AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY

Synchrotron radiation

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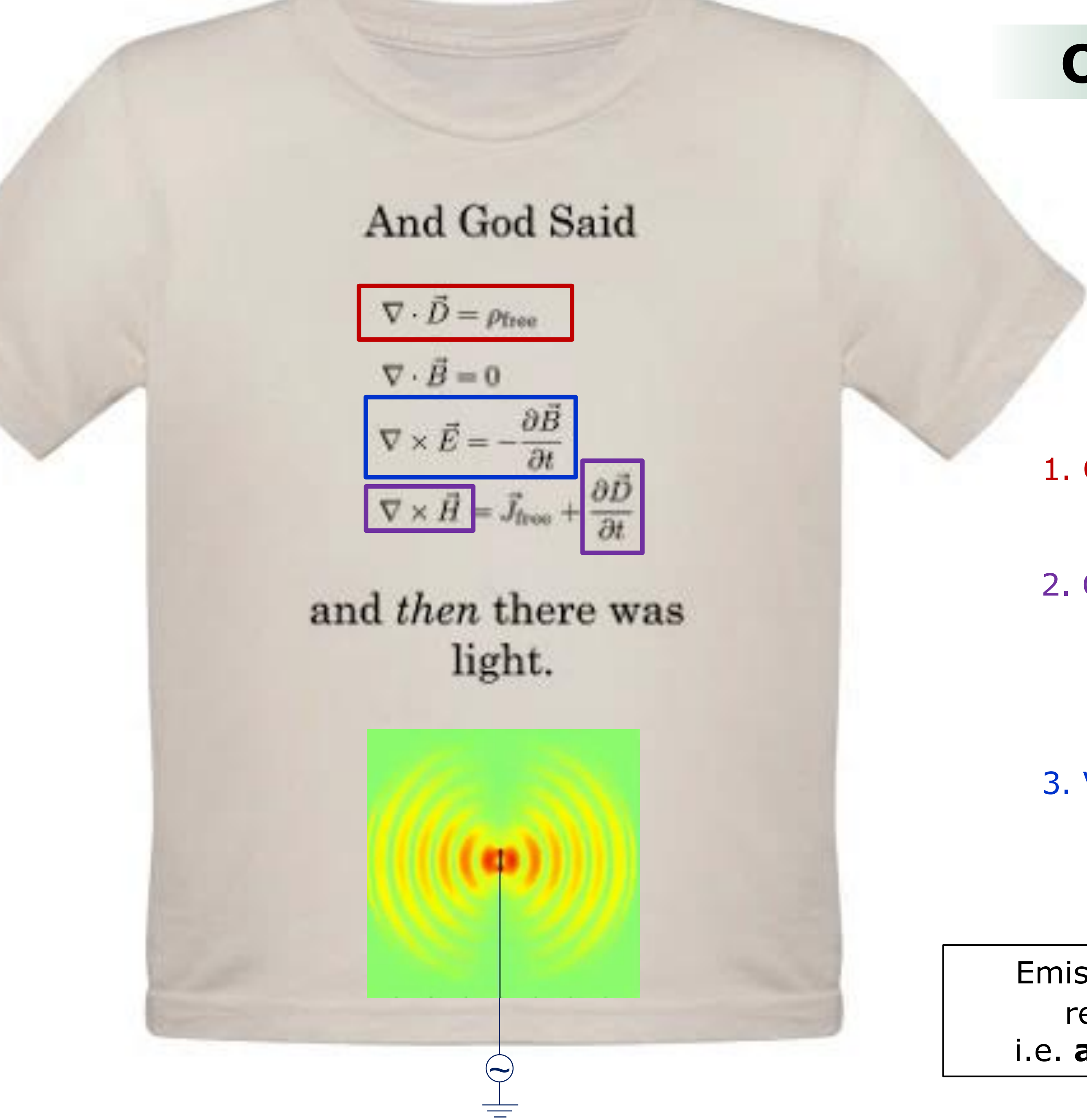
Origin of light



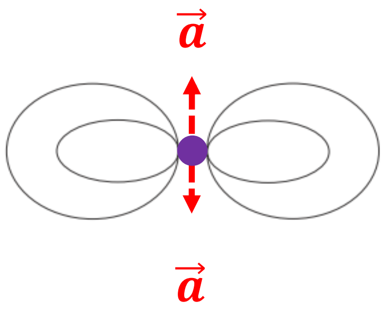
thebigblogtheory.wordpress.com

1. Charge: a source of electric field, $\vec{\boldsymbol{D}} = \varepsilon_0 \vec{\boldsymbol{E}}$.
2. Charge motion results in variable field, $\partial \vec{\boldsymbol{D}}/dt \neq 0$, a source of perpendicular magnetic field, $\vec{\boldsymbol{B}} = \mu_0 \vec{\boldsymbol{H}}$.
3. Variable magnetic field, $\partial \vec{\boldsymbol{H}}/dt \neq 0$, a source of perpendicular $\vec{\boldsymbol{E}}$ field …

Emission of light (E-M wave) requires that $\partial^2 \vec{\boldsymbol{E}}/dt^2 \neq 0$, i.e. **acceleration of charge**

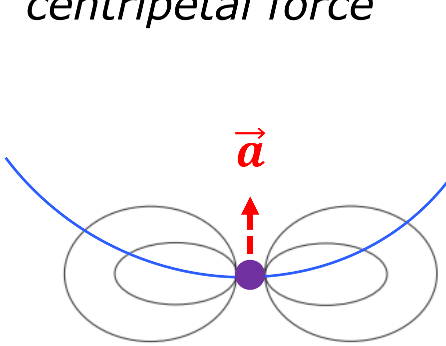
Origin of synchrotron light

Electric dipol



Electron in ring

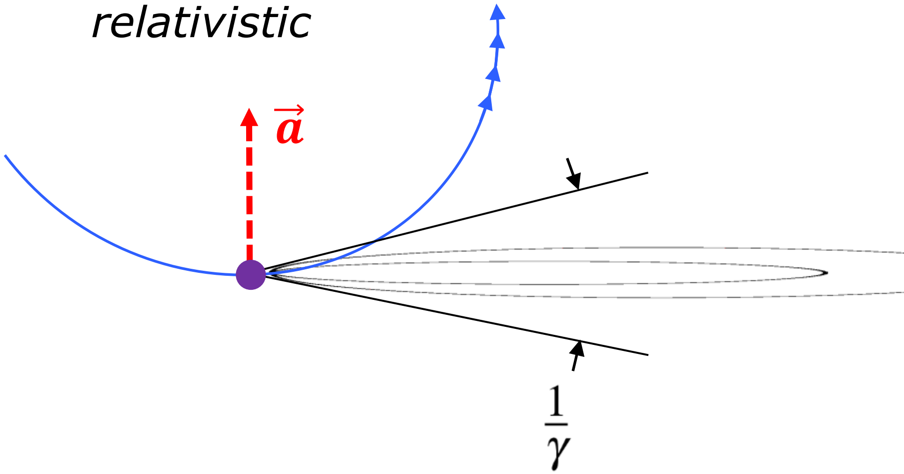
centripetal force



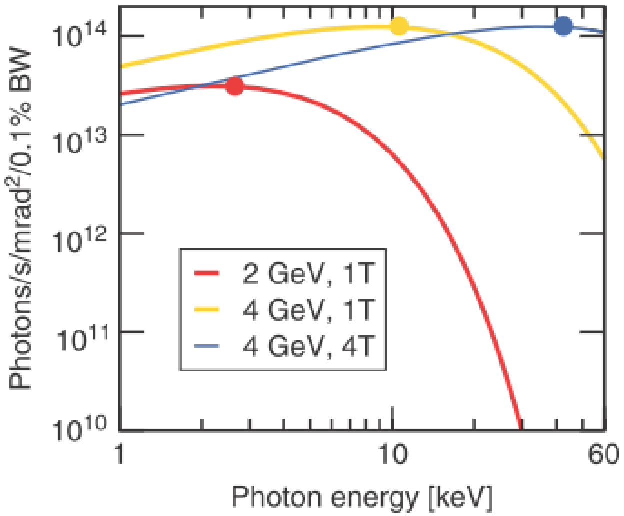
$$\rho = \frac{\gamma mc}{eB}$$

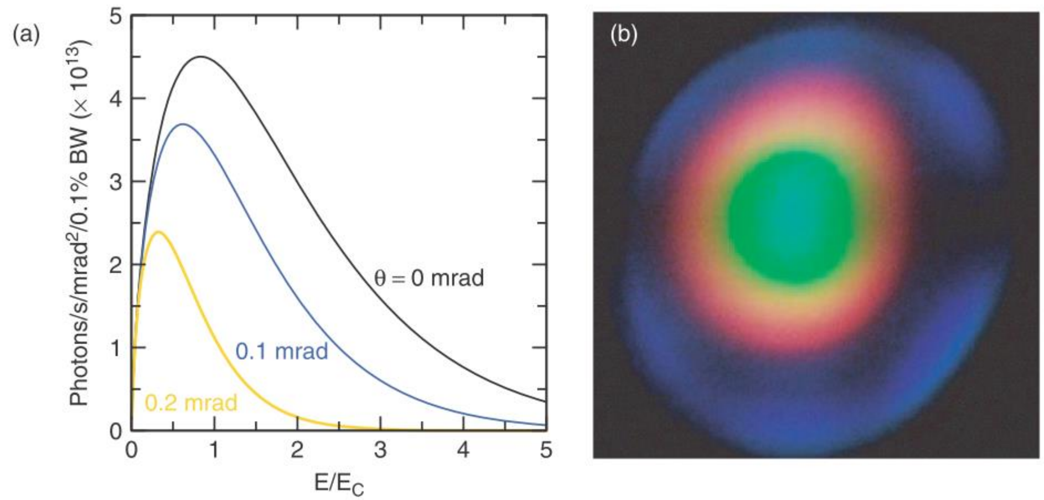
Electron in ring

relativistic



Synchrotron light spectrum



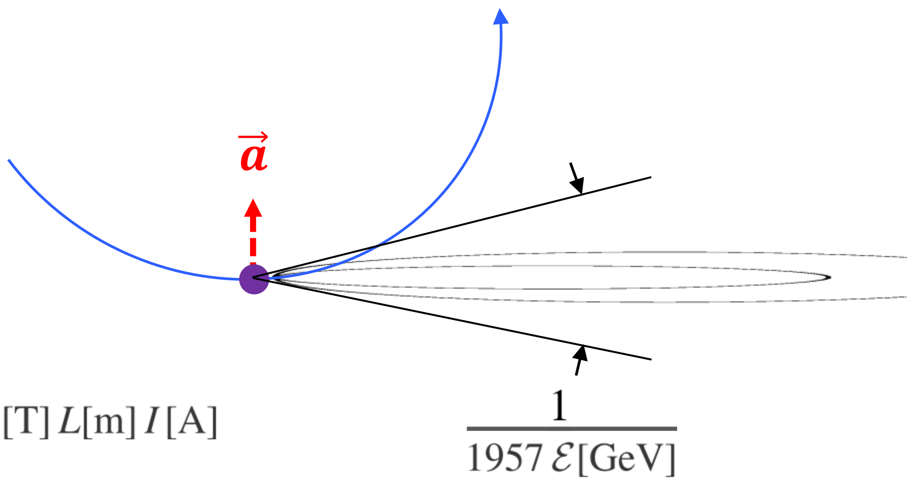


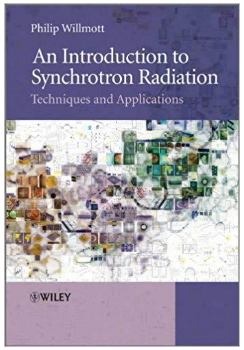
Critical energy

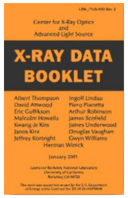
$$\hbar\omega_c[\mathrm{keV}] = 0.665\,\mathcal{E}^2[\mathrm{GeV}]\,B\,[\mathrm{T}]$$

Orbital radius

$$\rho[\mathrm{m}] = 3.3\,\frac{\mathcal{E}[\mathrm{GeV}]}{B\,[\mathrm{T}]}$$



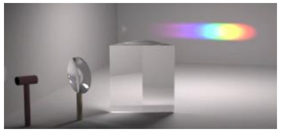


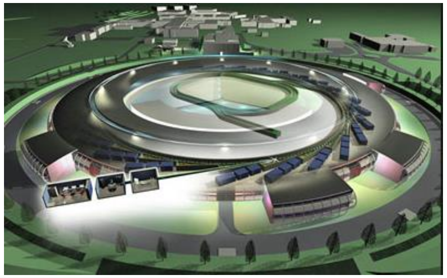


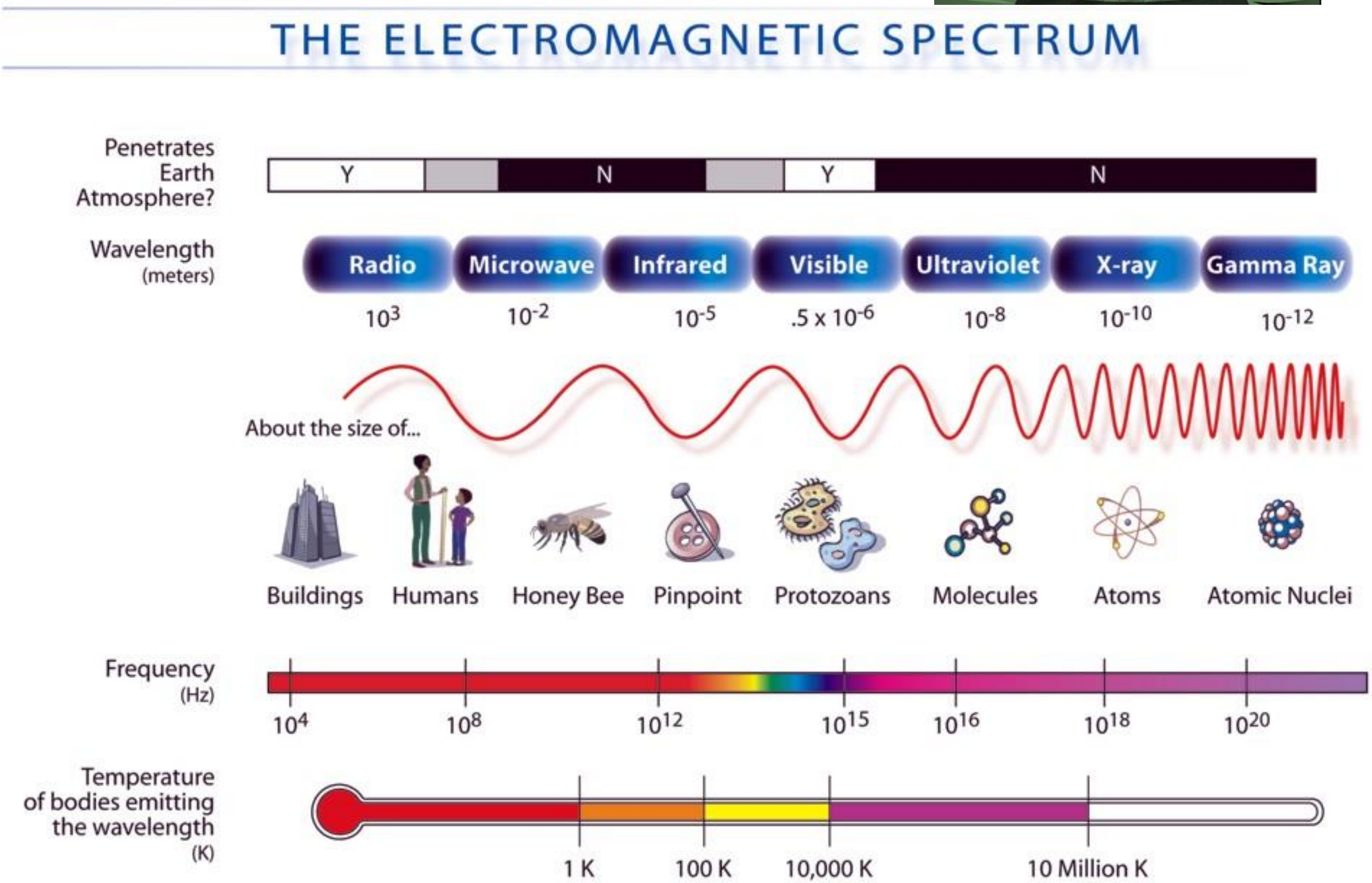
Radiated power

$$P\,[\mathrm{kW}] = 1.266\,\mathcal{E}^2[\mathrm{GeV}]\,B^2[\mathrm{T}]\,L[\mathrm{m}]\,I\,[\mathrm{A}]$$

