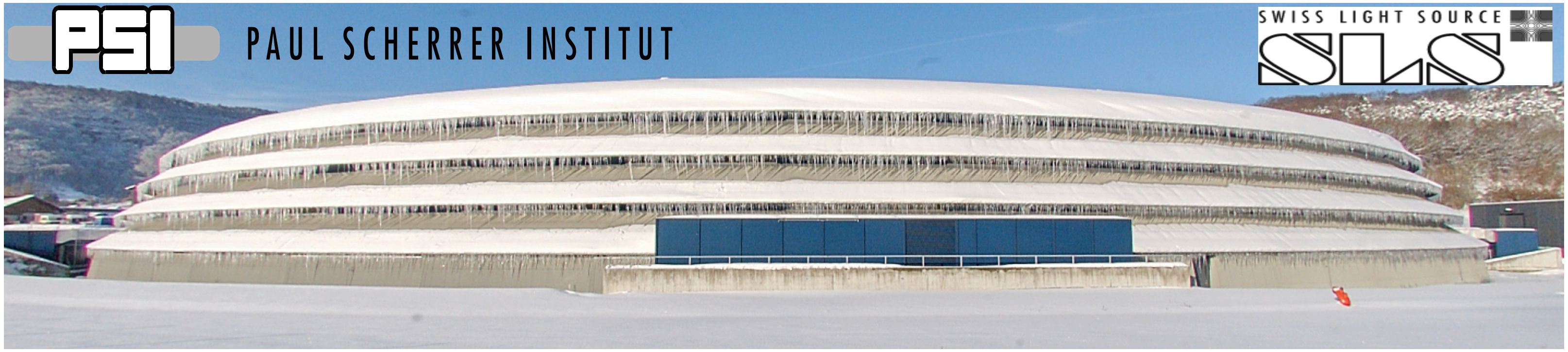
X-Ray Microscopy Techniques



The Swiss Light Source, Paul Scherrer Institut

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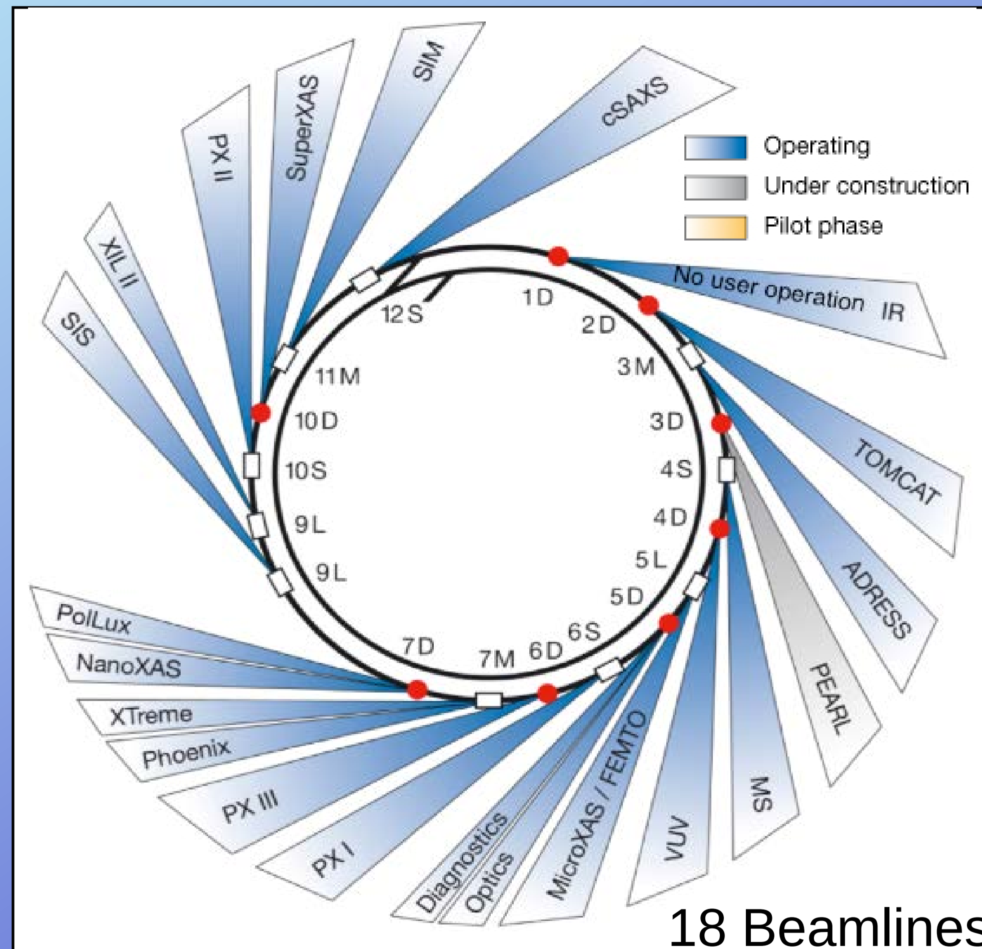
- The electrons are accelerated close to the speed of light in a linear accelerator and injected into the storage ring
- Bending magnets or insertion devices (wigglers or undulators) cause electrons to bend or wobble through the section and emit light.



Reference energy: 2.4 GeV

Circumference: 288 m

Current: 350 mA (**400 mA)**

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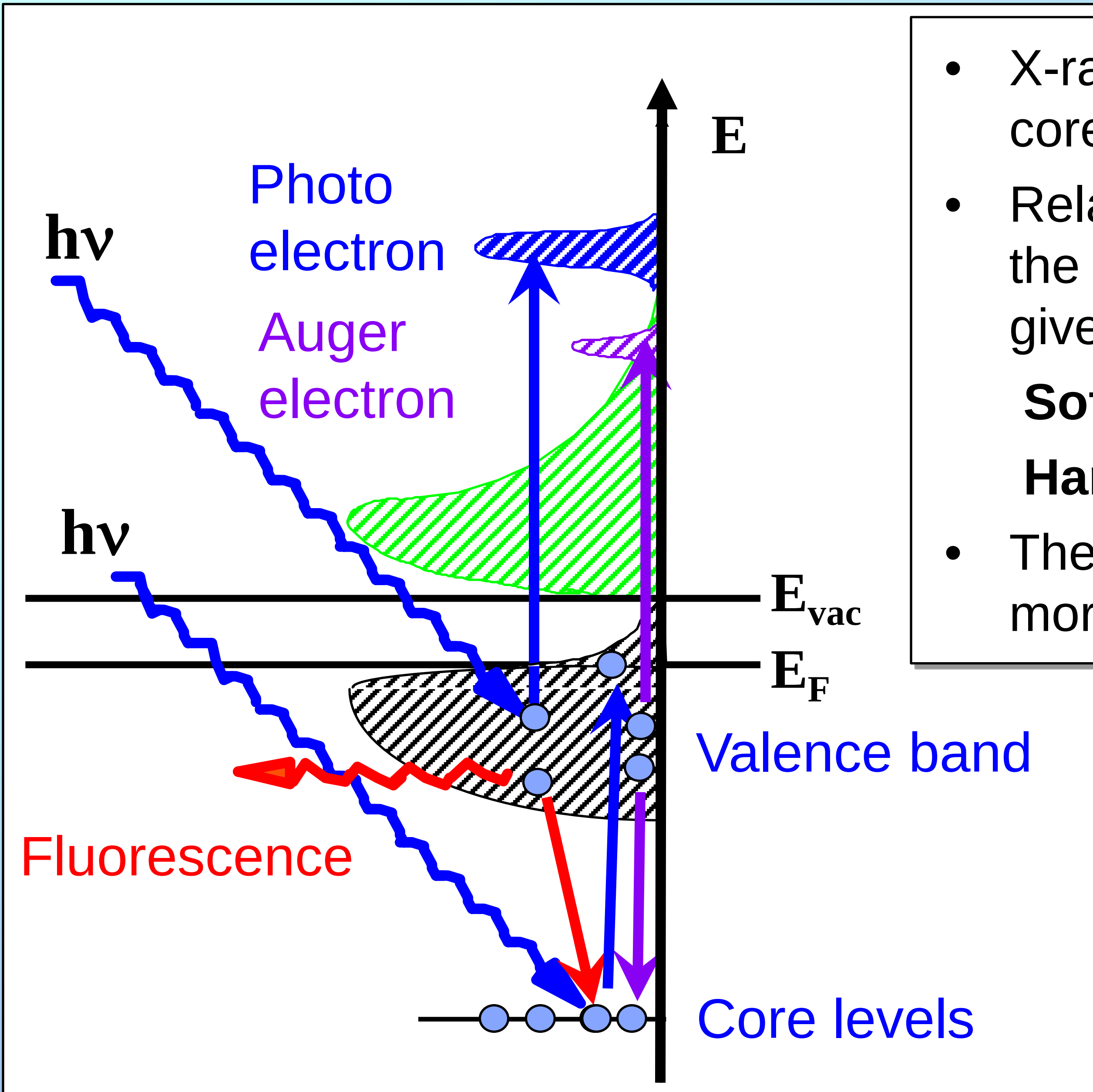
X-ray Absorption Spectroscopy



- X-rays excite an electron from the core to the valence band
- Relaxation of the electron from the valence to the core level gives:

  Soft x-rays: more Auger es

  Hard x-rays: more fluorescence
- Therefore different interactions: more than just imaging

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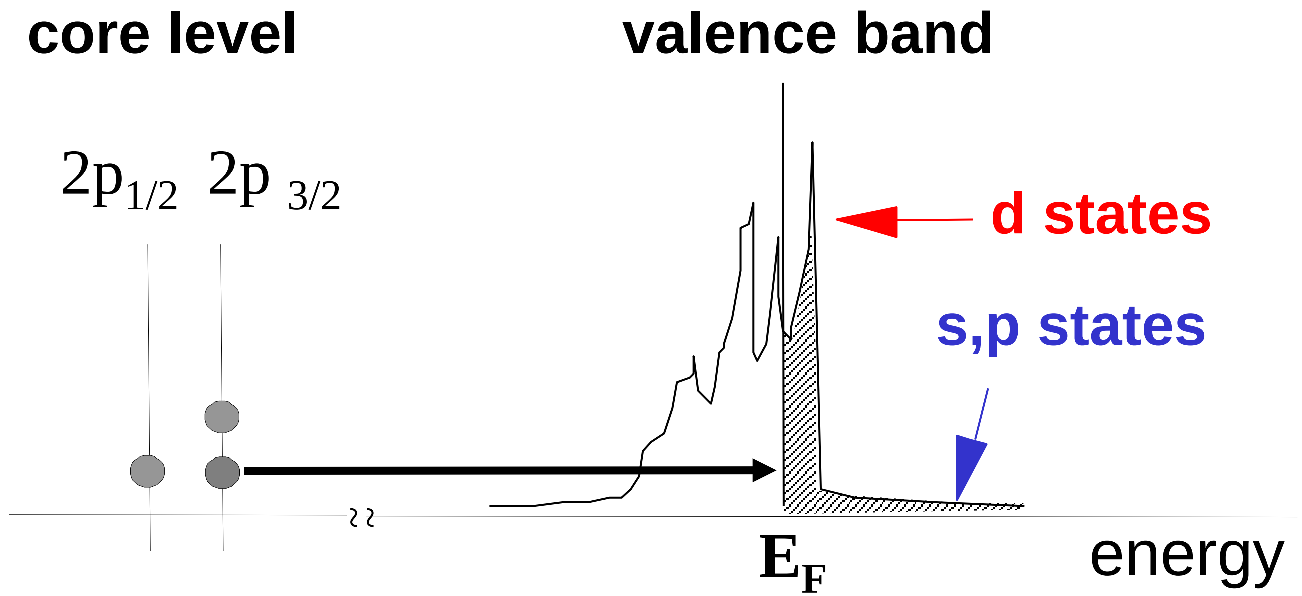
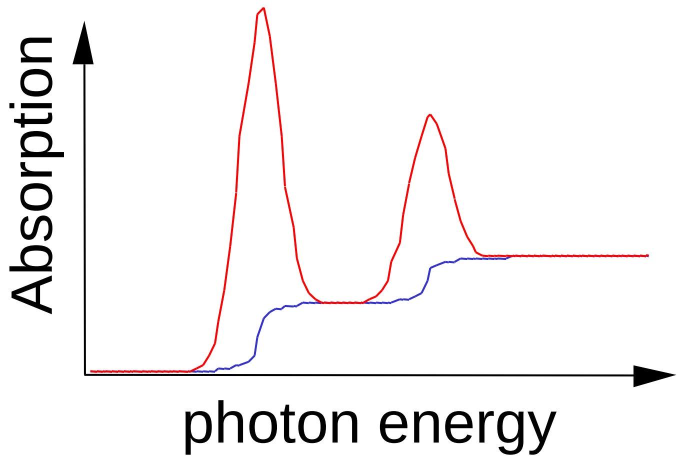
X-ray Absorption Spectroscopy

Spectrum:
change energy & observe absorption:





- Peak corresponds to (set of) transition(s) from core level to valence band
- Density of unoccupied states above Fermi level
- Each element: own characteristic peaks

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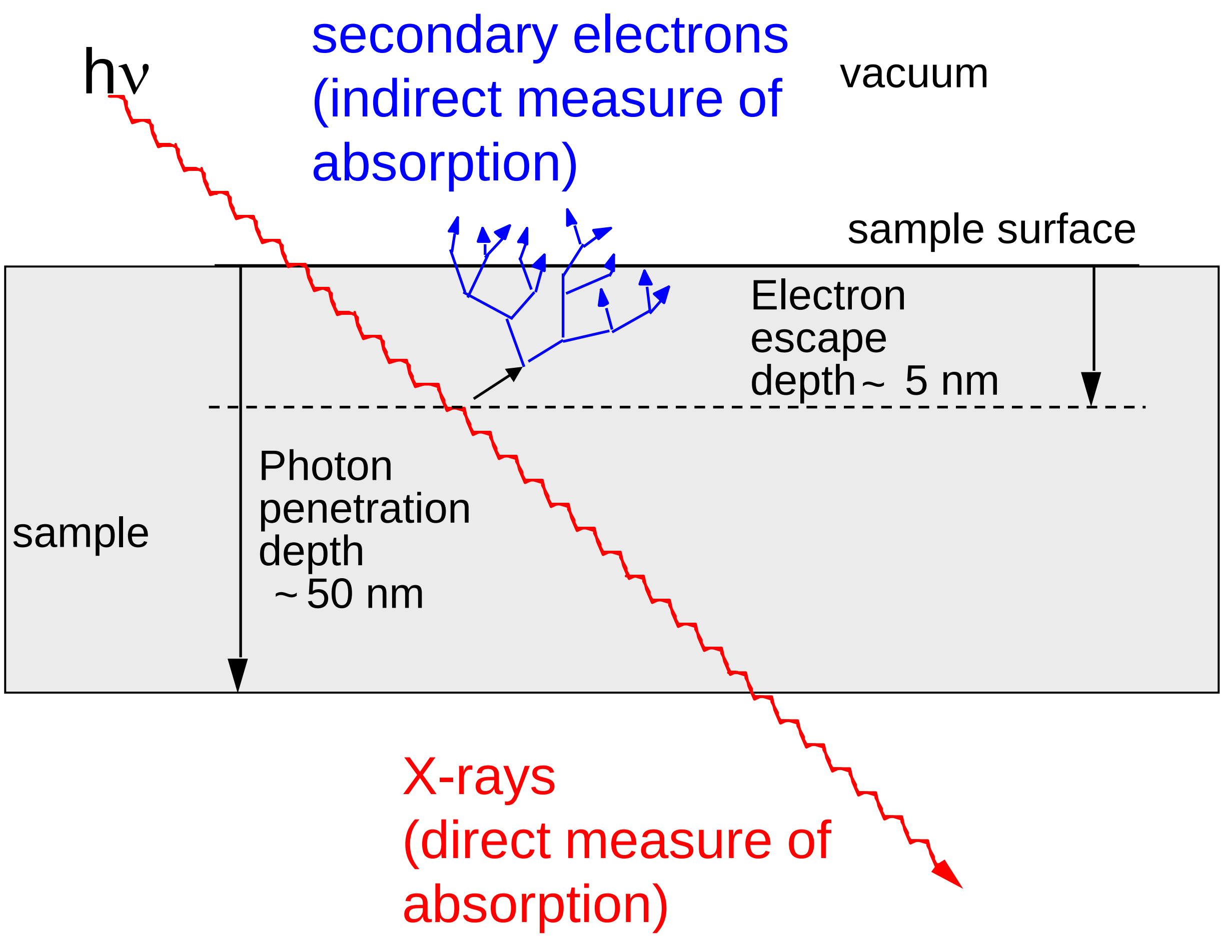
PEEM & TXM



Photoemission Electron Microscopy (PEEM) to probe surface / interfaces

Transmission X-ray Microscopy (TXM)

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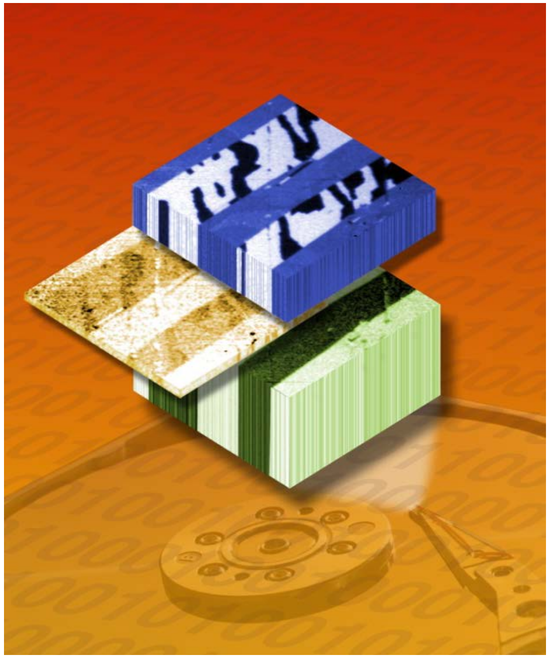
Photoemission Electron Microscopy



Slow electrons: mean free path is submono to several monolayers (few nm's)

Surfaces, thin films and interfaces

….consequences for electron optics.

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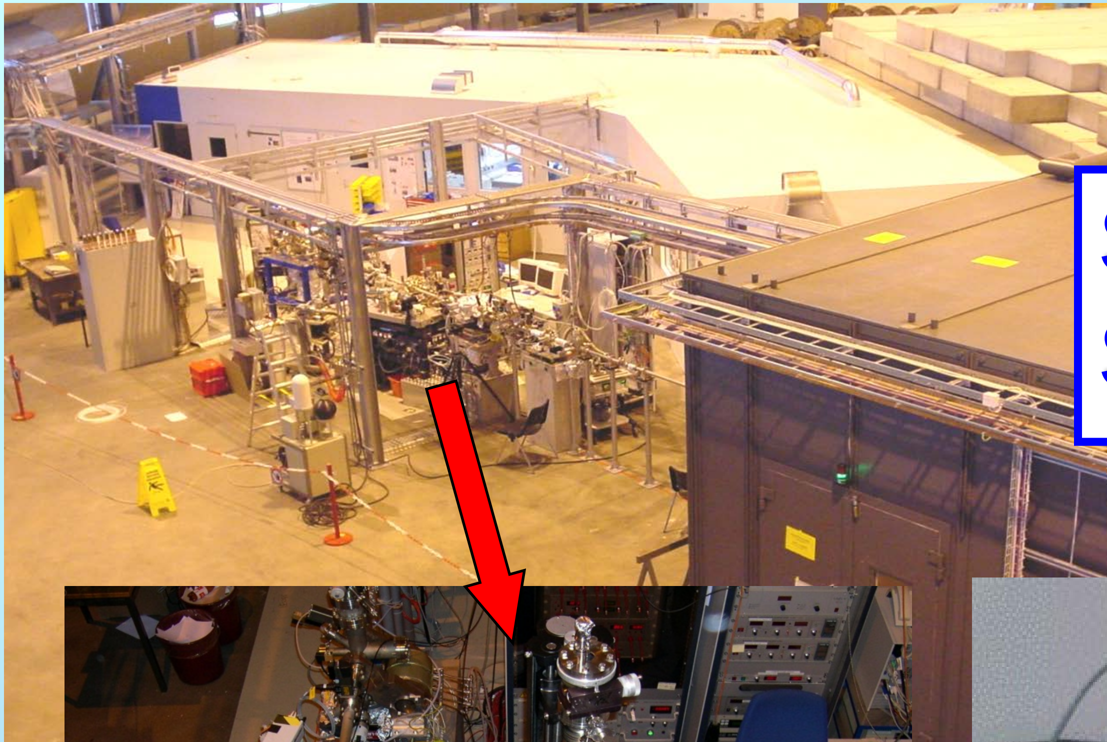
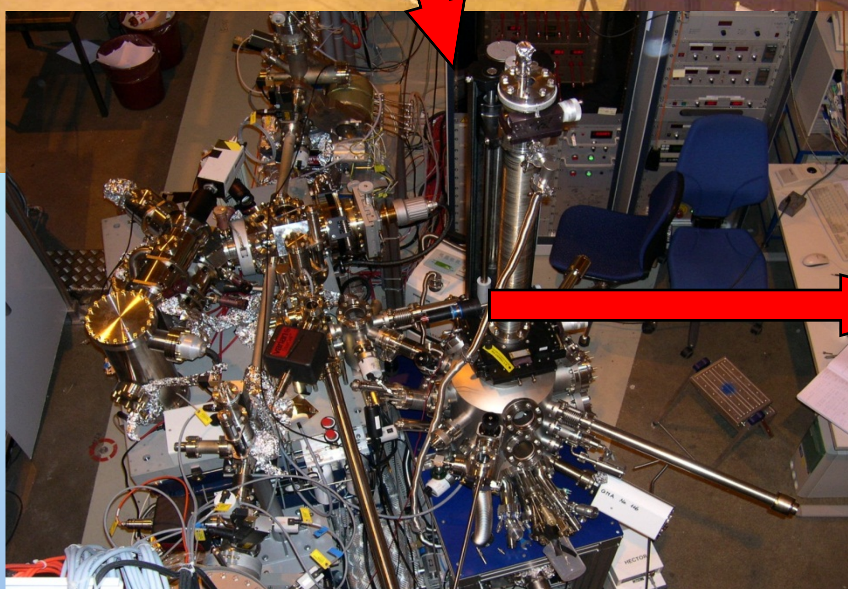
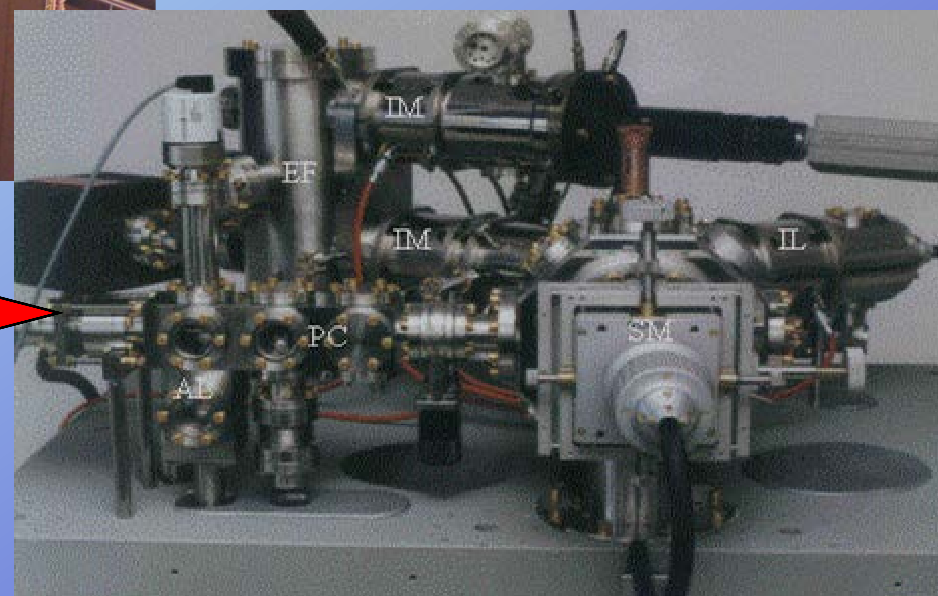
The Surface and Interface Microscopy (SIM) Beamline



