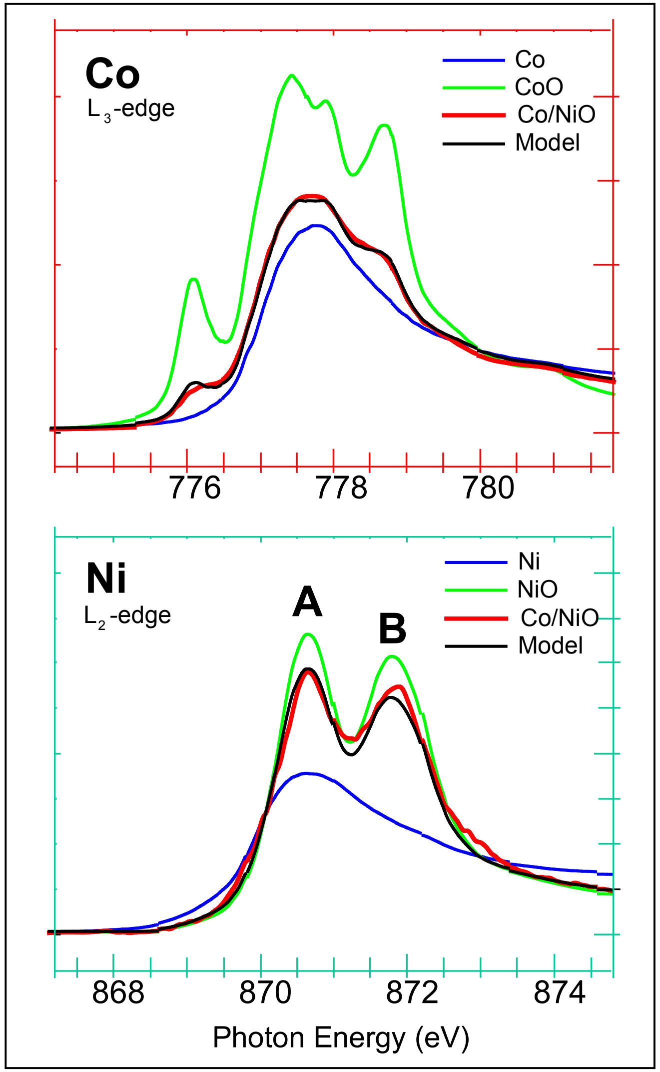
XMCD for imaging of **ferromagnetic** spin order in Co film

Parallel alignment of spins on both sides of the FM – AFM interface

Chemical environment influences NEXAFS

M ↔ M_xO_y

X-ray absorption spectroscopy



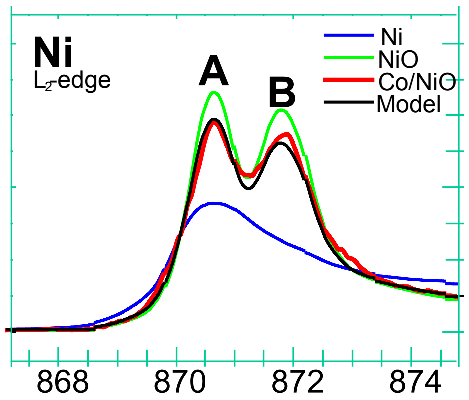
Upon deposition of 2 ML of Co on NiO

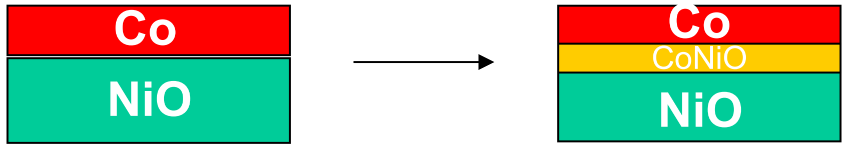
2 ML CoO (Co oxidized)

2 ML Ni (Ni reduced)

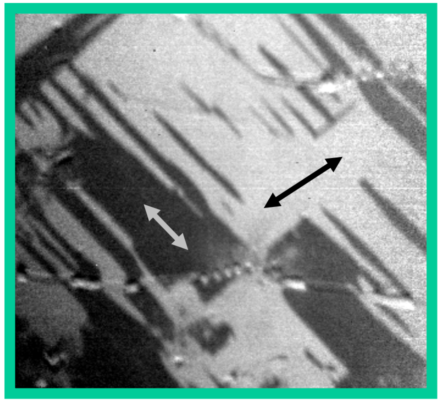
linear combination of metal and oxide spectra possible