$$f = \frac{c}{\lambda}$$



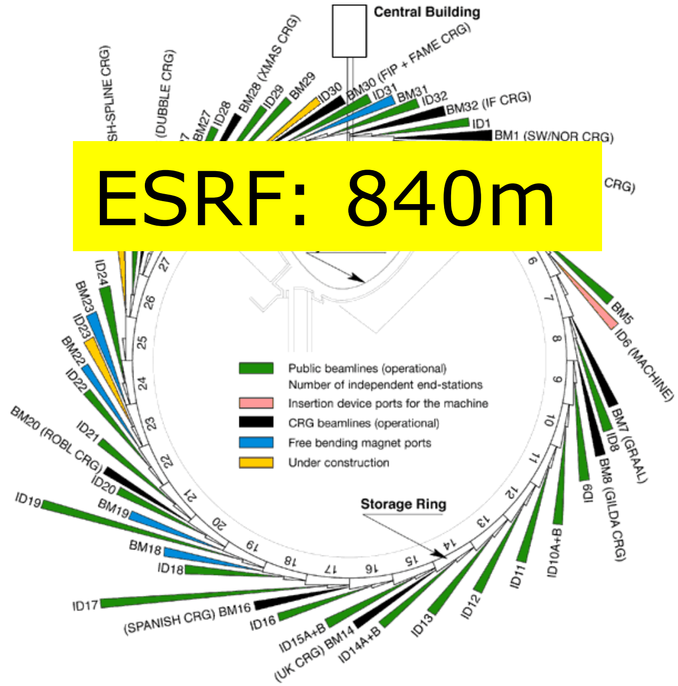




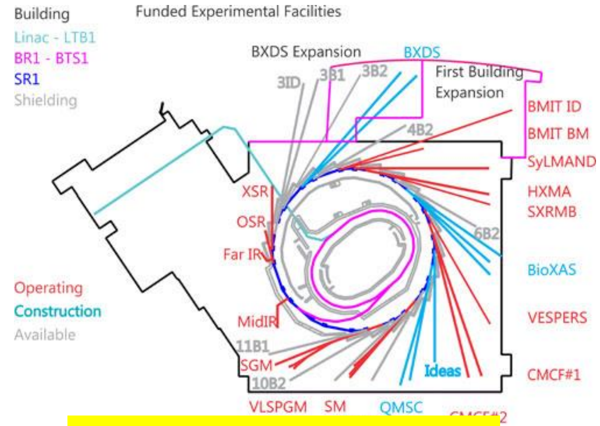
nasa.gov; www.lightsources.org

Topology of synchrotrons

ESRF: 840m



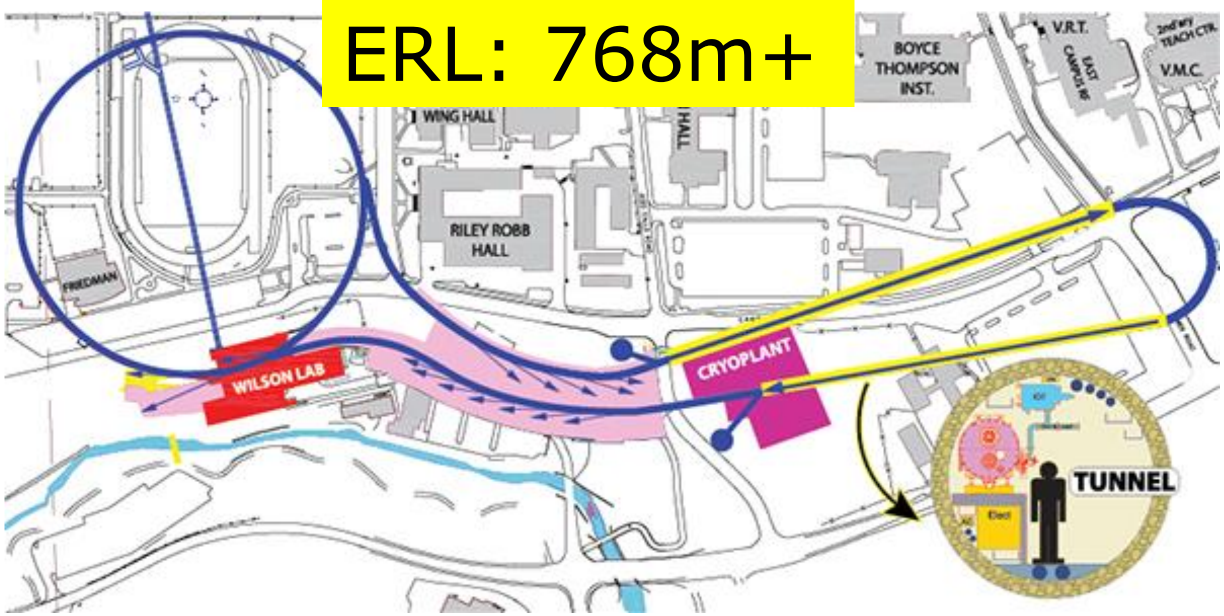
CLS:171m



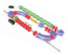
LHC: 27km

234m

ERL: 768m+



~10m



lightsources.org, cern.ch, lynceantech.com

Outline

Development of SR sources

Properties of SR, instrumentation

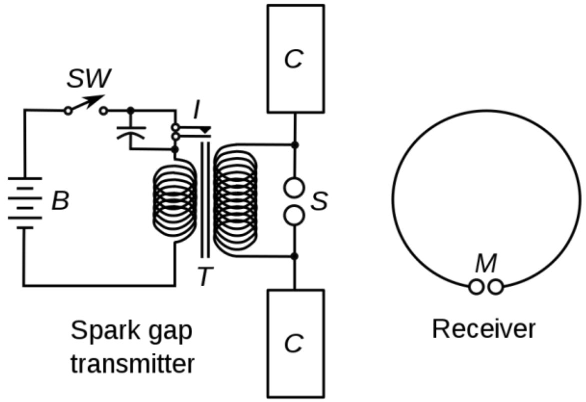
Applications of SR
- *diffraction*
- *imaging*
- *spectroscopy*

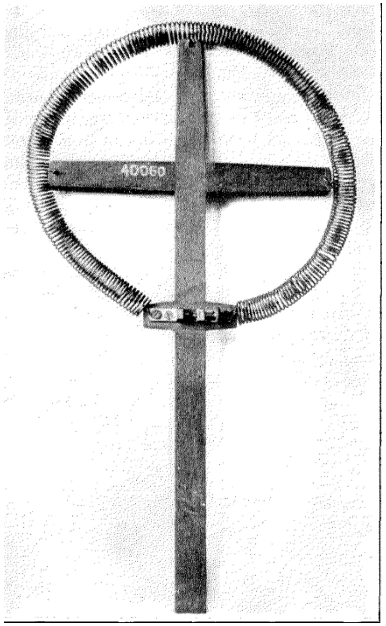
Applications to magnetism
- *magnetic structure*
- *element selective magnetometry*
- *magnetic imaging*
- *time resolved study*
- *extreme conditions*

Theoretical and experimental foundations

1865: J.C.Maxwell's paper *A Dynamical Theory of the Electromagnetic Field*

1887: experimental observation of E-M waves by H.Hertz





Appleyard R. Electrical Communication 6 (1927) 63

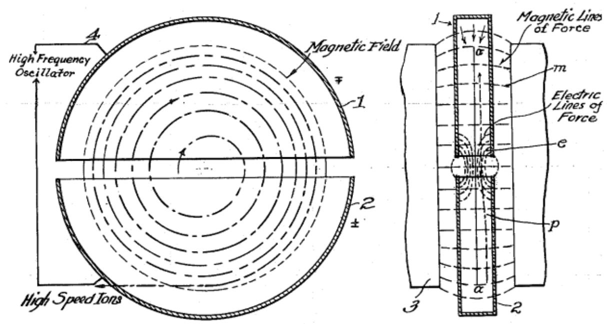
1897: discovery of electron by J.J.Thompson

1898-1900: Liénard and Wiechert formulate the theory of retarded potential

1907: G.A.Schott's formulates the full theory of radiation from electrons travelling at close to the speed of light

Cyclic particle accelerators

1932: First cyclotron build by S.Gaál and
E.O.Lawrence (4.8 MeV, ∅ = 69 cm)



1935: First betatron build by M.Steenbeck
(original concept from Rolf Widerøe)

1944-1945: First synchrotrons by Vladimir Veksler and Edvin McMillan’s

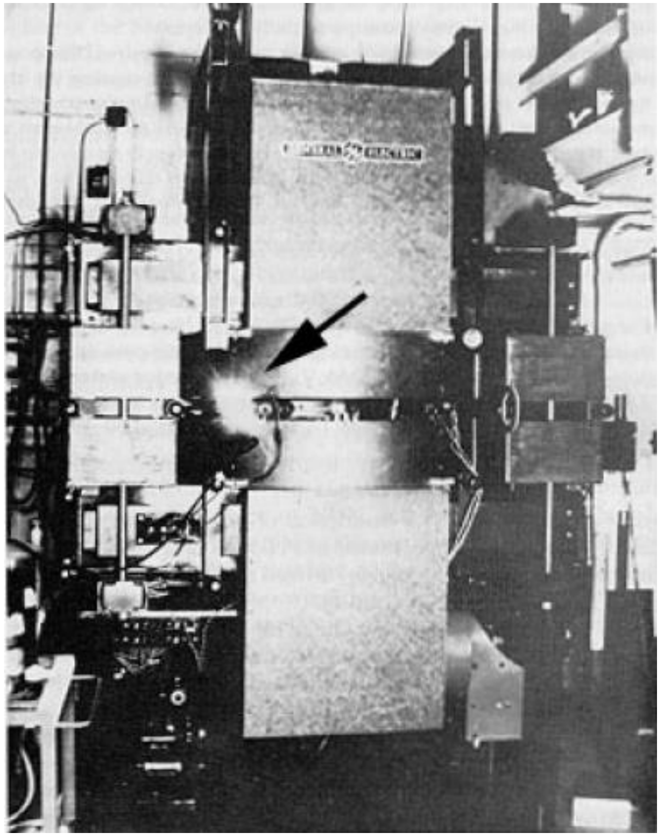
wikipedia.org

Discovery

1944: Ivanenko and Pomeranchouk calculate energy loss of electrons in betatron

1945: observation of modified trajectory of electrons in 100MeV betatron (Blewett), no traces of radiation detected

1947, April 24: Pollock, Langmuir, Elder and Gurewitsch observe light produced inside vacuum tube of newly built 70MeV synchrotron (GE, Schenectady, Nowy Jork), called **synchrotron radiation**



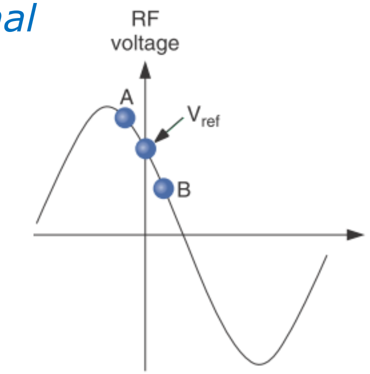
1949: Schwinger's theory of SR

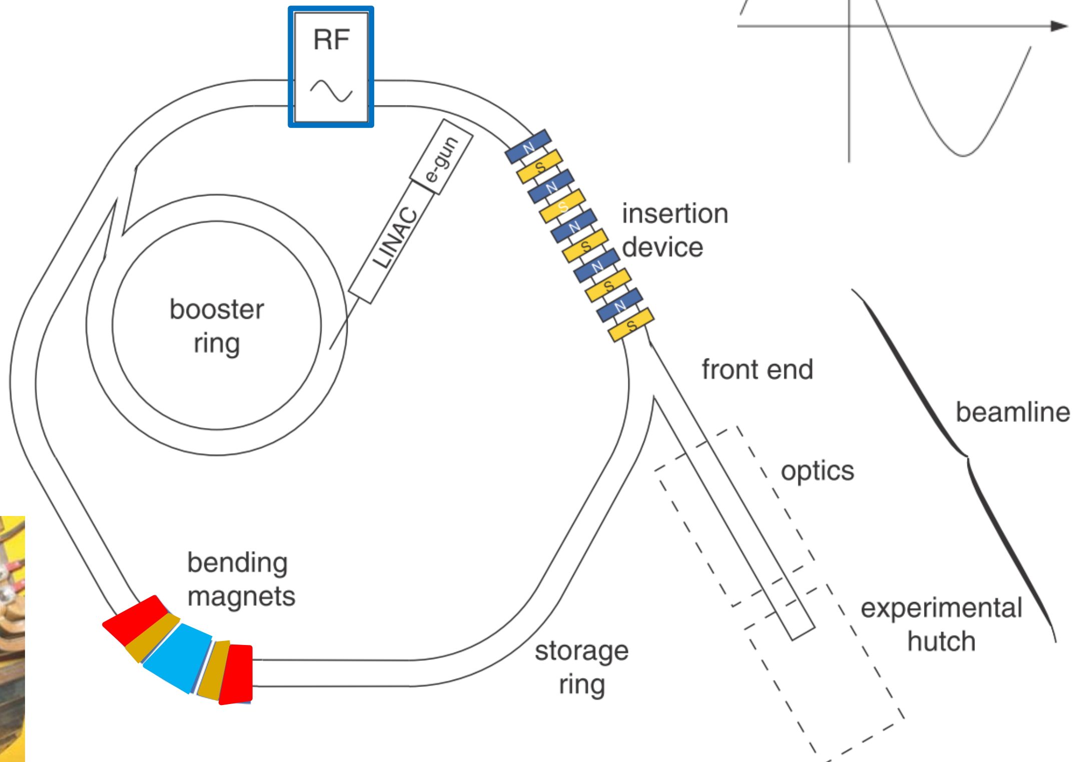
1969: Ginzburg & Syrovatskiy publish *Development of the Theory of Synchrotron Radiation and Its Reabsorption* based on Shklovsky's theory of cosmic radiation

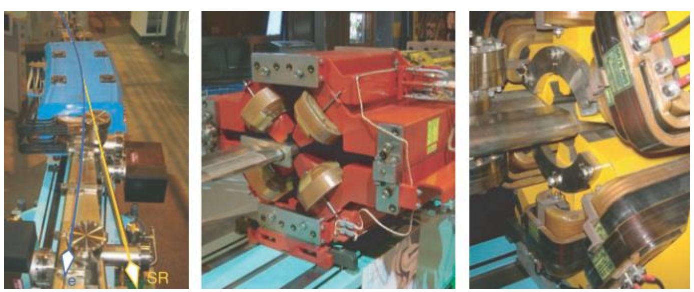
Synchrotron lattice

„Race track" synchrotron by D. Crane (Univ. of Michigan, 1949)

*Replenishment of electron energy and longitudinal focussing using **RF cavities***

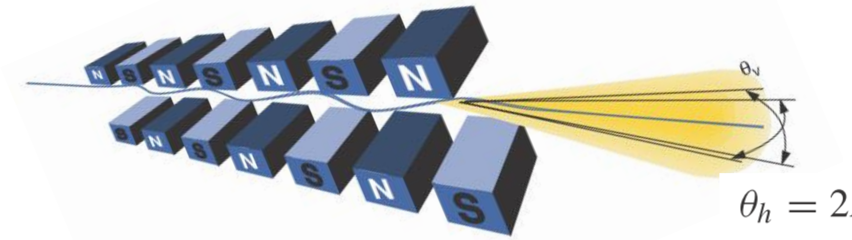






*Guiding and lateral focussing of el. bunches using **magnets**:*
dipole, quadrupole, sextupole, N-pole …

Willmott P. An Introduction to Synchrotron Radiation, Willey 2011



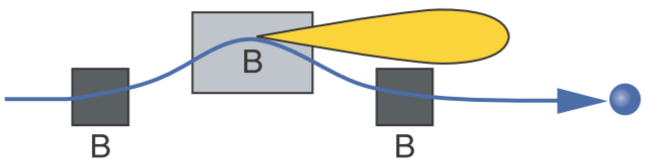
$\theta_h = 2K/\gamma$

Maximum angular deviation of the electron orbit, ϕ_{max}, define undulator parameter:

$$K = \phi_{\max}\,\gamma = \frac{eB_0}{mck_{u,w}}$$

$$= 0.934\,\lambda_{u,w}[\mathrm{cm}]\,B_0[\mathrm{T}]$$

Wavelength shifter

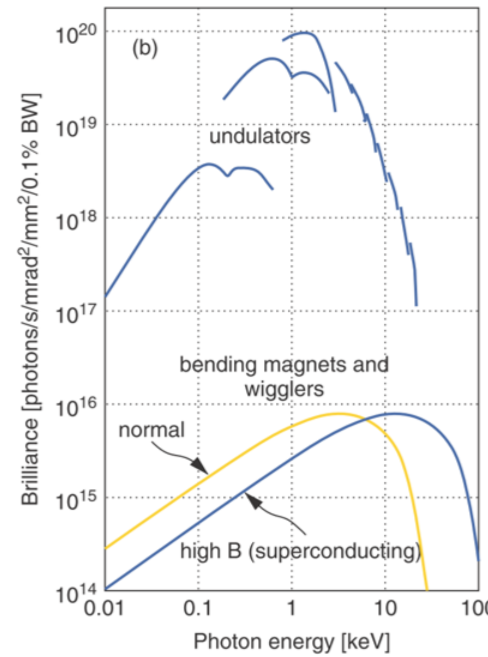


Undulator
K~1

$I_{peak} \sim n_{el} N^2$

Wiggler
K~10

$I_{max} \sim n_{el} N$



Willmott P. An Introduction to Synchrotron Radiation, Willey 2011

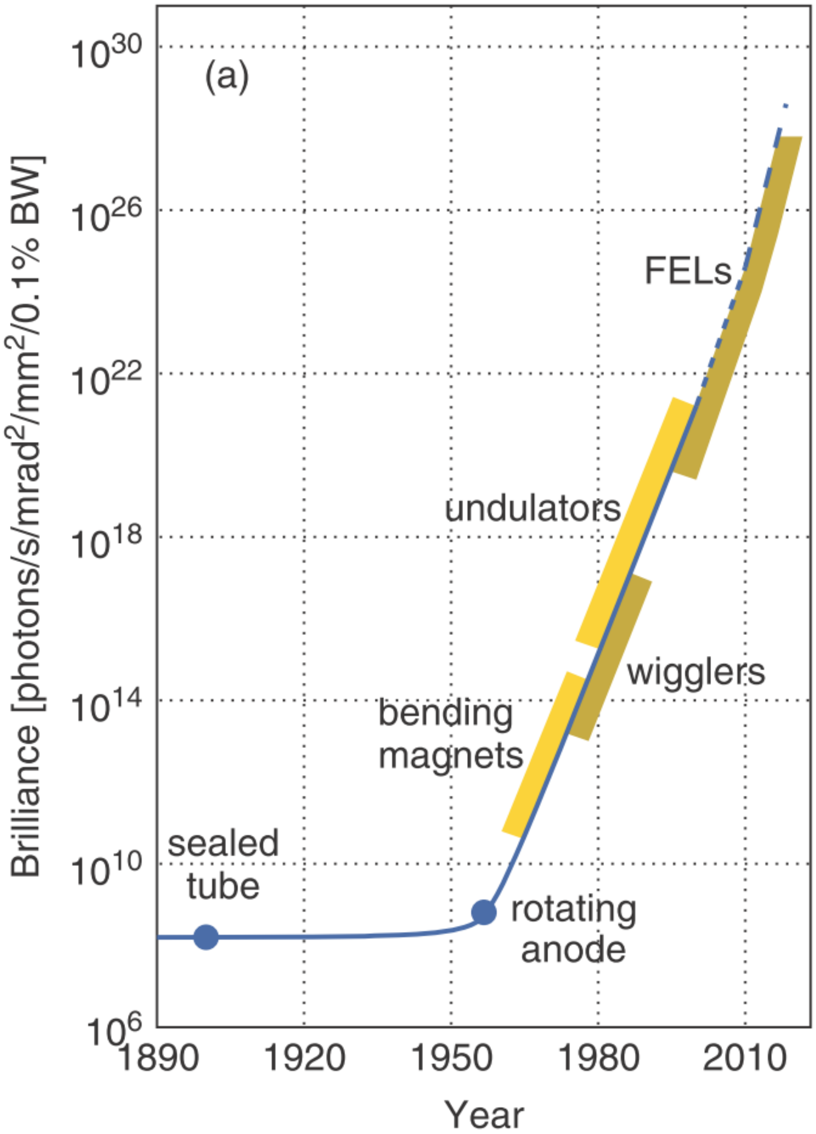
Generations of SR sources

4th: optimized for coherence free electron lasers (FEL) & diffraction limited storage rings (DLSR) ►