SIM Beamline,
Swiss Light Source

Close-up of the PEEM





The Photoemission Electron Microscope (PEEM)

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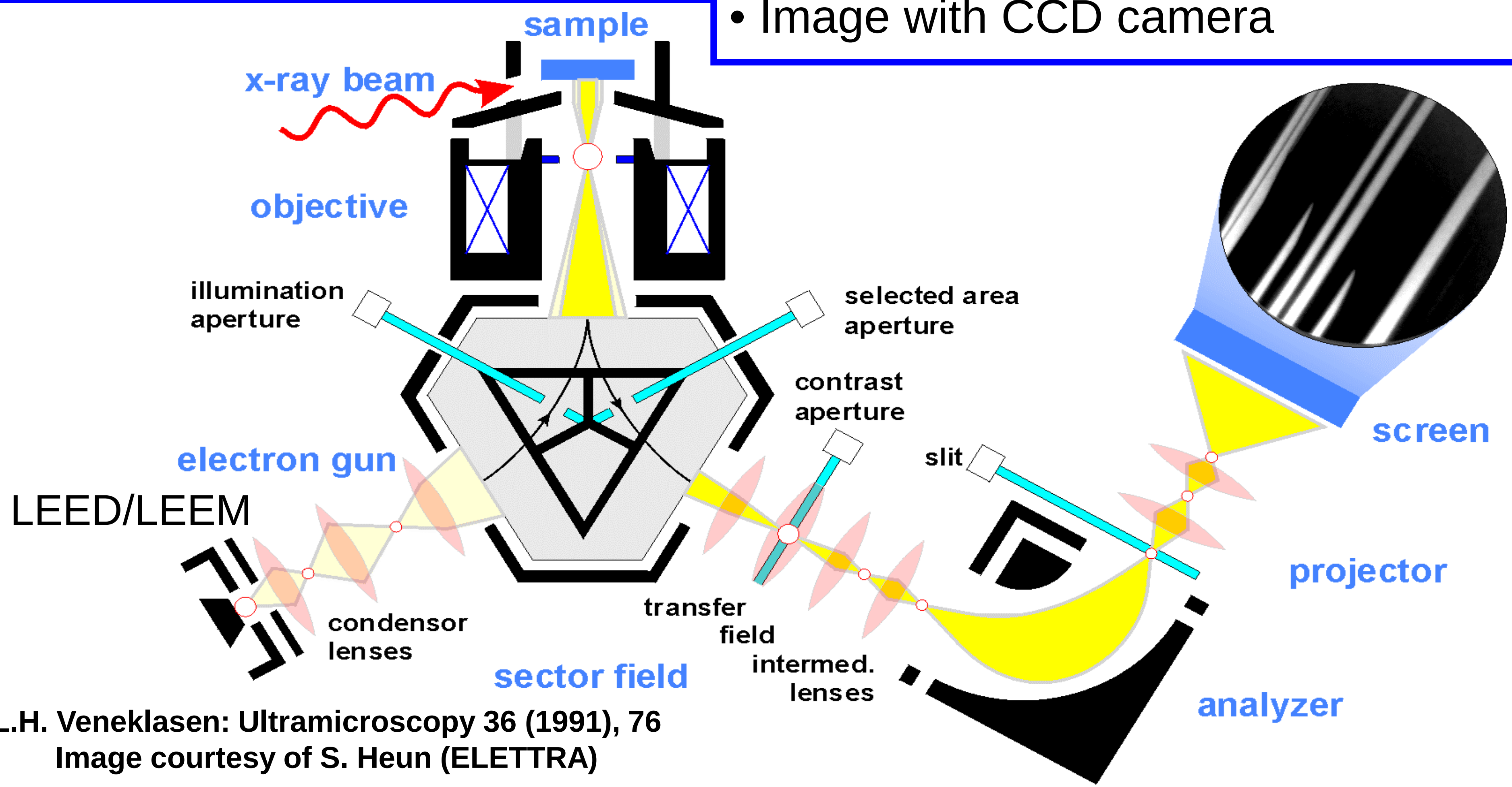
Spectromicroscope

- Channel plate: amplifies electrons
- Phosophor screen: converts to light
- Image with CCD camera



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

Elmitec Elektronenmikroskopie GmbH
Clausthal-Zellerfeld, Germany

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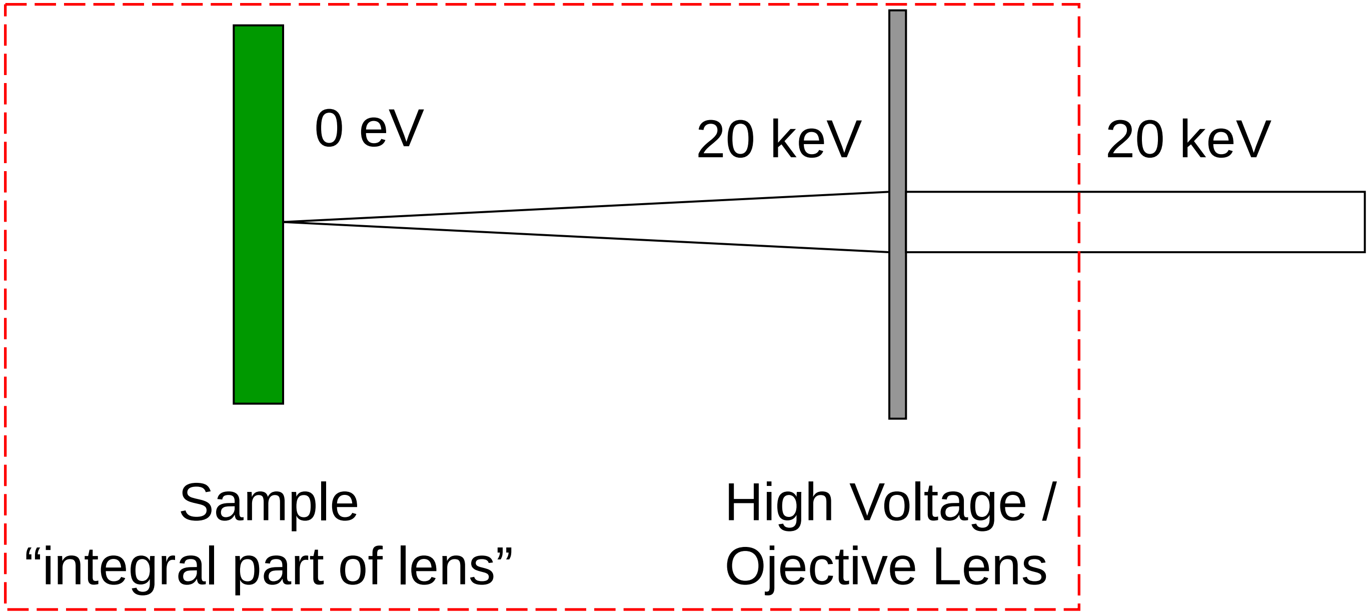
Slow Electrons

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

Lens Equivalent has two functions: accelerating field due to potential & focussing function



High voltage:

- reduced sensitivity to external magnetic fields
- reduced energy spread and smaller electron beam diameters

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

Cathode lens: Sample is cathode
electron microscope is anode

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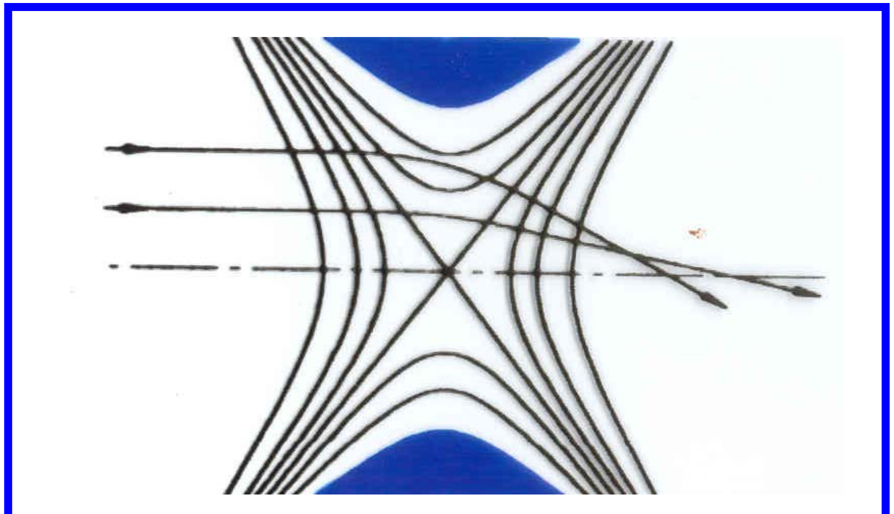
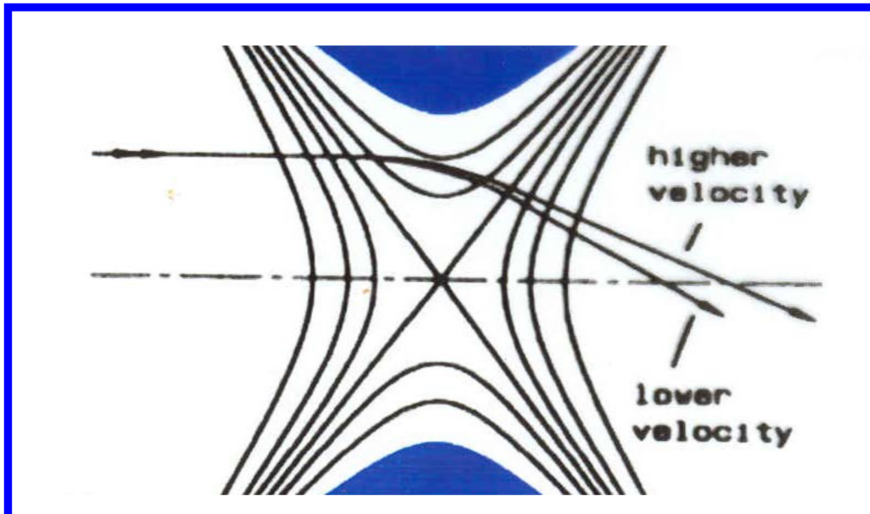
Two Kinds of Aberrations

Spherical



Beams parallel away from the lens axis are focused in a slightly different place than beams close to the axis and therefore a blurring of the image.

Chromatic



Different wavelengths of light are focused to different positions.

Light ➔ electrons
Glass ➔ electrostatic/magnetic lenses

http://en.wikipedia.org/wiki/Lens_(optics)#Spherical_aberration

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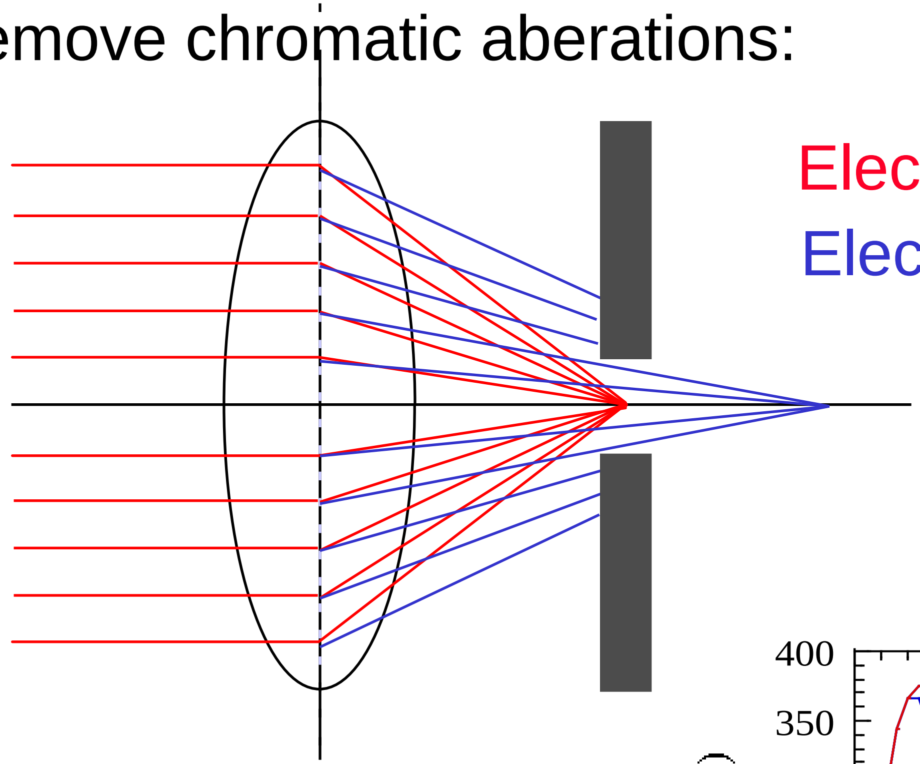
Energy Filter

To remove chromatic aberations:

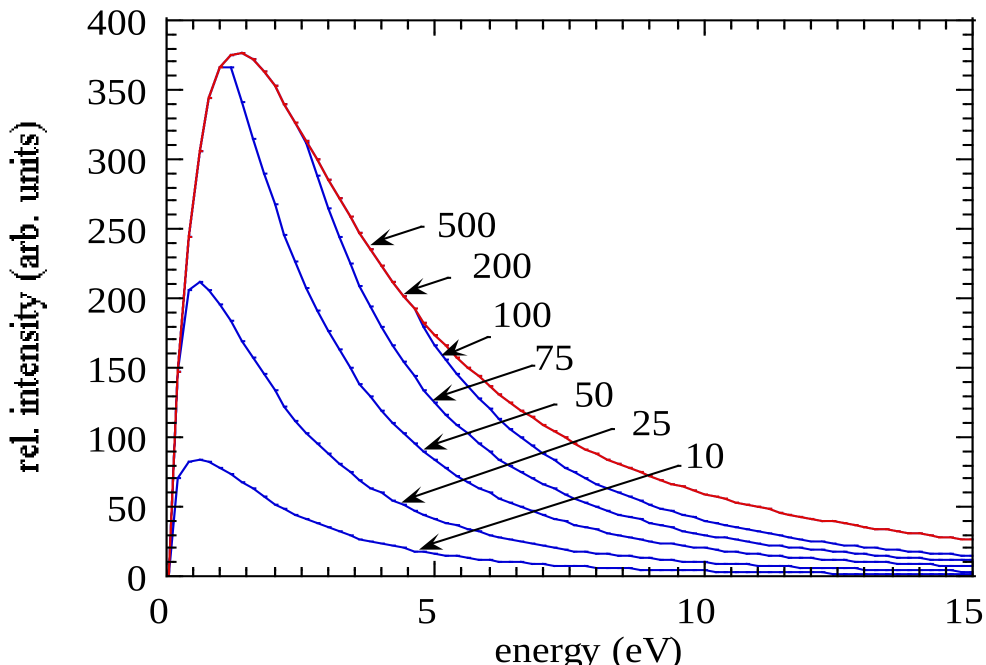


Electron energy E

Electron energy E+ΔE

Aperture cuts off transmission of electrons with higher energy

Energy distribution is narrowed but transmission (intensity) is reduced. Therefore need to find compromise.



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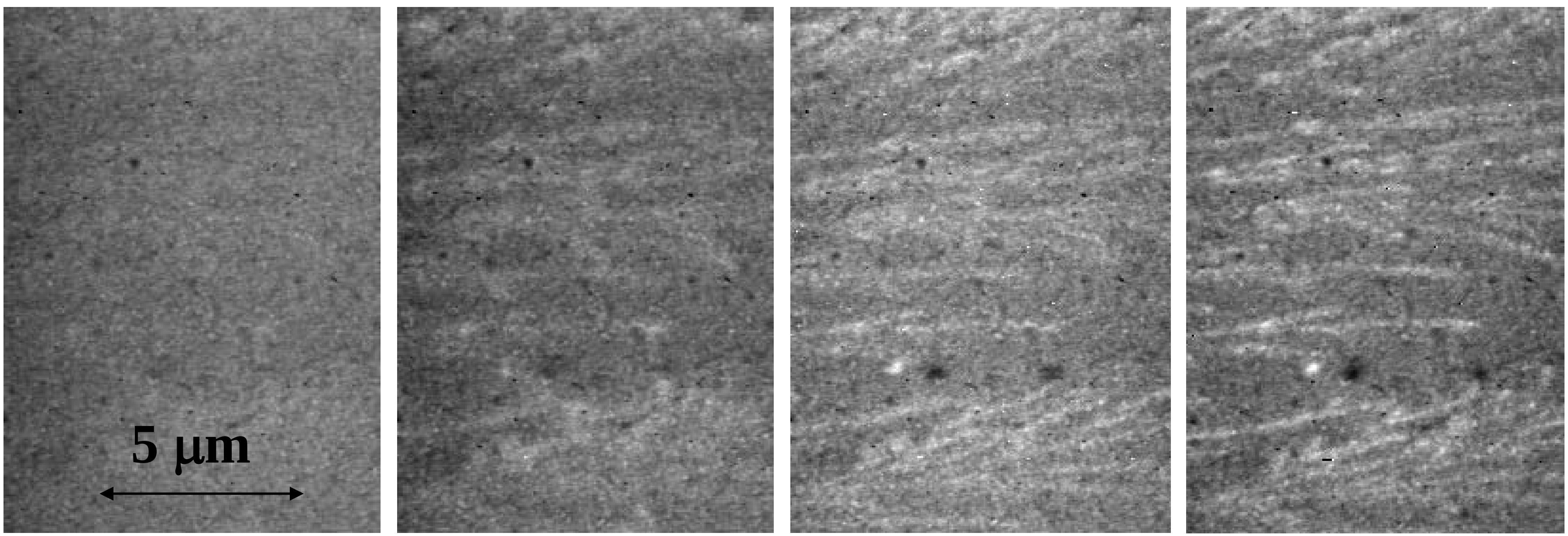
Effect of aperture size on resolution

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



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Spatial Resolution for Magnetic Imaging

PEEM with X-rays: **50-20 nm** spatial resolution

Aberration-corrected instruments using an electron mirror:

SMART (spectromicroscope for all relevant techniques)
- at BESSY II, Berlin, Germany
- collaboration of seven Universities in Germany

PEEM III
- at ALS, Berkeley, USA
- mainly ALS

down to a few nm spatial resolution

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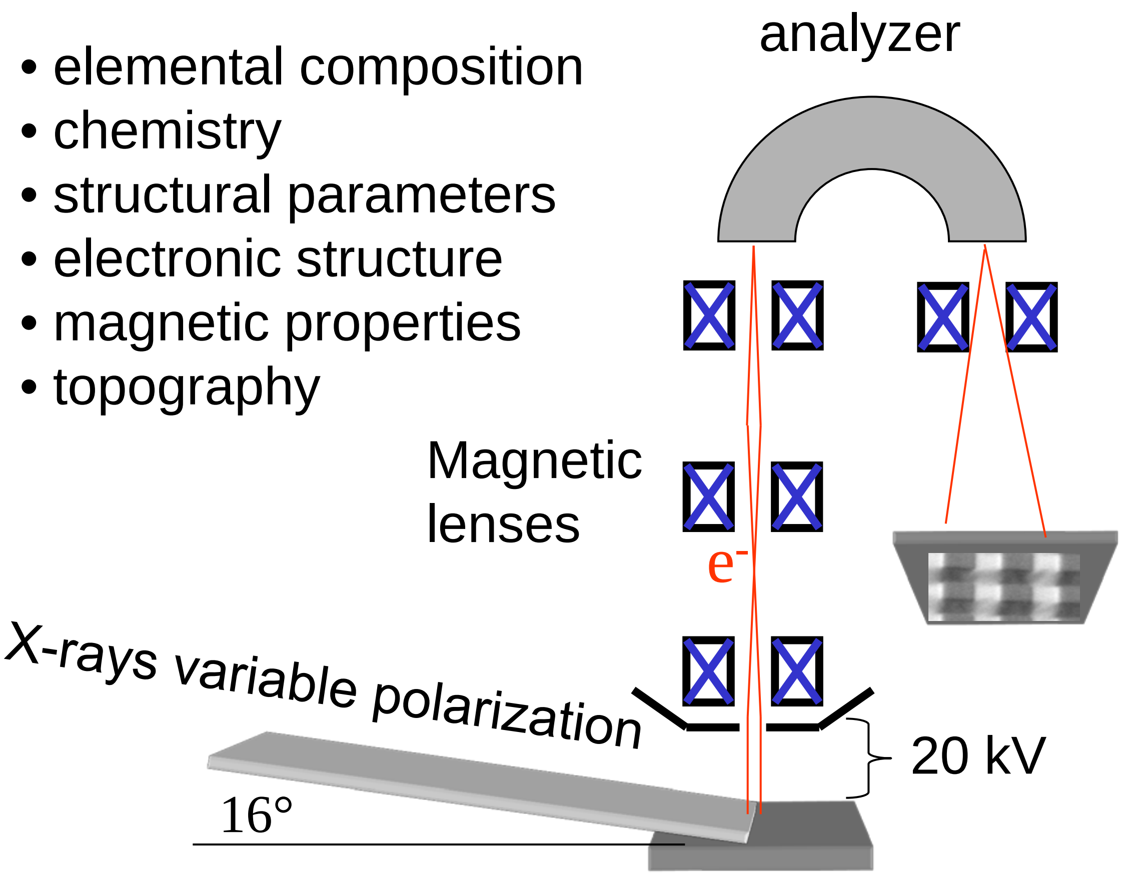
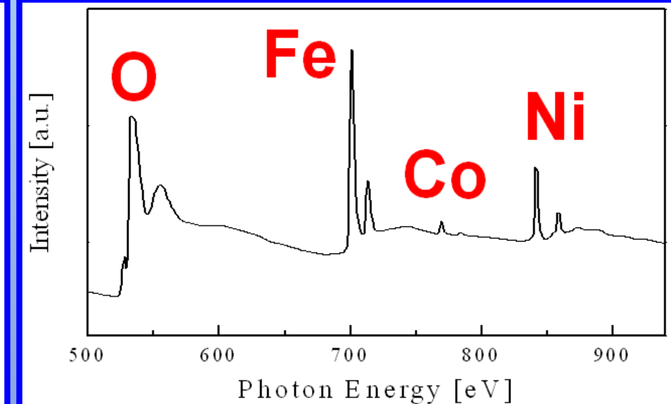
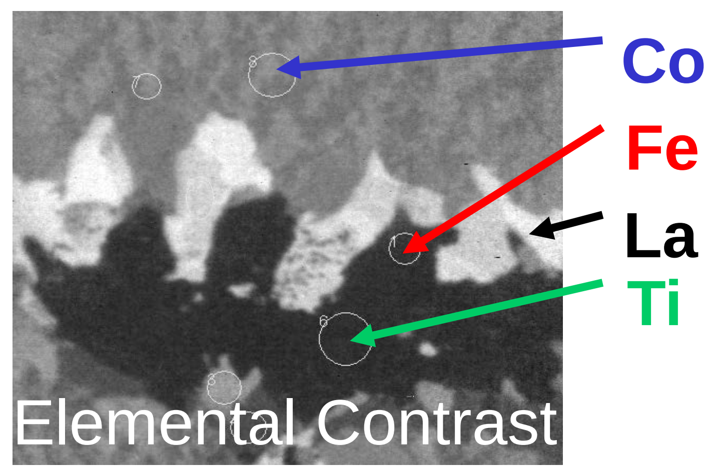
Photoemission Electron Microscope SIM beamline (SLS)

Armin Kleibert
Carlos Vaz

- elemental composition
- chemistry
- structural parameters
- electronic structure
- magnetic properties
- topography







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Photoemission Electron Microscope
SIM beamline (SLS)

