

Photoelectron Emission Microscopy (X)PEEM

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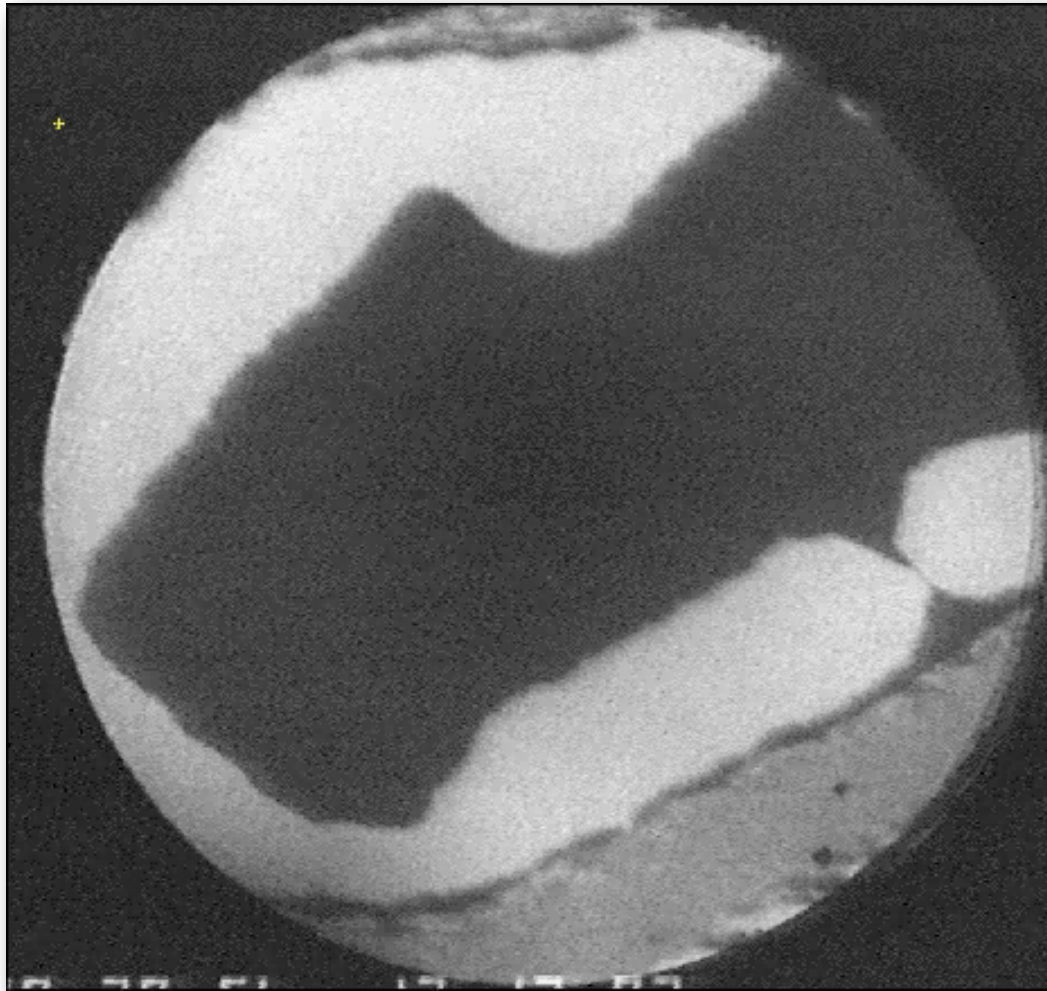
- Introduction and motivation
 - Immersion lens microscopy
 - Contrast mechanisms
 - Chemical selectivity
 - Magnetic sensitivity
 - Energy filtering
 - Aberration correction