3rd: optimized for brilliance (insertion devices) ►

2nd: dedicated storage rings ►

1st: refurbished storage rings & parasitic operation ►



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Generations of SR sources

4th: optimized for coherence
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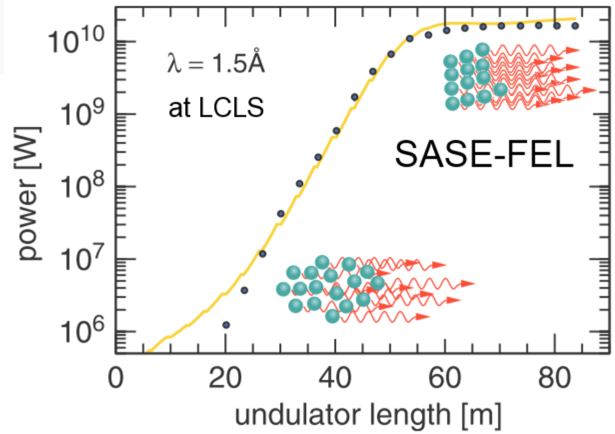
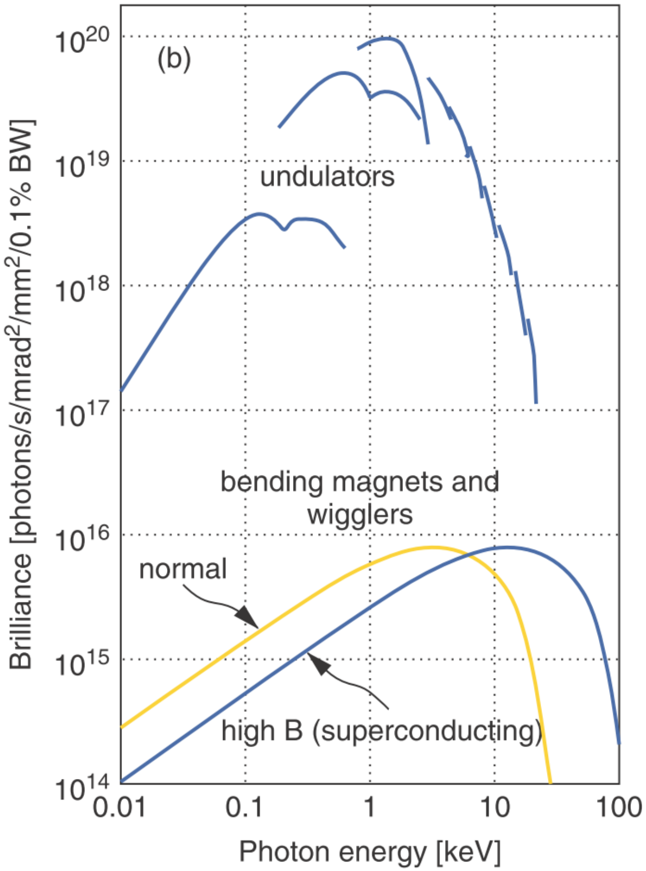


3rd: optimized for brilliance
(insertion devices) ►



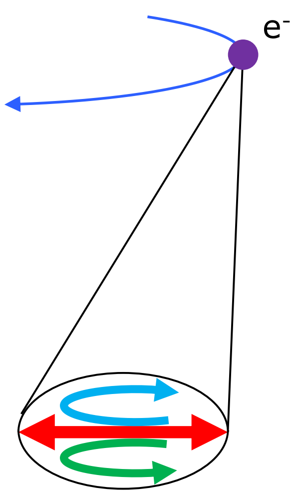
2nd: dedicated storage rings ►

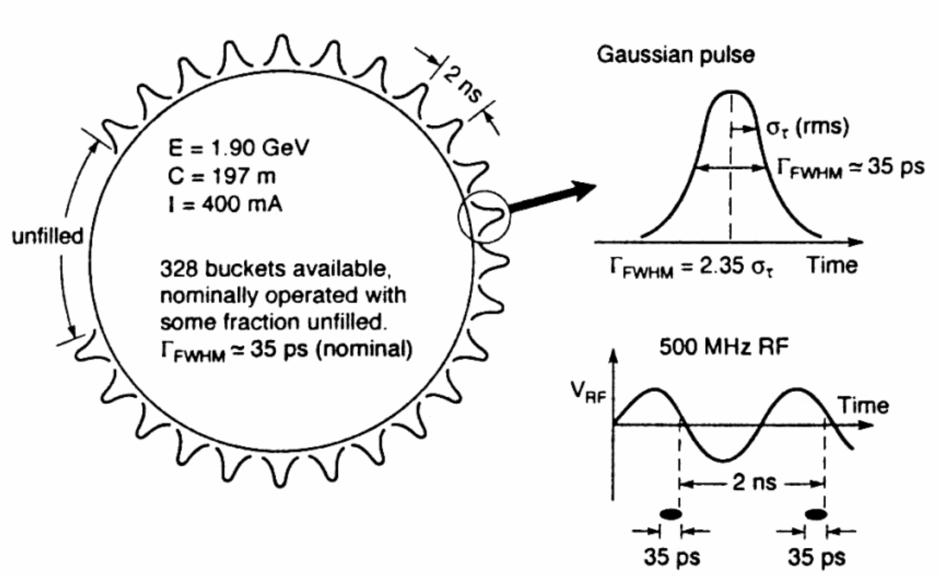
1st: refurbished storage rings
& parasitic operation ►

Willmott P. An Introduction to Synchrotron Radiation, Willey 2011

Unique properties od SR

- Stable, high flux source of photons
- Broad spectrum
- Collimated and coherent
- Discrete time structure
- Polarized
  (linearly, circularly)





Attwood D. Soft X-Rays and Extreme Ultraviolet Radiation, Cambridge University Press 1999

Synchrotron radiation labs

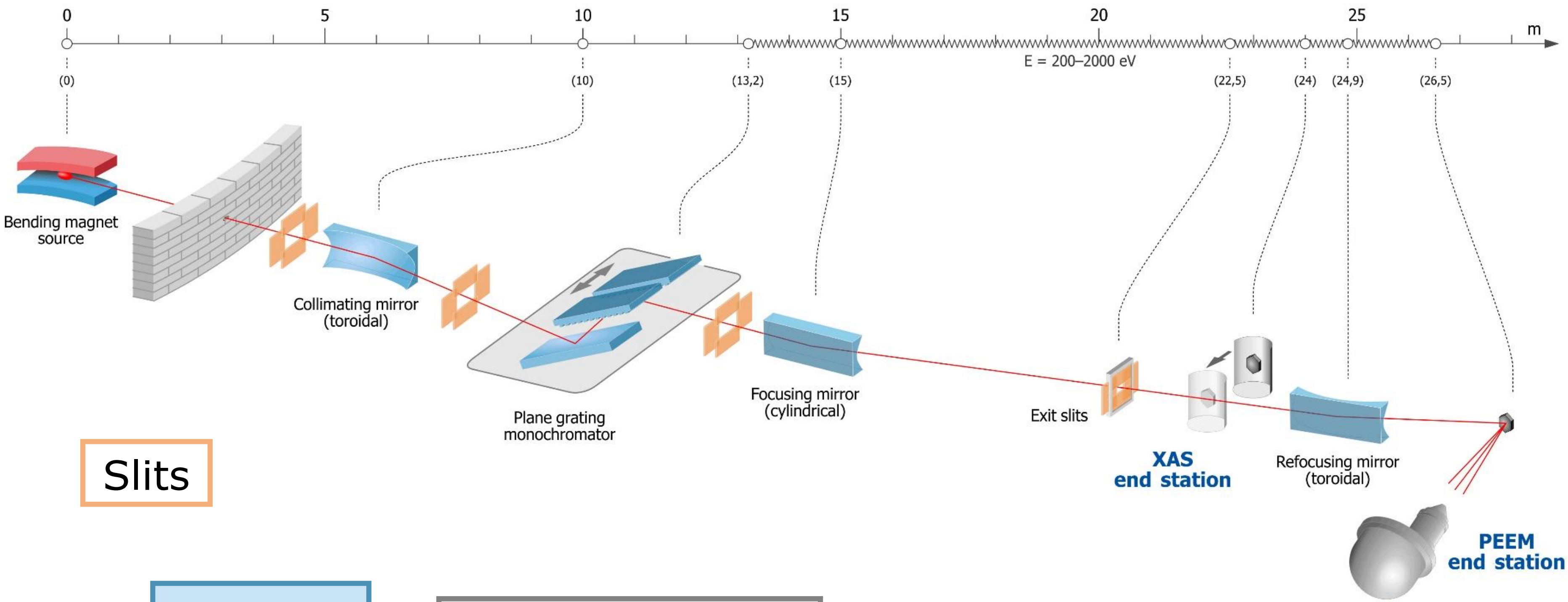
There are more than 50 light sources in the world (operational, or under construction).
Most of them offer free of charge access upon succesful beamtime applications (peer-reviewed).

www.lightsources.org

Elements of X-ray optics and instrumentation

SOLARIS NATIONAL SYNCHROTRON RADIATION CENTRE

www.synchrotron.pl



Slits

Mirrors
deflecting
& focusing

Monochromators

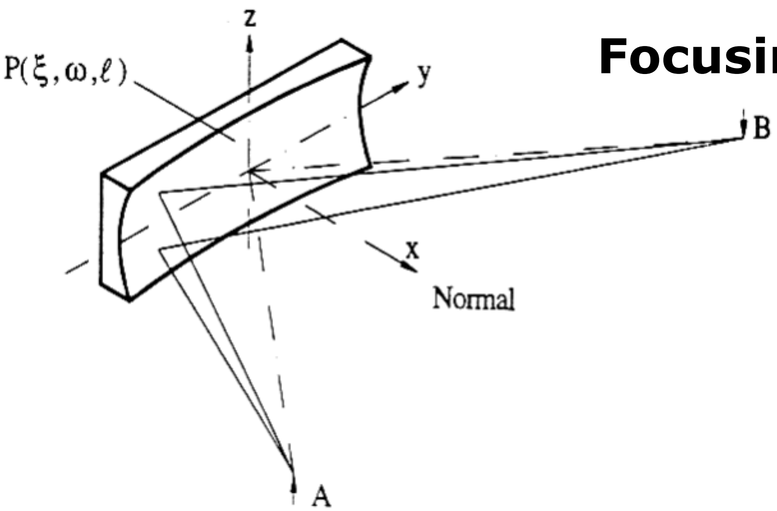
Detectors/endstations

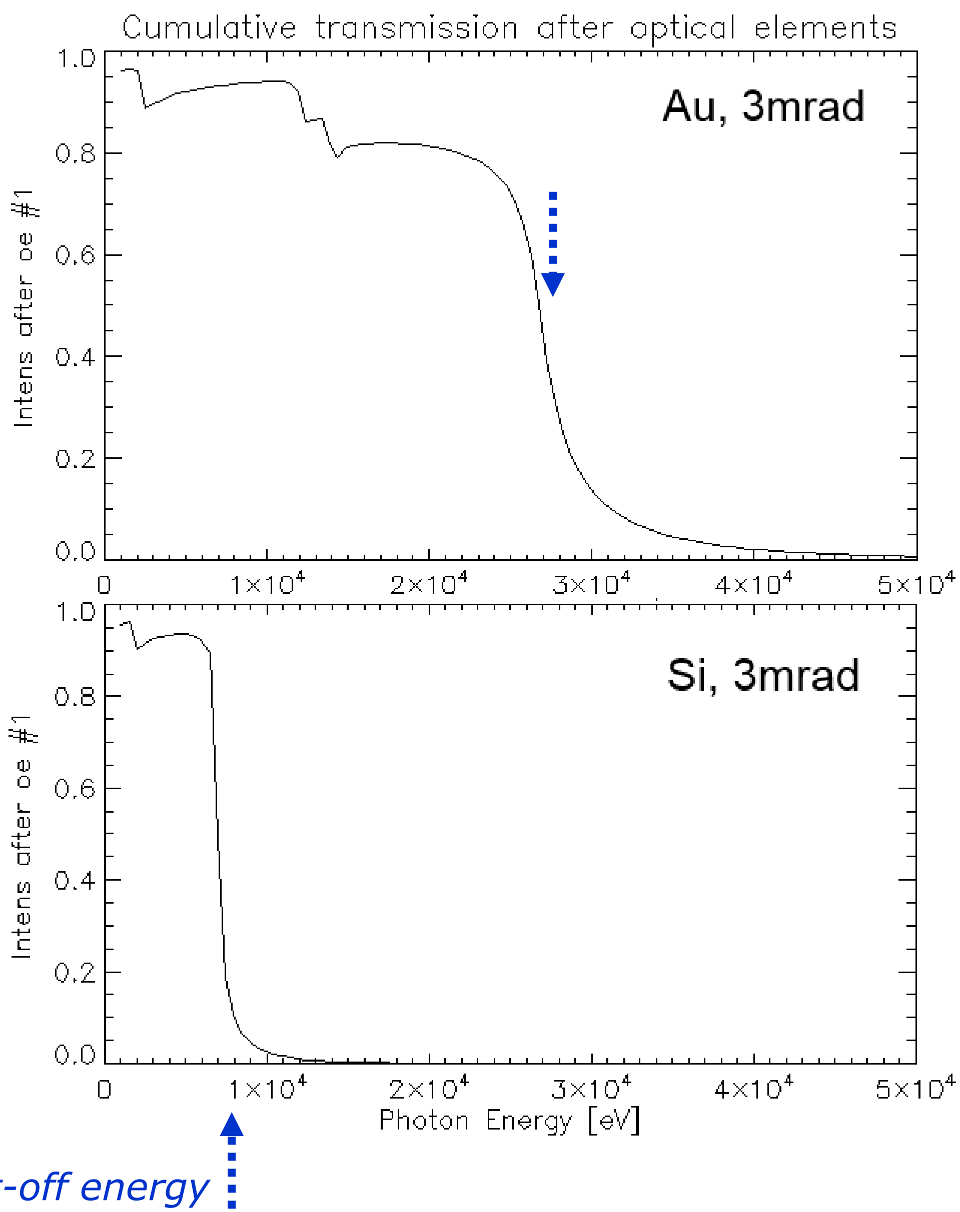
http://ftp.esrf.fr/pub/scisoft/xop2.3/

X-ray mirrors

Deflection

Focusing

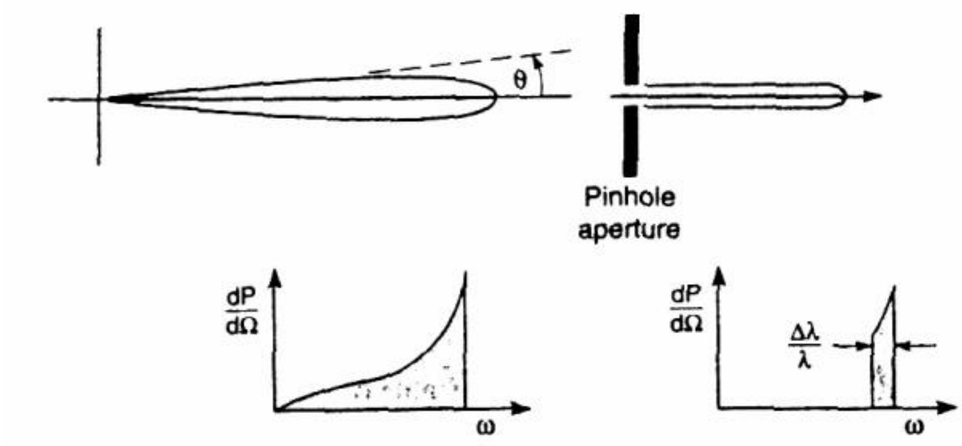




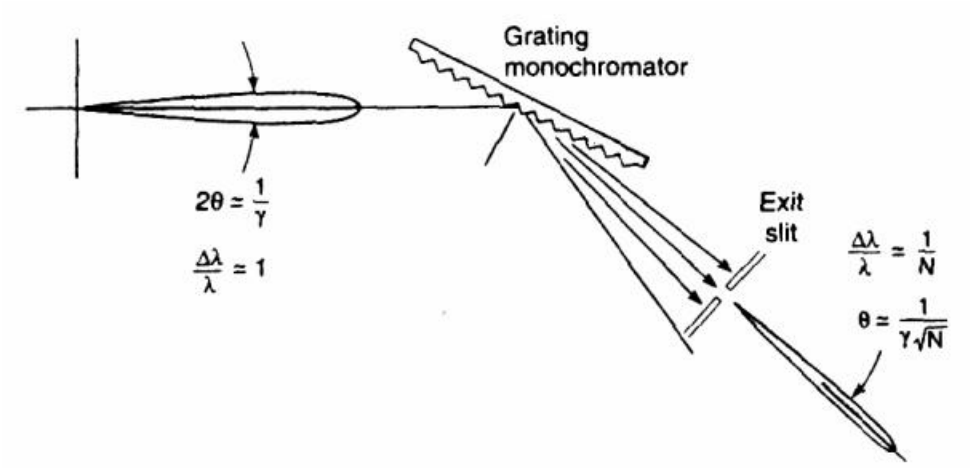
Filtering

Monochromators

Pinhole

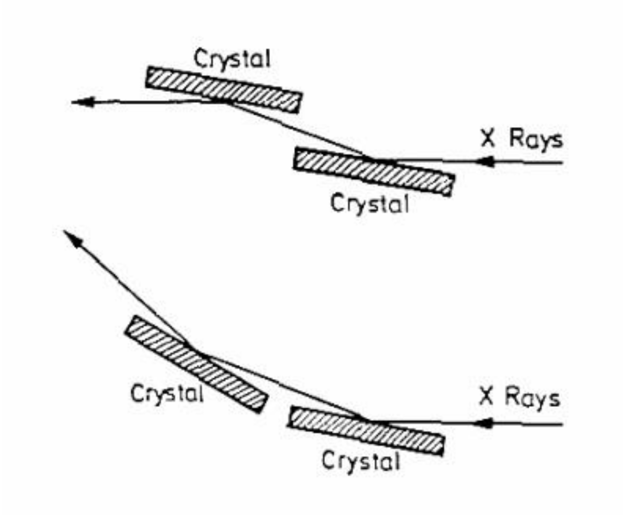


Grating
VUV & soft X-rays



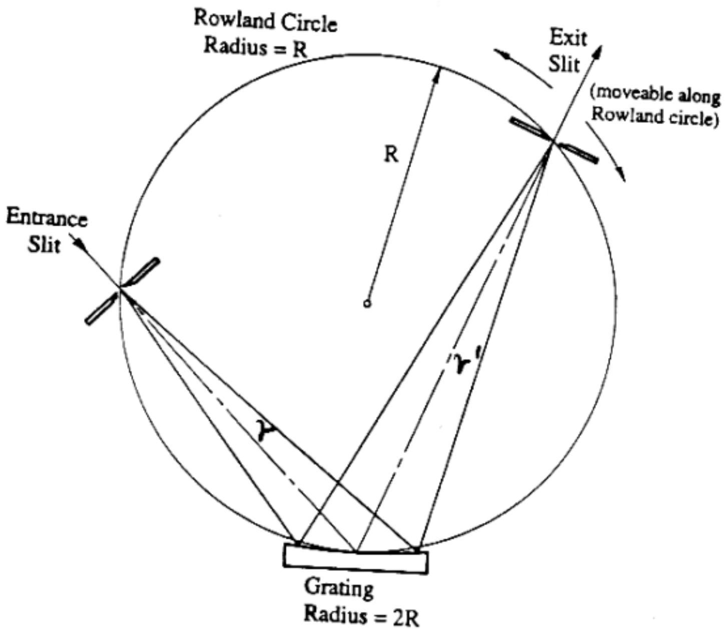
Attwood D. Soft X-Rays and Extreme Ultraviolet Radiation, Cambridge University Press 1999

