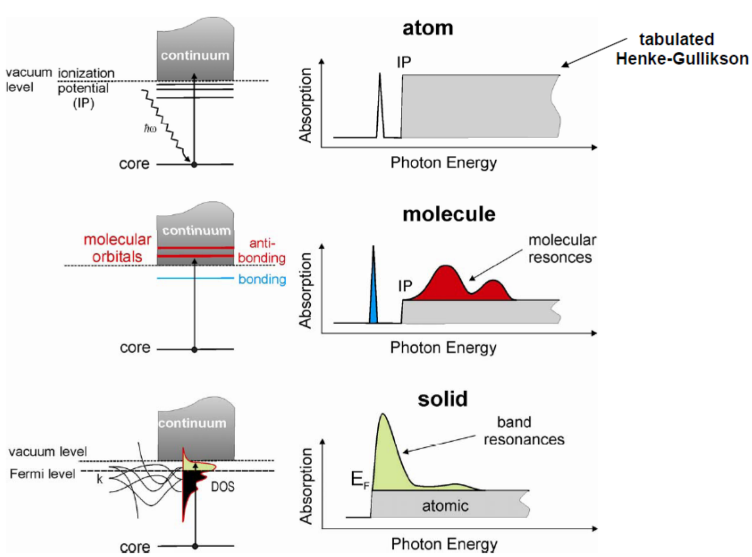
Surface Science Lecture

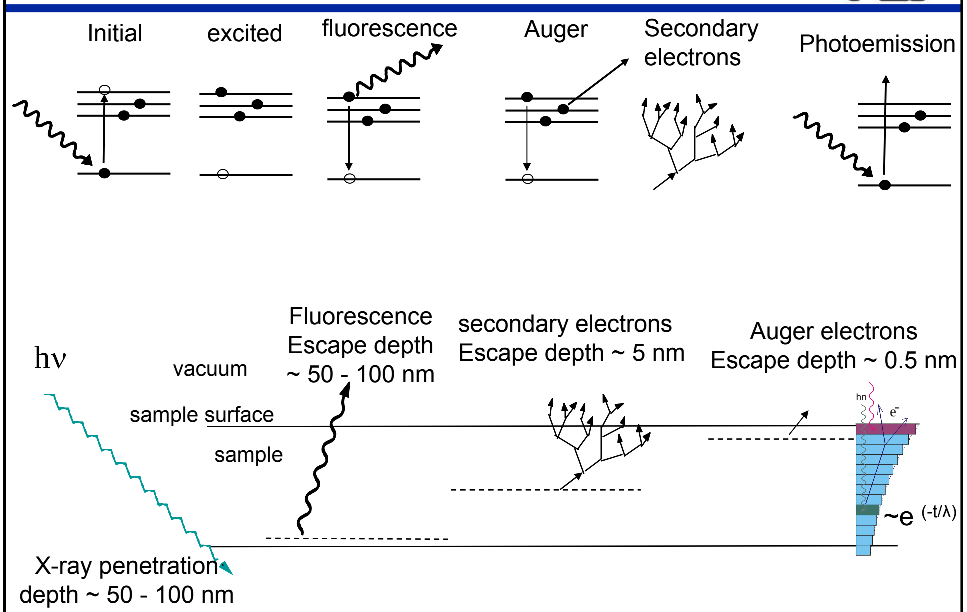
Di, 30.03.2010 X-ray Absorption Spectroscopy (F. Nolting)
Di, 06.04.2010 X-ray Microscopy (F. Nolting)
Both with an emphasis of magnetism

- Repetition Spectroscopy
- Crash course nanomagnetism
- Introduction
- Photoemission electron microscope (PEEM)
  - Technique
  - Nanocrystals
  - Heterostructure/Magnetisation dynamics
- Transmission X-ray microscope (Scanning: STXM/ full field: TXM)
- Combine X-rays with scanning probe microscopy
- PEEM without X-rays

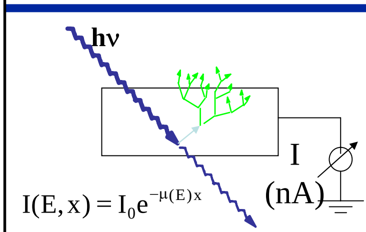
X-ray Absorption Spectra in a Nutshell



Decay channels / sampling depth

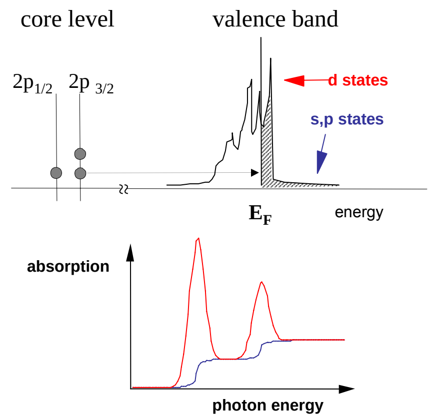


X-ray Absorption Spectroscopy



Fermi's golden rule $\mu \propto |\langle f | e \cdot p | i \rangle|^2 \rho(E)$

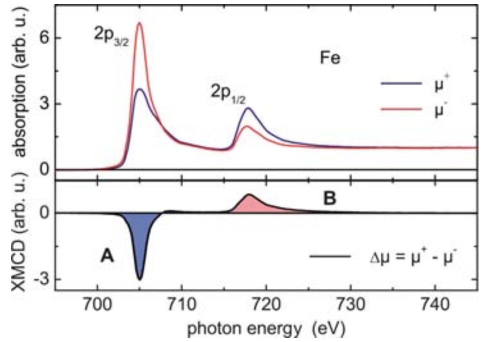
Dipole selection rules



Sensitive to:
- elemental composition
- chemical bonds
- structural parameters
- electronic structure
- magnetic properties

Near Edge X-ray Absorption Fine Structure
reflects density of unoccupied states

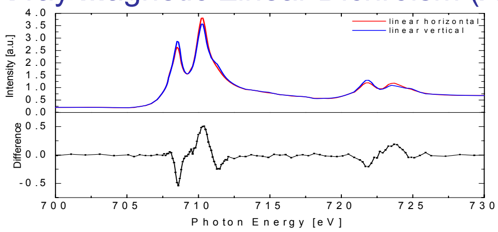
X-ray **M**agnetic **C**ircular **D**ichroism (XMCD)



XMCD ~ **M** cos(**M**,**S**)

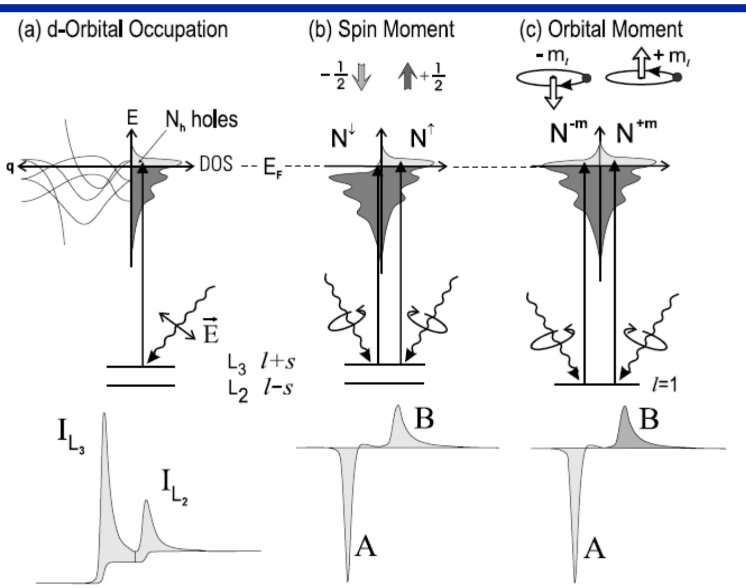
Spin and Orbital moment
Element resolved hysteresis
Look at interfaces
Look at small effects

X-ray **M**agnetic **L**inear **D**ichroism (XMCD)



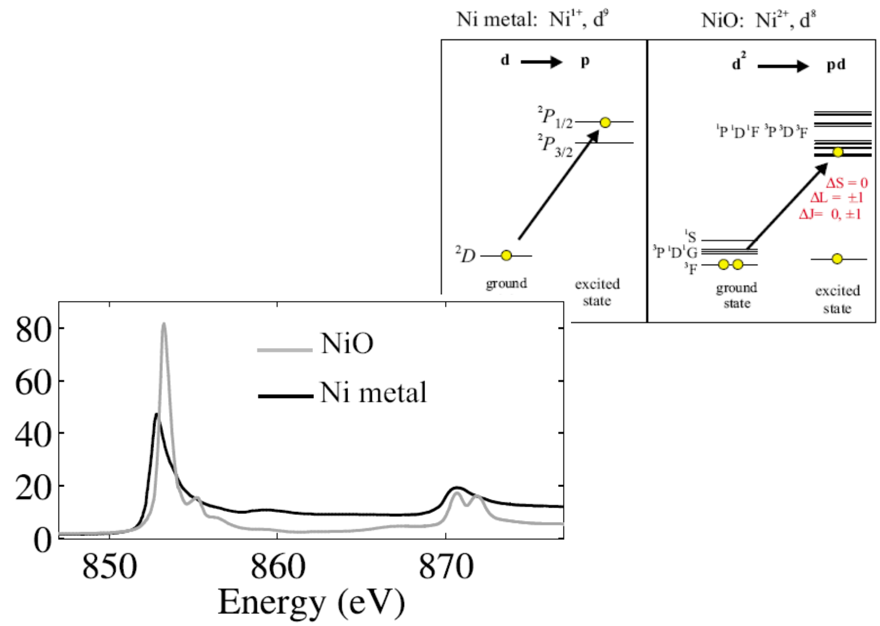
XMLD ~ $<\mathbf{M}^2>$

Sum rules



$N_h = \langle I_{L_3} + I_{L_2} \rangle / C$ | $m_s = \mu_B \langle |A| + 2|B| \rangle / C$ | $m_o = 2\mu_B \langle |A| - |B| \rangle / 3C$

Ni metal vs NiO

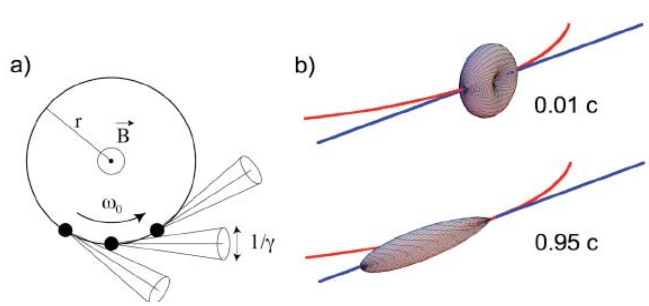


Creation of electromagnetic radiation

The Liénard–Wiechert field $\boldsymbol{E}(t)$ of a point charge q detected by an observer at a time t is determined by the distance r^*, the velocity v^*, and acceleration a^* of the charge at the emission or retarded time $t^* = t - r^*/c$. Defining $\boldsymbol{\beta}^* = \boldsymbol{v}^*/c$ we have

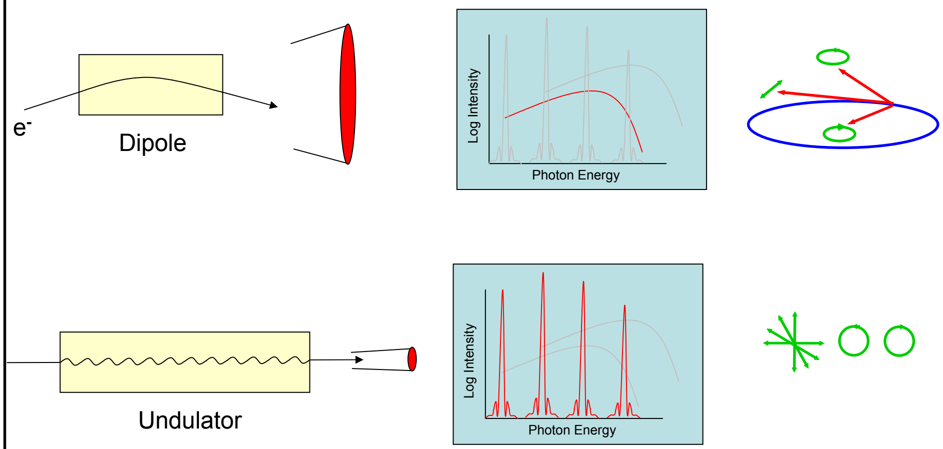
$$\boldsymbol{E}(t) = \underbrace{\frac{q}{4\pi\epsilon_0}\frac{1-(\beta^*)^2}{(r^*)^2\,(1-\boldsymbol{n}^*\cdot\boldsymbol{\beta}^*)^3}\,[\boldsymbol{n}^* - \boldsymbol{\beta}^*]}_{\text{velocity field}} + \underbrace{\frac{q}{4\pi\epsilon_0}\frac{1}{c^2\,r^*\,(1-\boldsymbol{n}^*\cdot\boldsymbol{\beta}^*)^3}\,\{\boldsymbol{n}^* \times ([\boldsymbol{n}^* - \boldsymbol{\beta}^*] \times \boldsymbol{a}^*)\}}_{\text{acceleration field}}. \quad (4.58)$$

We have indicated all retarded quantities by an asterisk.



polarized X-rays!