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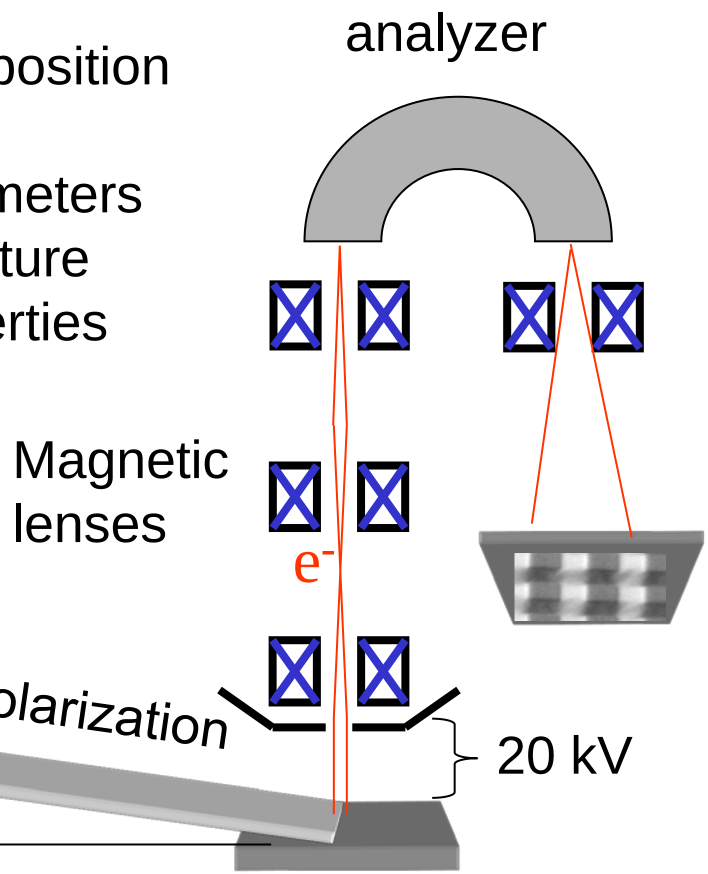
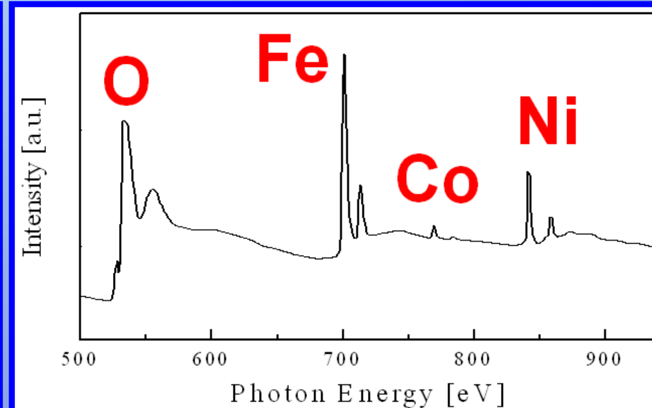
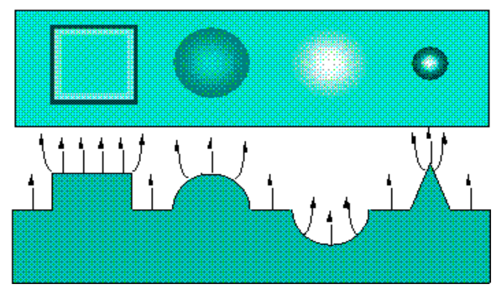




Topographical Contrast



Microfocussing due to distortion of the local electric fields

Photoemission Electron Microscope
SIM beamline (SLS)

Armin Kleibert
Carlos Vaz

- elemental composition
- chemistry
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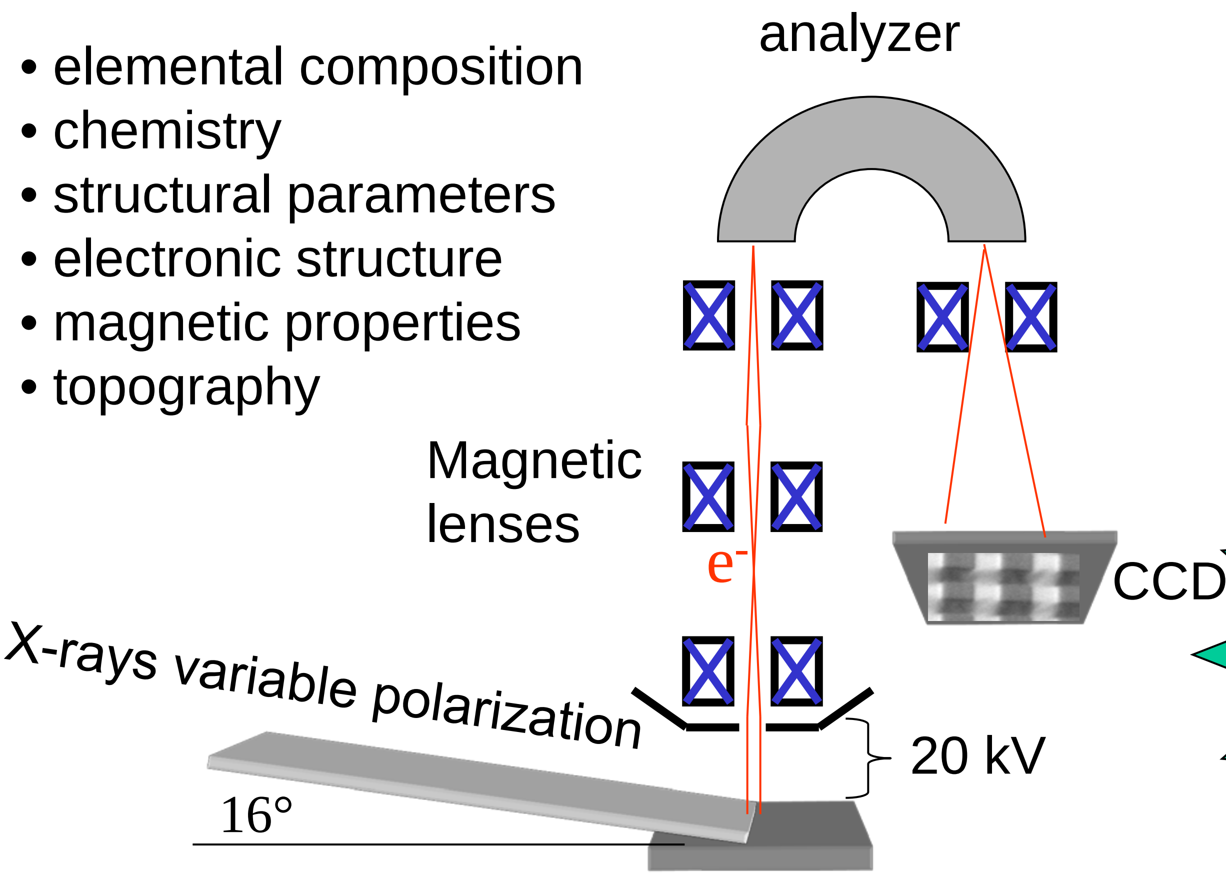

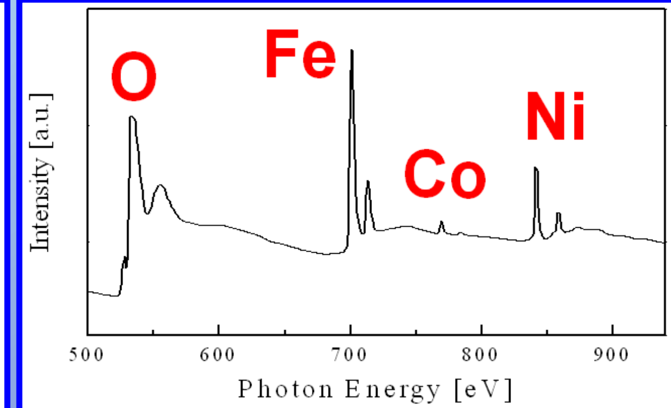

Element Specific
Antiferromagnet
Interfaces
Time Resolved

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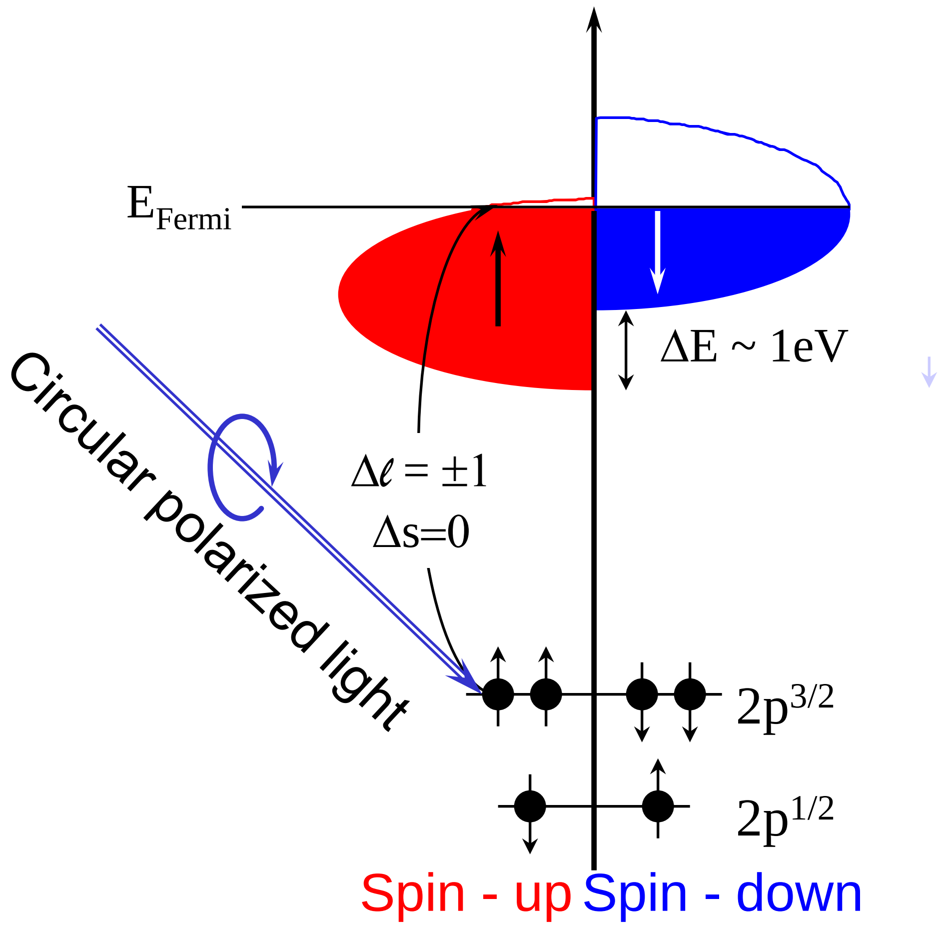
X-Ray Magnetic Circular Dichroism (XMCD)

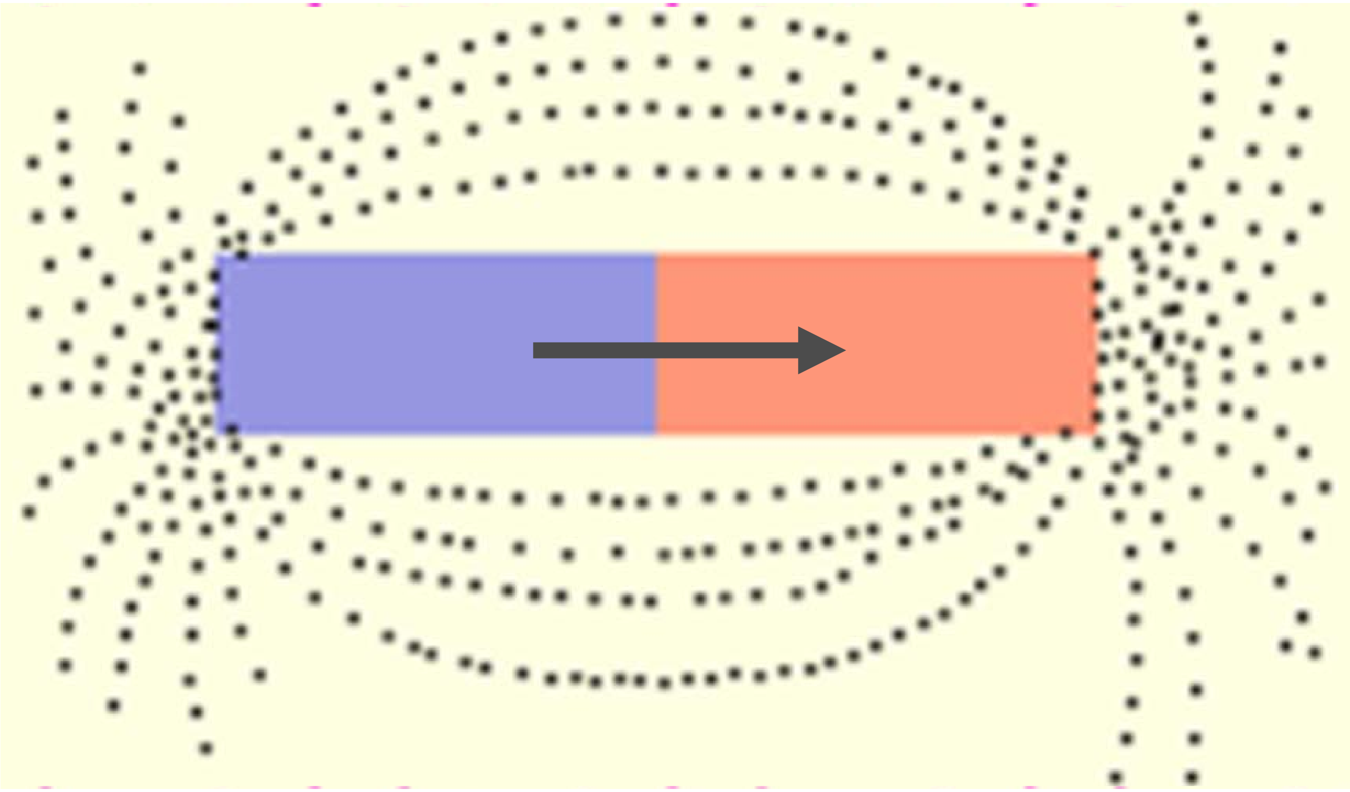


G. Schütz et al. PRL (1987)

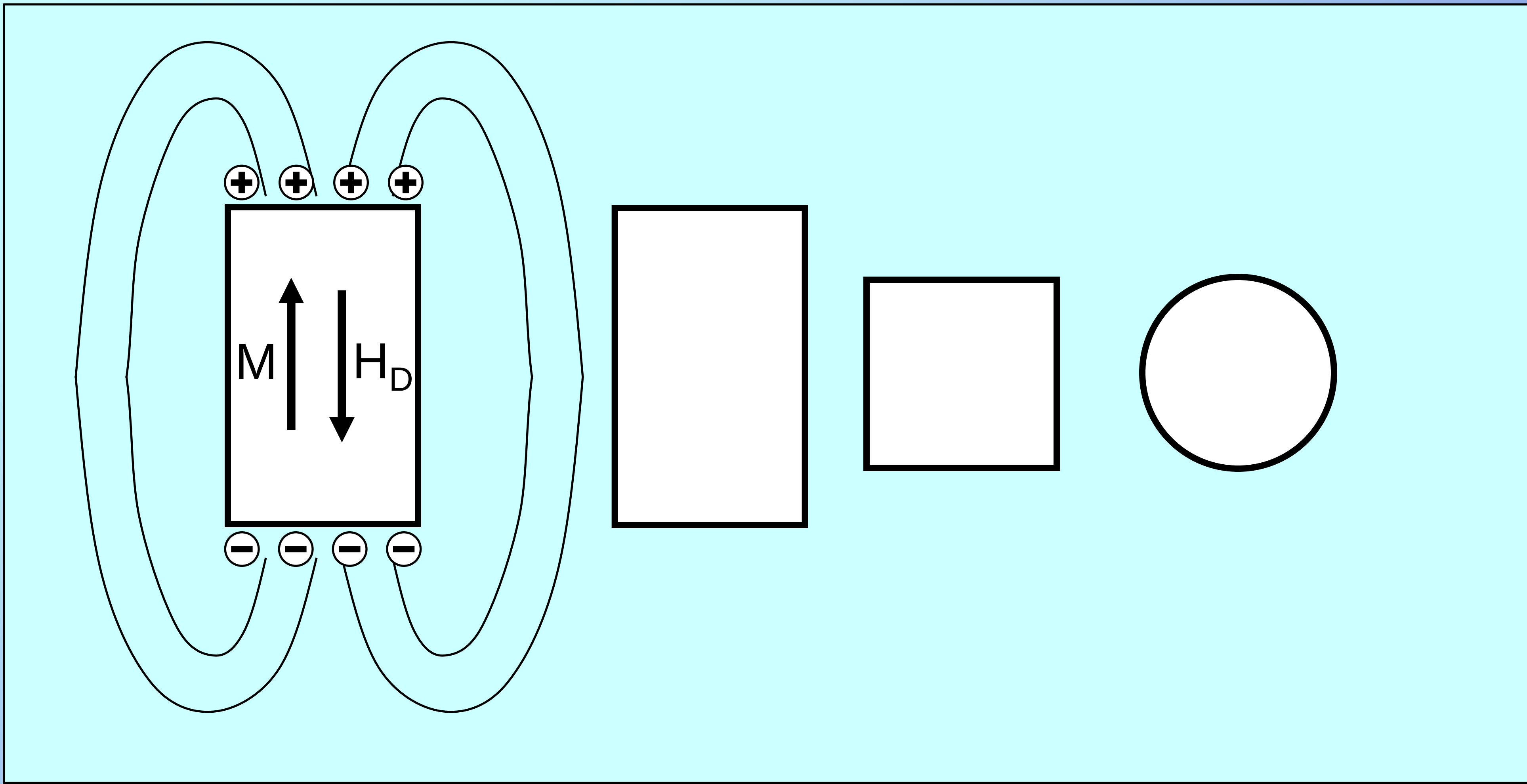
- L-edge absorption in d band transition metal
- Magnetic metal: d valence band split into spin-up and spin-down with different occupation
- Absorption of right/left circular polarisation: light mainly excites spin-up/down photoelectrons
- Spin flips forbidden: measured resonance intensity reflects number of empty d-band states of a given spin
- Can determine sizes and directions of atomic magnetic moment

Time for a game....

Magnetostatic or Stray Field Energy



Rectangle, Square, Disk



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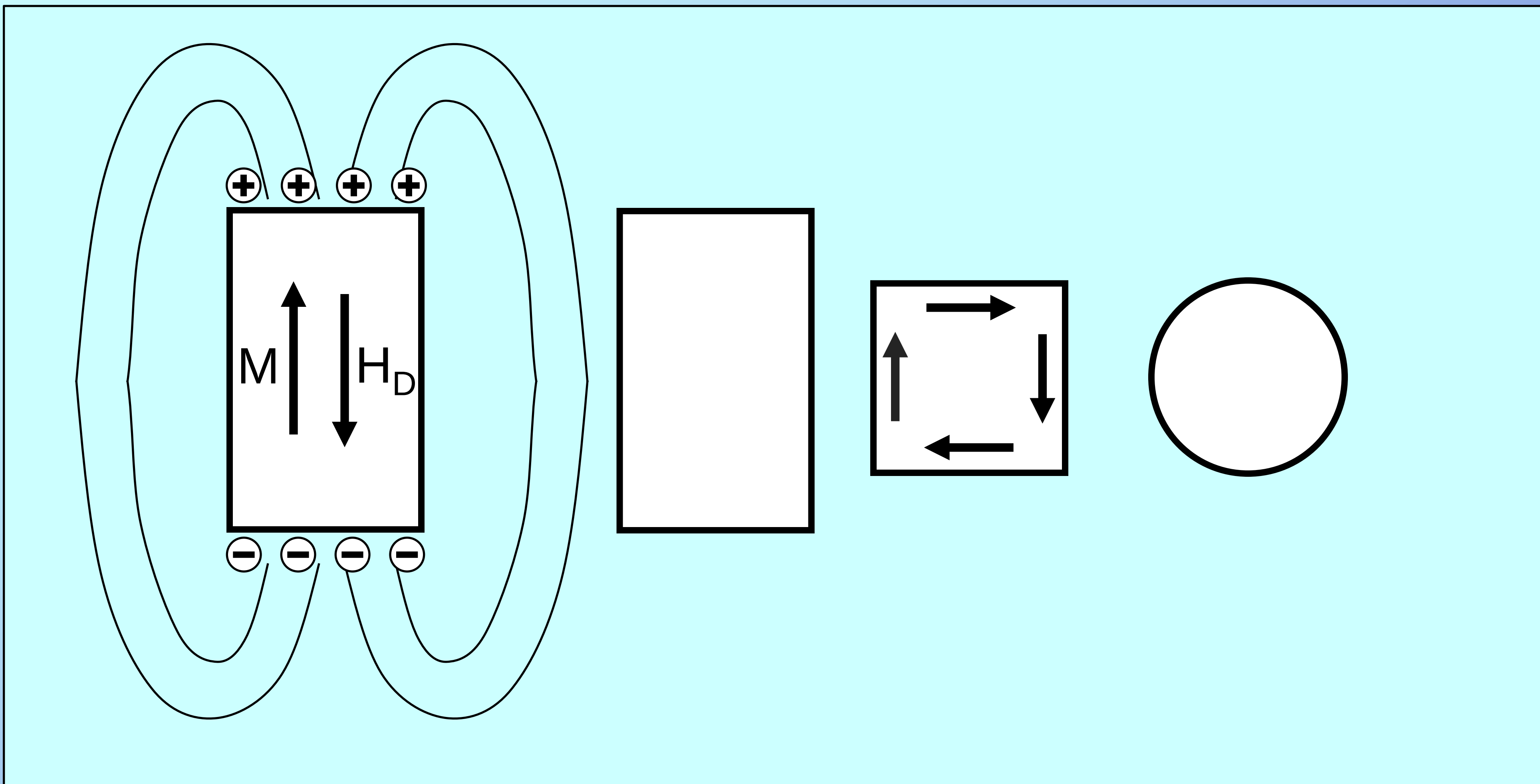
Rectangle, Square, Disk



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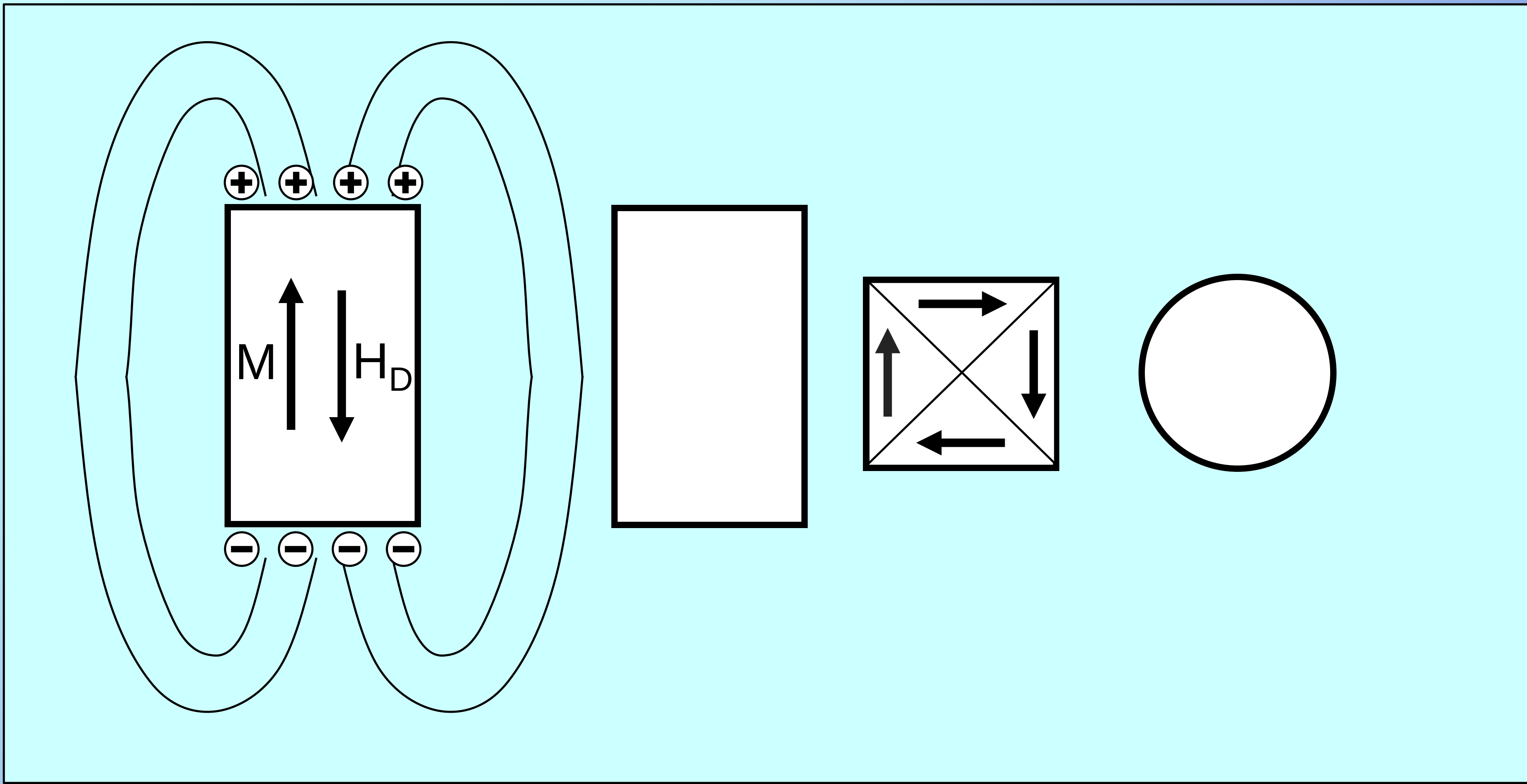
Rectangle, Square, Disk