Crystals, multilayers
hard X-rays



Bragg law

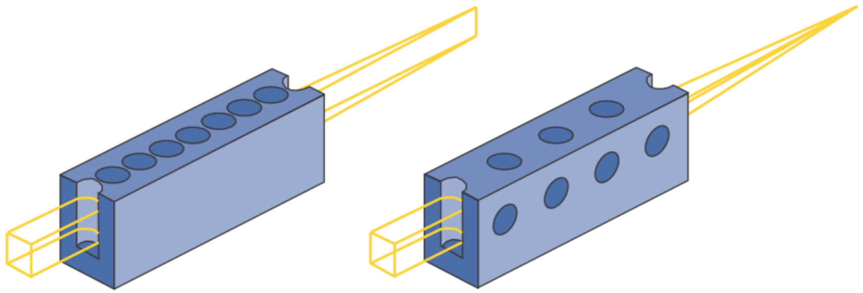
$$n\lambda = 2\frac{a}{\sqrt{h^2 + k^2 + l^2}} sin\theta$$

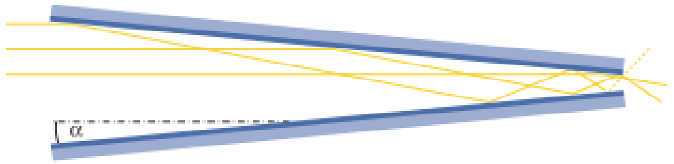


bent crystals/gratings
Rowland circle geometry

Attwood D. Soft X-Rays and Extreme Ultraviolet Radiation, Cambridge University Press 1999

$$f = R/2n_h\delta$$

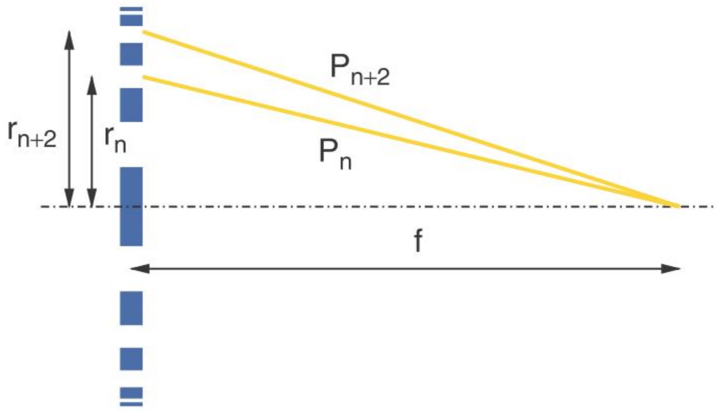


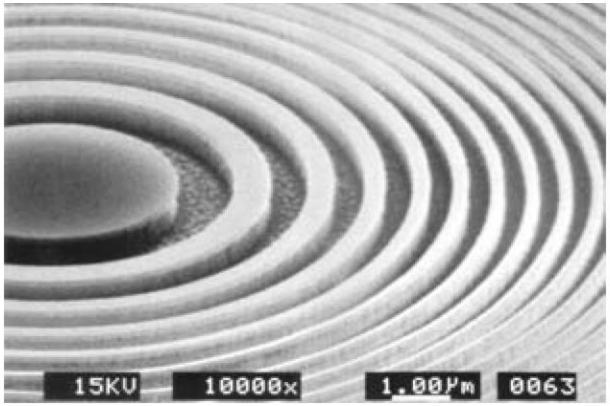


Compound refractive lenses
hard X-rays

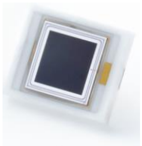
Coated glass capilary
hard X-rays

Fresnel zone plates
soft X-rays





Willmott P. An Introduction to Synchrotron Radiation, Willey 2011



- Ionization chambers
- Scintilators
- Si/Ge pin diodes
- Silicon drift detectors (SDD)
- Avalanche photodiode (APD)
- Position sensitive detectors (PSD)

- *Photocurent*
- *Drain current*
- *Phosphor screen + CCD*
- *….*

www.ketek.net; www.dectris.com; www.hamamatsu.com; www.canberra.com

Outline

Development of SR sources

Properties of SR, instrumentation

Applications of SR
- *diffraction*
- *imaging*
- *spectroscopy*

Applications to magnetism
- *magnetic structure*
- *element selective magnetometry*
- *magnetic imaging*
- *time resolved study*
- *extreme conditions*

Applications of synchrotron radiation

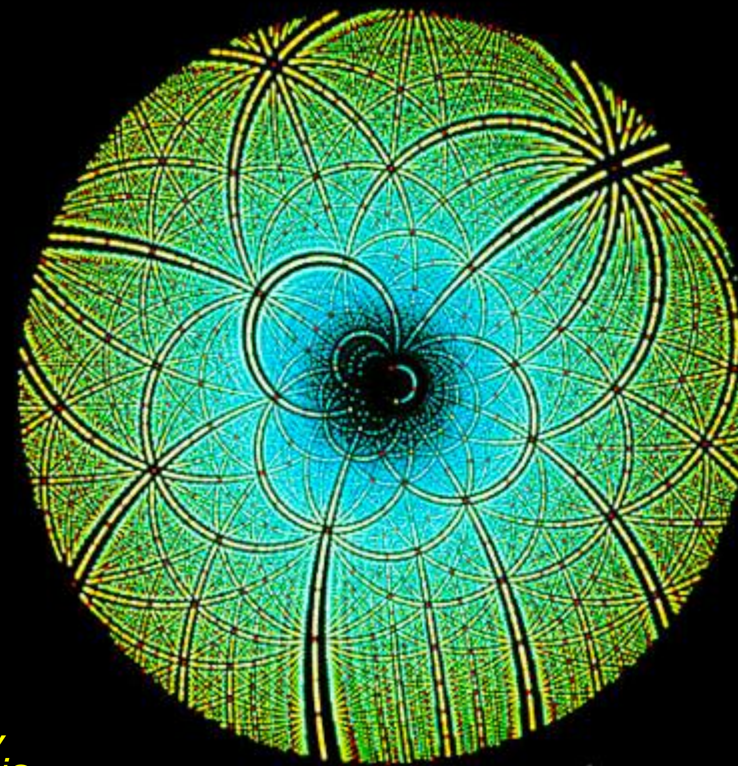
X-ray diffraction

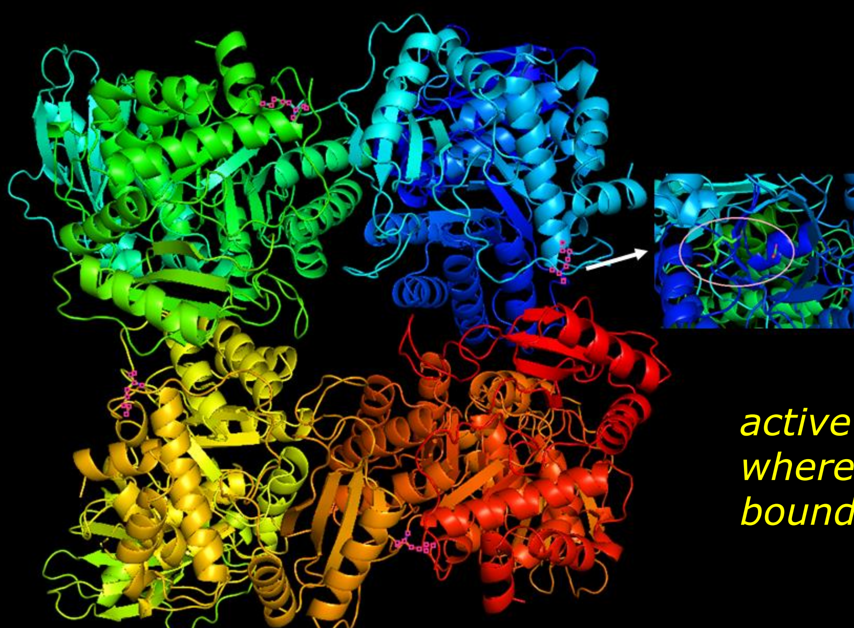
Vimeo.com/diamondlightsource

Applications of synchrotron radiation

Crystal structure of proteins

e.g. RuBisCO enzyme





active sites, where CO_2 is bound

www.wikipedia.org

Applications of synchrotron radiation

Time resolved and in-situ study

Release of oxygen from Myoglobine protein

Courtesy: esrf.eu

Applications of synchrotron radiation

Phase contrast image

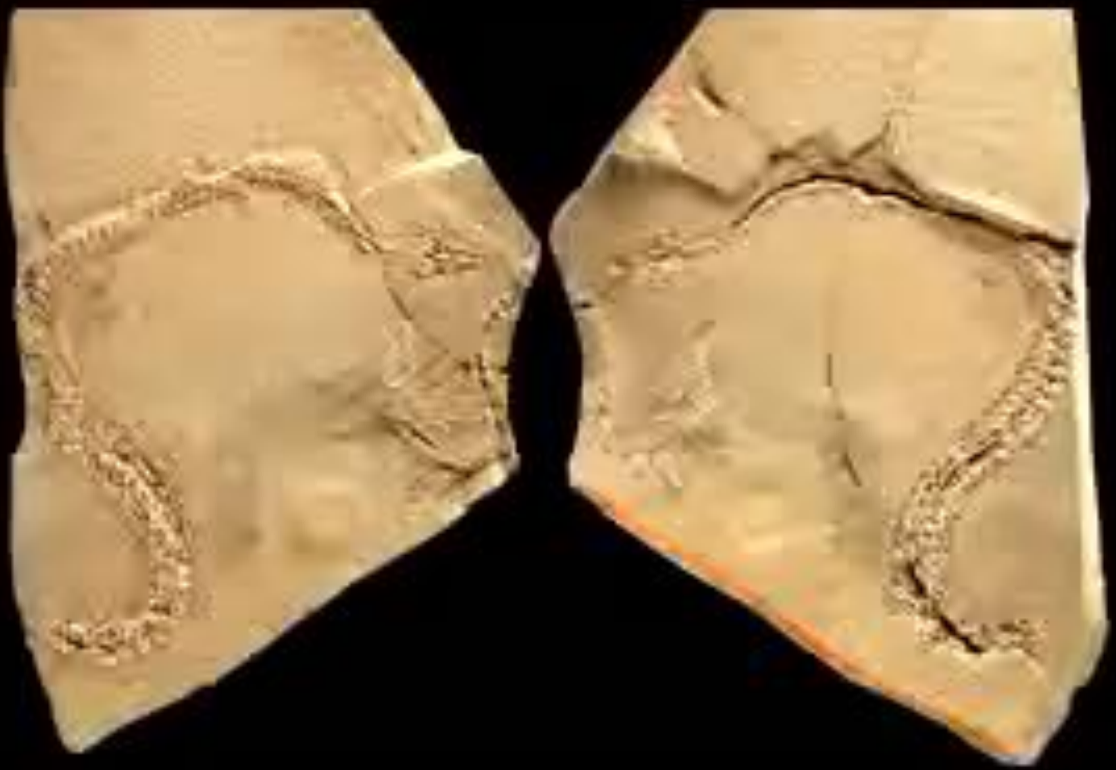
Coherent photon beam
~20μm lateral size
up to 150m projection

Contrast due to small variations of refractive index

Courtesy: esrf.eu

Applications of synchrotron radiation

Phase contrast tomography

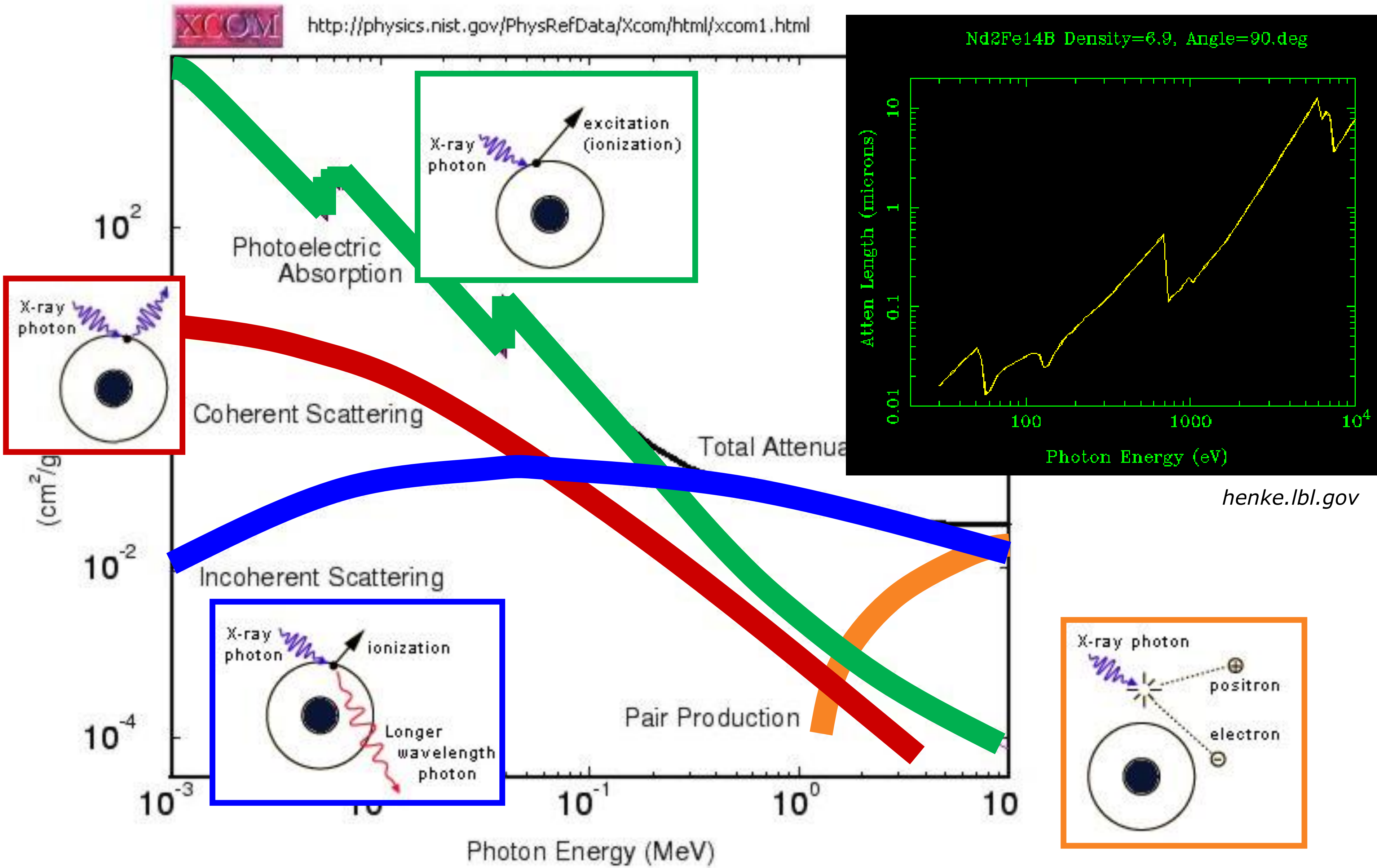


Non-destructive testing of fossils

e.g. anatomical details of ancient snakes

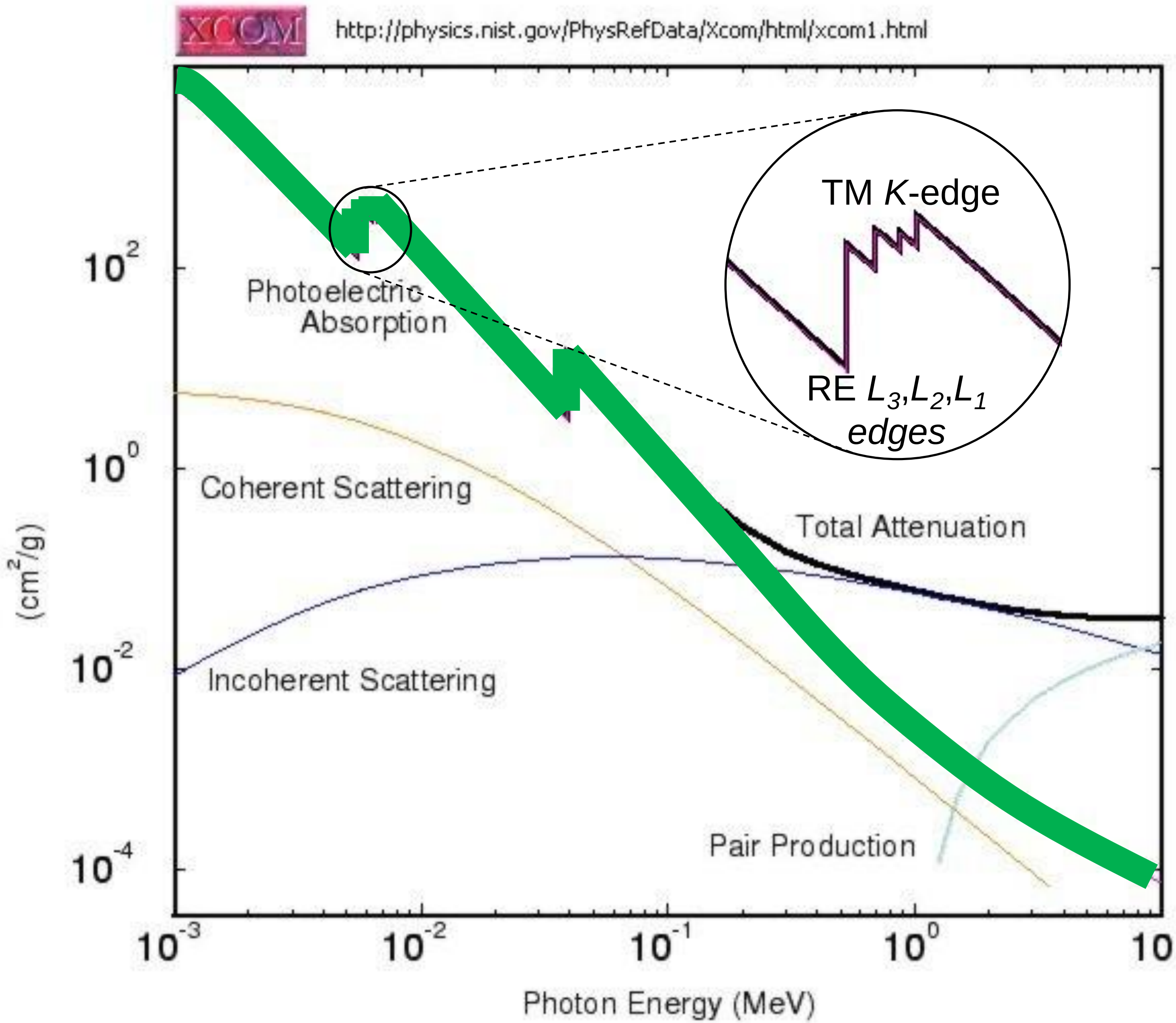
Courtesy: esrf.eu

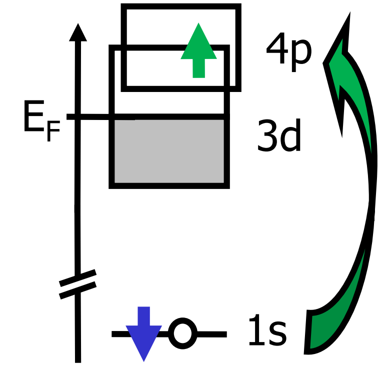
Interaction of X-rays with matter



henke.lbl.gov

X-ray absorption





Dipol selection rules:

