Magnetic Imaging Techniques

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Types of Magnetism

Ferromagnetism

Helimagnetism

Antiferromagnetism

Ferrimagnetism

Spin-Canted Magnetism

Paramagnetism

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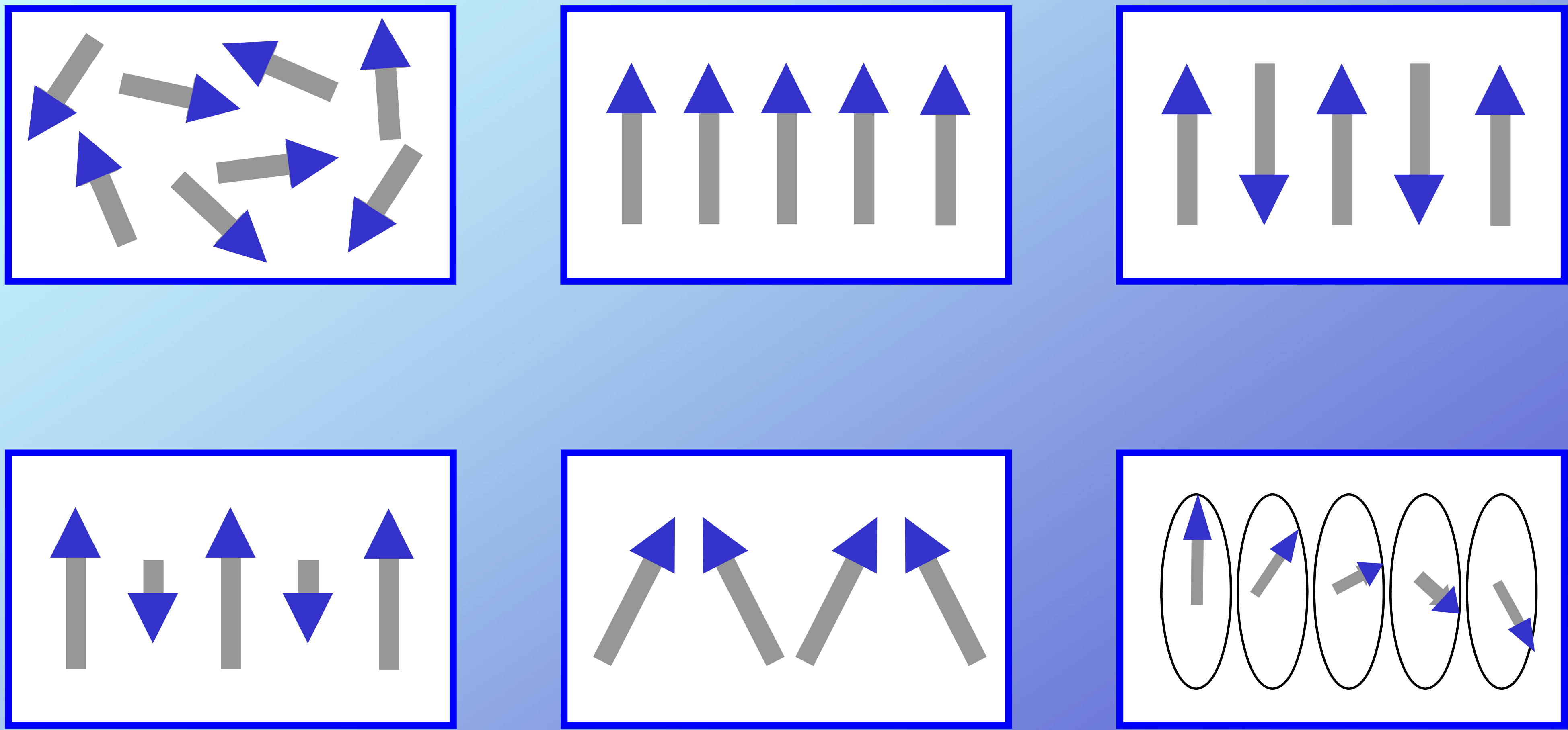
Types of Magnetism



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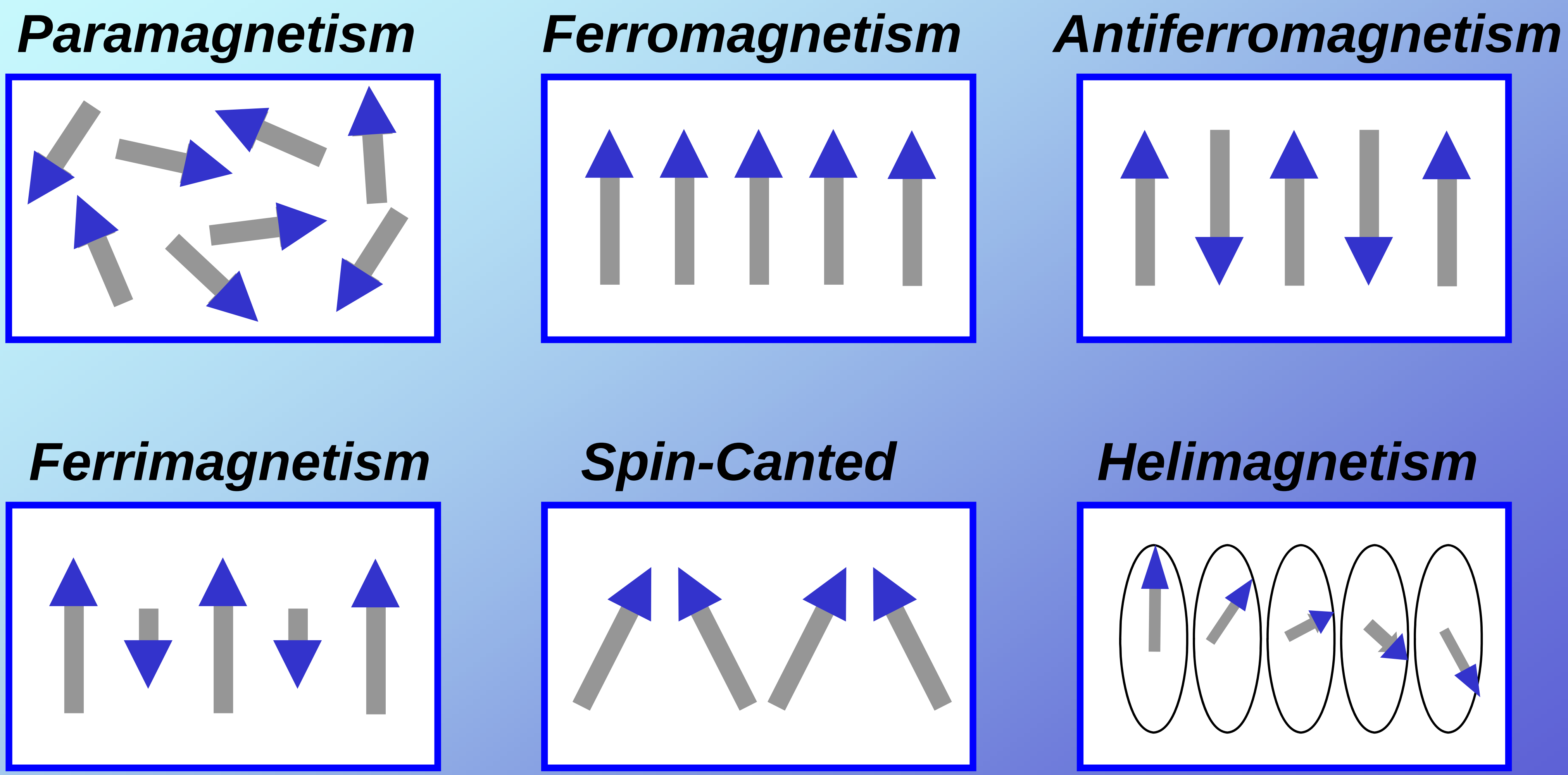
Types of Magnetism



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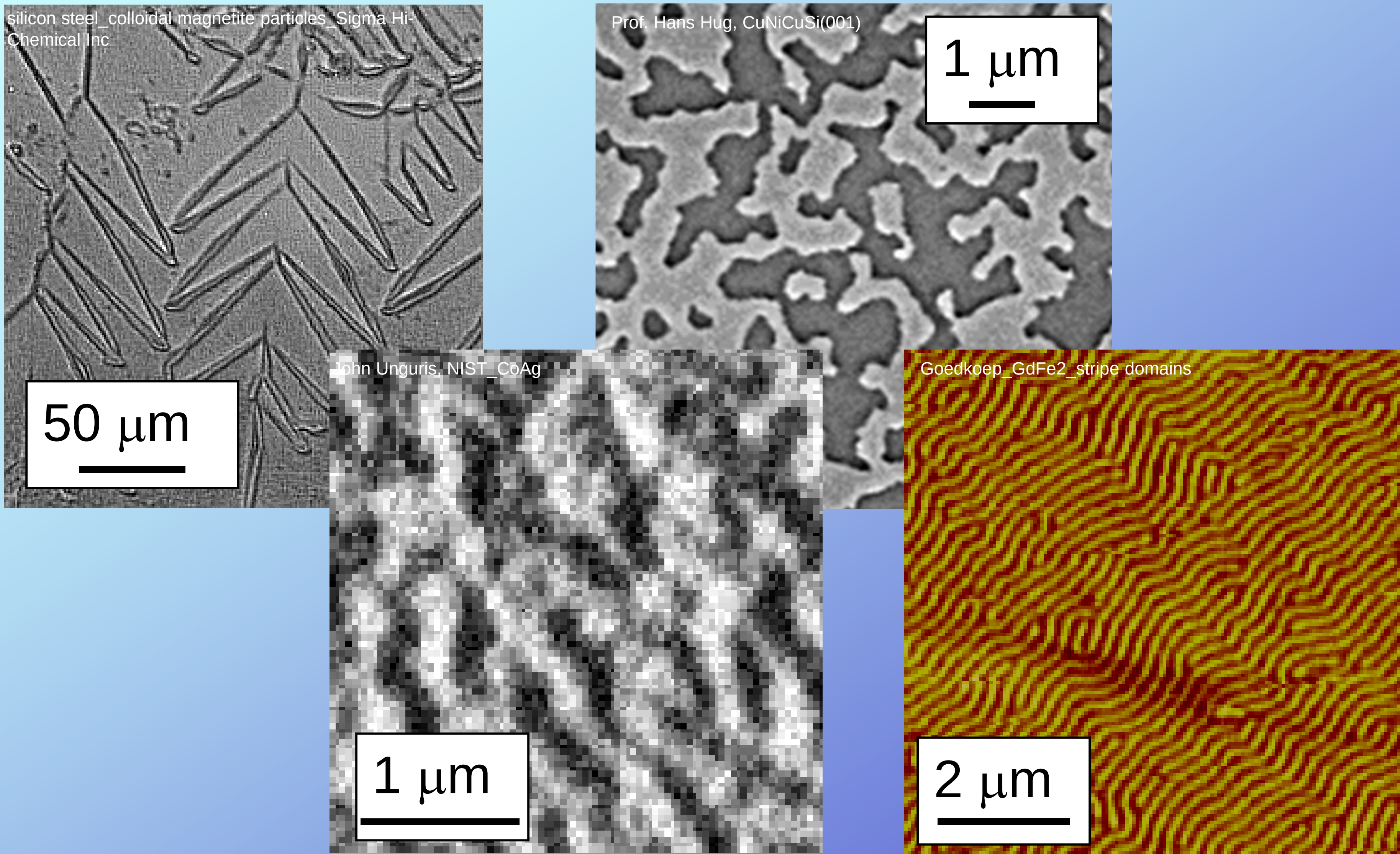
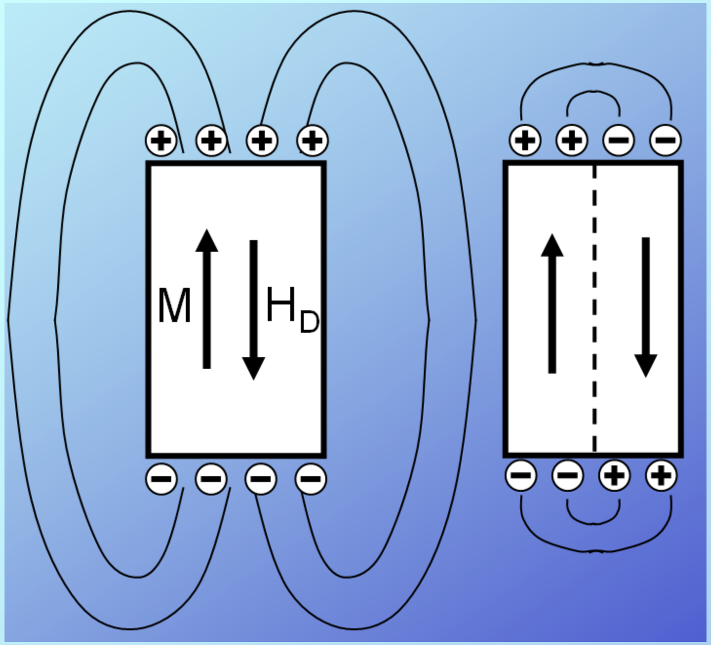
Magnetic Domains ?



Imaging Techniques



- Magnetic flux density (or induction):

$$\mathbf{B} = \mu_0\mathbf{H} + \mathbf{J}$$

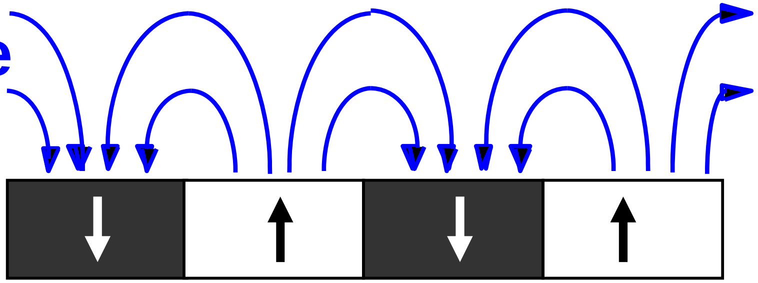
H = magnetic field (external + stray field)

J = magnetic polarization (magnetization μ_0**M**
= **q/V** magnetic moment / volume)

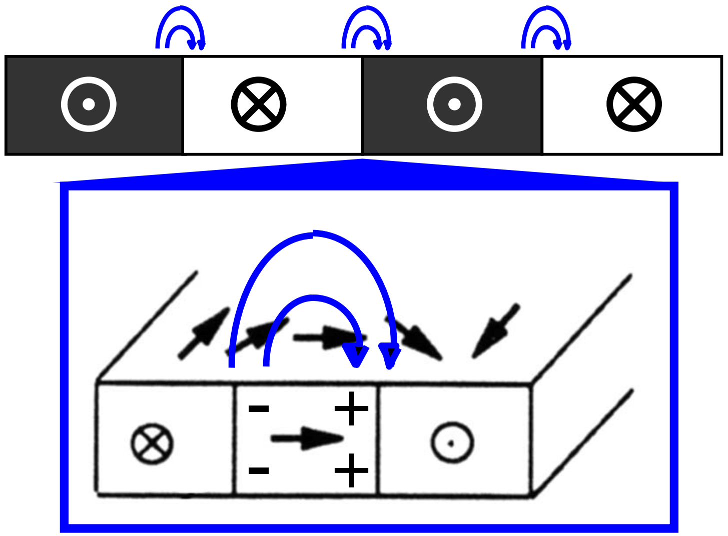
- Maxwell's equation div**B** = 0, therefore:

div**H** = -div**M** ➔ any divergence of **M** creates a stray field **H** (zero external field)

Out-of-plane



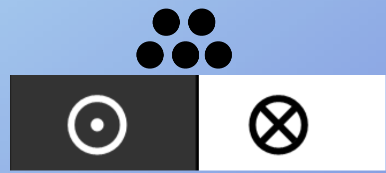
In-plane



Imaging techniques provide information on stray field, magnetization (magnitude and direction), magnetic induction (includes stray field and magnetization) at material surface or through a thin film

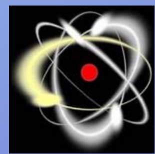
Imaging Techniques

Bitter Technique



Scanning Probe Microscopy

Electron Microscopy



Kerr Microscopy

X-Ray Microscopy Techniques

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Scanning Probe Microscopy

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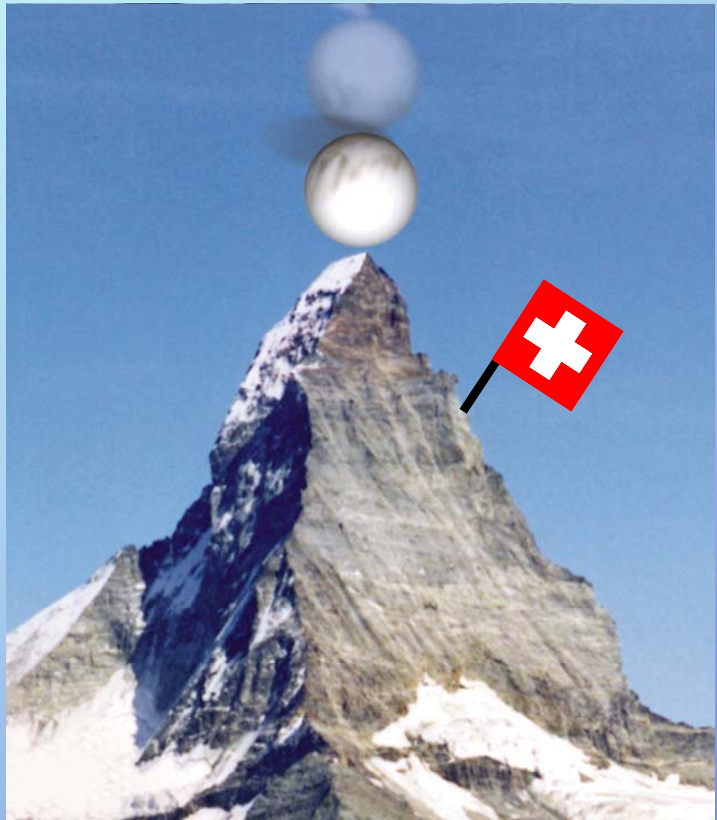
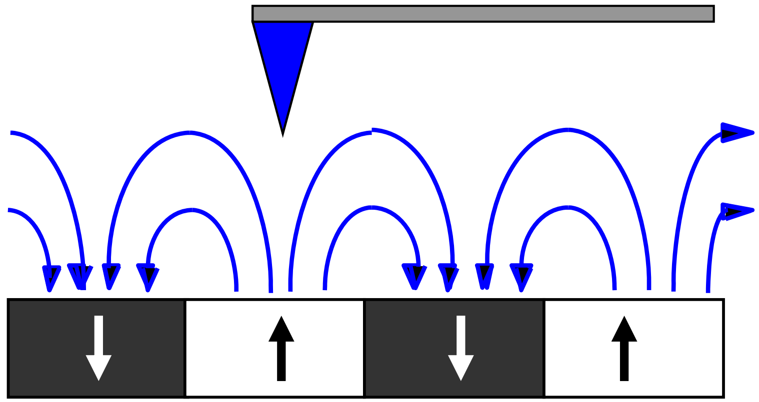
Scanning Probe Microscopy



If an atom was as large as a ping-pong ball…

…the tip would have the size of the Matterhorn!

Magnetic Force Microscopy



- Stray field interaction between film and magnetic tip
- Forces are on the order of 10^{-10} N
- Employ a cantilever (CL) "spring"
- The force sensing carried out in two ways:
  - Static force sensing: CL brought near to surface and bends down or up (interaction attractive or repulsive). But CL might "snap" onto the surface.
  - Dynamic force sensing: CL is oscillated at a certain frequency, typically at its resonance frequency or a bit off (5%)

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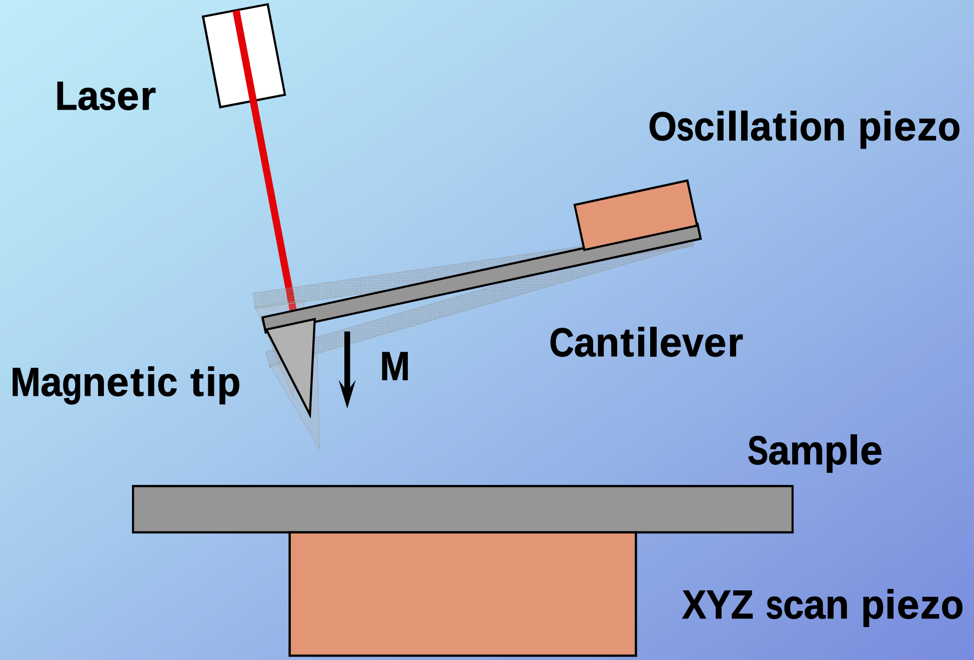
Non Contact Dynamic MFM

Schematic drawing:



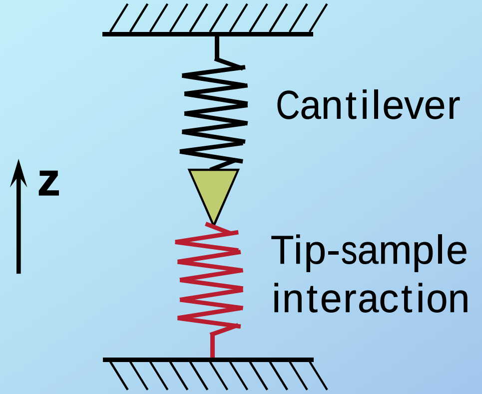
- The **cantilever** is oscillated with a fixed amplitude (nm).
- The **sample** is scanned by the XYZ scan piezo.
- The **measurement** signal is the *frequency shift* (shift of cantilever's resonance frequency), measured with a quadrant diode detector or laser interferometer.

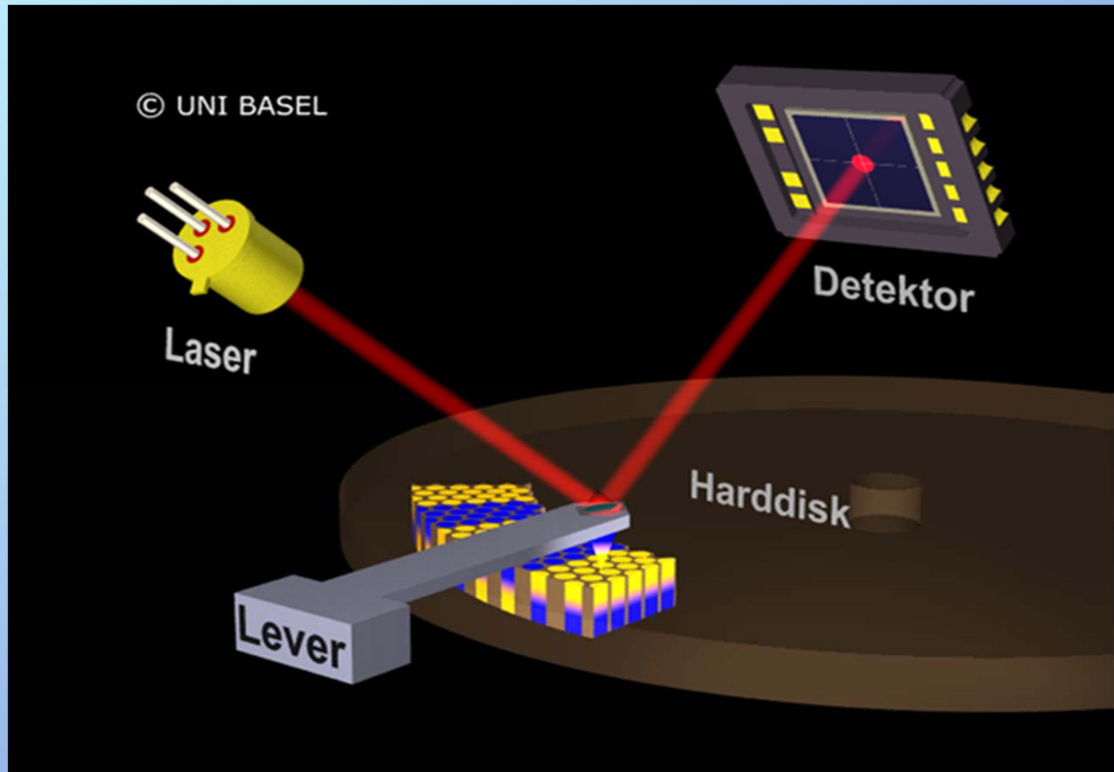
SFM Dynamic Operation Modes

Measurement Signal:

Massless spring system → harmonic oscillator

Freq. $$f_0 = \frac{1}{2\pi}\sqrt{\frac{c_L}{m}}$$ spring constant (c_L), mass (m)





Linear part of Taylor Expansion

$$f_P = \frac{1}{2\pi}\sqrt{\frac{1}{m}\left(c_L - \frac{\partial F}{\partial z}\right)}$$

$$\delta f \equiv f_P - f_0 \approx -\frac{f_0}{2c_L}\frac{\partial F}{\partial z}$$

$\frac{\partial F}{\partial z}$ interaction force gradient

Attractive forces → lower resonance frequency → -ve freq. shift
Repulsive forces → higher resonance frequency → +ve freq. shift

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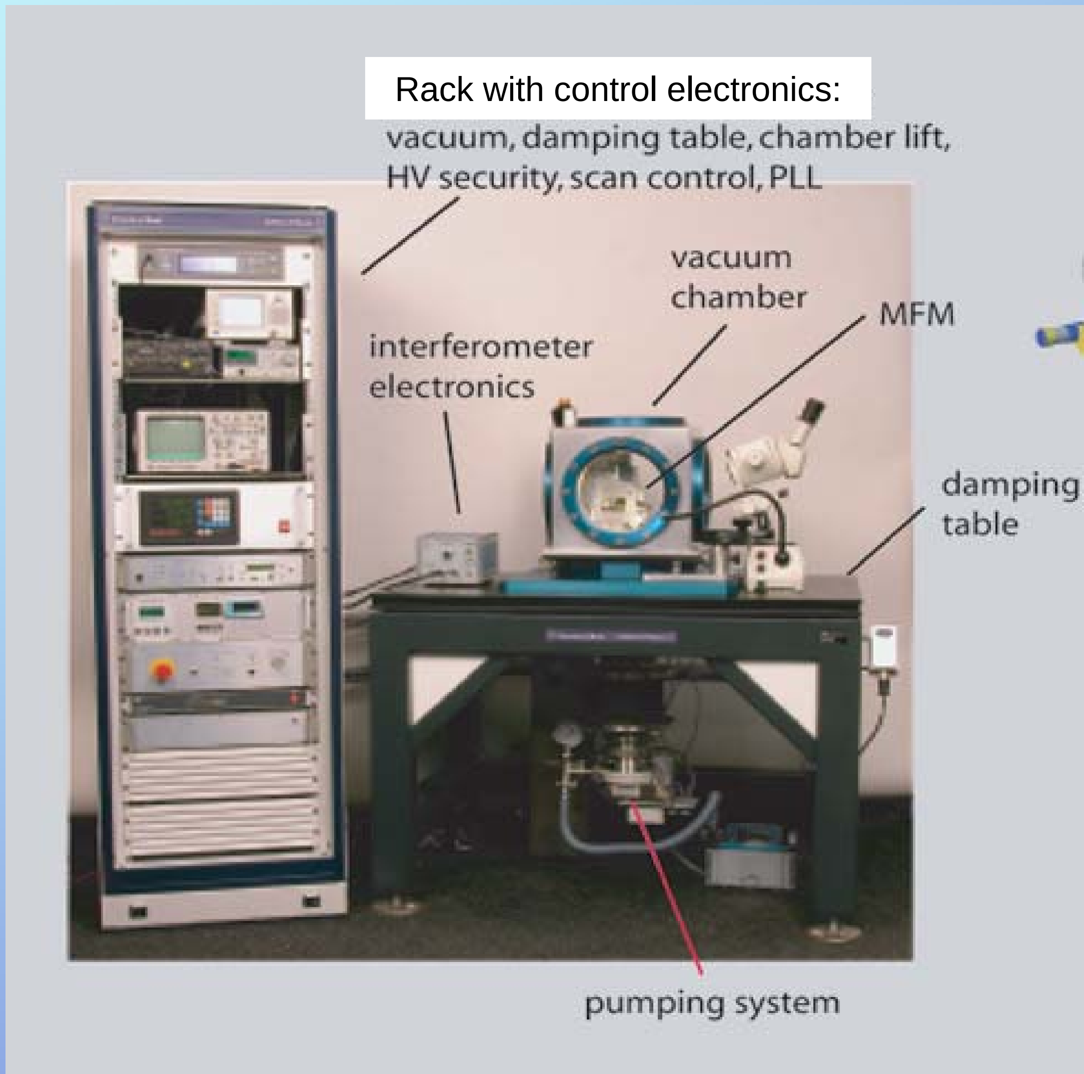
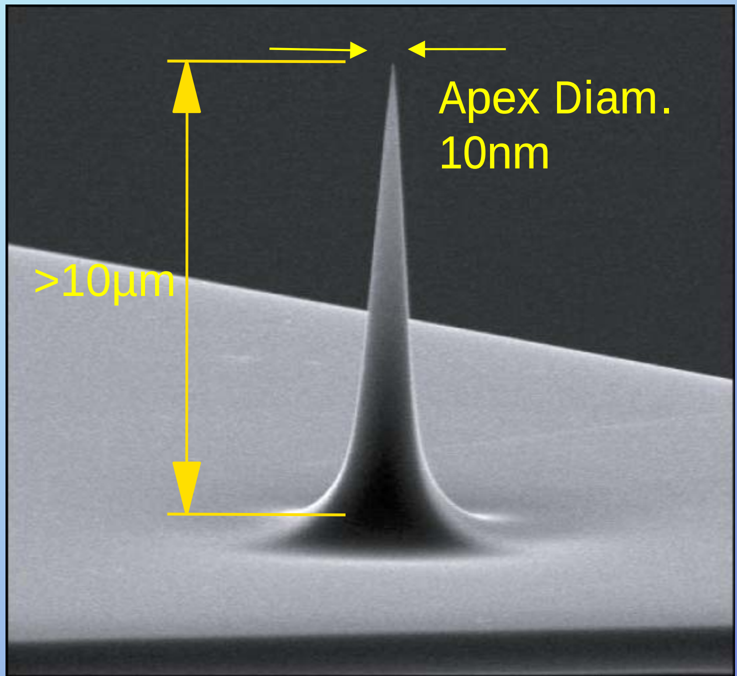
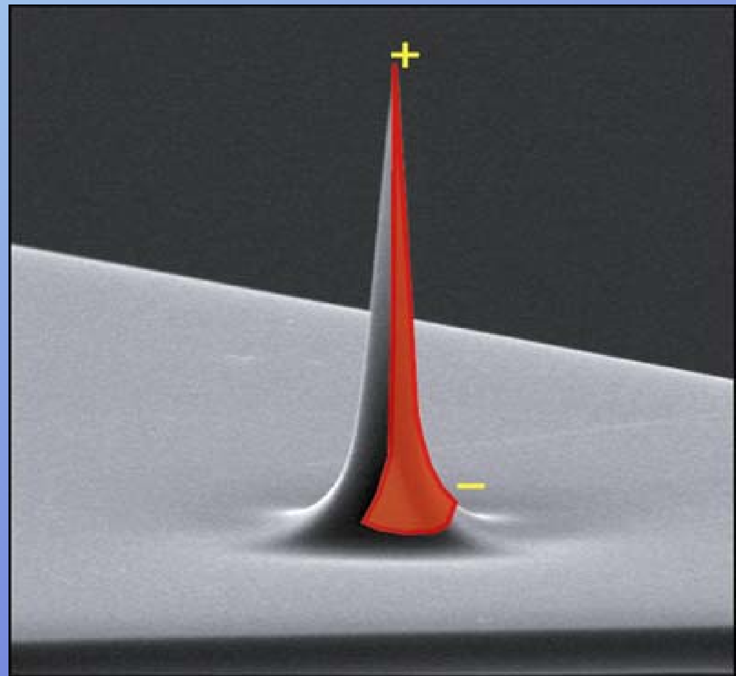
The High Resolution MFM



High Resolution MFM: Requirements

- High aspect ratio tip with small apex diameter, small cone angle.
- Ultra-thin & smooth ferromagnetic coating (3-6nm).
- High measurement sensitivity limited only by thermal noise of cantilever due to gas molecules hitting cantilever. Therefore need to go to vacuum (results in a large Q, i.e. a low damping).





T.R. Abrecht, J. Appl. Phys. **69**(2), p668 (1994)

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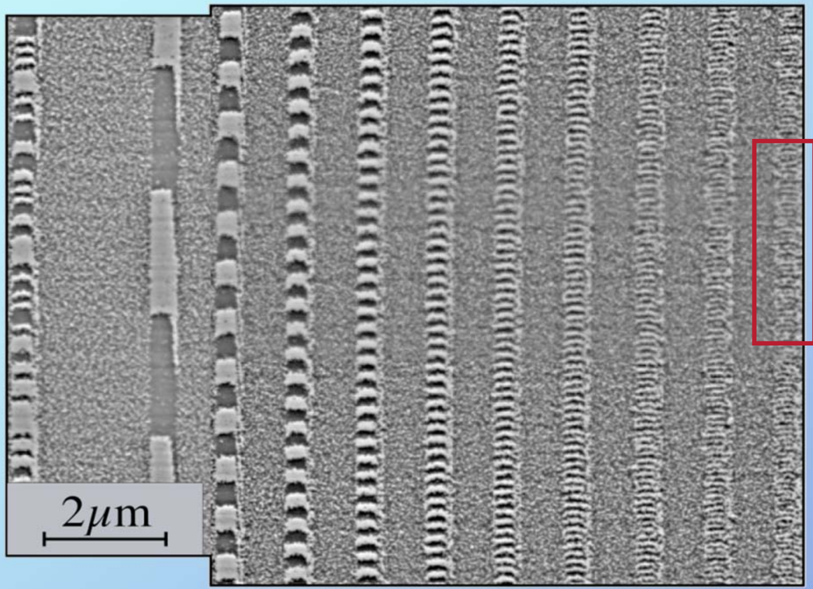
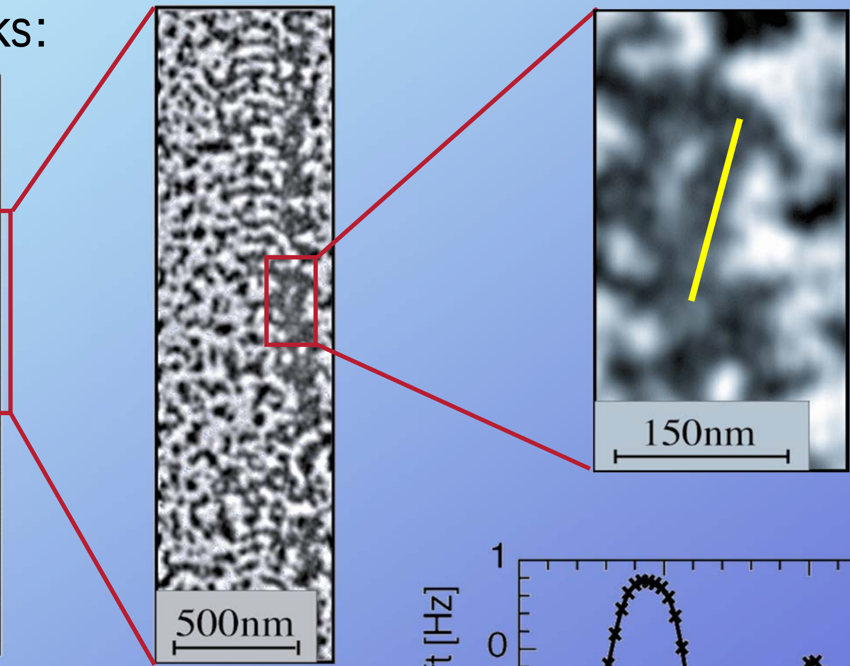
High Resolution MFM: Example

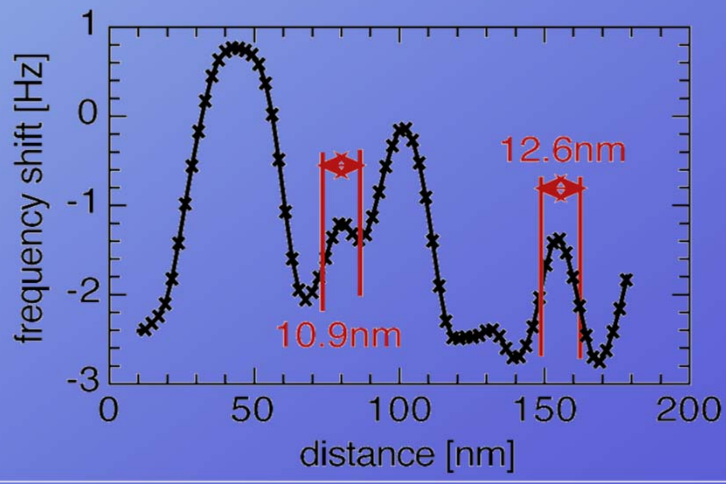
High resolution MFM images of hard disk media (sample by Seagate Research):

Bits organised in circumferential tracks:





Increasing density / decreasing bit size



hr-MFM images important in HD research:

- detect defects in the bits
- measure media properties

A. Moser et al. J. Magn. Magn. Mater. (2005)

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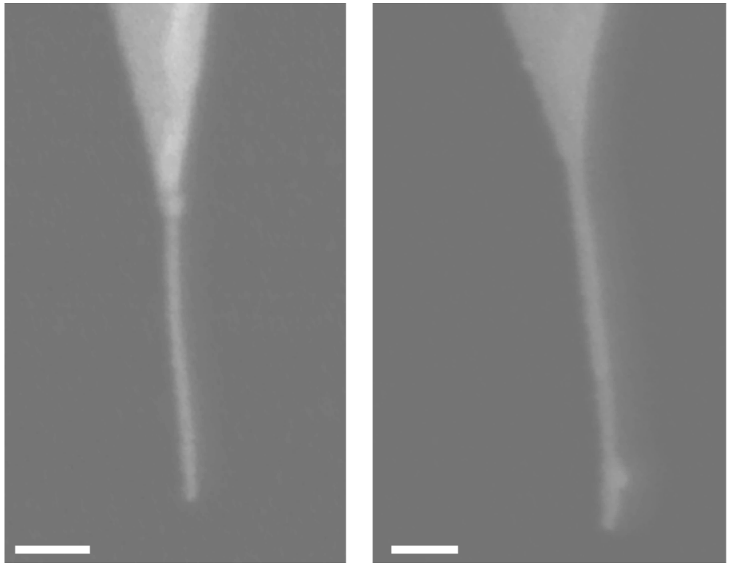
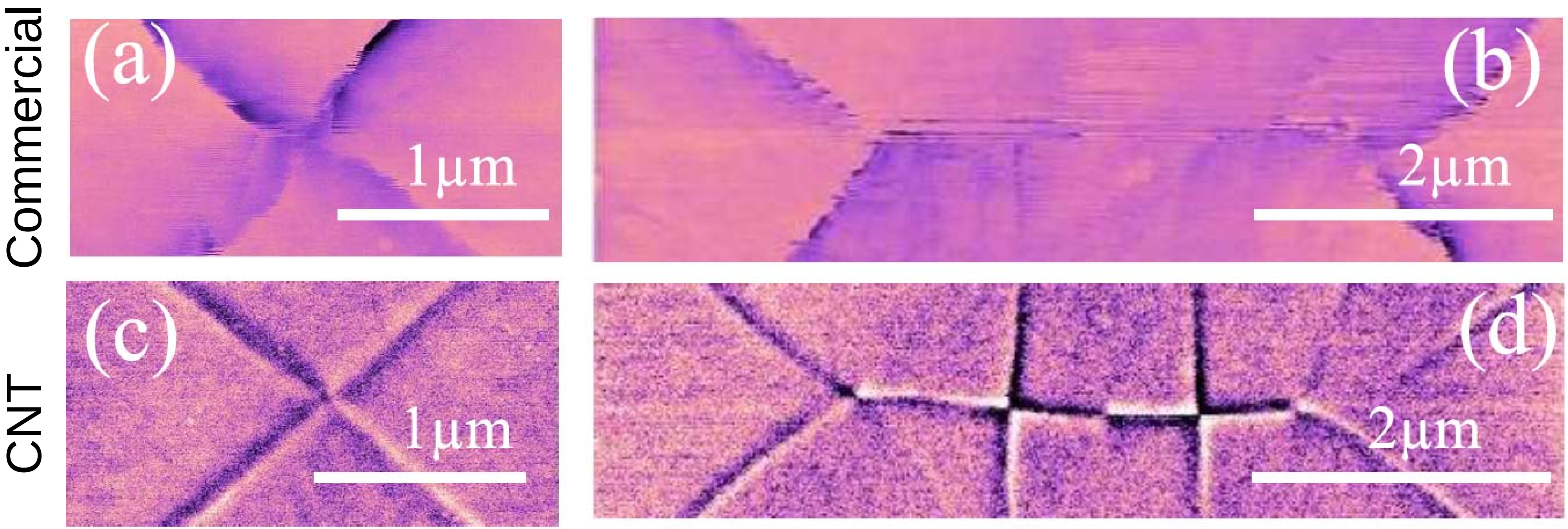
In-Plane Structures with CNT Tip



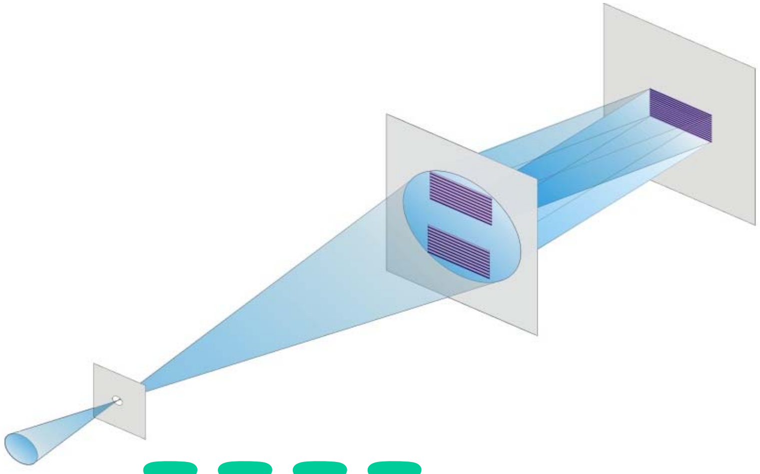
Y. Lisunova, J. Heidler, I. Levkivskyi, I. Gaponenko, A. Weber, Ch. Caillier, L.J. Heyderman, M. Kläui and P. Paruch
Nanotechnology Accepted (2013)

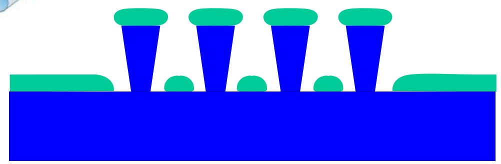
High resolution with no vacuum!

Scale Bar: 100 nm



Magnetic Islands with EUV-IL





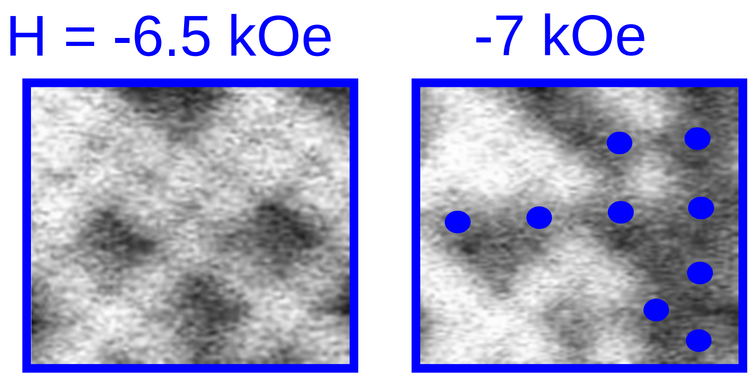
Co/Pd Multilayer on SiO_x Pillars

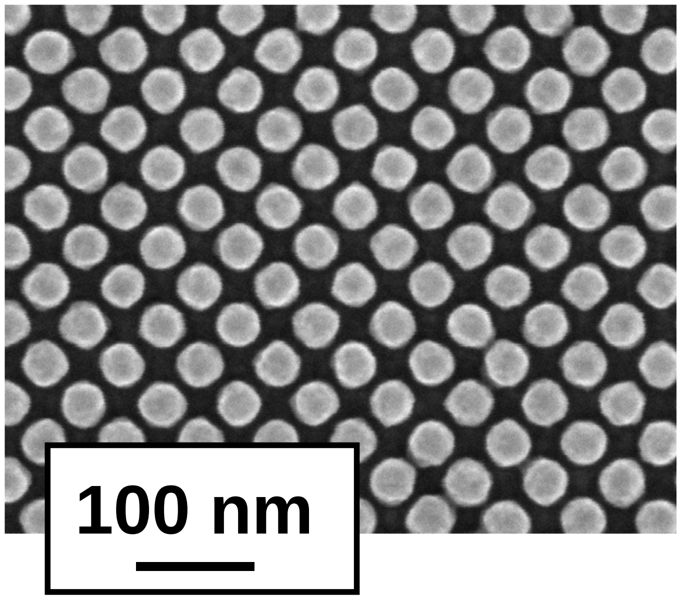
Period = 50 nm → 263 Gbit/in^2

Diameter = 28.4 nm, σ = 5 %

MFM measurements

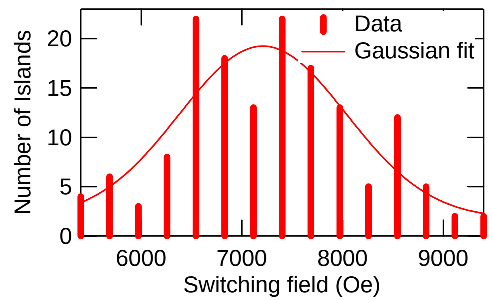
Switched Islands: •





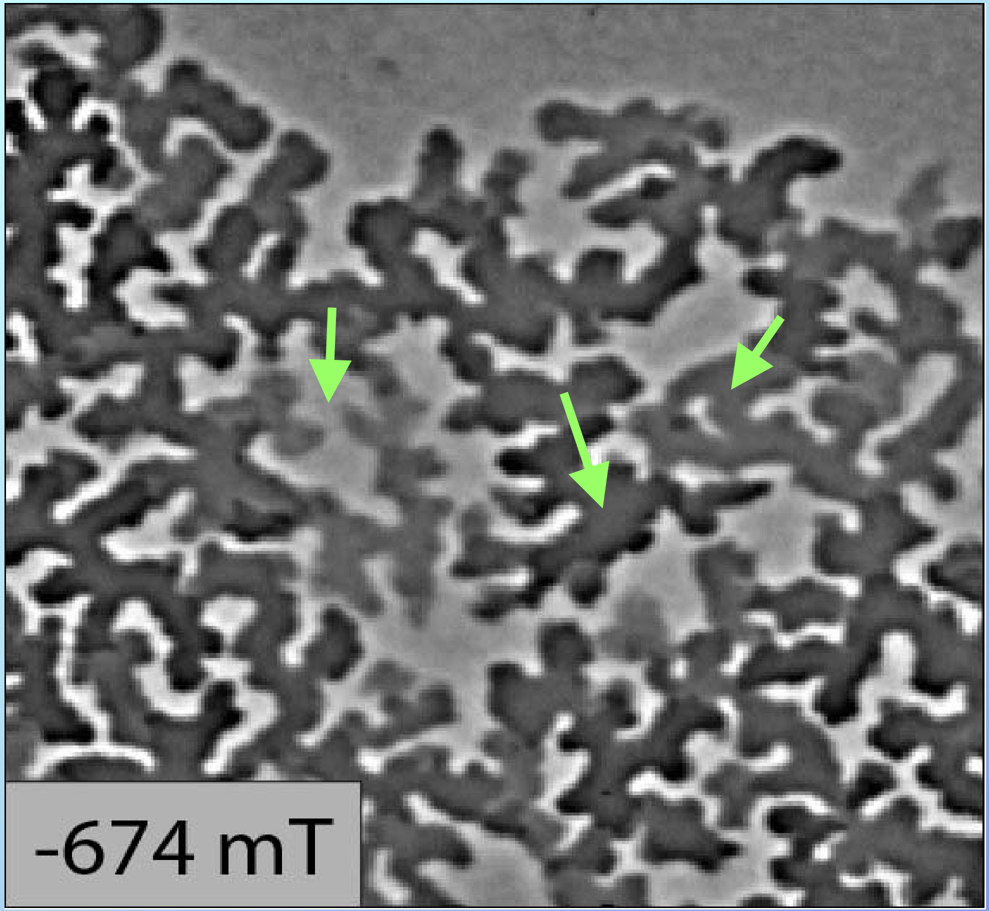
Mean switching field: 7200 Oe

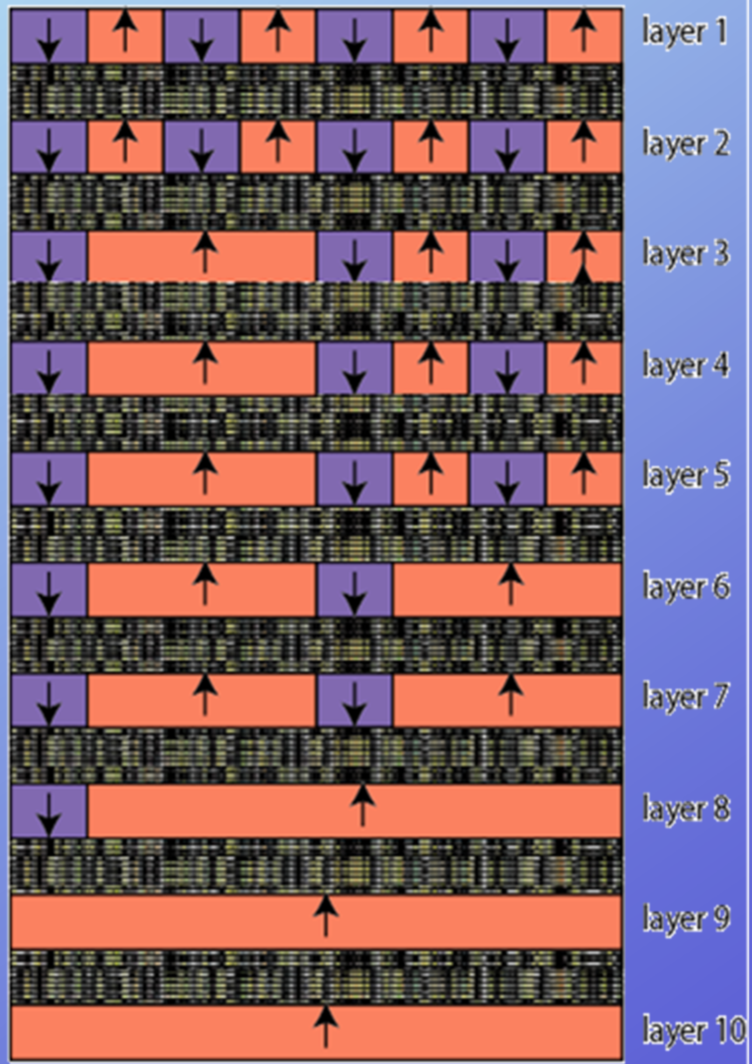
SFD (σ/mean) = 11.5 %



F. Luo, L. J. Heyderman, H. H. Solak, T.Thomson, M. E. Best APL (2008)

CoPt Multilayer in Hysteresis Loop





- Magnetization of layers from top to bottom.
- Which grey level corresponds to which layer?
- Take a calibrated tip and compare simulation with image.