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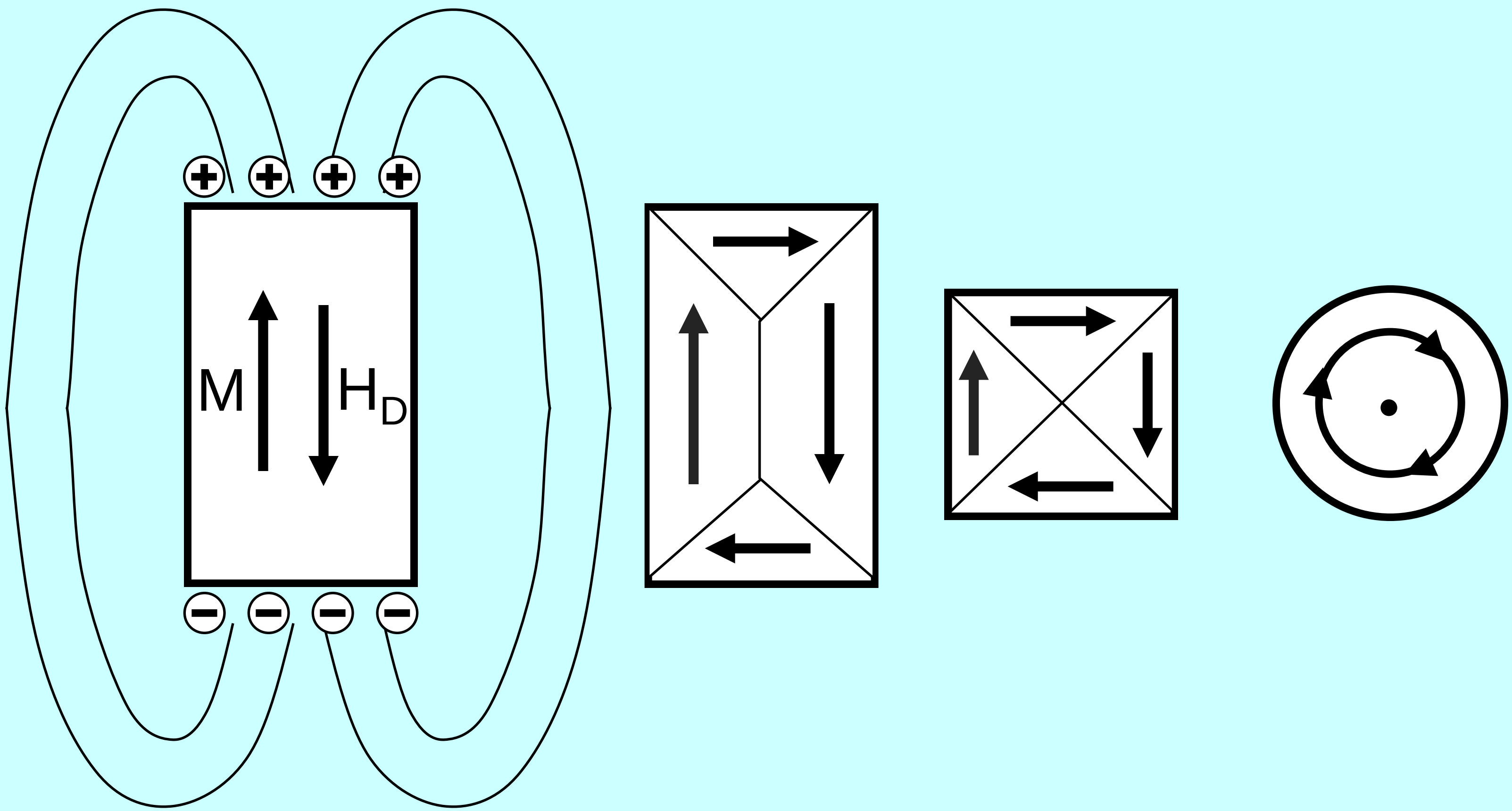
Rectangle, Square, Disk



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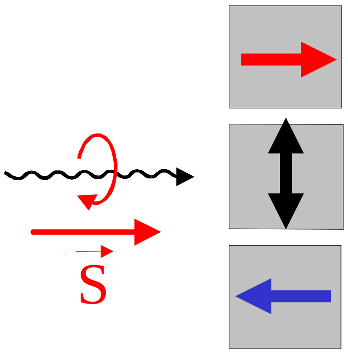
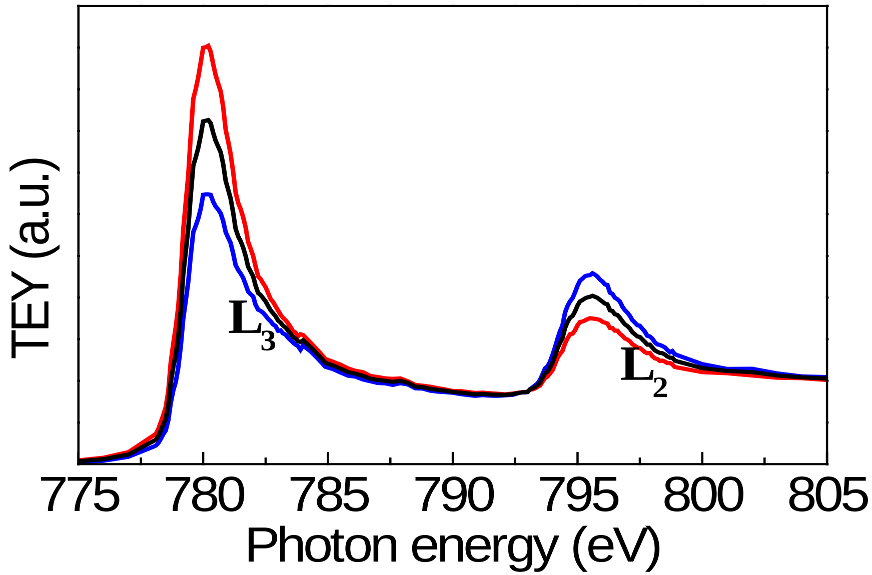
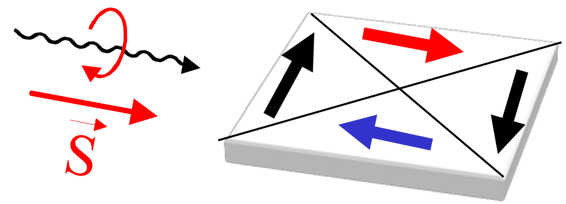
X-ray Magnetic Circular Dichroism (XMCD)

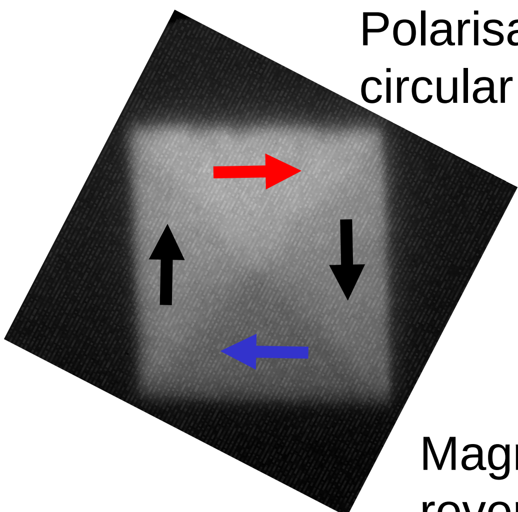




XMCD ~ **M** cos(**M**,**S**)

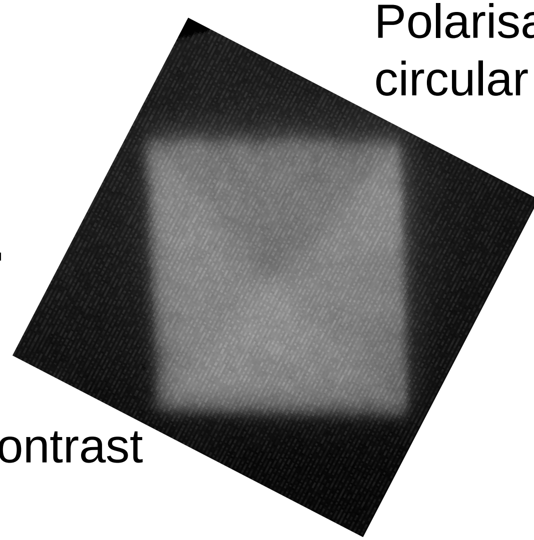


Square Ferromagnetic Element: Landau Domain Pattern



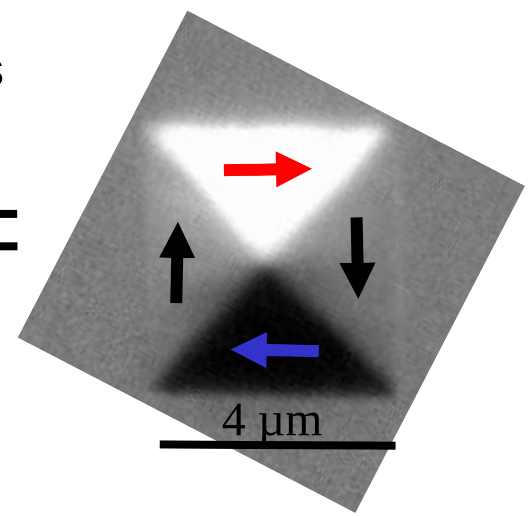
Polarisation: circular plus

—



Polarisation: circular minus

=



Magnetic contrast reverses

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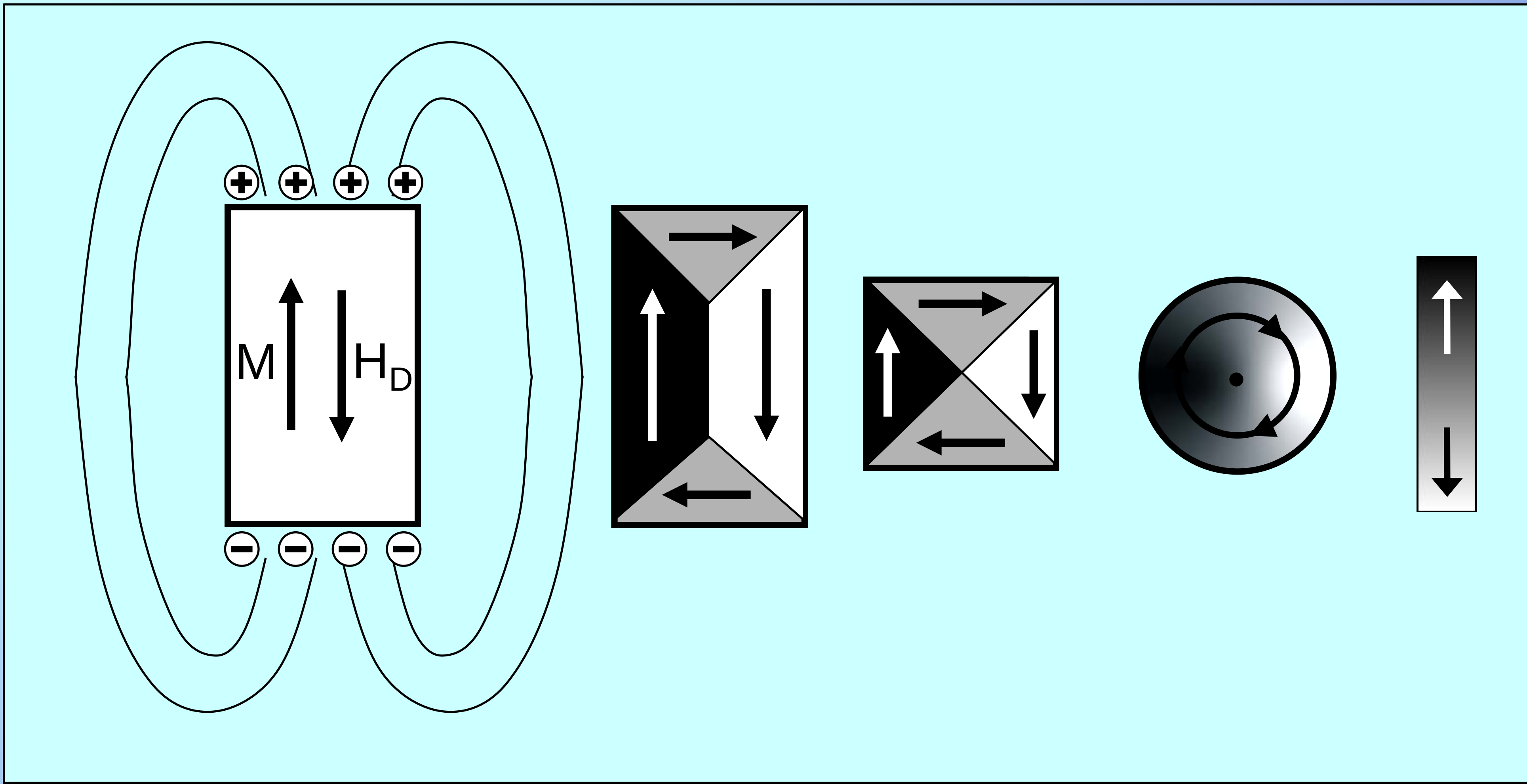
Rectangle, Square, Disk



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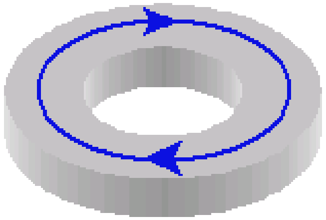
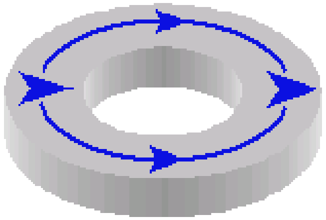
Ring



Vortex



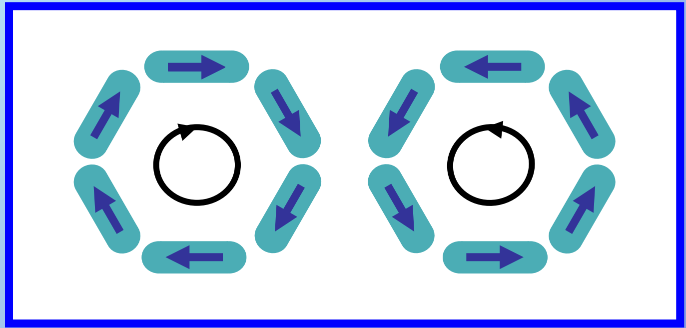
Onion

Interacting Magnets…..

….with the help of some frogs….!

Interacting Magnetic Frogs

Ring of Nanomagnets



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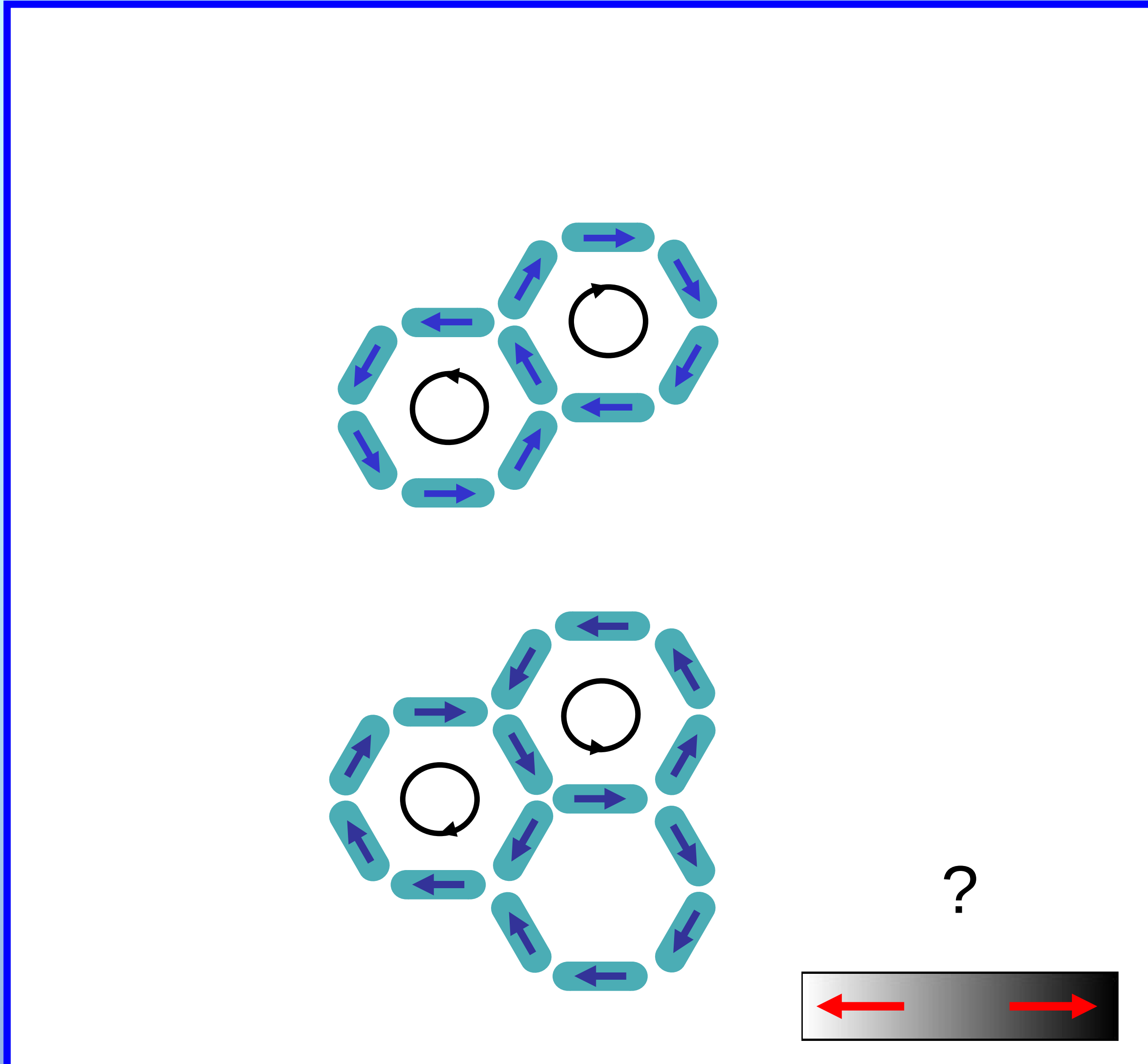
Rings of Nanomagnets



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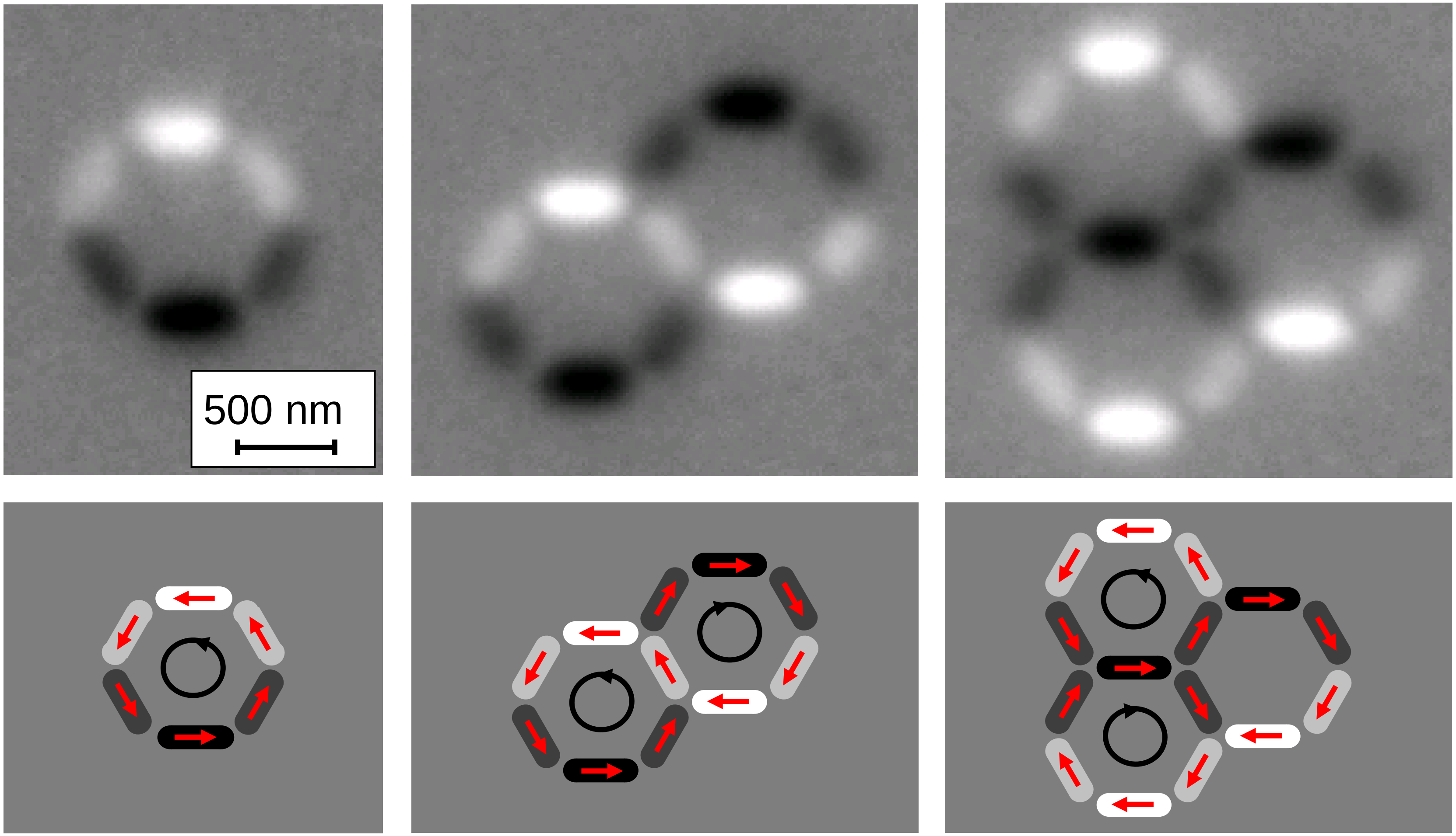
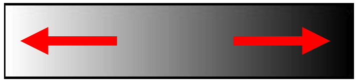
Artificial Spin Ice in PEEM