Spin structure in a magnetic multilayer



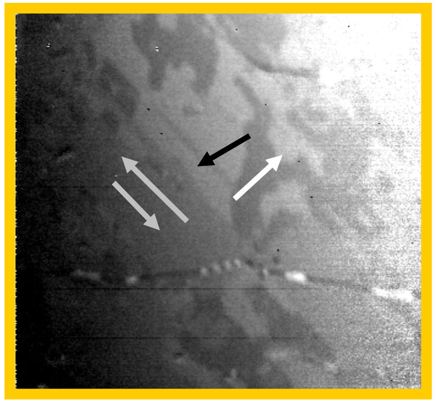


NiO XMLD



XMLD for imaging of **antiferromagnetic** spin order in NiO substrate

Ni(O) XMCD



XMCD for imaging of **ferromagnetic** spin order in NiO substrate

Co XMCD

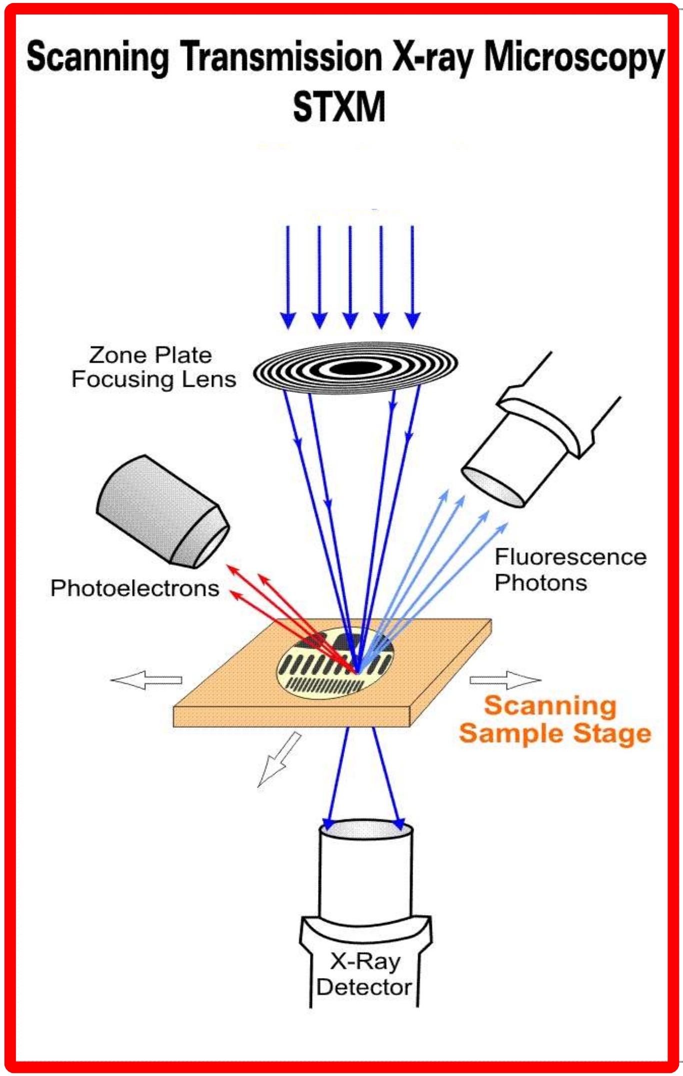
XMCD for imaging of **ferromagnetic** spin order in Co film

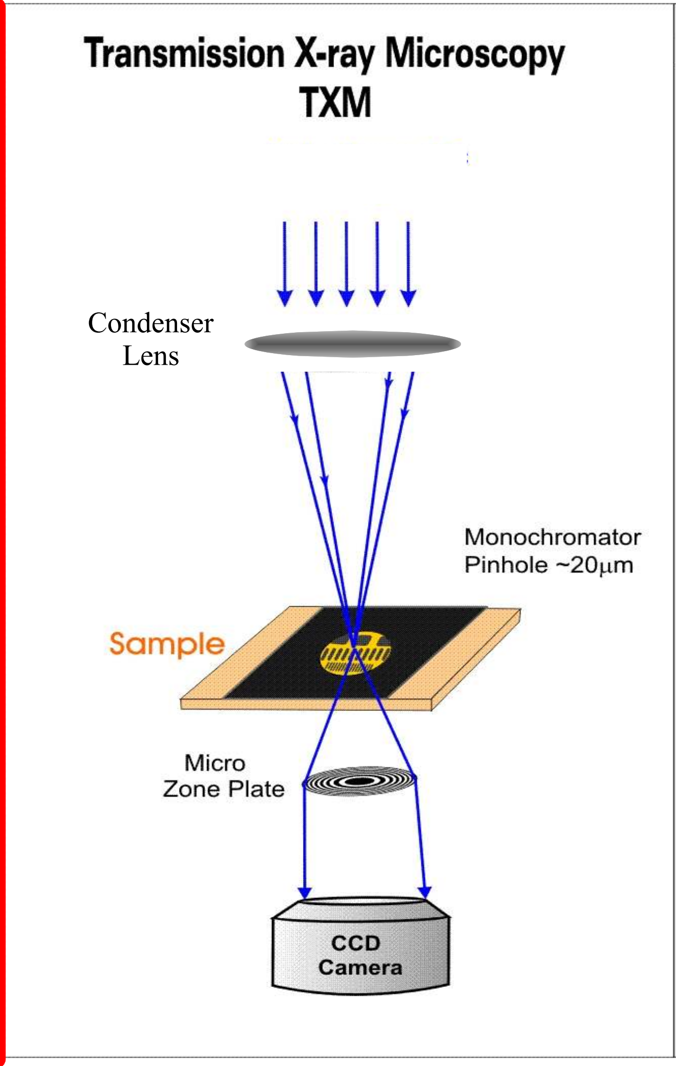
Interfacial chemical reaction → uncompensated ferromagnetic Ni spins at interface

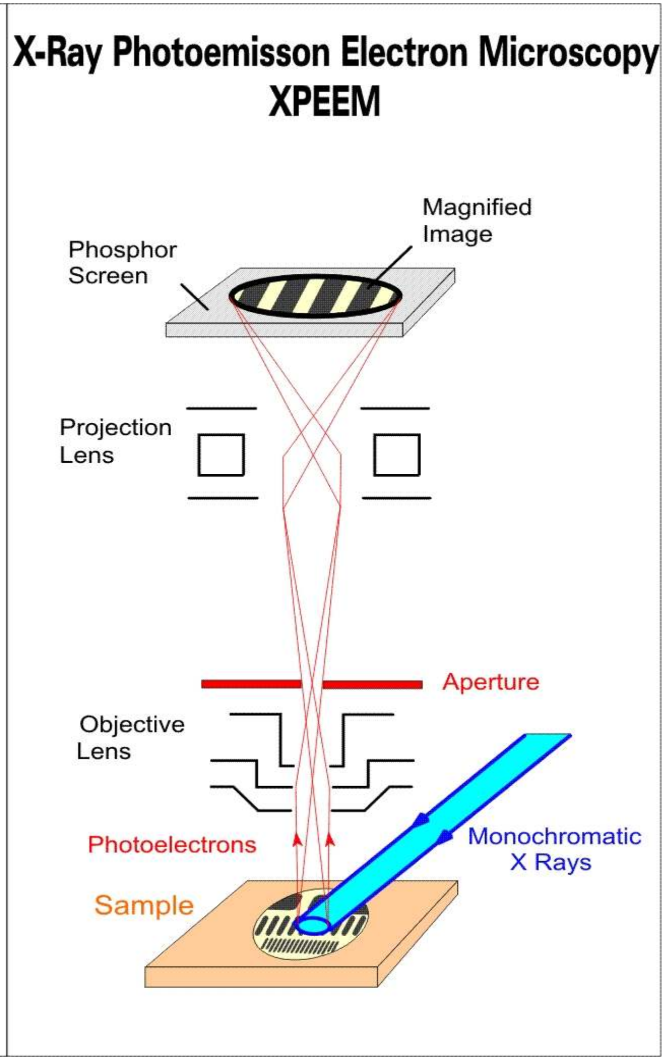
Adding time resolution to X-ray spectro-microscopy