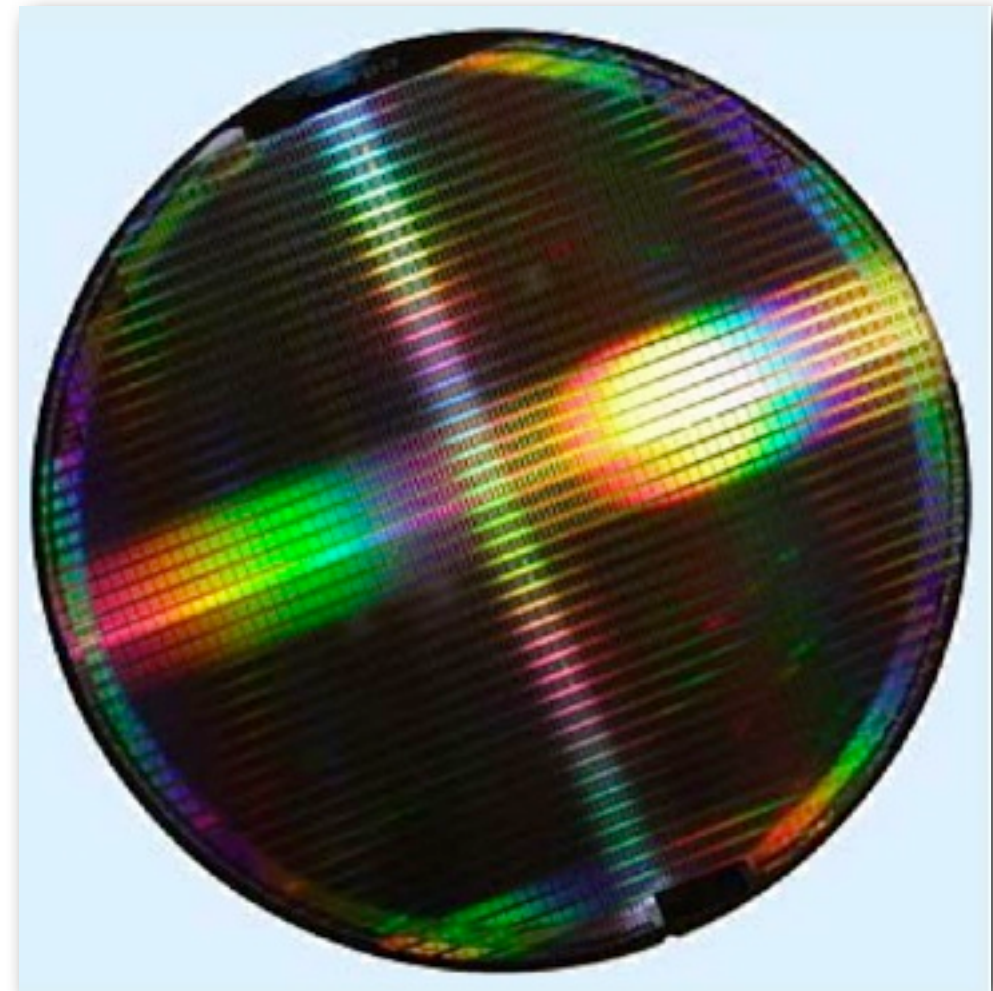
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surface physics



wafer analysis



- fundamental problems on the nanoscale
- growth – morphology – catalysis – surface chemistry ...
- chemical selective analysis with high lateral resolution
- microelectronics – magnetism – spintronics ...



- ◆ chemical selectivity
- ◆ surface sensitivity
- ◆ arbitrary samples
- ◆ information depth
- ◆ high lateral resolution
- ◆ fast image acquisition
- ◆ magnetic sensitivity
- ◆ time resolution