One ring **Two rings** **Three rings**





X-ray direction →

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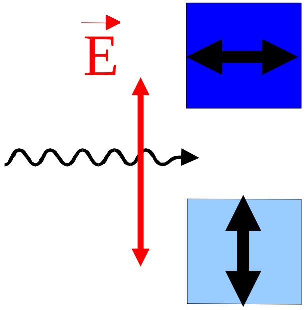
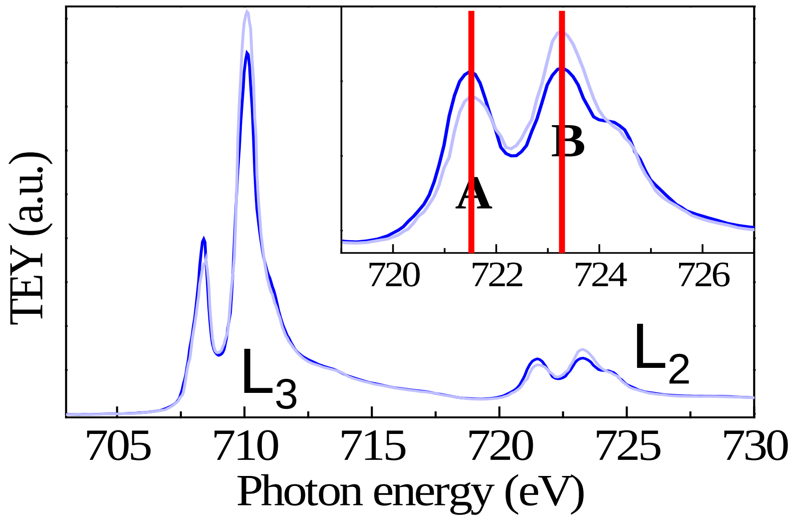
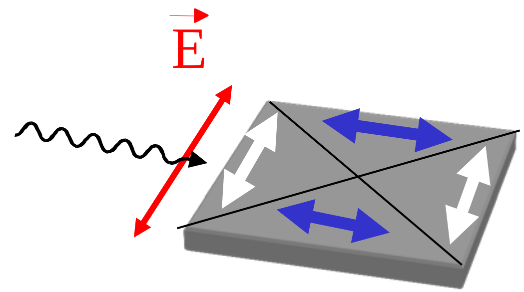
X-ray Magnetic Linear Dichroism (XMLD)



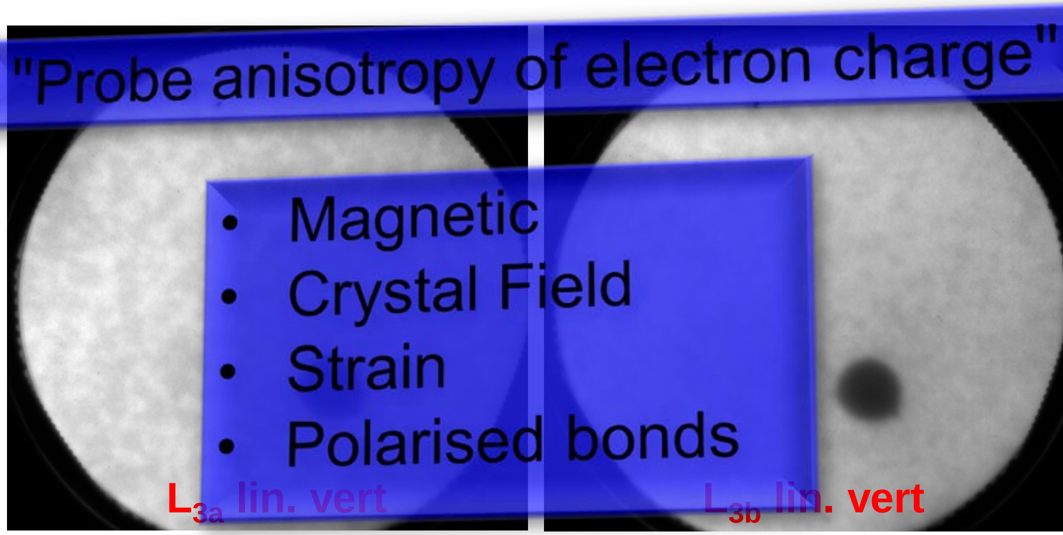


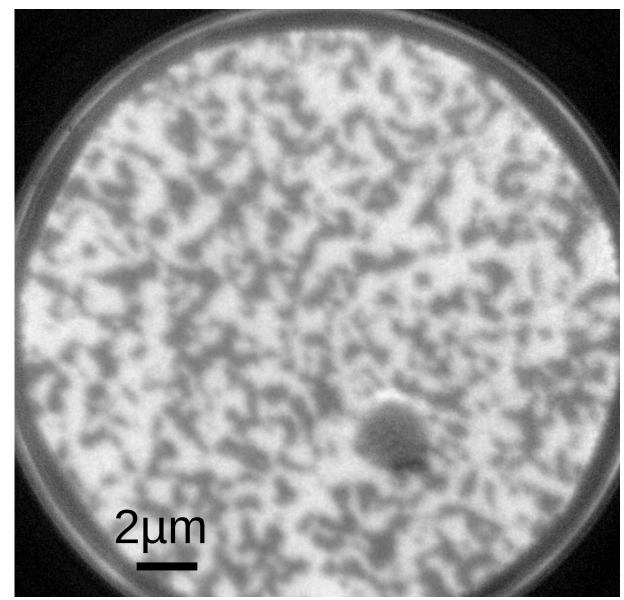
XMLD ~ <**M²**> cos²(**M**,**E**)



"Probe anisotropy of electron charge"

- Magnetic
- Crystal Field
- Strain
- Polarised bonds





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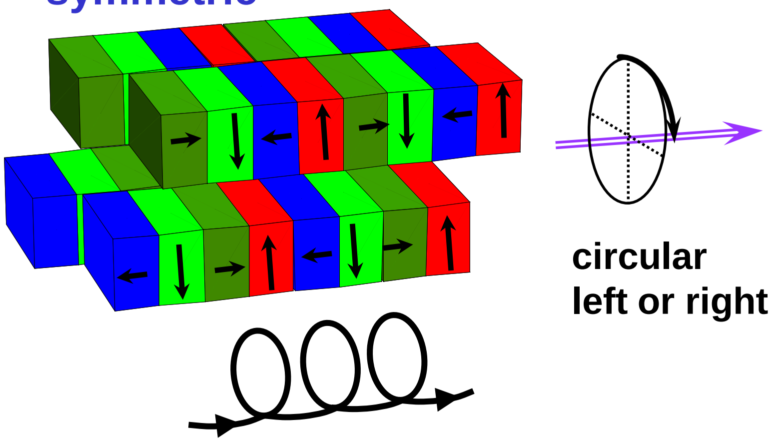
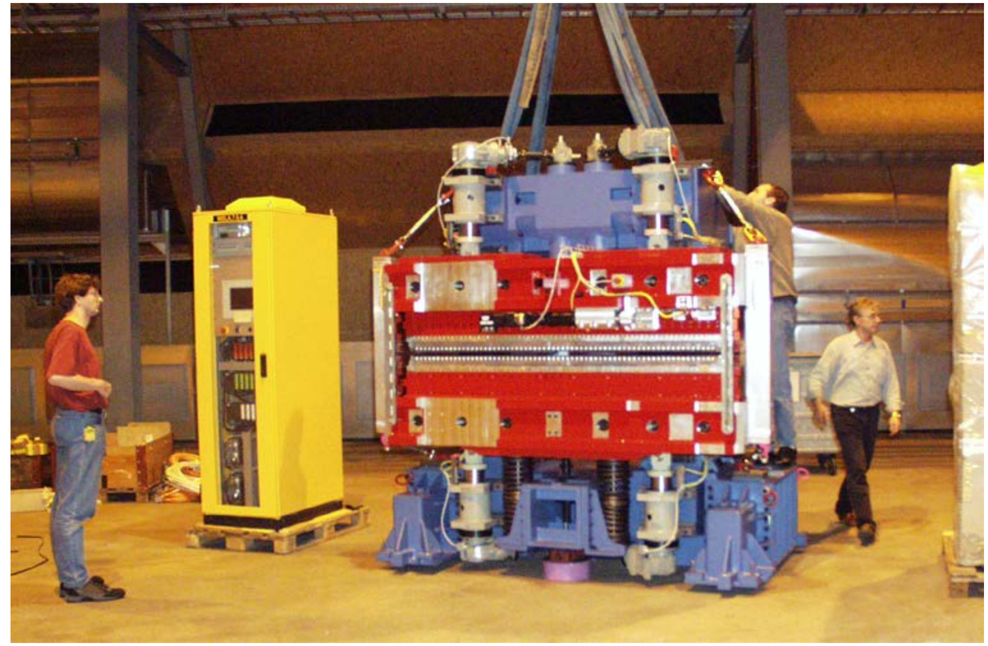
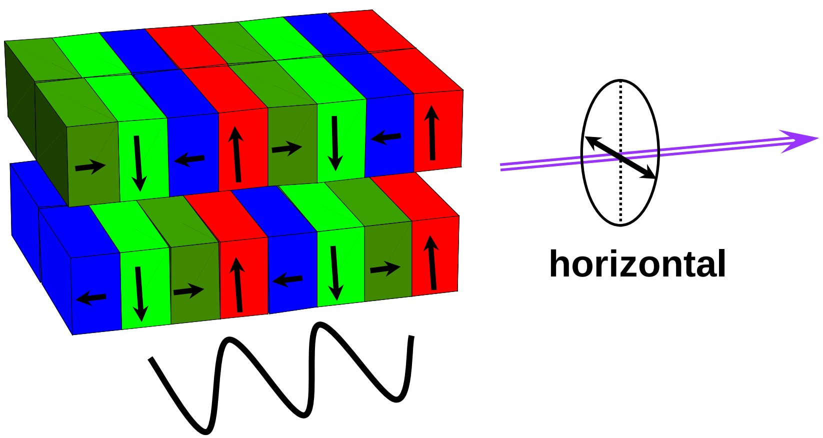
Magnetic Structure: changing phase, changes polarisation

symmetric

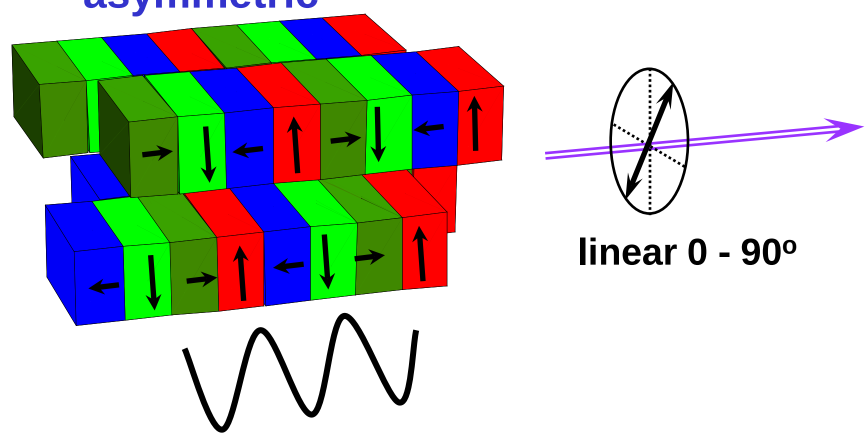




shift 0



shift $\pi/2$
asymmetric



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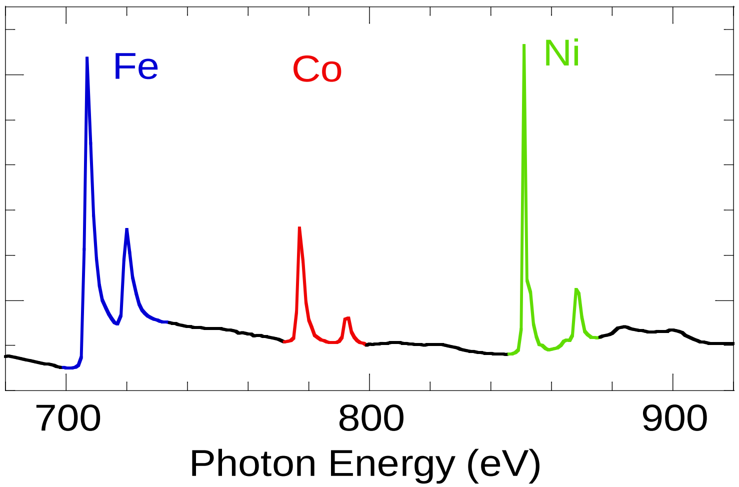
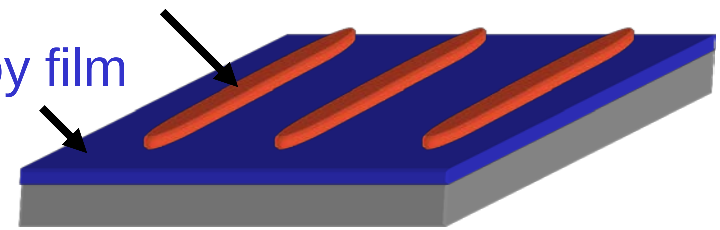
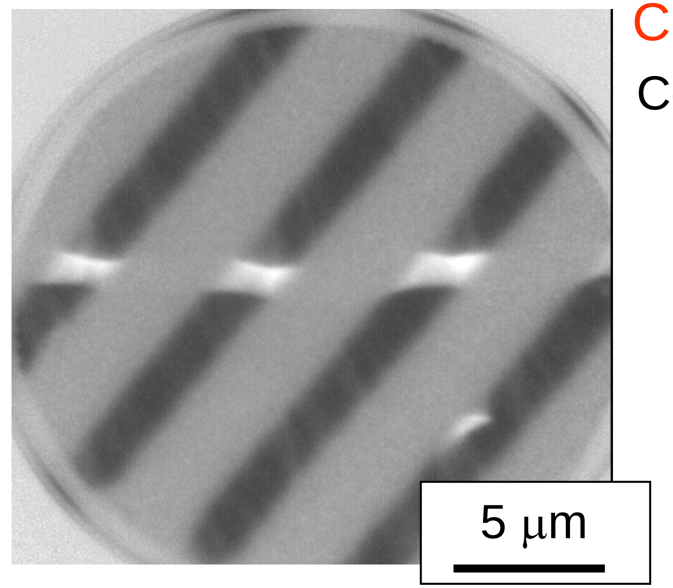
Brief Examples

Element specific contrast

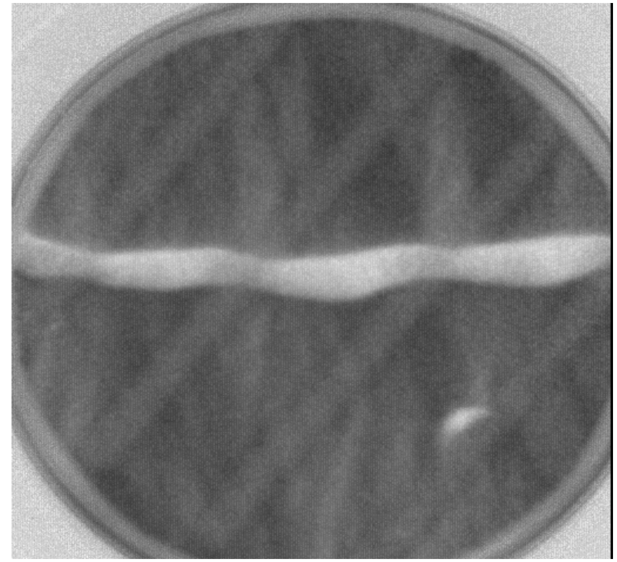






Cobalt lines

Co L_3



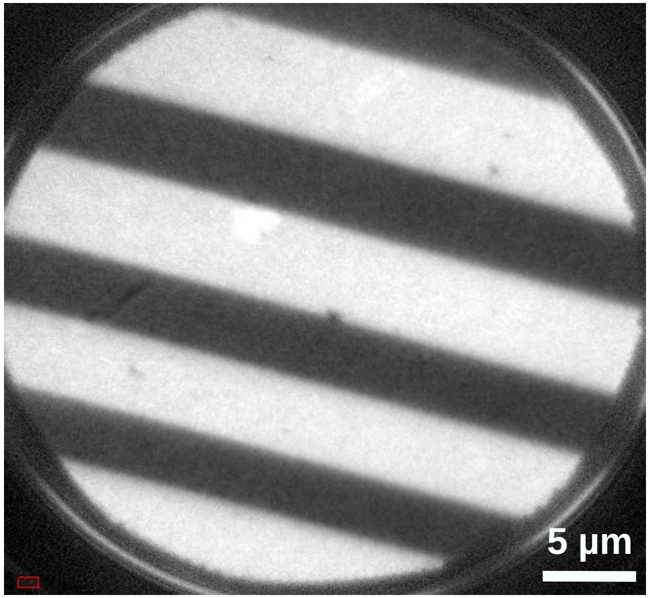
Permalloy film

Fe L_3

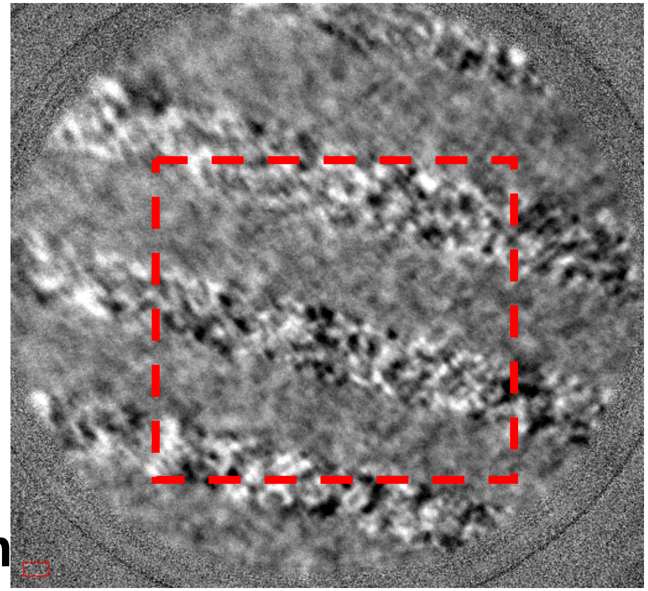
Coupling of hard and soft magnetic layer:
L. Heyderman, A. Fraile-Rodriguez, A. Hoffmann

L. J. Heyderman

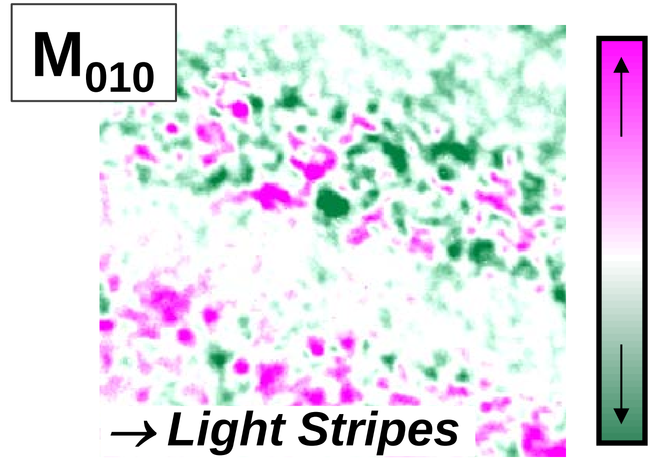
Strain and Magnetic Domains

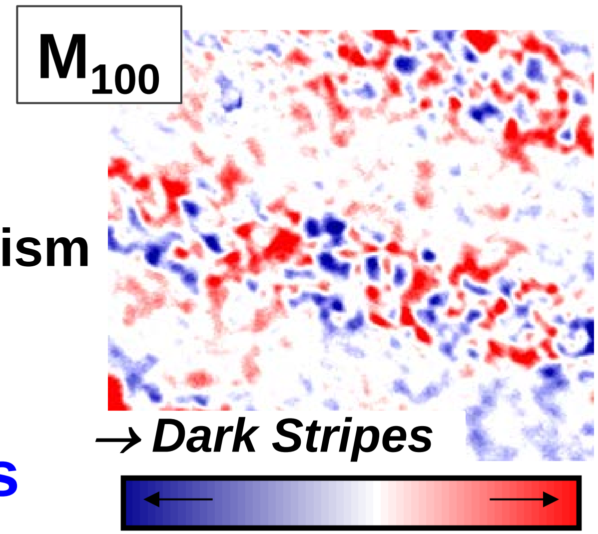


Fe X-ray Linear Dichroism

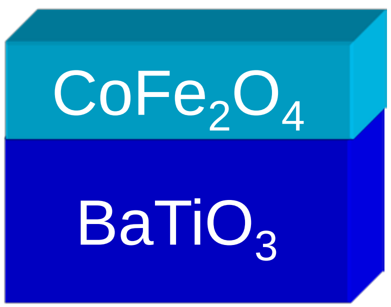


Fe X-ray Magnetic Circular Dichroism





M_{001} ~ 0



- **Fe XLD: strain domains**
- **Fe XMCD: magnetic domains**
- **Substrate-induced strain strongly modifies magnetic anisotropy**

RV Chopdekar et al. PRB (2012)

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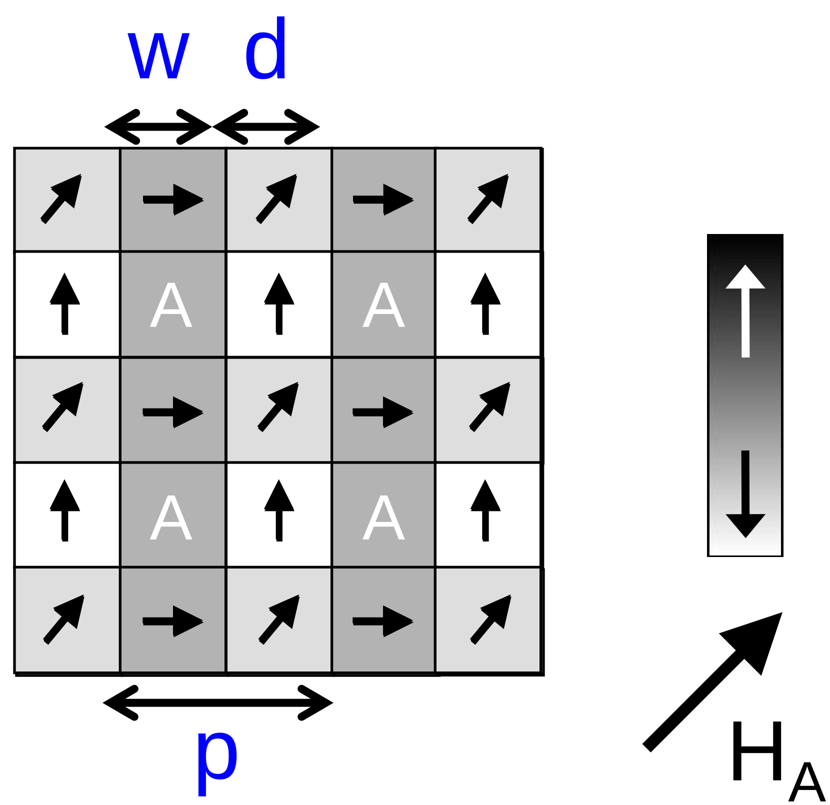
Antidot Arrays – Basic Domain Configuration



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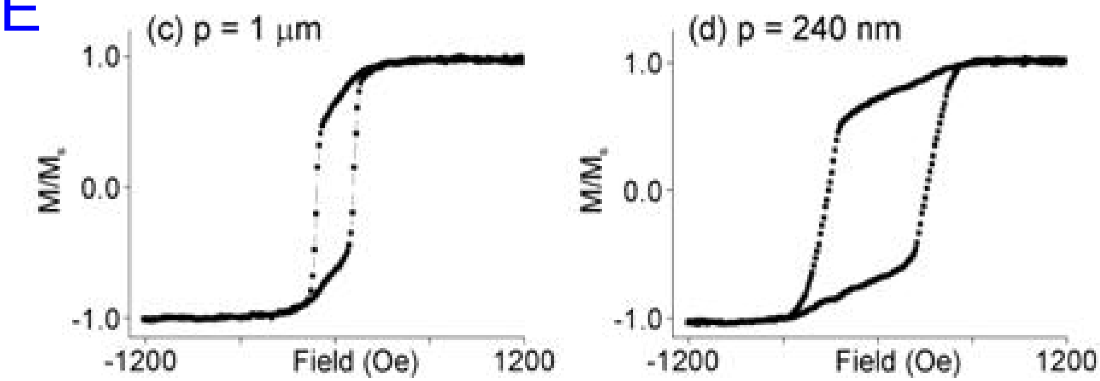
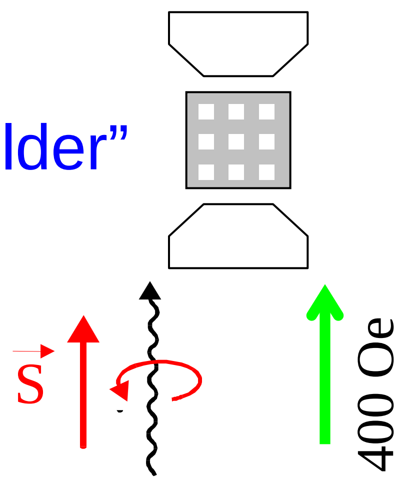
Remanent Hysteresis Loop in Antidot Arrays