Example: Magnetization switching by spin injection

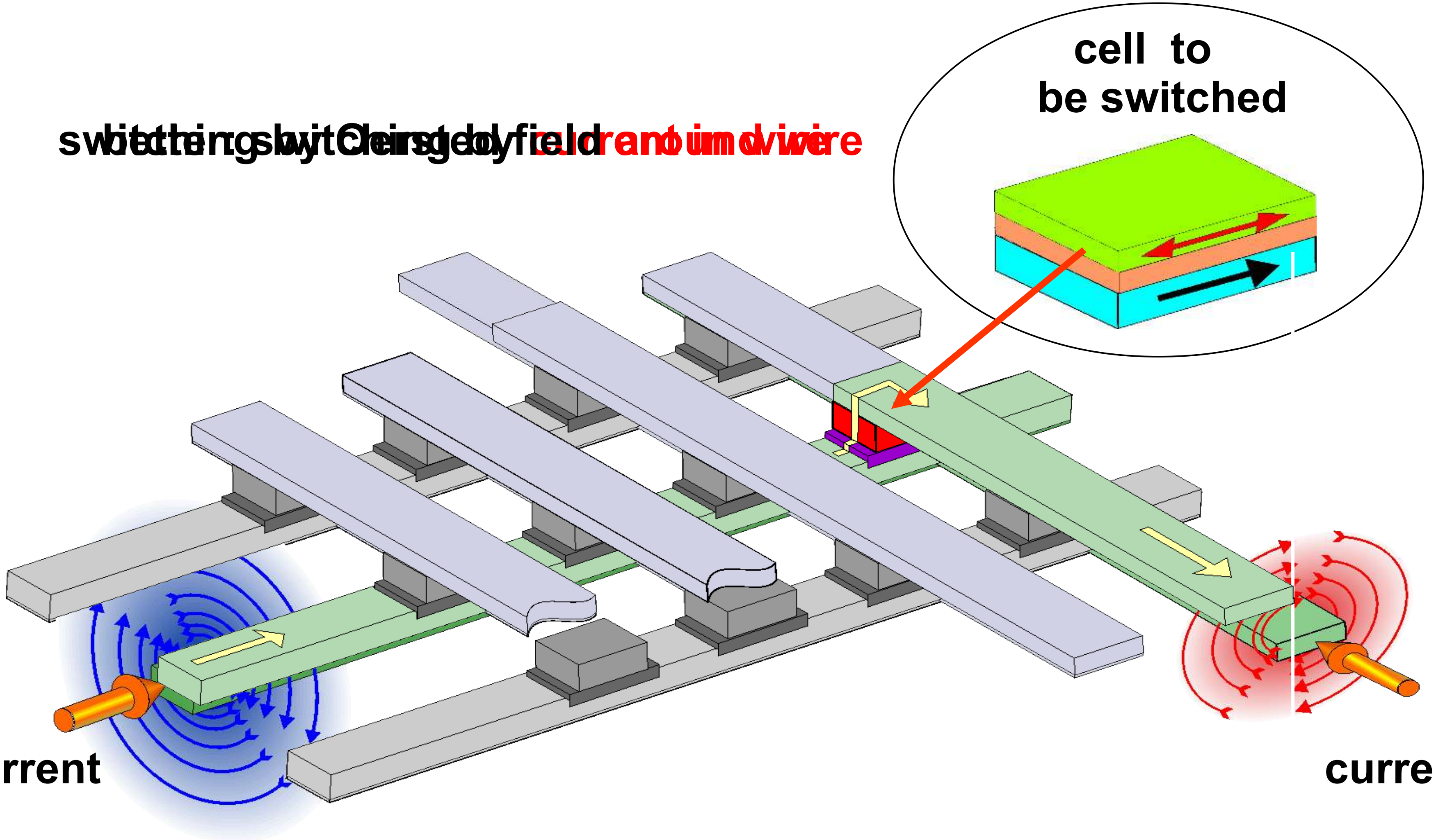
Quantitative imaging with sensitivity to
elemental and chemical distribution and charge/spin ordering