Slide Courtesy: Thomas Schmidt



Outline

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- Crash course nanomagnetism
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- Photoemission electron microscope (PEEM)
  - Technique
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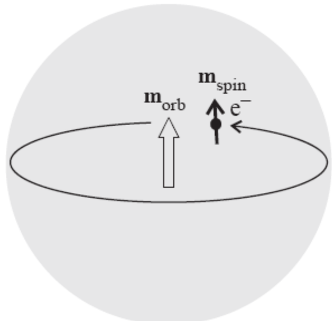
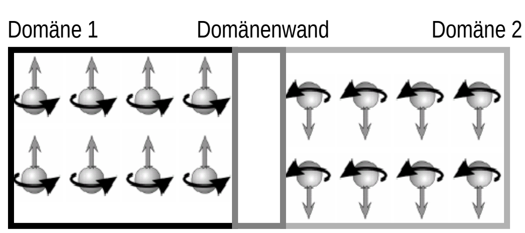
Magnetic moment

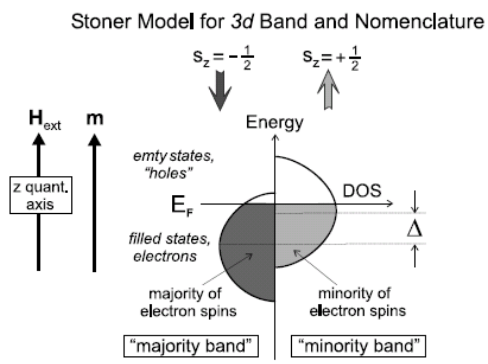


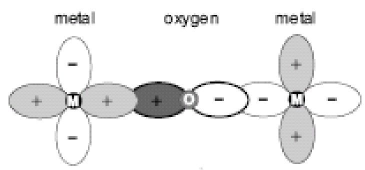
Spin moment	~ 1.5 μ_B / atom	isotropic
Orbital moment	~ 0.1 μ_B / atom	isotropic/anisotropic

They interact via the spin-orbit coupling $L \cdot S$

Ordering, e.g. ferromagnetismus



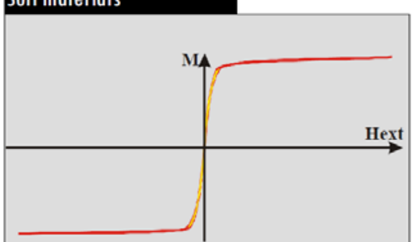




Superexchange

Double exchange

Soft materials

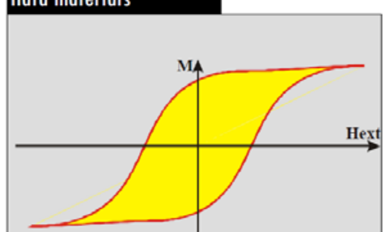


Transformers

Flux guides, sensors

Magnetic shielding

Hard materials



Permanent magnets, motors

Magnetic recording

Domains - Energy Minimization

PAUL SCHERRER INSTITUT PSI

REVIEWS OF
MODERN PHYSICS
VOLUME 21, NUMBER 4 OCTOBER, 1949

Physical Theory of Ferromagnetic Domains

CHARLES KITTEL
Bell Telephone Laboratories, Murray Hill, New Jersey

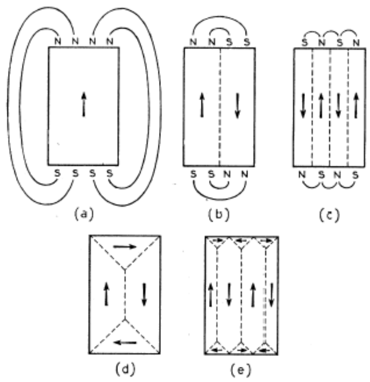


FIG. 9. The origin of domains.

1907 Weiss
1931 Sixtus and Tonks
1932 Bitter
1935 Landau and Lifshitz

Reviews
C. Kittel Rev. Mod. Phys **21** (1949) 541
A. Hubert and R. Schäfer "Magnetic Domains" (Berlin: Springer) 1998

Domains - Energy Minimization

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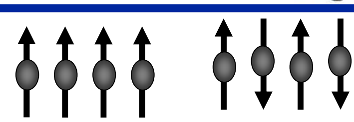
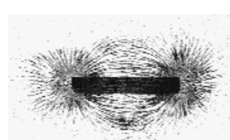
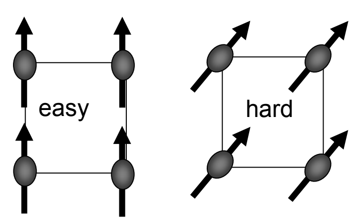
Exchange energy:
ferromagnet parallel spins
antiferromagnet antiparallel spins



Magnetostatic energy
Closure



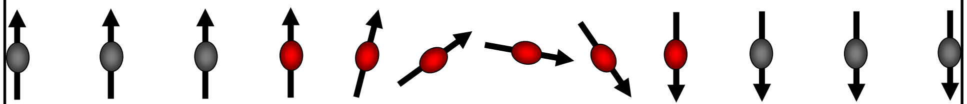
Magnetic Anisotropy
preferential magnetization along axes
easy / hard axis



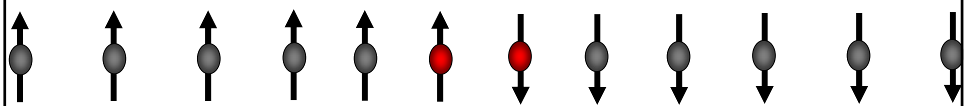
Zeeman :
spin alignment in the external magnetic field

Domain Walls

Exchange energy favors wide walls:



Anisotropy energy favors narrow walls:

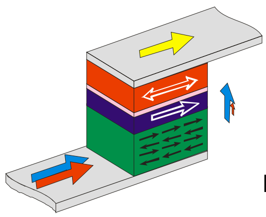


Domain wall width

$$\lambda \sim a \left(\frac{E_{exchange}}{E_{anisotropy}} \right)^{1/2}$$

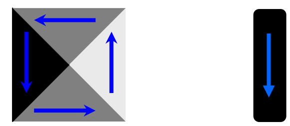
http://perso.neel.cnrs.fr/olivier.fruchart/

one dimension below critical length scale

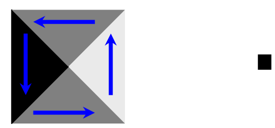


Domain size, domain wall width, Exchange length
Spin diffusion length, Spin precession length

Effect of shape



Effect of size



Effect of composition, coupling …

Dealing with multielements, ferromagnetic, antiferromagnetic

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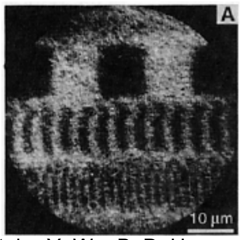
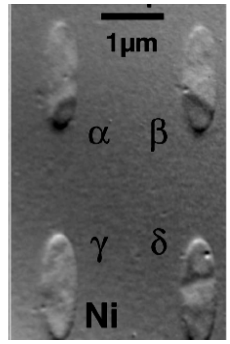
How far did we got?

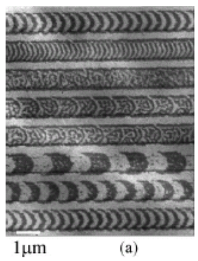


About x 50

J. Stohr, Y. Wu, B. D. Hermsmeier, M. G. Samant, G. R. Harp, S. Koranda, D. Dunham, B. P. Tonner, Science 259, 660 (1993)



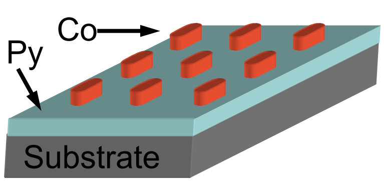
M. Hehn, D. Lacour, F. Montaigne, J. Briones, R. Belkhou, S. El Moussaoui, F. Maccherozzi, N. Rougemaille, APL 92, 072501 (2008)

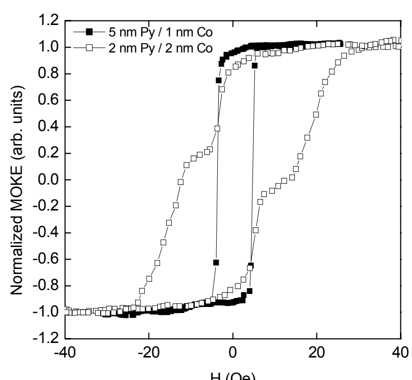


P. Fischer, T. Eimüller, G. Schütz et al.: Rev. Sci. Instrum. **72**, 2322 (2001)

Why do we care?

It's the function

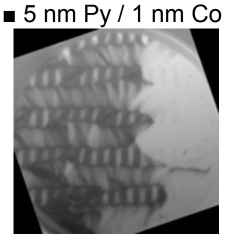


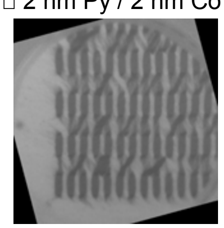


■ 5 nm Py / 1 nm Co

□ 2 nm Py / 2 nm Co

Magnetic domain configuration in the Py film

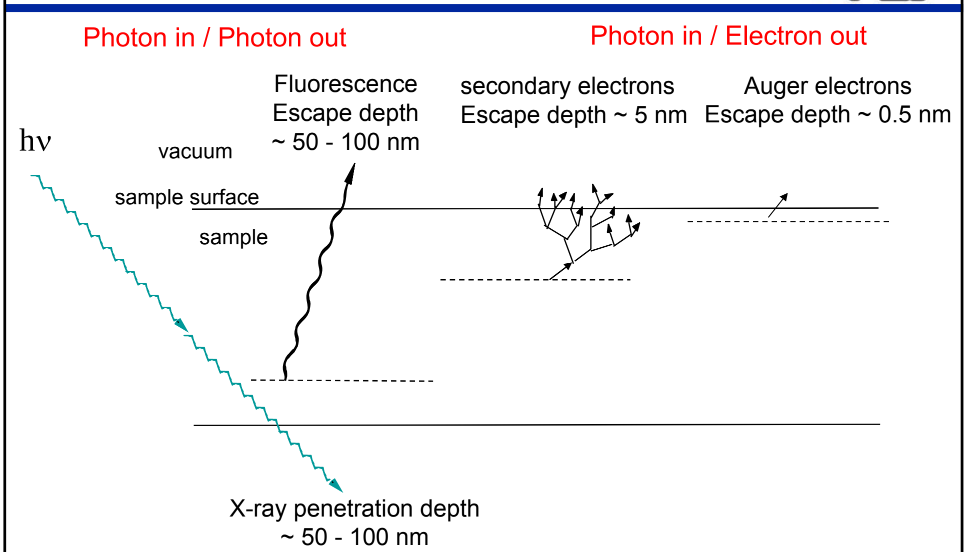




10 µm

A. Fraile Rodríguez, L. J. Heyderman, F. Nolting, A. Hoffmann, J. E. Pearson, L. M. Doeswijk, M. A. F. van den Boogaart, and J. Brugger, Appl. Phys. Lett. **89**, 142508 (2006).

Detecting methods

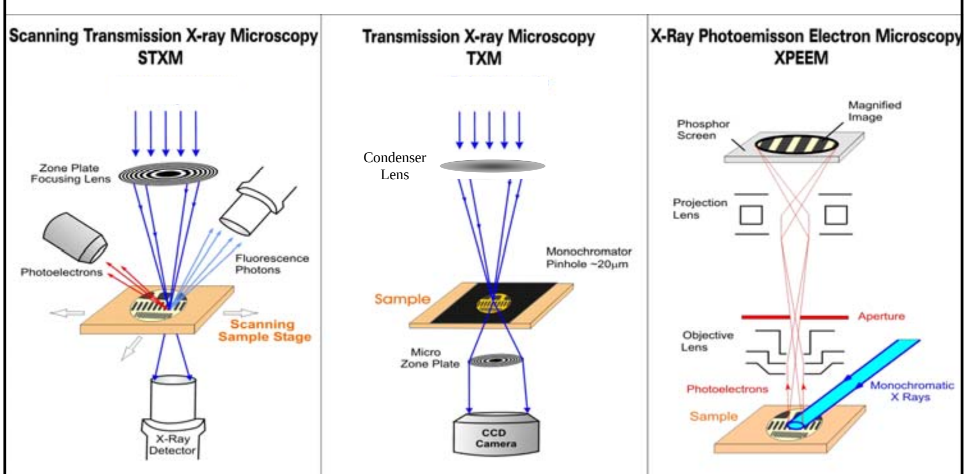


How?