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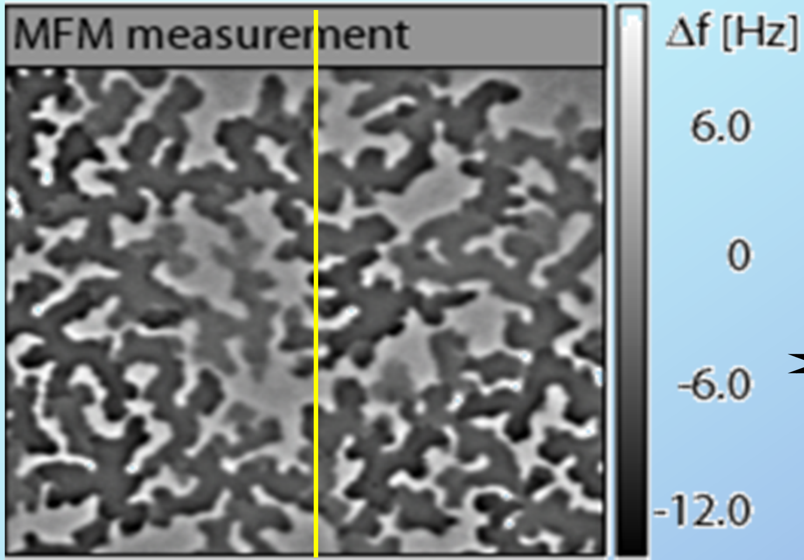
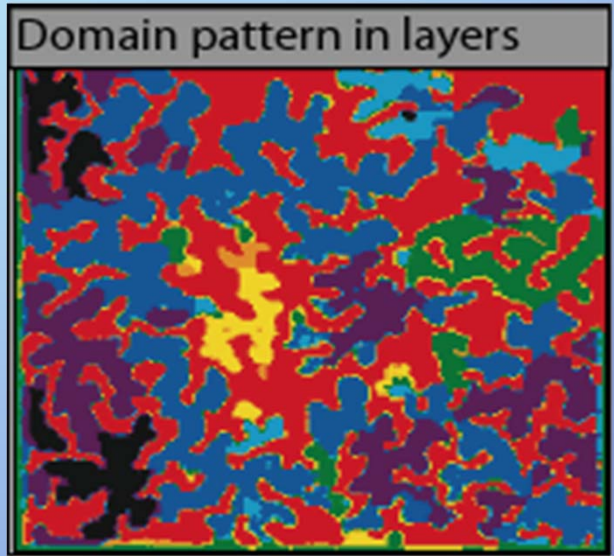
Simulation of MFM Images

1



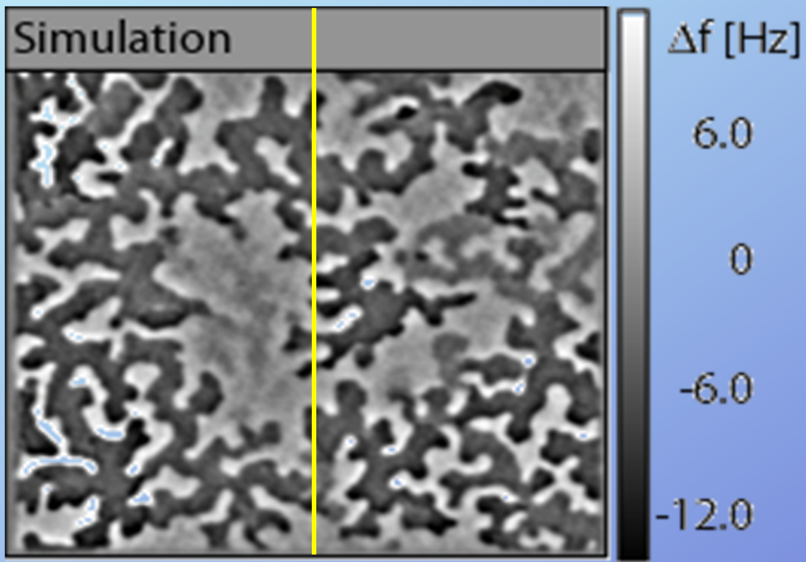
Guess

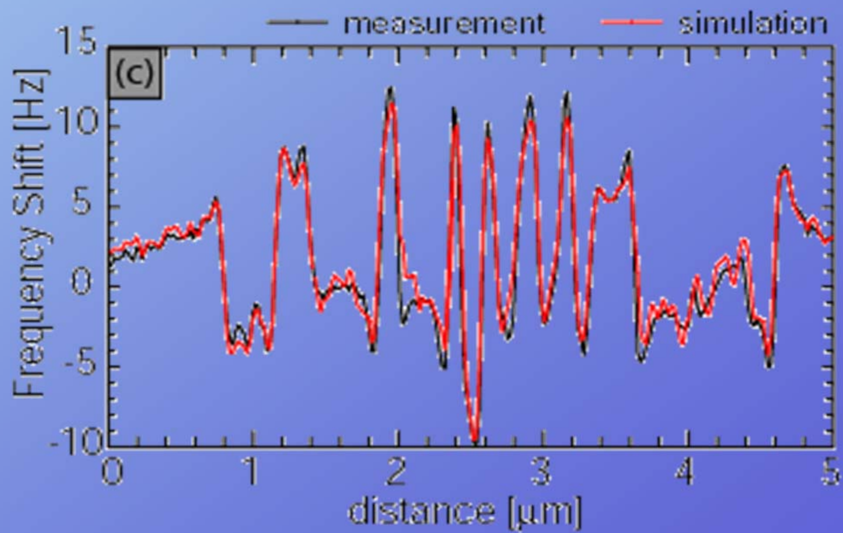
2



Colours: domains in different layers

3





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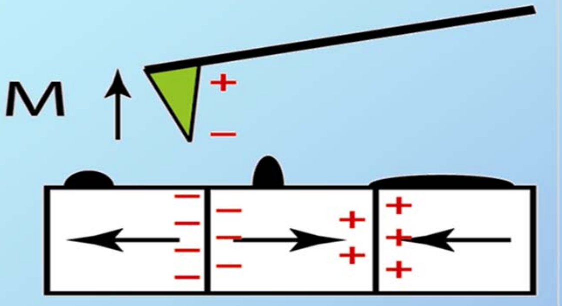
Topography Separation

Magnetic contrast inverts when rotating the tip magnetization by 180°.
Topographic contrast remains (van der Waals is always attractive).

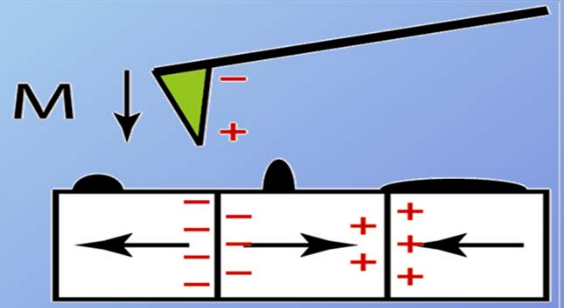
⇨ Acquire two images with opposite tip magnetization states.

A

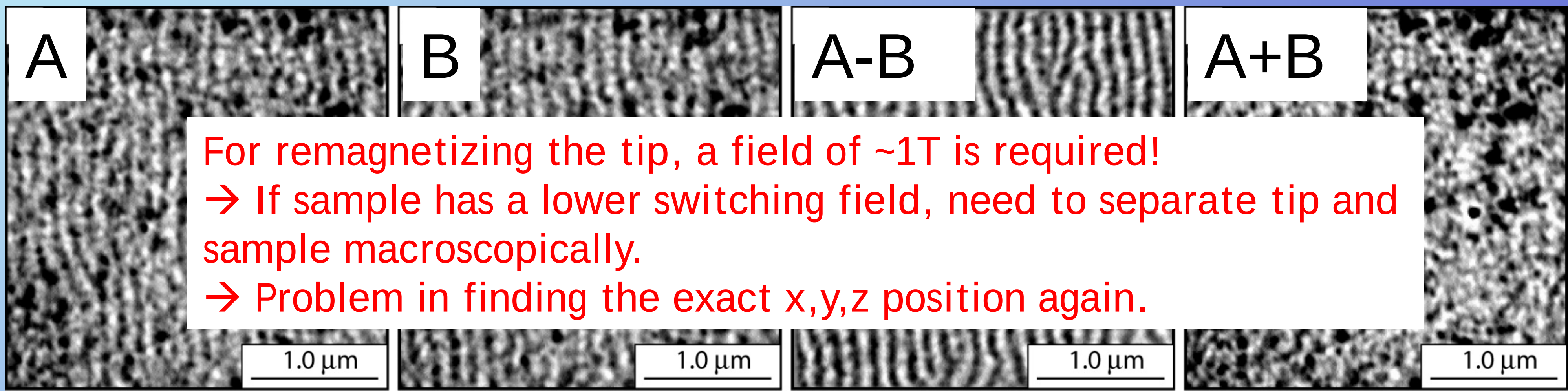


Tip magnetization up

B



Tip magnetization down



For remagnetizing the tip, a field of ~1T is required!
→ If sample has a lower switching field, need to separate tip and sample macroscopically.
→ Problem in finding the exact x,y,z position again.

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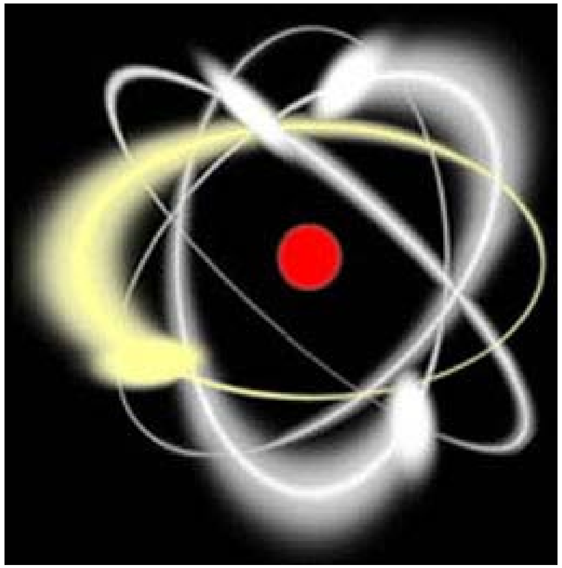
MFM Summary

- Maps the magnetic stray field (or derivative)
- Resolution: typically 20-30 nm, high resolution: 10 nm
- Non-destructive
- Especially sensitive to z-component of stray field: ideal for perpendicular anisotropy materials (e.g.magnetic media) but can also image domain walls in in-plane samples
- Requires virtually no sample preparation
- Surface should be relatively flat
- Tip quality is critical
- Influence of tip: difficult to measure magnetically soft samples

Electron Microscopy



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Transmission Electron Microscopy

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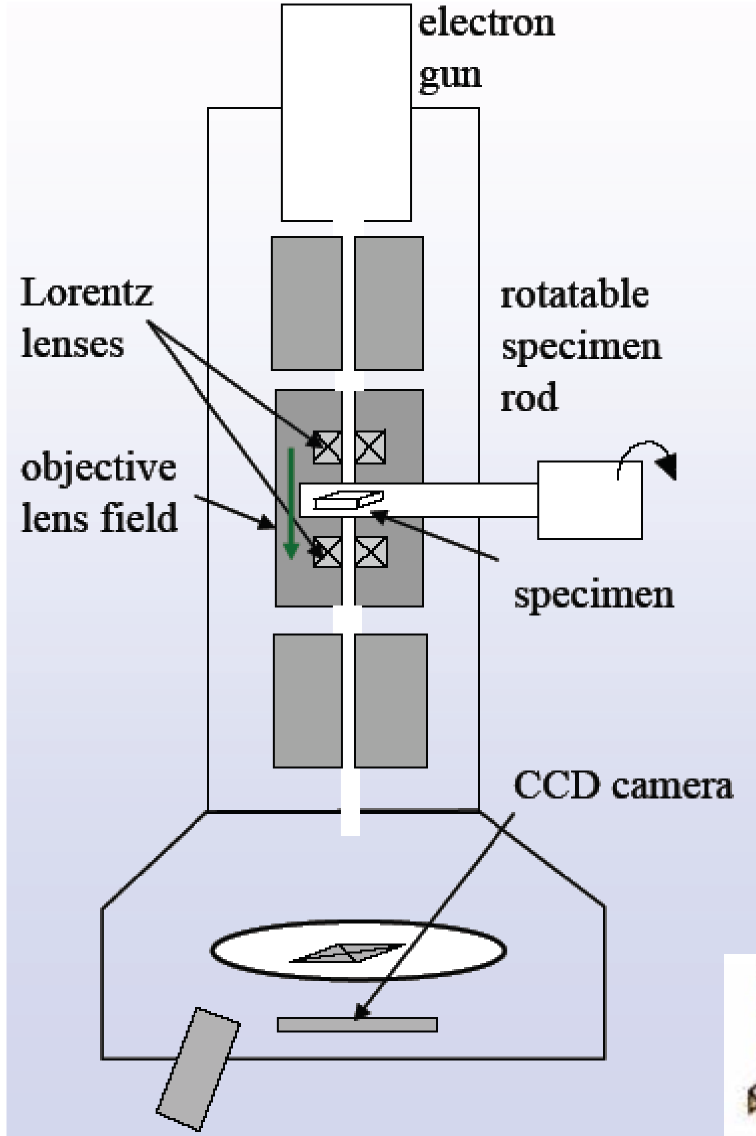
Transmission Electron Microscope



Lenses

Condenser
illuminate

Objective
focus

Projector
image

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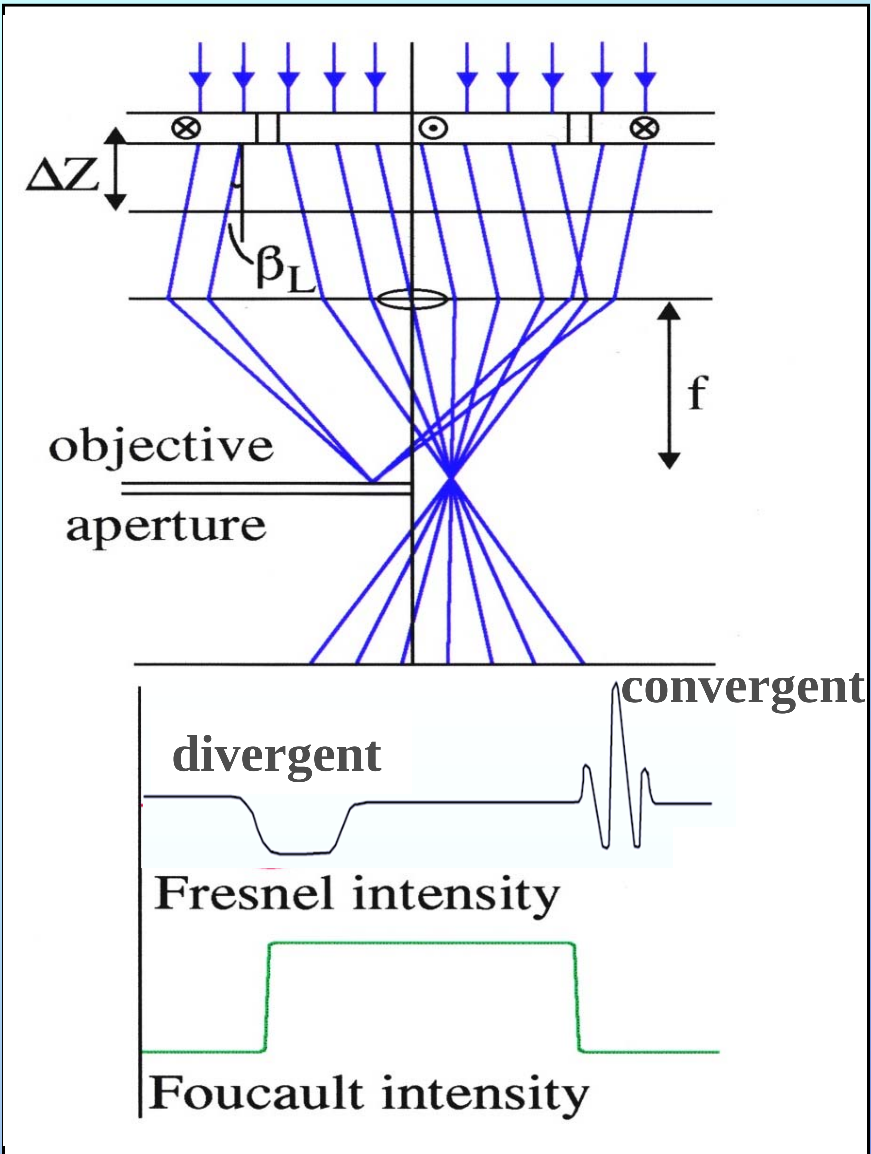
Lorentz Microscopy Classical Theory



- Electron voltage 100 - 200 keV
- Particle representation, corresponding to classical beam optics, the electrons are deflected by the Lorentz force:

$$\mathbf{F = q(v \times B)}$$

q = electron charge

v = electron velocity

B = magnetic flux density

- With deflection angle: $\boldsymbol{\beta = (e\,\lambda\,B\,t\,)/\,h}$
- Only components of B perpendicular to the electron beam are effective
- Includes stray fields outside sample

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Fresnel and Foucault Microscopy

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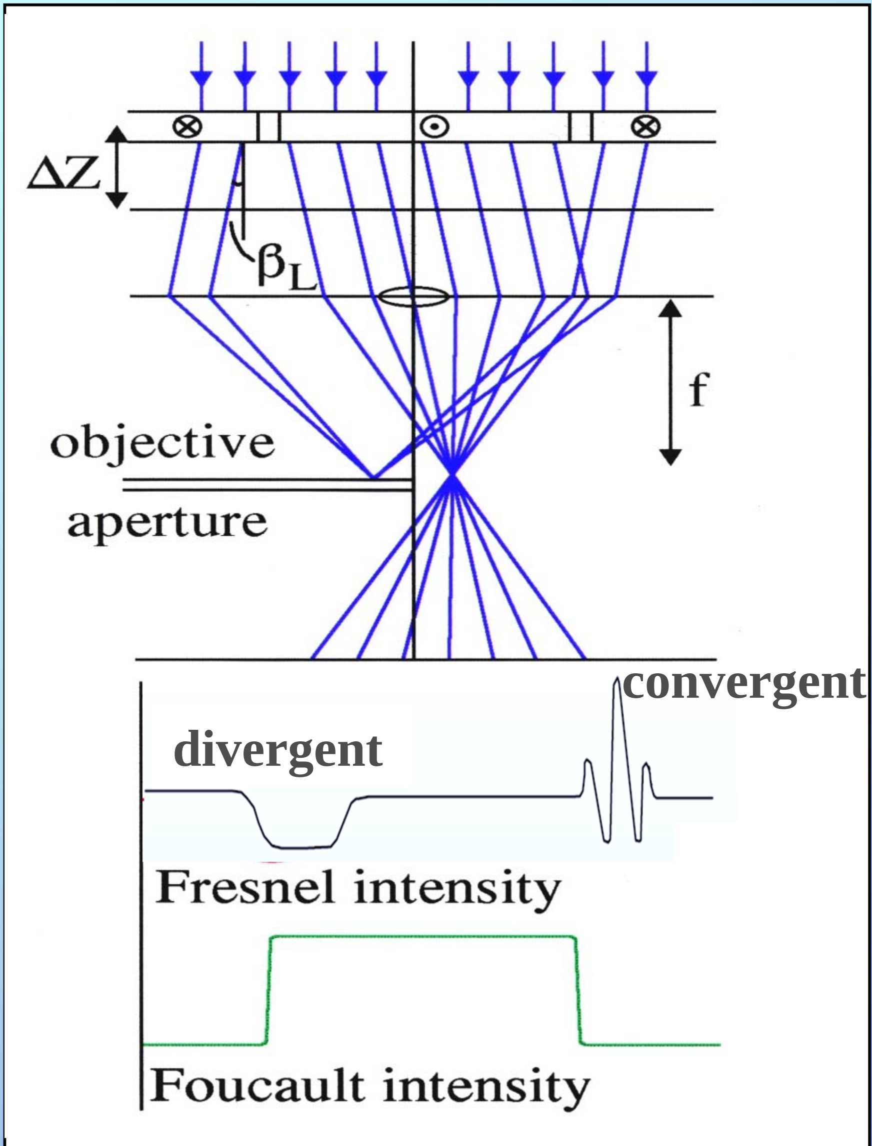
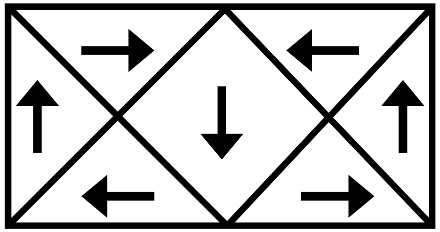
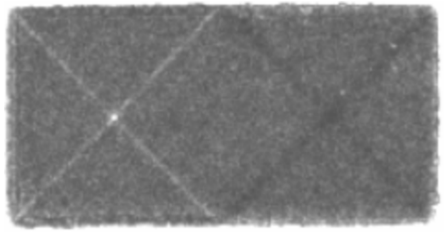
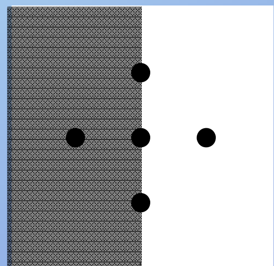
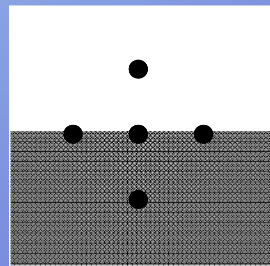


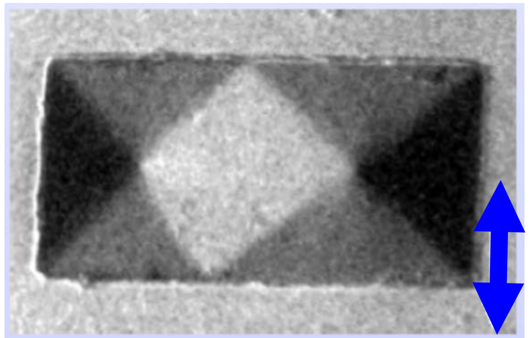


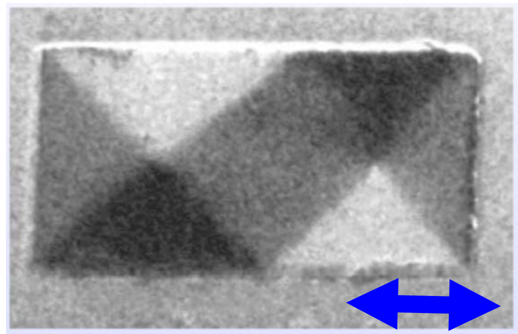


4 x 20 μm









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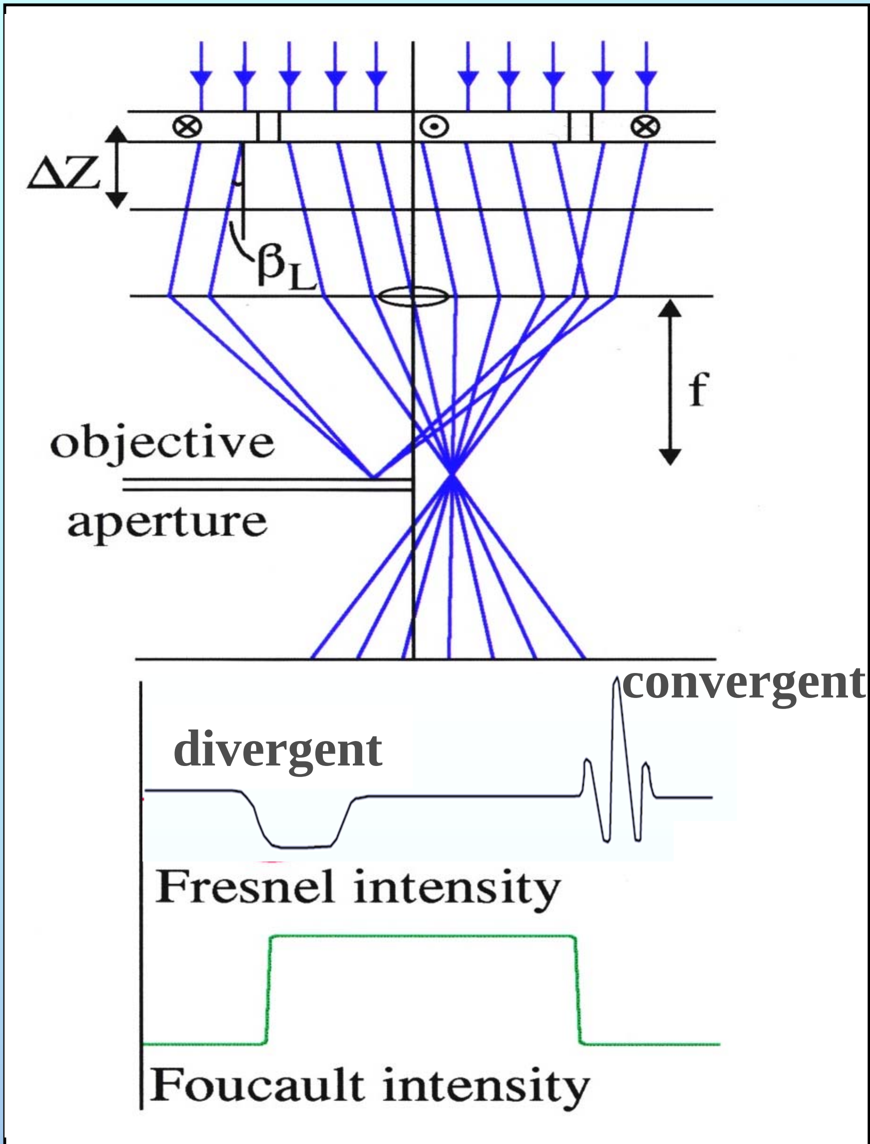
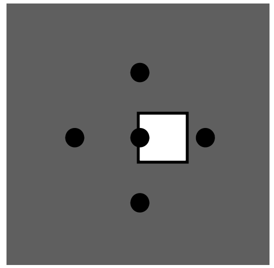
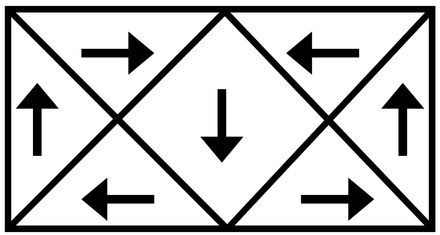
Coherent Foucault

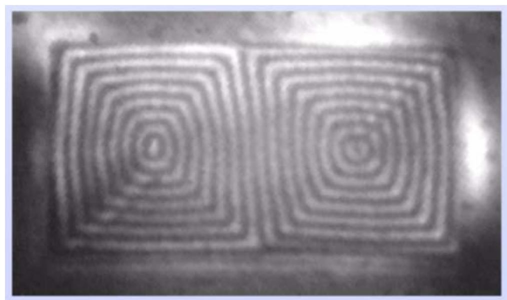


- Field Emission Gun source: small source angle
- Electron transparent phase shifting aperture: holes in SiN membrane, 50 nm thick, 200 keV, gives π phase shift of all magnetic spots
- Interference fringes parallel to induction direction with periodicity h/eBt



- In-line Holography !





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4 x 20 μm

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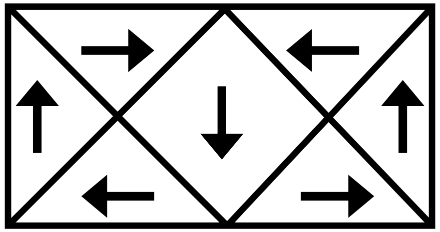
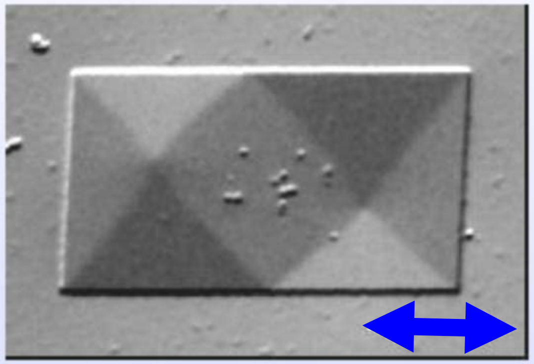
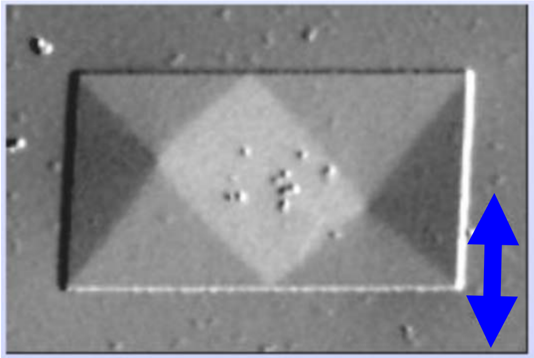
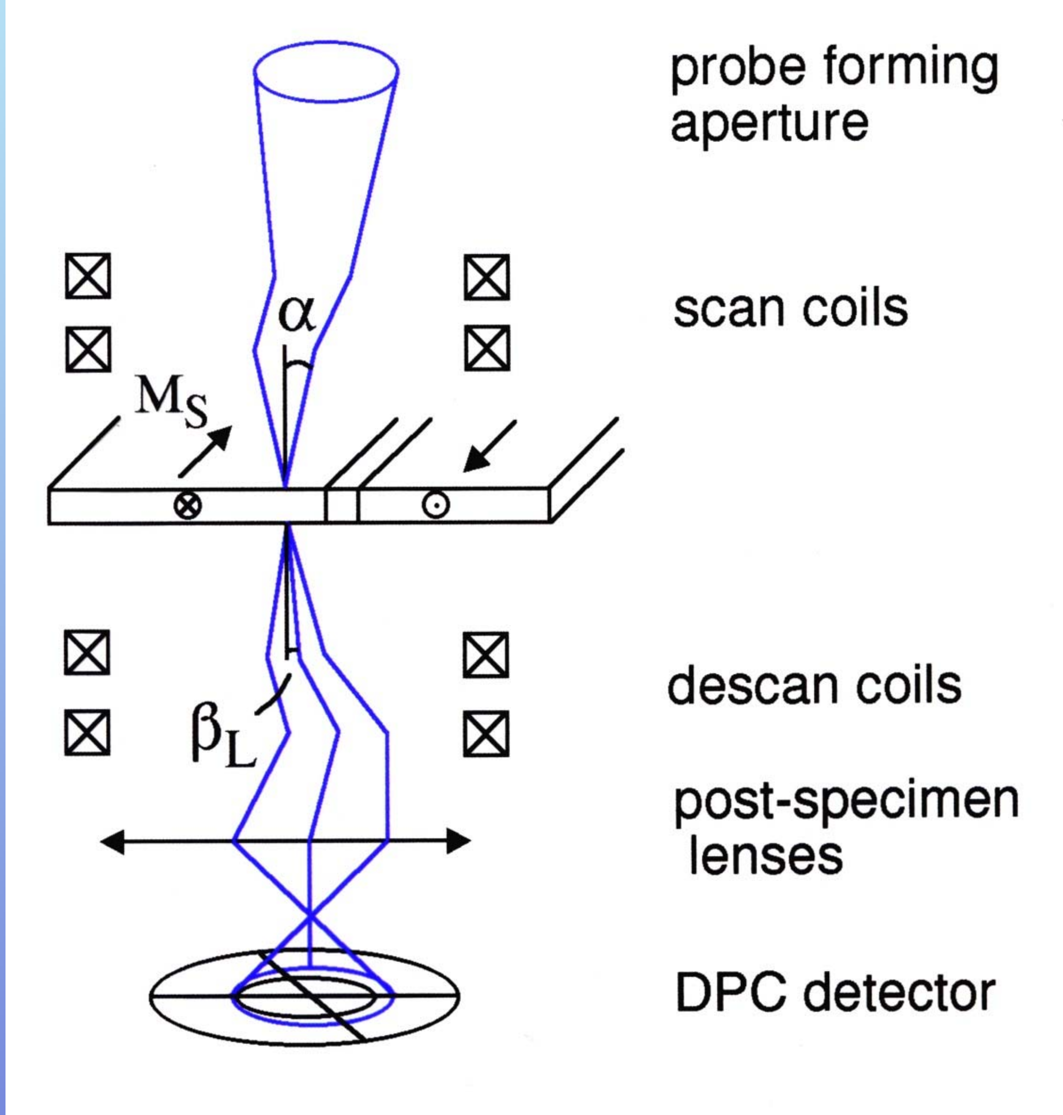
Differential Phase Contrast





4 x 20 μm





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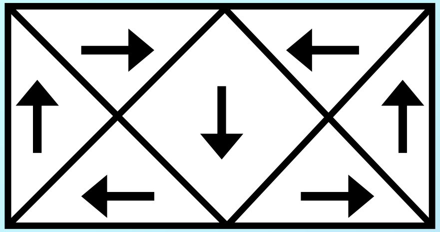
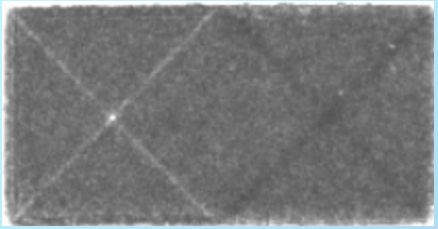
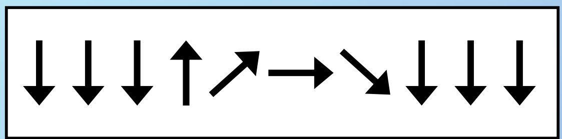
Fresnel Microscopy of Different Domain Walls

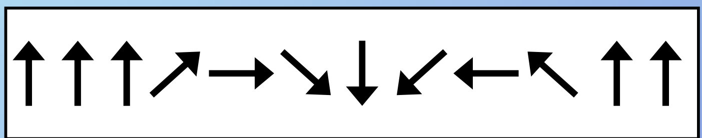


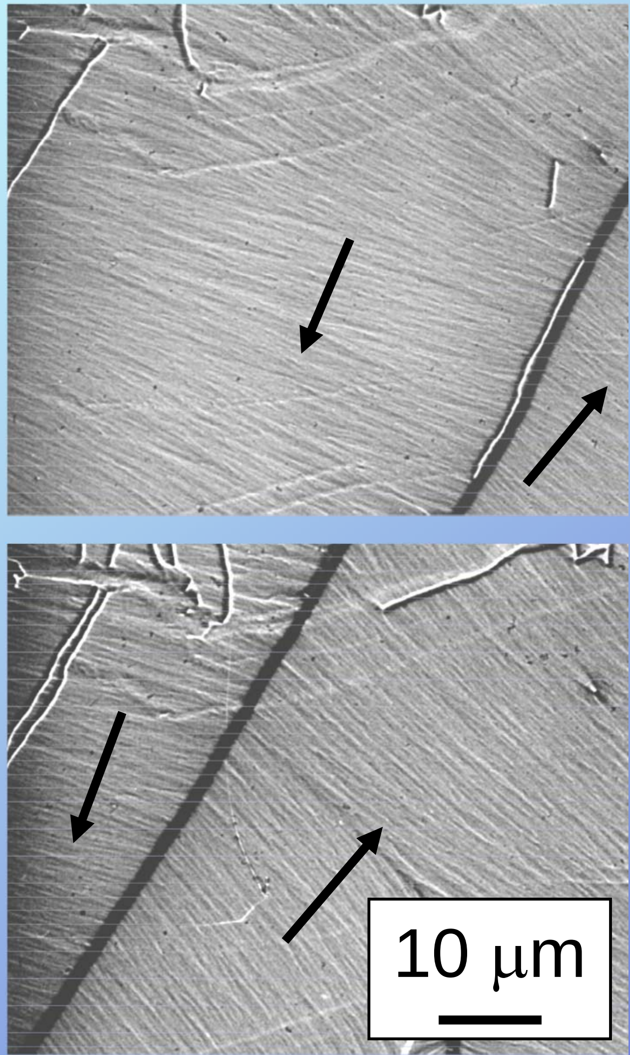


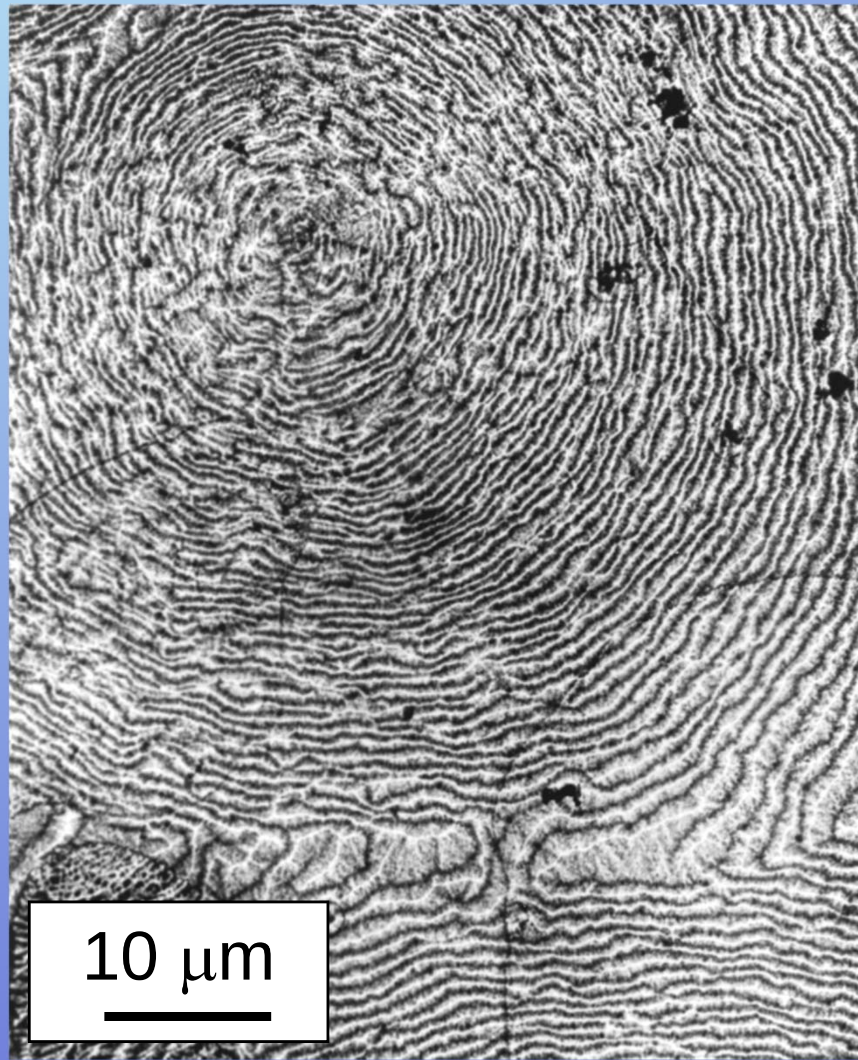
180° Wall



360° Wall







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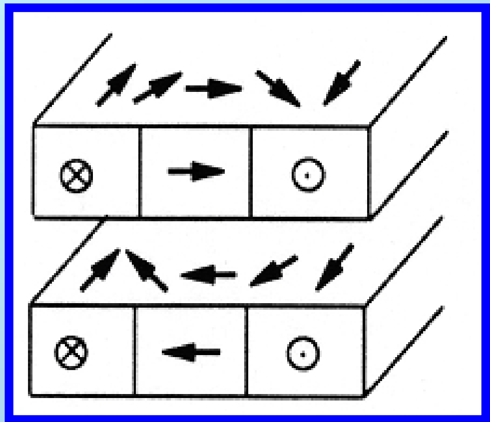
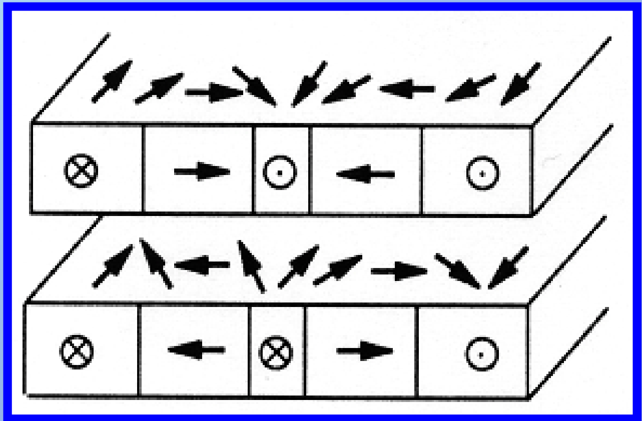
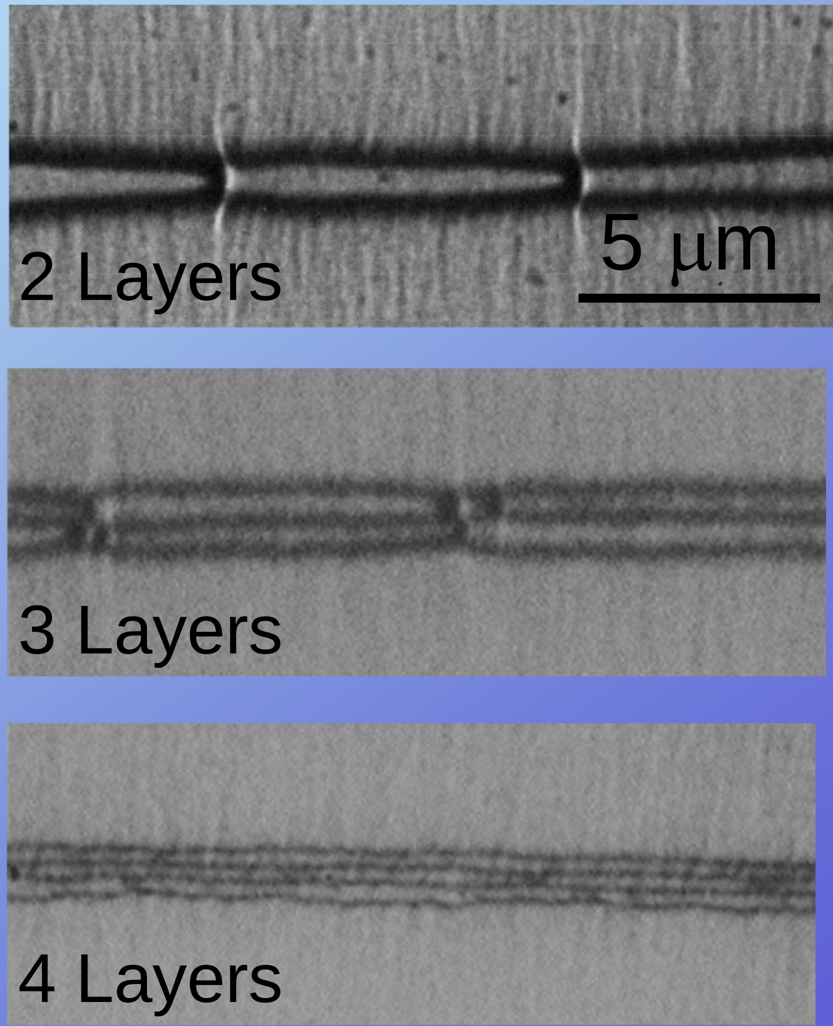
Fresnel Microscopy: Domain Walls in Multilayers

Single wall



Twin wall





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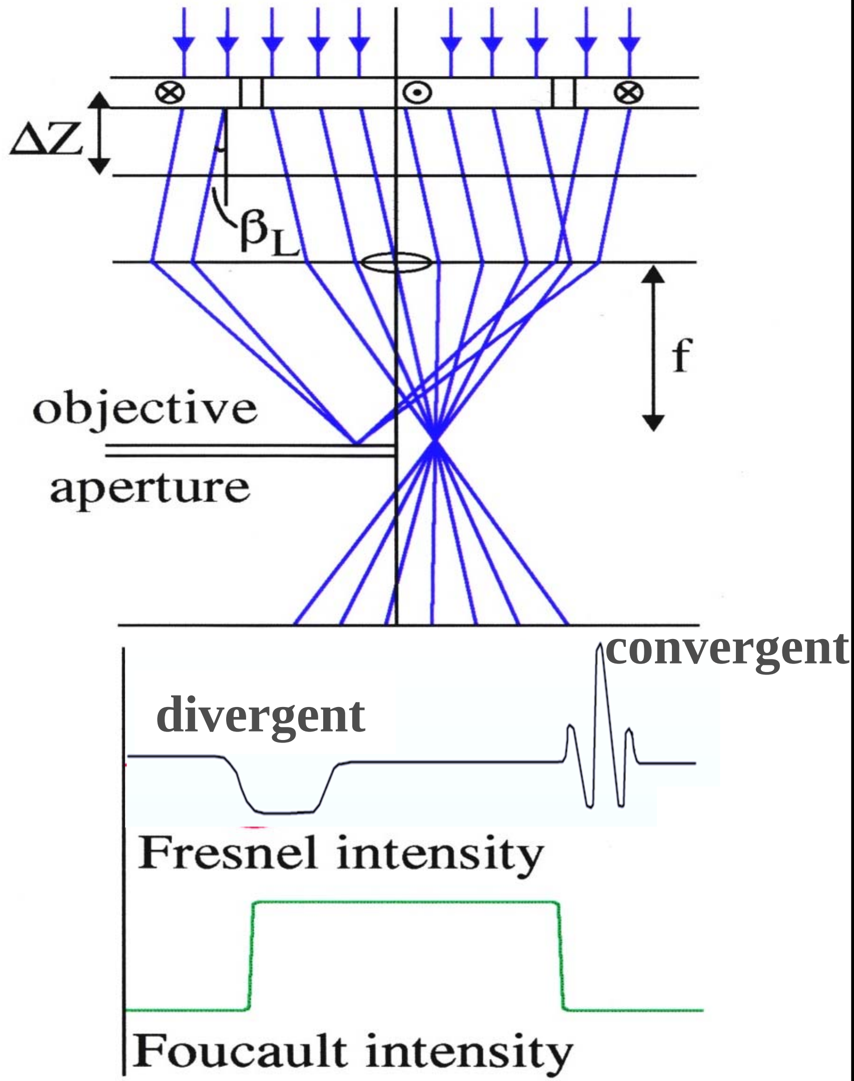
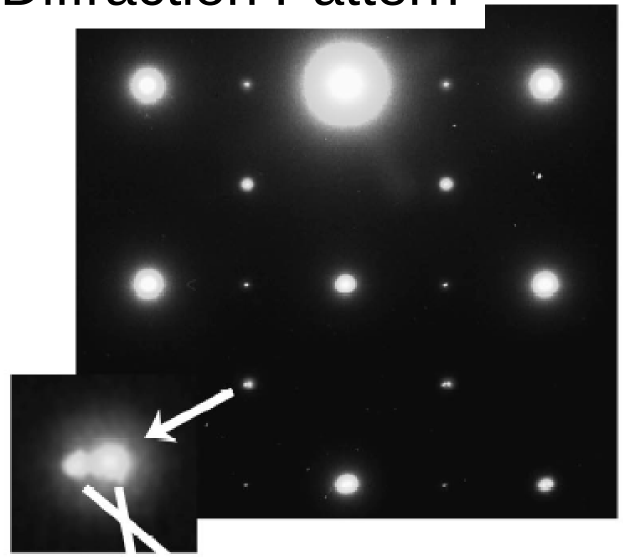
Microstructure and Magnetic Information