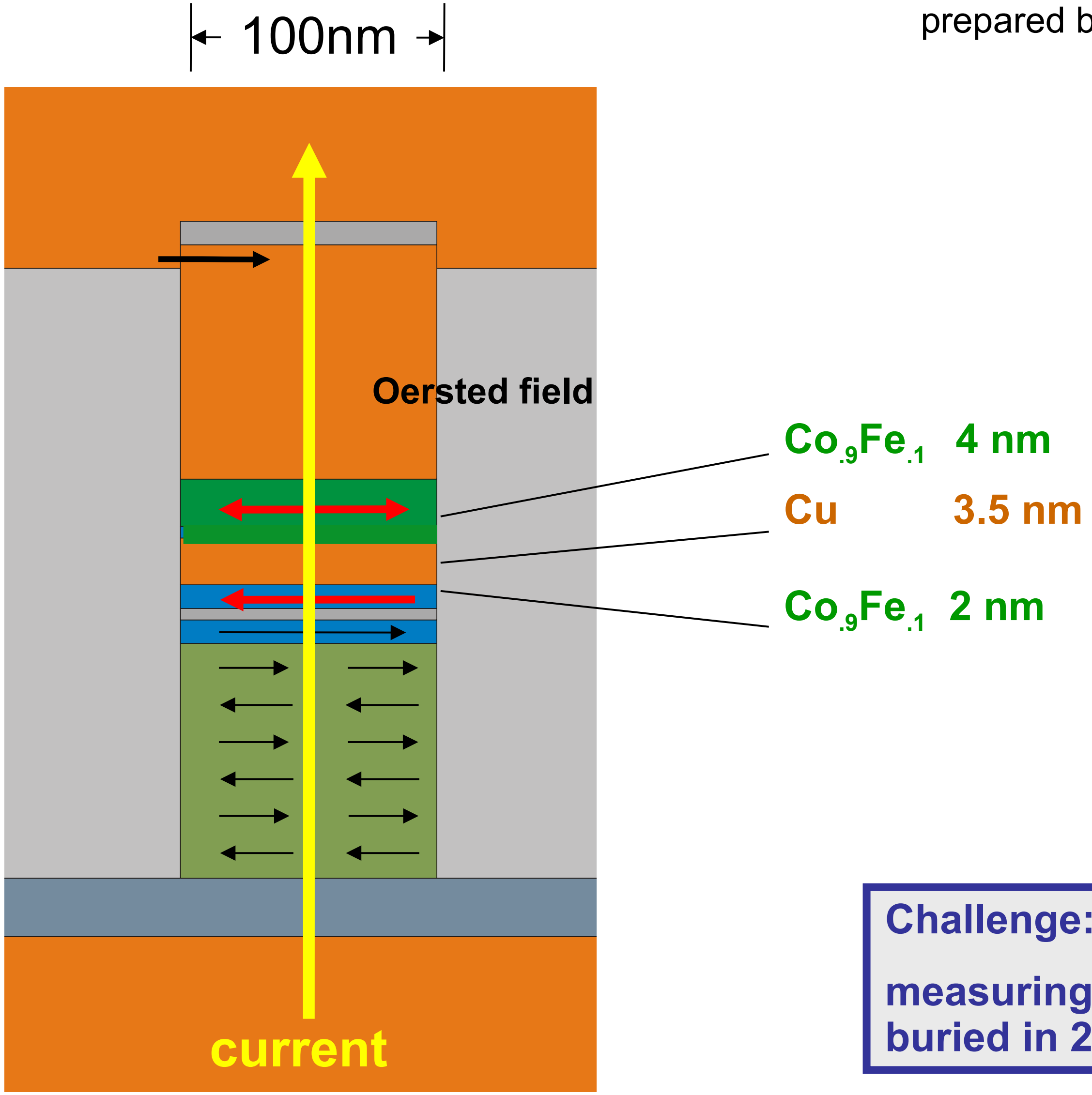


switching by Oersted field current in wire



Sample realization for spin-injection experiment

prepared by Jordan Katine, *Hitachi Global Storage*



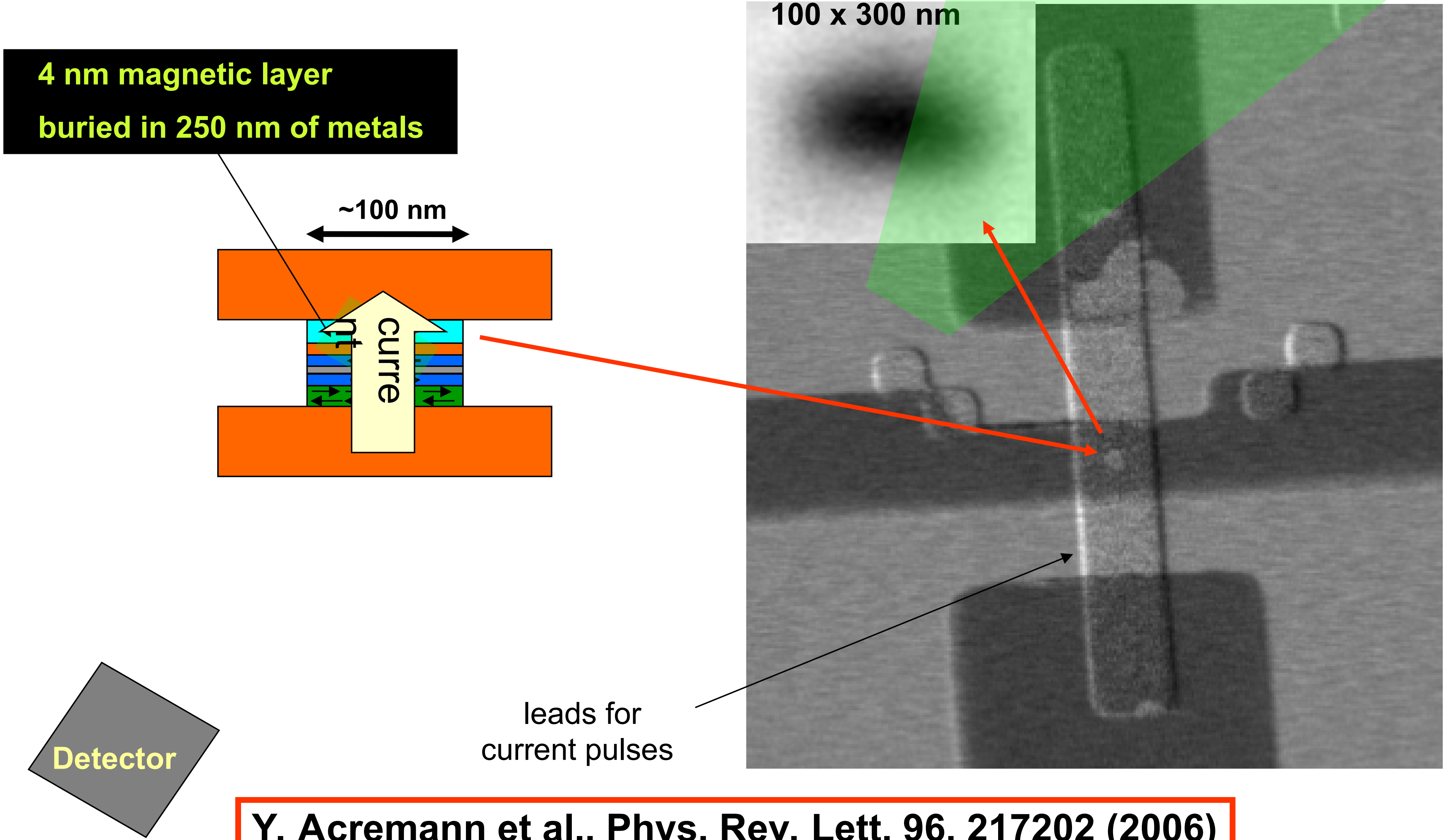
to be switched back and forth

polarizes spins

Challenge:

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

STXM image of spin injection structure



Y. Acremann et al., Phys. Rev. Lett. 96, 217202 (2006)