Different ways of measuring X-ray absorption

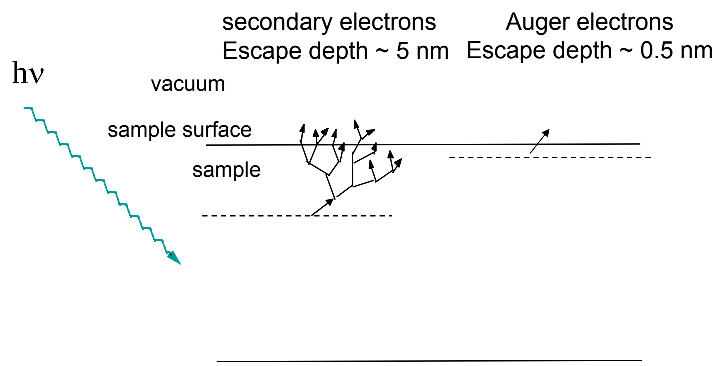
=

Different ways of magnetic imaging with X-rays



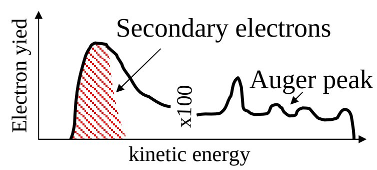
Courtesy J. Stöhr

Photon in / Electron out

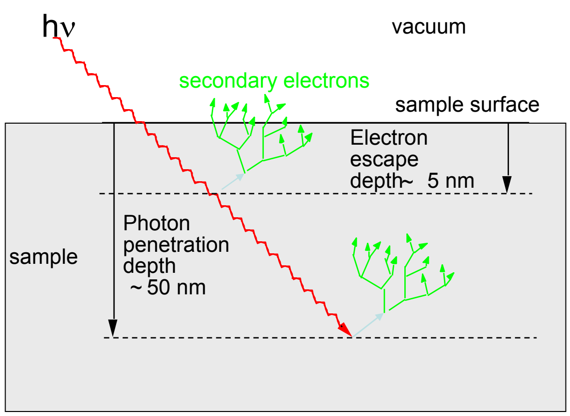


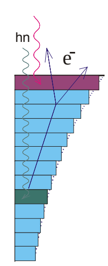
You need an optic for the electrons

This is good!



Probing surface/interface





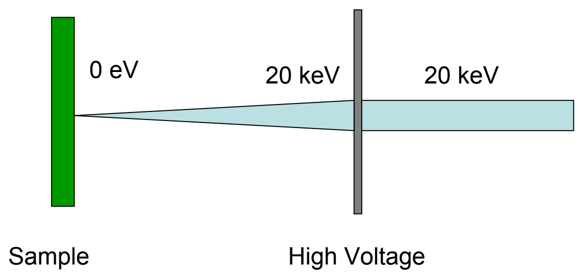
First layer

Second layer

Slow Electrons

Probe : slow electrons

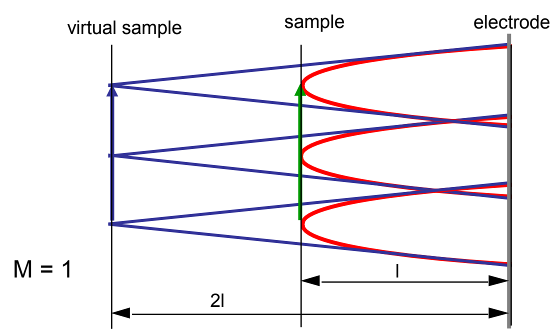
Imaging : high energy electrons
(more stable and maintain spatial information)



Immersion lens: electrons have before and after the lens different velocity (different wavelength)

Cathode lens: Sample is cathode
electron microscope is anode

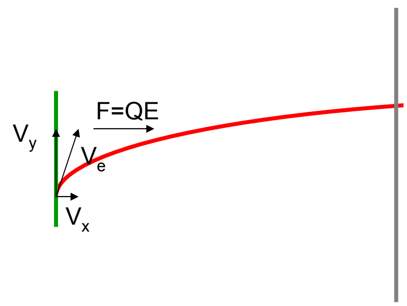
Why is the accelerating field a lens?



Accelerated electrons form parabolic trajectory
Tangents to parabolas are the incident rays
Extrapolated backwards form a virtual image
at unit lateral magnification

Just another lens?

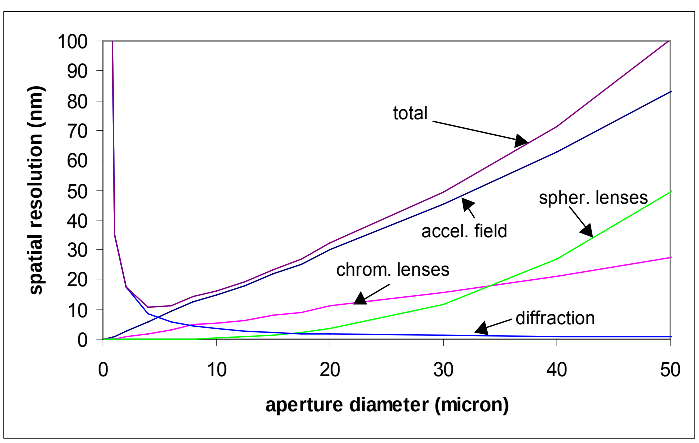
Classical: electron in homogenous electric field
calculate electron trajectory



Trajectory depends on emission angle and velocity

No, it is a very important lens in a PEEM, dominating the spatial resolution due to its spherical and chromatic aberrations.

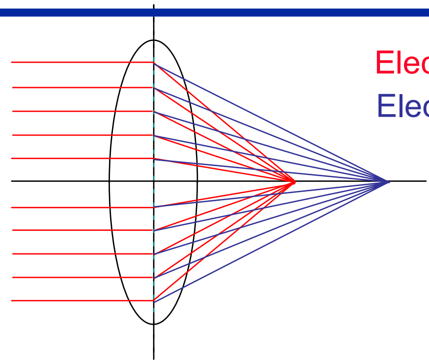
Calculated Spatial Resolution

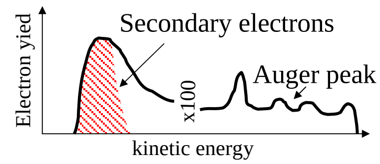


PEEM 2 at the ALS, Simone Anders
Work function 4 eV, sample voltage 30 kV, X-rays

Energy Filter

Electron energy E
Electron energy E+ΔE





Energy Filter

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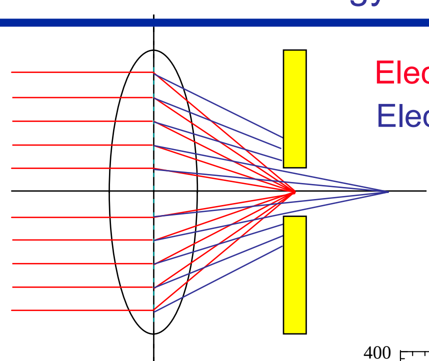
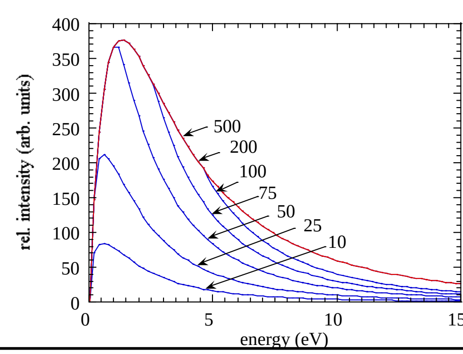


Aperture cuts off transmission of electrons with higher energy

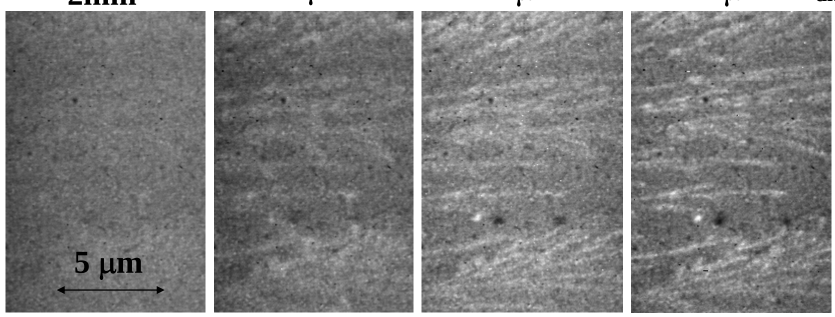
Energy distribution is narrowed but transmission is reduced



Effect of Aperture Size on Resolution

- Spatial resolution depends on aperture size - limits pencil angle of transmitted electrons and transmission
- Highest resolution is achieved with 12 μm aperture for PEEM2, ALS

2mm	50 μm	20 μm	12 μm	Aperture diameter



0.4 s	1s	4.2 s	10 s	Exposure time
100 %	39 %	9 %	4 %	Transmission

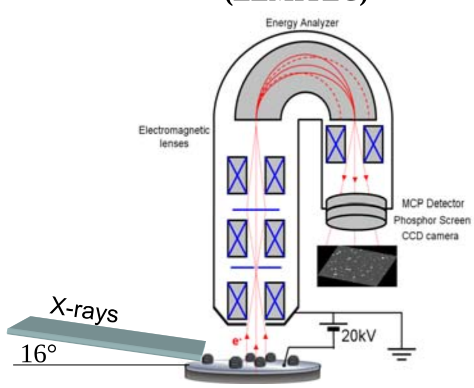
Photoemission Electron Microscopy using X-Rays

Spatially resolved X-ray absorption spectroscopy

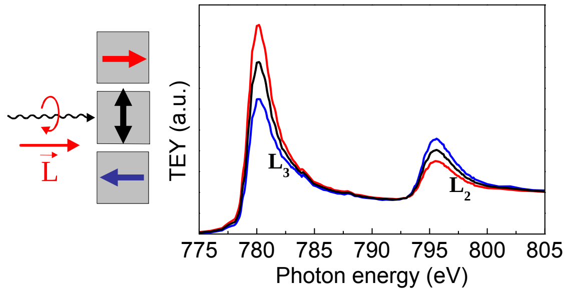
Sensitive to:
- elemental composition
- chemical bonds
- structural parameters
- electronic structure
- magnetic properties

SIM beamline at the SLS
Energy range 100 – 2000 eV
Circular and linear polarization

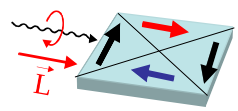
Schematic layout of the PEEM (ELMITEC)



X-ray Magnetic Circular Dichroism (XMCD)

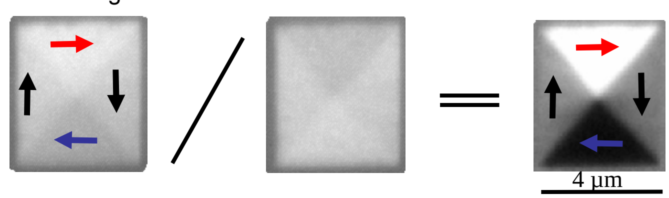


XMCD ~ <**M**> cos(**M**,**L**)



A/B ≈ (A-B)/(A+B)
magnetization direction
Domain shape

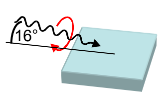
Circular right   Circular left



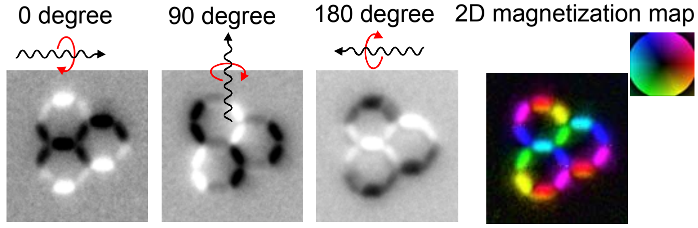
e.g. J. Stohr et al Surface Rev. Lett. **5**, 1297 (1998).

X-ray Magnetic Circular Dichroism (XMCD)

In-plane system

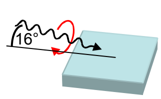


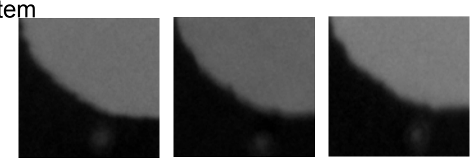
0 degree   90 degree   180 degree   2D magnetization map



Co structures (600 nm)

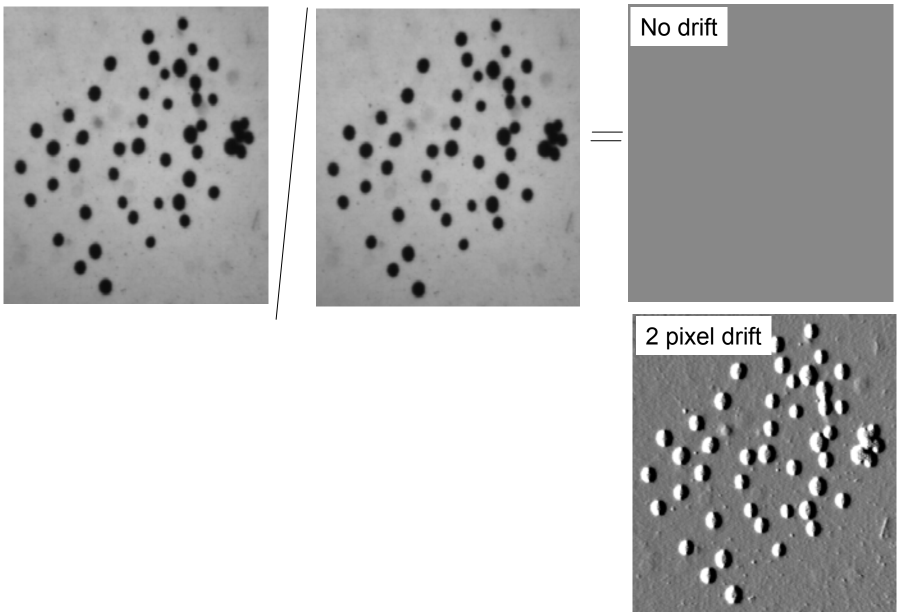
Out-of-plane system





20nm GdFeCo film

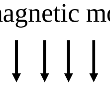
Be critical: Image drift!