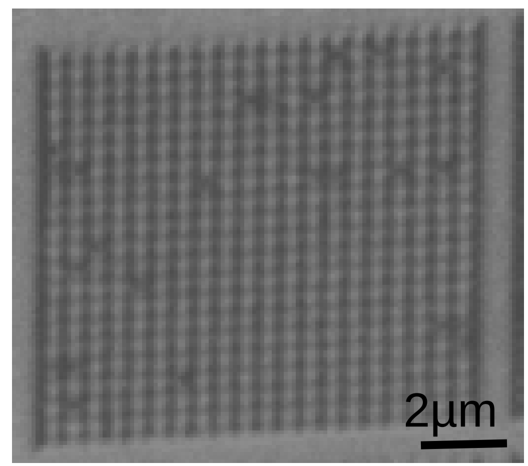
MOKE



Observe magnetisation reversal in applied magnetic field:

PEEM
“Magnetising Holder”



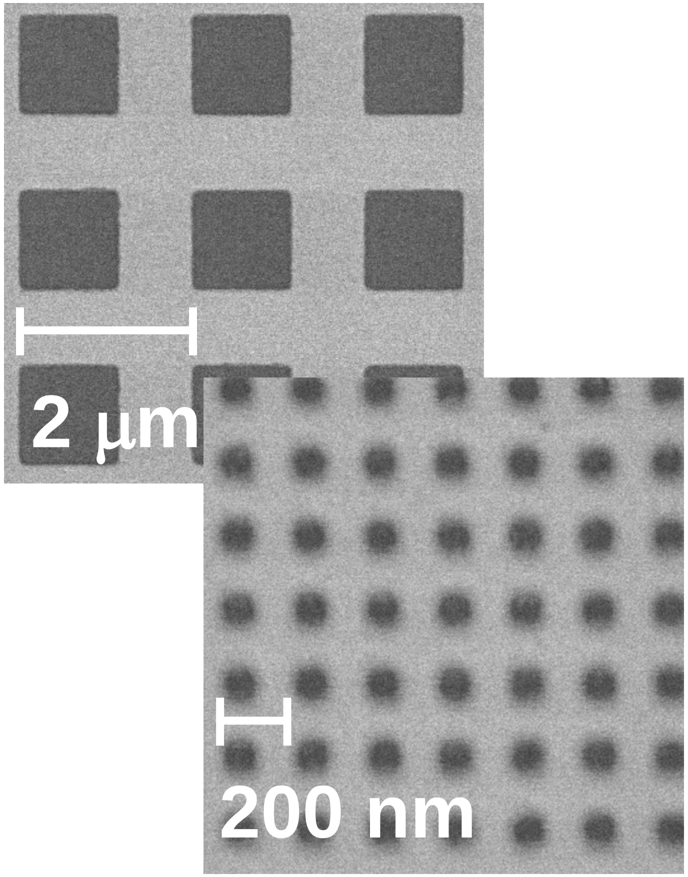


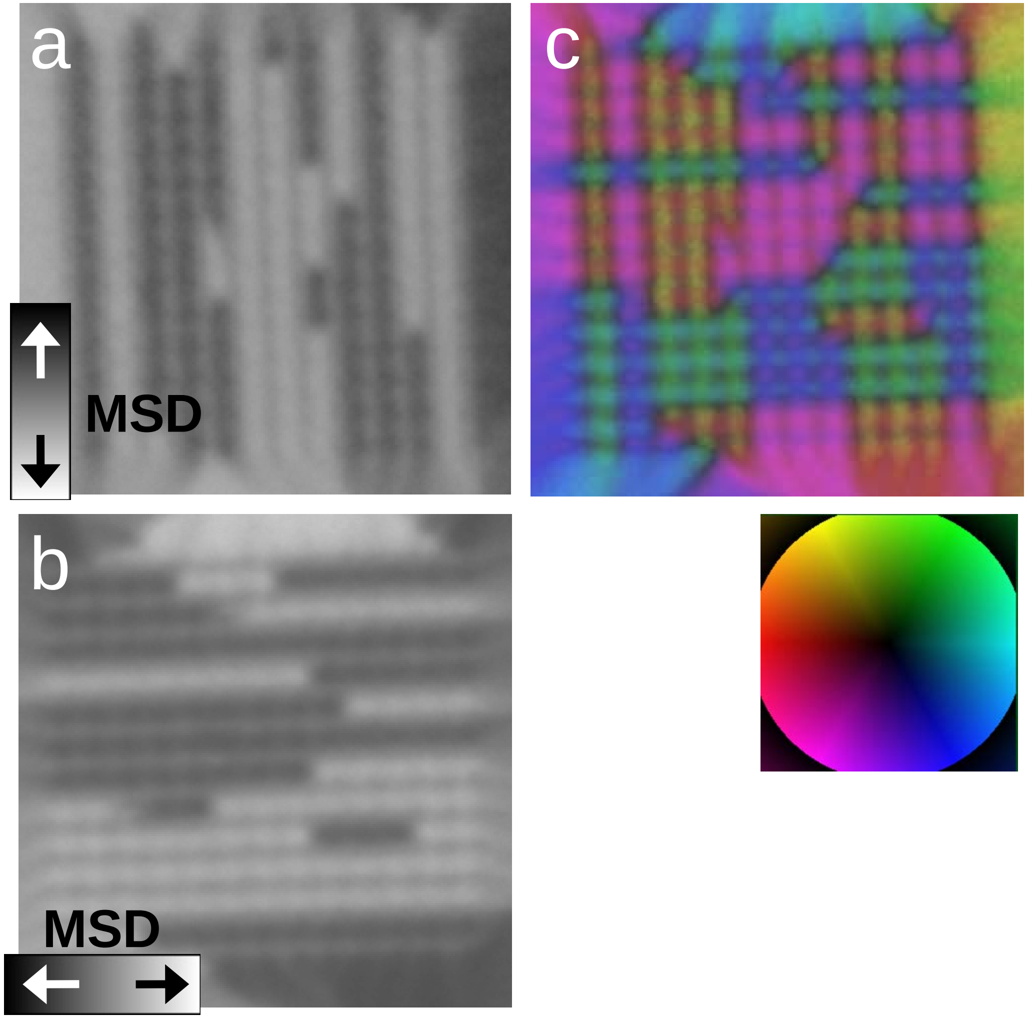
Spins ↑ to Spins ↓

L. J. Heyderman, F. Nolting, D. Backes, S. Czekaj, L. López-Díaz, M. Kläui, U. Rüdiger et al

L. J. Heyderman

Cobalt Antidot Arrays





L. J. Heyderman et al., APL (2003), JAP (2004), PRB (2006), JMMM (2007)
Mengotti et al., JAP (2007)

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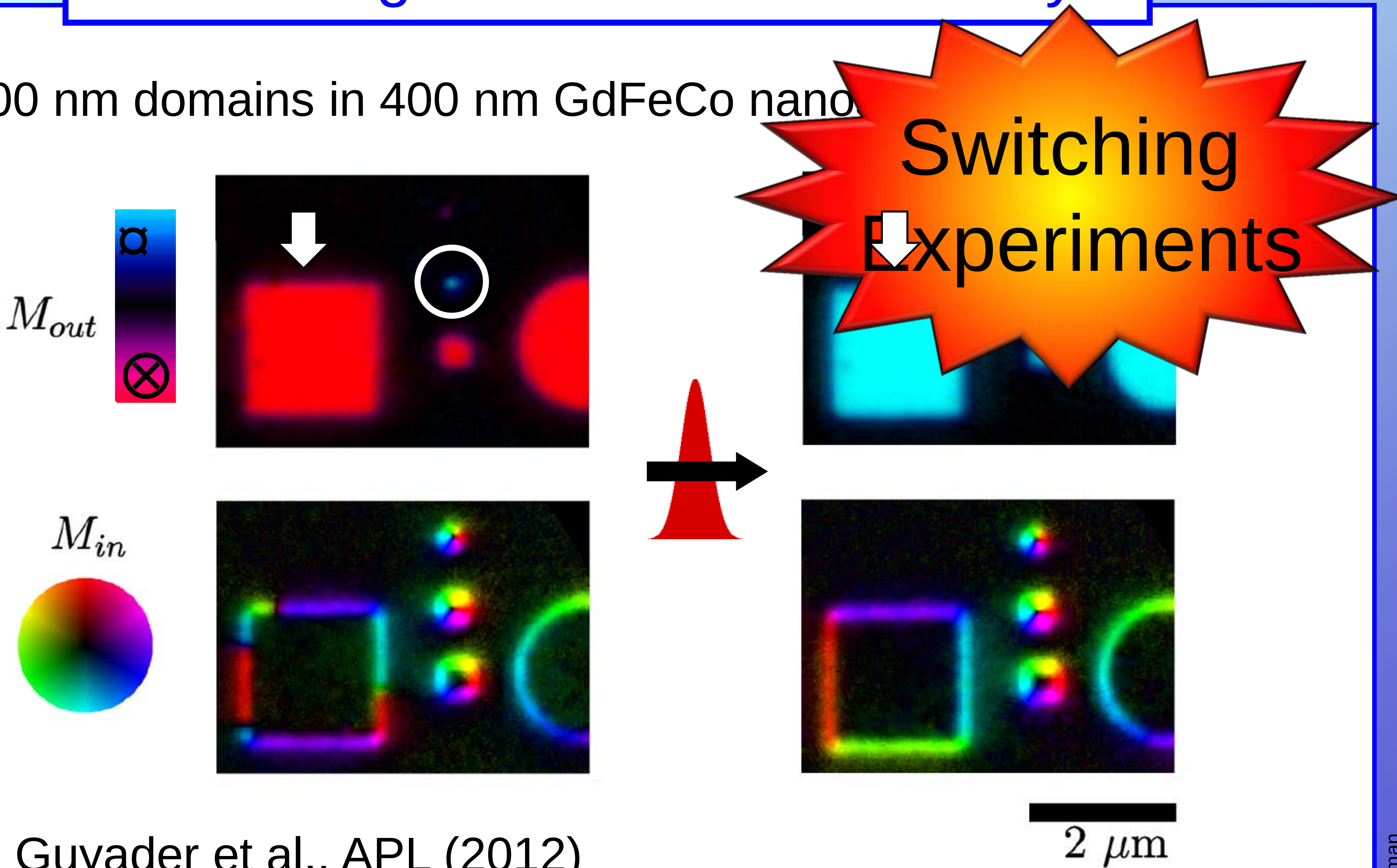
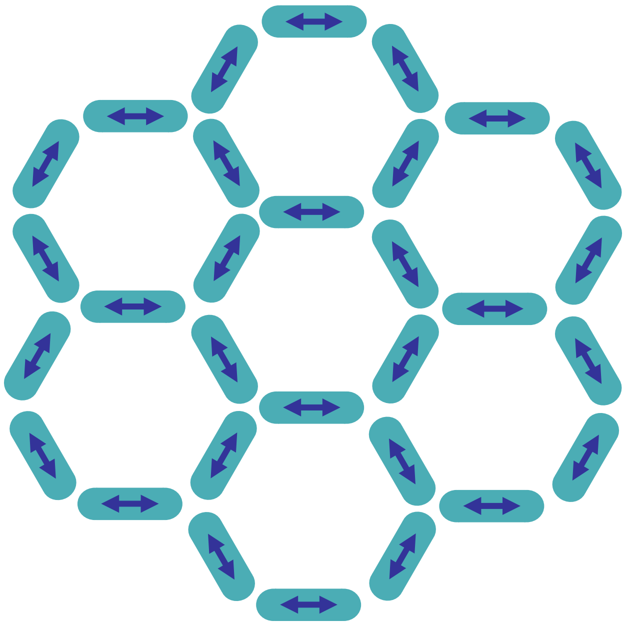
Switching with a Heat Pulse Only

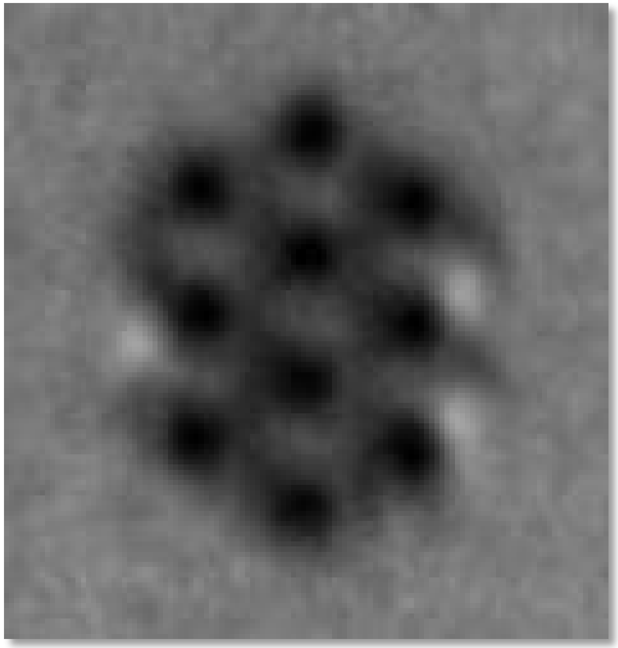
❖ 200 nm domains in 400 nm GdFeCo nano



L. Le Guyader et al., APL (2012)
T. A. Ostler et al., Nature Communications (2012)

Thermally Active Switching





A. Farhan et al. Nature Physics (2013), PRL (2013) & PRB (2014)

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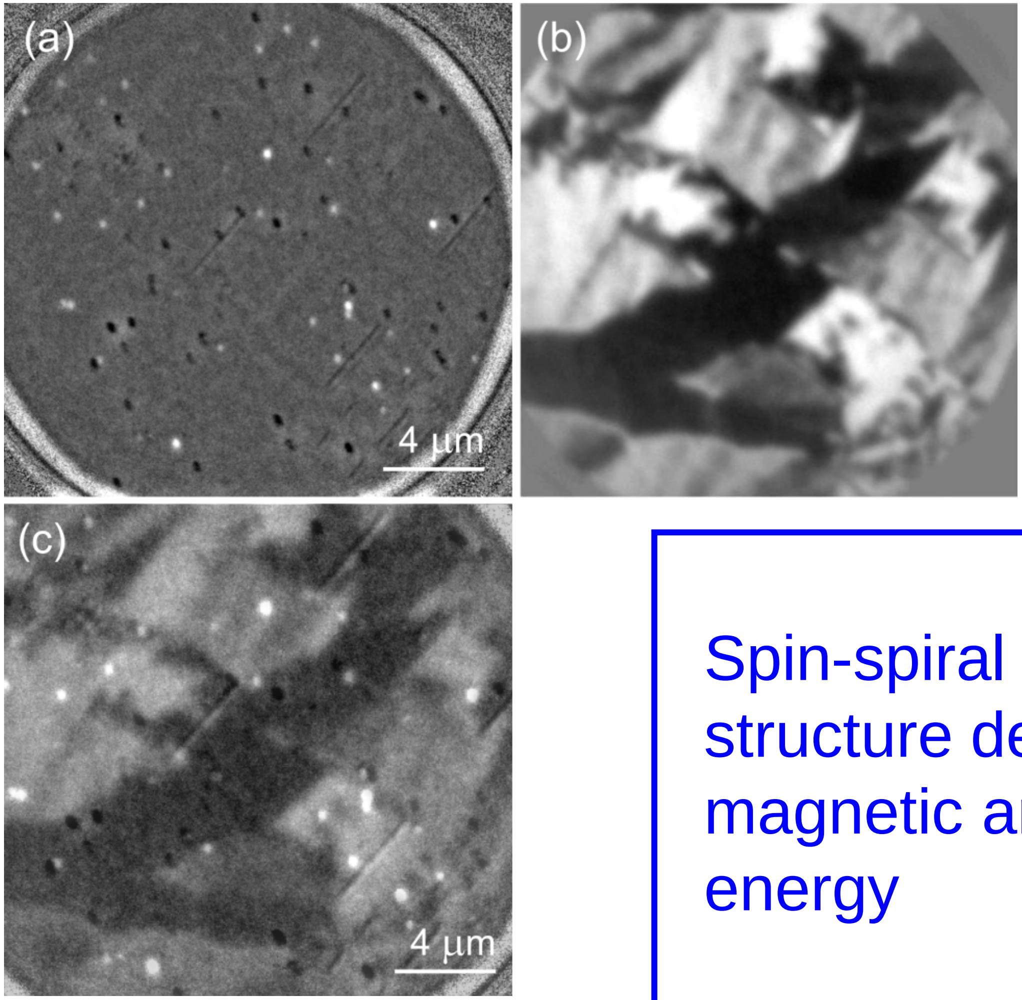
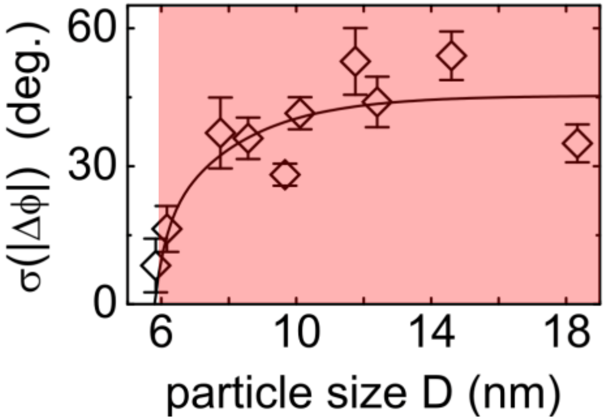
Iron Nanoparticles Coupled to Cobalt Thin Film

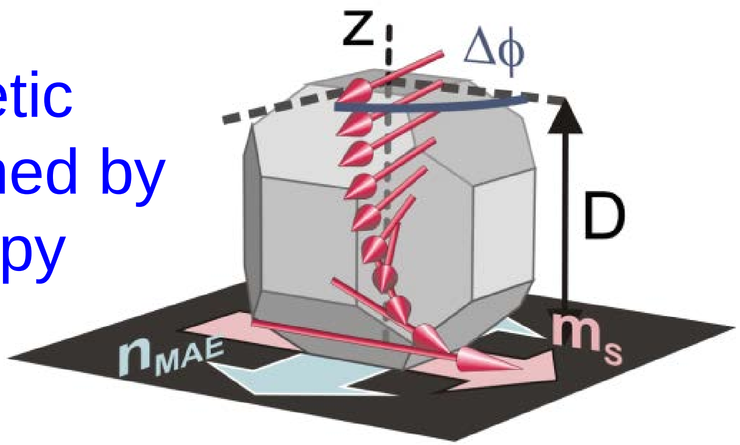
5-25 nm Fe particles/Co thin Film



Noncollinear alignment for particles > 6 nm

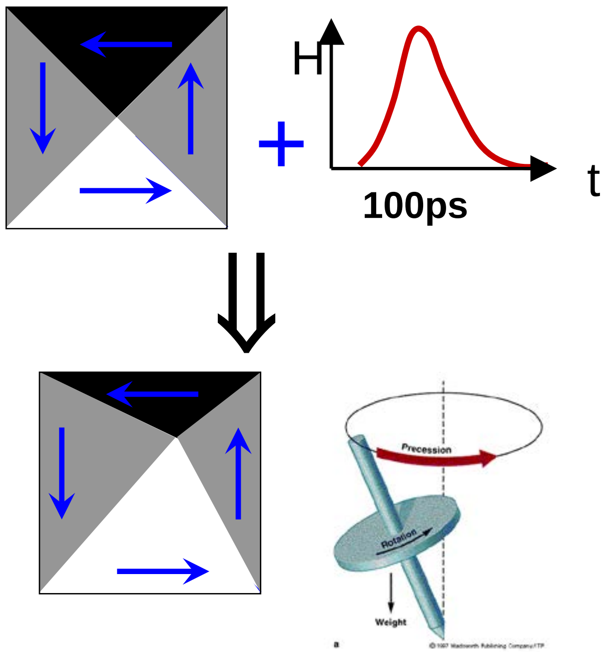


Spin-spiral magnetic structure determined by magnetic anisotropy energy



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

Time Resolved Imaging

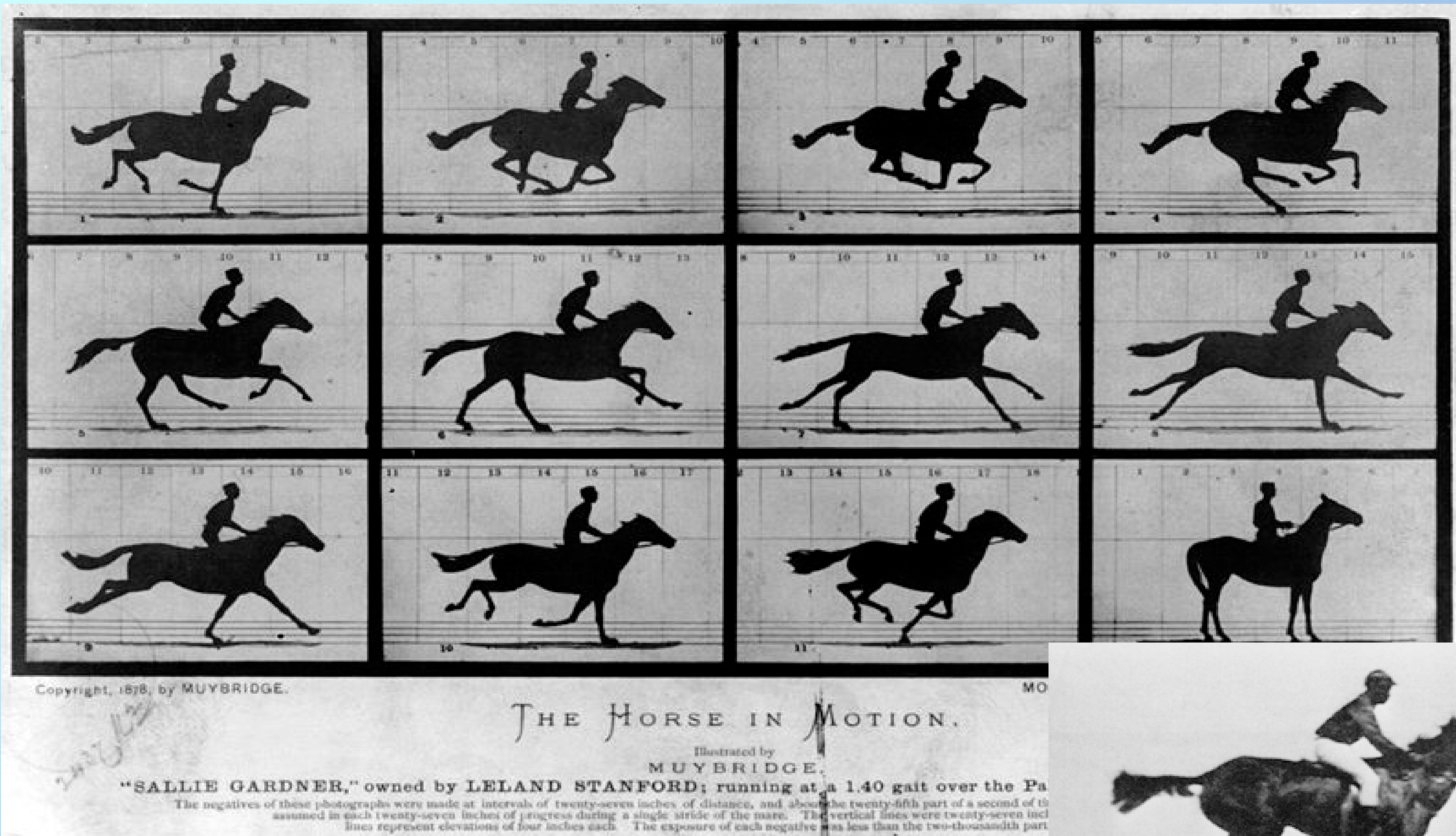


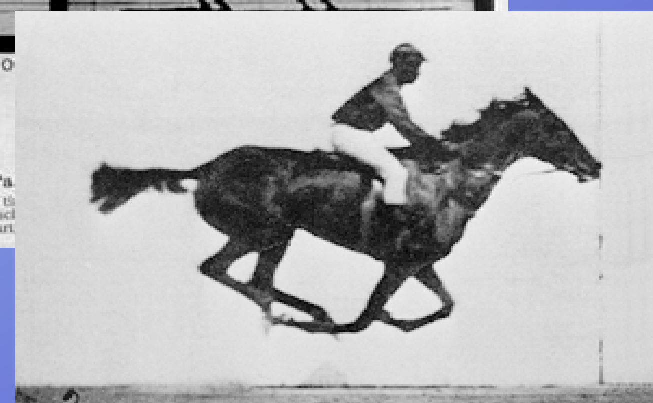
- Image excitations in magnetic nanostructures
- Precession frequency & damping
- Pump-probe experiment
- SLS: X-ray stroboscope

J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

L. J. Heyderman

Why perform time-resolved imaging?