$\Delta l = \pm 1$

$\Delta j = \pm 1 \; or \; 0$

$\Delta s = 0$

Element selective *& symmetry sensitive probe of unoccupied electronic structure*

Magnetic scattering and absorption

Atomic form factor

$$f = f_0 + f'(E) + if''(E)$$

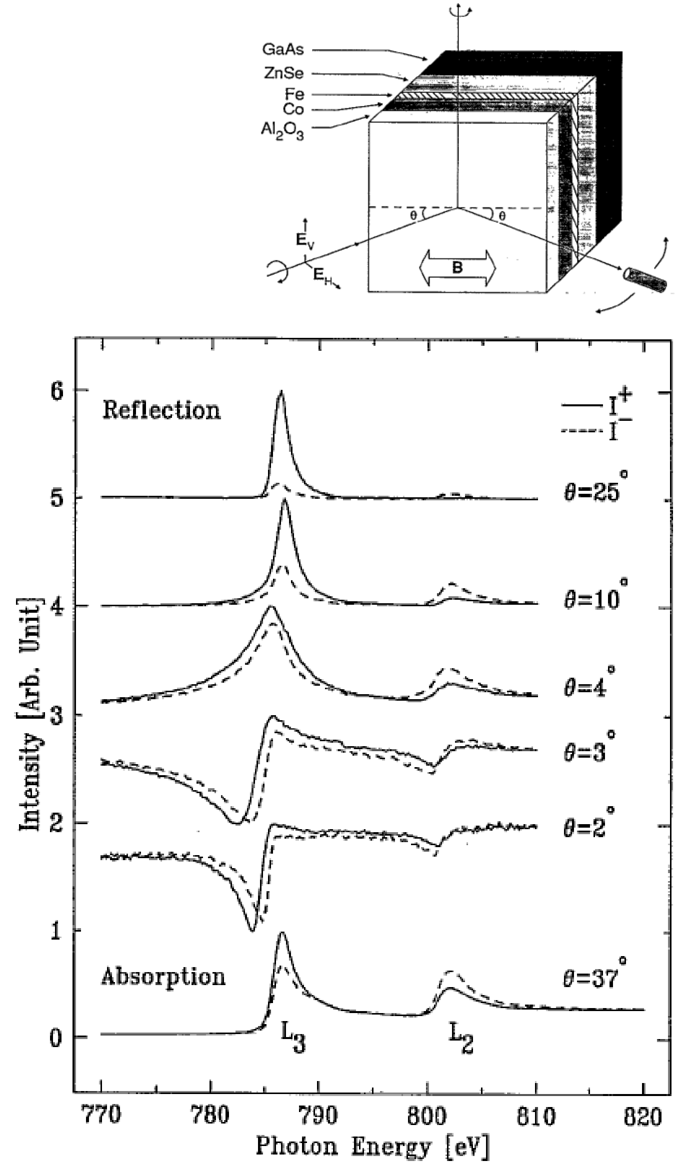
Elastic *Reflectivity* *Absorption*

Magnetic vs. charge scattering

$$f_{magnetic} \sim \frac{f_{charge}}{10^{2\div4}}$$

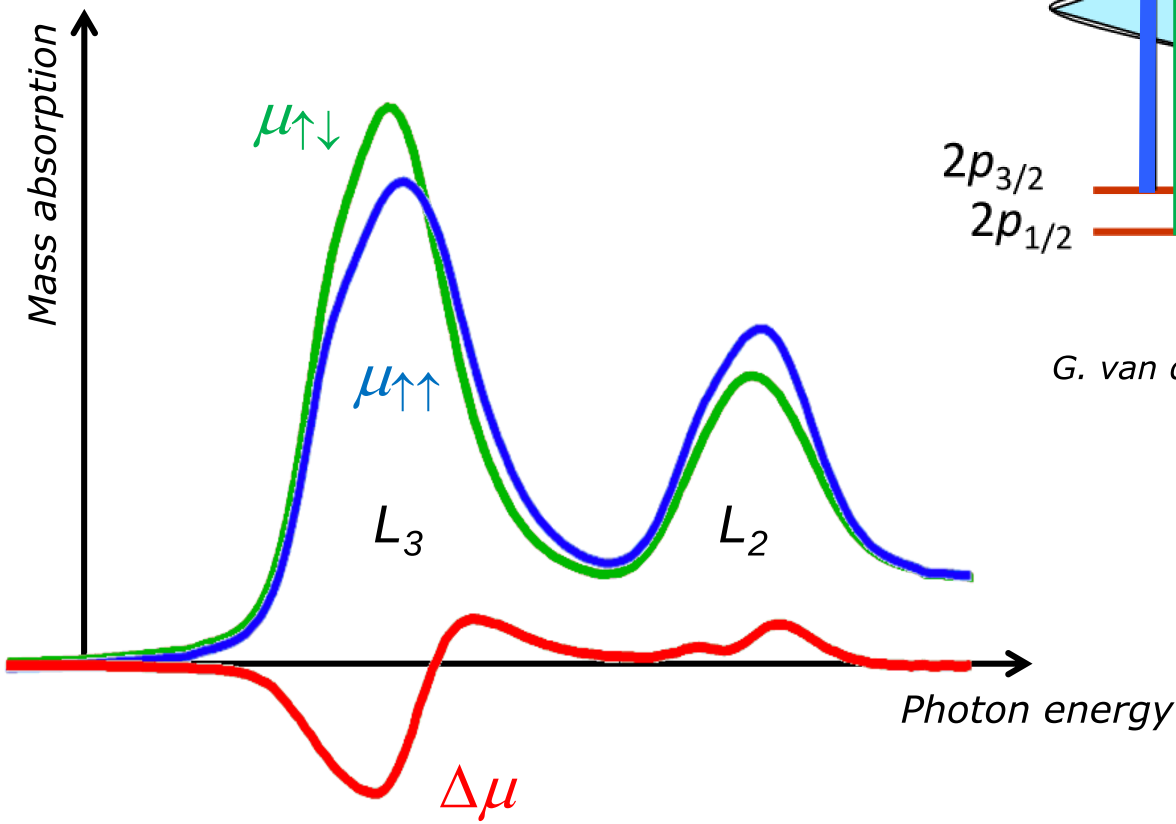
$$f_{magnetic} \sim \mathbf{A}\cdot\mathbf{L} + \mathbf{B}\cdot\mathbf{S}$$

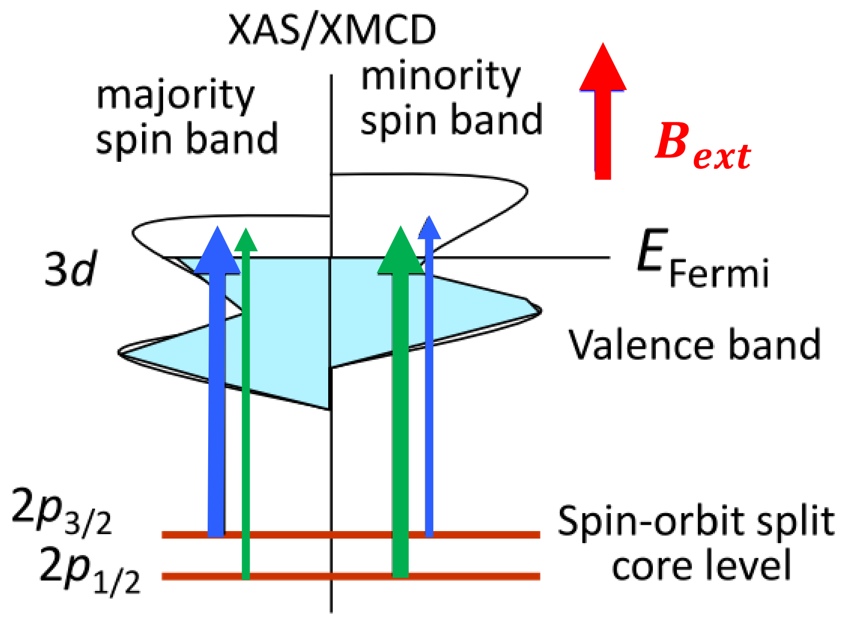
Orbital *Spin*



C.C. Kao at al., Phys. Rev. B (1994)

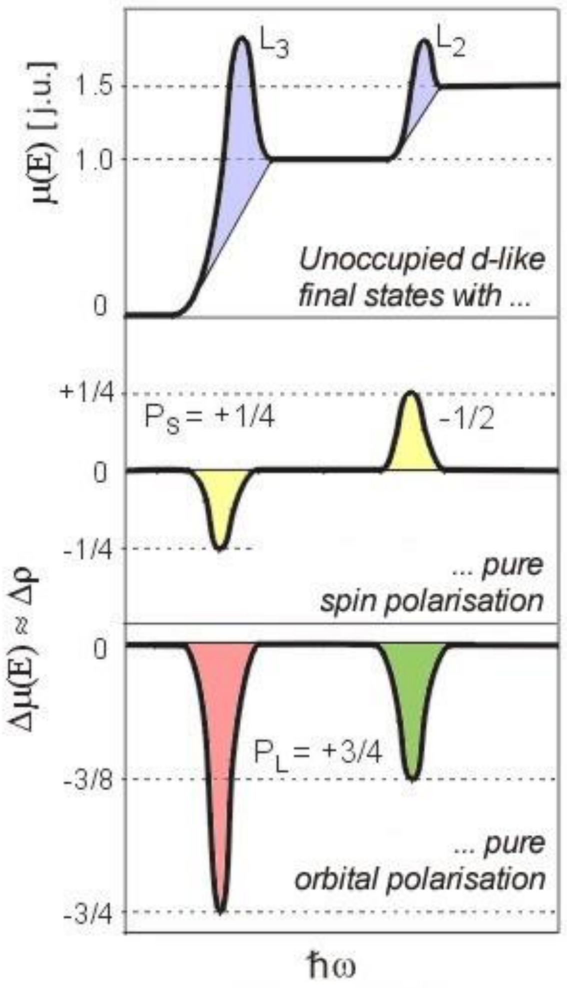
X-ray magnetic circular dichroism





G. van der Laan, J. Phys.: Conf. Series (2013)

Sum rules



B.T.Thole et al., PRL 68 (1992) 1943
P.Carra et al., PRL 70 (1993) 694

$$L_z = -(4/3)\cdot n \cdot \frac{\int_{L_3+L_2} (\Delta\mu)\, dE}{\int_{L_3+L_2} (\mu_0)\, dE}$$

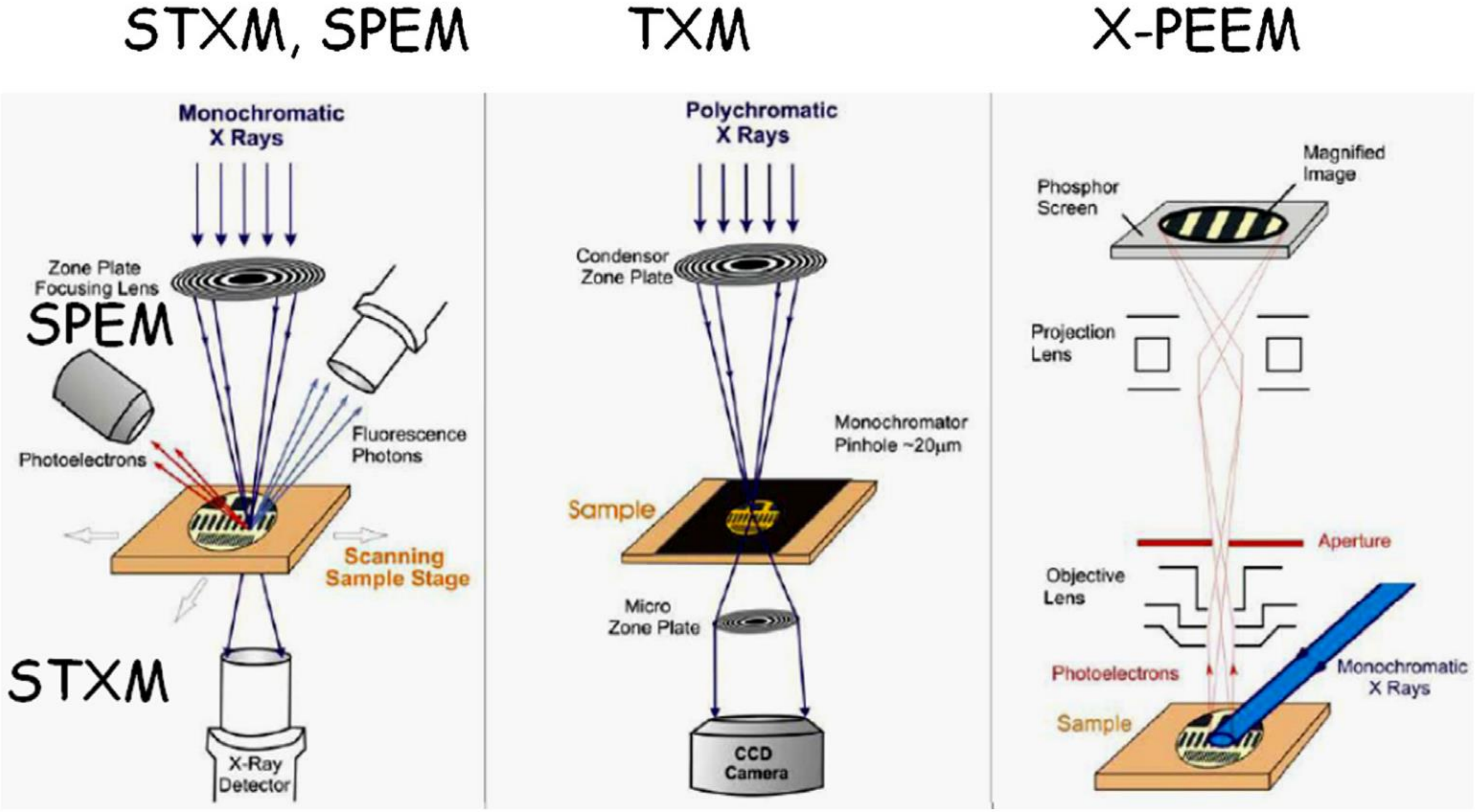
$$S_z = -n \cdot \frac{\int_{L_3} (\Delta\mu)\, dE - 2\int_{L_2} (\Delta\mu)\, dE}{\int_{L_3+L_2} (\mu_0)\, dE}$$

where ***n*** denotes the number of holes in the final states

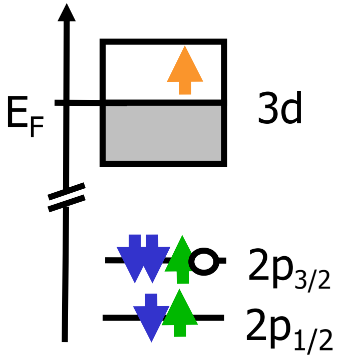
Enable to separate spin and orbital moments

Magnetic X-ray microscopy

XMCD using ultrasmall X-ray beam or magnification optics
& position sensitive detector for photons/photoelectrons

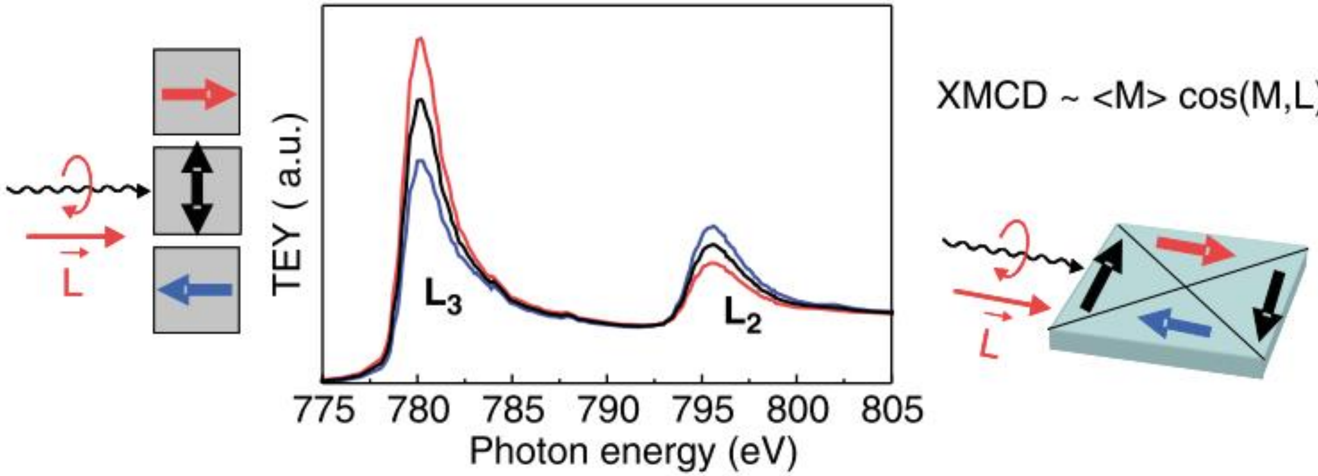


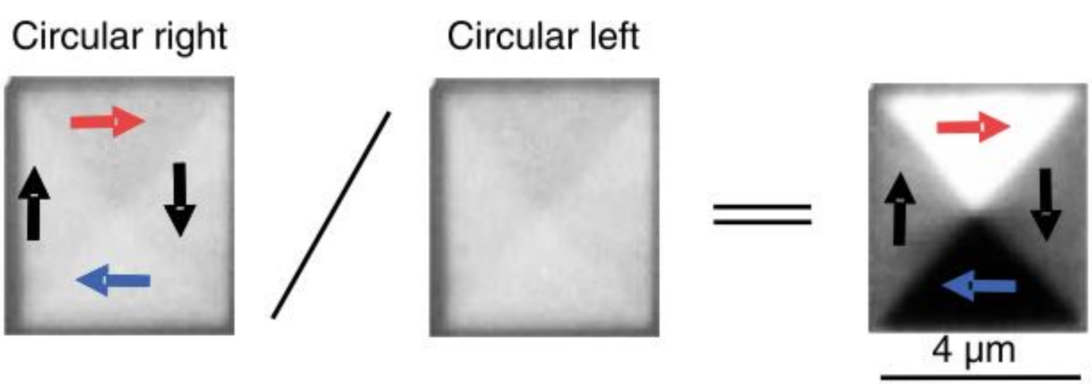
A.P. Hitchcock, J. Electron Spectrosc. Relat. Phenom. (2015)