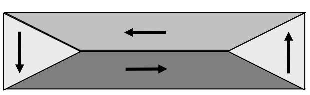


Antiferromagnet

Ferromagnet (FM)

Net magnetic moment

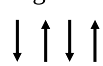


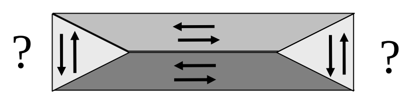


Magnetostatic energy
Exchange energy
Anisotropy energy

Antiferromagnet (AFM)

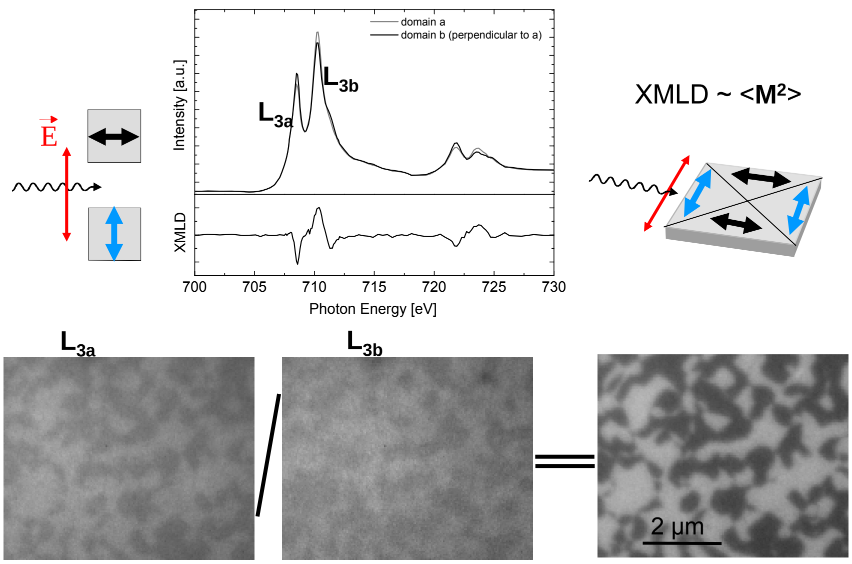
No net magnetic moment





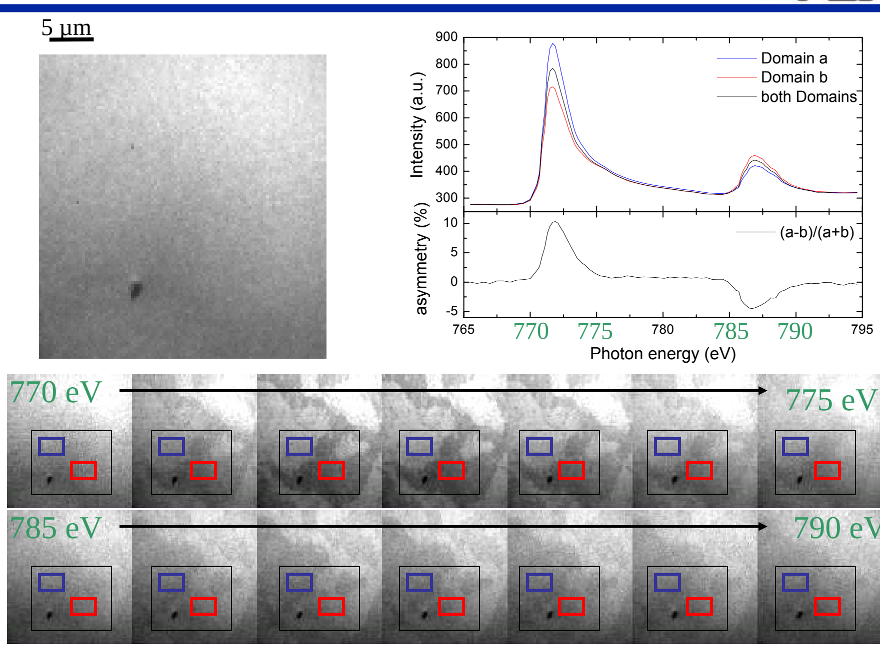
Exchange energy
Anisotropy energy
(magnetoelastic)

X-ray Magnetic Linear Dichroism (XMLD)

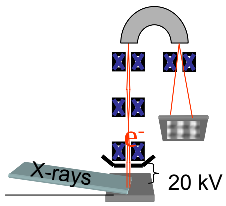


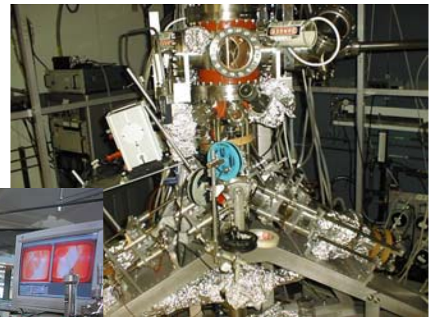
e.g. A. Scholl et al Science **287**, 1014 (2000)

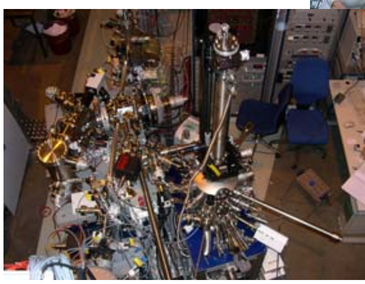
PEEM : Local Spectra

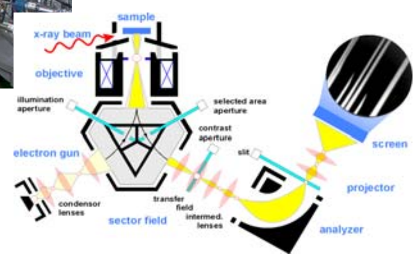


Instrument of course more complex





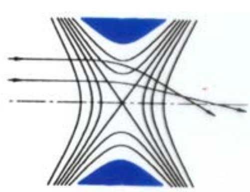


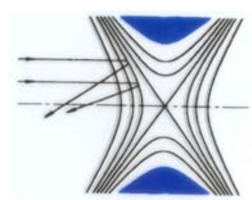


Aberrations and their correction

Spherical aberrations

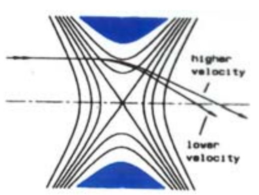
Lens

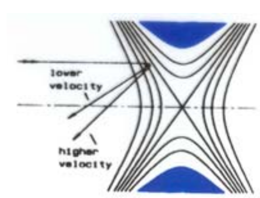


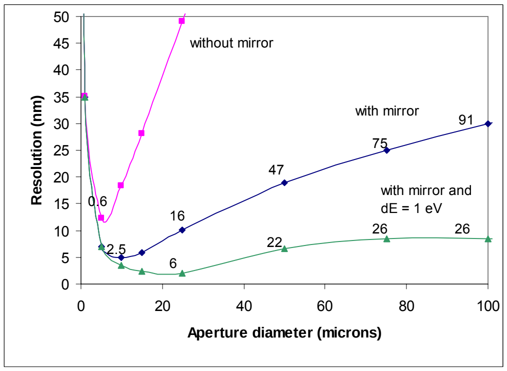


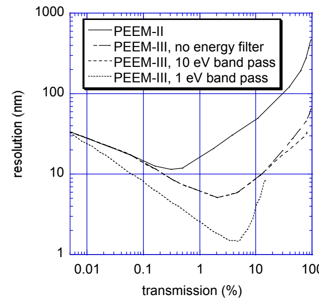
Mirror

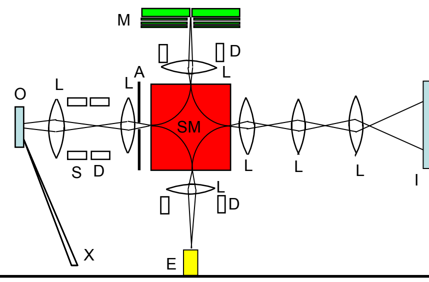
Chromatic aberrations











Aberration-corrected instruments

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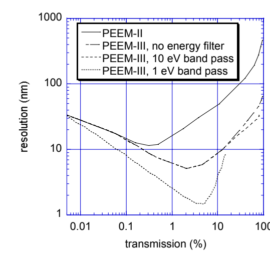
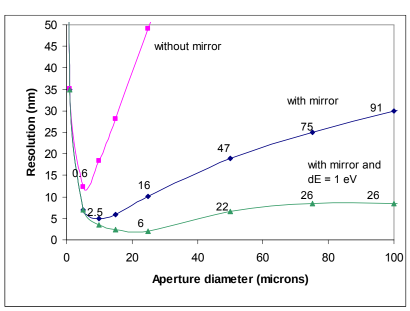
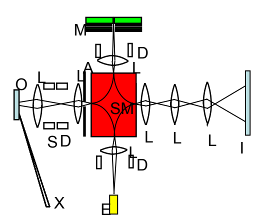
SMART (SpectroMicroscope for All Relevant Techniques)
at BESSY II, Berlin, Germany
collaboration of seven Universities in Germany
status: LEEM 3 nm, X-PEEM about 20 nm

PEEM III
at ALS, Berkeley, USA
aberration corrected not yet build

Companies with aberration correction:
ELMITEC
SPECS







Outline

- ○Repetition Spectroscopy
- ○Crash course nanomagnetism
- ○Photoemission electron microscope (PEEM)
  - ○Technique
  - ○Nanocrystals
  - ○Heterostructure/Magnetisation dynamics
- ○Transmission X-ray microscope (Scanning: STXM/ full field: TXM)
- ○Combine X-rays with scanning probe microscopy
- ○PEEM without X-rays

Spectroscopy of individual nanoclusters

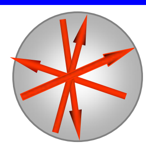
Size-dependent spin structures in iron nanoparticles

A. Fraile Rodríguez[1], A. Kleibert[1], J. Bansmann[2], A. Voitkans[2], L. J. Heyderman[1], and F. Nolting[1]

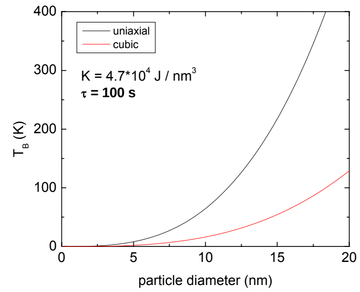
[1]Paul Scherrer Institut, Villigen PSI, CH-5232 Switzerland.
[2]Institute of Surface Chemistry and Catalysis, University of Ulm, D-89069 Ulm, Germany.
[3]Institute of Physics, University of Rostock, D-18051 Rostock, Germany.