Soft x-ray spectro-microscopy at its best

- **Sensitivity to buried thin layer (4 nm)**

  Cross section just right - can see signal from thin layer X-rays can distinguish layers, tune energy to Fe, Co, Ni or Cu L edges

- **Resolving nanoscale details (< 100 nm)**

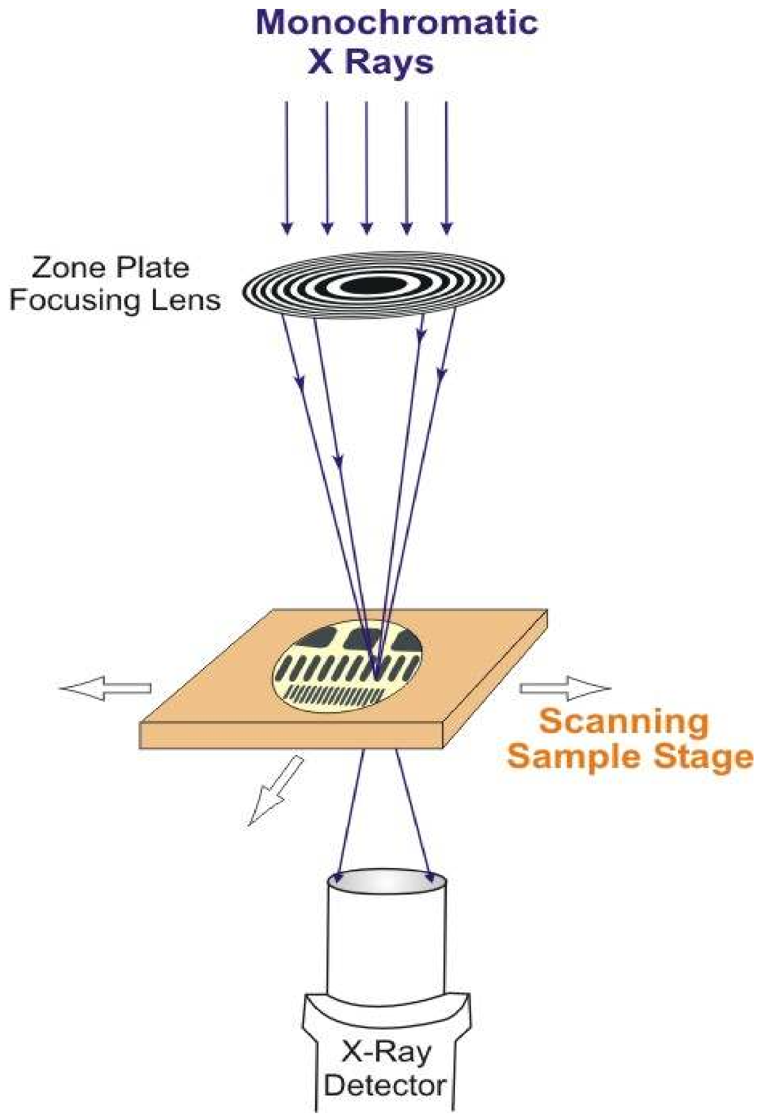
  Spatial resolution, x-ray spot size ~30 nm

- **Magnetic contrast**

  Polarized x-rays provide magnetic contrast (XMCD)