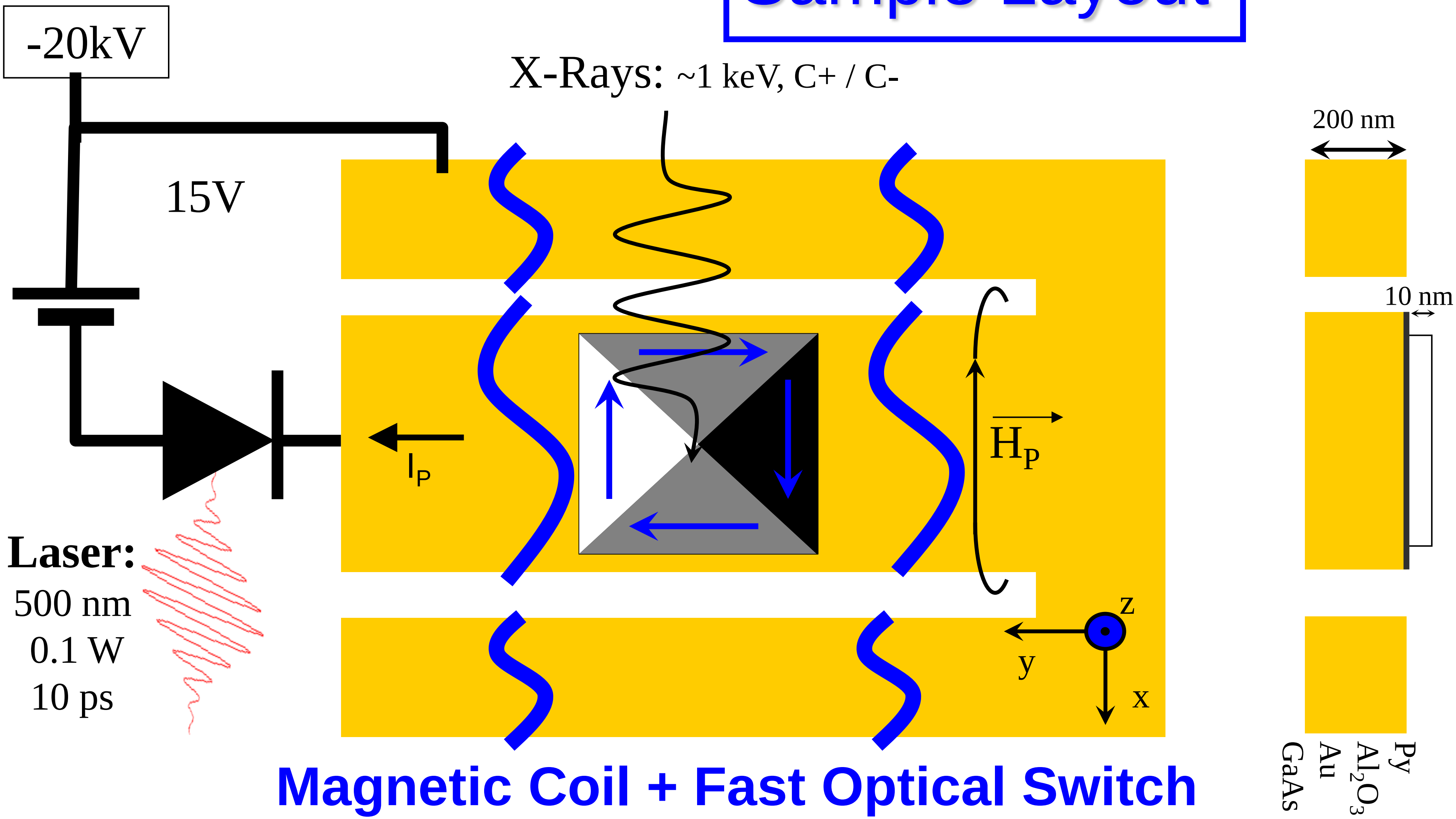


Are all four feet of a horse off the ground at the same time during a gallop.

The Horse in Motion 1878, animated in 2006, using photos by Eadward Muybridge, Wikipedia

L. J. Heyderman

Sample Layout



Magnetic Coil + Fast Optical Switch

Pulsed laser illuminates photodiode to give a current pulse.
This creates a magnetic field pulse exciting the magnetization.

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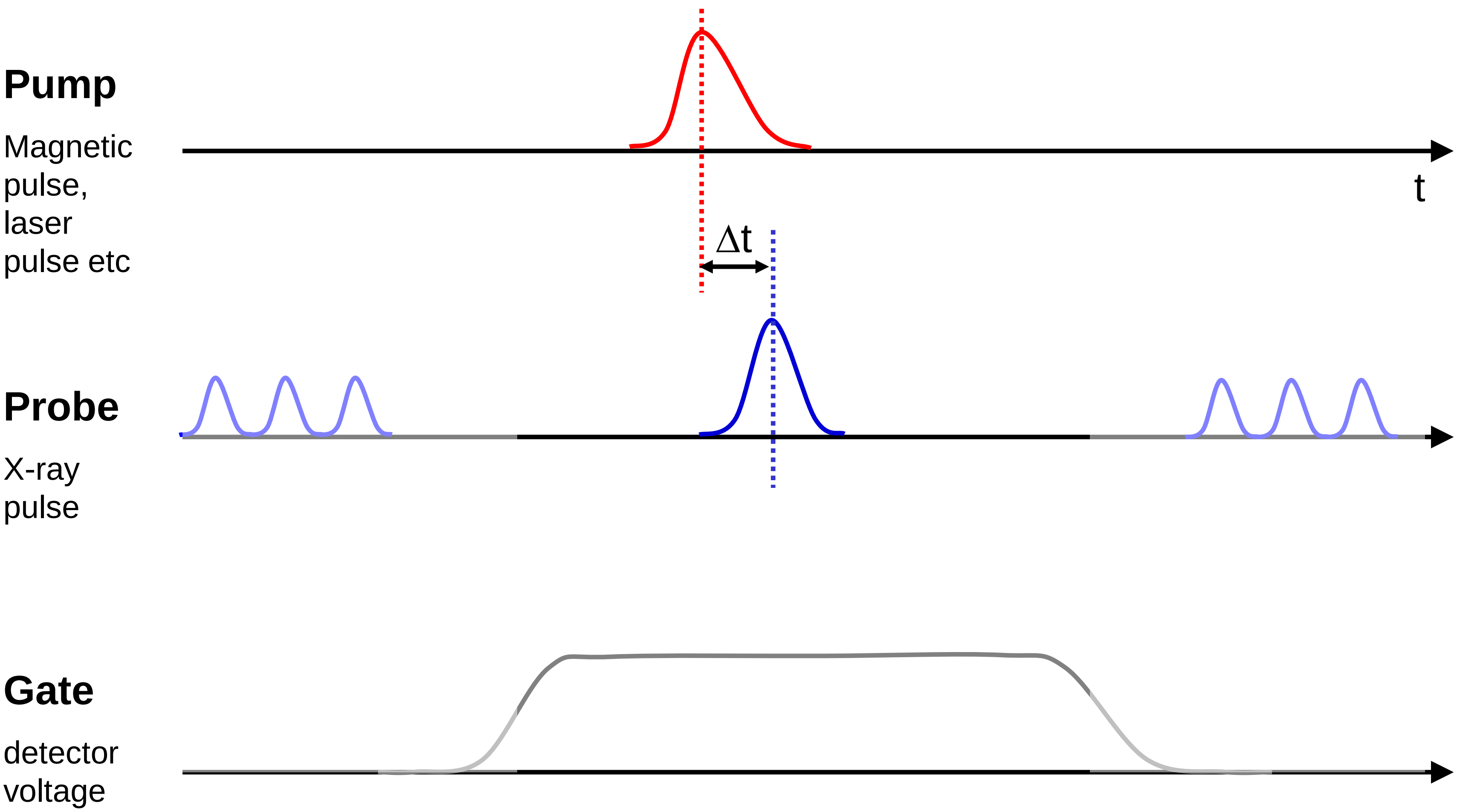
Magnetic Pump - X-ray Probe

- Excite system with magnetic pulse
- Time later: measure with an x-ray pulse



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Magnetic Pump - X-ray Probe

- Excite system with magnetic pulse
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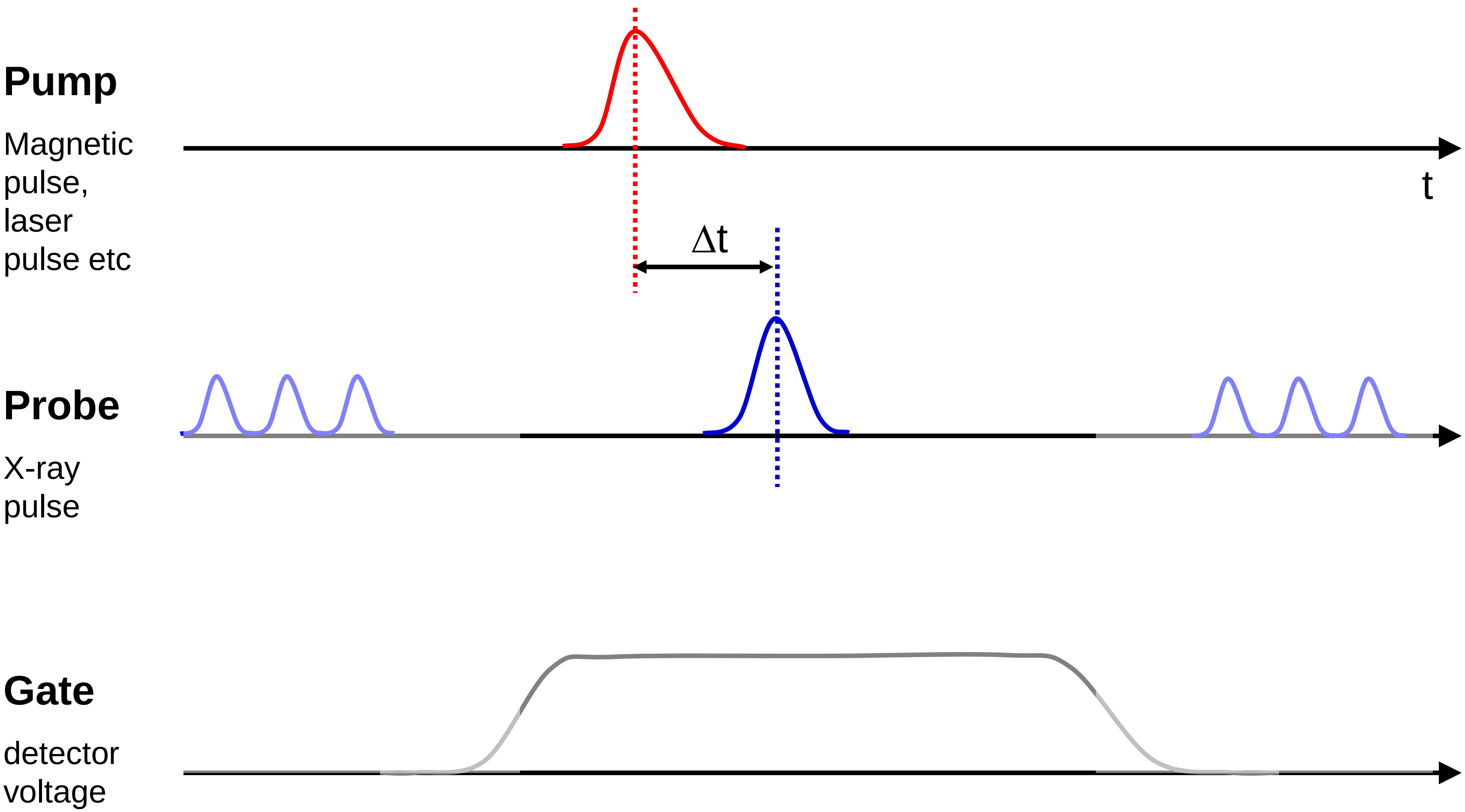

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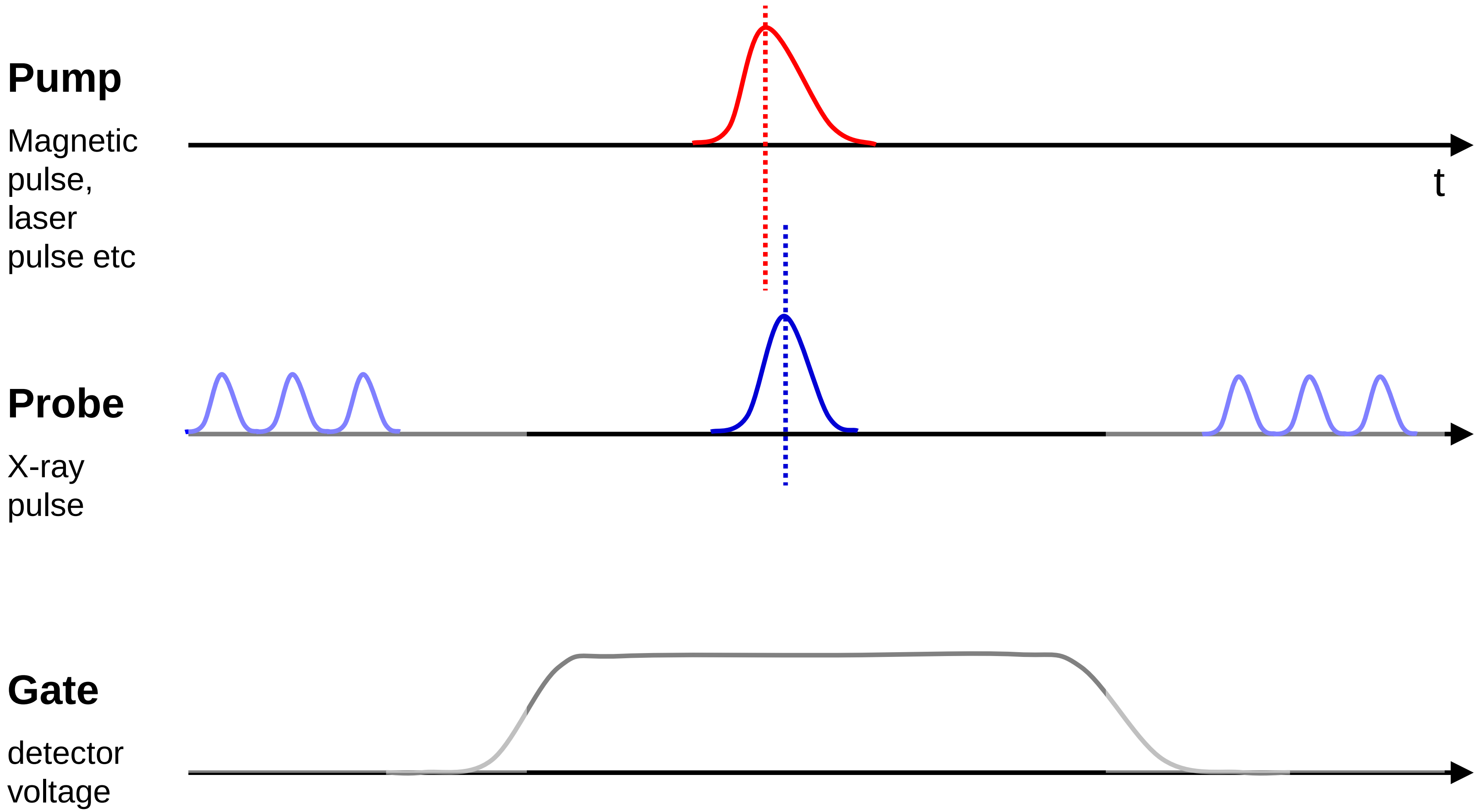
Magnetic Pump - X-ray Probe

- Not enough intensity in each shot so repeat several times: pump-probe



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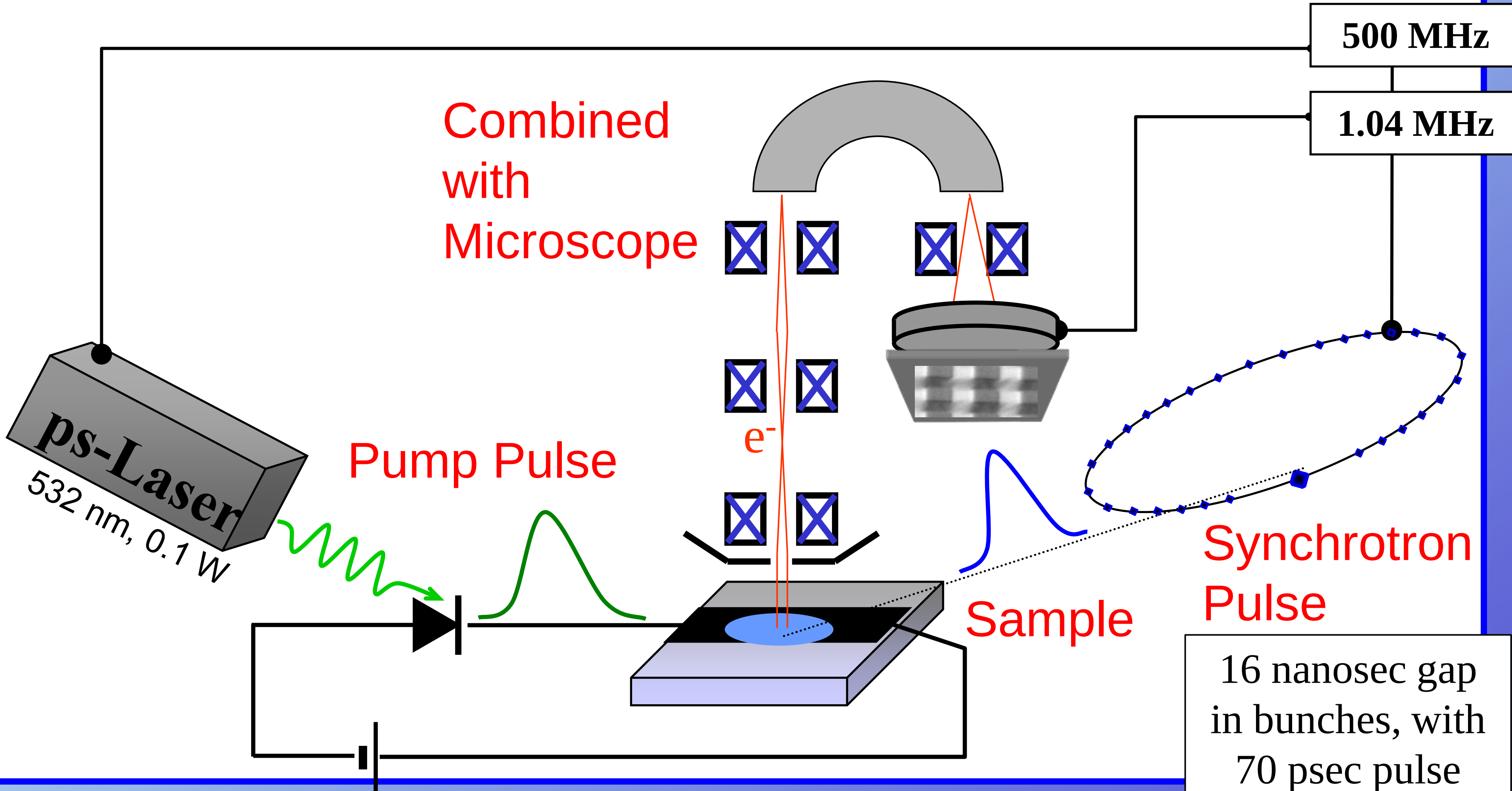
Summary

Pump:	Detect:	Probe:
stripline / coil	gated PEEM	X-ray stroboscope
Pulse: H < 100 G, 10^2 ps	Δx ~100nm, ~ 1 ML	~1keV, Δt= 70ps



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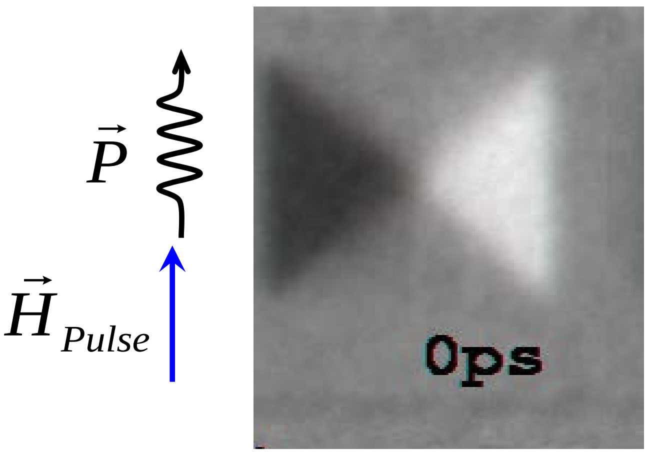
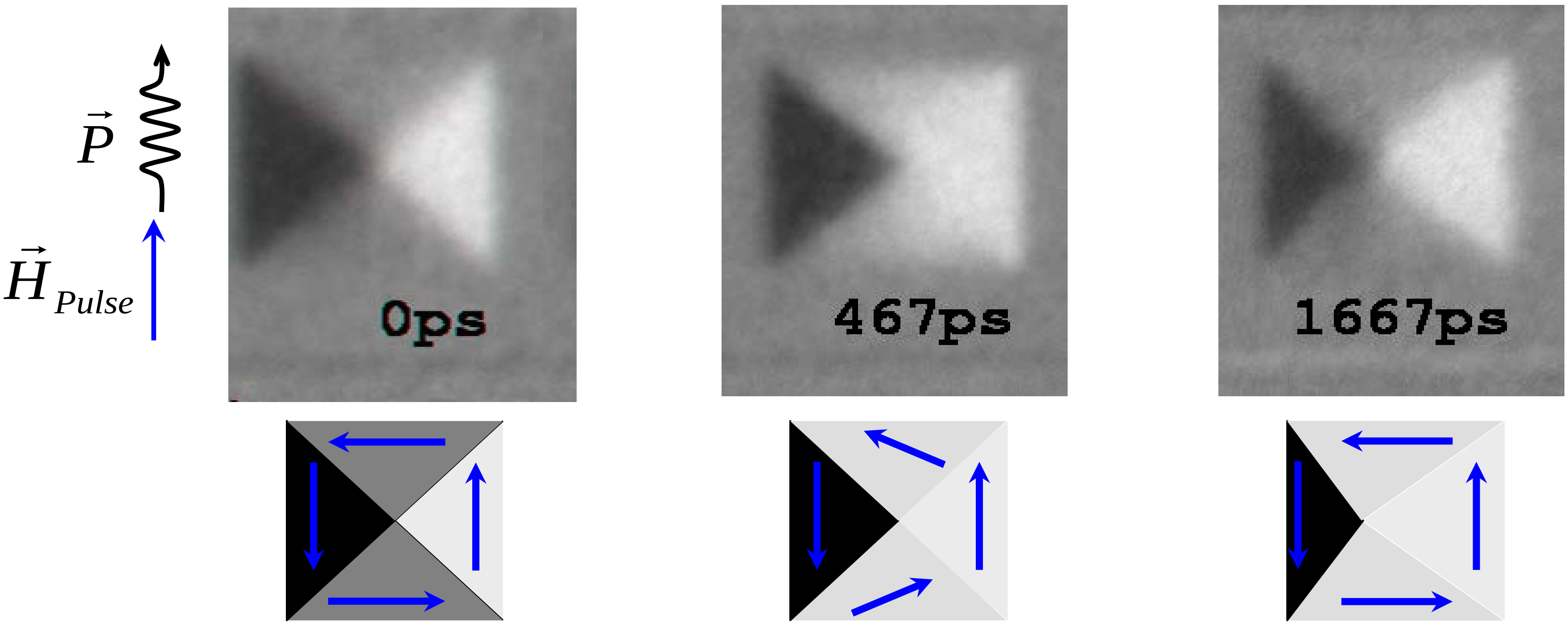
Py Square: Excitation