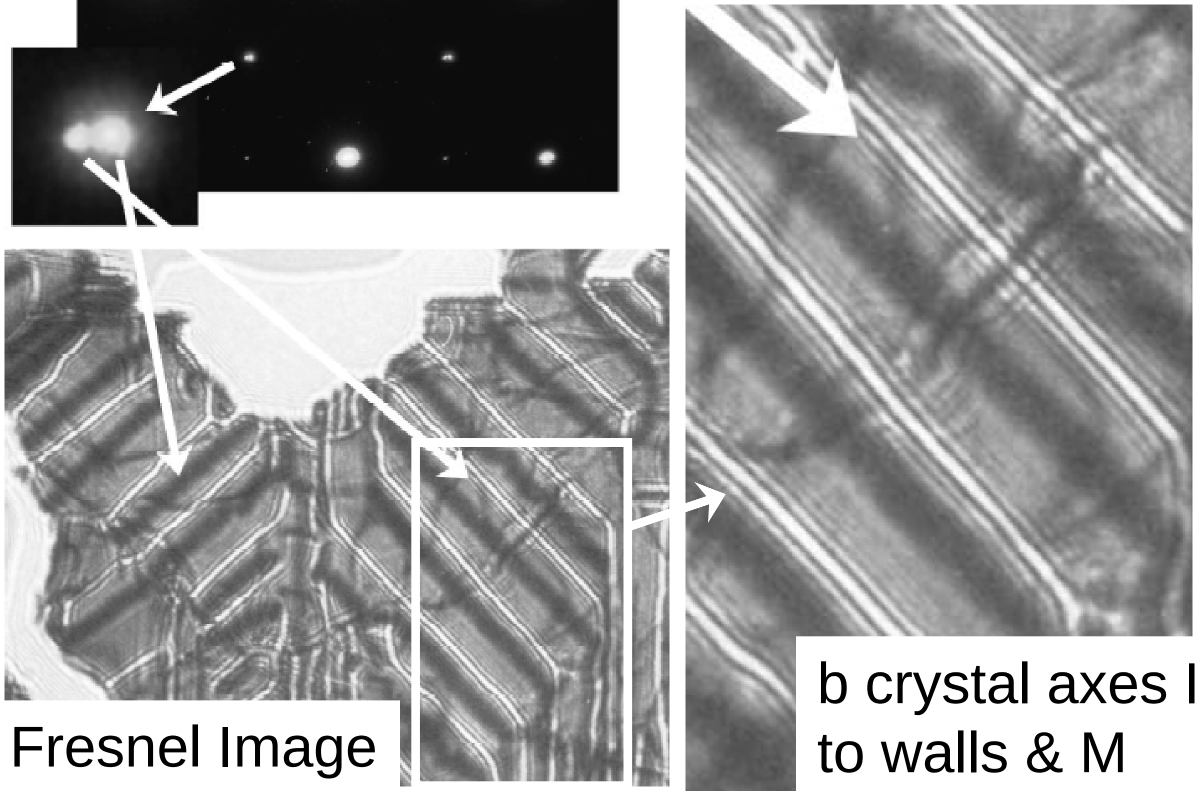


Diffraction Pattern



Domain walls in $SrRuO_3$

A. F. Marshall et al.
J. Appl. Phys. (1999)



Fresnel Image

b crystal axes II
to walls & M

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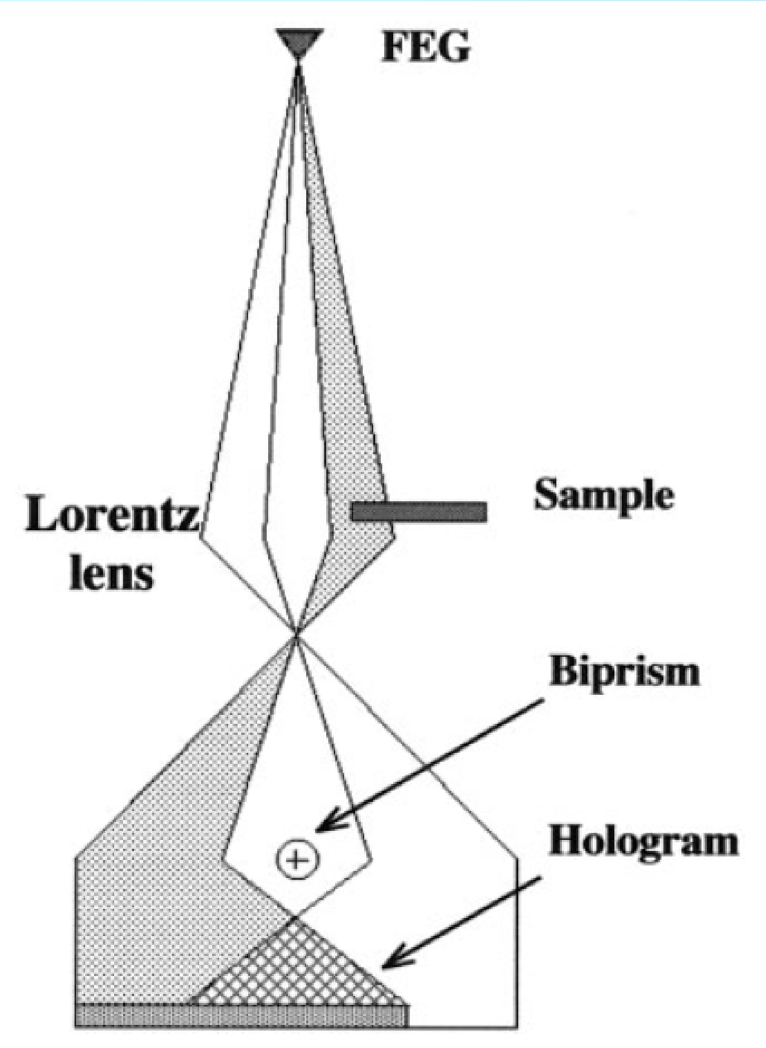
Off-axis Electron Holography



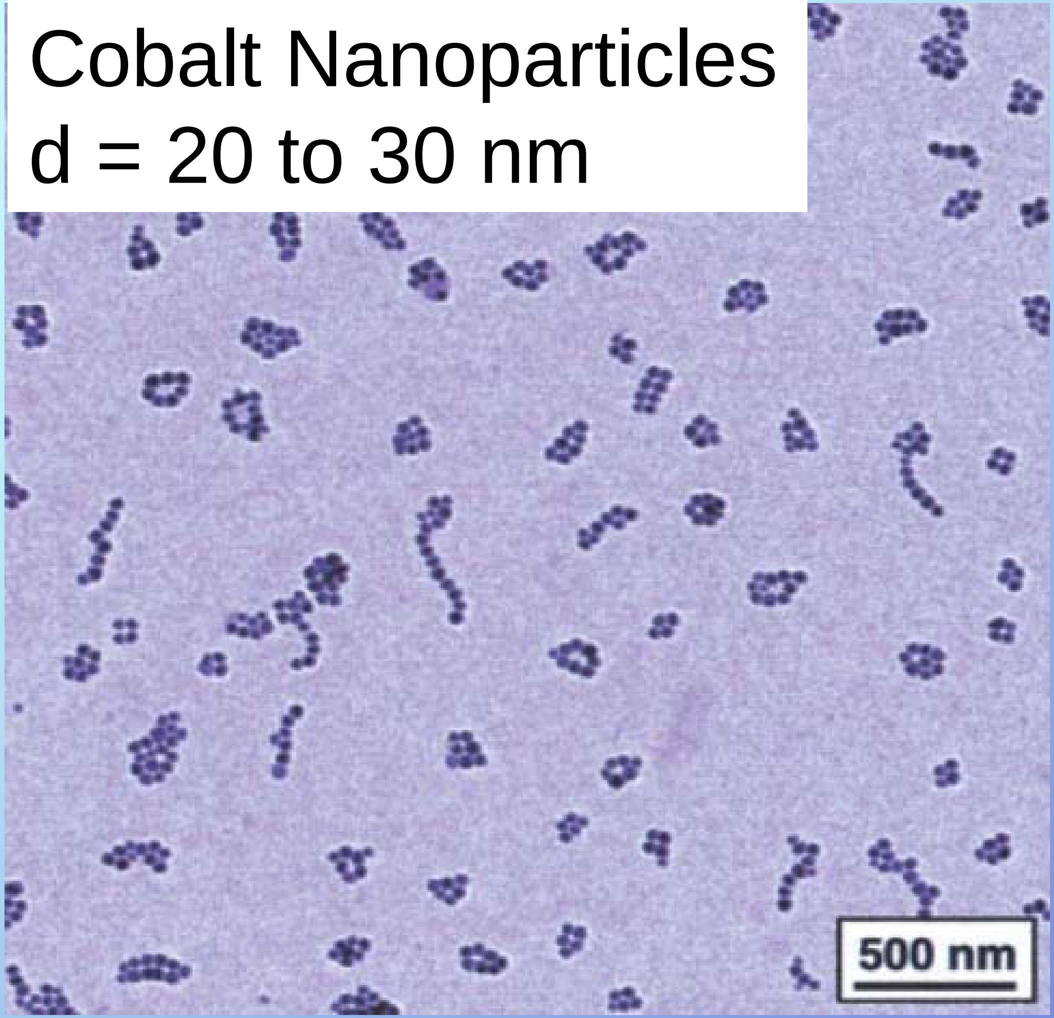
R.E. Dunin-Borkowski, et al.
Micr. Res. and Technique (2004)

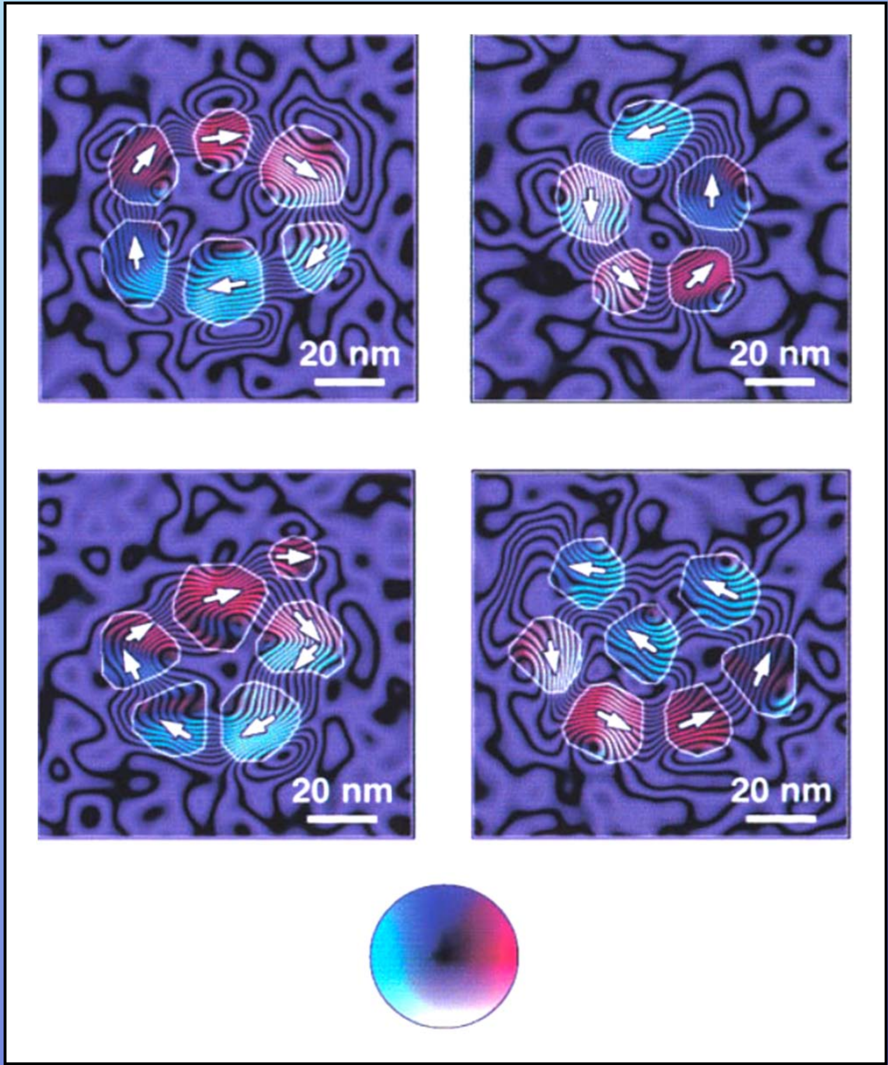
- apply a voltage to an electron biprism
- overlap of part of a coherent electron wave that has passed through a sample with the part that has passed through vacuum only.
- Analysis of resulting interference pattern allows the phase shift of the electron wave to be recovered and a quantitative map of the in-plane induction can be obtained.
- This provides a high spatial resolution information about domains, domain walls and stray field interactions.

Off-axis Electron Holography

- High resolution (≈ 5 nm)
- Magnetic induction: internal spin orientation + external stray field

Cobalt Nanoparticles
d = 20 to 30 nm





R.E. Dunin-Borkowski, et al. Micr. Res. and Technique (2004)

Lorentz Microscopy Summary

- high spatial resolution (< 5 nm has been demonstrated)
- information on domain and domain wall structures
- straightforward image interpretation (usually)
- sensitive to induction (so contrast from sample magnetisation and stray fields)
- quantitative information on spatial distribution of integrated induction components
- suitable for real time studies involving field & temperature variation
- availability of complementary (perfectly registered) nanostructural information
- Sample must allow transmission of electrons

Lorentz Microscopy Limitations

But……..

- phase shifts can be of magnetic or electrostatic origin, leading to severe problems when the latter contribution dominates
- no information about components of induction parallel to the direction of electron travel
- for multilayers, no way of separating contributions to images arising from individual layers
- no contrast from antiferromagnets
- time resolution is poor (typically ~1s, best ~20ms)

Kerr Microscopy

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ETH PSI

Kerr Effect

1845

Michael Faraday
(1791-1867)

small change of polarization plane due to magnetooptic interaction in transmission, circular birefringence, ~ M

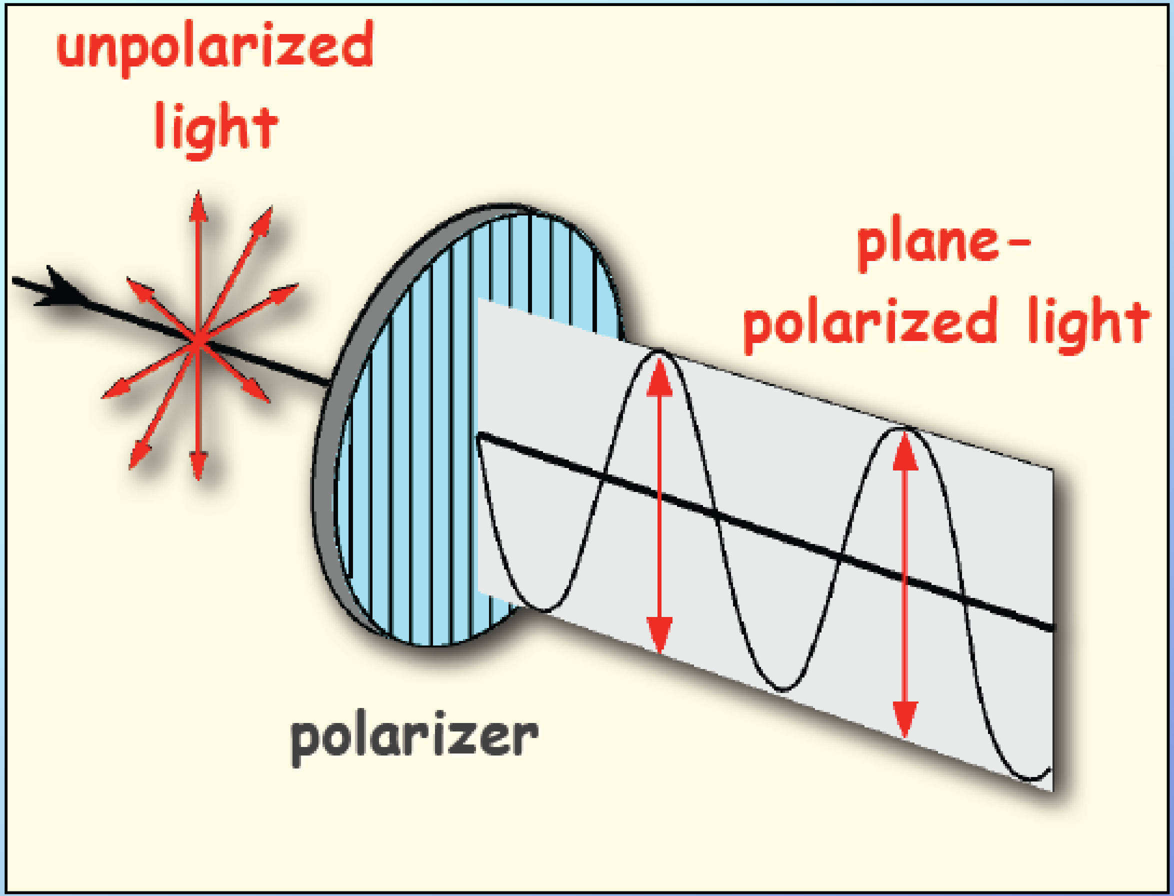
1877

John Kerr
(1824-1907)

small change of polarization plane due to magnetooptic interaction in reflection, circular birefringence, ~ M

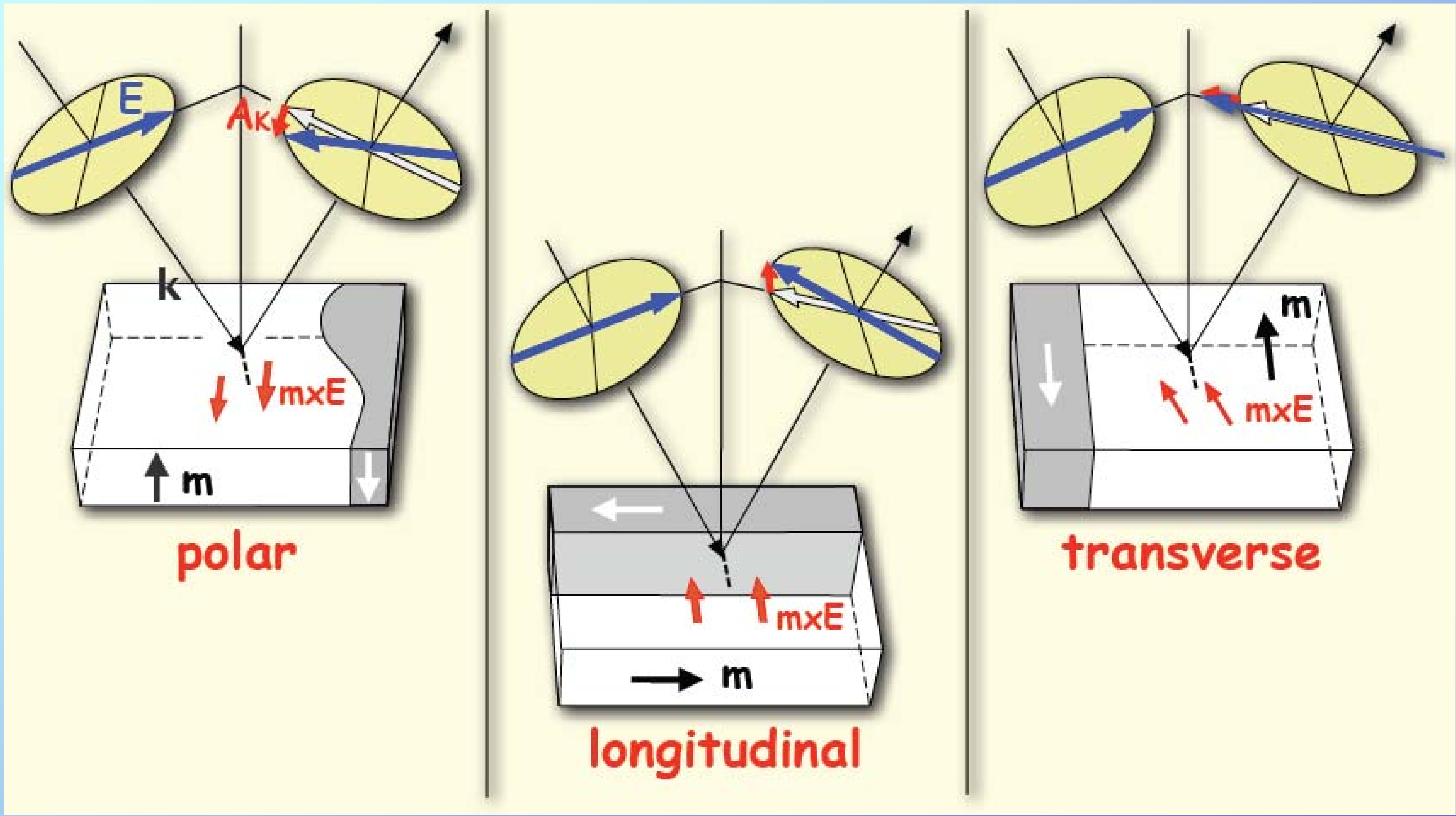
Rudolf Schäfer — IFW Dresden

Kerr Effect



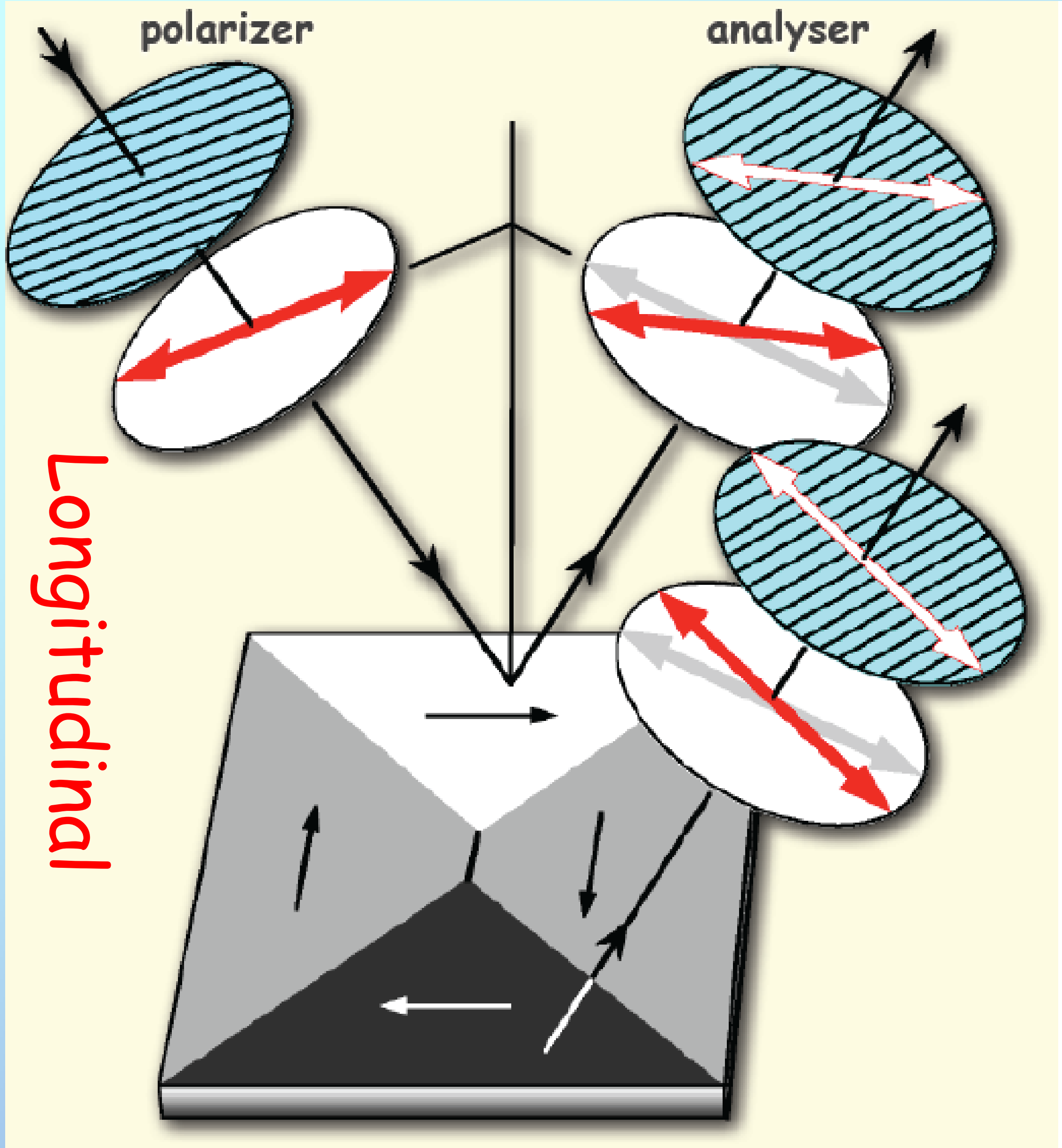
Rudolf Schäfer — IFW Dresden

Kerr Effect



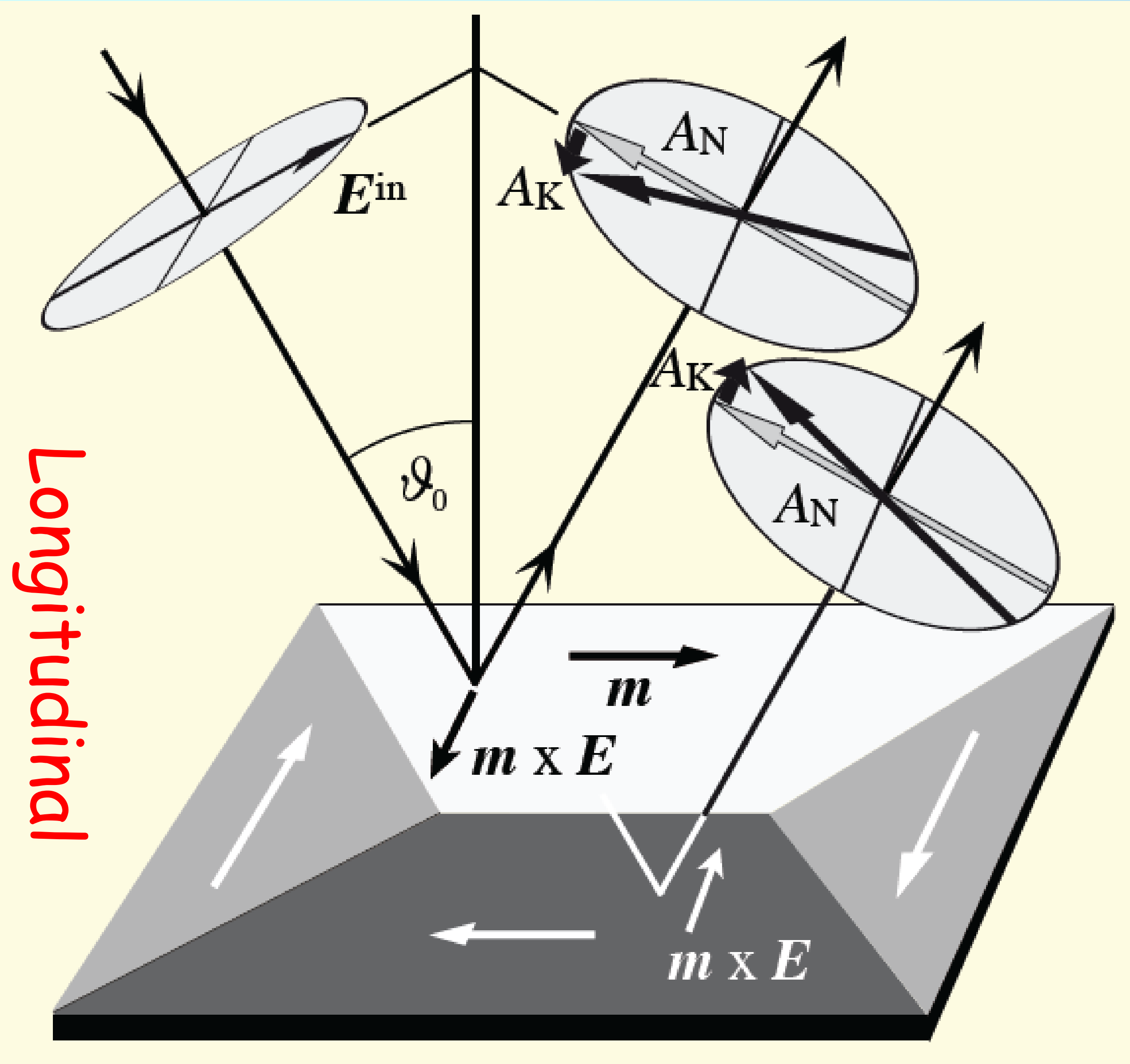
Rudolf Schäfer — IFW Dresden

Kerr Effect



Rudolf Schäfer — IFW Dresden

Kerr Effect – Lorentz Concept



Rudolf Schäfer — IFW Dresden

Linearly polarized light will induce electrons to oscillate parallel to its plane of polarization – the plane of the electric vector E of light

Secondary motion is proportional to –M x E, and generates the Kerr amplitude, A_K, for reflection ➔ rotation of polarisation

Opposite M direction ➔ opposite Kerr rotation

Kerr Microscopy

- Based on small rotations of the polarization plane of light
- Linearly polarized light will induce electrons to oscillate parallel to its plane of polarization – the plane of the electric vector E of light
- Regularly reflected light is polarised in the same plane as the incident light: A_N component
- Lorentz force induces a small component of vibrational motion perpendicular to original motion and to direction of magnetisation
- Secondary motion which is proportional to –M x E, and generates the Kerr amplitude, A_K, for reflection

Hubert & Schäfer, Magnetic Domains

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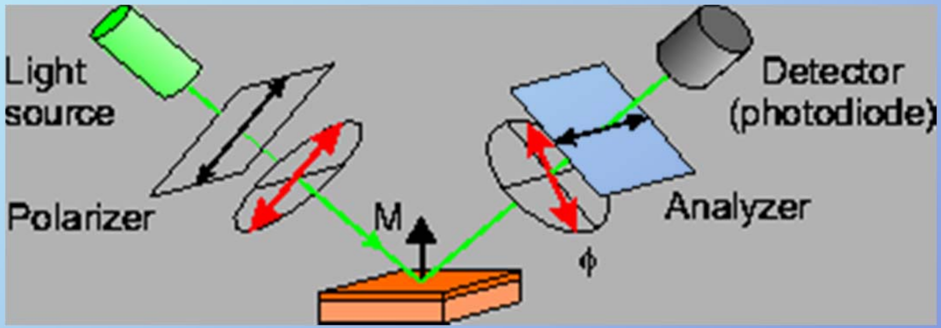
Image Signal

http://www.physik.fu-berlin.de/~bauer/habil_online/node9.html



If total signal amplitude:

$A_{TOT} = A_N$ +/- A_K (normal & Kerr)

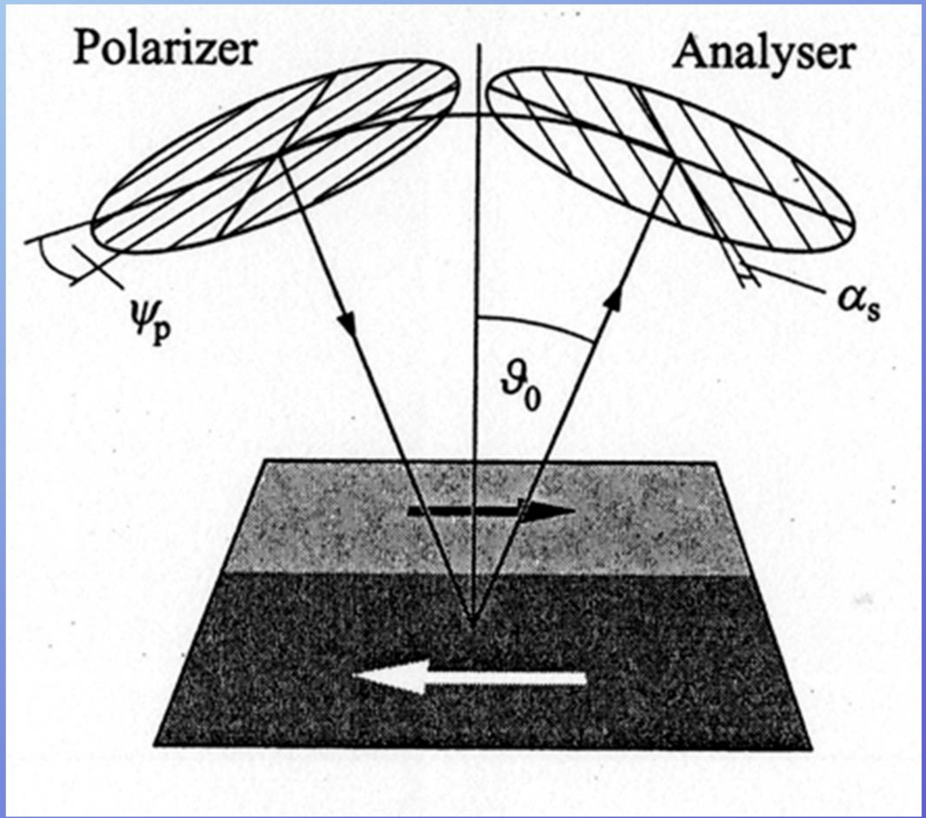
Then Kerr Rotation:

$$\phi_K = A_K / A_N$$

Start with $\alpha_S = \phi_K$; extinguishes light from one domain; one domain appears dark and the other light

Actually better to rotate the analyser beyound the extinction point.

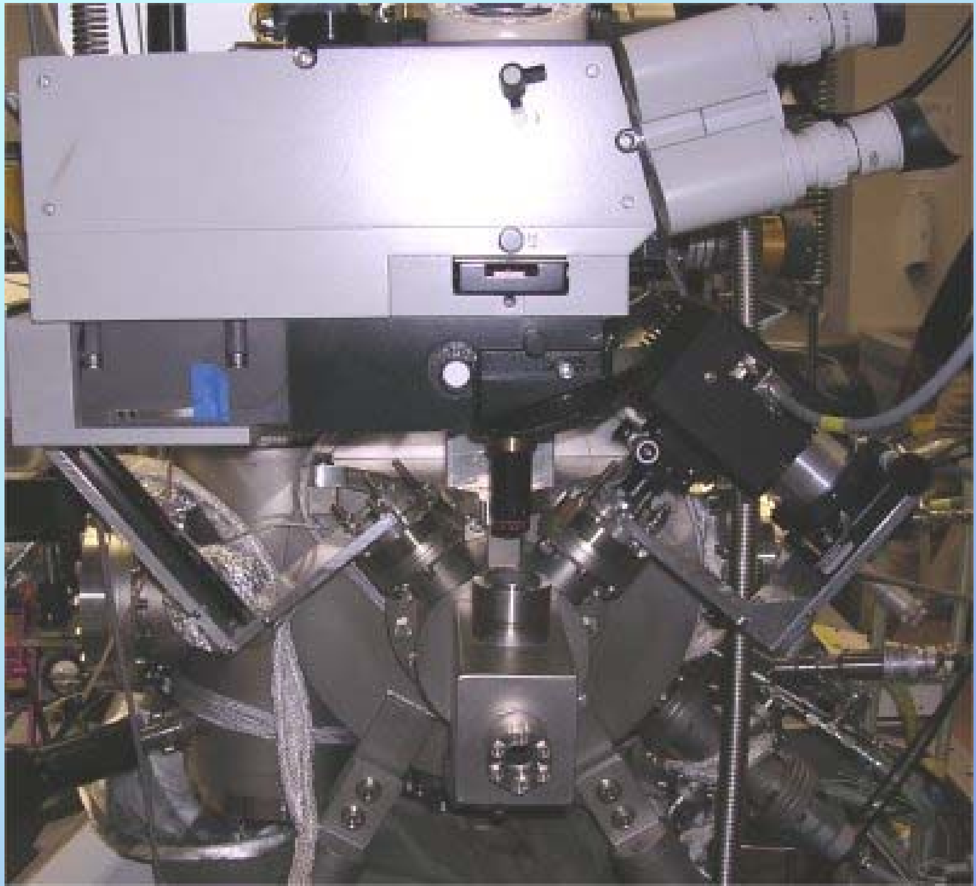
In practice, adjust polarizer and analyser until an image of satisfactory contrast and brightness is obtained.

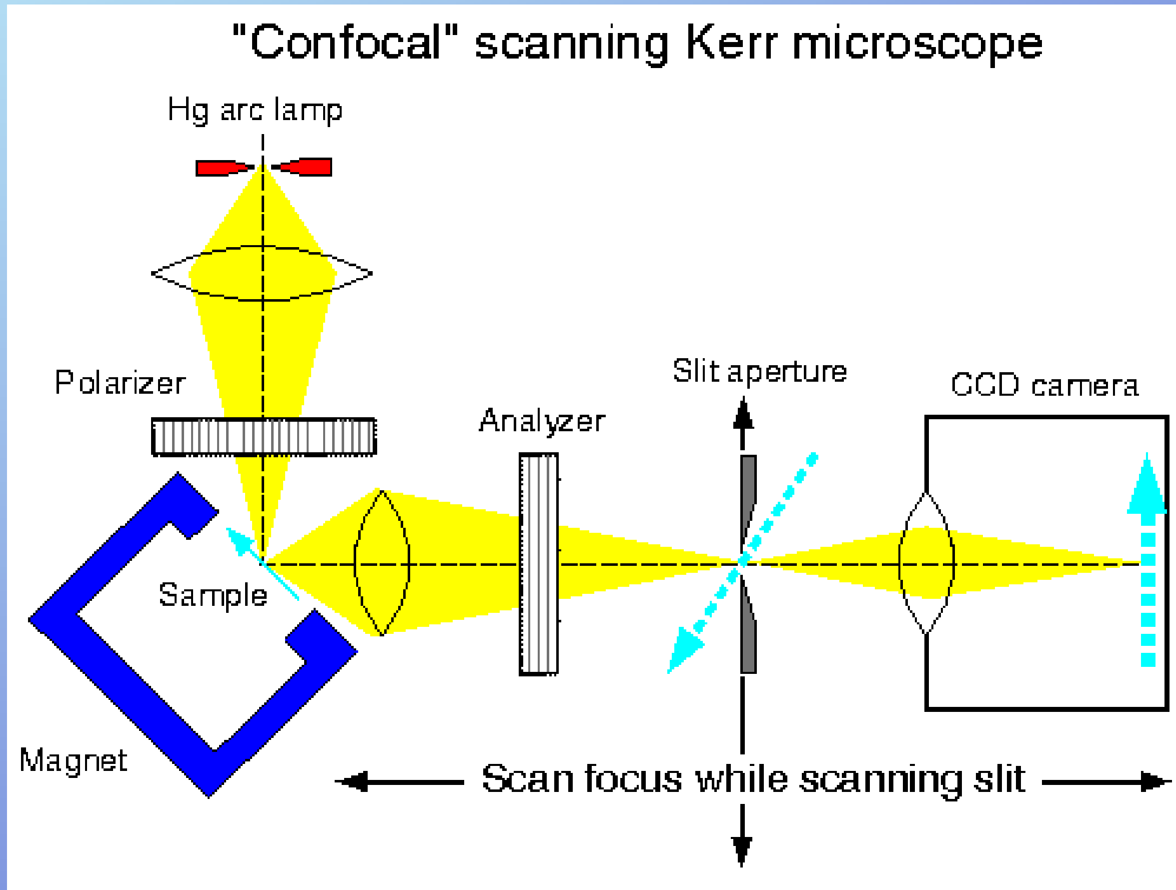


Hubert & Schäfer, Magnetic Domains

Polarising Microsope

http://physics.nist.gov/Divisions/Div841/Gp3/Facilities/kerr.html





http://www.fkf.mpg.de/kern/facilities/kerr/kerr.html

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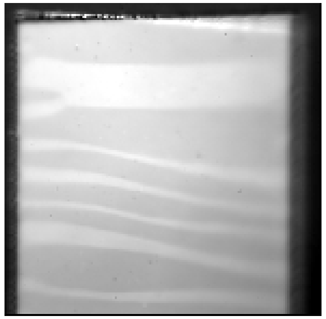
Digital Image Enhancement

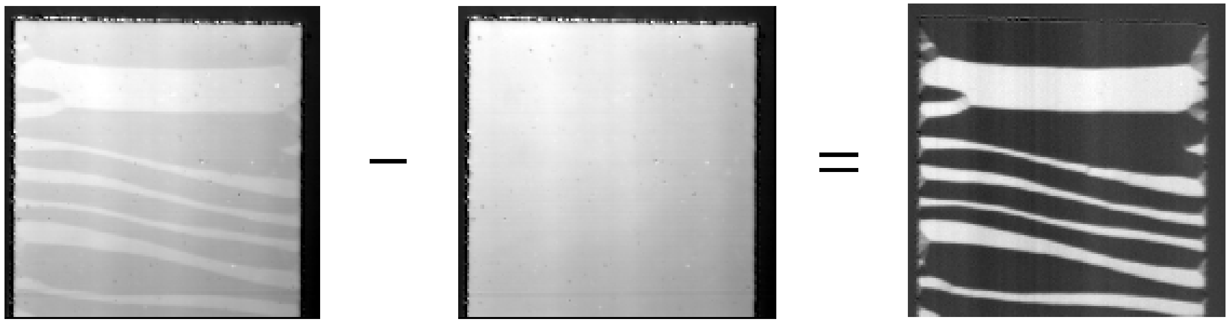
Digital difference technique:
non-magnetic background image is digitally subtracted

Images of 500 µm wide NiFe square



0 Oe field, no scanned slit

with confocal scanned slit



0 Oe field – 100 Oe field = Difference

Resolution approx. 200 nm

http://physics.nist.gov/Divisions/Div841/Gp3/Facilities/kerr.html

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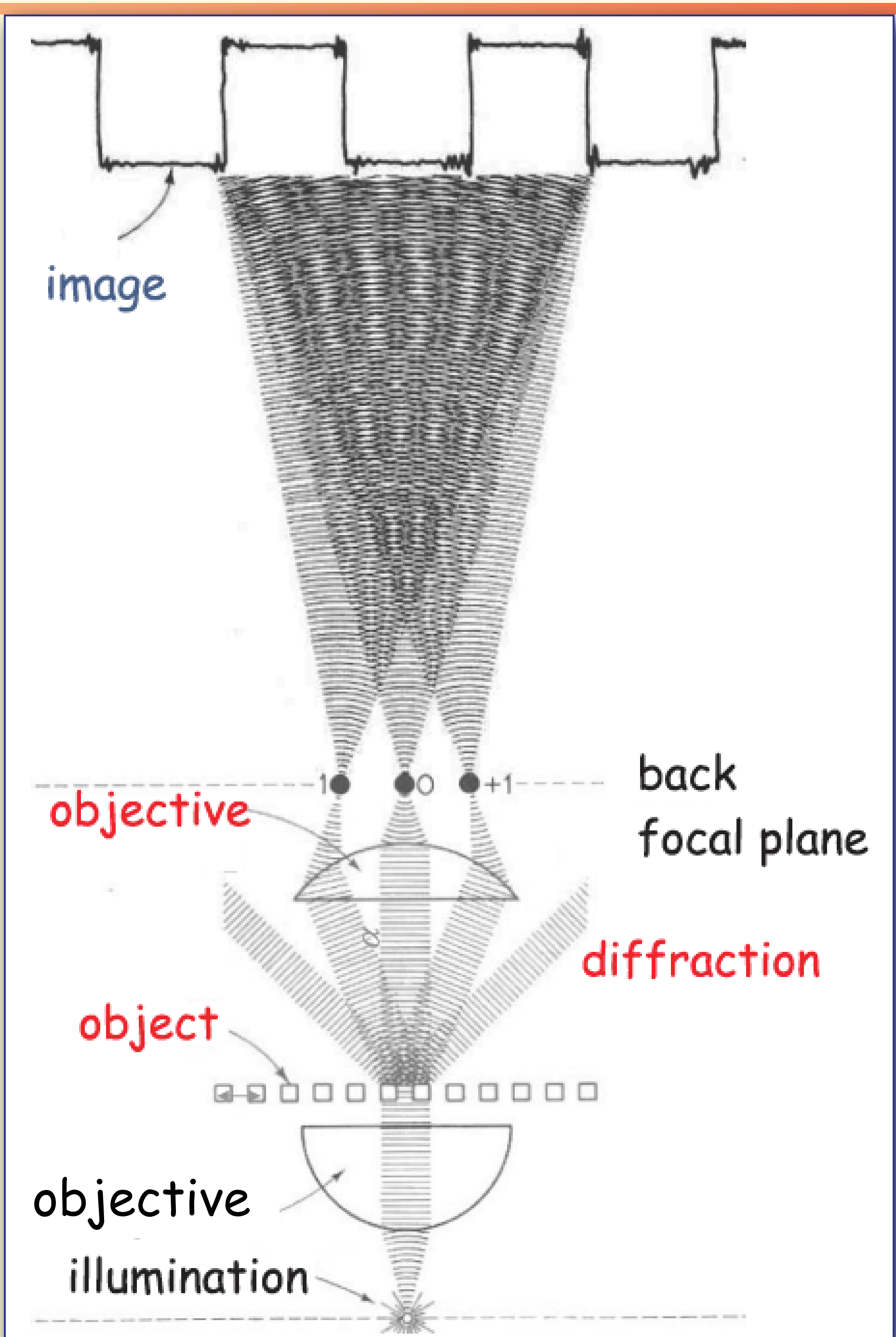
Resolution of optical microscopy (E. Abbe 1840 - 1905)

Rudolf Schäfer
IFW Dresden



resolution determined by constructive interference

diffraction limited image formation

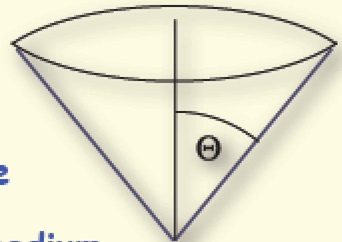
Rayleigh equation: $d = \frac{0.5\,\lambda}{NA}$

d = separation between particles, still allowing to see them

λ = wavelength

NA = numerical aperture of objective

$NA = n \sin\theta$



θ = half the cone angle of light accepted by objective

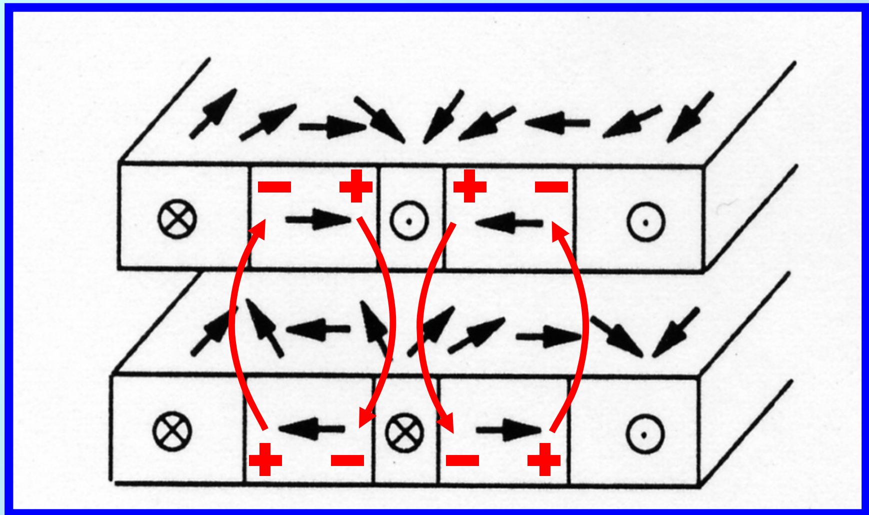
n = referaction index of medium between sample and objective

↓

best around 200 nm

Observation of Quasi-domain Walls

Twin Walls

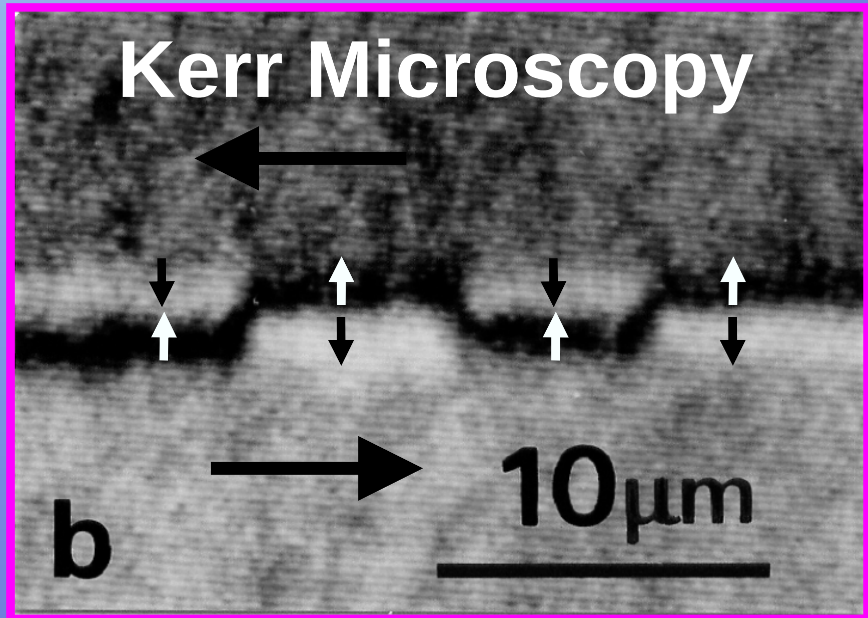


Ferromagnetic Thin Film

Non-magnetic Spacer Layer

Ferromagnetic Thin Film

Image shows domain wall (black line) and quasi-domain wall (white line) in top layer of sandwich film



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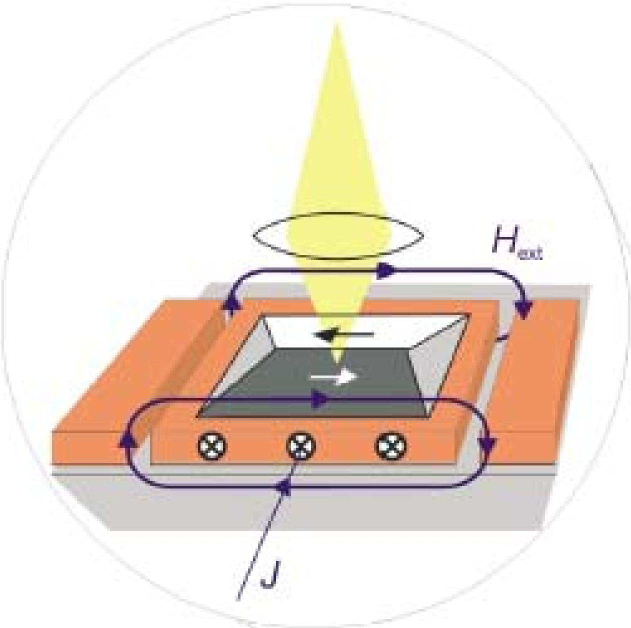
Time-Resolved Kerr Microscopy



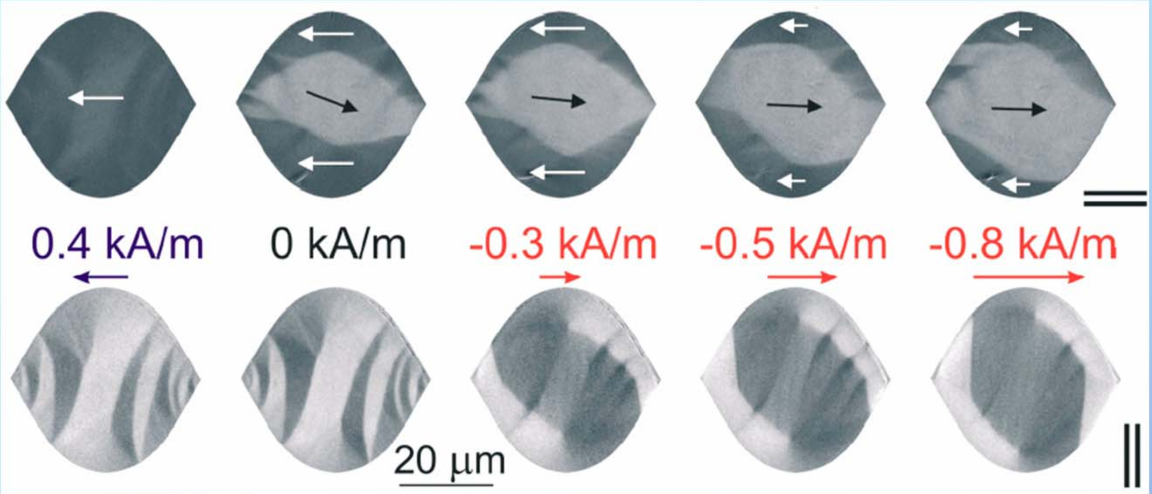
Stroboscopic technique:

- Short field pulses (e.g. 20 ns, 10 kA/m) with copper microstrip line
- With a defined time delay, the magnetization is probed
- Reasonable signal-to-noise ratio by integrating the optical signal
- Accumulation over repeatable magnetization processes is required.
- Gated & intensified CCD camera providing temporal resolution down to 200 ps

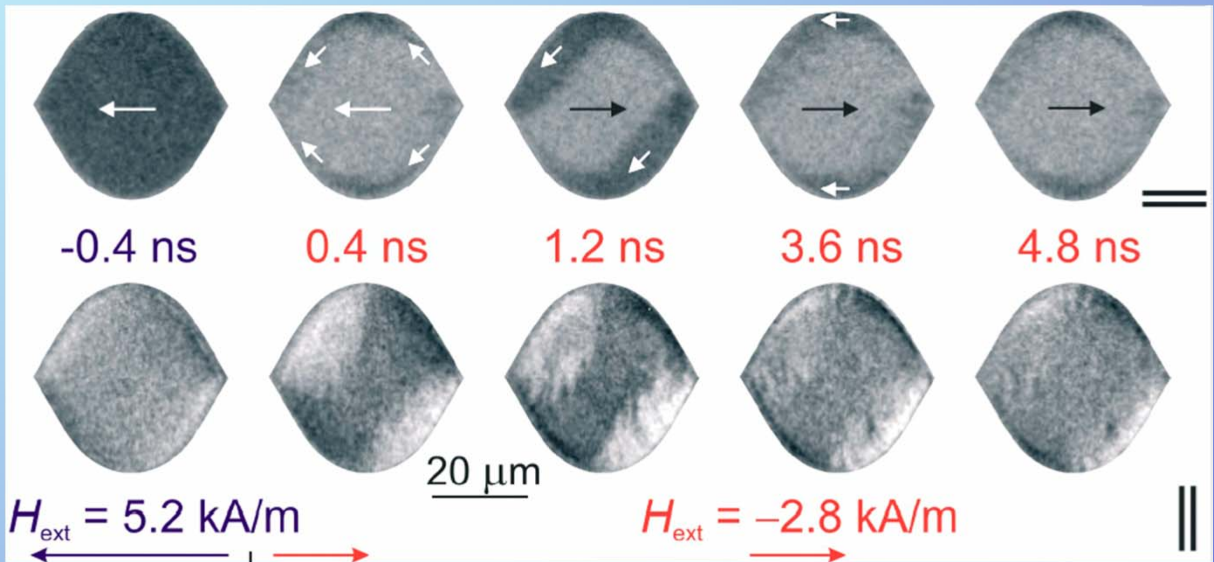
Chumakov, McCord, Schäfer, Schultz

Time-Resolved Kerr Microscopy

Applied Field: quasi-static reversal



Applied Field Pulse: time-resolved



Applying a field pulse: magnetization not able to instantaneously follow magnetic field.