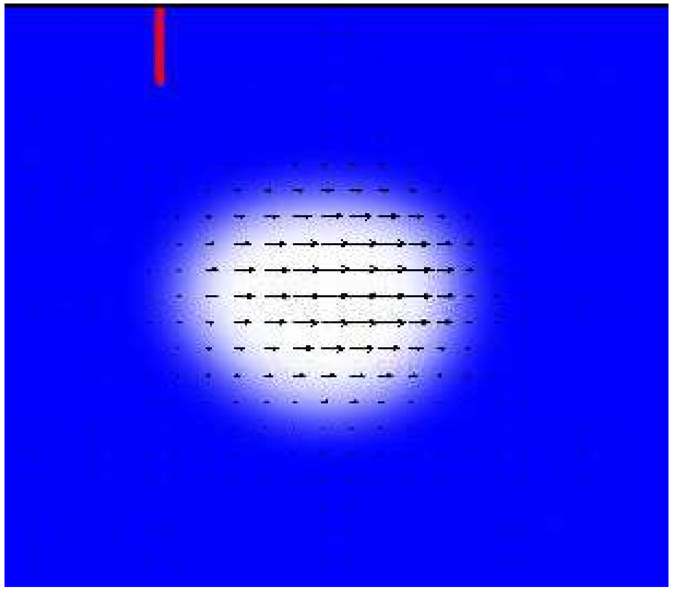
- **Sub-nanosecond timing**

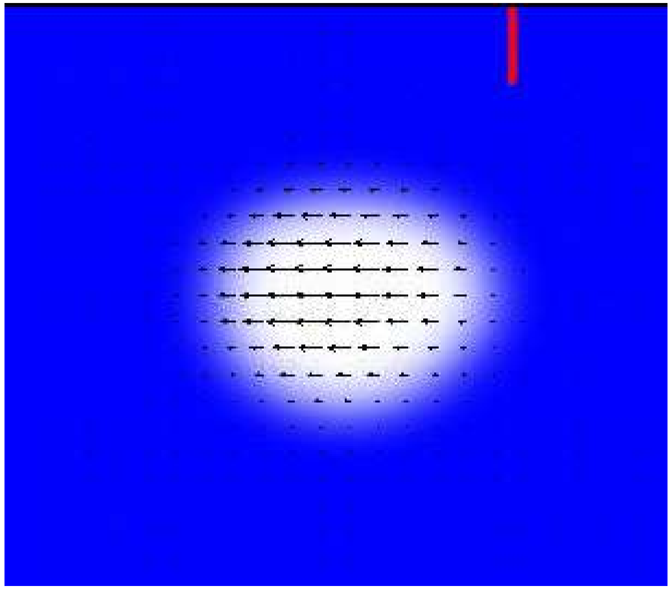
  Synchronize spin current pulses with ~50 ps x-ray pulses



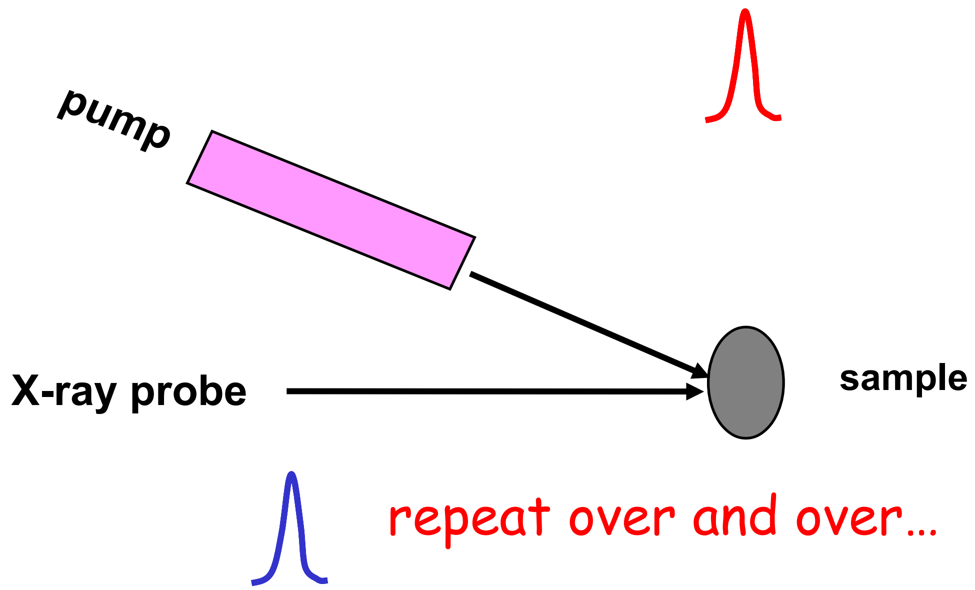
Fast detector for X-ray pulse selection

Static images of the burried layer's magnetization





Problem: Today not enough intensity for single shot experiments with nanometer spatial and picosecond time resolution