Spectroscopy of individual nanoclusters

Superparamagnetism

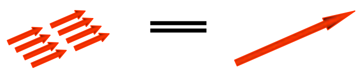


$K_{ani} \cdot V_{particle} \cong k_B \cdot T$

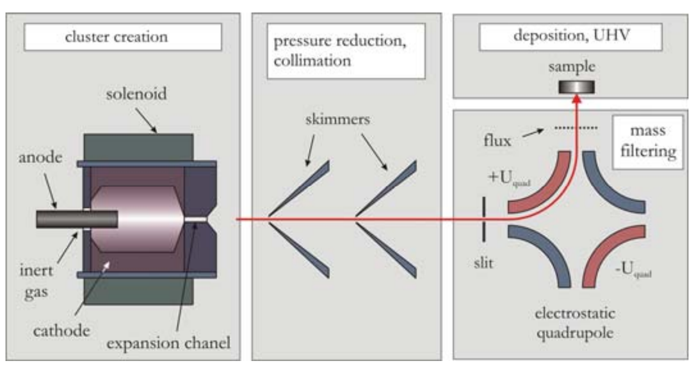


Single spin model

For particles smaller than 20 – 100 nm (material dependent)

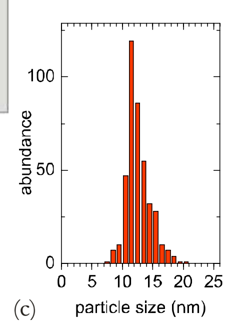


Mass-filtered nanoparticles: Arc-ion source



- particle size tunable between 4-15nm
- size distribution: ΔD/D ~10-15%
- *in situ* deposition
- transportable and UHV compatible

R. P. Methling et al., EPJD **16**, 173 (2001)



In-situ Fe particles deposited on cobalt surfaces

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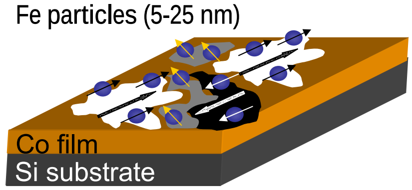
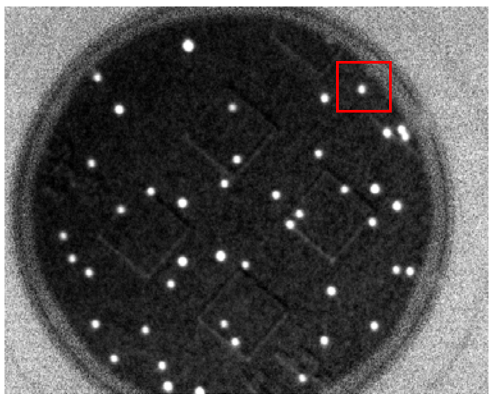
Fe particles (5-25 nm)

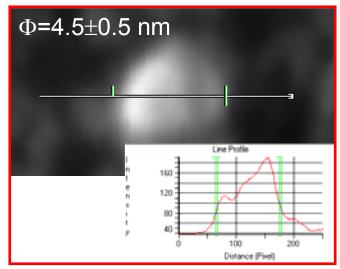


1. e-beam evaporation of cobalt thin films (2- 4 nm thickness)
2. in-situ deposition of Fe particles using arc-ion cluster source

Fe Elemental



SEM



FOV = 20 micrometer

XMCD spectra of individual Fe nanoparticles

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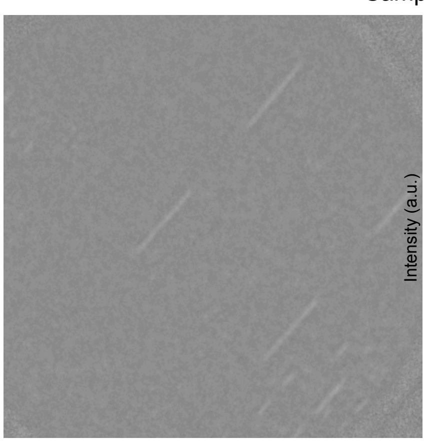
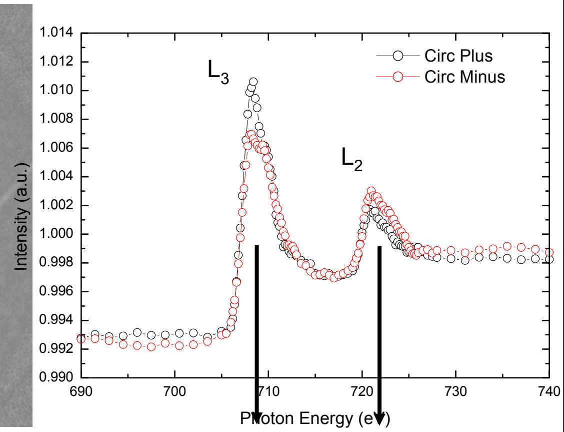
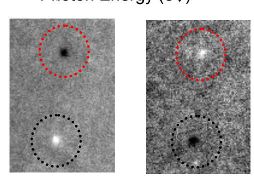
Sample: Fe nanoparticles with diameter = 9 nm





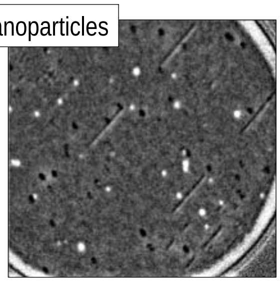
Images with increasing Photon Energy

XMCD image

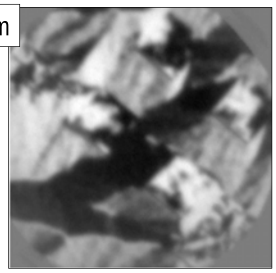


Coupling

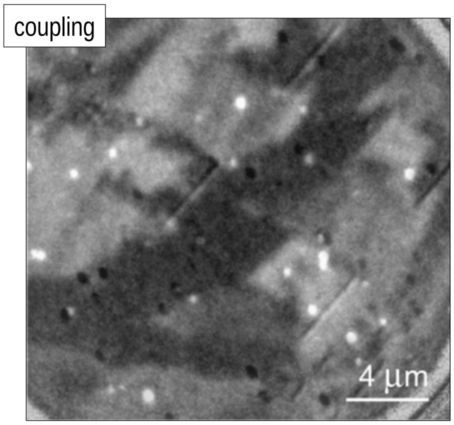
Fe Nanoparticles



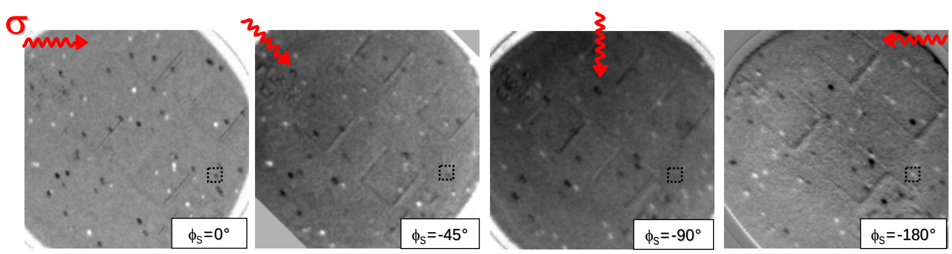
Co film

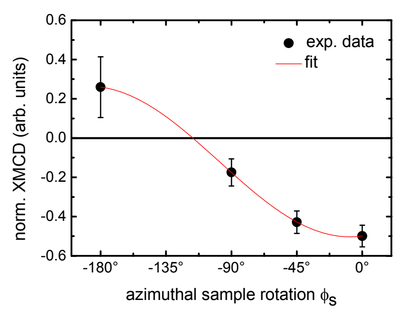


coupling

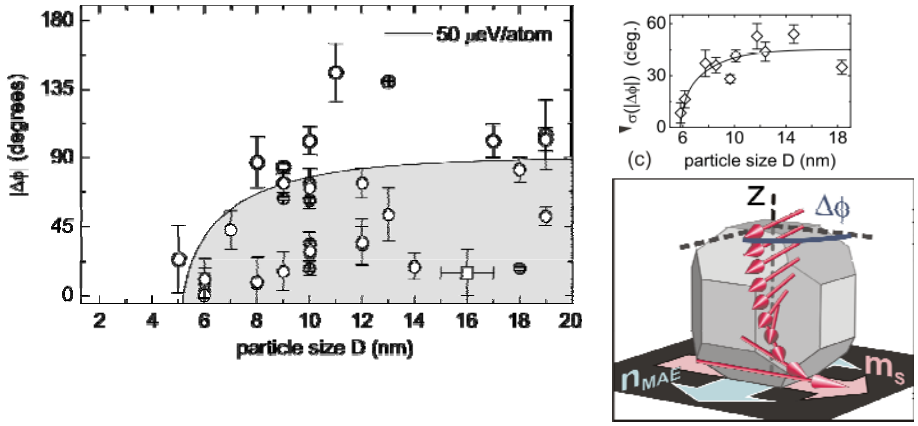


3D magnetization map





The smallest domainwall in a nanoparticle



Already for particles larger than 6 nm is the single-spin model not correct anymore

A. Fraile Rodríguez, A. Kleibert, J. Bansmann, A. Voitkans, L. J. Heyderman, and F. Nolting PRL 2010, in press

Spin reorientation in a coupled Antiferromagnetic/Ferromagnetic system

L. Joly, L. Le Guyader, A. Kleibert, and F. Nolting

SLS, Paul Scherrer Institut, Switzerland

A. V. Kimel, A. Kirilyuk, and Th. Rasing

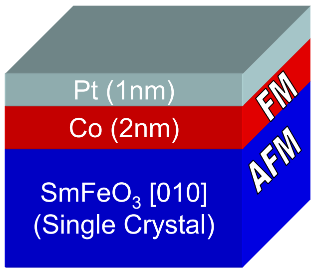
IMM, Radboud University Nijmegen, The Netherlands

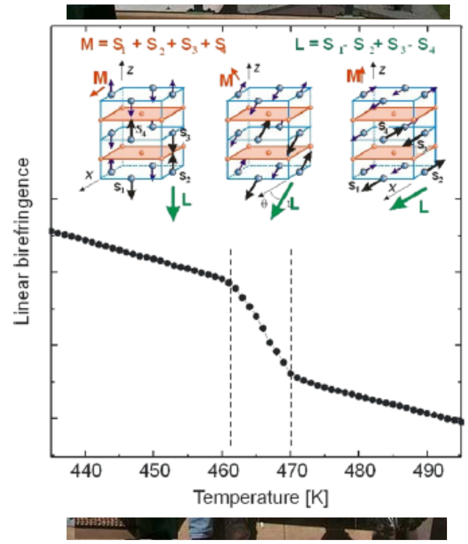
R. V. Pisarev

Ioffe Physical Technical Institute, St. Petersburg, Russia

Switching using an antiferromagnet

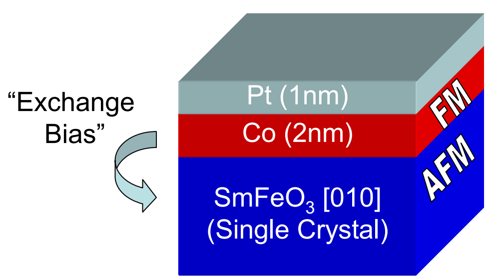
The dynamics in an antiferromagnet can be faster than in a ferromagnet





L. Le Guyader, L. Joly, A. Kleibert, F. Nolting, R. Pisarev, A. Kirilyuk, Th. Rasing, A. Kimel

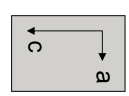
$SmFeO_3$ / Co



- coupling between the domains of the Co and $SmFeO_3$
- $SmFeO_3$: Spin-reorientation phase transition at about 420 – 460 K
  T_N = 675 K

Below spin reorientation temperature

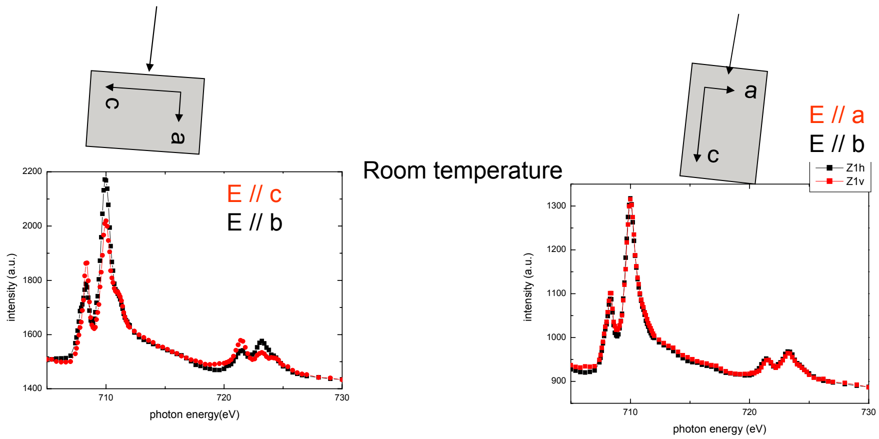
AFM axis	parallel to c
weak ferromagnet	parallel to a