To reach new magnetization direction, will have to spin about the field axis: precessional motion that is gradually opposed by damping.

Reversal looks very different!

Chumakov, McCord, Schäfer, Schultz

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Kerr Microscopy Summary

- Flat and smooth surface
- Resolution approx. 200 nm
- Magnetization can be observed directly
- Quantitative measurements possible but need to take care with calibration
- Observation does not influence magnetization
- Dynamic processes can be observed at high speed
- Sample may be easily manipulated: fields, high or low temperature, mechanical stress
- Surface magnetization: penetration depth of 10-20 nm
- Can look at back and front of sample

Hubert & Schäfer, Magnetic Domains

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X-Ray Microscopy Techniques

The Swiss Light Source, Paul Scherrer Institut

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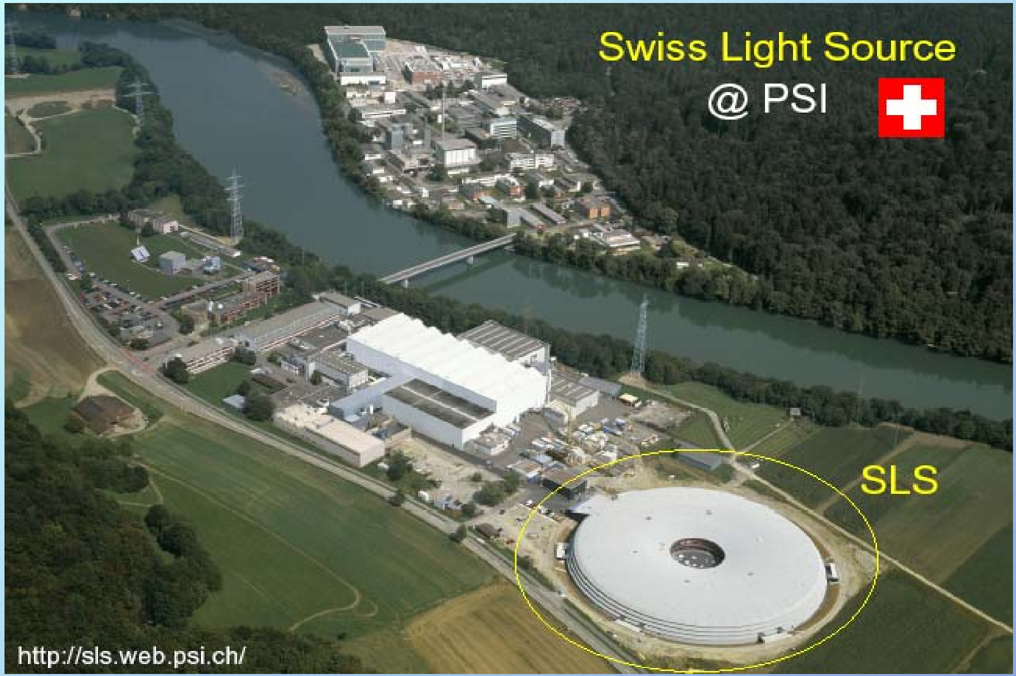
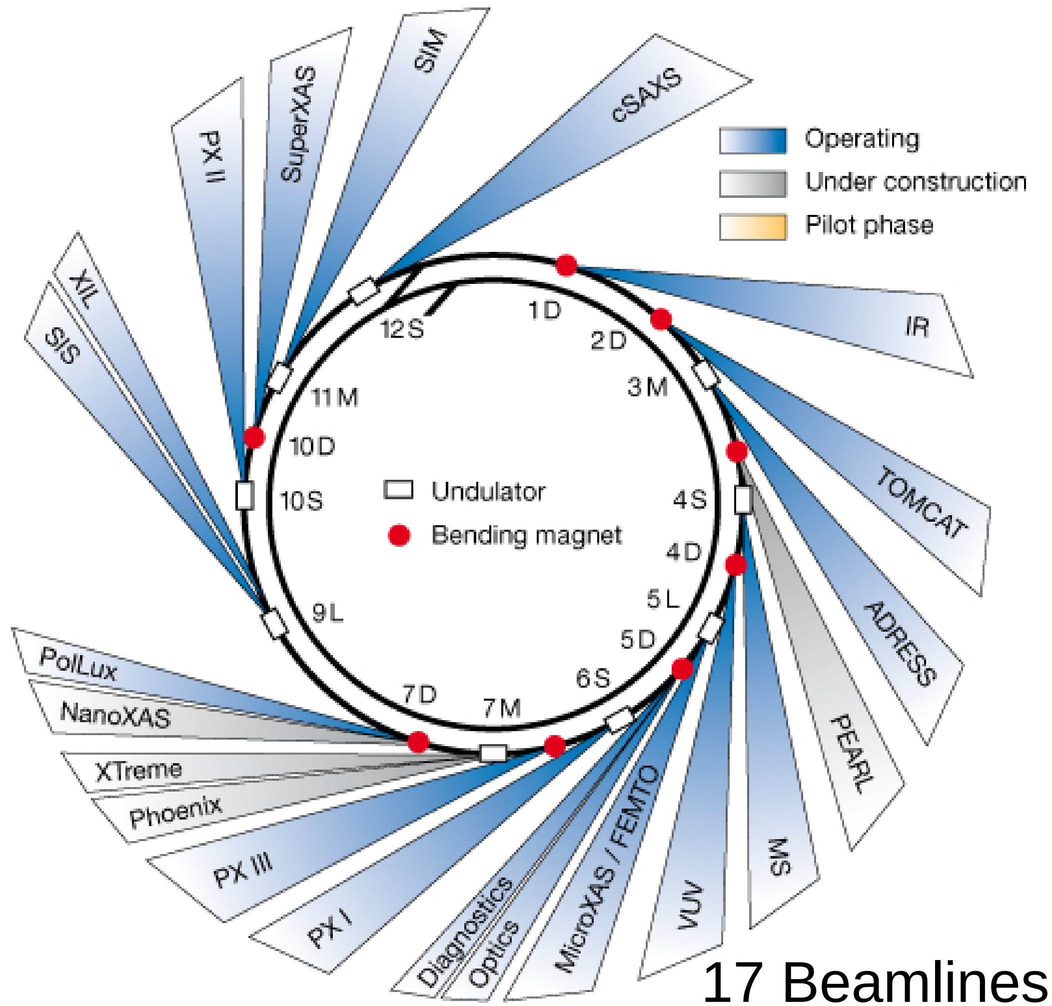
- The electrons are accelerated close to the speed of light in a linear accelerator and injected into the storage ring
- Bending magnets or insertion devices (wigglers or undulators) cause electrons to bend or wobble through the section and emit light.





17 Beamlines

Reference energy: 2.4 GeV

Circumference: 288 m

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

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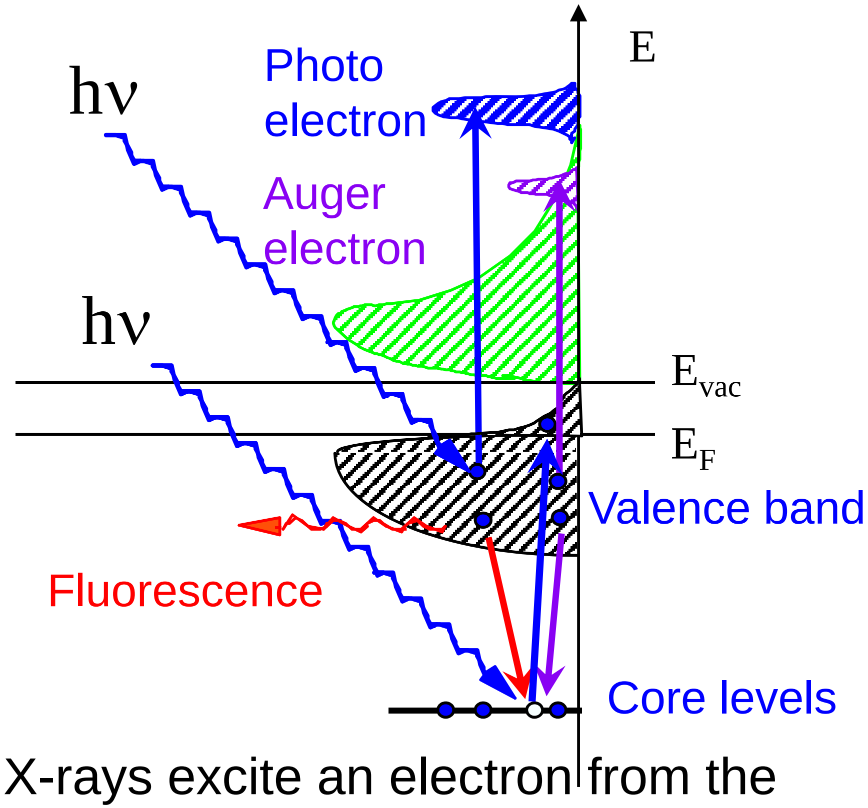
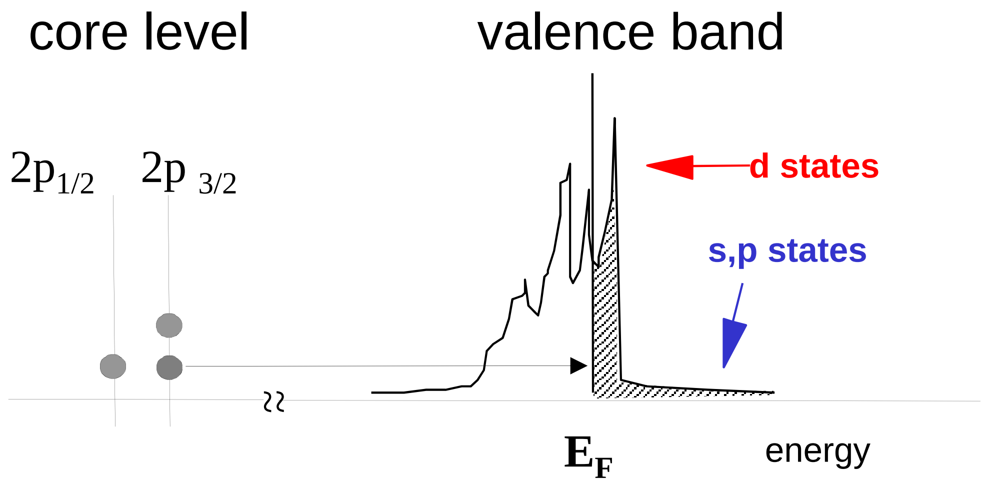
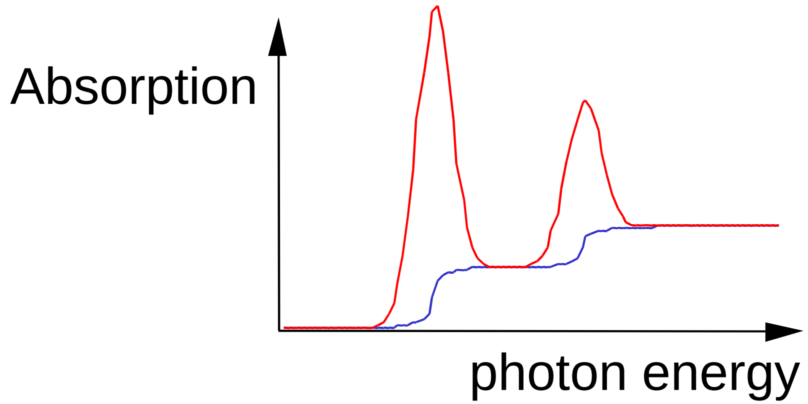
X-ray Absorption Spectroscopy



- 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



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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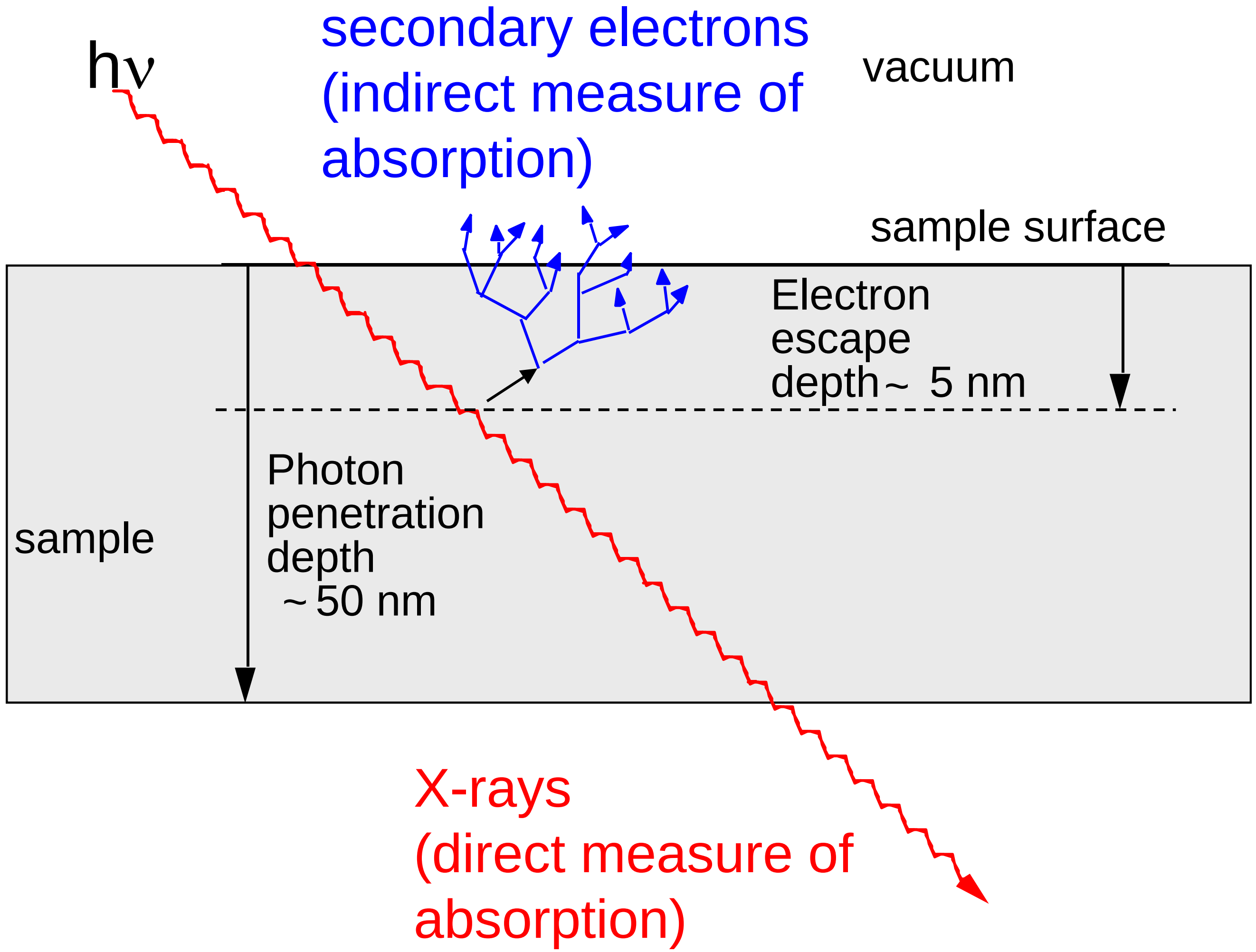
PEEM & TXM



Photoemission Electron Microscopy (PEEM) to probe surface / interfaces

Transmission X-ray Microscopy (TXM)

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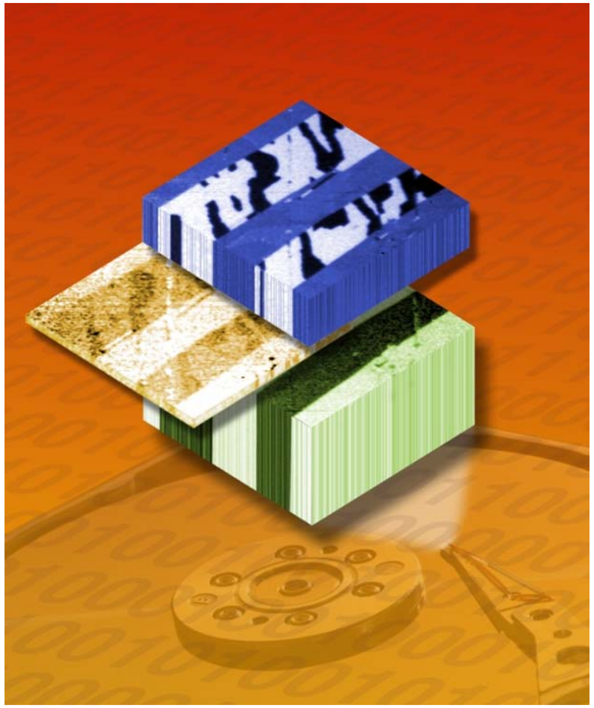
Photoemission Electron Microscopy



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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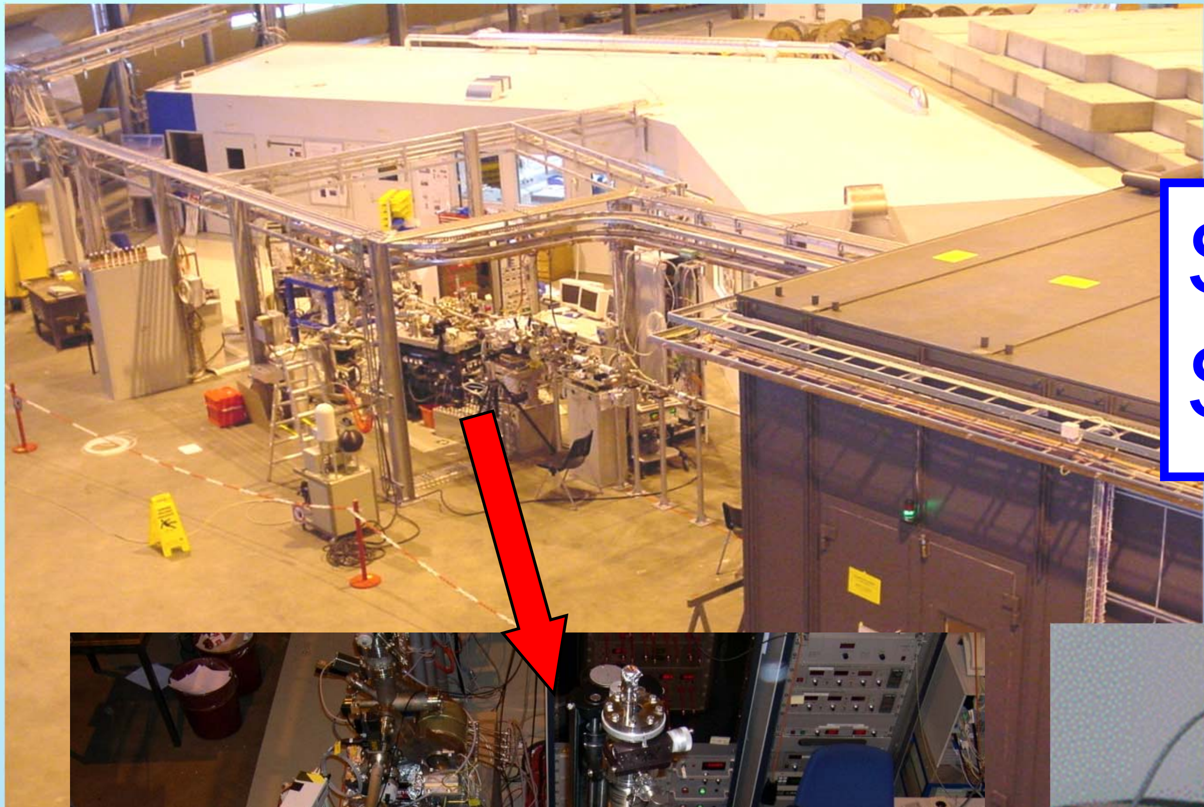
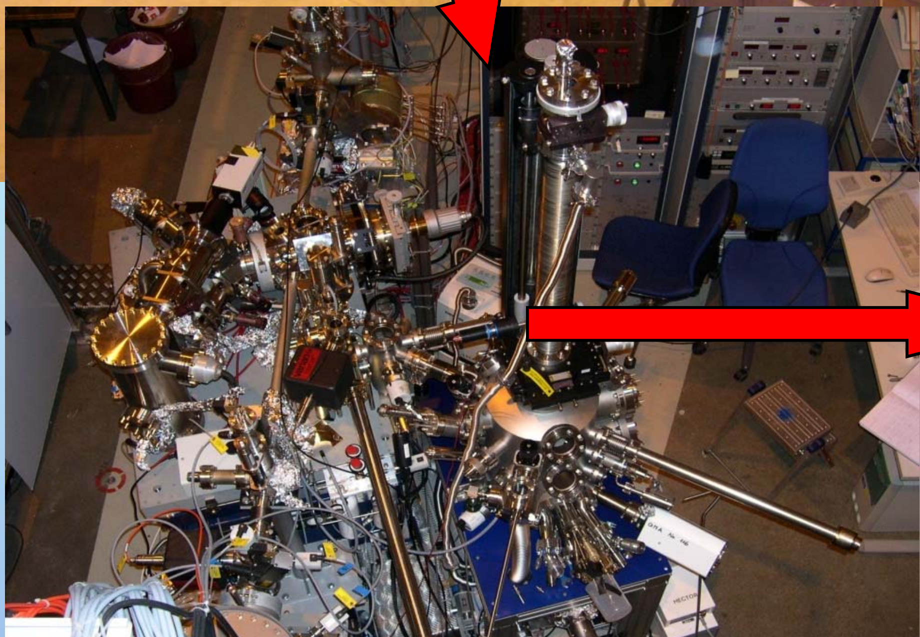
The Surface and Interface Microscopy (SIM) Beamline

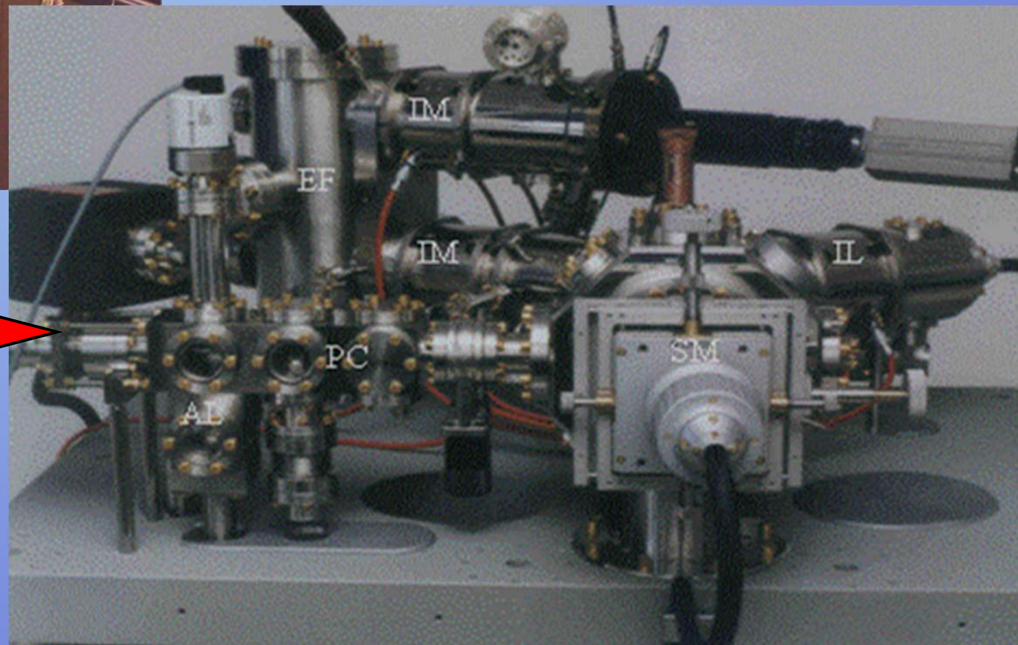


SIM Beamline, Swiss Light Source



The Photoemission Electron Microscope (PEEM)

Close-up of the PEEM



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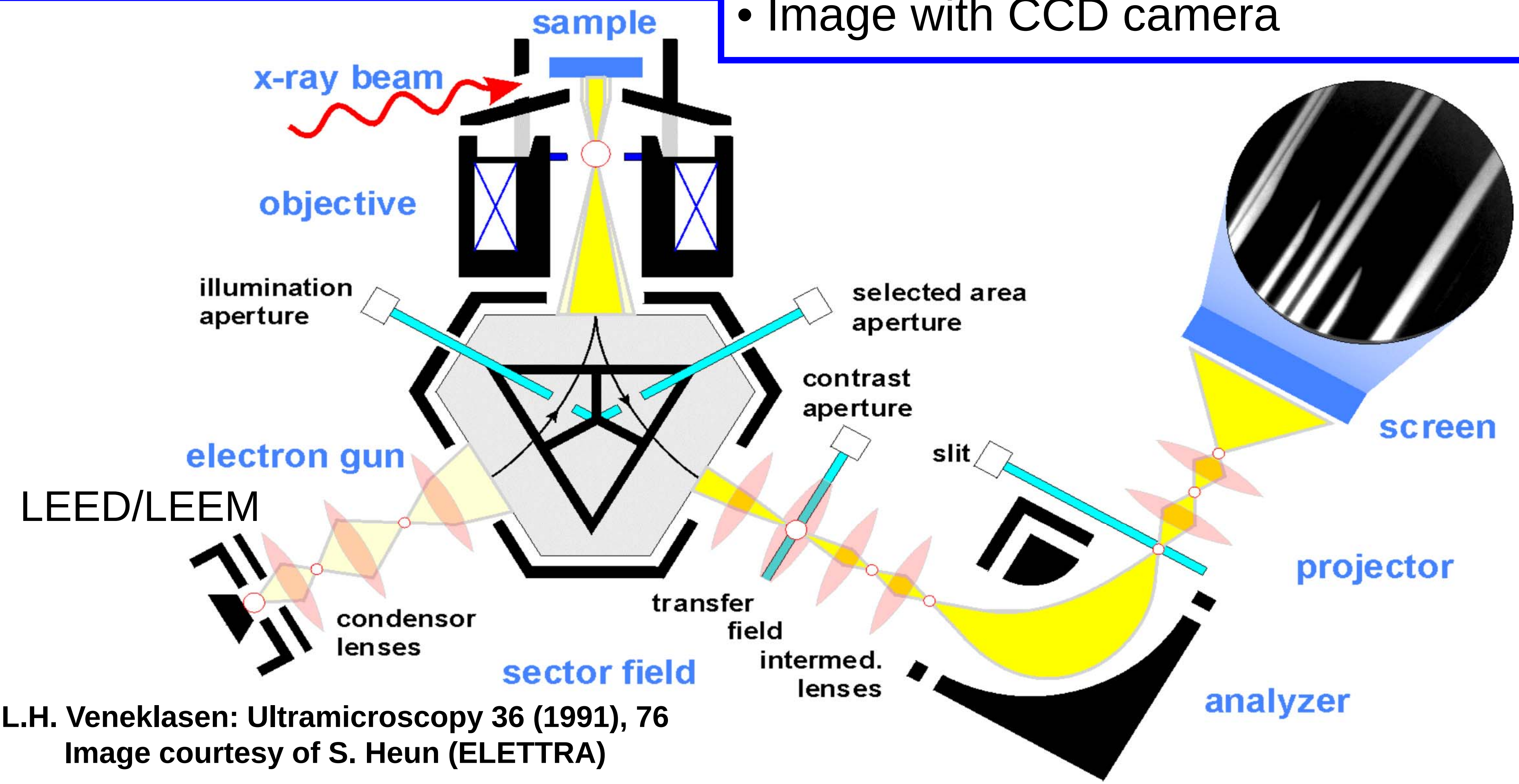
Spectromicroscope

- 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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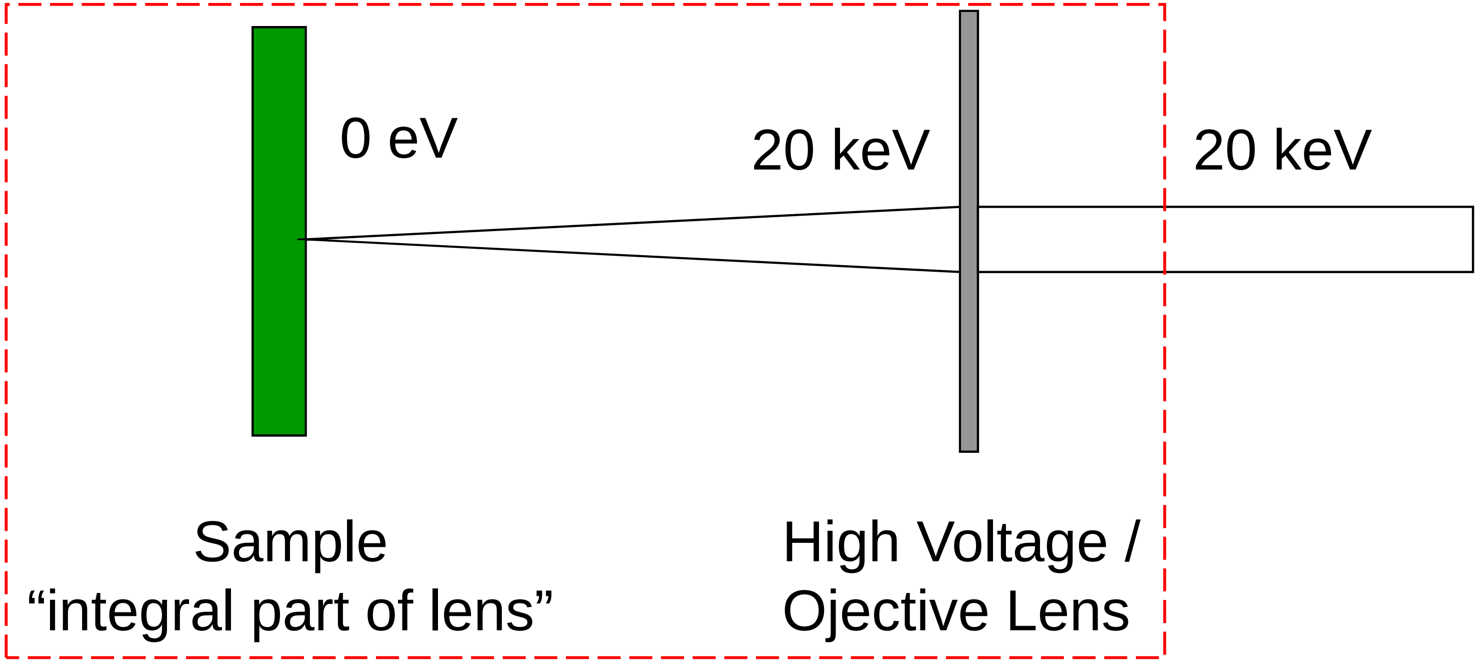
Slow Electrons

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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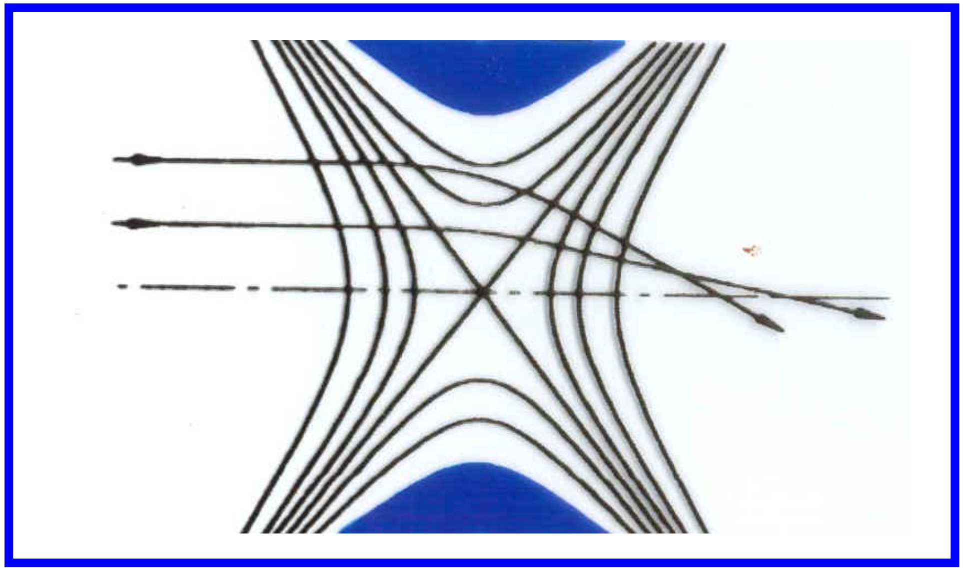
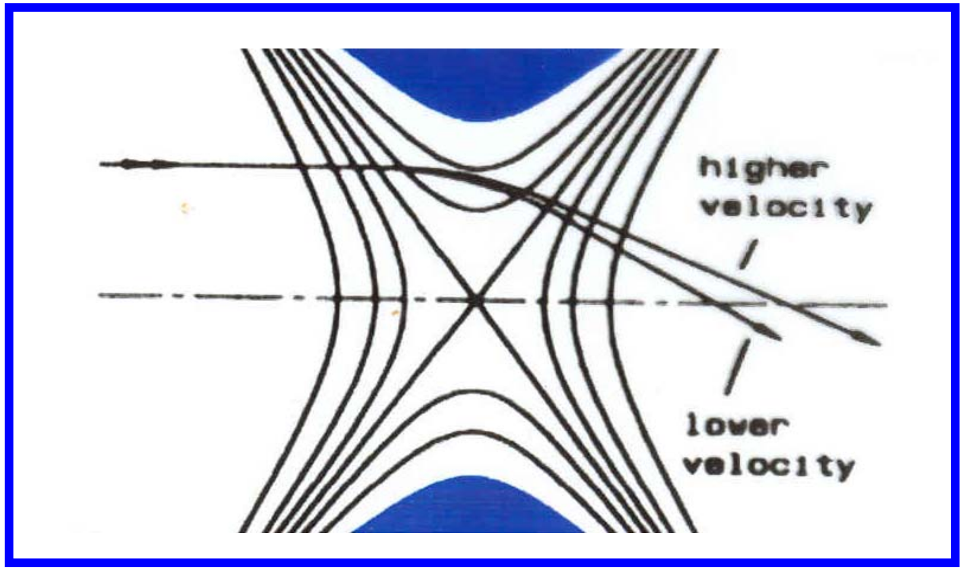
Two Kinds of Aberrations

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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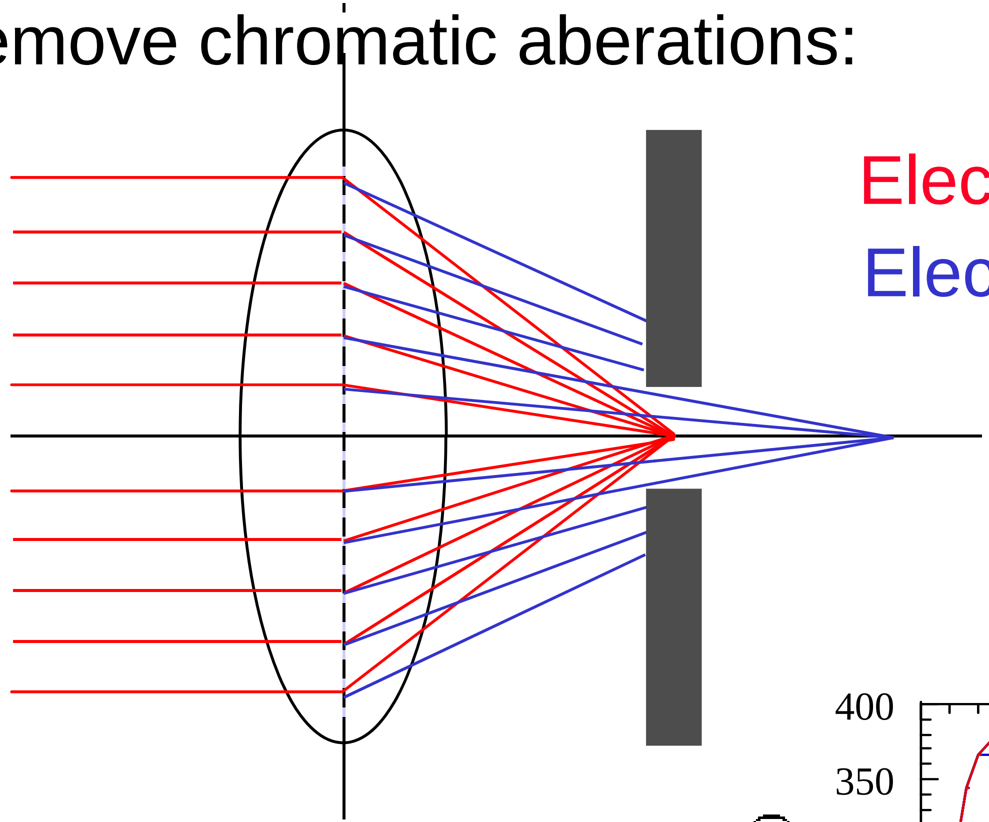
Energy Filter

To remove chromatic aberations:

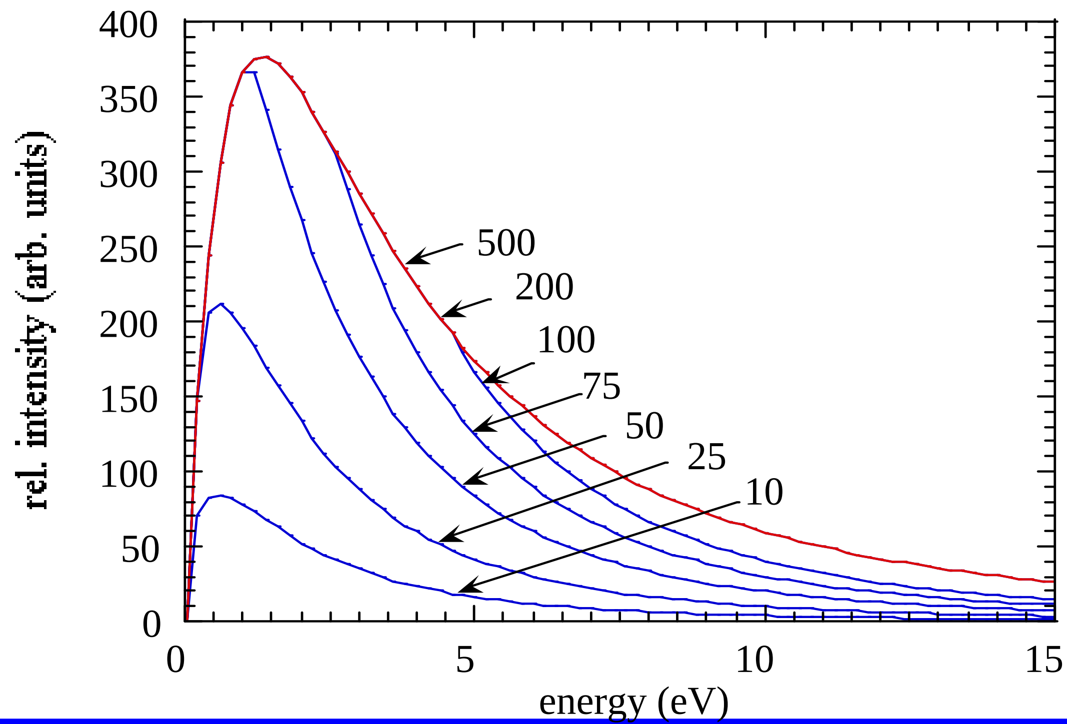


Electron energy E

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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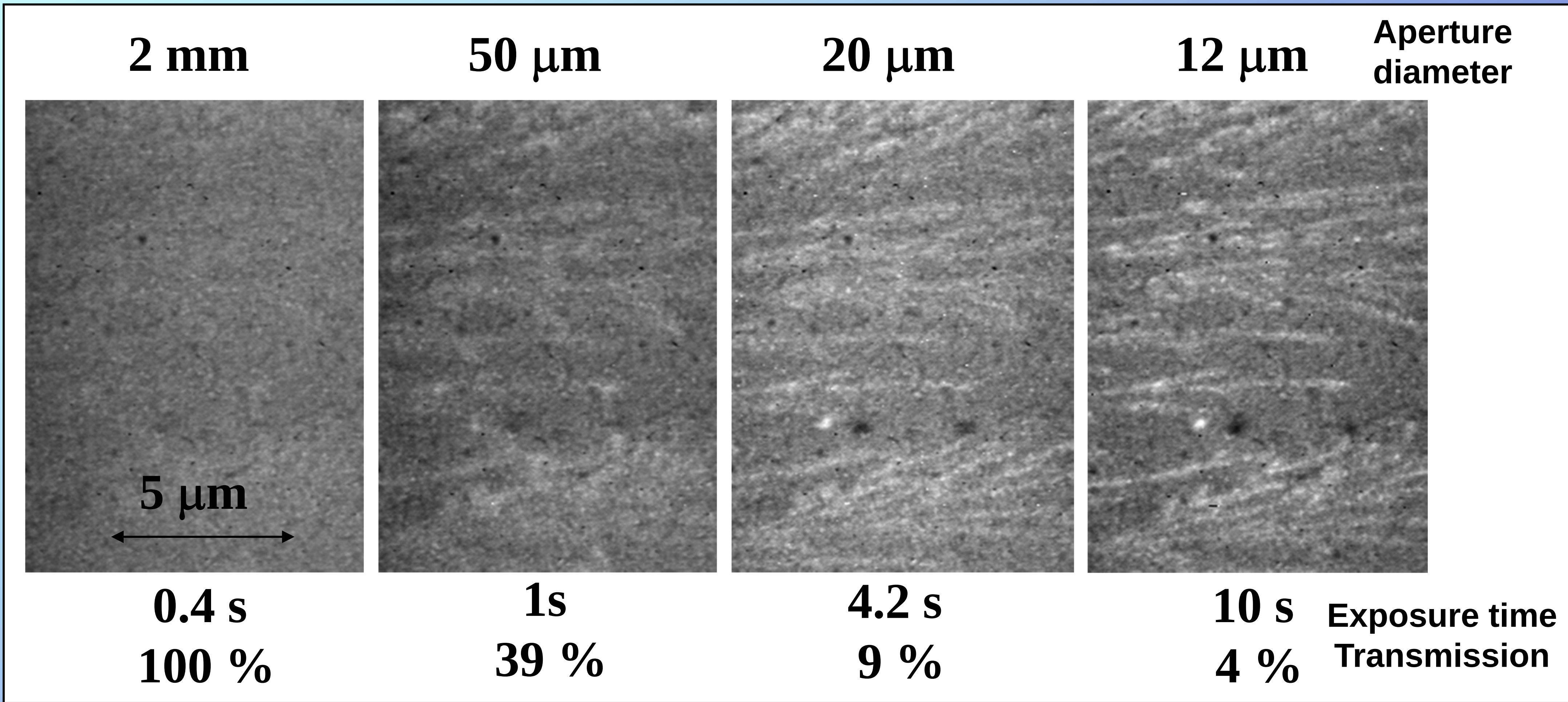
Effect of aperture size on resolution

- 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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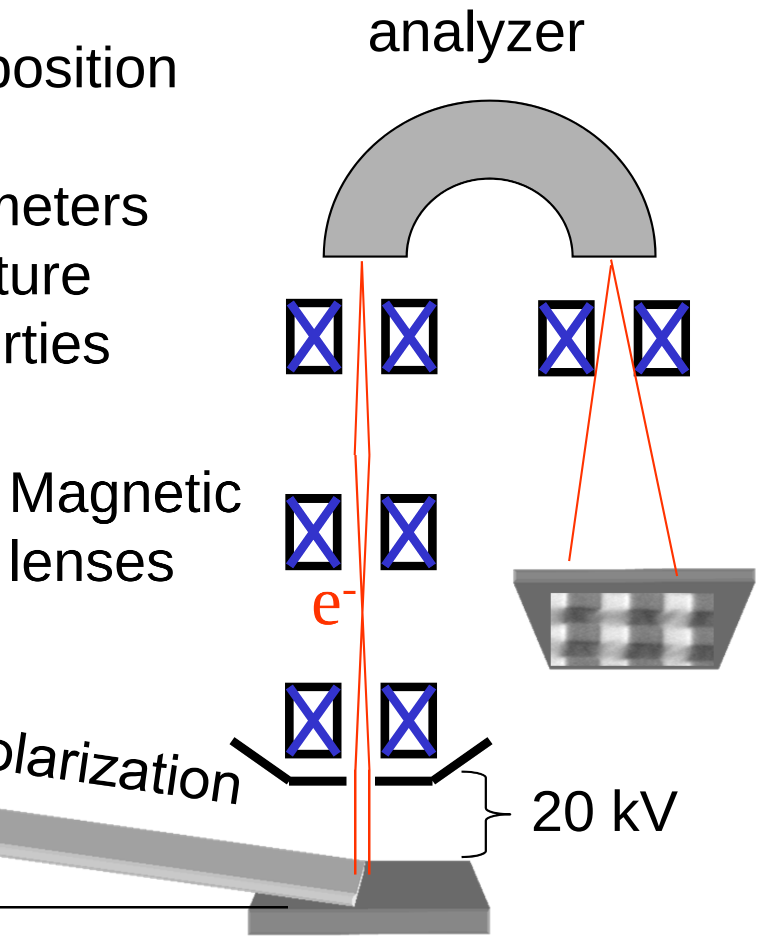
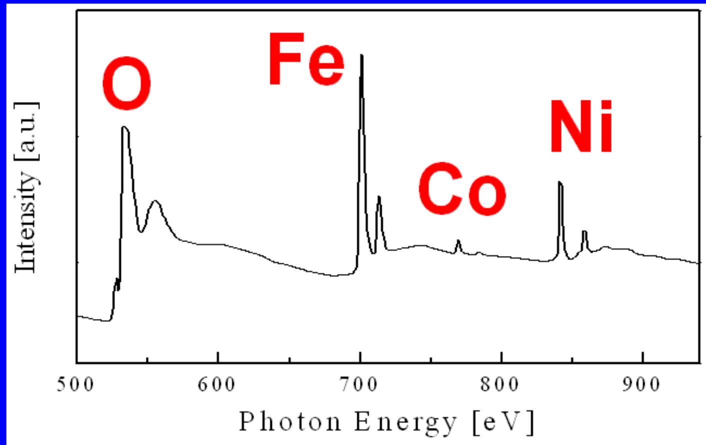
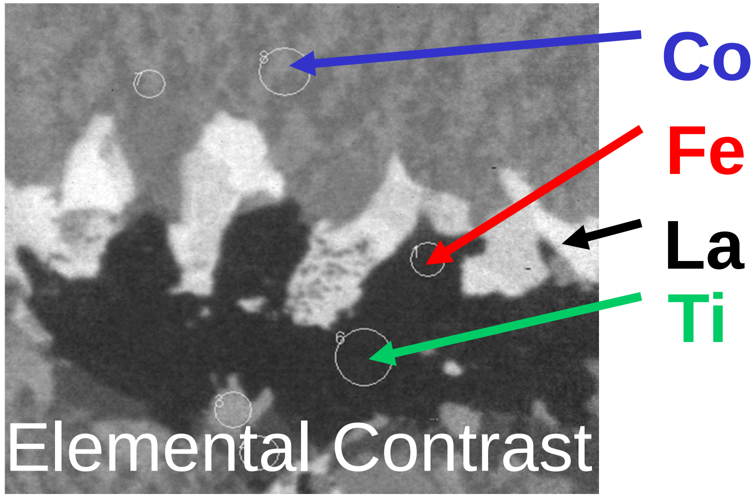
Photoemission Electron Microscope
SIM beamline (SLS)