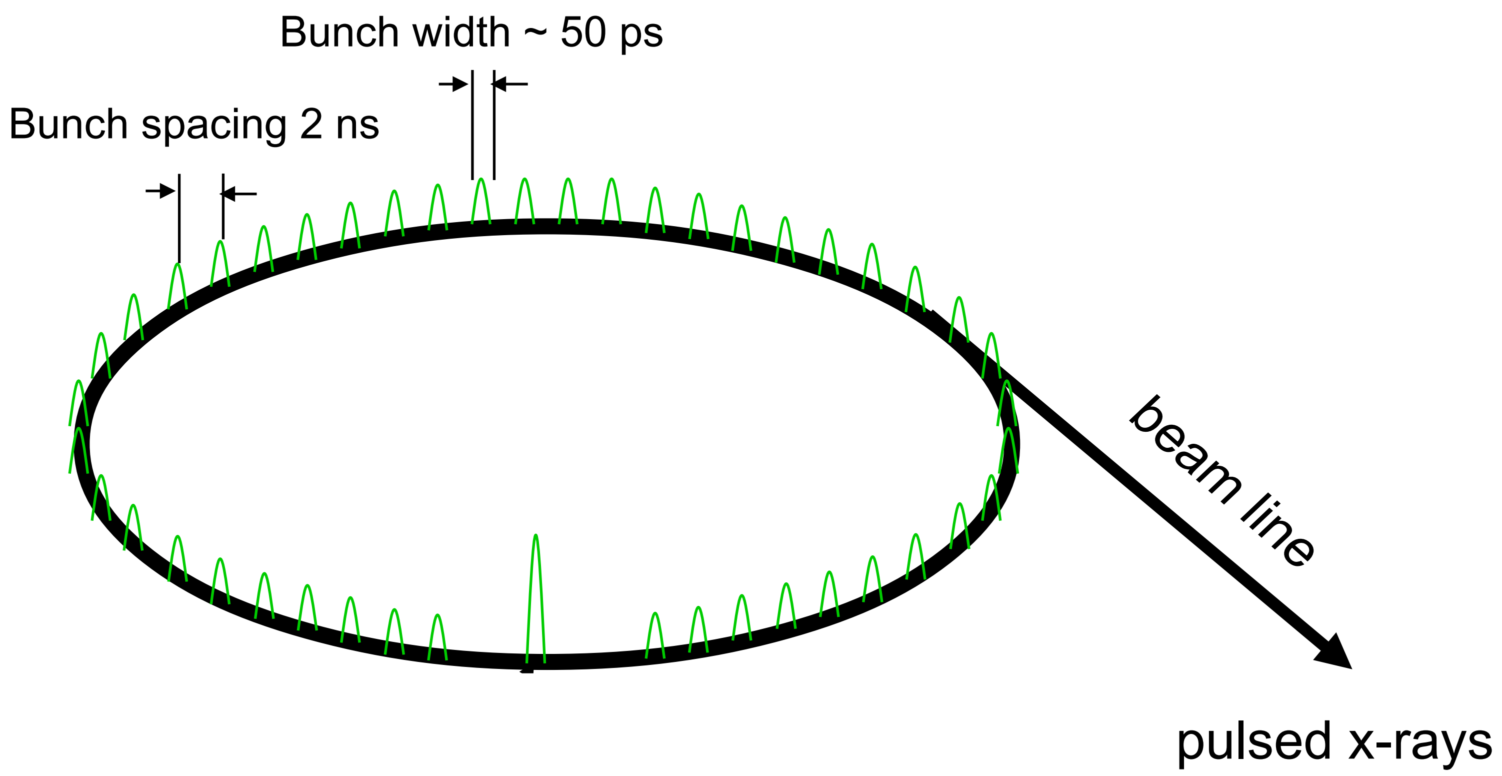


Limitation:

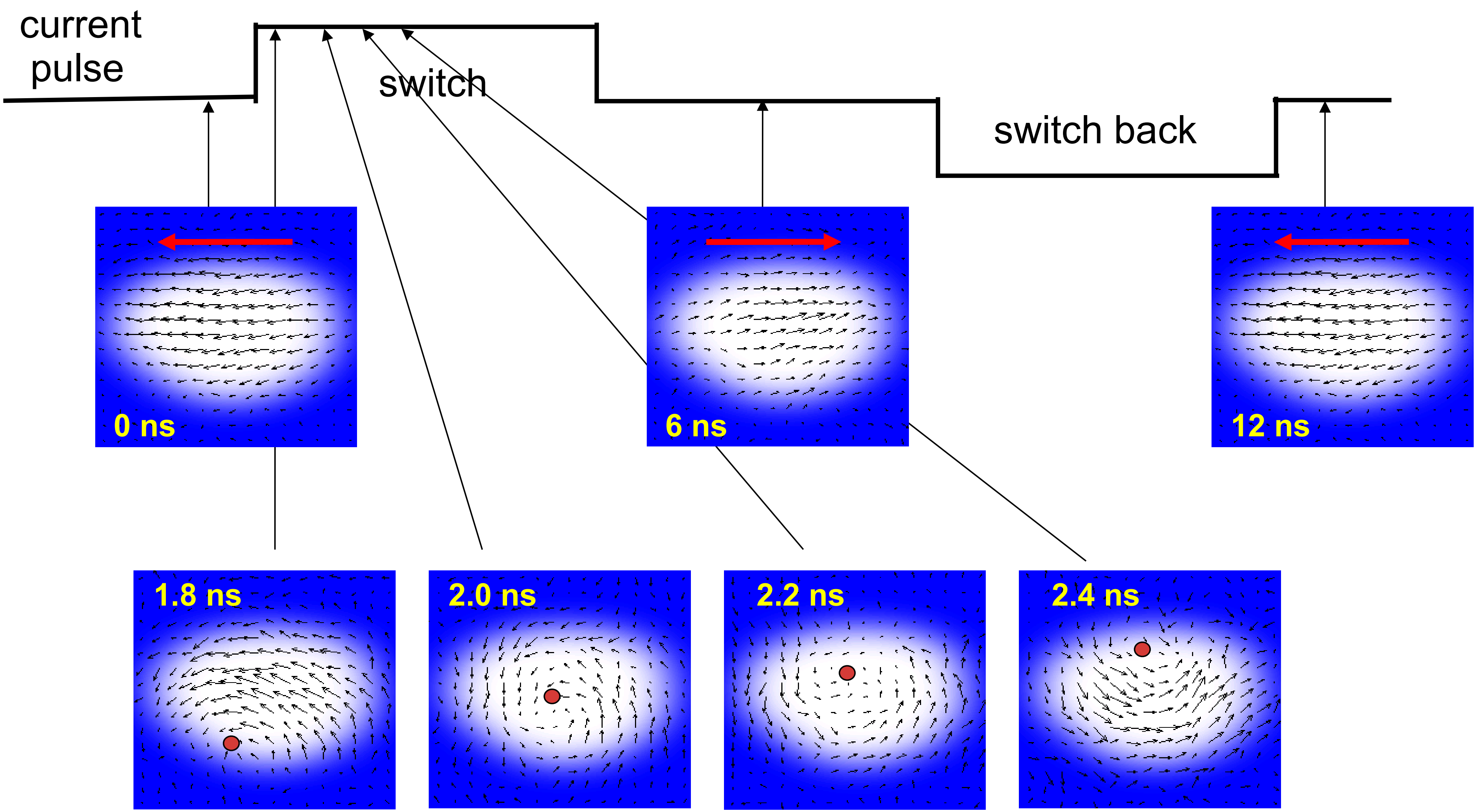
Process has to be repeatable

Pulse structure of synchrotron radiation

Storage ring is filled with electron bunches → emission of X-ray pulses



Magnetization reversal dynamics by spin injection



Switching best described by movement of vortex across the sample!