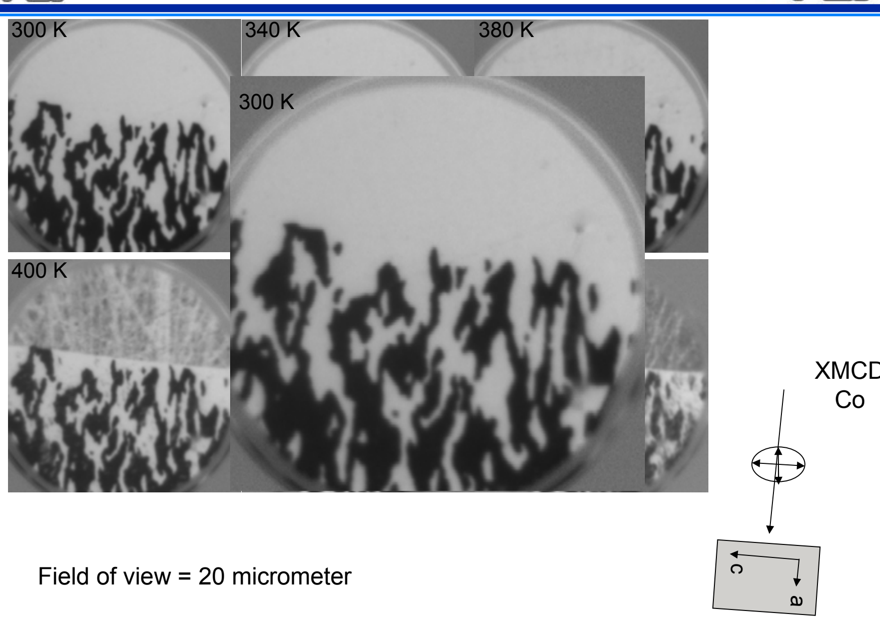
Above spin reorientation temperature

AFM axis	parallel to a
weak ferromagnet	parallel to c

AFM axis along c

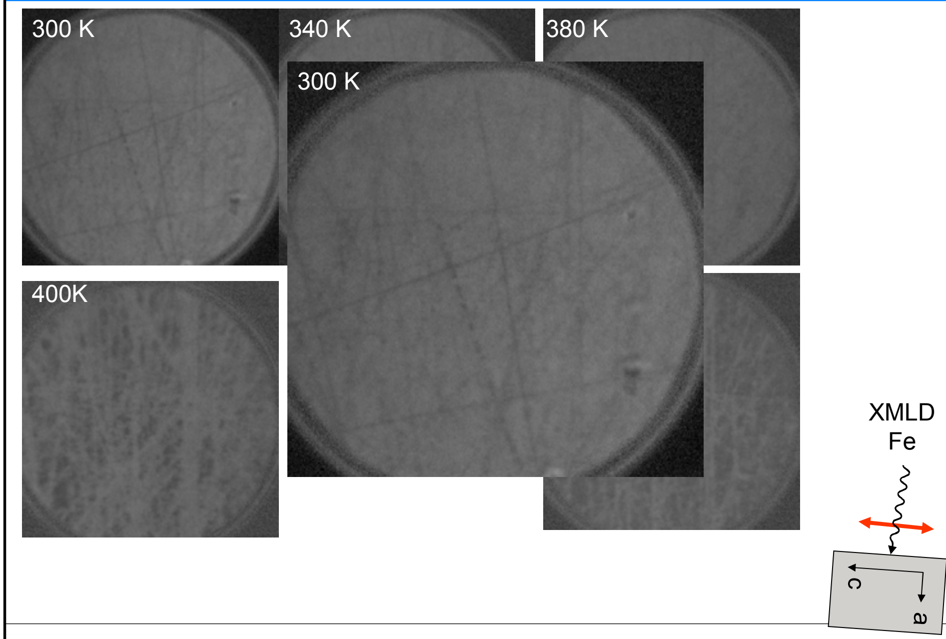


Co Domains

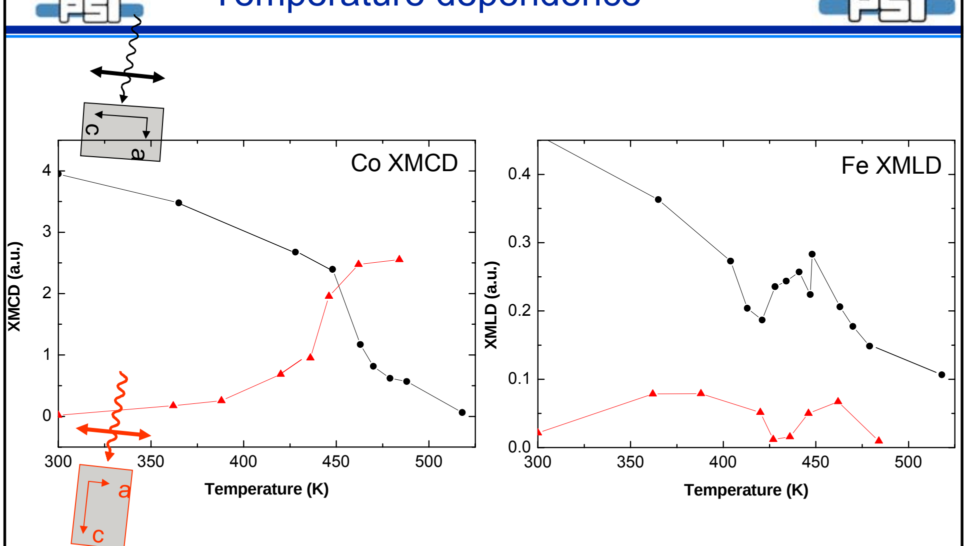


Field of view = 20 micrometer

AFM Domains in-plane

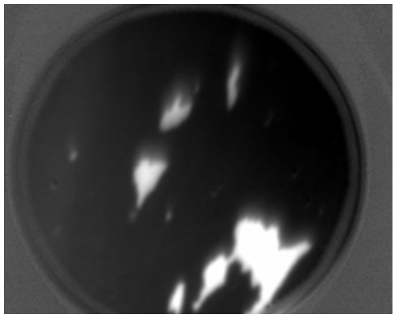


Temperature dependence

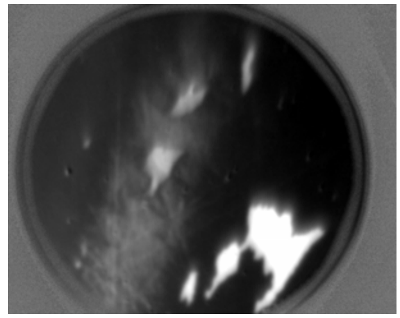


Laser heating

Co XMCD



Laser off



Laser on

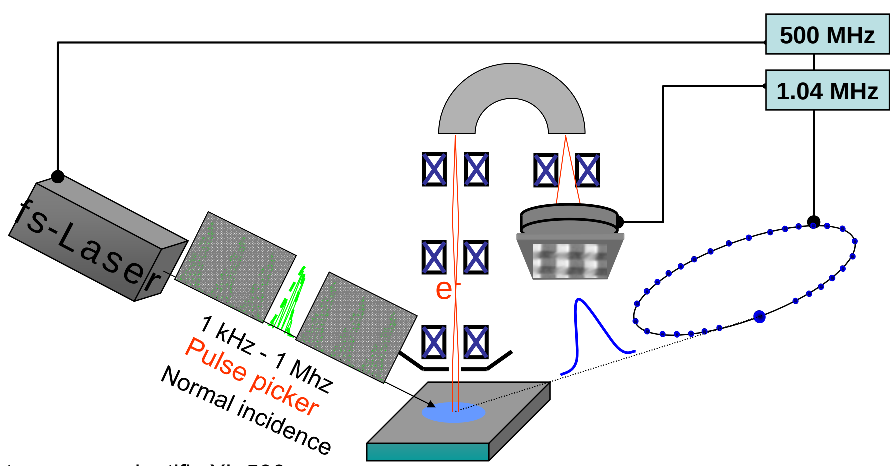
L. Joly, F. Nolting, A. Kimel, A. Kirilyuk, Th.Rasing, R.V. Pisarev, J. Phys.: Condens. Matter **21**, 446004 (2009).

Laser set-up combine with PEEM

Pump:
Pulse: 50 fs

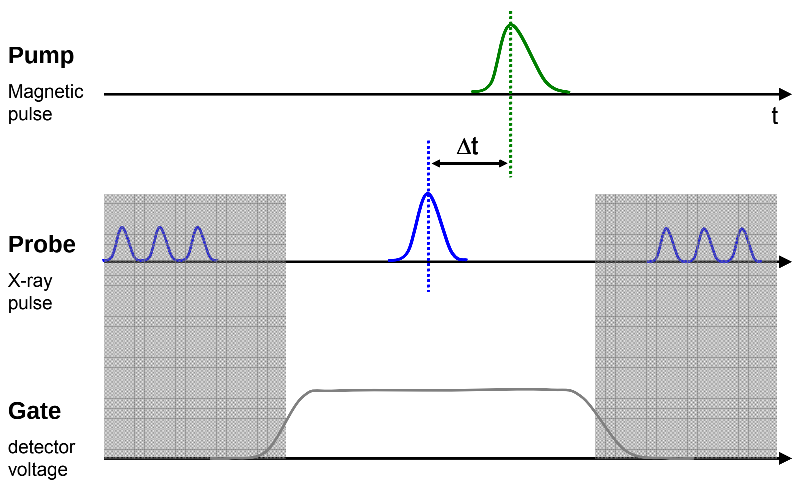
Detect:
gated PEEM
Dx ~100nm, ~ 1 ML

Probe:
X-ray stroboscope
~1keV, Δt= 70ps

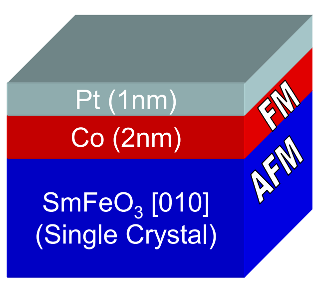


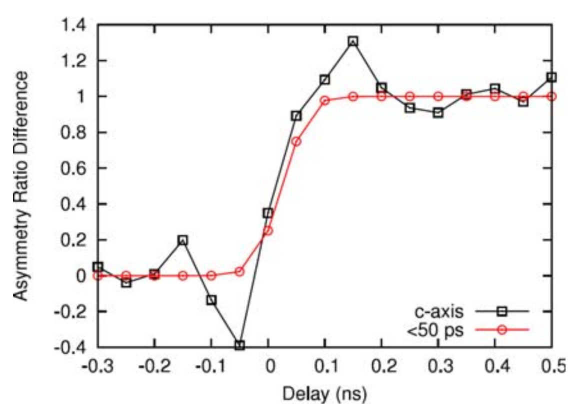
Femtosource, scientific XL 500
50fs, 500nJ, 5.2 MHz, 800 nm

Magnetic Pump - X-ray Probe



Switching using an antiferromagnet





Faster than our time resolution given by the X-ray pulse length of about 50 ps

L. Le Guyader, L. Joly, A. Kleibert, F. Nolting, R. Pisarev, A. Kirilyuk, Th. Rasing, A. Kimel

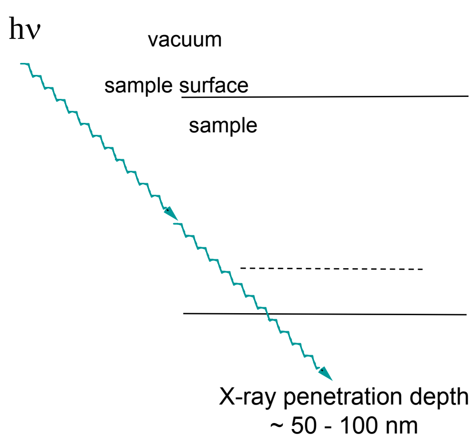
Outline

- Repetition Spectroscopy
- Crash course nanomagnetism
- Photoemission electron microscope (PEEM)
  - Technique
  - Nanocrystals
  - Heterostructure/Magnetisation dynamics
- Transmission X-ray microscope (Scanning: STXM/ full field: TXM)
- Combine X-rays with scanning probe microscopy
- PEEM without X-rays

Photon in / Photon out

Photon in / Photon out

You need an optic for the (incoming) photons



Spatial Resolution in X-ray Microscopy

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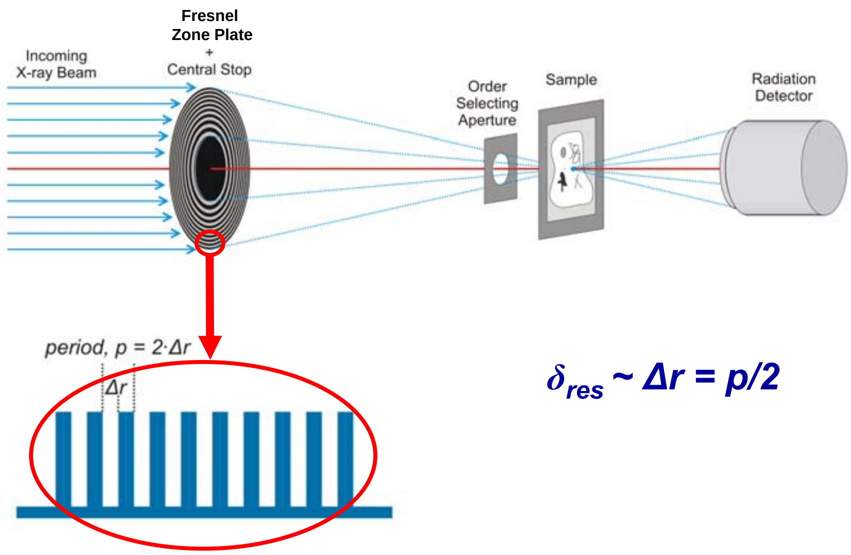

$\delta_{res} \sim \Delta r = p/2$

Courtesy J. Vila-Comamala (PSI)