Arantxa Fraile-Rodriguez
Frithjof Nolting

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







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Photoemission Electron Microscope

SIM beamline (SLS)

Arantxa Fraile-Rodriguez
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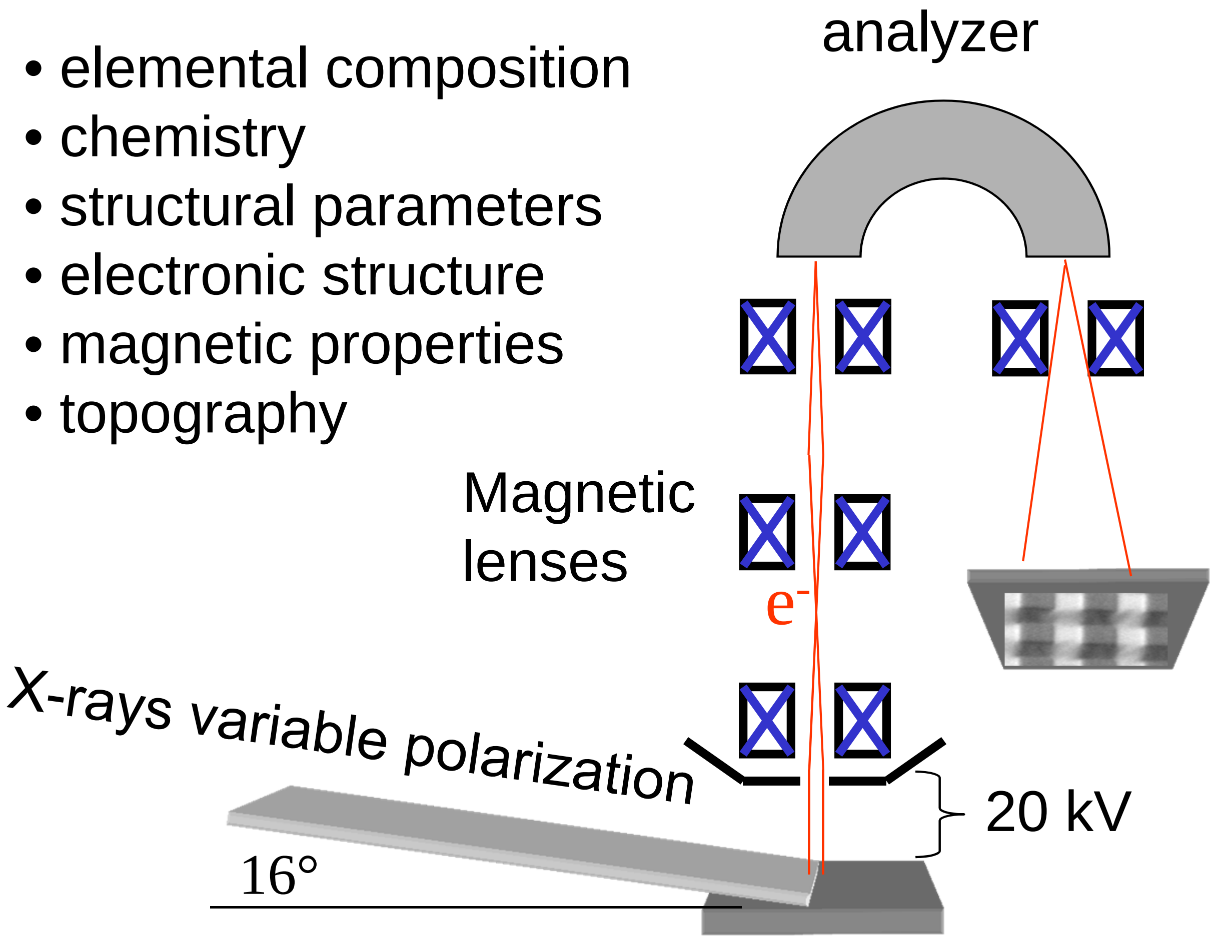
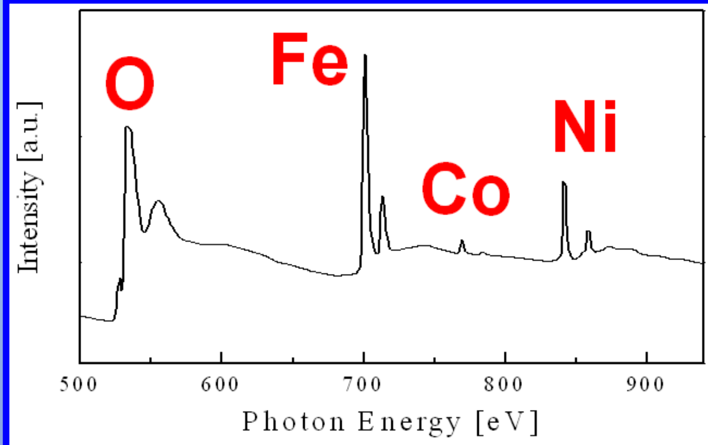
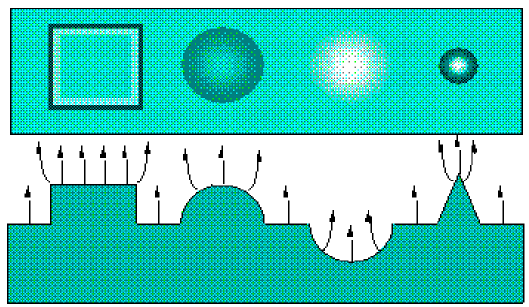
- magnetic properties
- topography





Topographical Contrast

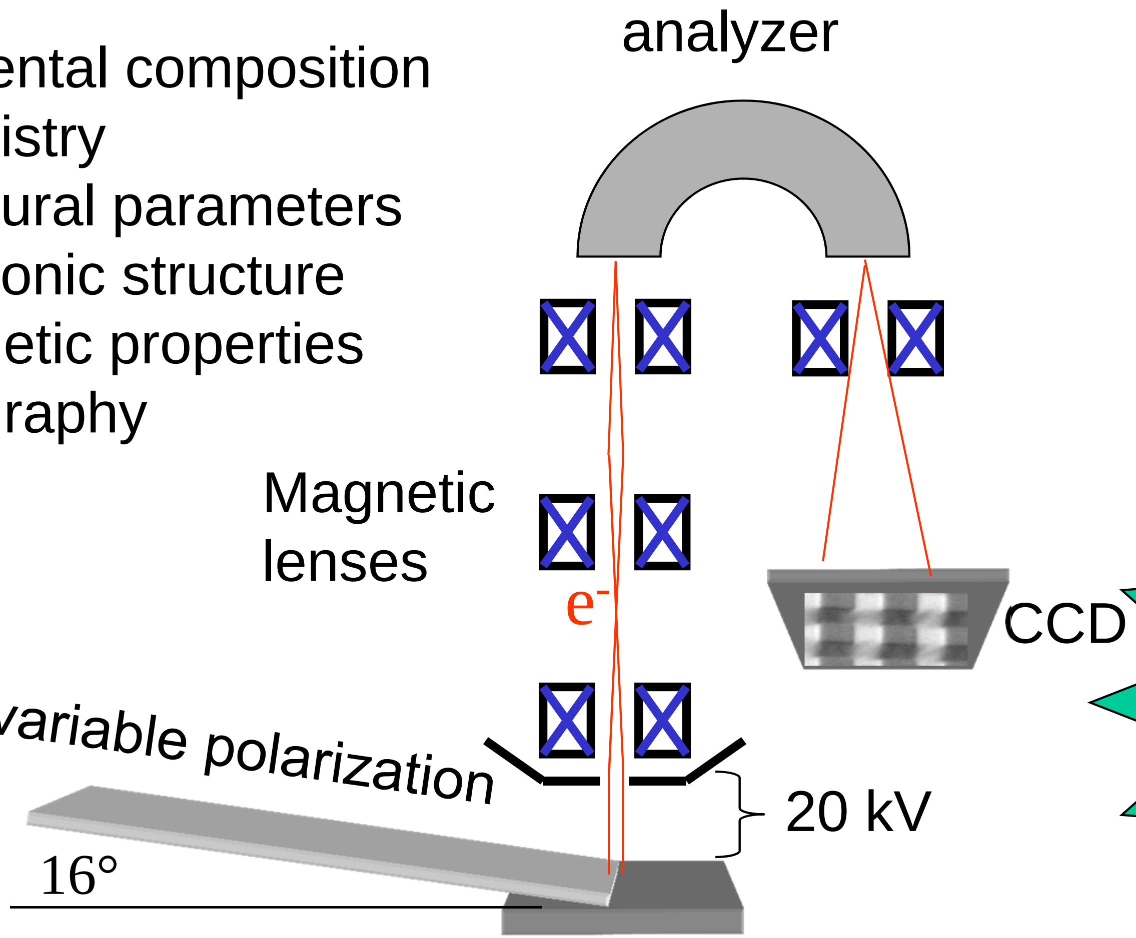


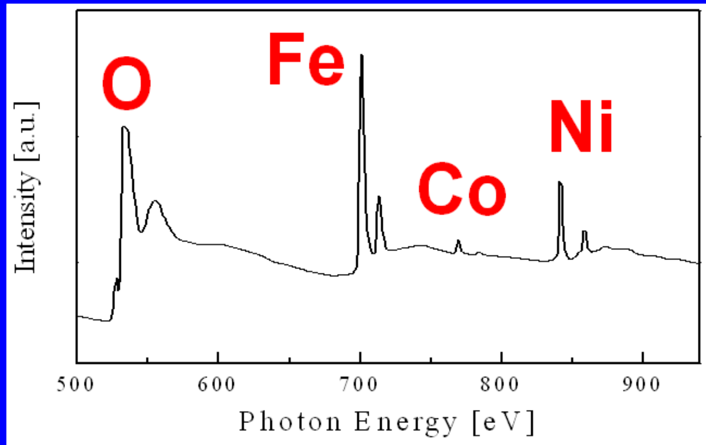
Microfocussing due to distortion of the local electric fields

Photoemission Electron Microscope
SIM beamline (SLS)

Arantxa Fraile-Rodriguez
Frithjof Nolting

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

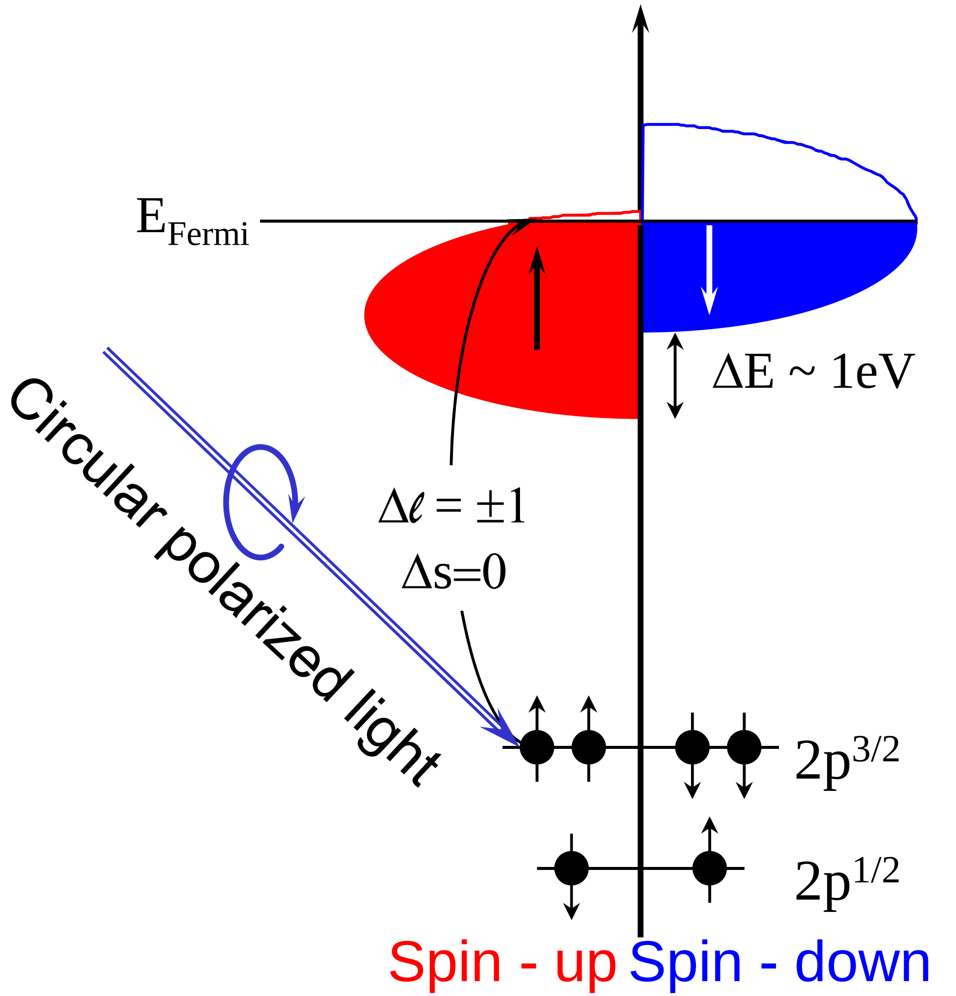




Element Specific
Antiferromagnet
Interfaces
Time Resolved

L. J. Heyderman

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

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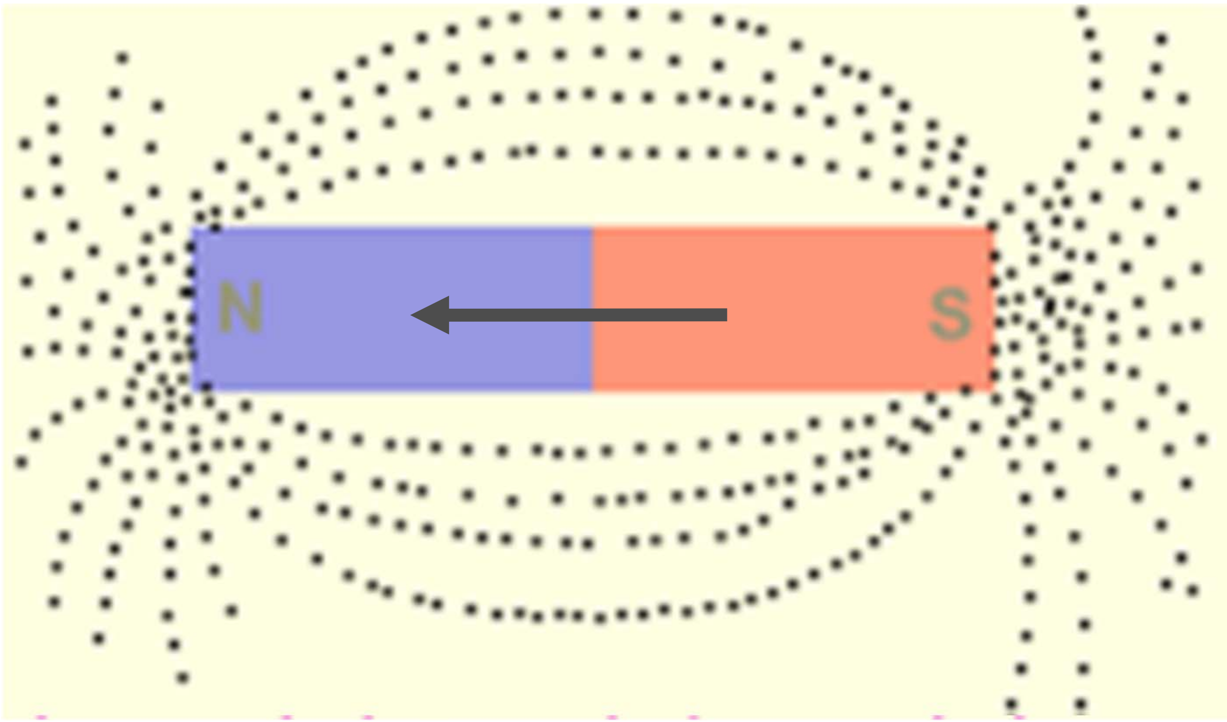
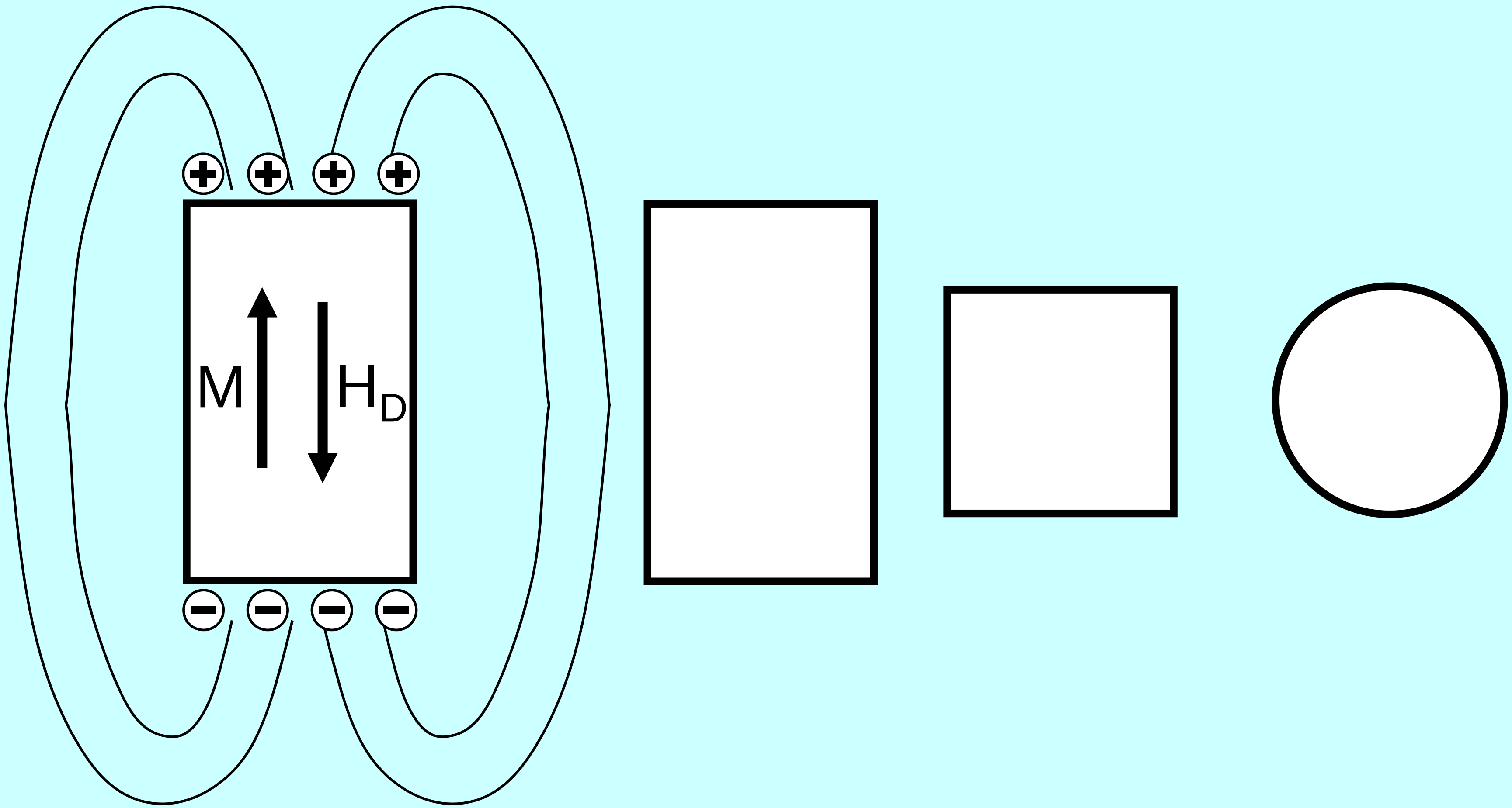
Time for a game….

Magnetostatic or Stray Field Energy



Rectangle, Square, Disk



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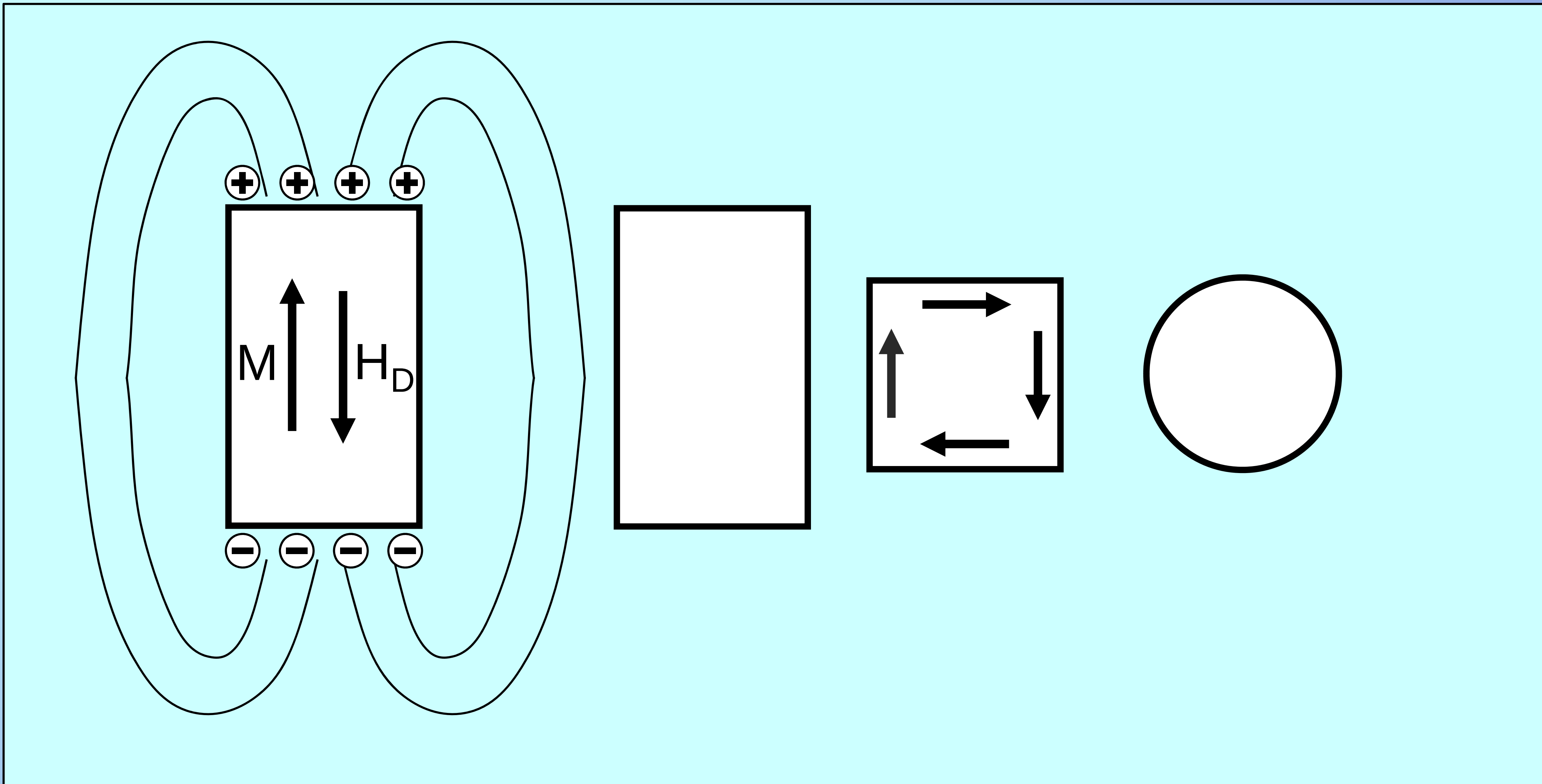
Rectangle, Square, Disk



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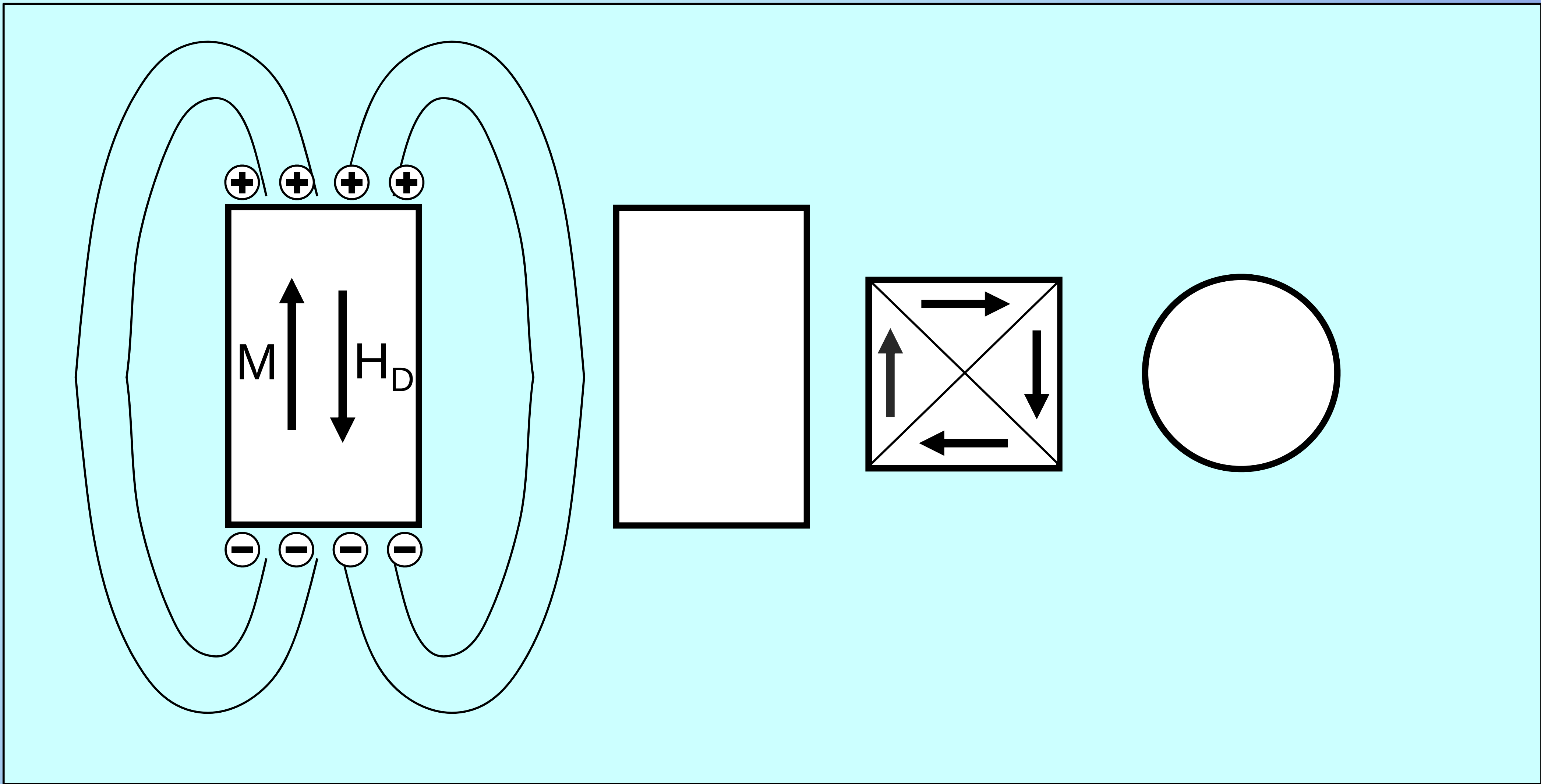
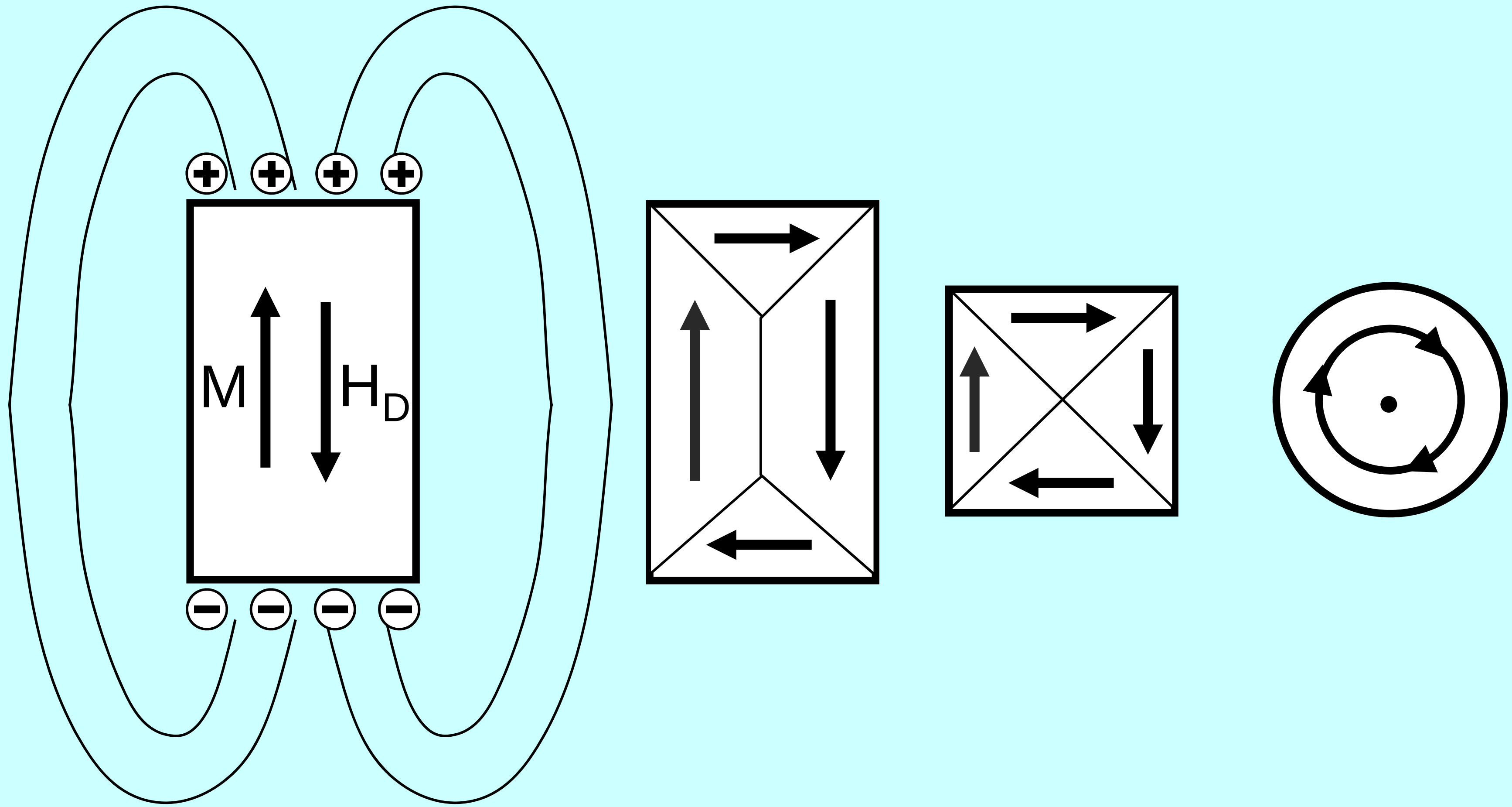
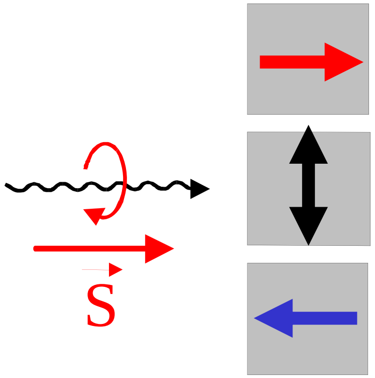
Rectangle, Square, Disk

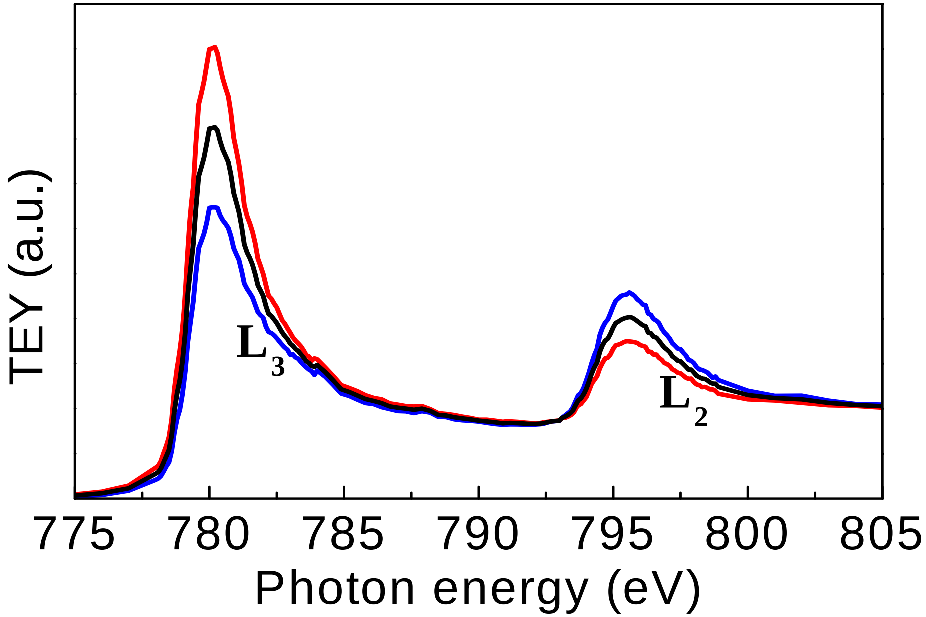


Rectangle, Square, Disk

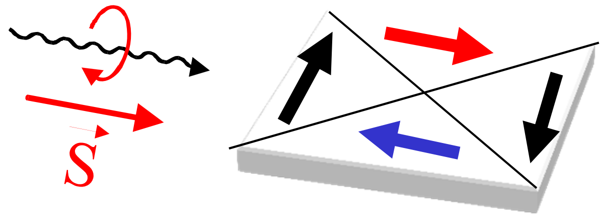


X-ray Magnetic Circular Dichroism (XMCD)

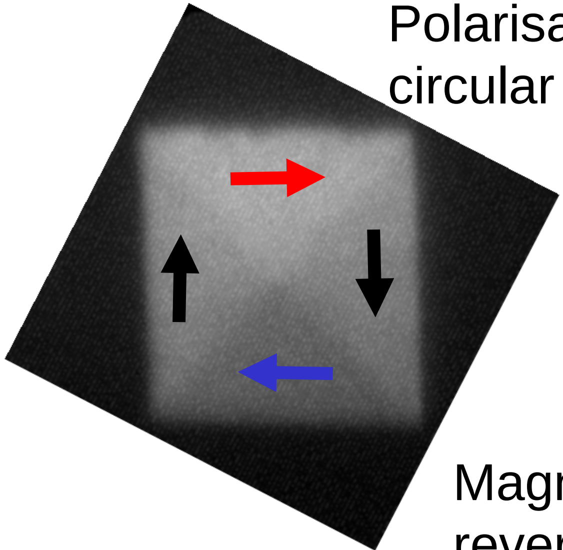




XMCD ~ **M** cos(**M**,**S**)

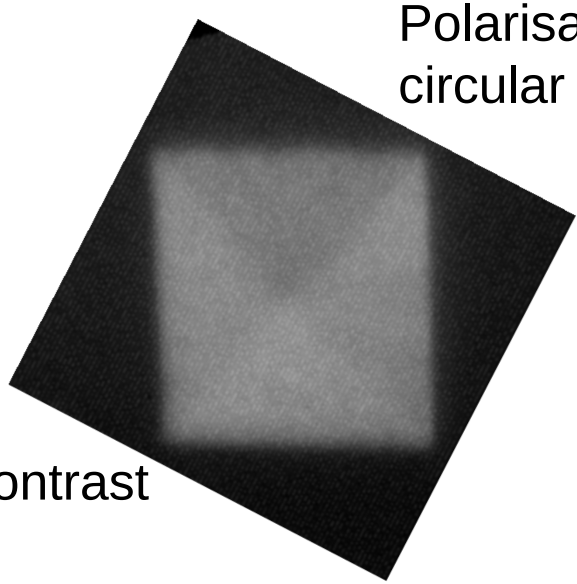


Square Ferromagnetic Element: Landau Domain Pattern



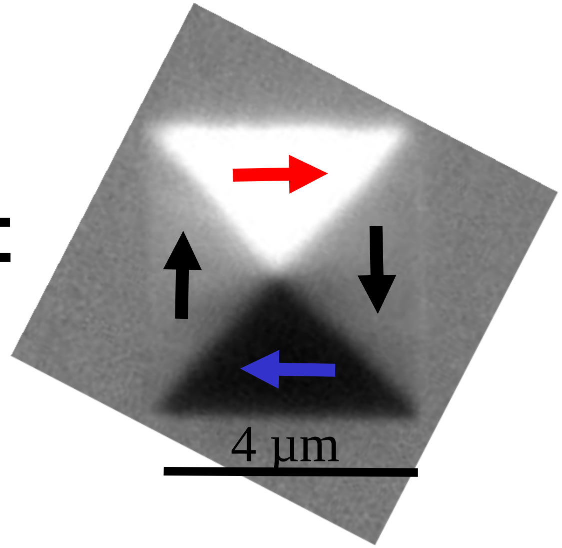
Polarisation: circular plus

—



Polarisation: circular minus

=



Magnetic contrast reverses

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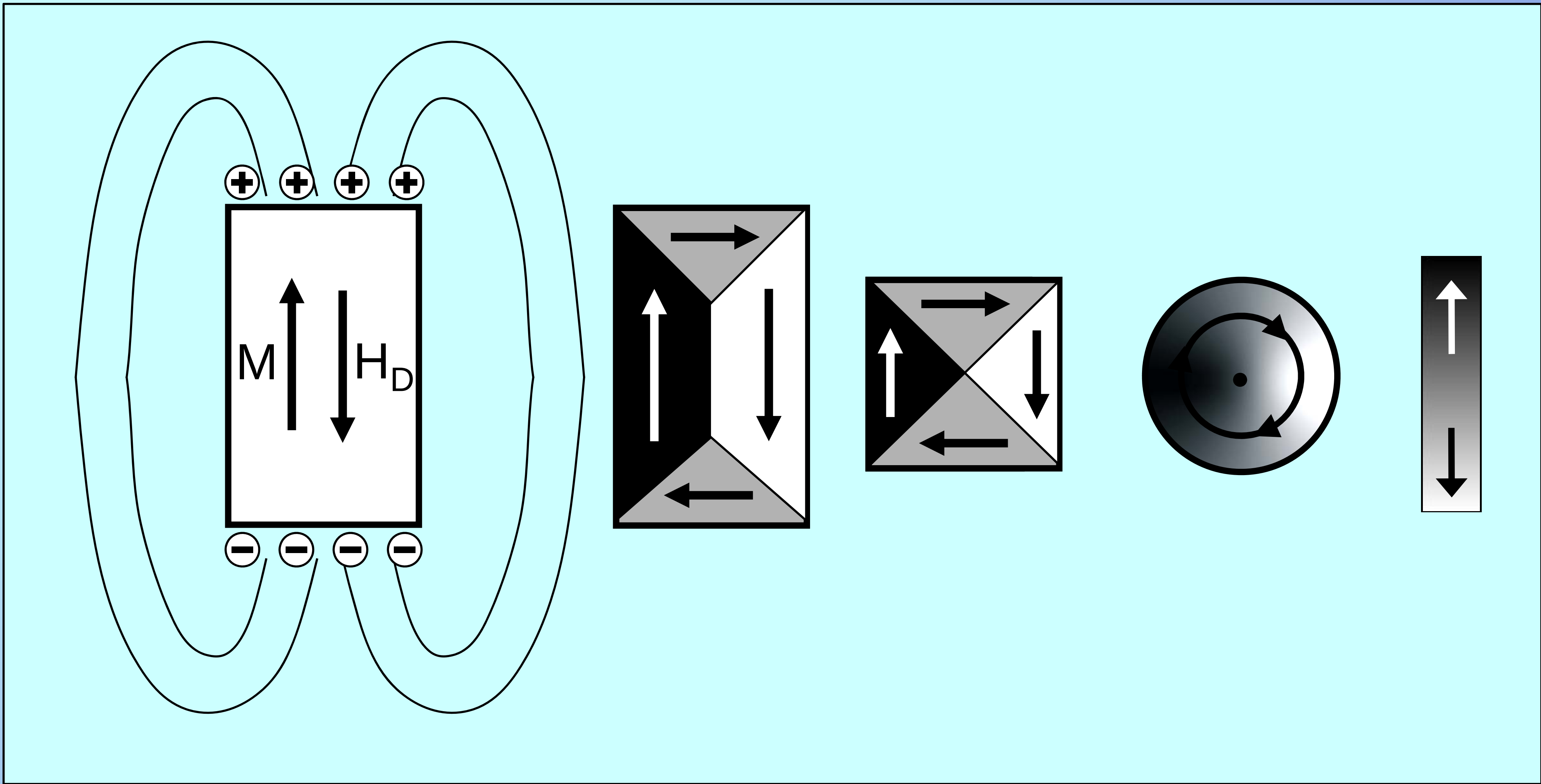
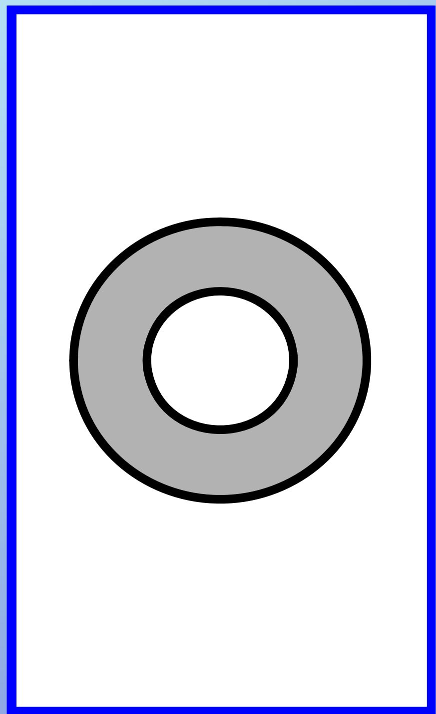
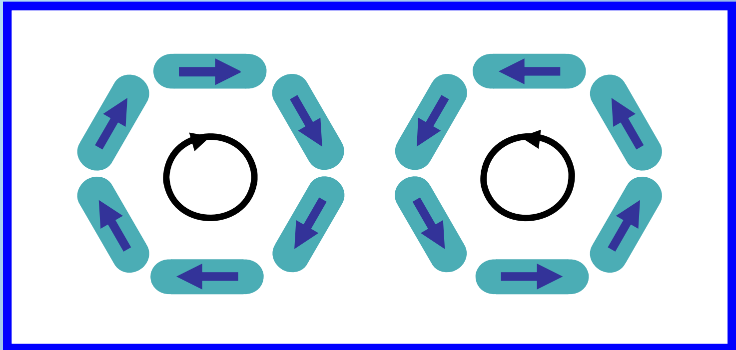
Rectangle, Square, Disk



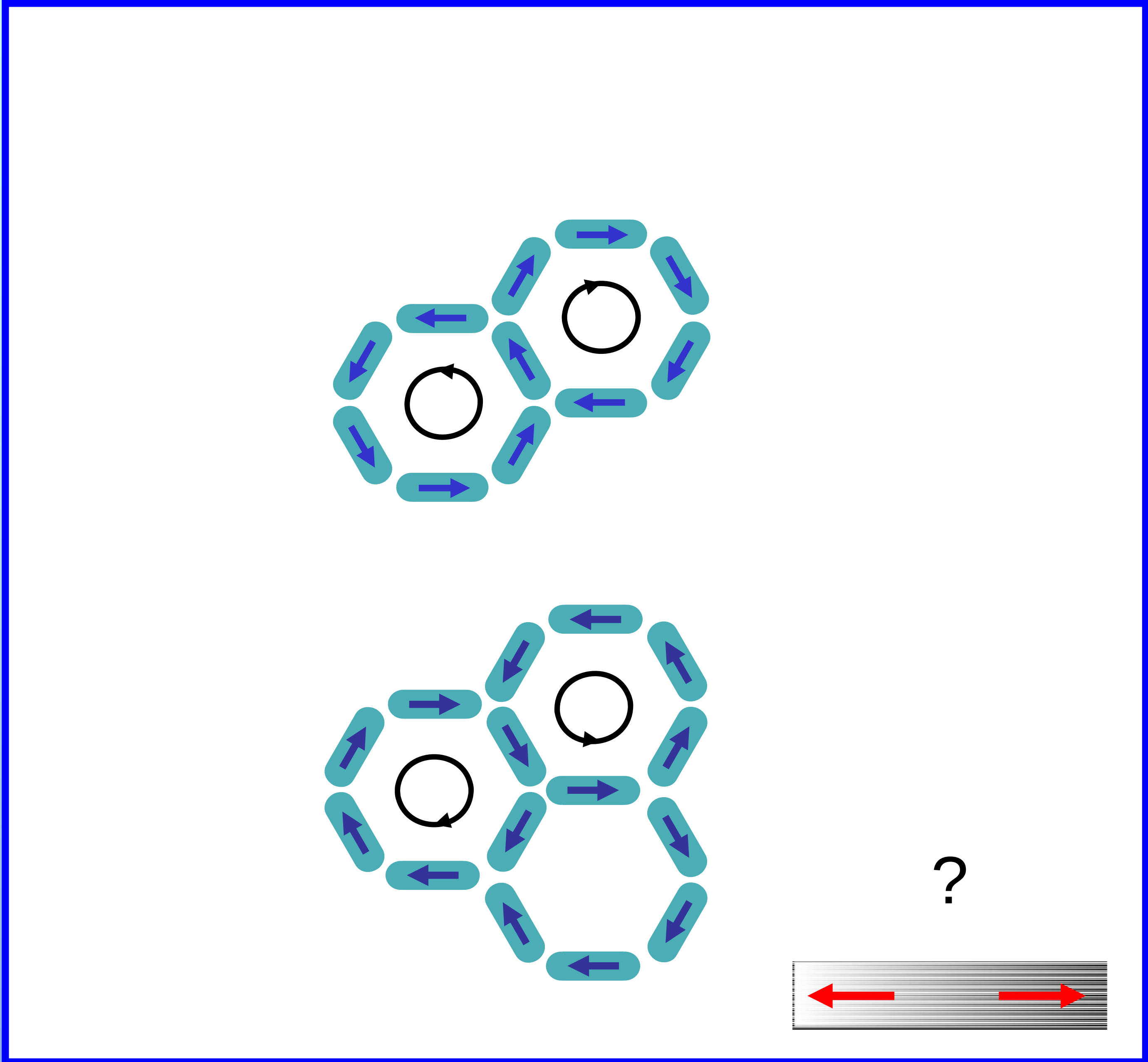
Ring



Ring of Nanomagnets



Rings of Nanomagnets



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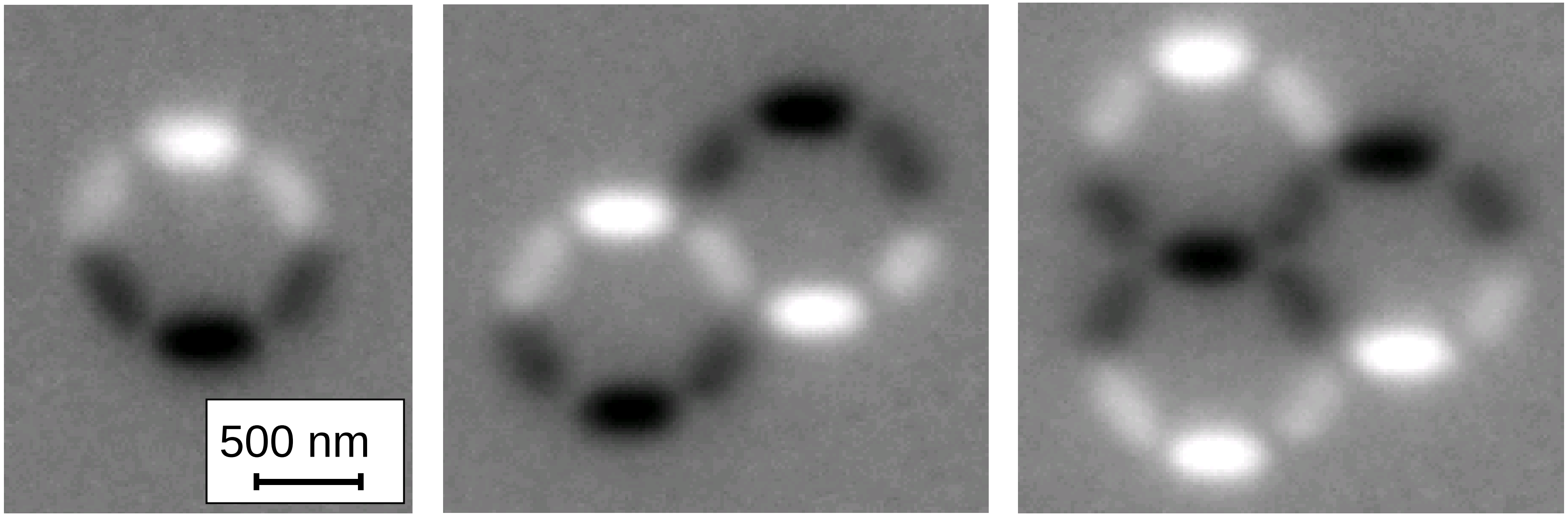
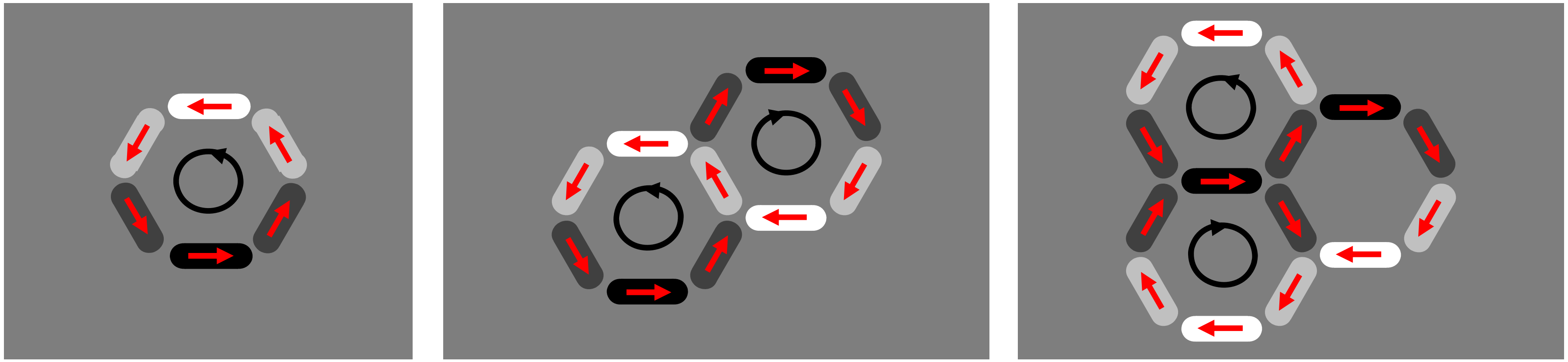
Artificial Spin Ice in PEEM