Magnetic X-ray microscopy

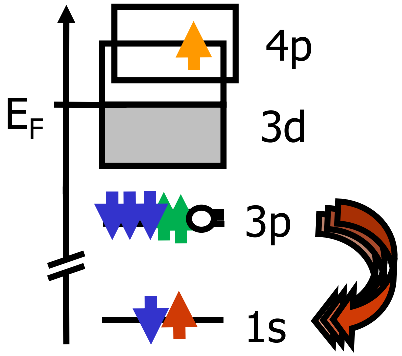
XMCD contrast proportional to the magnetization projection on incoming photon direction





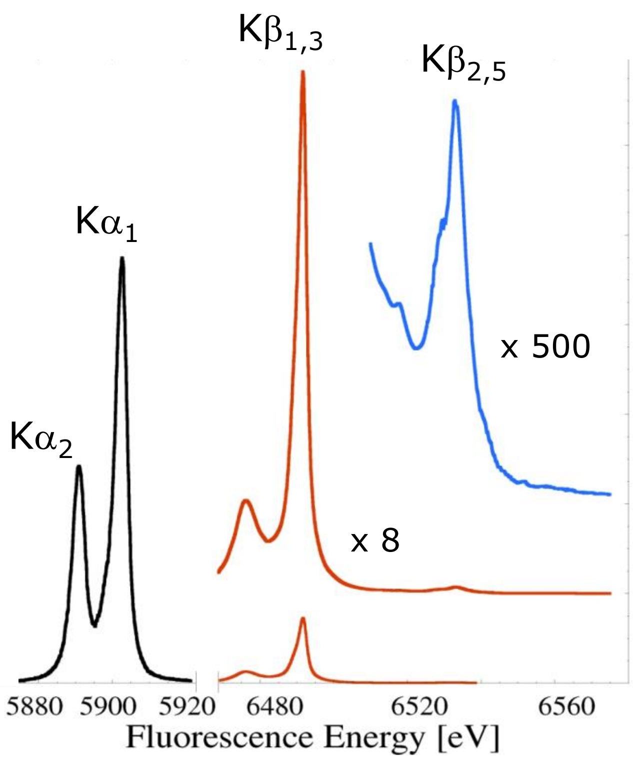
F. Noltig in Magnetism and Synchrotron Radiation New Trends, Springer 2010

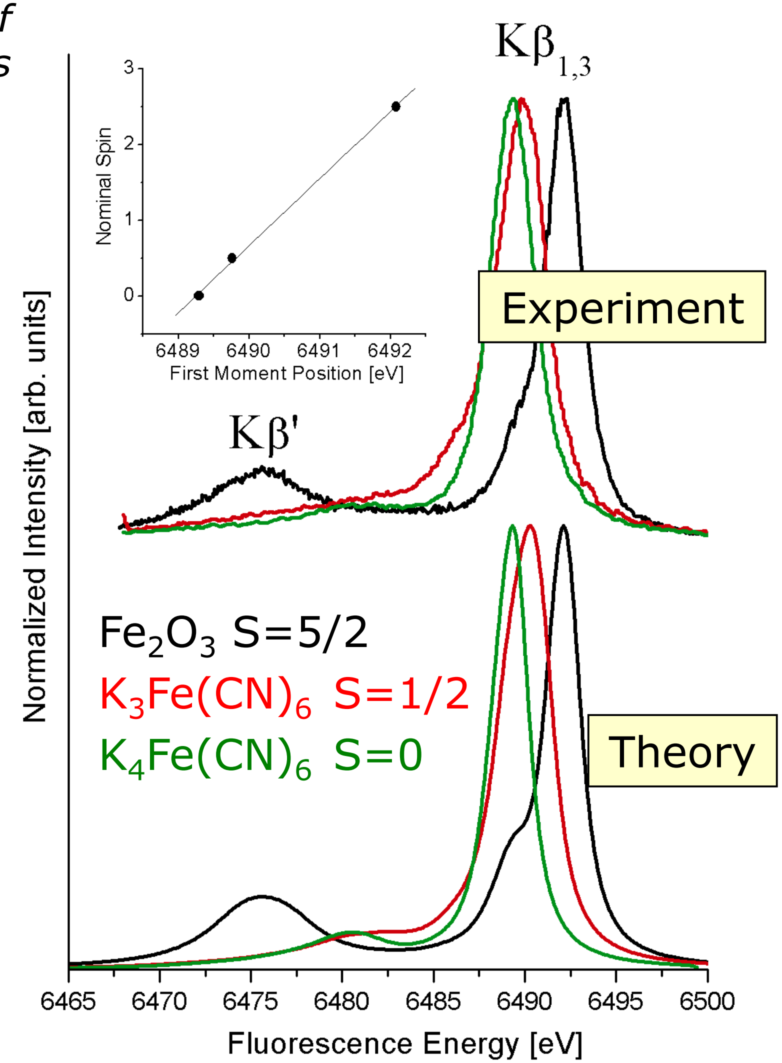
X-ray Emission



Similar information to XPS, but for** (diluted, insulating, buried …) **bulky samples

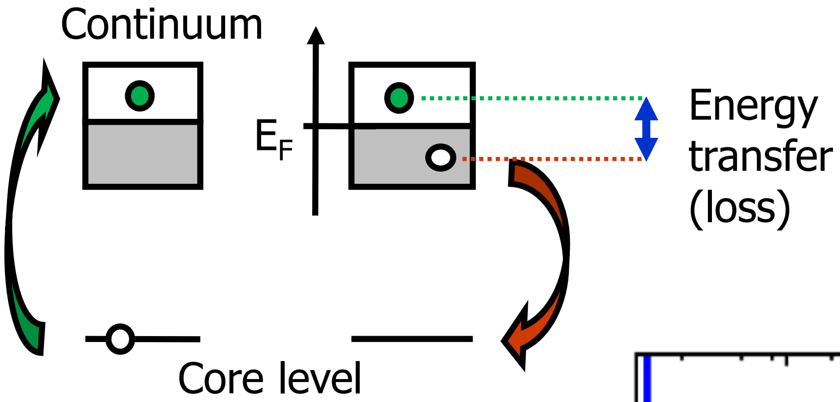
Sensitive to nominal spin of transition metals

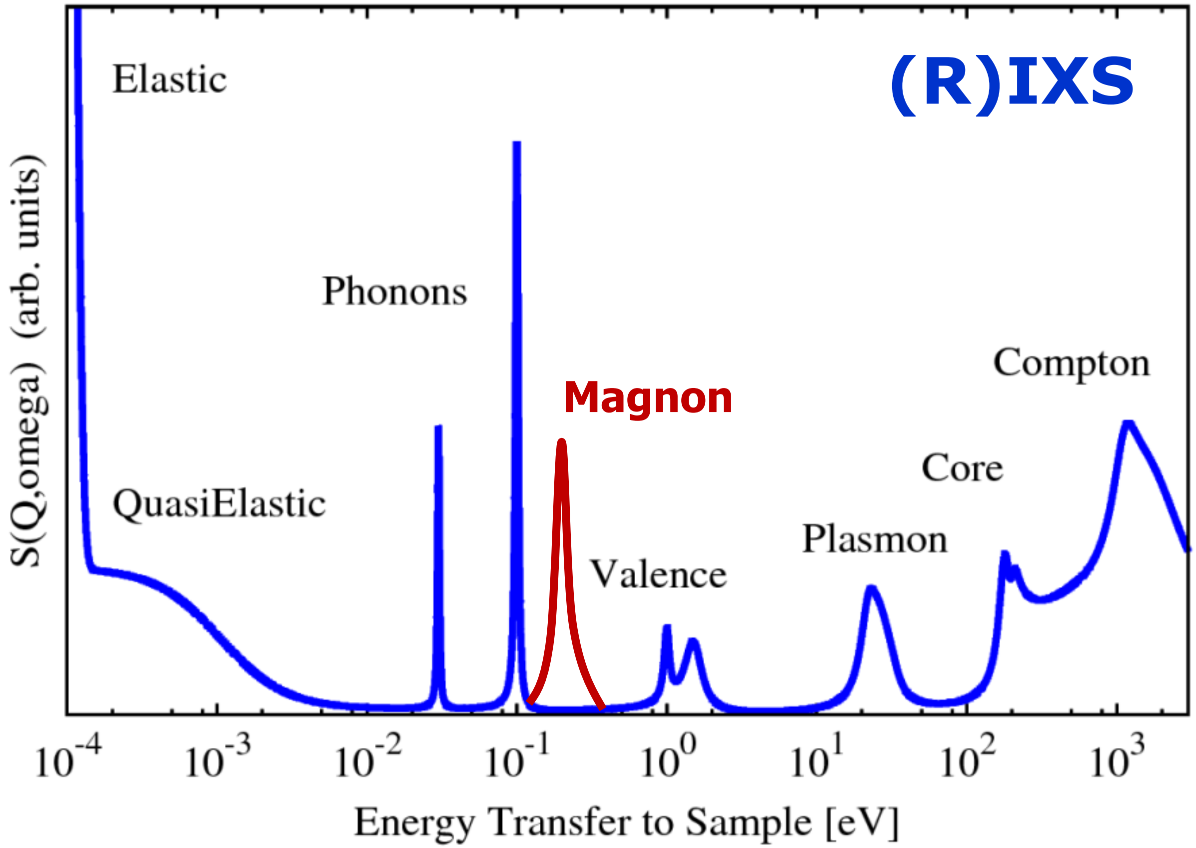




P.Glatzel & U.Bergmann, Coord. Chem. Rev. (2005)

(Resonant) Inelastic X-ray Scattering



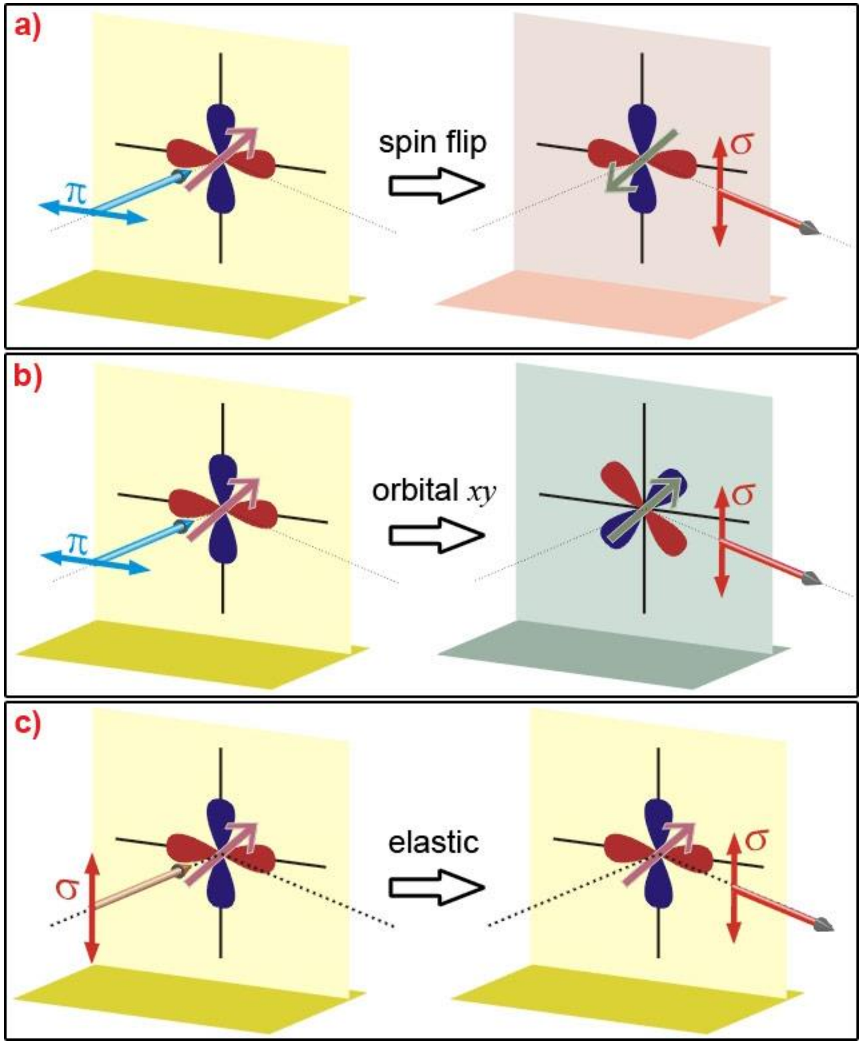


High resolution probe of elementary excitations including Q dependence

A.Baron, arxiv.org/1504.01098

Resonant (Inelastic) X-ray Scattering

Complete polarisation analysis allows to disentangle the origin of elementary excitation probed:



magnon

orbital (d-d) excitation

elastic scattering

L. Ament *et al.*, *Phys. Rev. Lett.* (2009)

Outline

Development of SR sources

Properties of SR, instrumentation

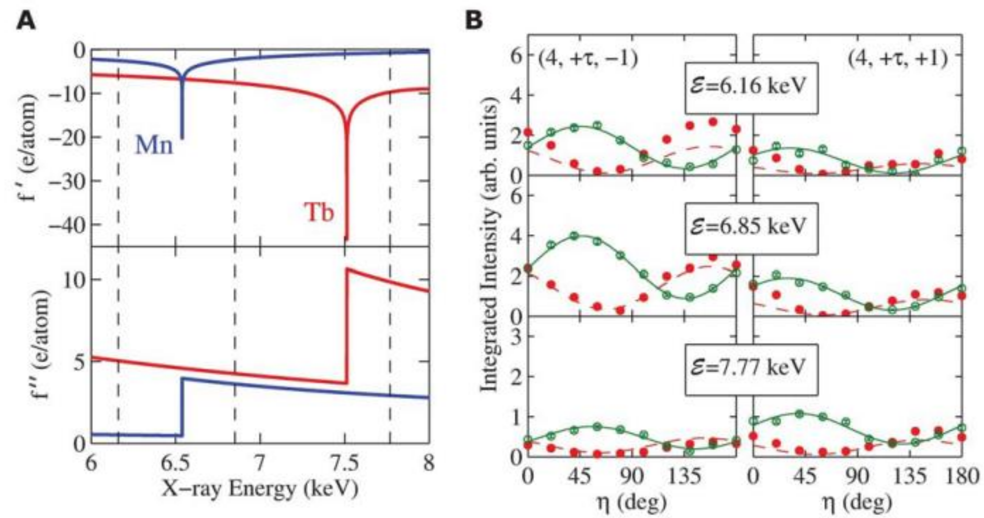
Applications of SR
- *diffraction*
- *imaging*
- *spectroscopy*

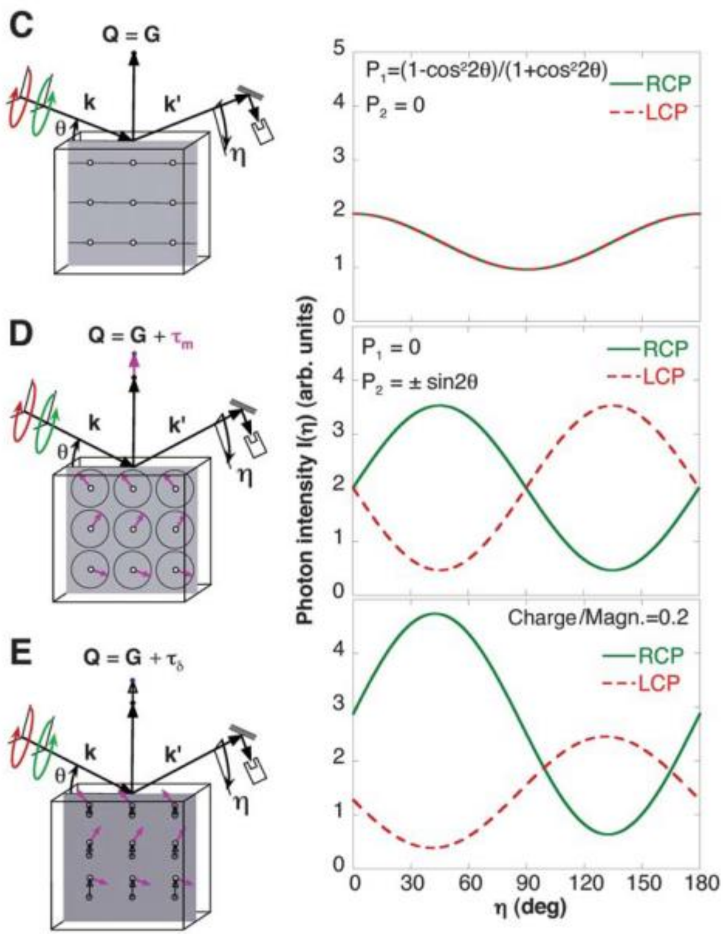
Applications to magnetism
- *magnetic structure*
- *element selective magnetometry*
- *magnetic imaging*
- *time resolved study*
- *extreme conditions*

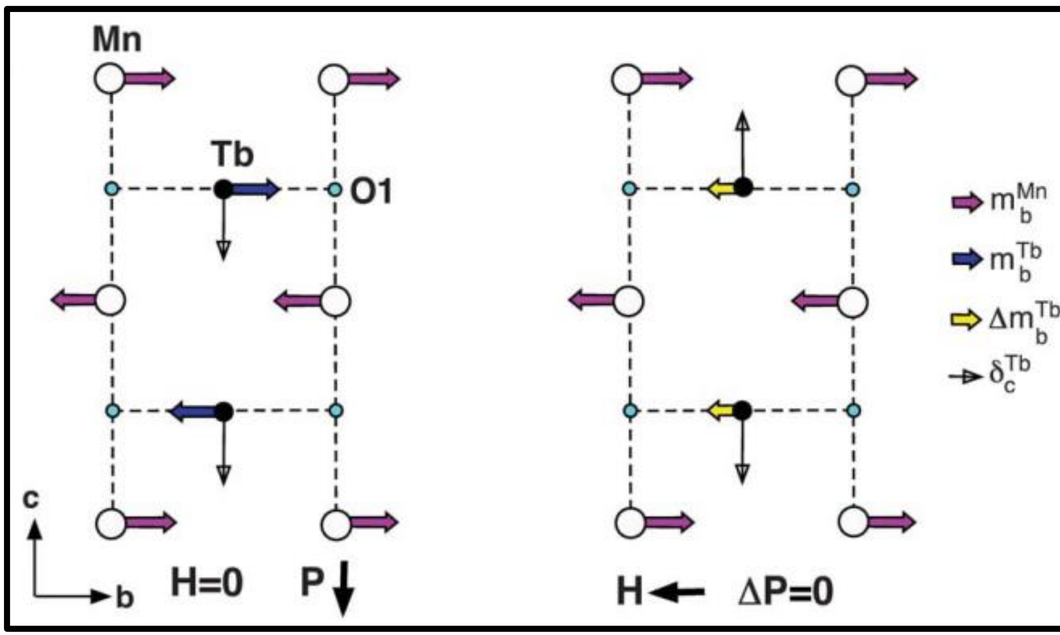
Magnetic diffraction

Femtoscale Magnetically Induced Lattice Distortions in Multiferroic $TbMnO_3$

H. C. Walker,[1]* F. Fabrizi,[1,2,3] L. Paolasini,[1] F. de Bergevin,[1] J. Herrero-Martin,[1] A. T. Boothroyd,[3] D. Prabhakaran,[3] D. F. McMorrow[2]