Permalloy ($Ni_{81}Fe_{19}$)
t=30nm
H_p~80 Oe
S040906_015

J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

Py Square: Excitation



Step 1:

$$\vec{T} = \vec{M} \times \vec{H}_{Pulse}$$

Coherent rotation

$\Delta t \sim T_{prec} / 2 \sim 500ps$

Step 2:

Domain wall motion

$$\vec{M} \uparrow\uparrow \vec{H}_{Pulse}$$

Permalloy ($Ni_{81}Fe_{19}$)

t=30nm

H_p~80 Oe

S040906_015

J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

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Summary

- **Element selective (multilayer, coupled systems)**
- **Surface/interface sensitive (sampling depth a few nm)**
- **Antiferromagnetic and Ferromagnetic domains**
- **Spatial resolution: 50-20 nm, future aberration corrected: few nm's**
- **Time resolved measurements**
- **Temperature 120 K – 1000 K**
- Submonolayer sensitivity
- Combination with other analytical techniques: LEEM & LEED
- In-situ and ex-situ sample preparation
- Sample size 3 to 15 mm diameter, 0.2 mm - 2 mm thick

Challenges (limitations):

- **UHV compatible (<10^{-7} mbar)**
- **Smooth surface (< 1 μm, hard to say)**
- **X-ray damage**
- **Image in applied magnetic field below 50 Oe**
- High voltage often leads to discharges (20 keV, at 2 mm distance)
- Charging effects due to electrical insulating sample (can get around this)

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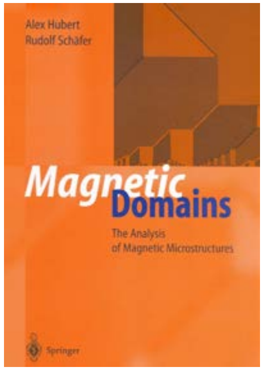
Conclusion

Information on Different Methods

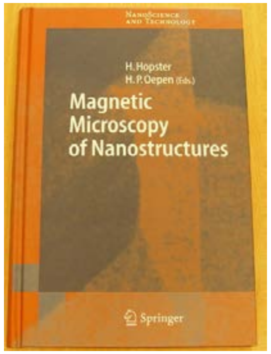
A. Hubert and R. Schäfer, Magnetic Domains
The Analysis of Magnetic Microstructures



Magnetic Microscopy of Nanostructures

An overview of techniques to image the magnetic structure on the nano-scale

H. Hopster and H. P. Oepen



Internet, for example:

Techniques to Measure Magnetic Domain Structures, R.J. Celotta, J. Unguris, M.H. Kelley, and D.T. Pierce, Methods in Materials Research (2000)

Comparison Between Different Techniques

- Contrast Origin: B, M, H_{ext}
- In Plane or Out-of-Plane components
- Quantitative or Qualitative
- Best Resolution, but better Typical Resolution
- Information depth
- Sensitivity, Acquisition Time
- Vacuum Equipment: none, HV, UHV
- Sample requirements: thickness, surface roughness, clean surface,insulators ?
- In-situ experiments: maximum field, heating, stress
- Additional information: crystallography, topography, chemical, electronic
- Commercial Availability, Cost & Complexity - Manpower

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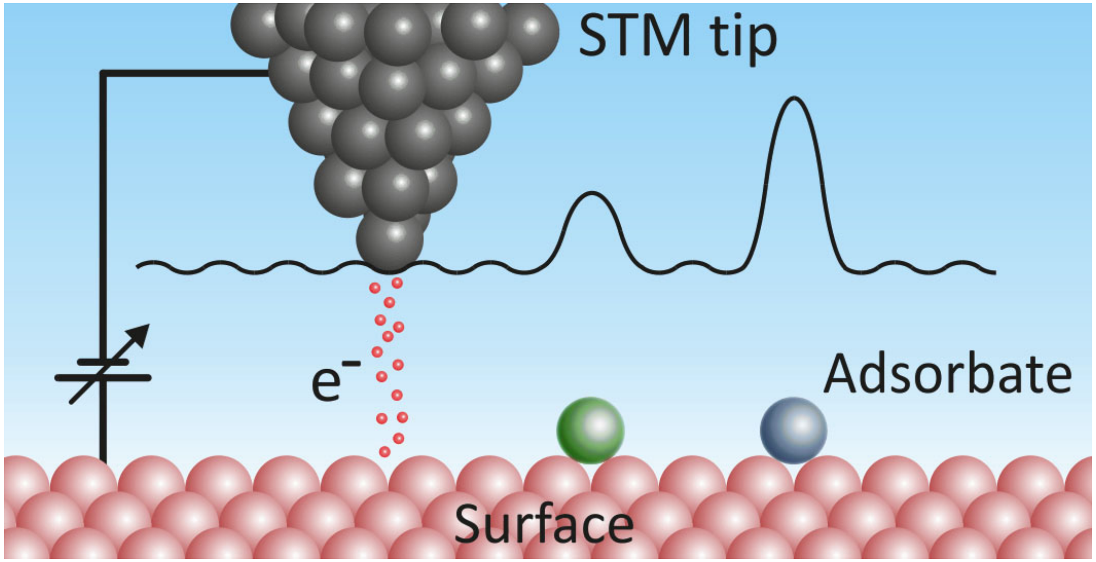
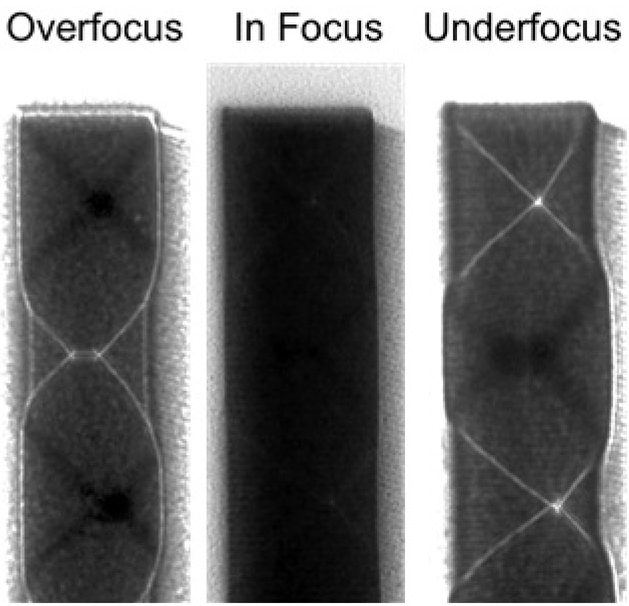
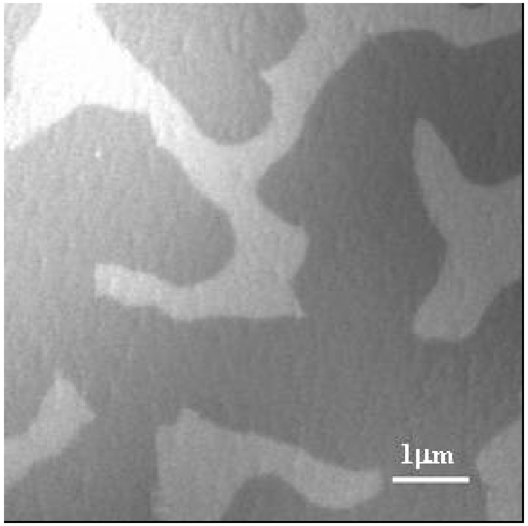
Further Techniques



http://www.fhi-berlin.mpg.de/



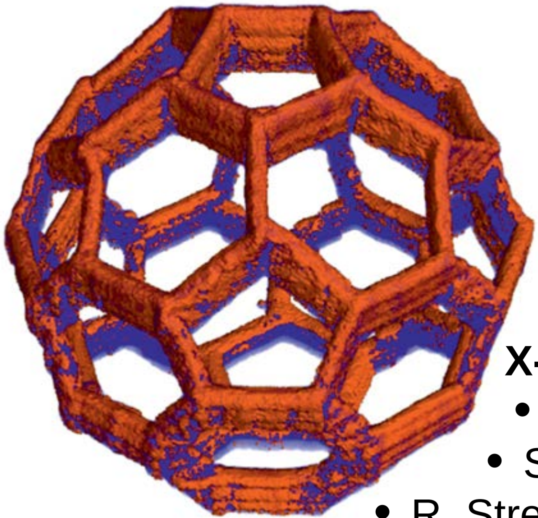
http://lma.unizar.es



B.-S. Kang et al.
J Appl. Phys 98 (2005) 093907

- Scanning Tunnelling Microscopy
- Lorentz Microscopy
- Transmission X-ray Microscopy
- X-ray & Neutron Tomography
- X-ray & Neutron Scattering
- Low Energy Muons

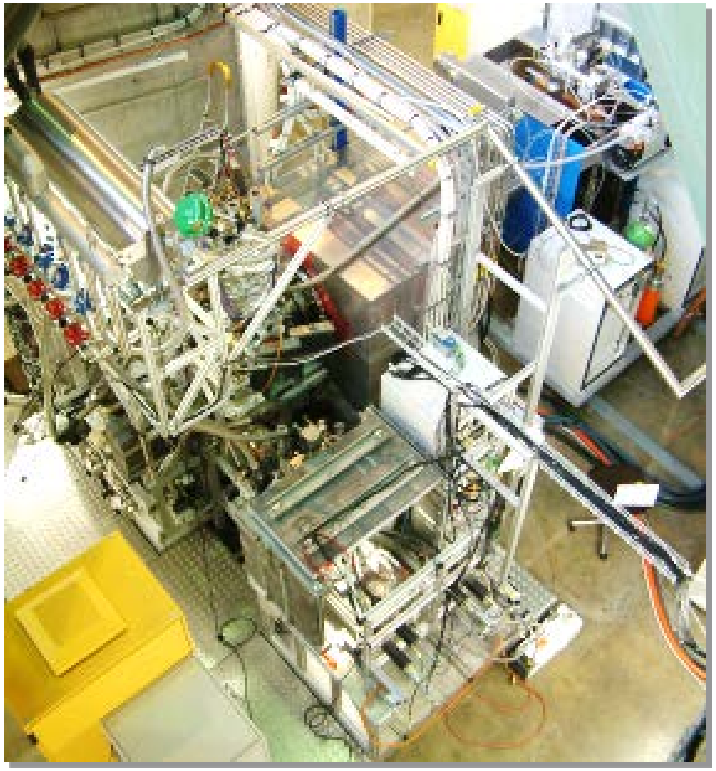
Further Techniques

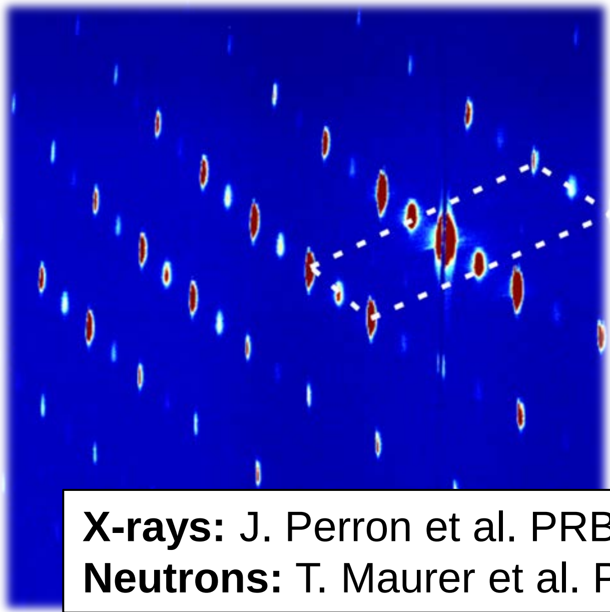


- **Muons:** L. Anghinolfi et al. Nat. Comm. (Accepted 2015)

X-rays:
- C. Donnelly et al. PRL (2015)
- S. Da Col et al. PRB(R) (2014)
- R. Streubel et al. Nat. Comm. (2015)

Neutrons: Manke et al. Nat. Comm. (2010)

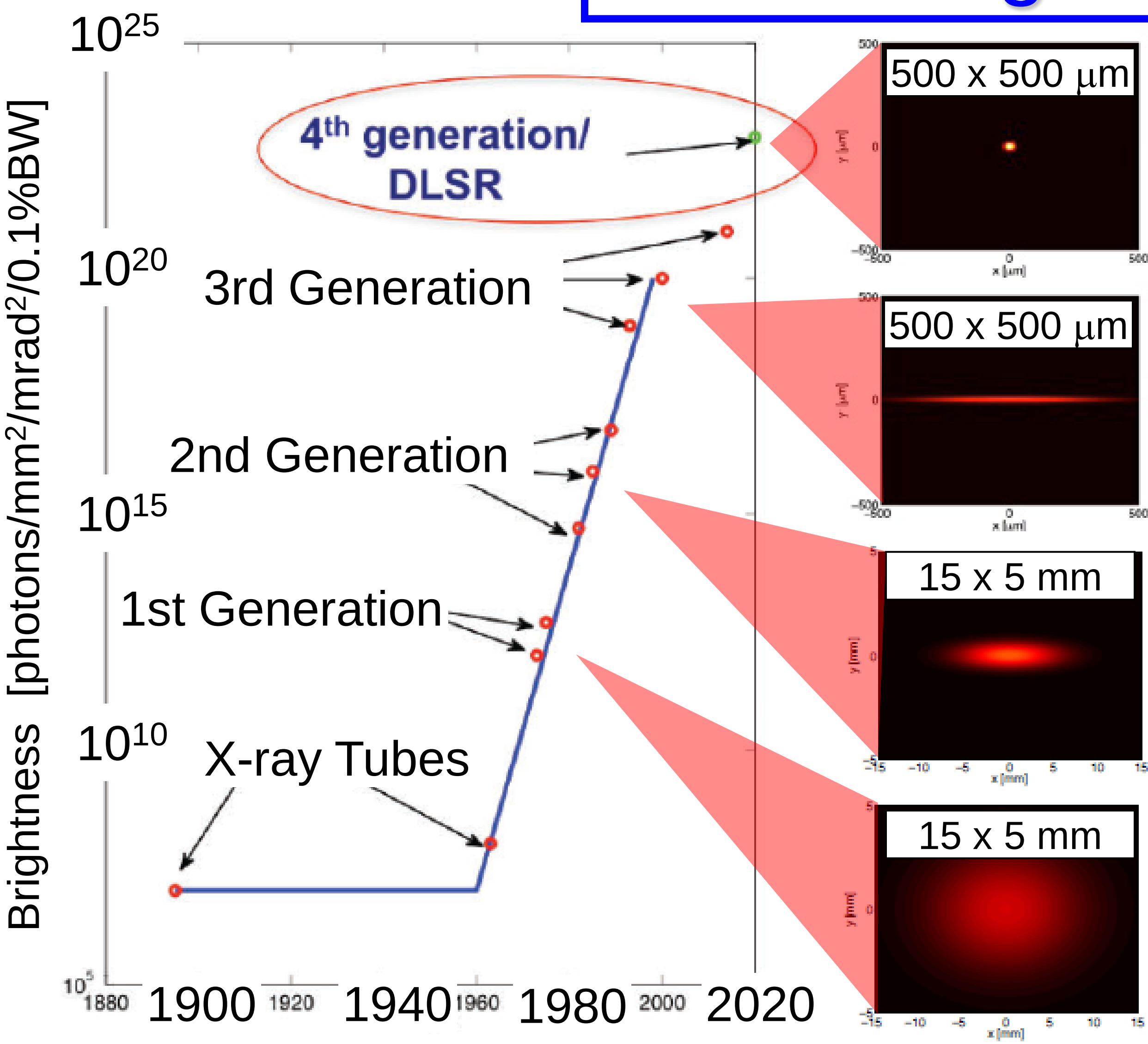




X-rays: J. Perron et al. PRB (2013)
Neutrons: T. Maurer et al. PRB (2014)

- Scanning Tunnelling Microscopy
- Lorentz Microscopy
- Transmission X-ray Microscopy
- X-ray & Neutron Tomography
- X-ray & Neutron Scattering
- Low Energy Muons

Future Light Sources



4th Generation/DLSR
(diffraction limited storage ring)

→ Multibend Achromat (MBA) accelerator lattices

→ Large increase in brightness

→ Several soft bend magnets in each storage ring sector replace 2-3 hard bend magnets

→ smaller horizontal beam dispersion corrected by stronger focusing magnets

→ elliptical profile replaced by compact and nearly circular profiles, with horizontal spatial & angular widths of source decreased by ~ factor of 10 relative to existing sources

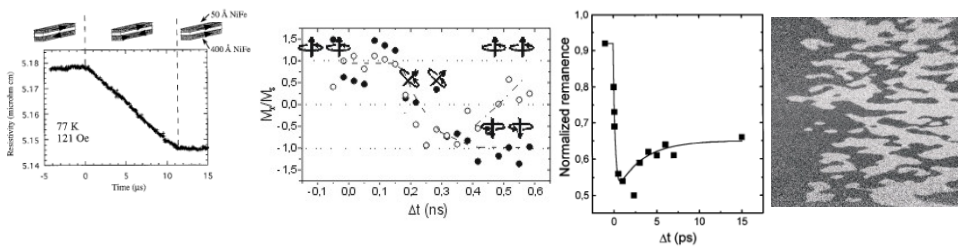
Soft X-ray Science Opportunities Using Diffraction-Limited Storage Rings, ALS 2014 (Scale → Rectangle Size)

Future Challenges

Time Resolution

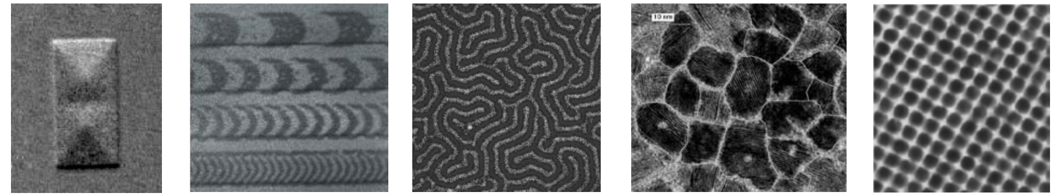
- Currently sub100ps (≈10ps): precession relaxation dynamics (LLG).
- Limited flux of photons: repeatable phenomena (stroboscopic pump-probe).

ns ps fs



exchange interactions $t(fs) \sim 4/E(eV)$

- Future challenge: fs time scale (exchange interaction time, spin fluctuation time)
- nm spatial resolution in single shot experiment.
- Need high flux (10^{12}ph/s) X-ray source
- Lensless imaging and Full-field X-ray microscopy

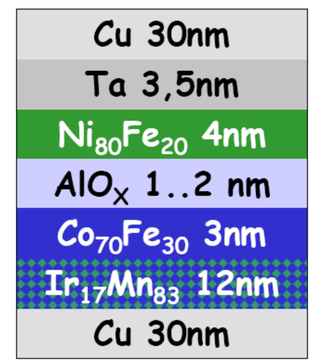


µm nm

Spatial Resolution

exchange length $l_K \sim \sqrt{A/K}$

Elemental Sensitivity

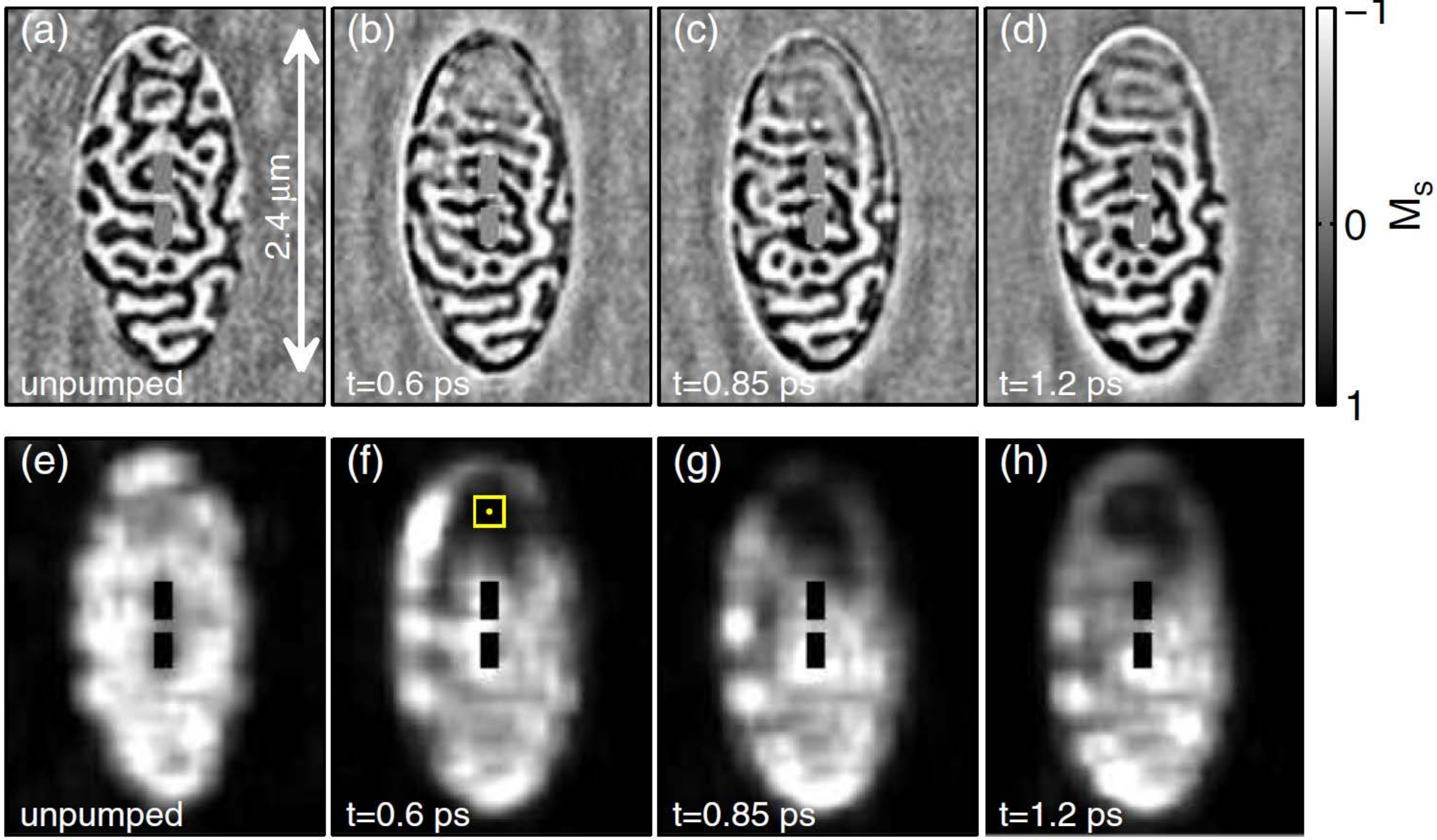


magnetic tunnel junction

Peter Fischer, ALS

L. J. Heyderman

Ultrafast Optical Demagnetisation (100 fs, l=780 nm, 0.2 μJ)



C. von Korff Schmising PRL (2014)

In their conclusions: Ultrafast transport of spin-polarized electrons

→ Domain size controls time scales & spatial extent.

However, exact mechanisms still to be determined…...

Test your understanding……

Magnetic Force Microscopy, Kerr Microscopy & PEEM

Which technique:

- is sensitive to the stray/external magnetic field?
- are sensitive samples with out-of-plane M?
- gives a value of spin and orbital moment?
- has the best spatial resolution?
- can be used to look at back surface of sample?
- requires UHV?
- is difficult for measuring insulators?
- can provide chemical and electronic information?

Can you name any other techniques for imaging magnetic domains?