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





X-ray direction

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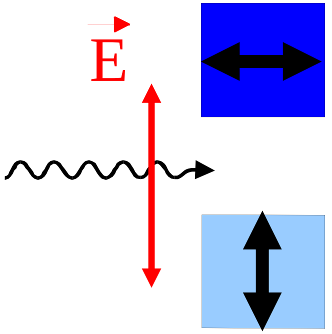
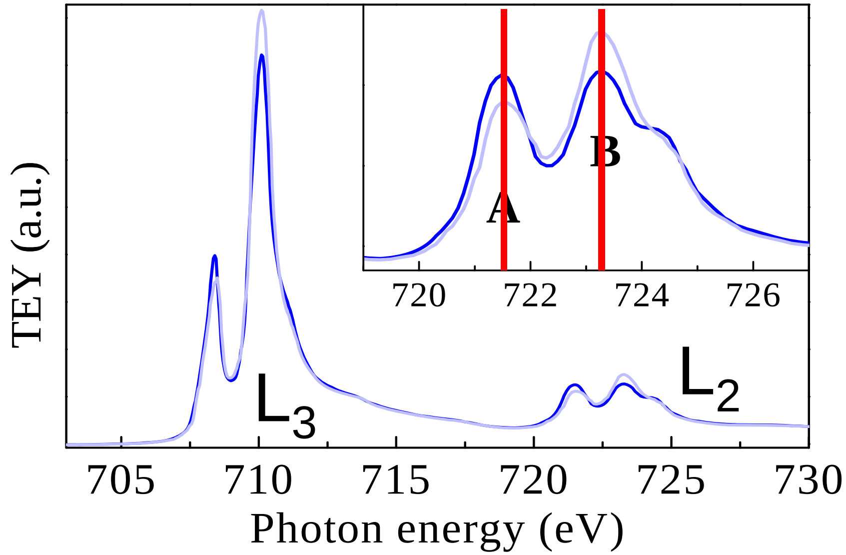
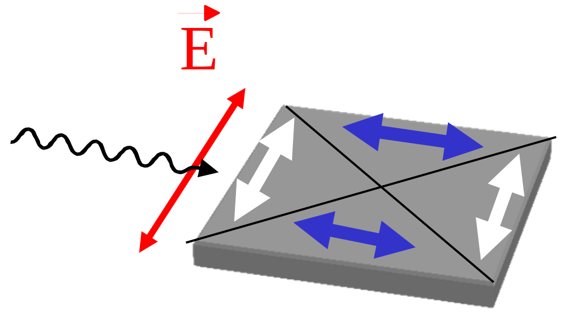
X-ray Magnetic Linear Dichroism (XMLD)



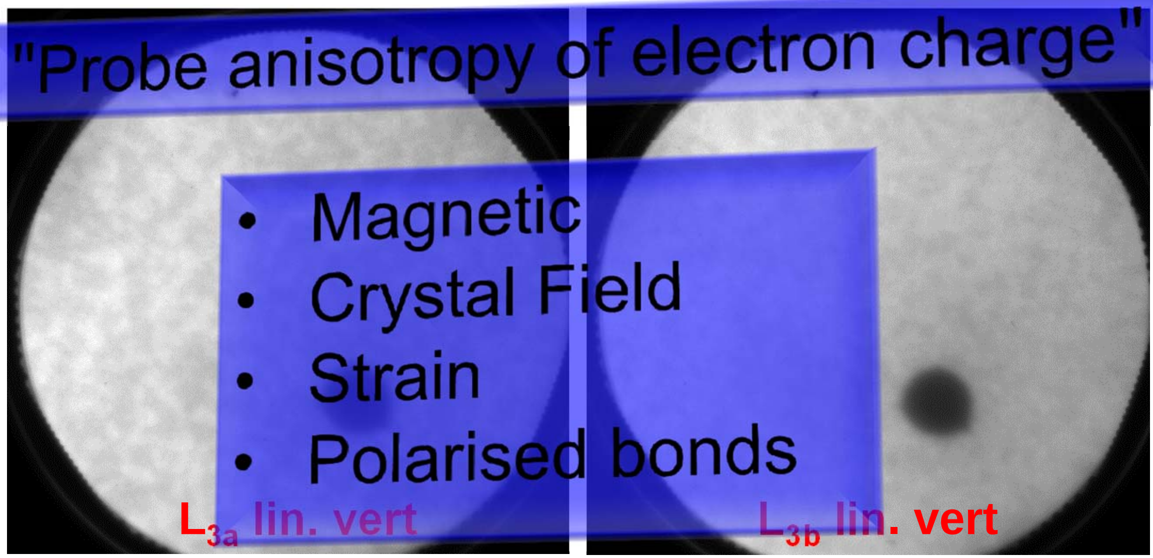


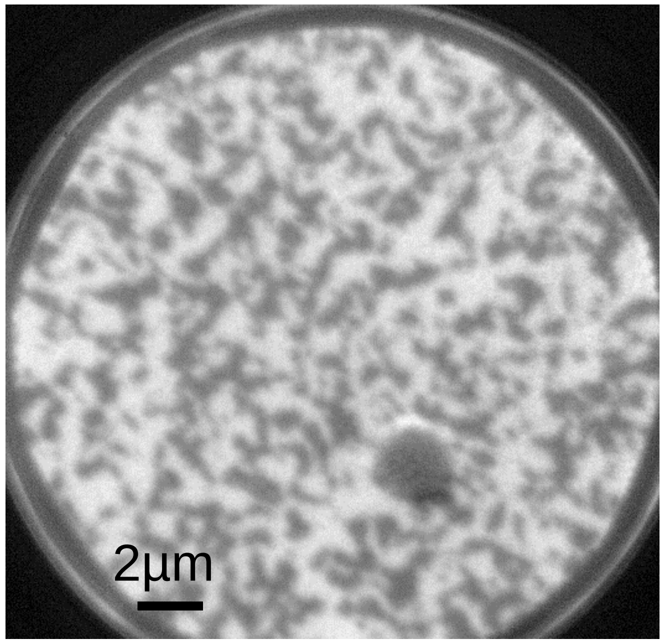
XMLD ~ <**M²**> cos²(**M**,**E**)



"Probe anisotropy of electron charge"

- Magnetic
- Crystal Field
- Strain
- Polarised bonds





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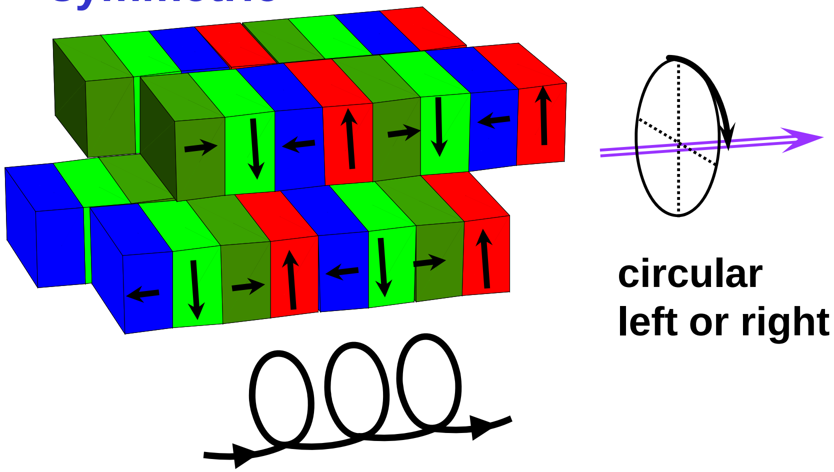
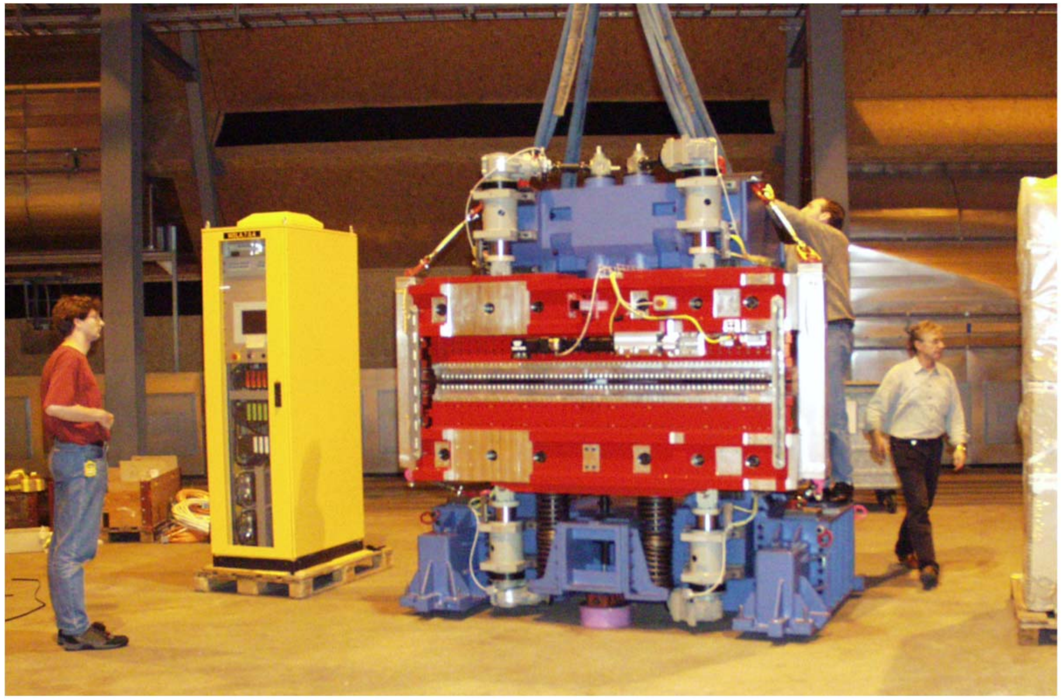
Undulator

Magnetic Structure: changing phase, changes polarisation

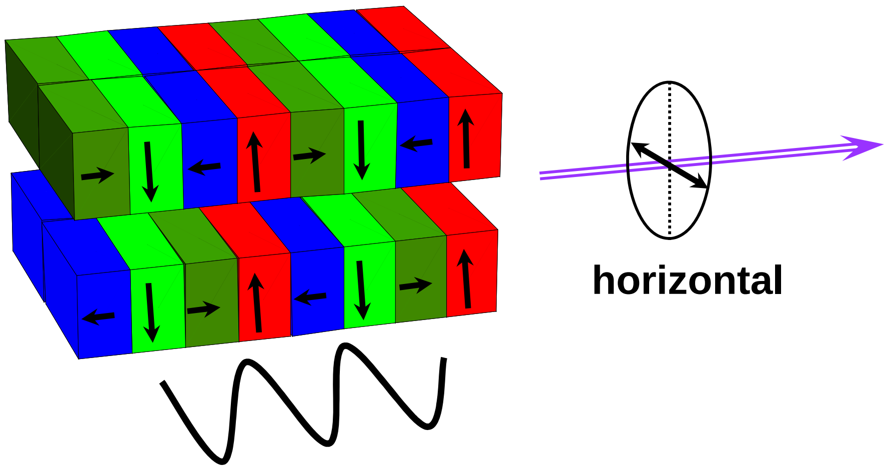
symmetric

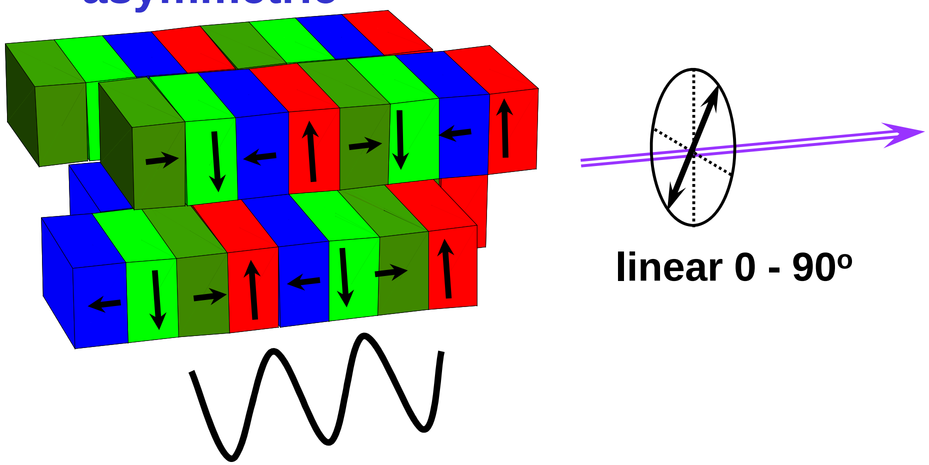




shift π/2
asymmetric

shift 0





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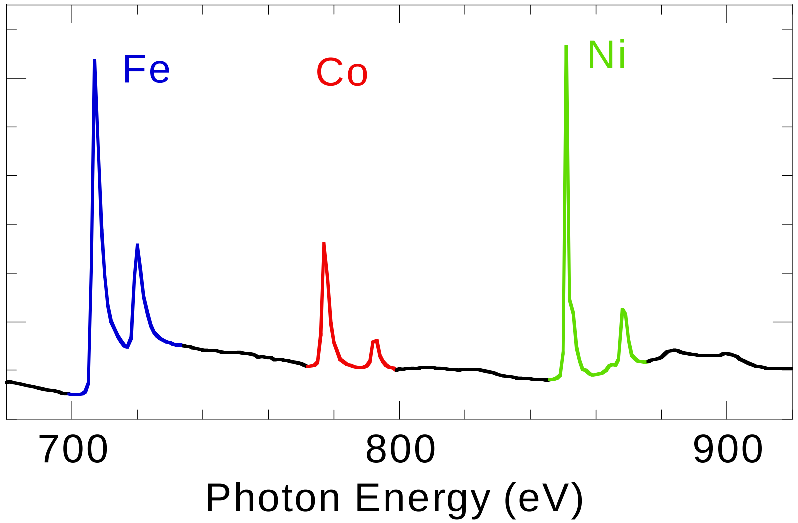
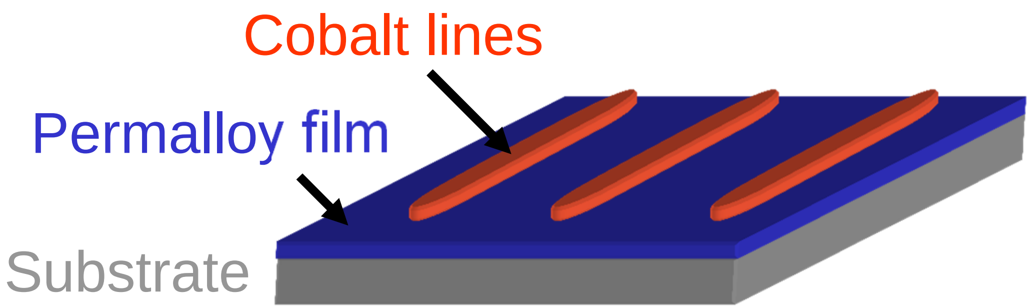
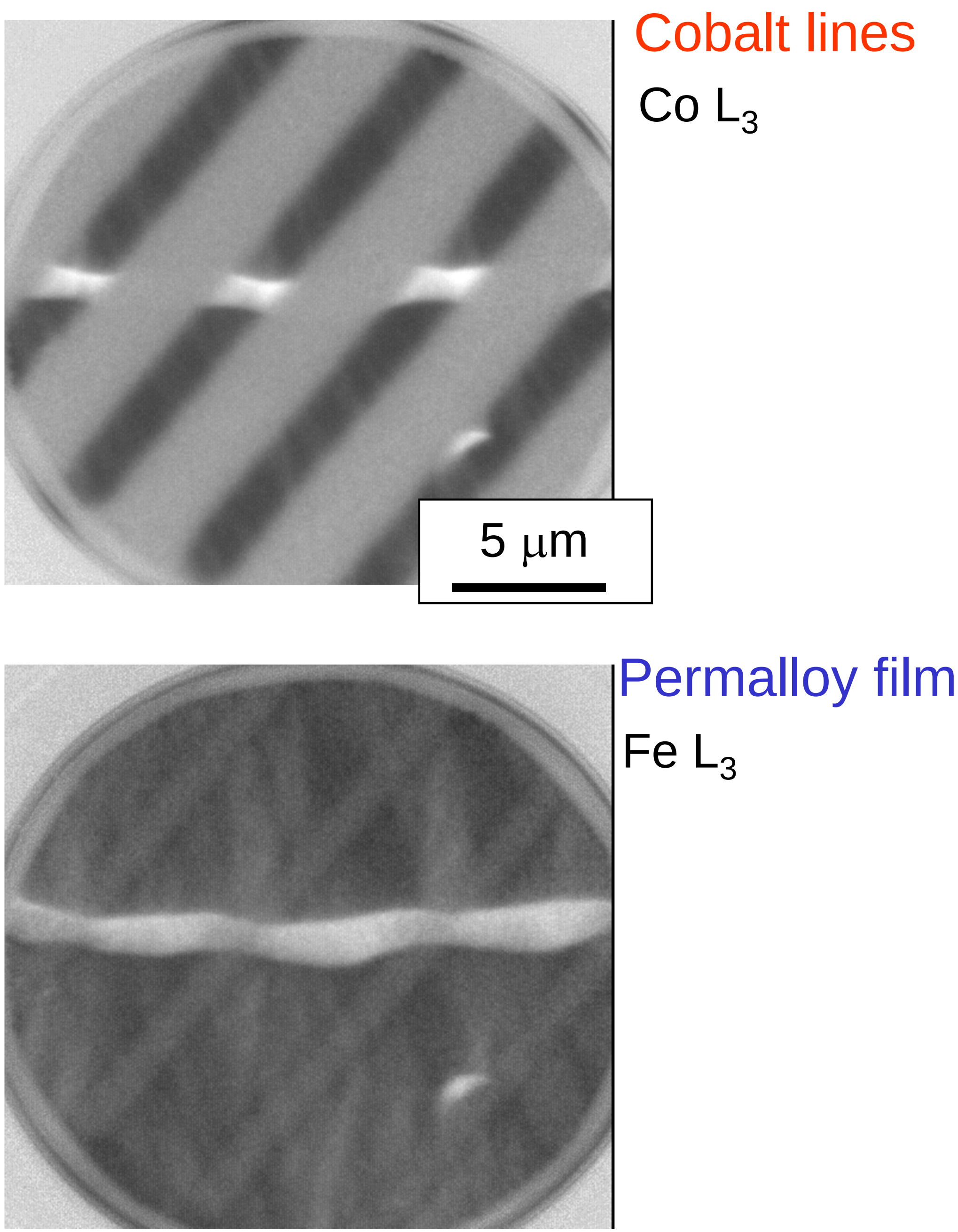
Element specific contrast

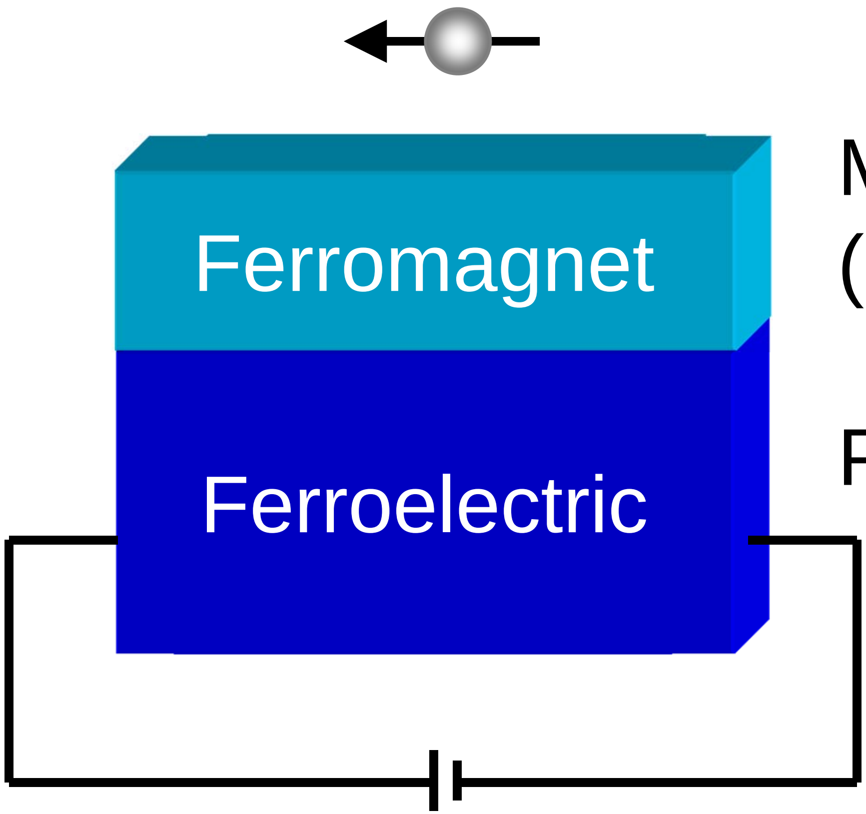






Coupling of hard and soft magnetic layer:
L. Heyderman, A. Fraile-Rodriguez, A. Hoffmann

Multiferroic Composites



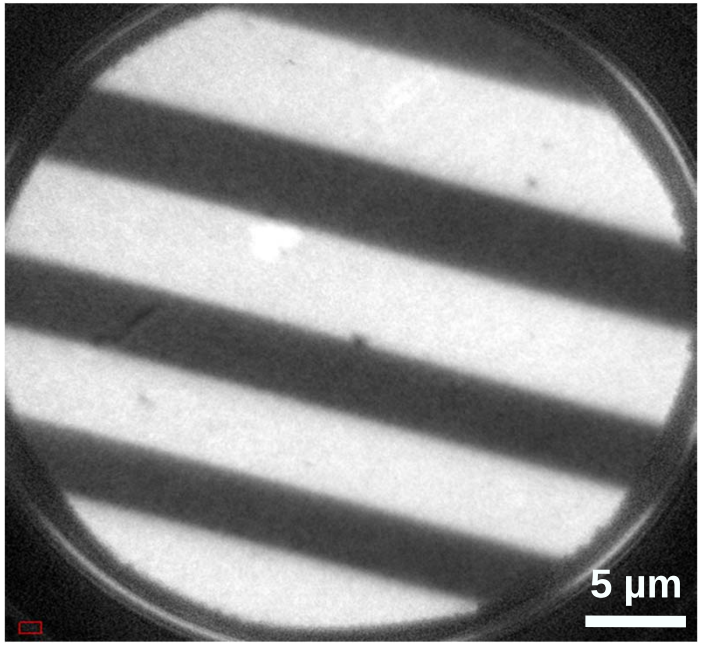
Magnetostrictive: $CoFe_2O_4$
(Ferrimagnetic Spinel)

Piezoelectric: $BaTiO_3$

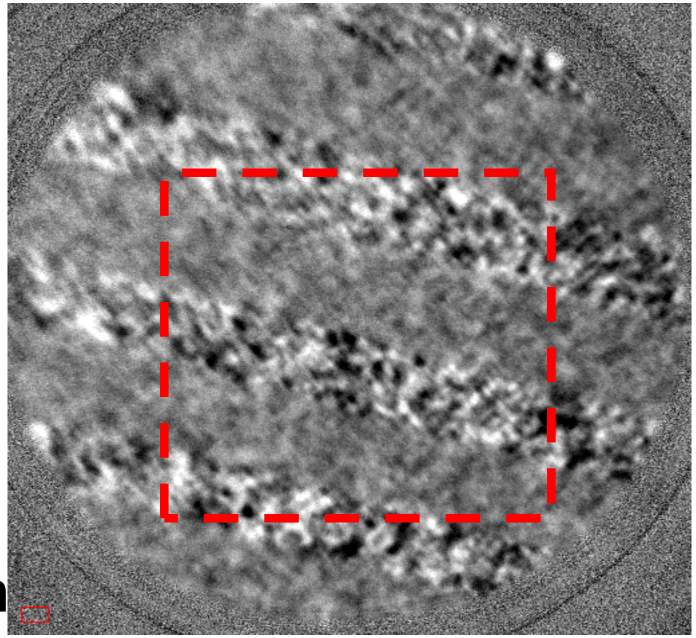
→ Coupling via strain

L. J. Heyderman

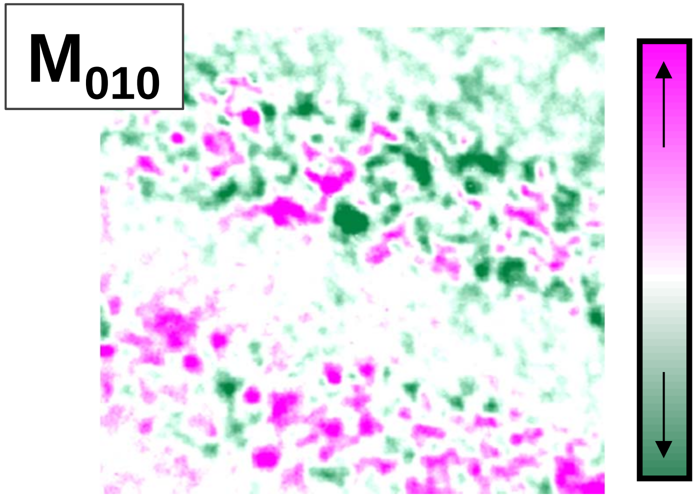
Strain and Magnetic Domains

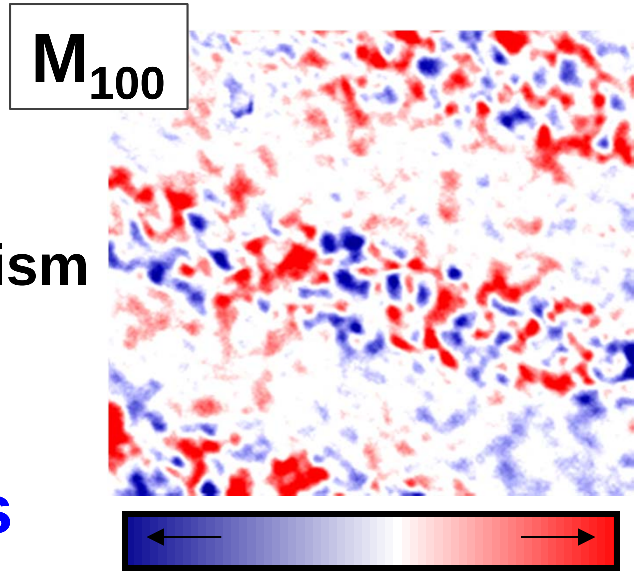


Fe X-ray Linear Dichroism

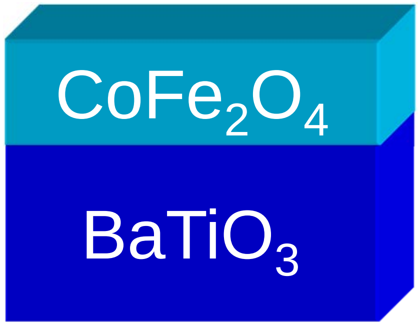


Fe X-ray Magnetic Circular Dichroism





M_{001} ~ 0

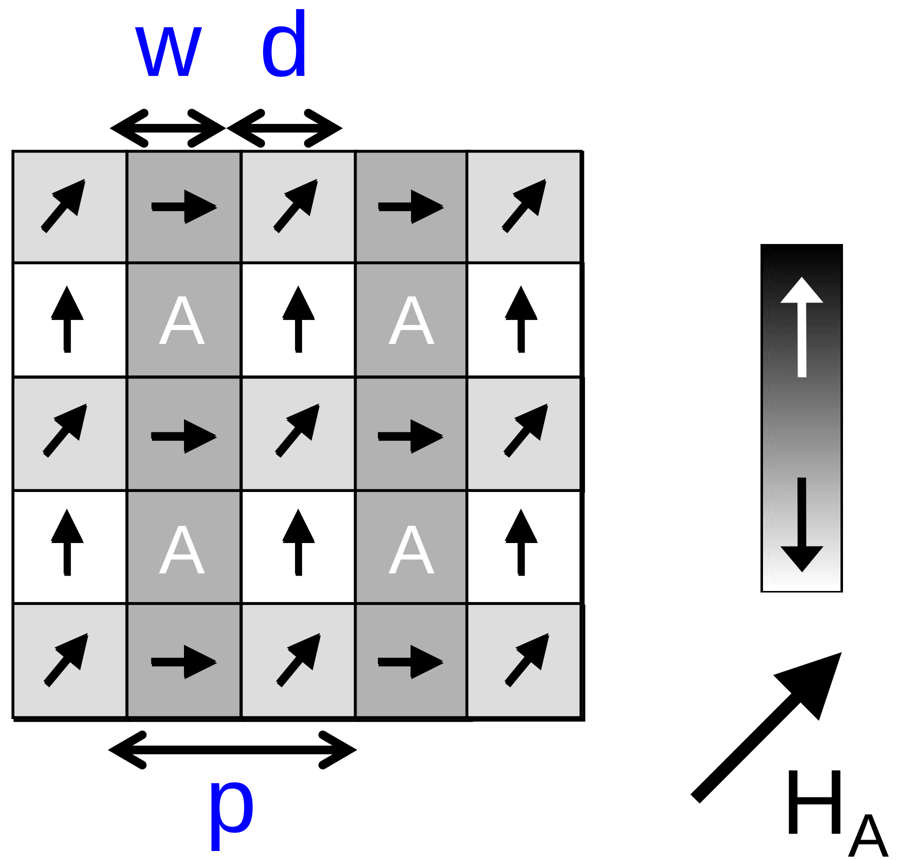


- **Fe XLD: strain domains**
- **Fe XMCD: magnetic domains**
- **Substrate-induced strain strongly modifies magnetic anisotropy**

RV Chopdekar et al. PRB (2012)

L. J. Heyderman

Antidot Arrays – Basic Domain Configuration



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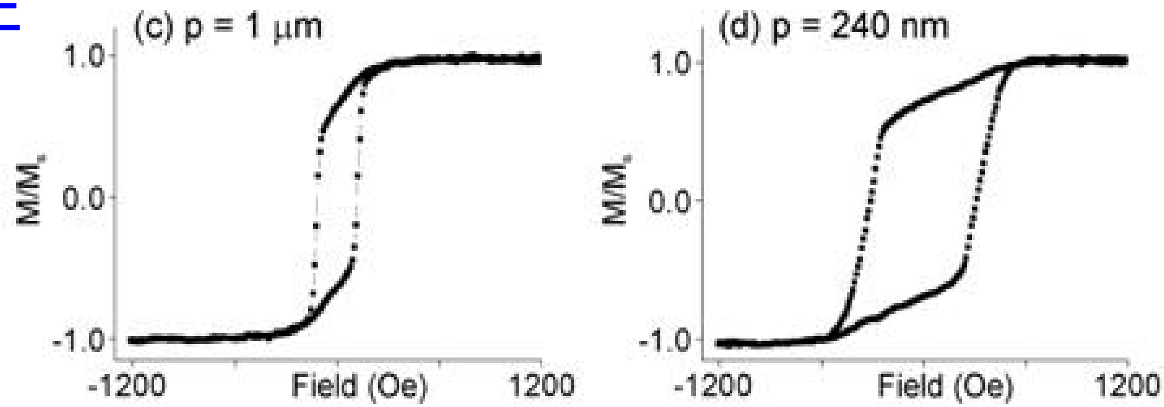
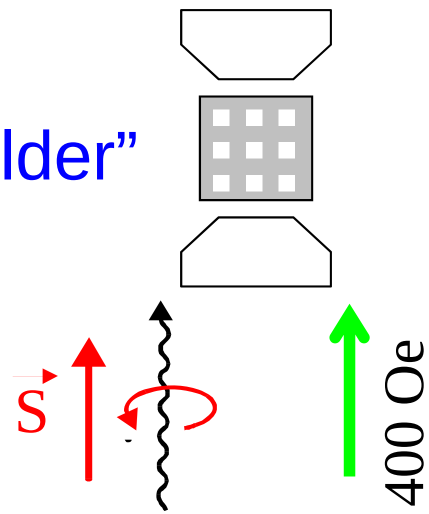
Remanent Hysteresis Loop in Antidot Arrays

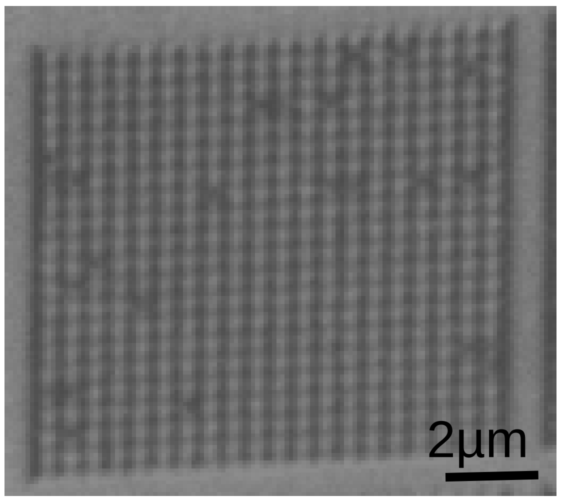
MOKE



Observe magnetisation reversal in applied magnetic field:

PEEM
"Magnetising Holder"



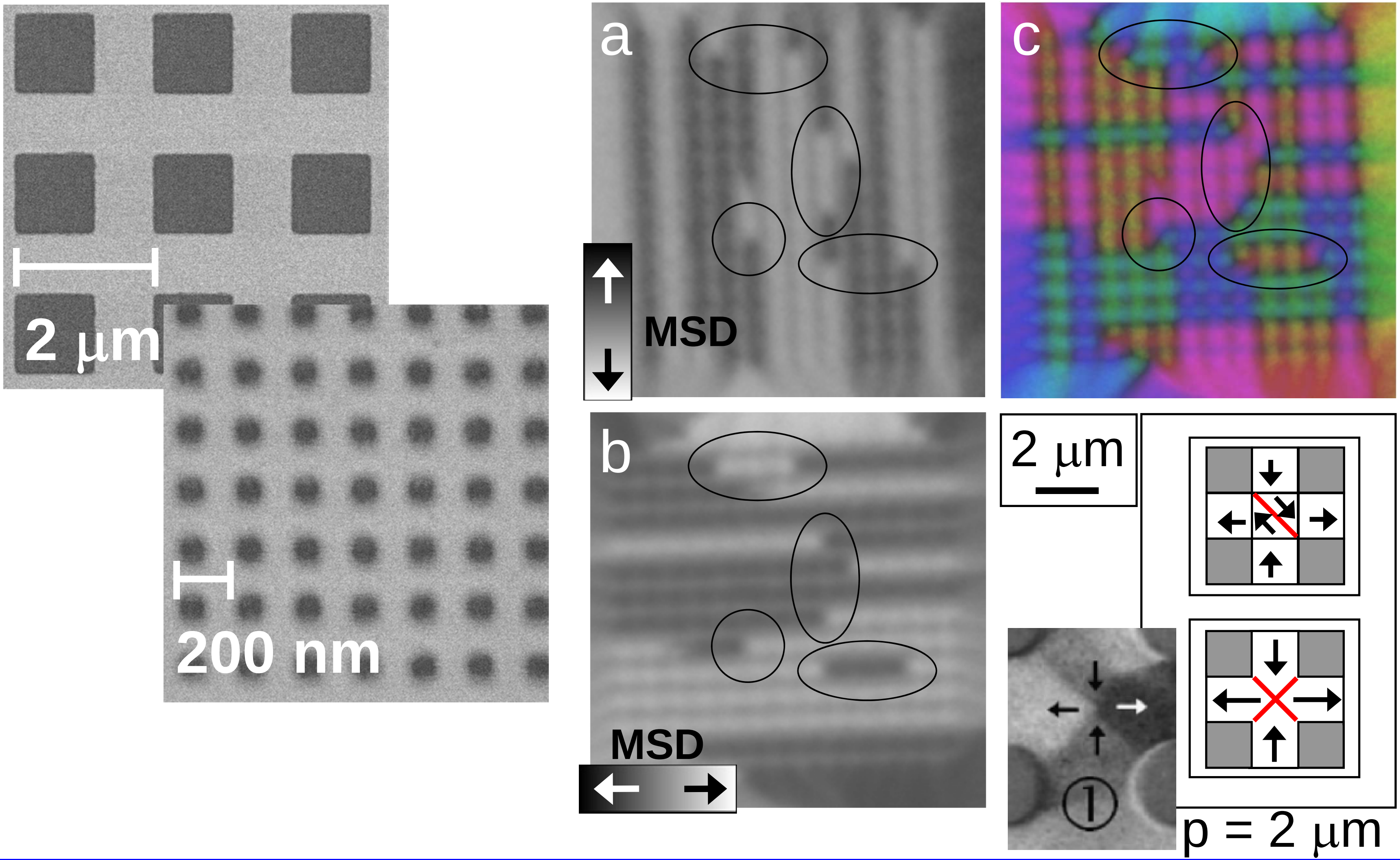


Spins ↑ to Spins ↓

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

L. J. Heyderman

Cobalt Antidot Arrays



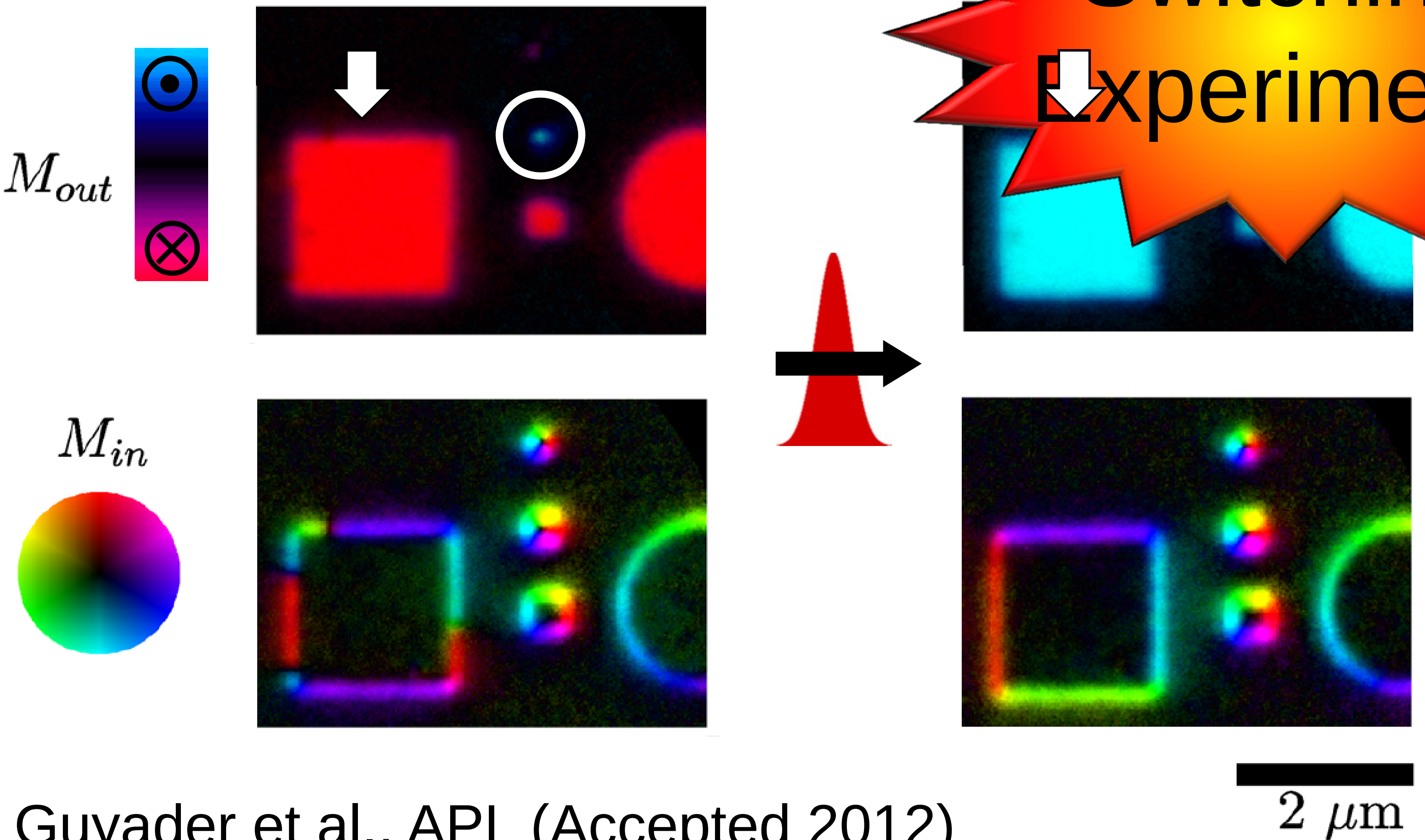
L. J. Heyderman et al., APL (2003), JAP (2004), PRB (2006), JMMM (2007)
Mengotti et al., JAP (2007)

L. J. Heyderman

Switching with a Heat Pulse Only

- 200 nm domains in 400 nm GdFeCo nano

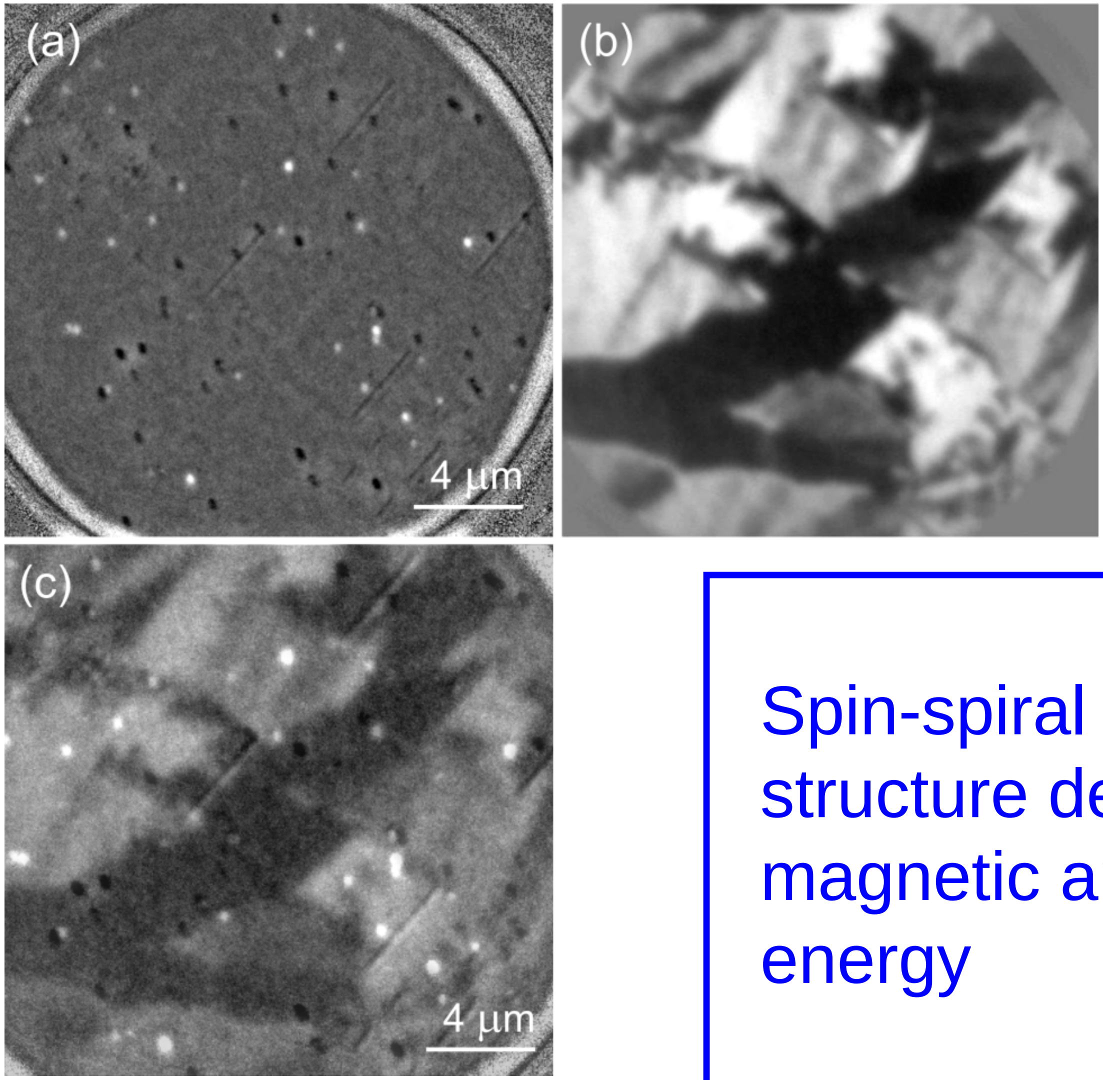
Switching Experiments



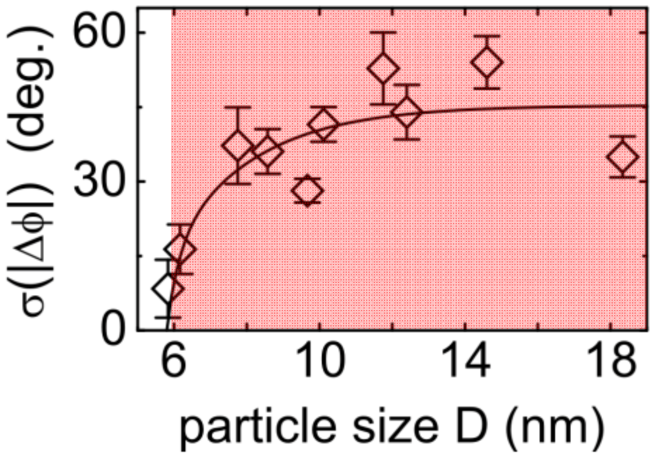
L. Le Guyader et al., APL (Accepted 2012)
T. A. Ostler et al., Nature Communications (2012)

Iron Nanoparticles Coupled to Cobalt Thin Film

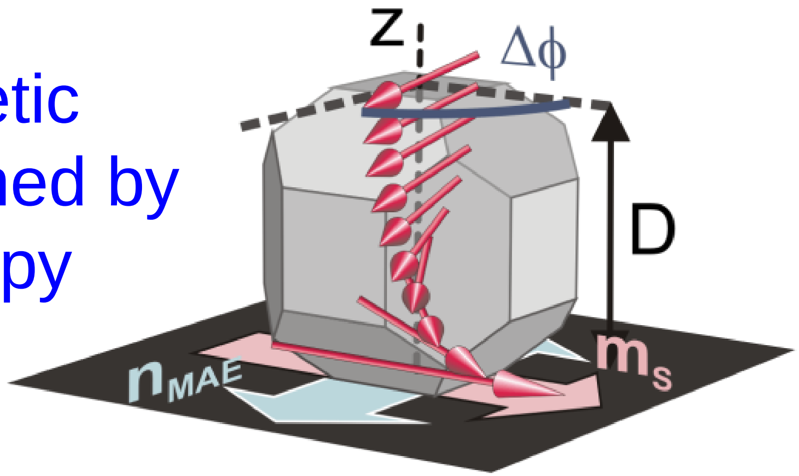
5-25 nm Fe particles/Co thin Film



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)

L. J. Heyderman

Time Resolved Imaging

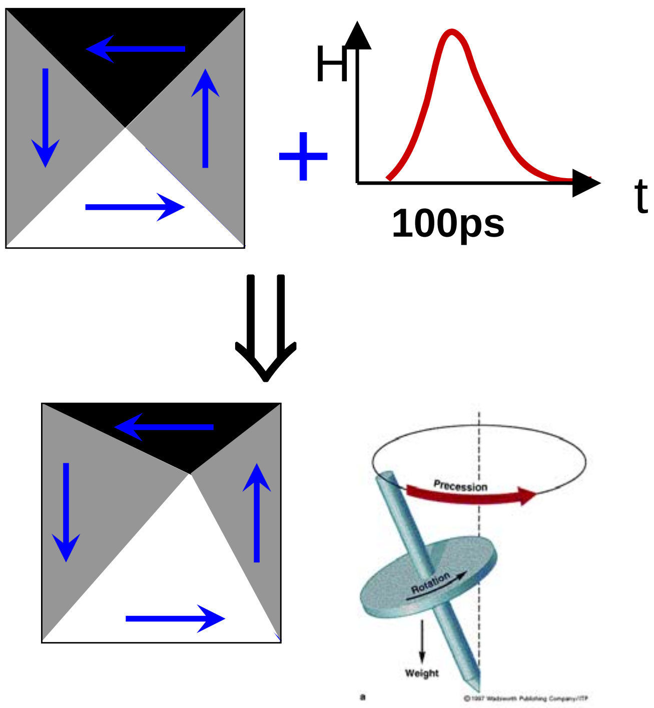


Image excitations in magnetic nanostructures

Precession frequency & damping

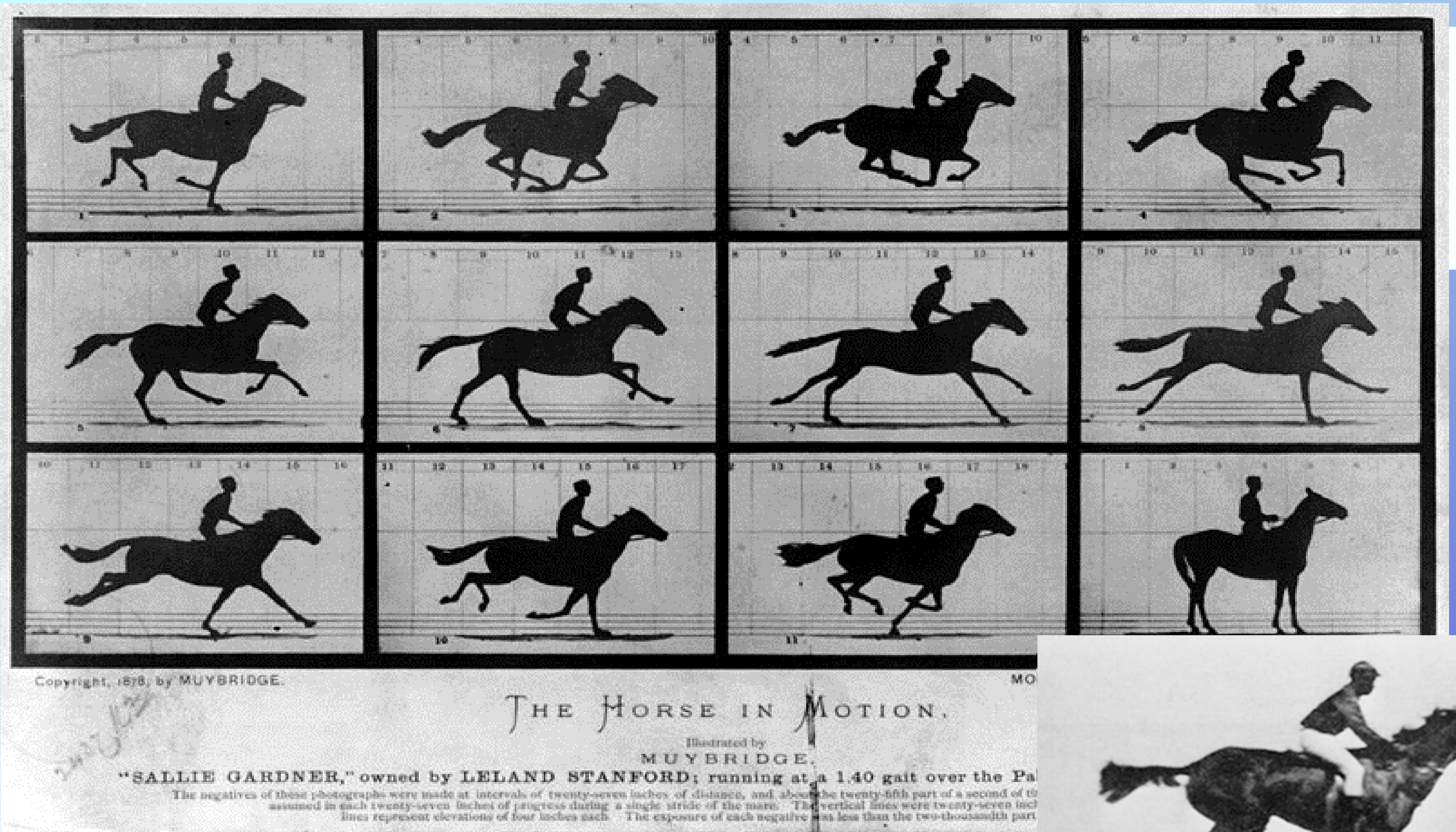
Pump-probe experiment

SLS: X-ray stroboscope

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

L. J. Heyderman

Why perform time-resolved imaging?