STXM at the PolLux beamline at the SLS

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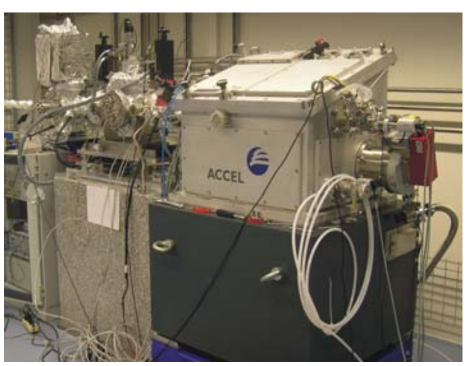
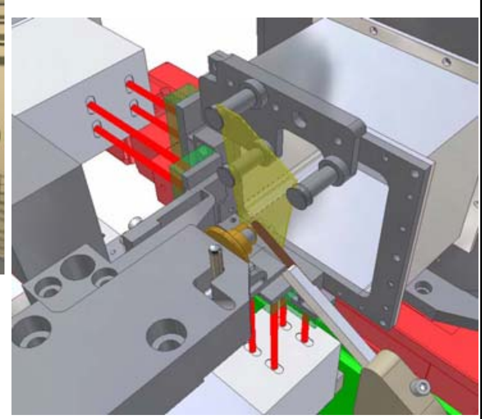
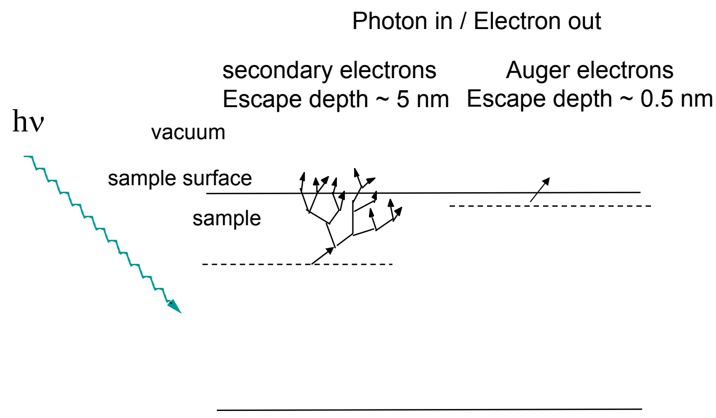




Back to Photon in / Electron out but …



Combine scanning probe microscopy with X-ray absorption spectroscopy

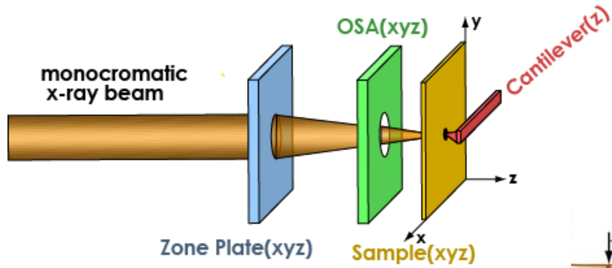
NanoXAS project at SLS

I. Schmid[1,2], J. Raabe[1], C. Quitmann[1], S. Vranjkovic[2], H. J. Hug[2] and R. H. Fink[3]

Endstation:
[1]PSI, Swiss Light Source, 3252 Villigen
[2]EMPA, Nanoscale Materials Science, 8600 Dübendorf

Beamline:
[3]Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

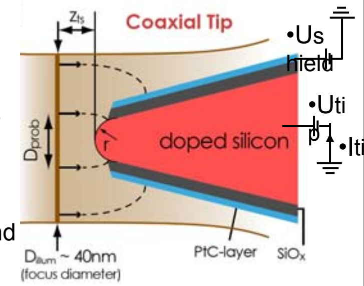
NanoXAS project at SLS



The NanoXAS instrument contains:

- Scanning Transmission X-ray Microscope (STXM) – chemical analysis
- Scanning Force Microscope (SFM) and in principle STM – sample topography
- Combination: STXM & SFM - chemical sensitivity and high spatial resolution.

  Cantilever Tip acts as a local photoelectron detector!



Very brief comparison to other techniques

Table 2. Summary of the features of the discussed magnetic imaging techniques. Columns with pictograms refer (from left to right) to resolution, image acquisition speed, type of imaging (parallel imaging or scanning), sensitivity to applied magnetic fields, type of depth information (surface based or transmission), information depth (path length for exponential weighting for surface based techniques, maximum sample thickness for transmission techniques), possibility to obtain depth selective information

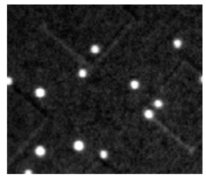
	📍	⧗	👁	🧲	▭	÷	▭←
Kerr microscopy	☹	☺	📍 ▤	☺	↘↗▭	< 20 nm	😐
Lorentz microscopy	☺	😐	📍 ▤	😐	↘▭↘	< 100 nm	☹
SEMPA	☺	☹	▤	☹	↘↗▭	< 0.5 nm	💣
SPLEEM	☺	☺	📍	💣	↘↗▭	< 1 nm	💣
XMCD-PEEM	😐	☺	📍	💣 (circled → ☹ "correction" F. Nolting)	↘↗▭	< 5 nm	☺
M-TXM	☺	☺	📍 ▤	☺	↘▭↘	< 200 nm	☺
MFM	☺	☹	▤	☺	↗▭	< 2 μm	☹
sp-STM	☺ ☺	☹	▤	☺ ☹	↗▭	< 0.2 nm	💣

☹ "correction" F. Nolting

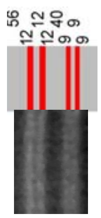
W. Kuch: *Magnetic Imaging*, Lect. Notes Phys. **697**, 275–320 (2006)

Spatial resolution?

4 nm Fe particles
PEEM

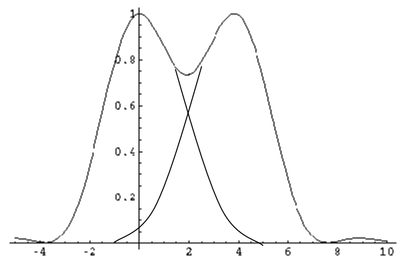


What is the spatial resolution?

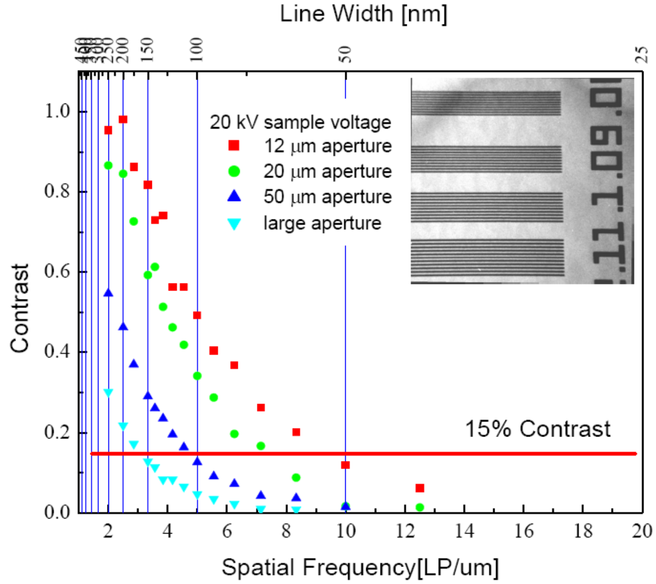


Is this contrast good enough to identify unknown, not periodic structures?

Which spatial resolution you need for spectroscopy?



Spatial resolution?



Courtesy Andreas Scholl (ALS)

Outline

- ○Repetition Spectroscopy
- ○Crash course nanomagnetism
- ○Photoemission electron microscope (PEEM)
  - ○Technique
  - ○Nanocrystals
  - ○Heterostructure/Magnetisation dynamics
- ○Transmission X-ray microscope (Scanning: STXM/ full field: TXM)
- ○Combine X-rays with scanning probe microscopy
- ○PEEM without X-rays

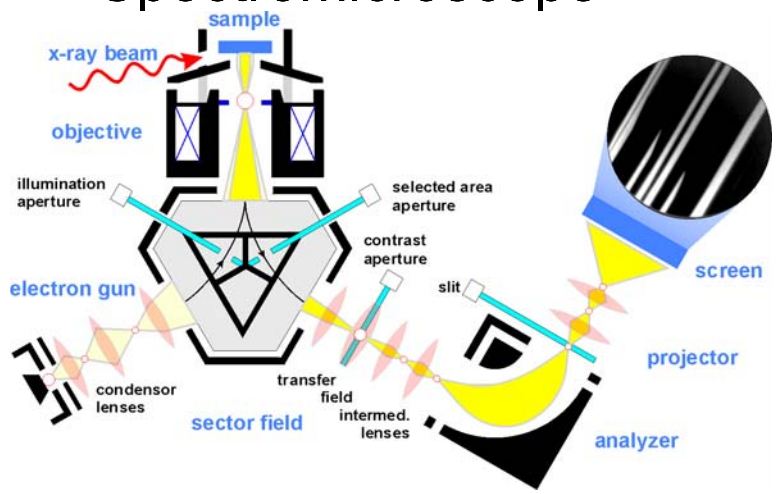
Not only with X-rays

PEEM with UV light
   10 nm spatial resolution
   workfunction and topography contrast

PEEM with slow electrons
   8 nm spatial resolution
   LEED, LEEM, MEM ….

PEEM with X-rays
   50-20 nm spatial resolution
   spectromicroscopy

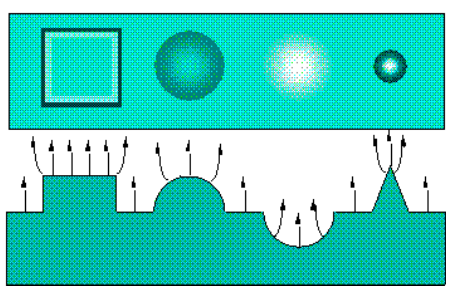
Spectromicroscope



L.H. Veneklasen: Ultramicroscopy 36 (1991), 76
Image courtesy of S. Heun (ELETTRA)

Elmitec Elektronenmikroskopie GmbH
Clausthal-Zellerfeld, Germany

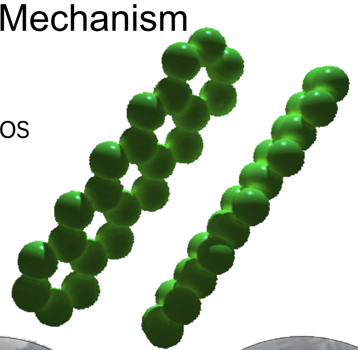
Topographical Contrast

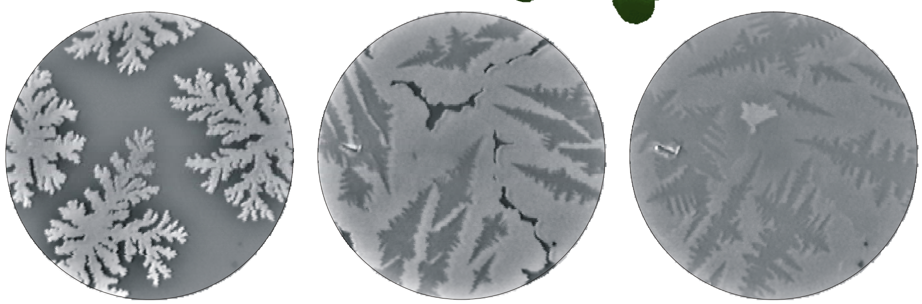


Distortion of the electric field due to topography

PEEM Contrast Mechanism

- Mercury lamp (5eV)
- Contrast either by Work Function or DOS
- Pentacene: 5 Benzene Rings
- Contrast Changes During Deposition
- FoV = 65µm





1 Layer   2 Layers   3 Layers

F.-J. Meyer zu Heringdorf et al., NATURE 412 (517), 2001

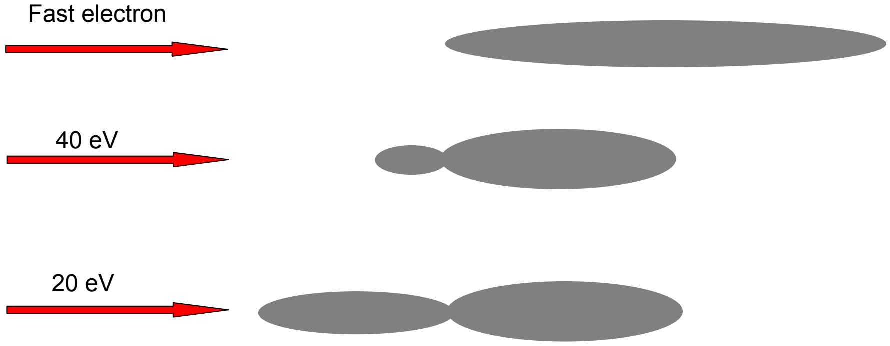
Source: slow electrons

How slow electrons interact with matter

Fast electron

40 eV

20 eV



Elastic backscattering

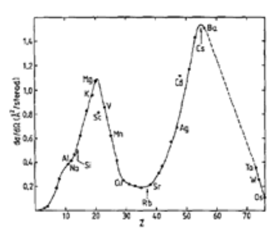
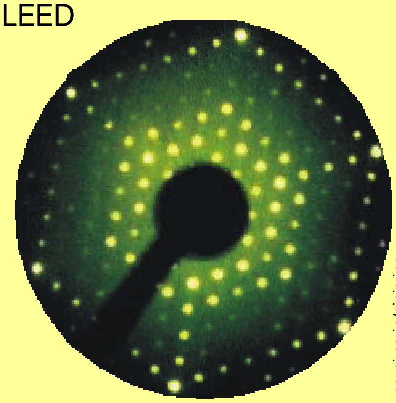


Figure 2. Elastic backscattering cross sections $d\sigma/d\Omega$ (178°) of free atoms as a function of nuclear charge Z for 100 eV electrons. The dashed line is a simple interpolation.