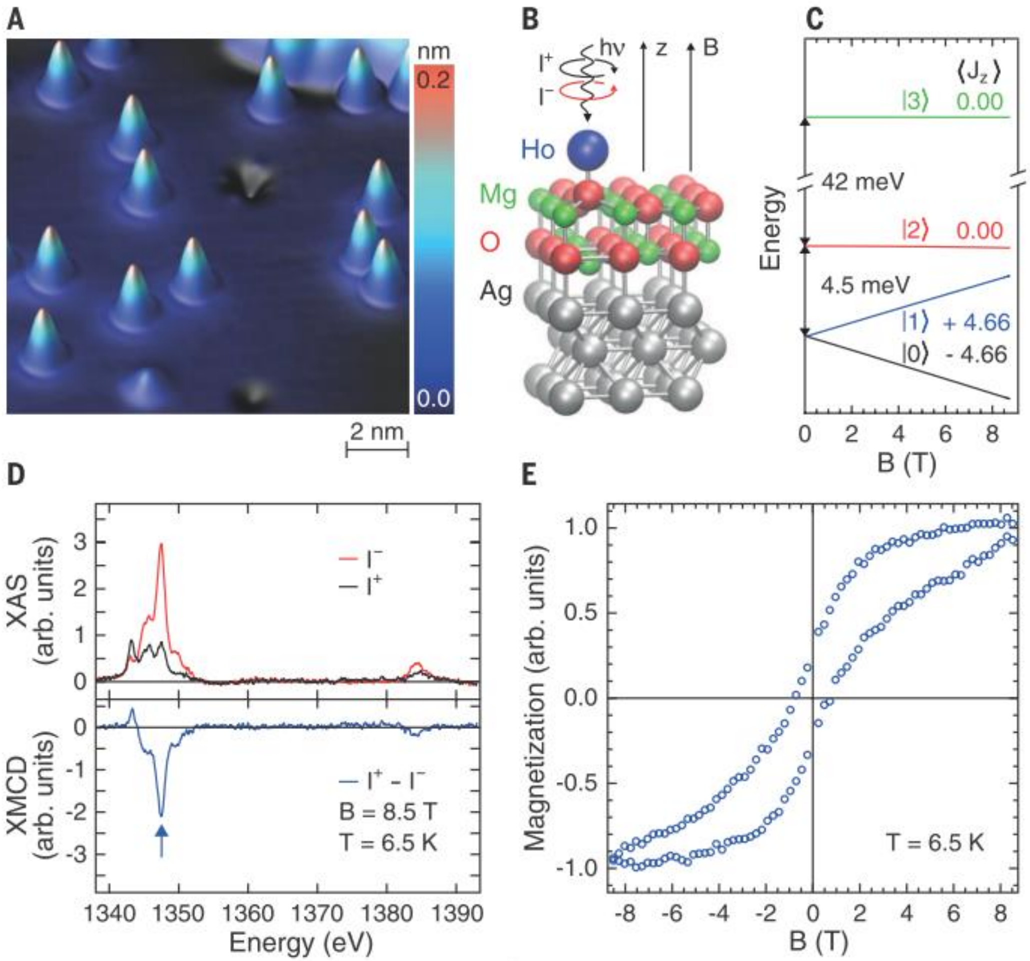


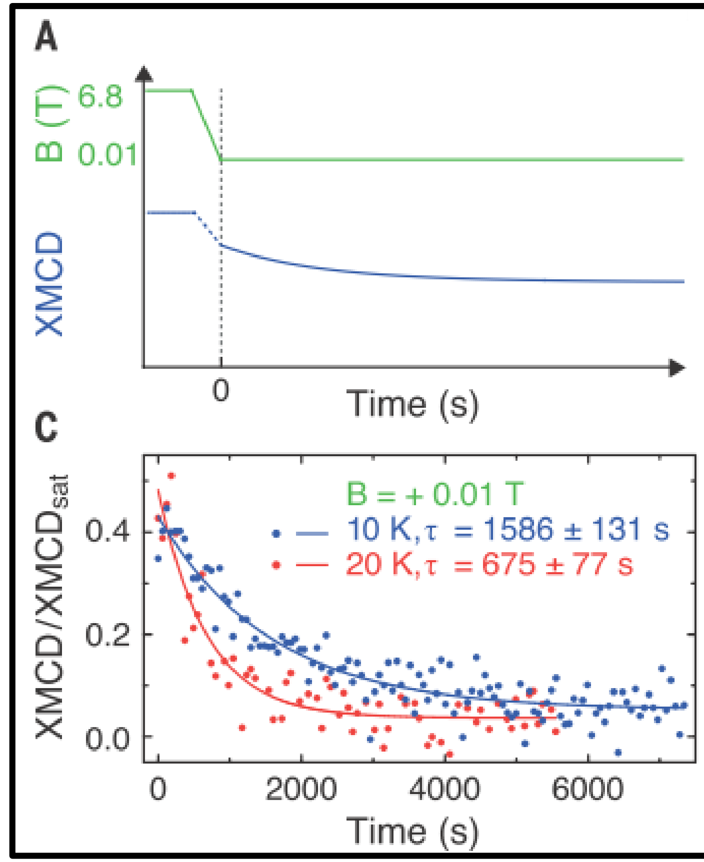
SCIENCE VOL 333 2 SEPTEMBER 2011 1273

Magnetic remanence in single atoms

XMCD spectroscopy

F. Donati,[1] S. Rusponi,[1] S. Stepanow,[2] C. Wäckerlin,[1] A. Singha,[1] L. Persichetti,[2] R. Baltic,[1] K. Diller,[1] F. Patthey,[1] E. Fernandes,[1] J. Dreiser,[1,3] Ž. Šljivančanin,[4,5] K. Kummer,[6] C. Nistor,[2] P. Gambardella,[2*] H. Brune[1*]





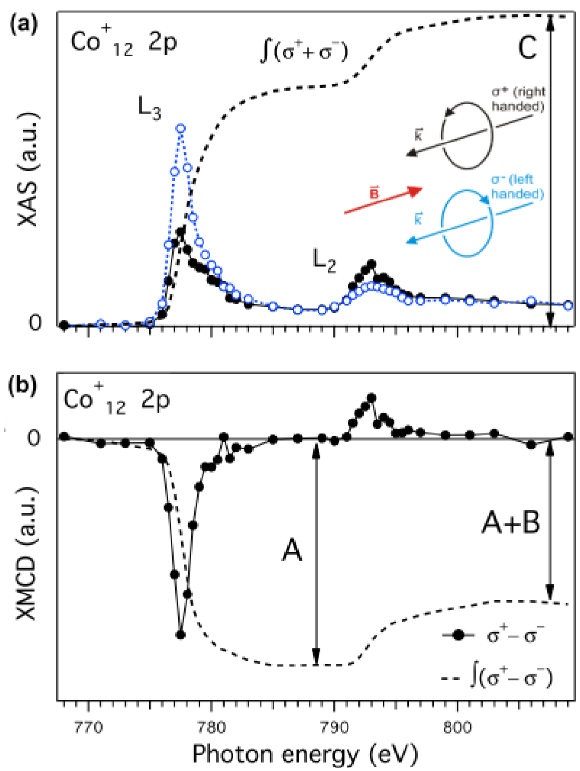
SCIENCE 15 APRIL 2016 • VOL 352 ISSUE 6283 319

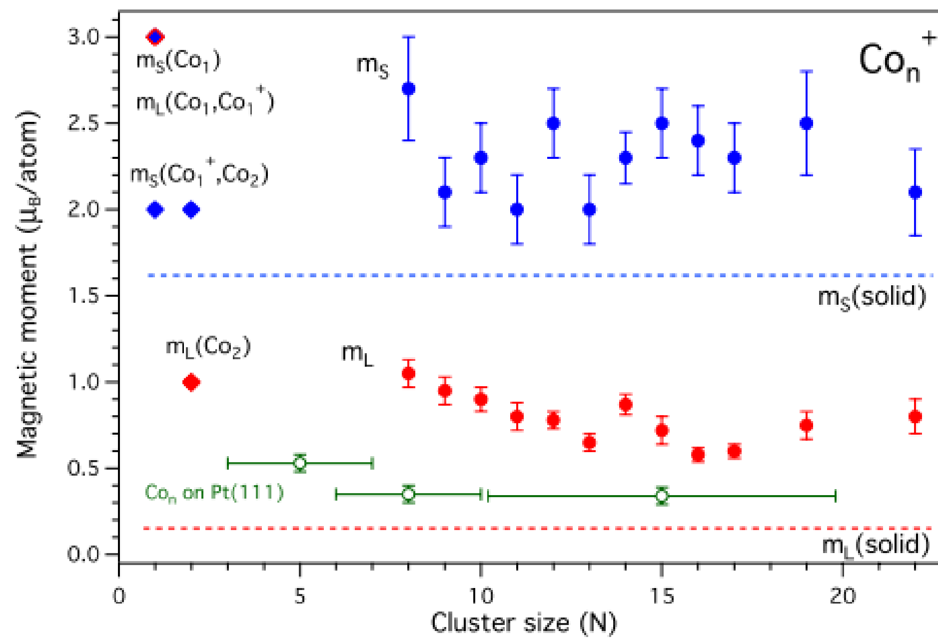
XMCD – sum rules

PRL 107, 233401 (2011) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2011

Spin and Orbital Magnetic Moments of Free Nanoparticles

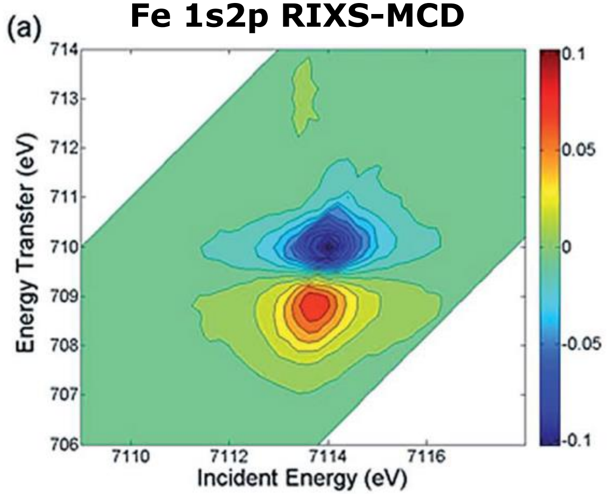
S. Peredkov,[1] M. Neeb,[2] W. Eberhardt,[1] J. Meyer,[3] M. Tombers,[3] H. Kampschulte,[3] and G. Niedner-Schatteburg[3]
[1]*Institut für Optik und Atomare Physik, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany*
[2]*Helmholtz-Zentrum Berlin für Materialien und Energie, BESSY II, Albert-Einstein-Strasse 15, 12489 Berlin, Germany*
[3]*Fachbereich Chemie und Forschungszentrum OPTIMAS, TU Kaiserslautern, 67663 Kaiserslautern, Germany*
(Received 27 June 2011; published 30 November 2011)





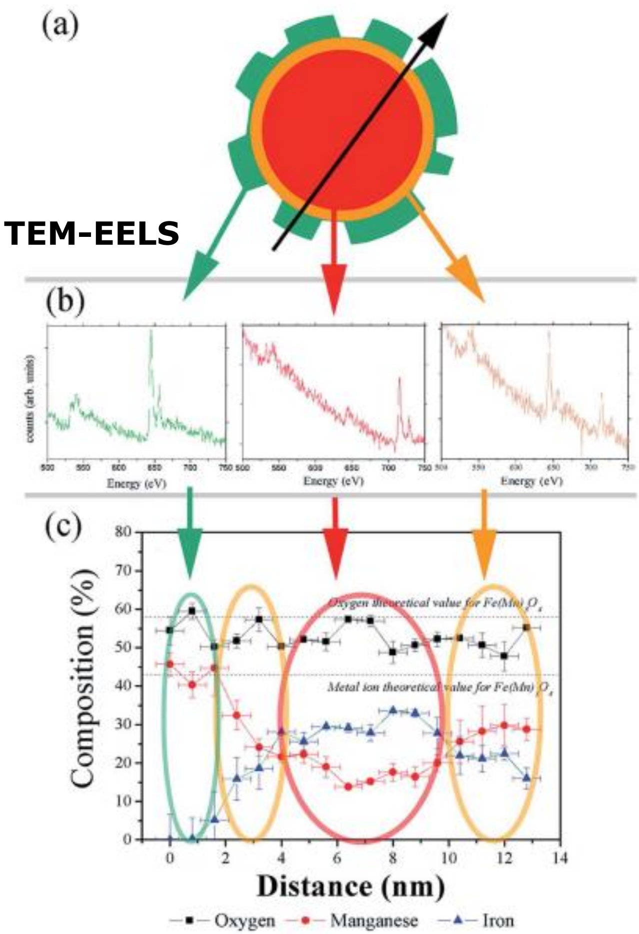
Element selective magnetometry

Fe 1s2p RIXS-MCD



Direct evidence for an interdiffused intermediate layer in bi-magnetic core–shell nanoparticles†

Amélie Juhin,*[a] Alberto López-Ortega,*[bc] Marcin Sikora,[d] Claire Carvallo,[a] Marta Estrader,[be] Sònia Estradé,[fg] Francesca Peiró,[f] Maria Dolors Baró,[h] Philippe Sainctavit,[a] Pieter Glatzel[i] and Josep Nogués[bhj]

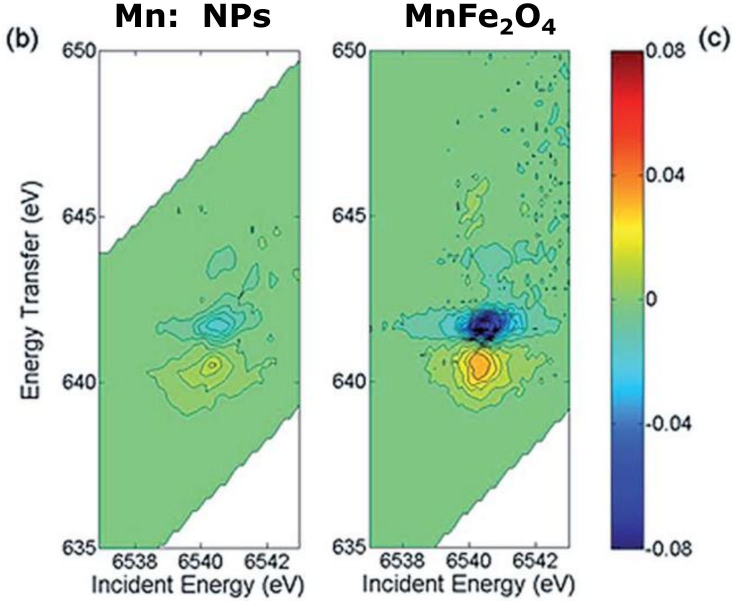


Mn_3O_4
d=0.3nm

$(MnFe)_3O_4$
d=1.1nm

γFe_2O_3
R=5.0nm

Mn: NPs $MnFe_2O_4$

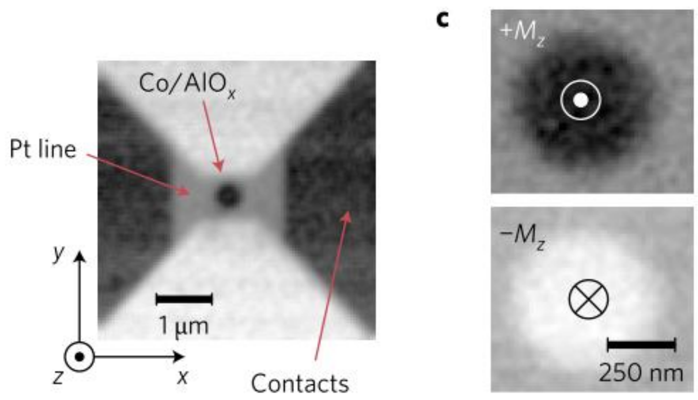


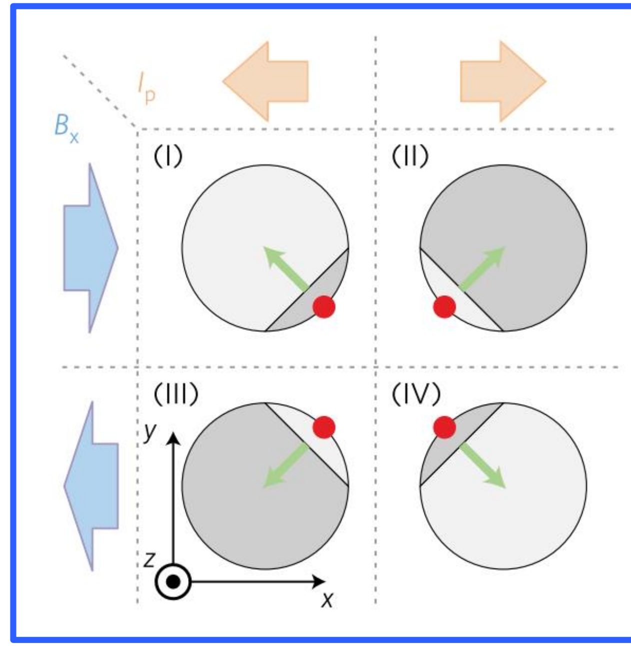
Nanoscale, 2014, **6**, 11911

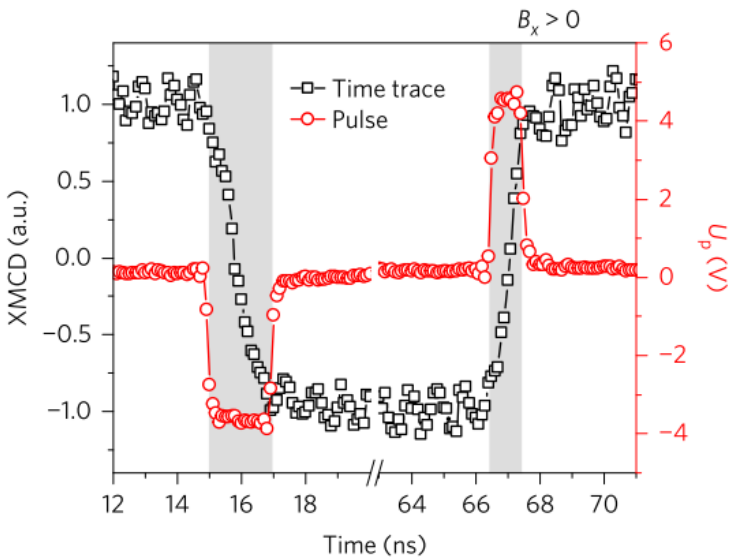
X-ray magnetic microscopy

Spatially and time-resolved magnetization dynamics driven by spin-orbit torques

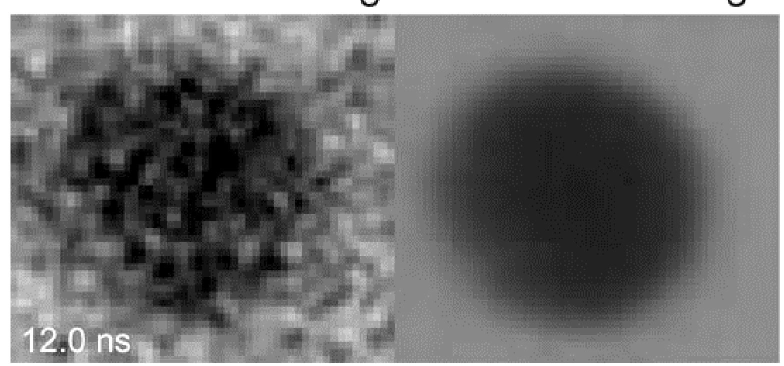
Manuel Baumgartner[1]*, Kevin Garello[1,2]*, Johannes Mendil[1], Can Onur Avci[1], Eva Grimaldi[1], Christoph Murer[1], Junxiao Feng[1], Mihai Gabureac[1], Christian Stamm[1], Yves Acremann[3], Simone Finizio[4], Sebastian Wintz[4], Jörg Raabe[4] and Pietro Gambardella[1]*