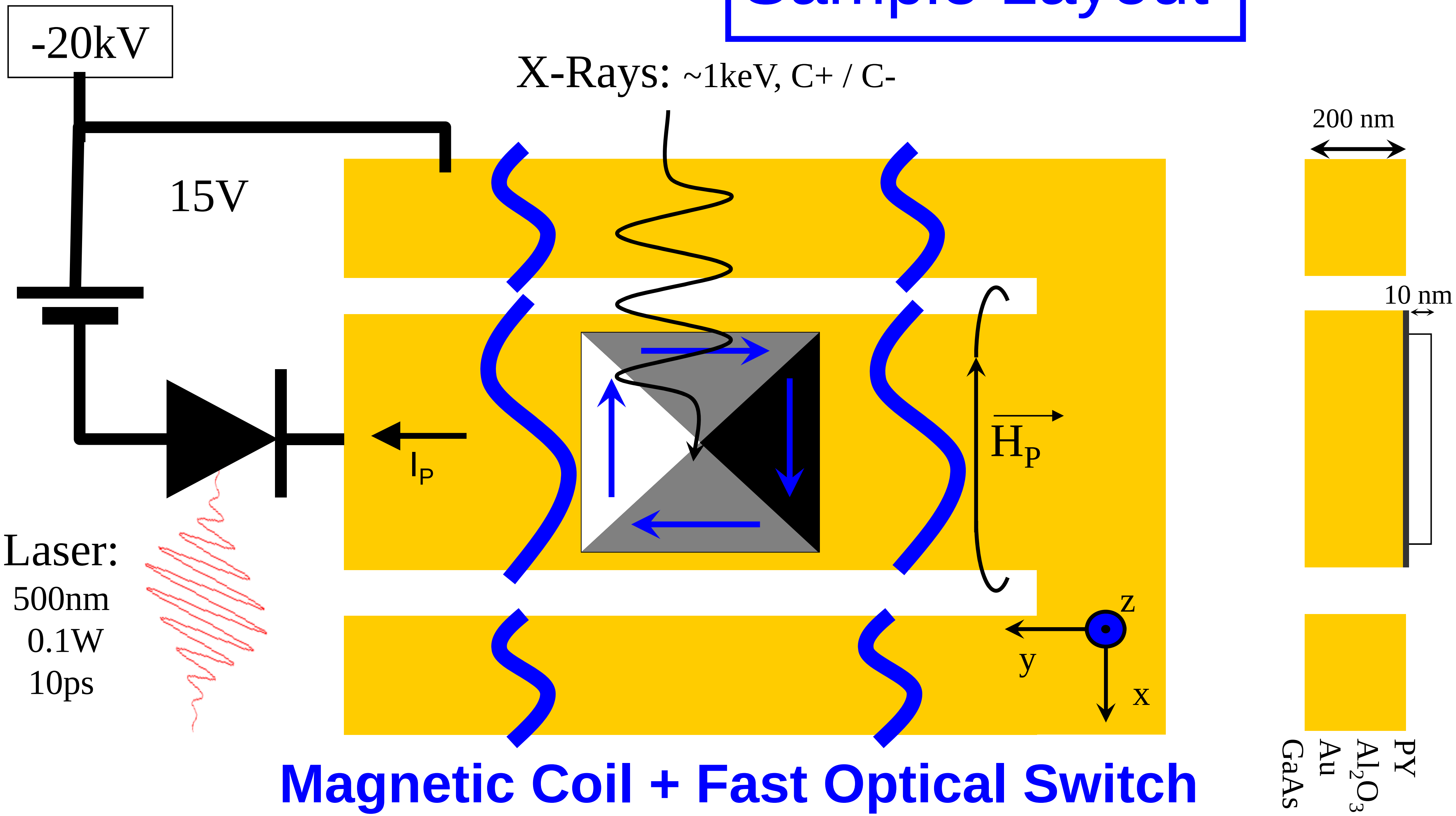


Are all four feet of a horse off the ground at the same time during a gallop.

Galloping horse, animated in 2006, using photos by Eadward Muybridge, Wikipedia

L. J. Heyderman

Sample Layout



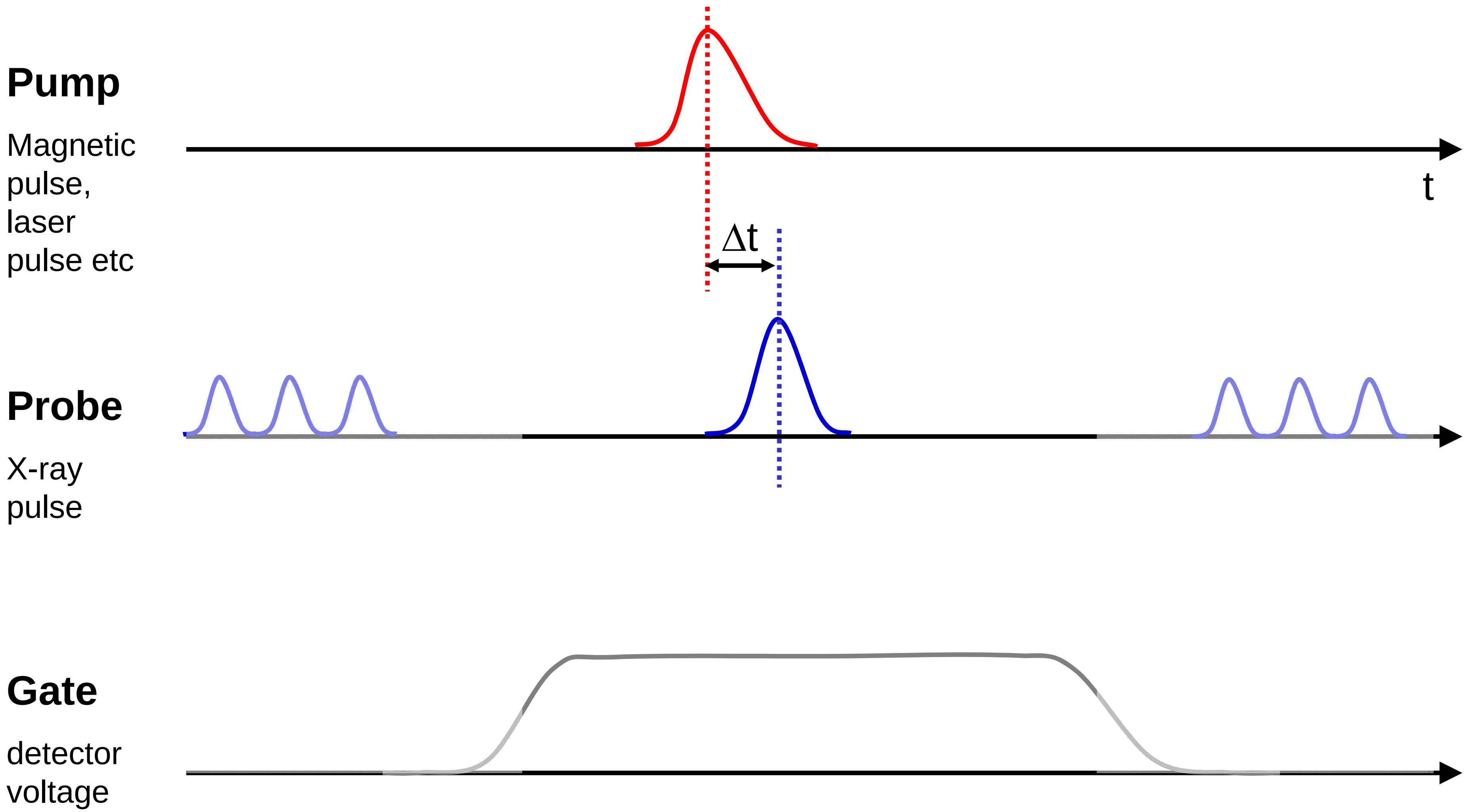
Magnetic Coil + Fast Optical Switch

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

L. J. Heyderman

Magnetic Pump - X-ray Probe

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



L. J. Heyderman

Magnetic Pump - X-ray Probe

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

Pump

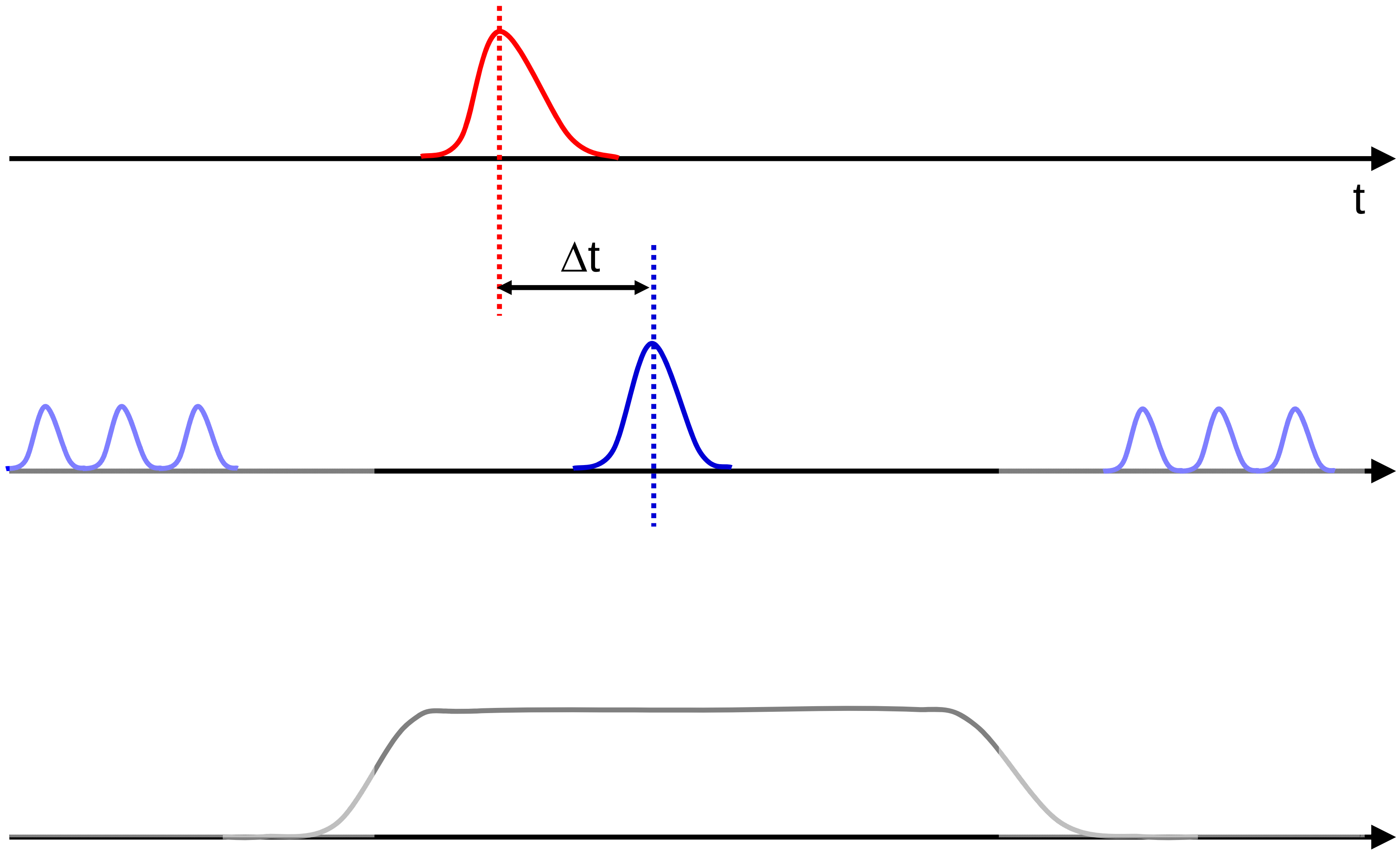
Magnetic pulse, laser pulse etc

Probe

X-ray pulse

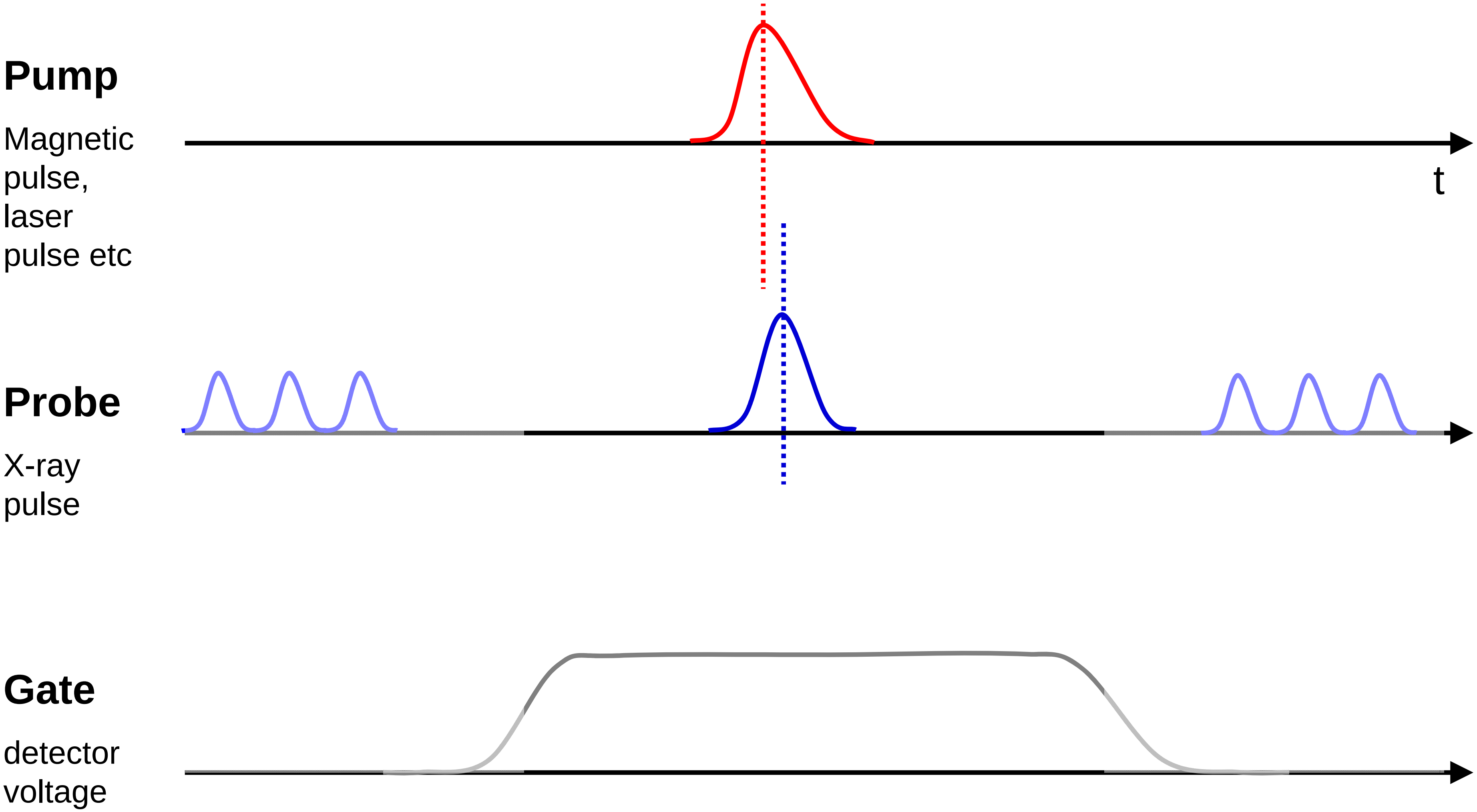
Gate

detector voltage



Magnetic Pump - X-ray Probe

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



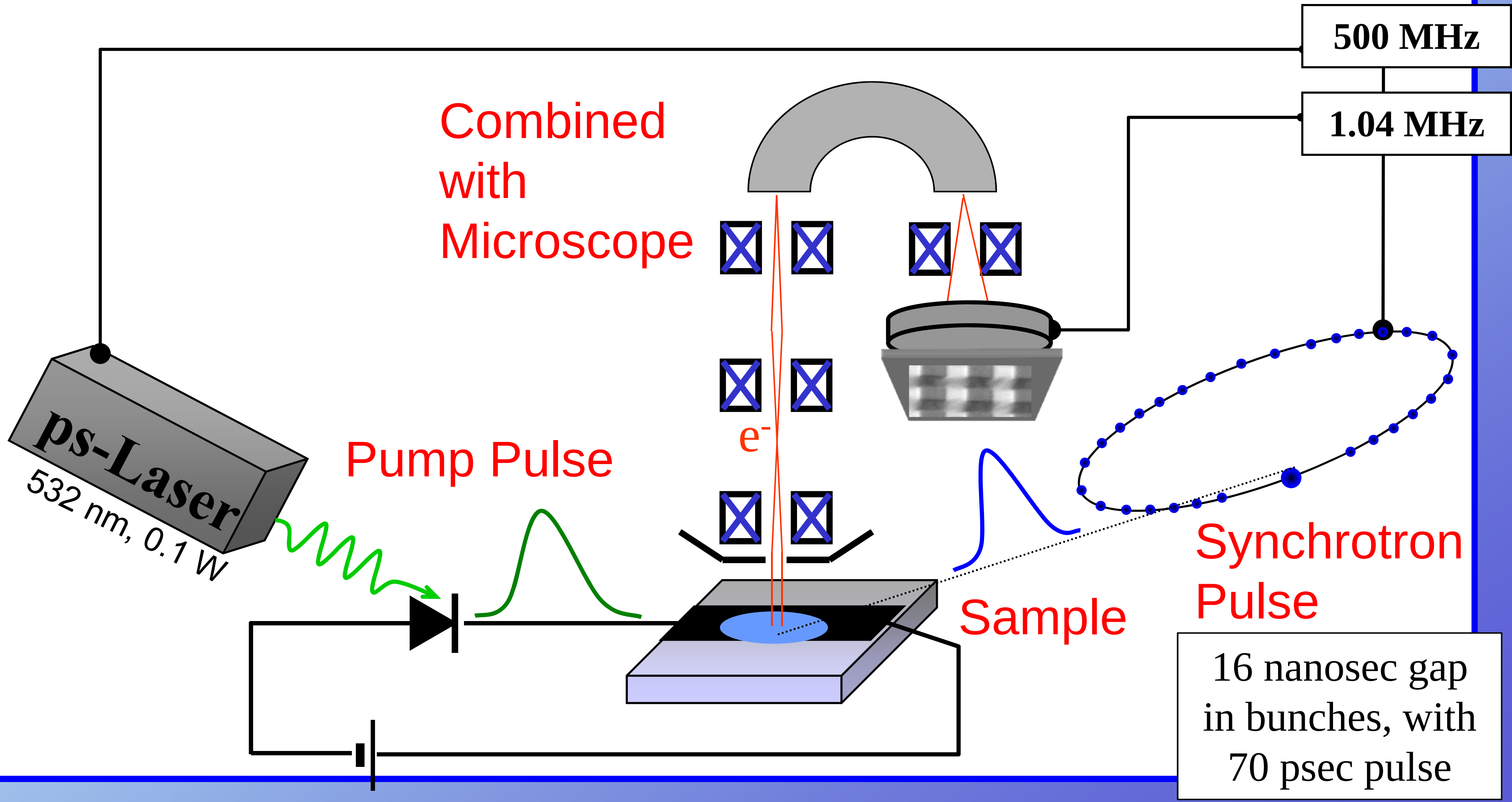
L. J. Heyderman

Summary

Pump:
stripline / coil
Pulse: H < 100 G, 10^2 ps

Detect:
gated PEEM
Δx ~100nm, ~ 1 ML

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



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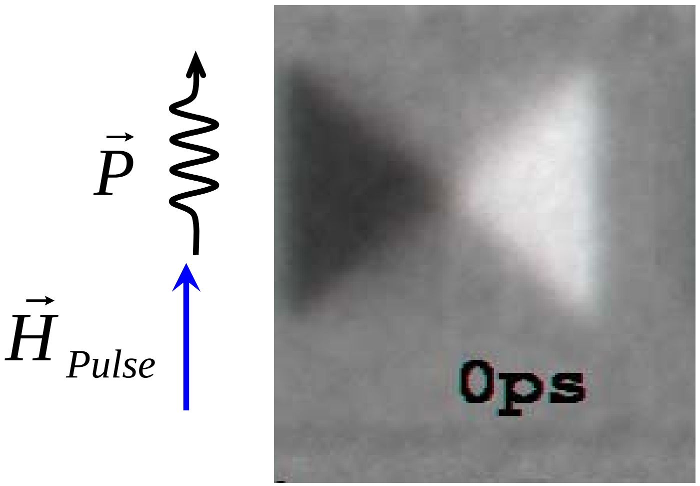
Py Square: Excitation

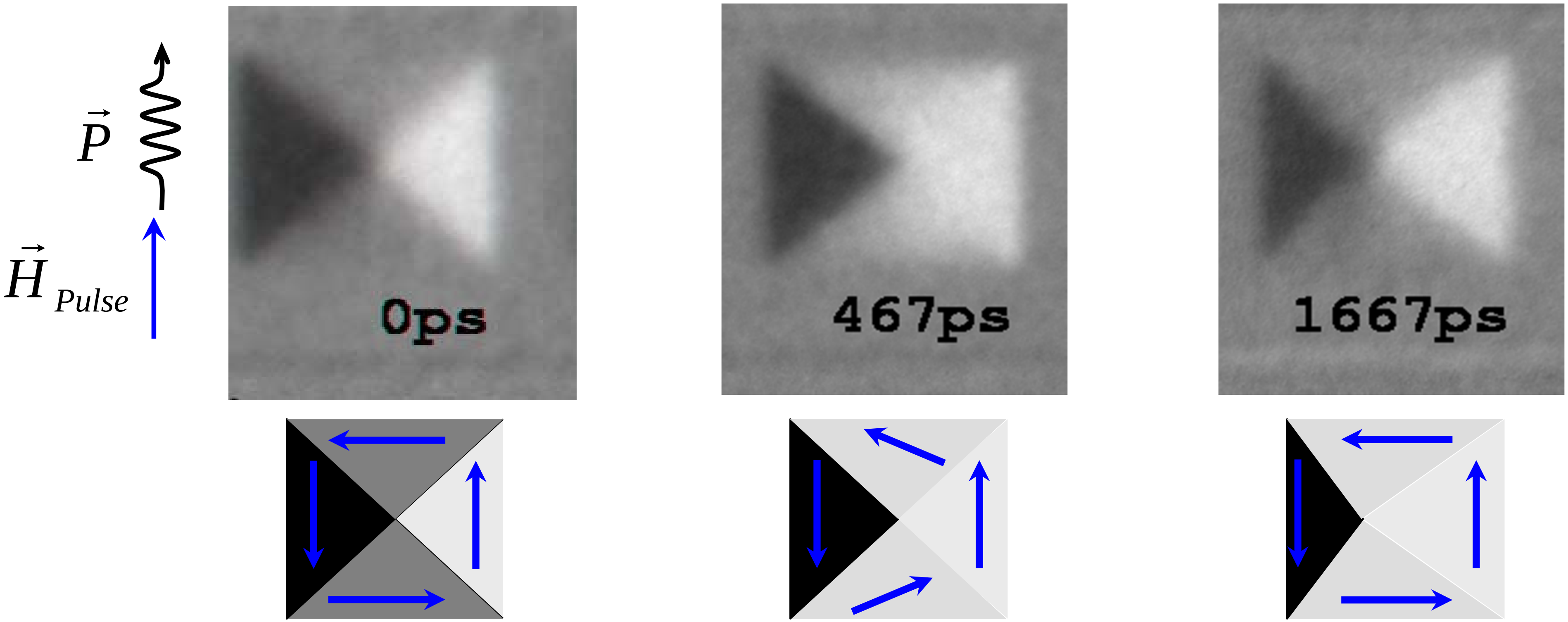


Permalloy ($Ni_{81}Fe_{19}$)
t=30nm
H_p~80 Oe
S040906_015

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

L. J. Heyderman

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)

L. J. Heyderman

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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Transmission X-Ray Microscopy

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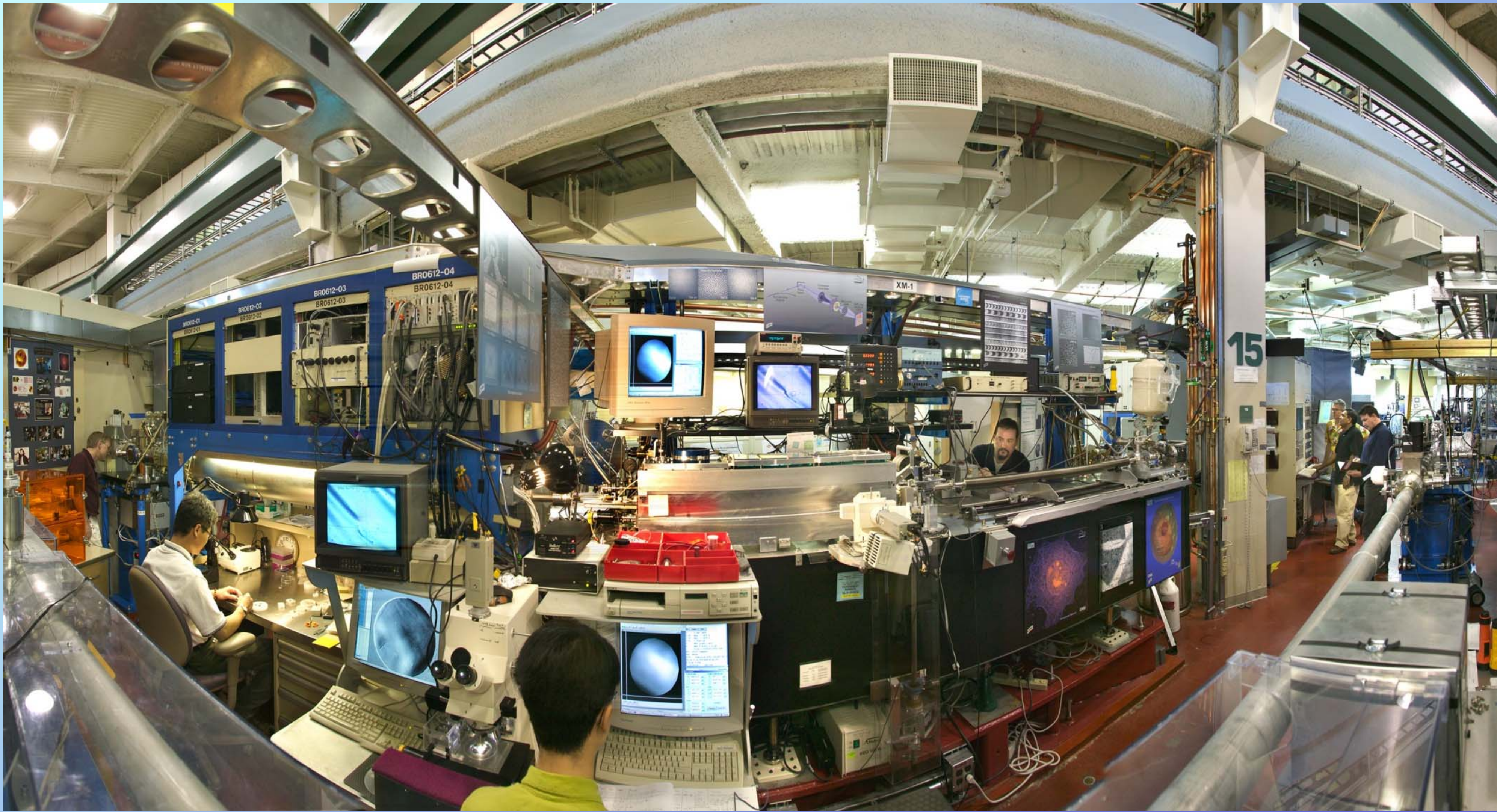
Magnetic Soft X-ray microscopy, ALS



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http://www.cxro.lbl.gov/BL612/

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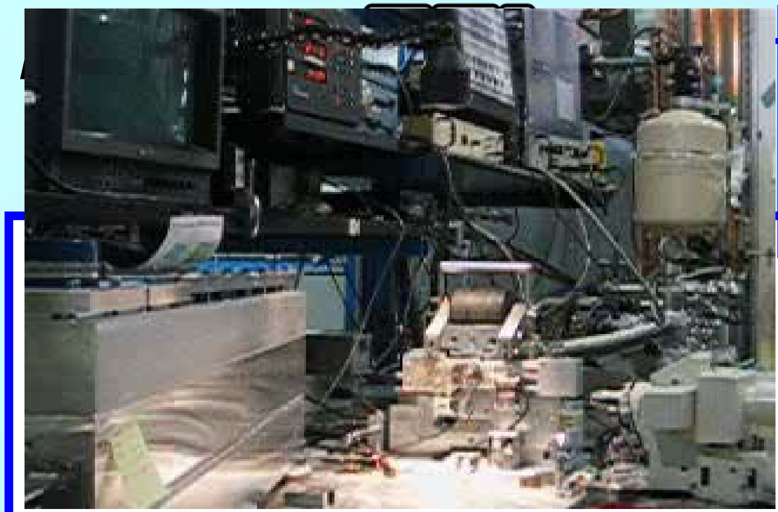
Soft X-ray microscope XM-1, Advanced Light Source



element specificity

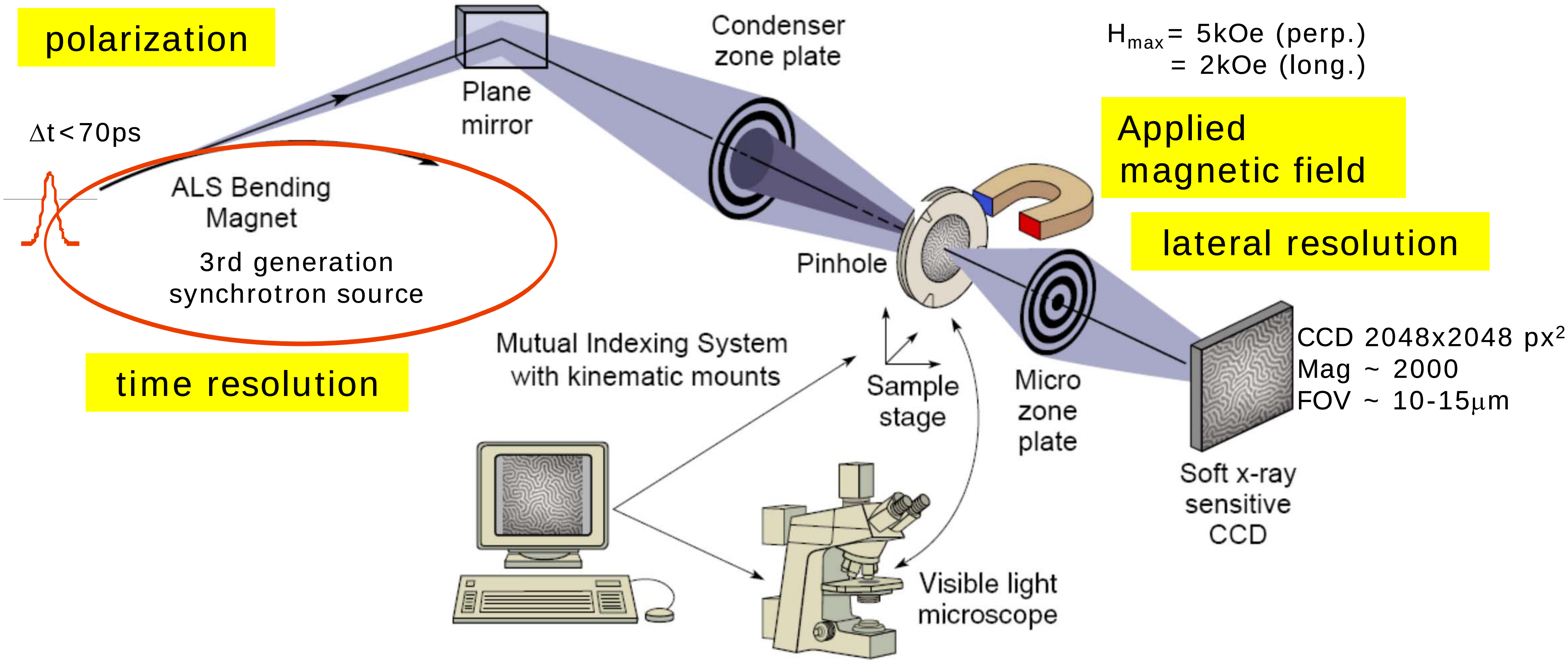
E = 250eV - 1.8 keV
λ= 0.7 nm - 5 nm
$\Delta E/E$=500

polarization

H_{max}= 5kOe (perp.)
= 2kOe (long.)

Applied magnetic field

lateral resolution



time resolution

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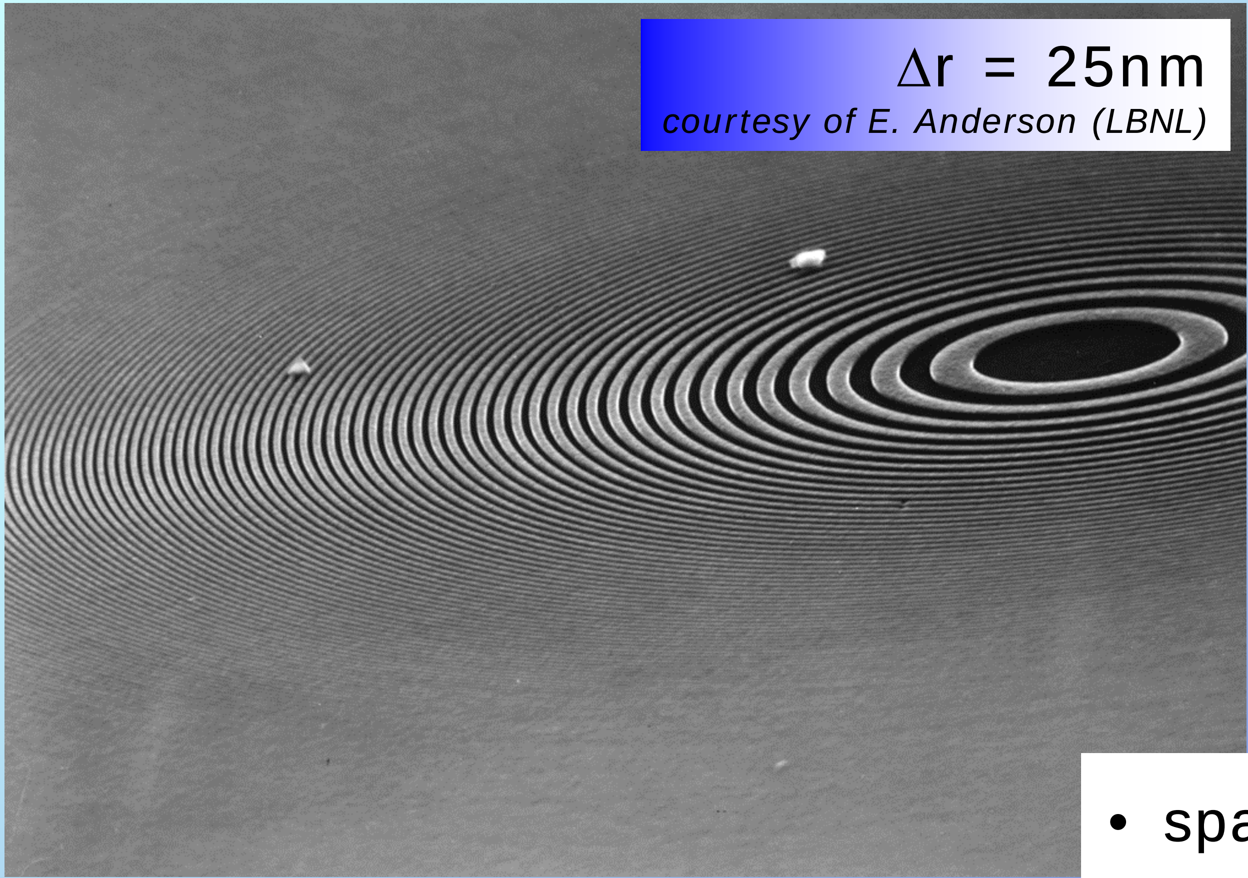
Fresnel Zone Plate Lenses



diffractive optics:

concentric rings

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

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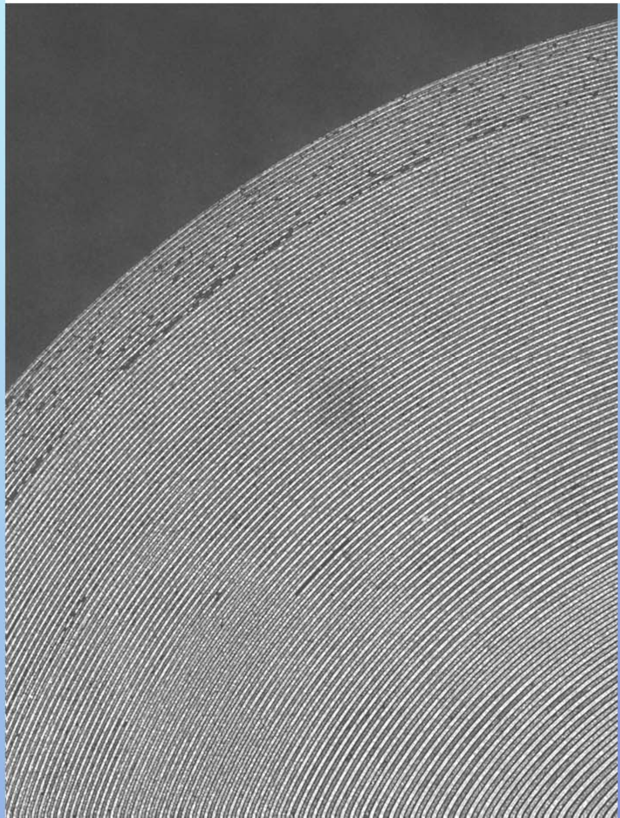
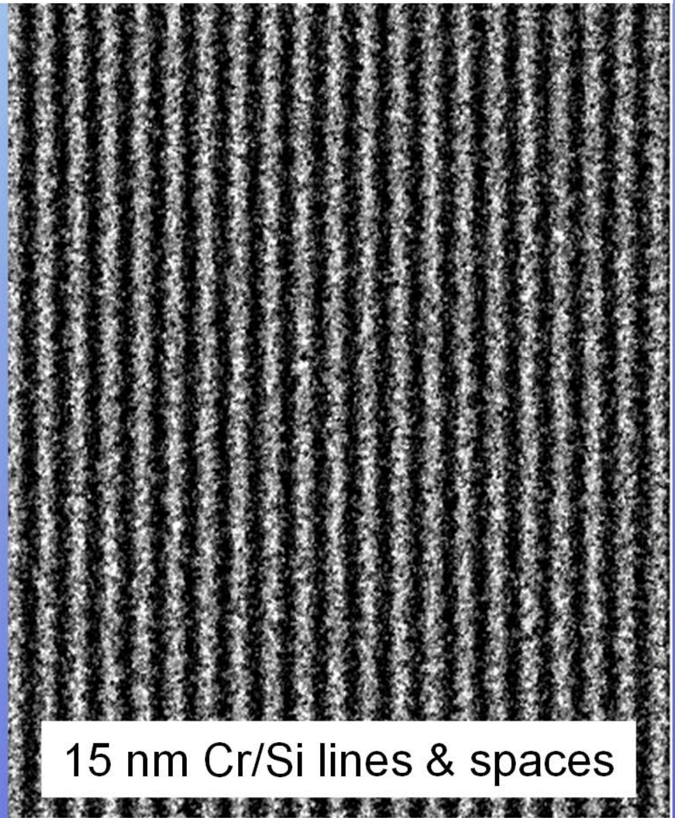
nature Vol 435|30 June 2005|doi:10.1038/nature03719

LETTERS

Soft X-ray microscopy at a spatial resolution better than 15 nm

Weilun Chao[1,2], Bruce D. Harteneck[1], J. Alexander Liddle[1], Erik H. Anderson[1] & David T. Attwood[1,2]





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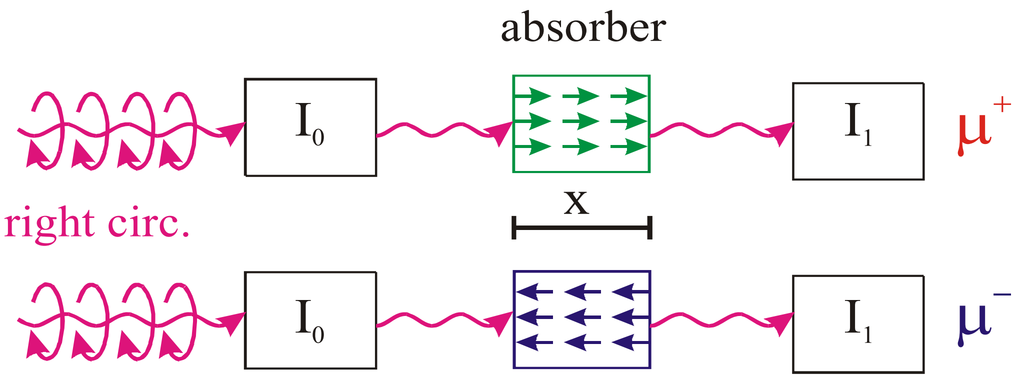
Magnetic absorption contrast

X-ray magnetic circular dichroism

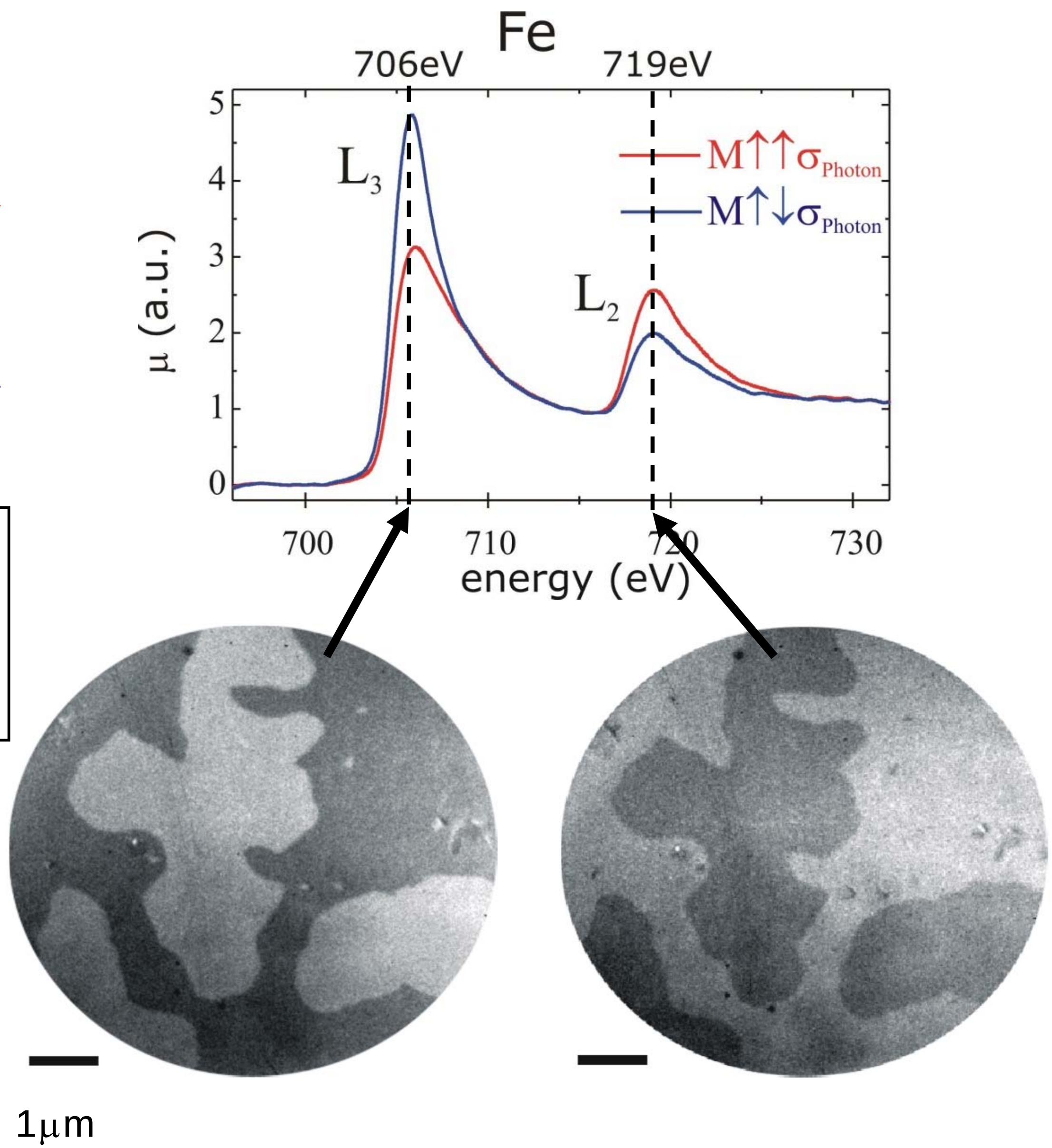


Absorption coefficient

$$(I_1/I_0)^{\pm} = \exp(-\mu^{\pm} x)$$

intensity thickness

- element-specific
- huge magnetic contrast
- $\underline{M} \cdot \underline{\sigma}_{Photon}$ (polarisation vector of photons)
- spin-orbit information