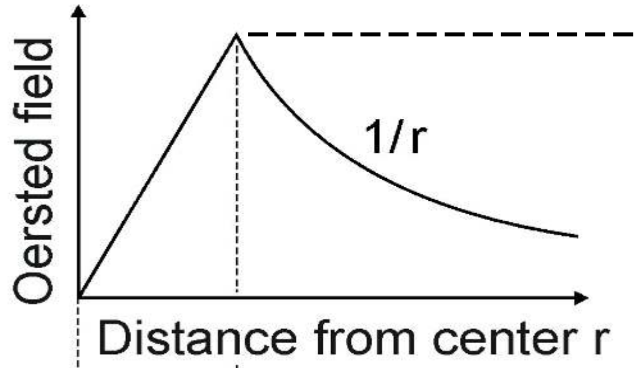
Magnetic switching by interplay of charge and spin current

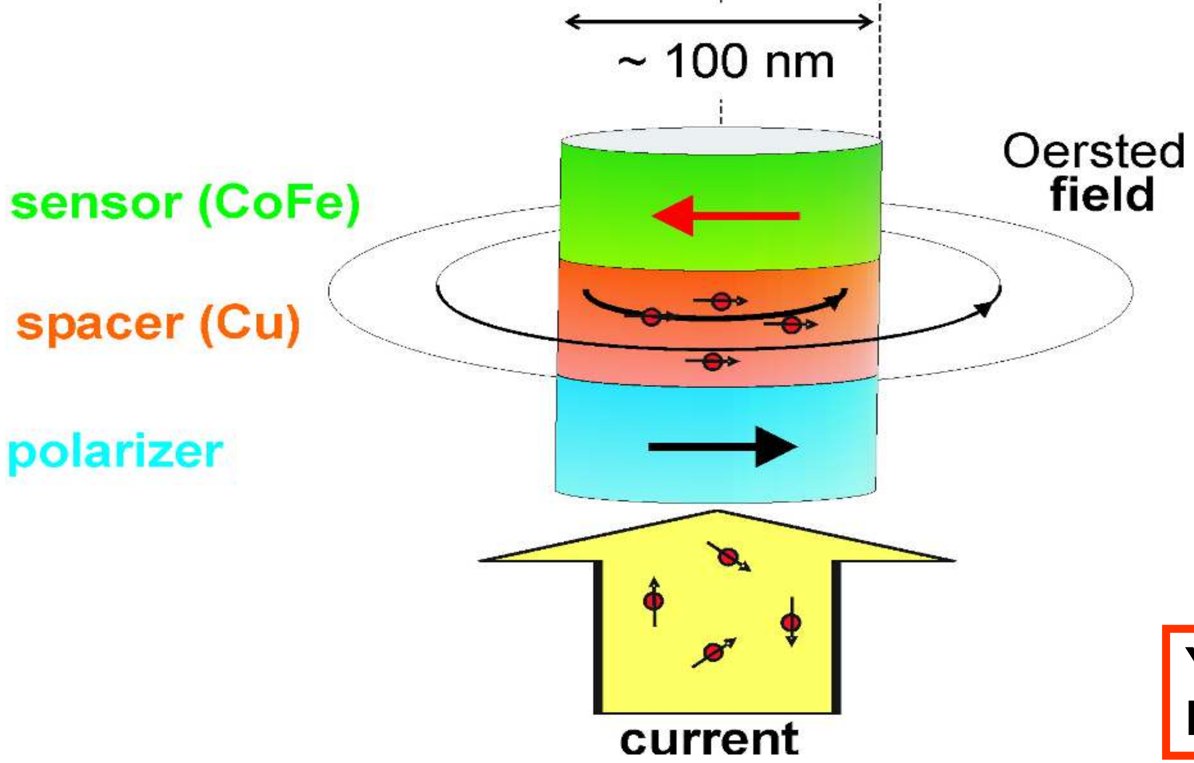
CHARGE CURRENT:

creates vortex state

SPIN CURRENT:

drives vortex across sample

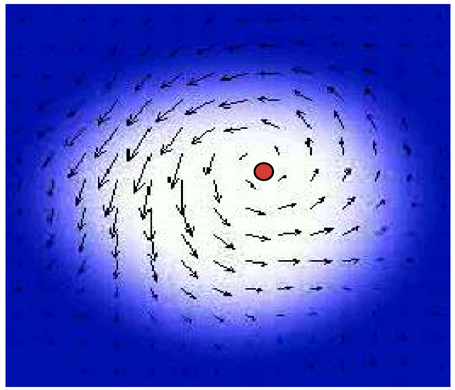




= 950 Oersted

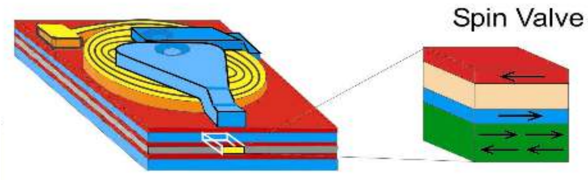
for 150x100nm,

$j = 2\times10^8$ A/cm^2



Y. Acremann et al.,
Phys. Rev. Lett. 96, 217202 (2006)

Requirements for exploring modern magnetic materials



General requirements:	*Technique requirements:*
distinguish components	**elemental (chemical) specificity**
study thin films and interfaces	**large cross section for "signal"**
look below the surface	**depth sensitivity**
see the invisible	**nanoscale spatial resolution**
resolve dynamic motions	**time resolution < 1 nanosecond**
separate spin and orbital contributions	**sensitive to s-o coupling**

x-rays cover them all

- x-ray cross section and flux
- x-ray tunability: resonances
- x-ray polarization
- sum rules
- x-ray spatial resolution
- x-ray temporal resolution

But:

Never ignore the power of other experimental techniques, because:

- *Good* argument: Each technique has specific strengths
- *Good but dangerous* argument: More readily accessible for you