Low Energy Electron Diffraction

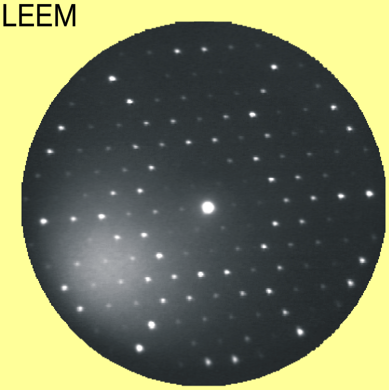
LEED



Electron Gun Visible
High Linearity
Spots move with Energy

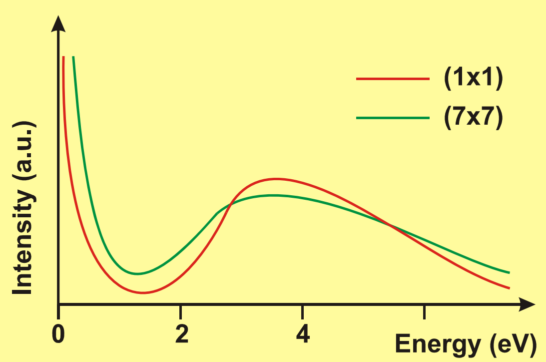
http://www.vgsysj.co.jp/sipic.jpg

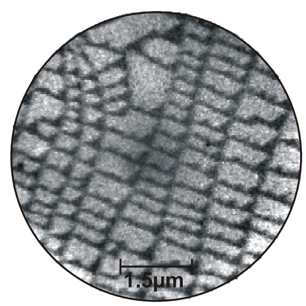
LEEM

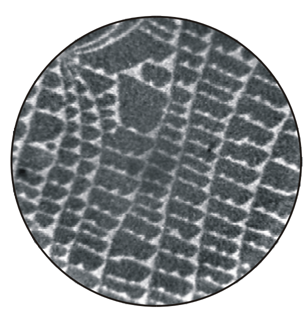


No Apparent Electron Gun
Secondary Electrons
Spots Don't Move

Bright Field Imaging of Si (111)



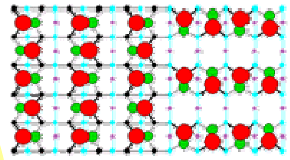




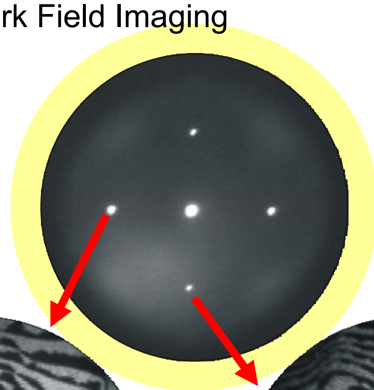
- Different Reflectivity of (1x1) and (7x7)
- Reflectivity Energy Dependent
- Contrast Reversal Dependent on Imaging Conditions

Dark Field Imaging

Si (001)



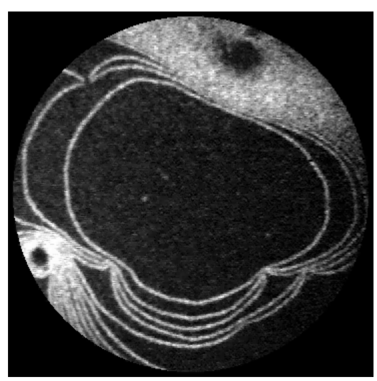
- Creator of the LEED Spots Lights up in Bright



- The Rest of the Surface Remains Dark

Direct Observations of Nanoscale Self-Assembly and Pattern Formation Solid Surfaces
by R. Plass, N. C. Bartelt, and G. L. Kellogg

LEEM-Movie of the growth of Pb on a Cu(111) surface.



Nature, 412 (2001) 875

PHYSICAL REVIEW B **72**, 214409 (2005)

Three-dimensional magnetic-flux-closure patterns in mesoscopic Fe islands

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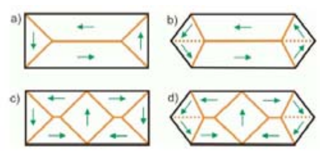
(Received 23 June 2005; revised manuscript received 6 September 2005; published 6 December 2005)

We have investigated three-dimensional magnetization structures in numerous mesoscopic Fe/Mo(110) islands by means of x-ray magnetic circular dichroism combined with photoemission electron microscopy (XMCD-PEEM). The particles are epitaxial islands with an elongated hexagonal shape with length of up to 2.5 μm and thickness of up to 250 nm. The XMCD-PEEM studies reveal asymmetric magnetization distributions at the surface of these particles. Micromagnetic simulations are in excellent agreement with the observed magnetic structures and provide information on the internal structure of the magnetization which is not accessible in the experiment. It is shown that the magnetization is influenced mostly by the particle size and thickness rather than by the details of its shape. Hence these hexagonal samples can be regarded as model systems for the study of the magnetization in thick, mesoscopic ferromagnets.



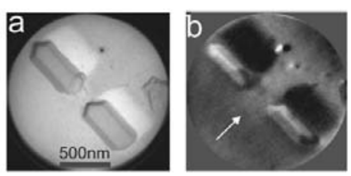


FIG. 2. Example of an experimental observation of the particle shape and the magnetization structure. (a) Two Fe islands, incidentally located next to each other, imaged with LEEM. (b) The XMCD-PEEM image displays the in-plane magnetization component parallel to the incident beam. The beam direction is sketched by the white arrow. Due to grazing incidence of the photons (74° with respect to the plane normal) the back side of the island is shadowed; thus it appears dark in the XMCD-PEEM image.

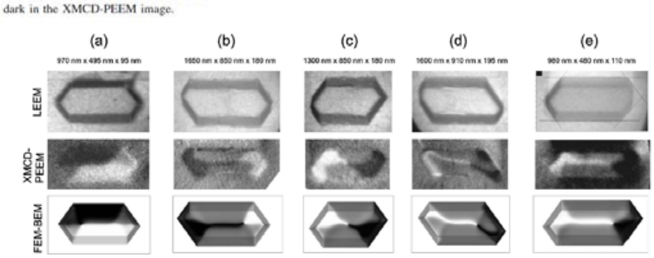
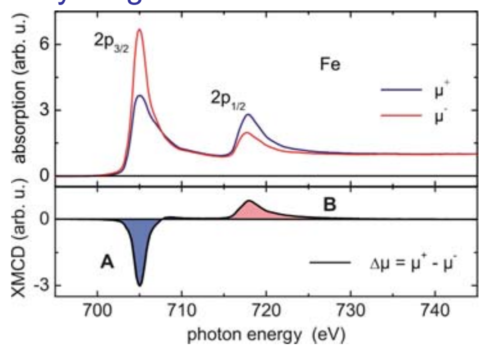
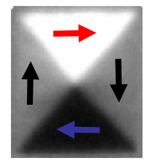


FIG. 6. Experimental and simulated data for five self-assembled Fe/Mo(110) islands of different size and shape (a)–(e). *First row*: The shape of the particle is obtained by LEEM imaging. The particle thickness is derived from the width of the (001) facets, which appear as a dark border around the hexagonal top surface, by using the known inclination angles of the inclined facets (cf. Fig. 1). The sample's approximate lateral dimension and thickness is displayed on top of each column. *Second row*: One magnetization component in the surface plane is imaged as grey scale with XMCD-PEEM. In sample (a), the contrast refers to the magnetization component parallel to the long edge while in the other samples the in-plane magnetization component perpendicular to the long edge is displayed. Notice that only the top surface, i.e., the light grey internal hexagon in the first row, is imaged. *Third row*: Micromagnetic simulation results. To compare the results with the XMCD-PEEM experiments, the same magnetization component is displayed in grey scale. The sample shape was modeled according to the LEEM images and the model explained in Fig. 1.

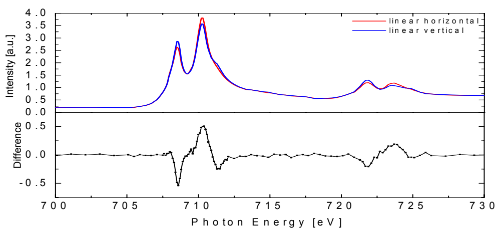
X-ray Magnetic Circular Dichroism (XMCD)



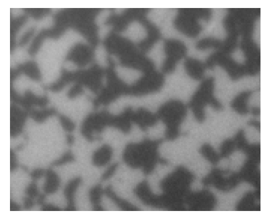
XMCD ~ **M** cos(**M**,**S**)



X-ray Magnetic Linear Dichroism (XMCD)



XMLD ~ <M^2>



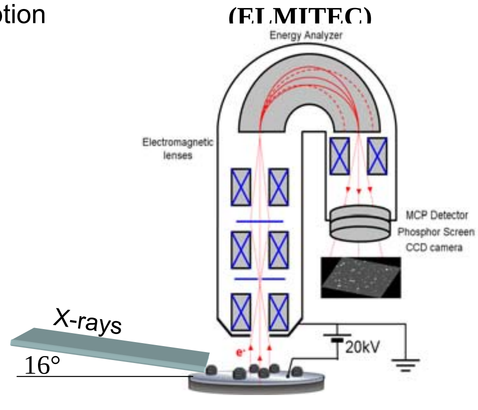
Photoemission Electron Microscopy using X-Rays

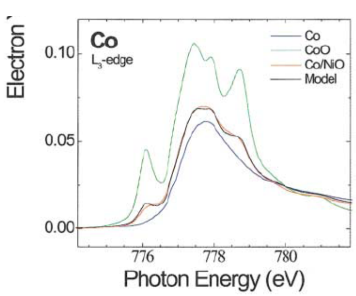
PAUL SCHERRER INSTITUT PSI

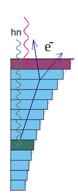
Schematic layout of the PEEM (ELMITEC)

Spatially resolved X-ray absorption spectroscopy

Sensitive to:
- elemental composition
- chemical bonds
- structural parameters
- electronic structure
- magnetic properties

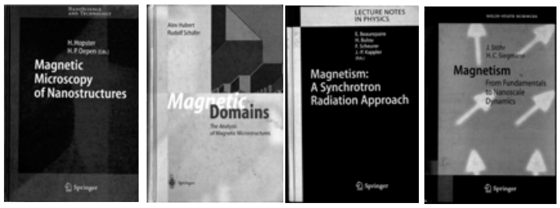






Probing surface/interface

Some good books/ reviews



Magnetic imaging,
F U Hillebrecht, J. Phys.: Condens. Matter 13, 11163 (2001)

Photoelectron microscopy and applications in surface and materials science,
S. Günther, B. Kaulich, L. Gregoratti, M. Kiskinova, Progress in Surface Science 70, 187 (2002)

Recent advances in chemical and magnetic imaging of surfaces and interfaces by XPEEM,
A Locatelli and E Bauer J. Phys.: Condens. Matter 20, 093002 (2008)

Principles of X-ray magnetic dichroism spectromicroscopy,
J. Stöhr, S. Anders, T. Stammler, and M.R. Scheinfein, Surface Review and Letters, 5, 1297 (1998)

Brief History PEEM

1930s Electron lenses/electron microscopy
Photoemission electron microscope (PEEM)
E. Brueche, Z. Phys. (1933) 448
Low Energy Electron Diffraction (LEED)
W. Ehrenberg, Philos. Mag. **18** (1934) 878

1960s improved LEED
E.J. Scheibner, L.H. Germer and C.D. Hartman,
Rev. Sci. Instrum. **31** (1960) 112
Invention of Low energy electron microscop (LEEM) by Ernst Bauer
Glass-Based Vacuum Apparatus (1962)

1985 First Operational LEEM Instrument
Telieps and Bauer, Ultramicroscopy **17** (1985) 57

1991 IBM LEEM-I
Tromp and Reuter

Since 1990 several groups and companies:
Elmitec LEEM (Former Coworkers of E. Bauer)
Staib, Omicron
Schoenhense, Kirschner
De Stasio

Synchrotron based PEEM
pioneering G. Harp and B. Tonner, Rev. Sci. Instrum. 59 (1988) 853
Magnetism: Stöhr et al, Science 259 (1993) 658

Since 2000
world wide several beamlines for PEEM

Future
Aberration-corrected instruments (SMART / Germany, PEEMIII / USA)
spatial resolution ~ nm

Reviews (X-PEEM)
J. Stöhr et al., Surf. Rev. Lett. **6** (1998) 1297
E. Bauer, J. Phys.: Condens Matter **13** (2001) 11391
Th Schmidt et al., Surf. Rev. Lett. **9** (2002) 223