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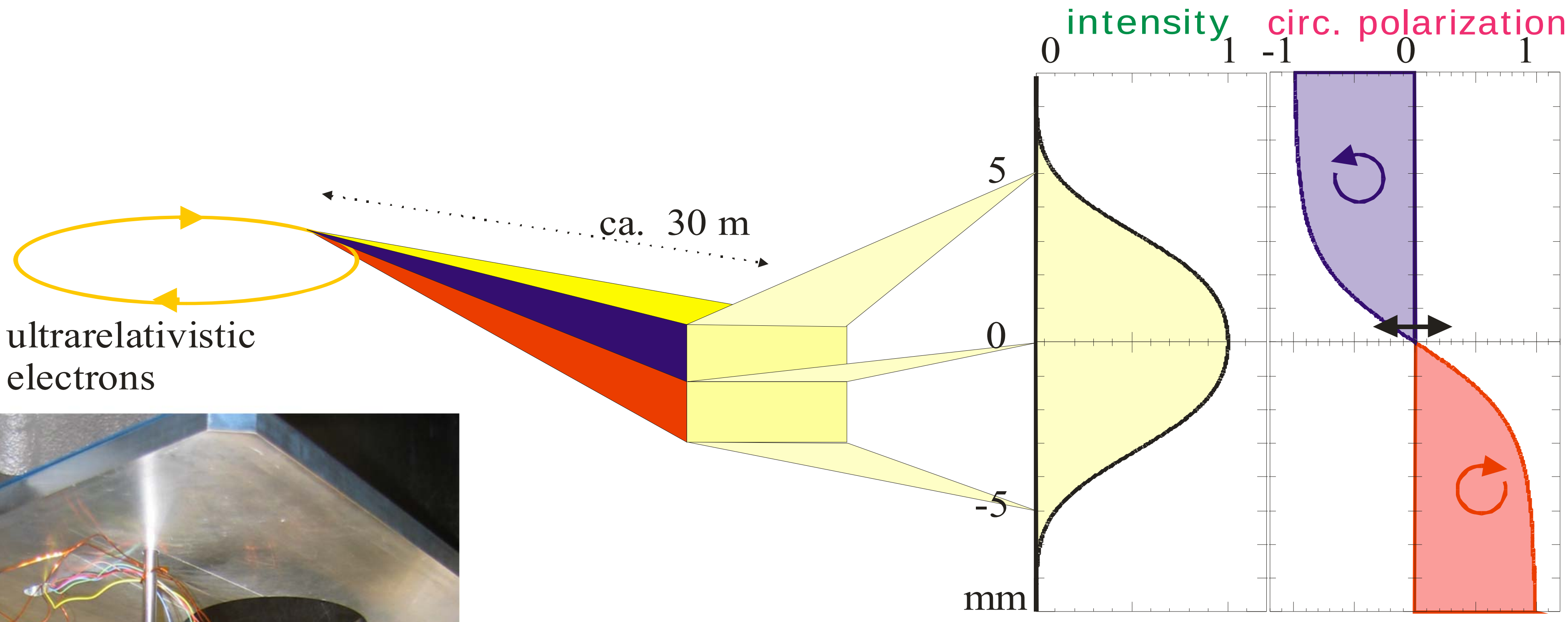
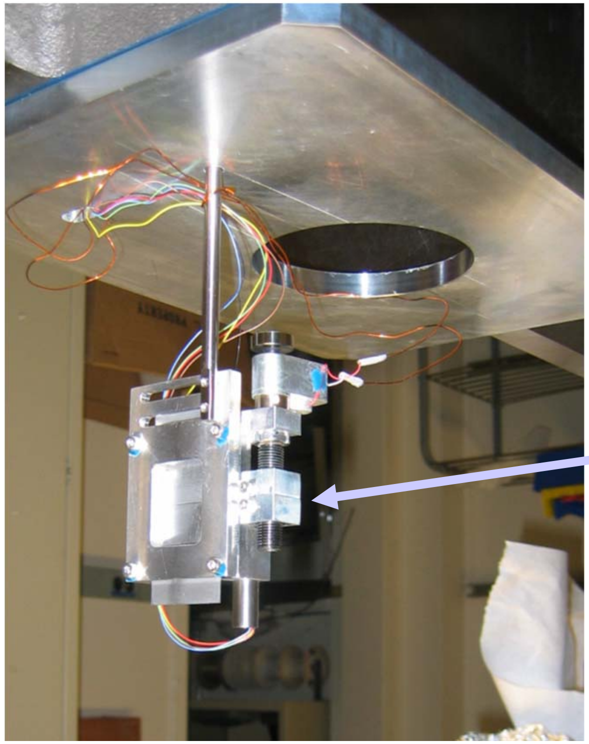
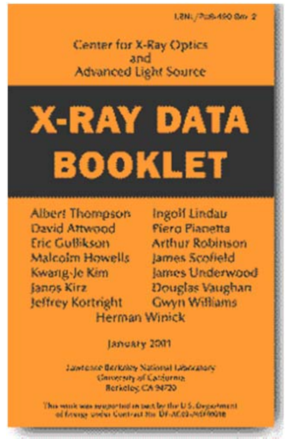
Polarization properties at bending magnet



sect. 2.1 K.-J. Kim



movable and expandable aperture



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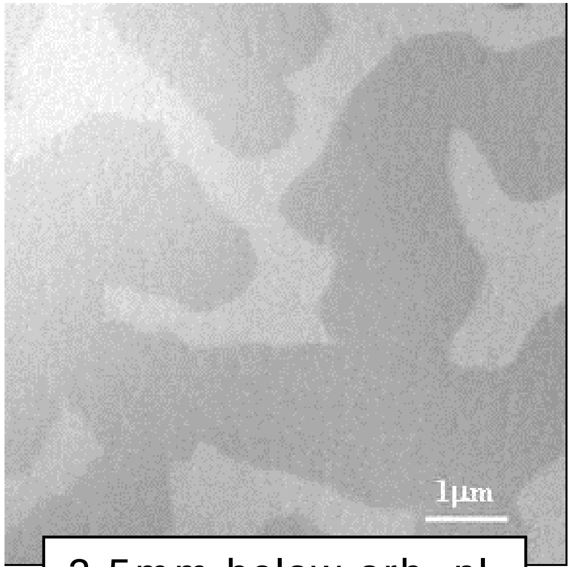
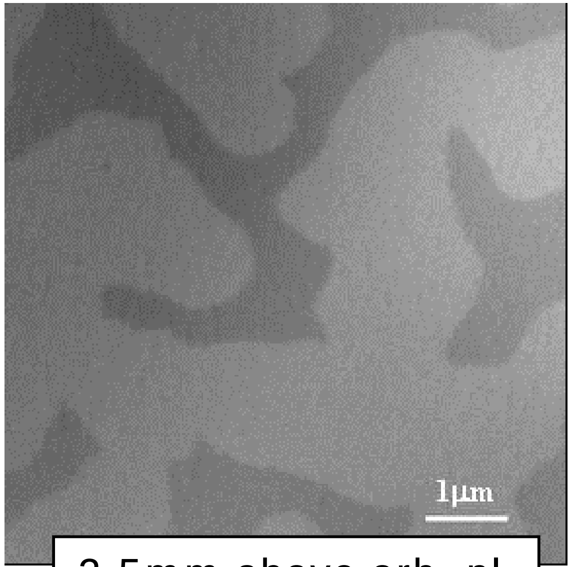
Modulation of circ. polarization

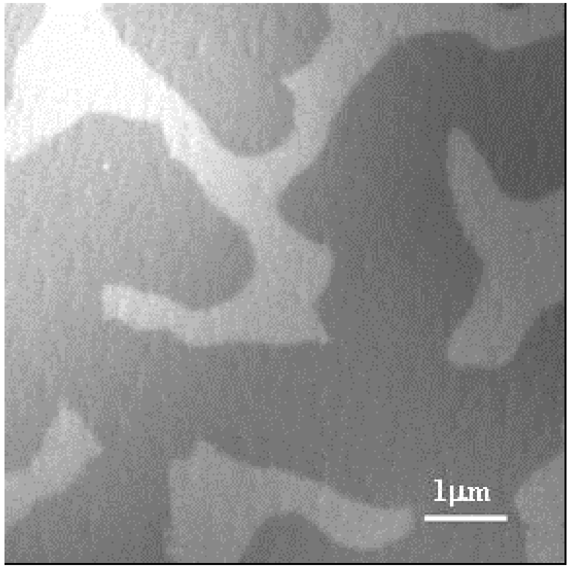


2.5mm below orb. pl.



2.5mm above orb. pl.

- reducing non-magnetic background
- increase magnetic contrast

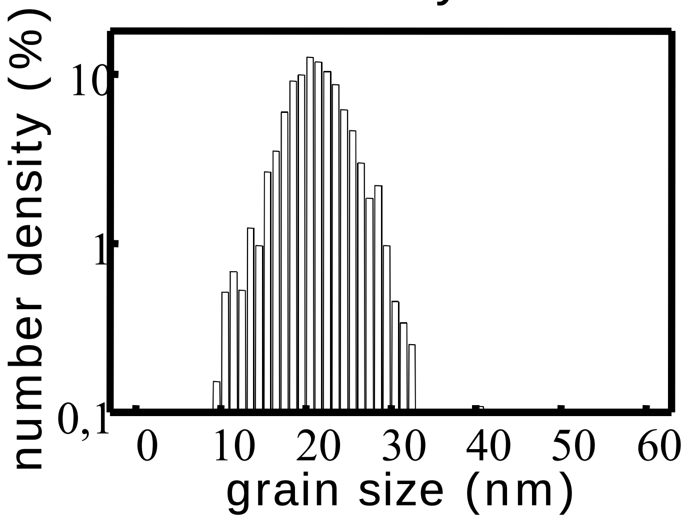


*B.-S. Kang et al., J Appl. Phys **98** (2005) 093907*

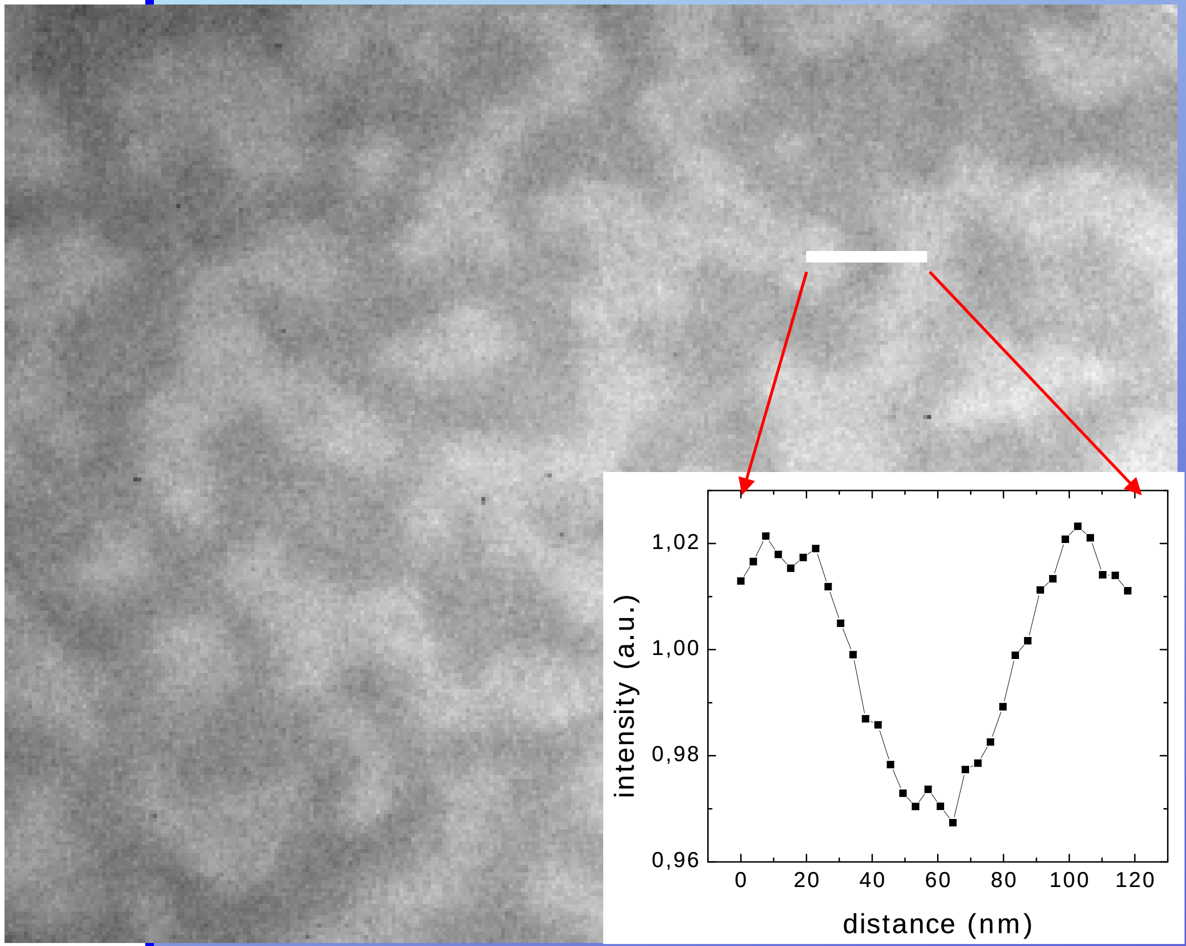
Magnetic imaging at 15 nm resolution

sample:
$(Co_{84}Cr_{16})_{87}Pt_{13}$ (50nm)

TEM analysis



► imaging at fundamental magnetic length scales



Co L_3 edge @777eV

D.-H. Kim et al., J. Appl. Phys. 99, 08H303 (2006)

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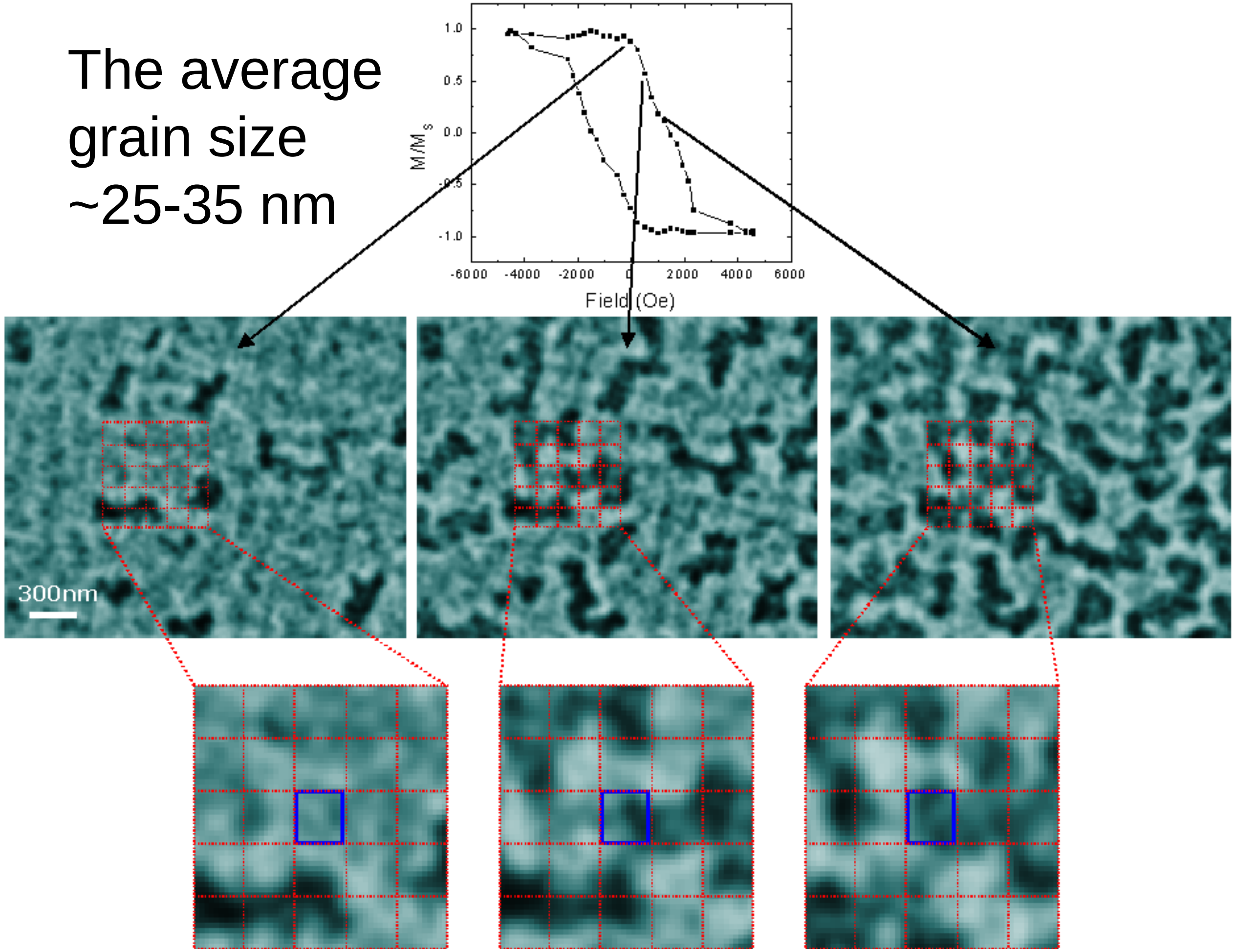
Reversal at the nanogranular scale

- CoCrPt alloy films: possible high-density magnetic recording media:
  - strong perp. anisotropy
  - low media noise: exchange decoupled at grain boundaries

- Dark & white areas correspond to regions where the Co magnetization is pointing in and out.

The average grain size ~25-35 nm

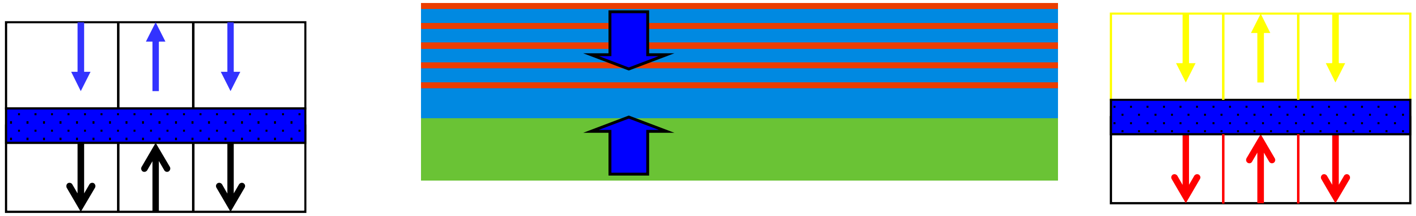


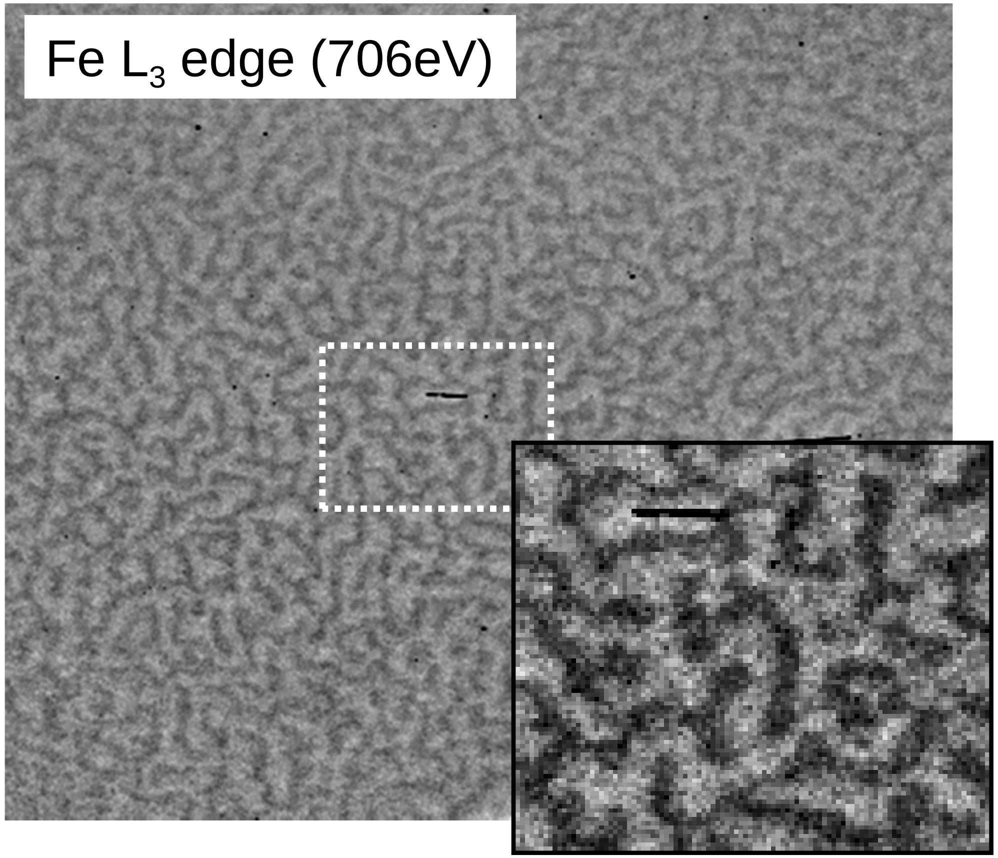
Details of magnetization reversal for each grain: closely related to the size, irregularity, and stability of written domains.

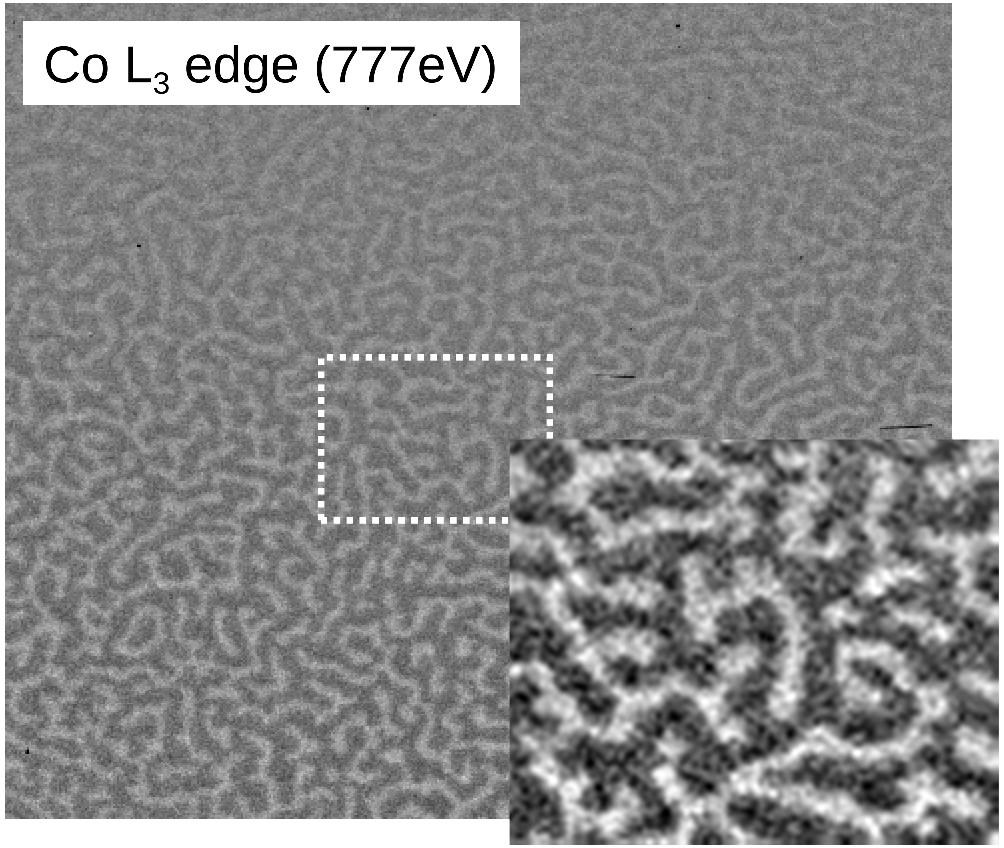
D.-H. Kim et al., J. Appl. Phys. 99, 08H303 (2006)

Layer resolution via element specificity

Pt/[Pt 0.75nm/**Co 0.35nm**]$_{50}$/Pt 3nm/Tb$_{45}$**Fe$_{55}$** 25nm)/Pt 5nm







w/ S.Mangin, A. Berger, E. Fullerton (HITACHI/Almaden) (2005)

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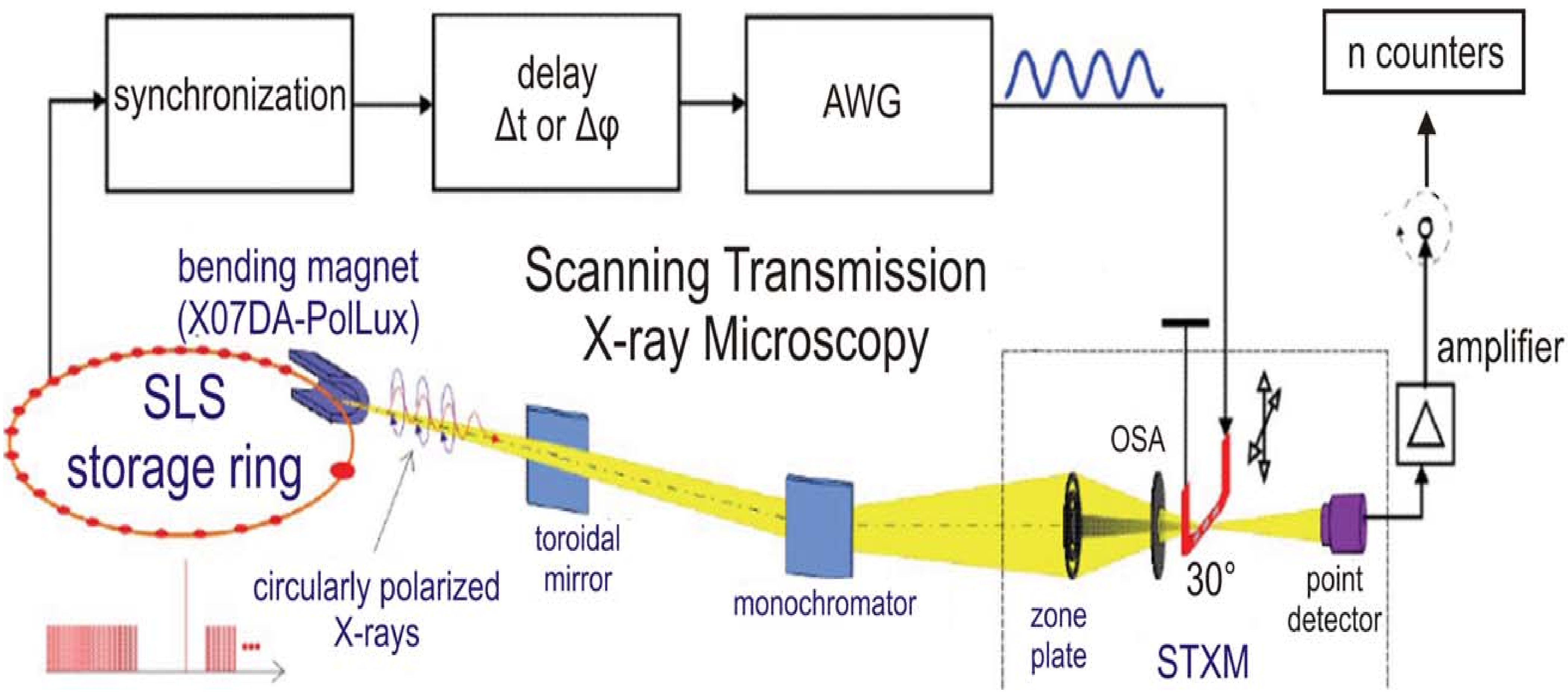
Time Resolved Imaging with STXM



PolLux Beamline, Swiss Light Source

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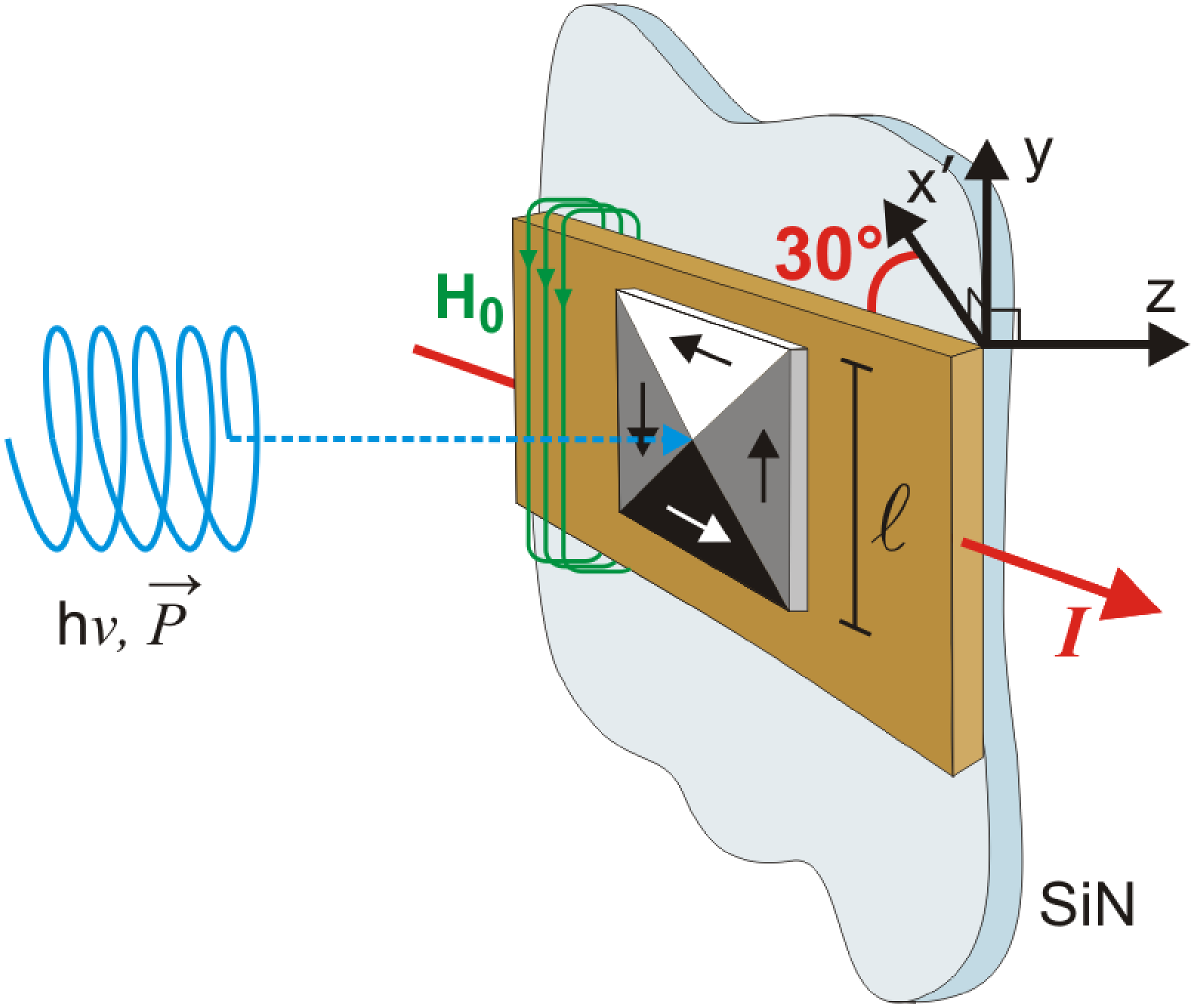
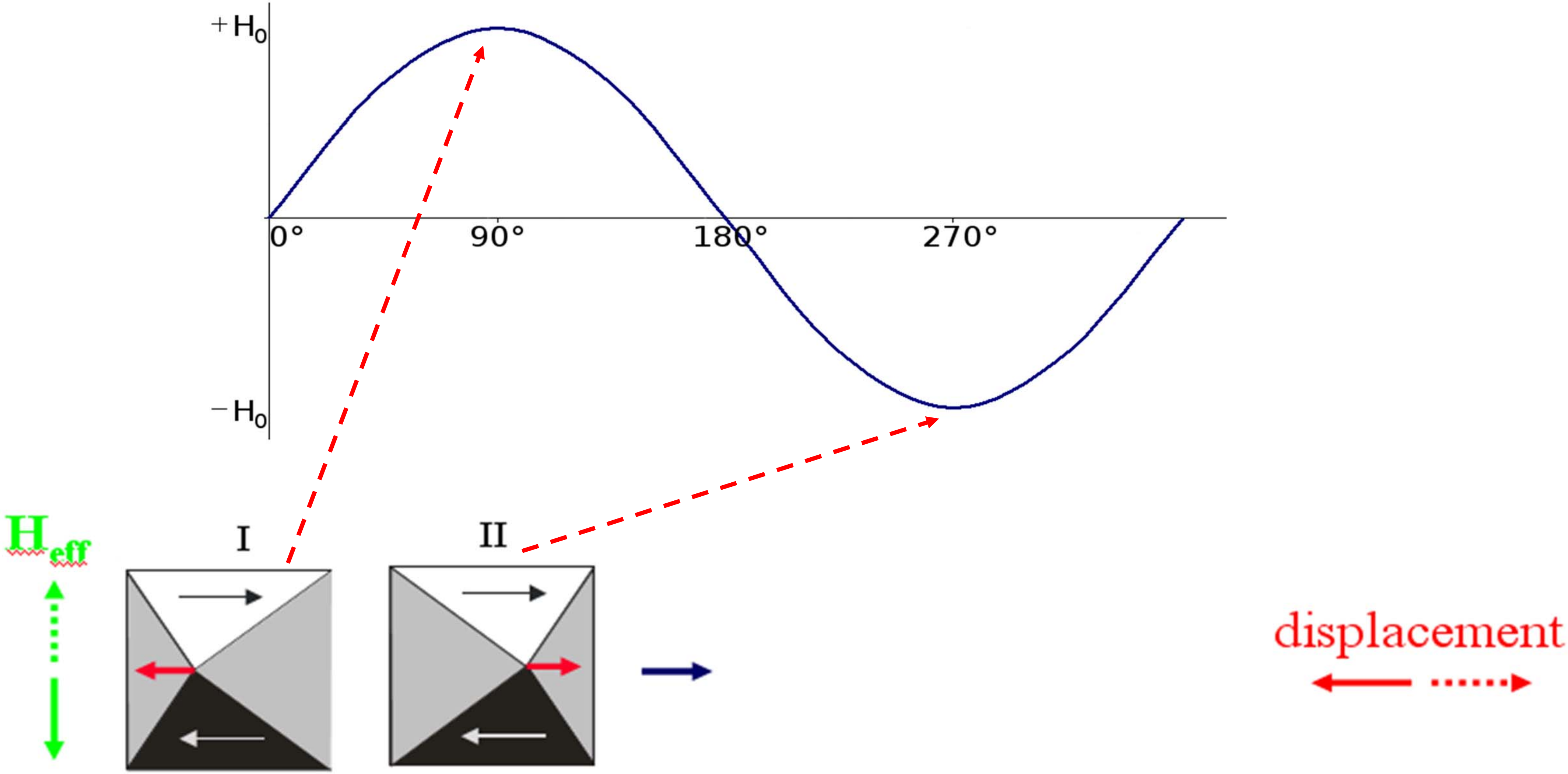
Towards fundamental time scales

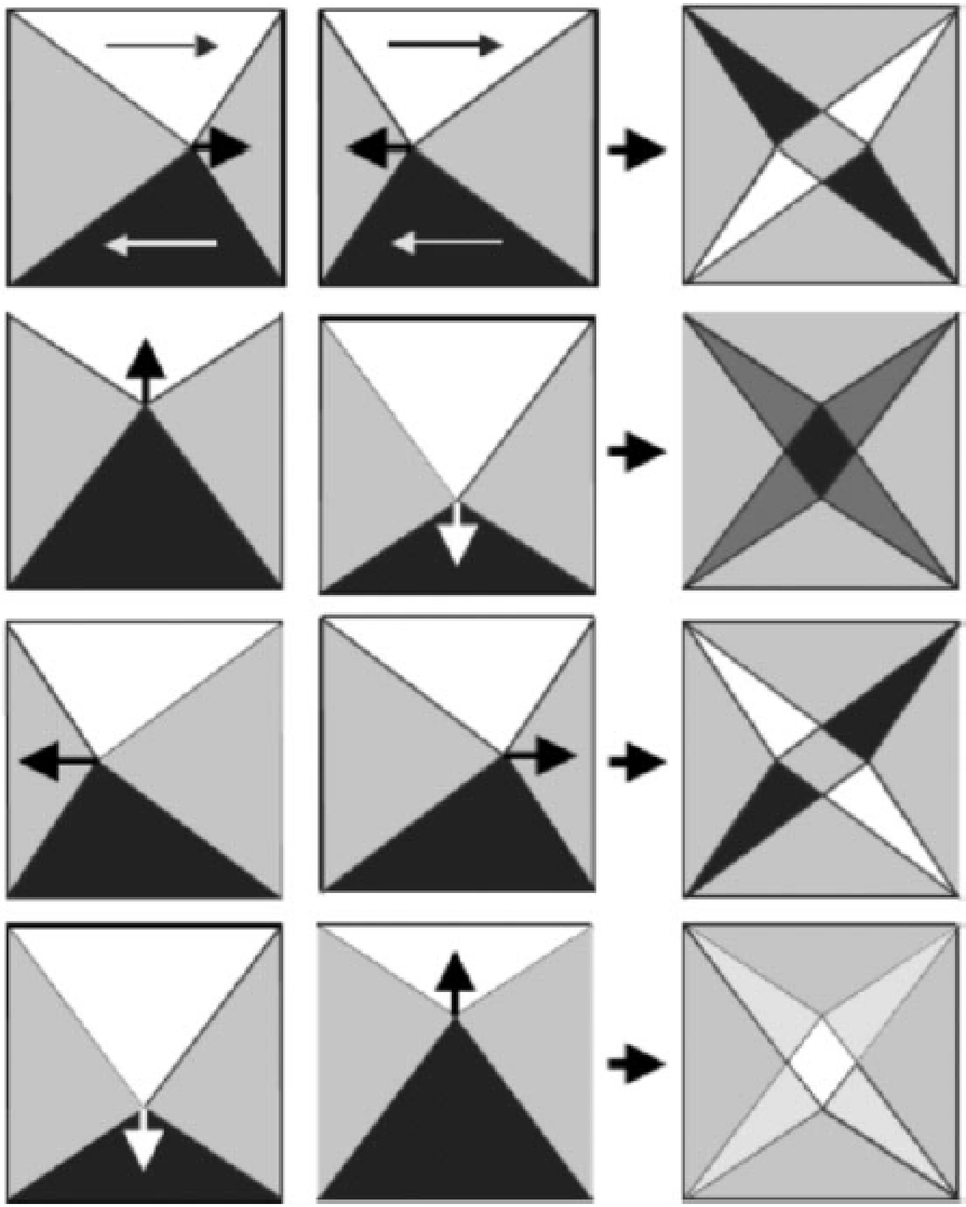


S. Stevenson et al. PRB (2013)

Dynamic Differential Imaging



Towards fundamental time scales

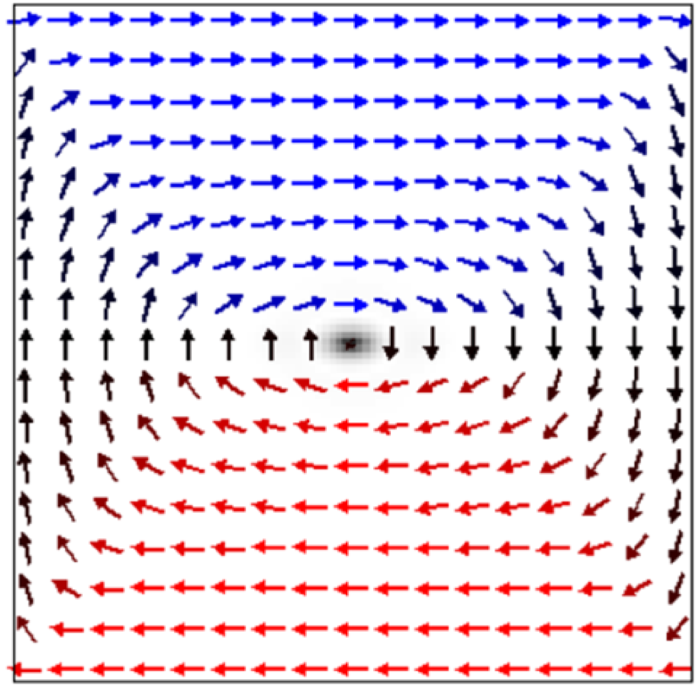


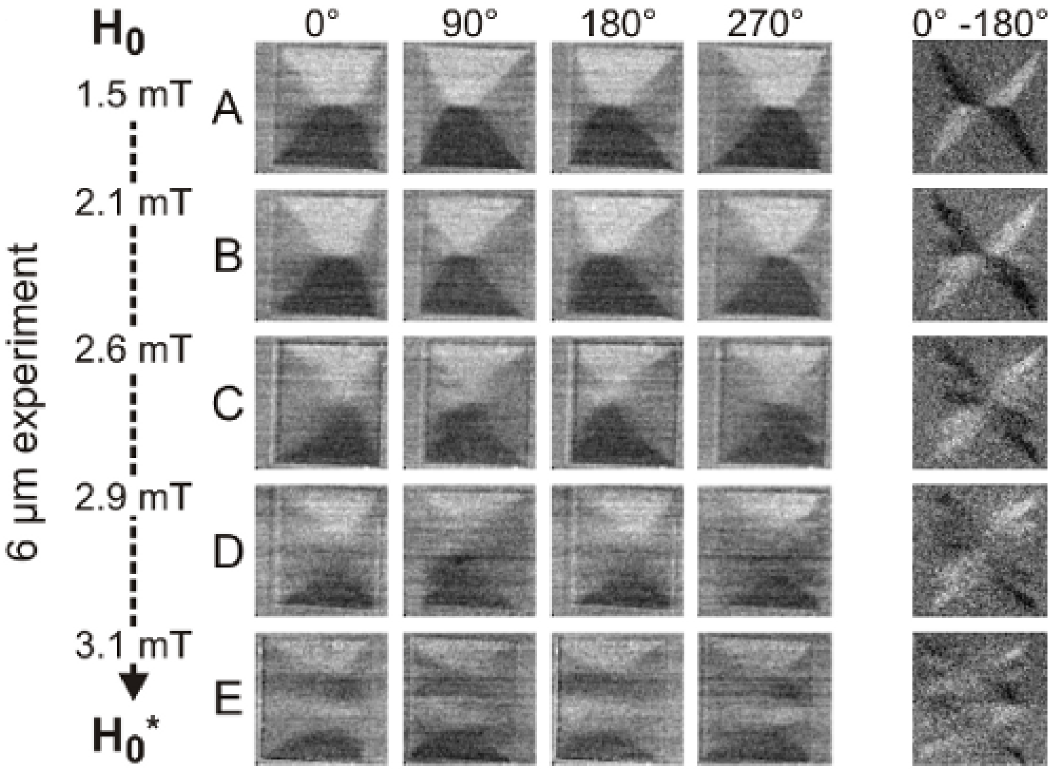
Puzic et al.
JAP 2005

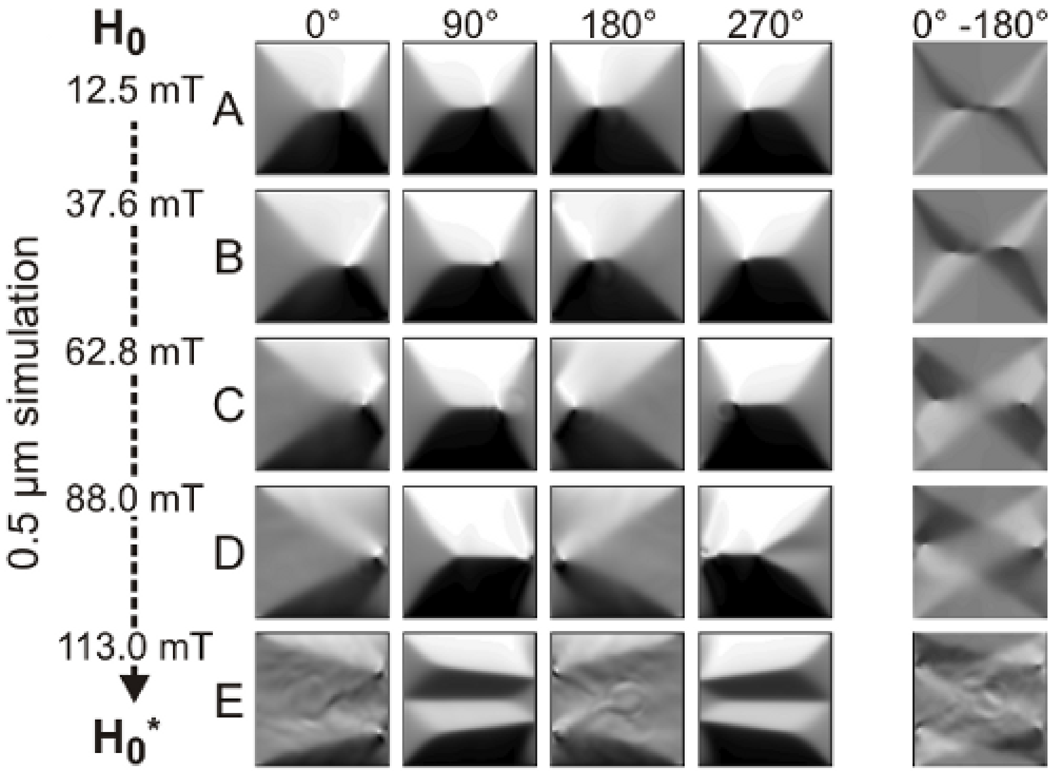
Dynamic Differential Imaging

S. Stevenson et al.
PRB 2013

6 µm







Summary

- Element selective (multilayer, coupled systems)
- Sample can be in air or HV
- Spatial resolution currently down to below 15 nm
- Sensitivity to out-of-plane magnetisation, but sample can be tilted
- Image in applied fields
- Time resolved measurements

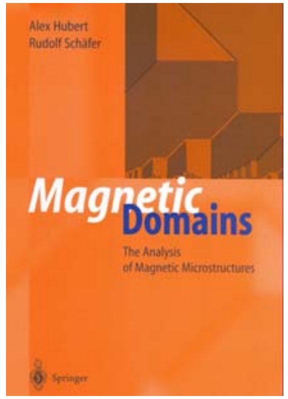
Some Challenges (limitations):

- X-ray damage
- Sample must allow transmission of x-rays

Conclusion

Information on Different Methods

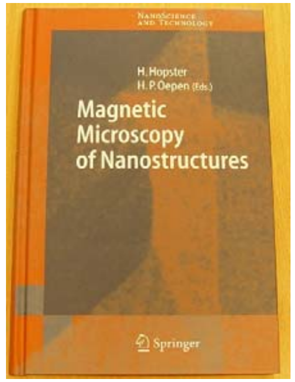
A. Hubert and R. Schäfer, Magnetic Domains
The Analysis of Magnetic Microstructures



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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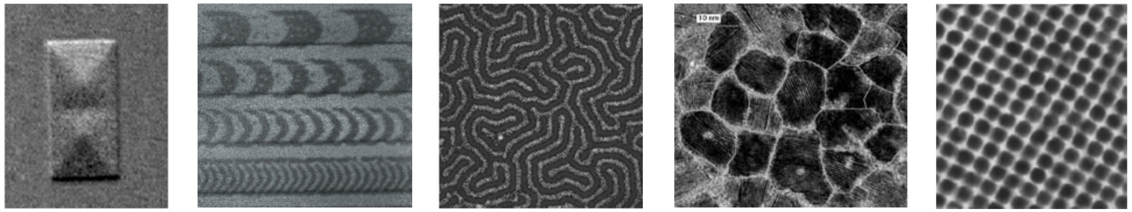
Future Challenges



µm → nm

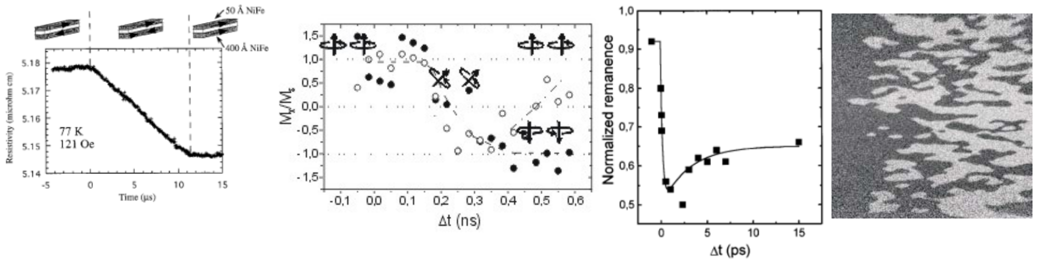
Spatial Resolution

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

Time Resolution

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

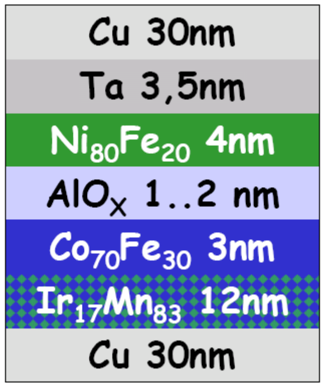
ns → ps → fs



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

- Future challenge: fs time scale (times associated with exchange interactions, spin fluctuation rates)
- 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

Elemental Sensitivity



magnetic tunnel junction

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