SOT-induced magnetization switching



B_x = -124 mT, τ_p = 2 ns, U_P = ± 4 V

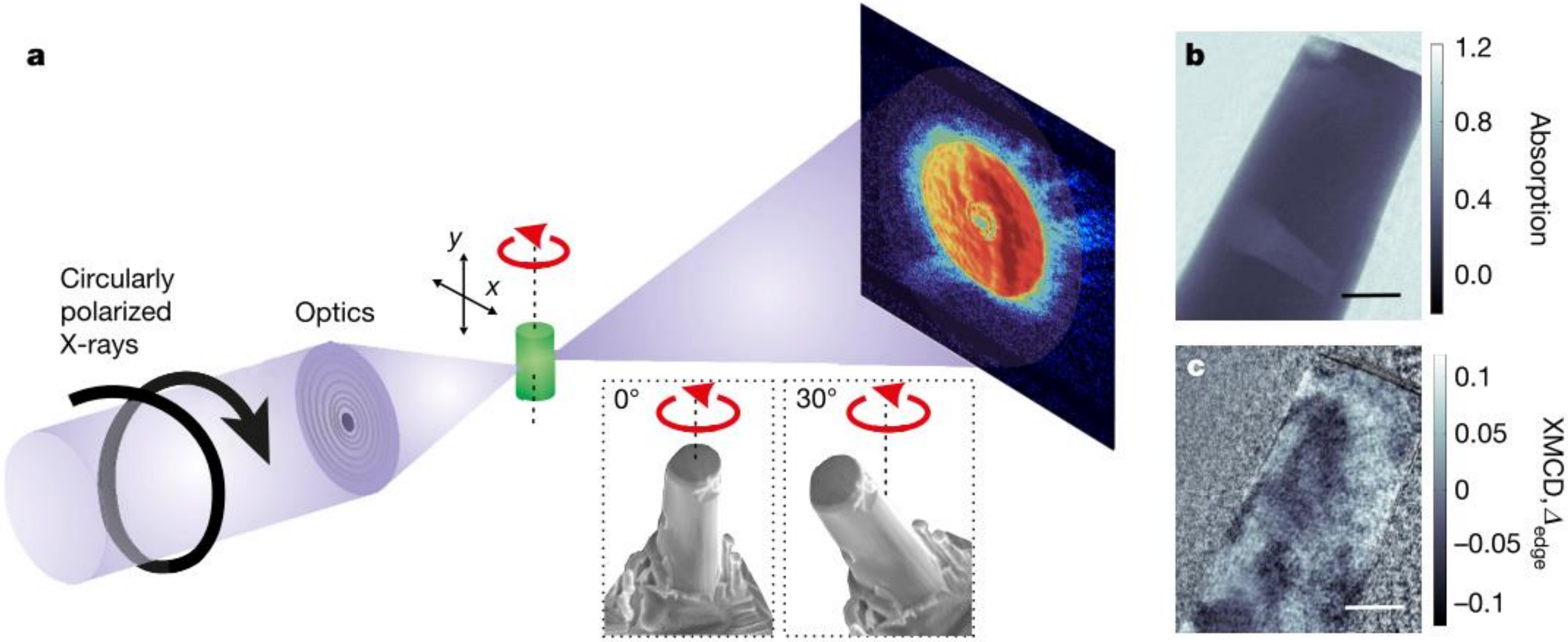
Nature Nanotechnology 12 (2017) 980

Three-dimensional magnetization structures revealed with X-ray vector nanotomography

Claire Donnelly[1,2], Manuel Guizar-Sicairos[2], Valerio Scagnoli[1,2], Sebastian Gliga[3], Mirko Holler[2], Jörg Raabe[2] &
Laura J. Heyderman[1,2]

Tomography

Magnetization topology inside $GdCo_2$ nanopillar



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Three-dimensional magnetization structures revealed with X-ray vector nanotomography

Claire Donnelly[1,2], Manuel Guizar-Sicairos[2], Valerio Scagnoli[1,2], Sebastian Gliga[3], Mirko Holler[2], Jörg Raabe[2] & Laura J. Heyderman[1,2]

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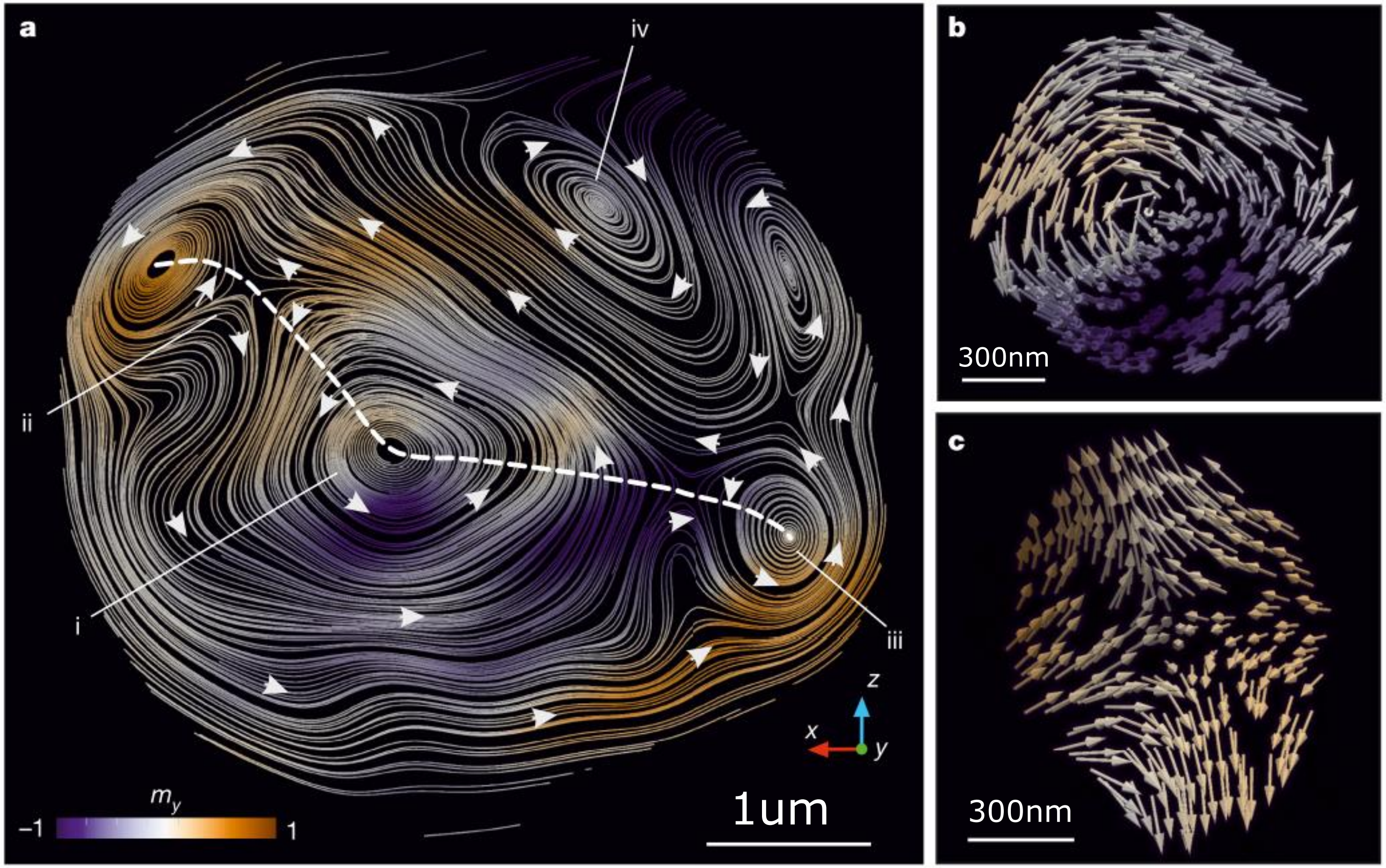
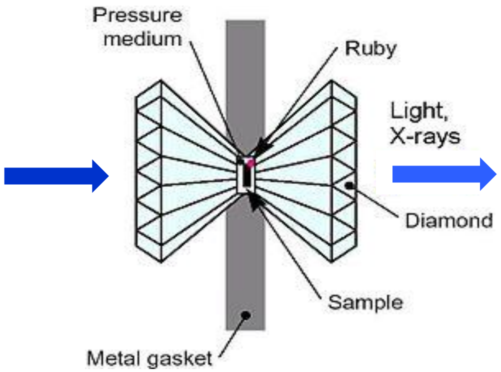
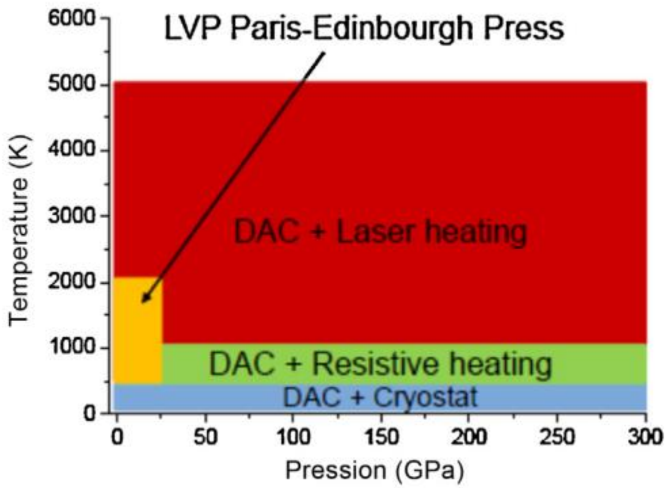


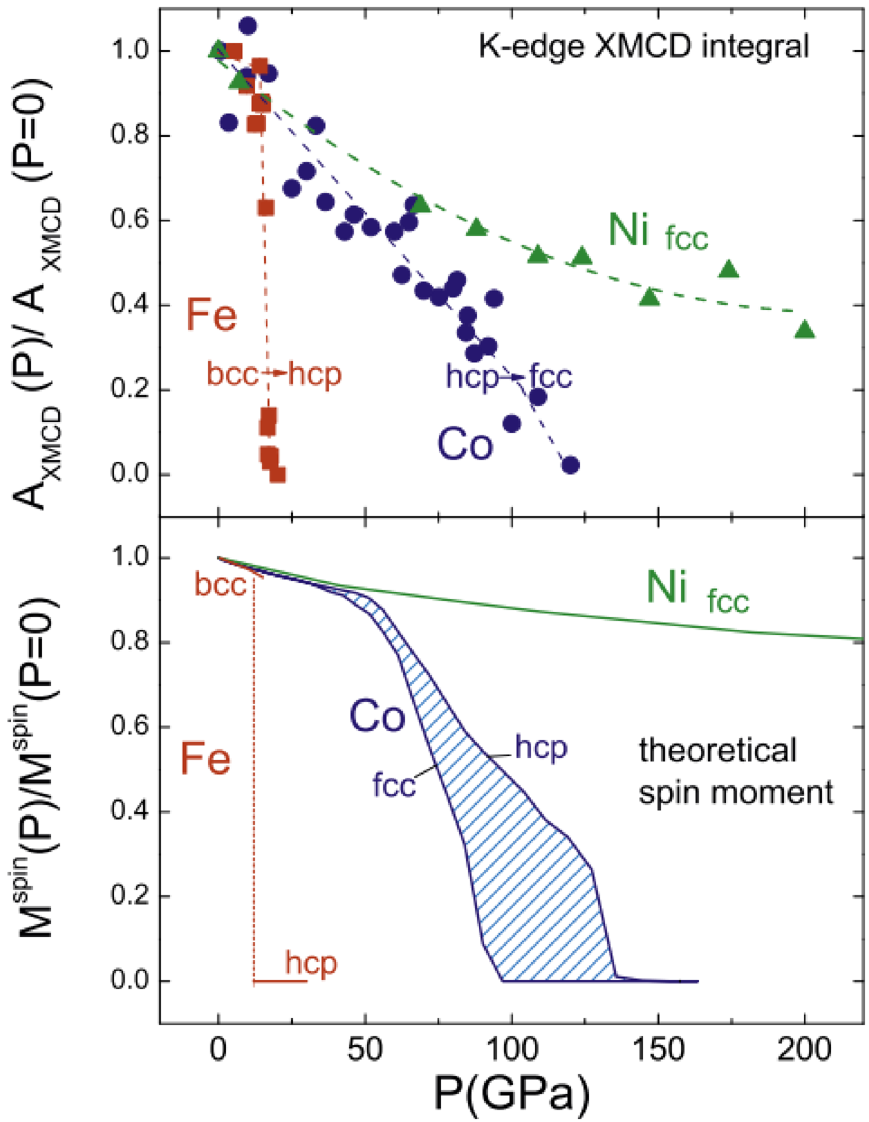
328 | NATURE | VOL 547 | 20 JULY 2017

Extreme conditions

www.esrf.eu





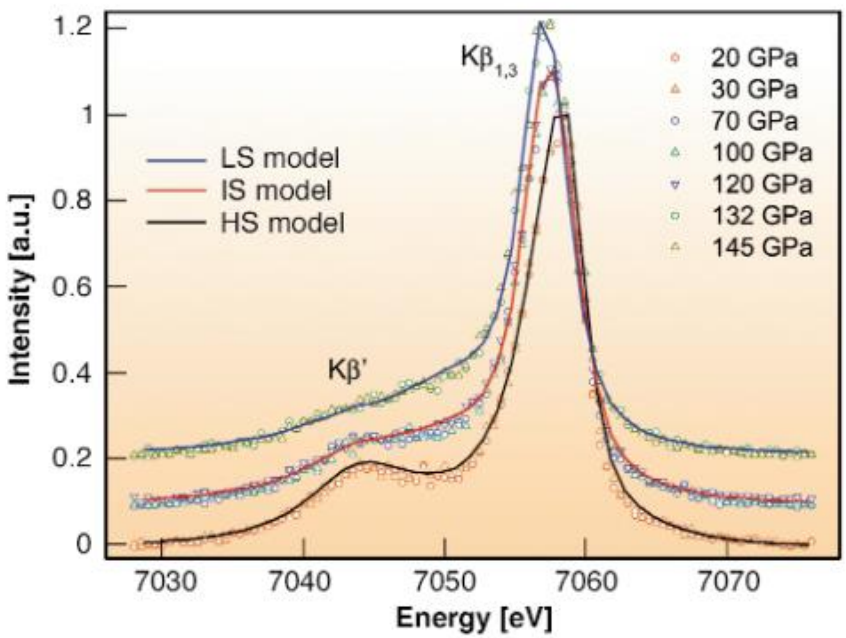


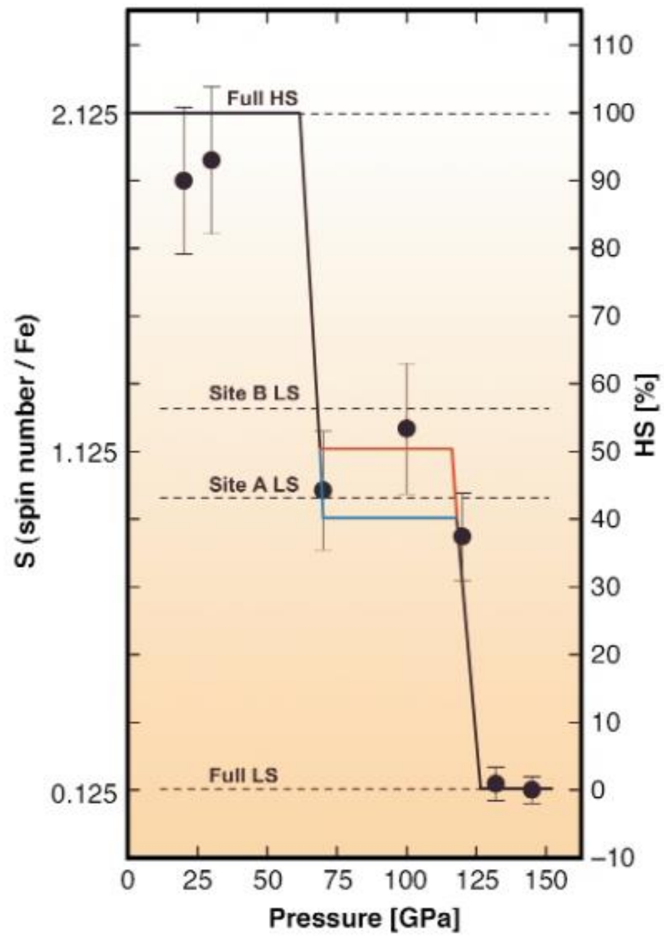
R. Torchio et al., Coordination Chem. Rev. (2014)

Electronic Transitions in Perovskite: Possible Nonconvecting Layers in the Lower Mantle

James Badro,[1]* Jean-Pascal Rueff,[2] György Vankó,[3]
Giulio Monaco,[3] Guillaume Fiquet,[1] François Guyot[1]

$Mg_{0.9}Fe_{0.1}SiO_3$





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Further reading

For regional synchrotron schools and specialized workshops check regularly at www.lightsources.org, www.calipso.eu and www.ceric-eric.eu