X
P
E
E
M

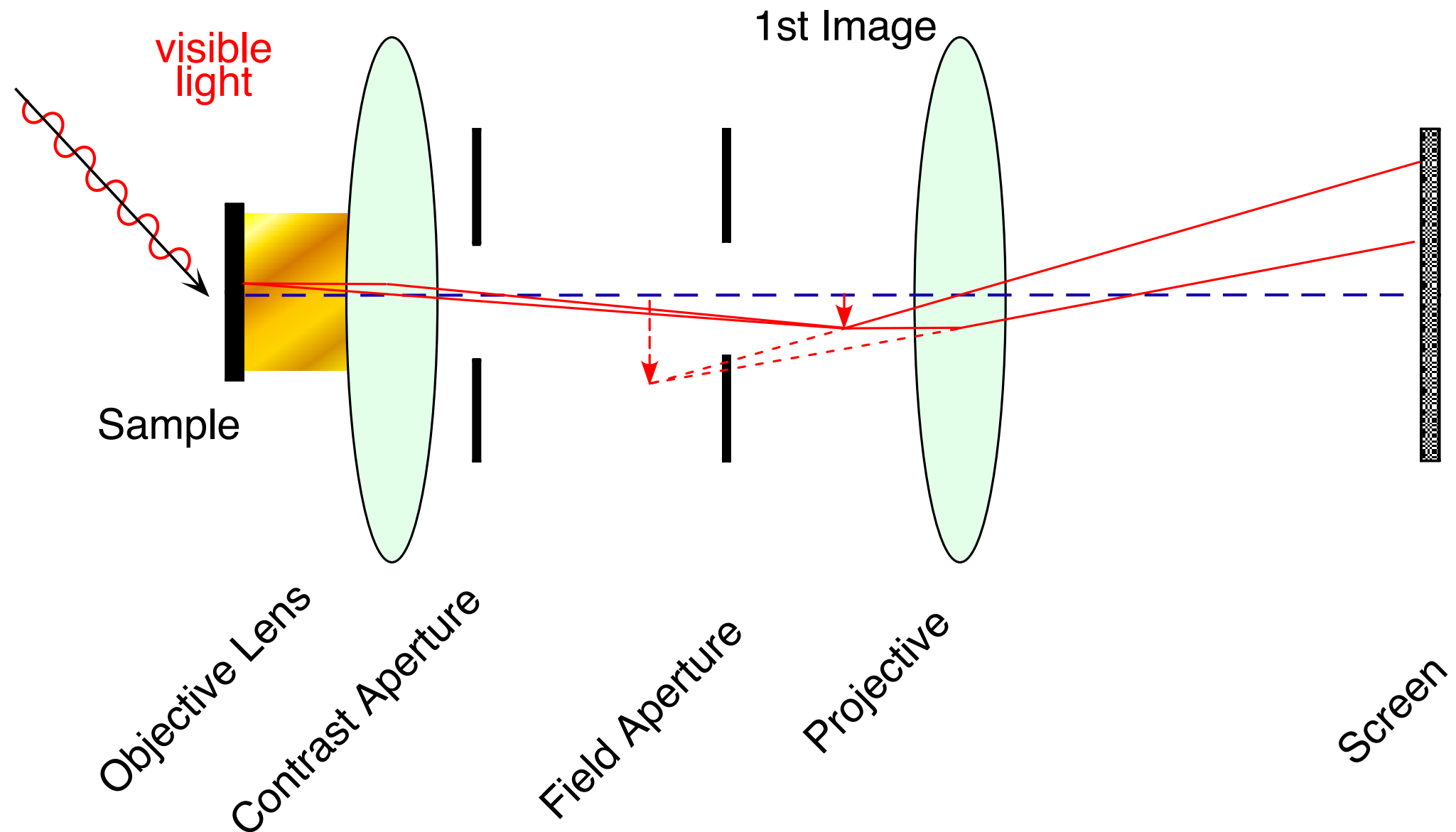
- core level excitation
- electrons as carriers
- cascade processes
- adapted electron optics
- parallel imaging
- MXCD, MXLD
- photoexcitation

X-Ray Photoelectron Emission Microscopy

C.M. Schneider and G. Schönense, Rep. Prog. Phys. **65** (2002) R1785



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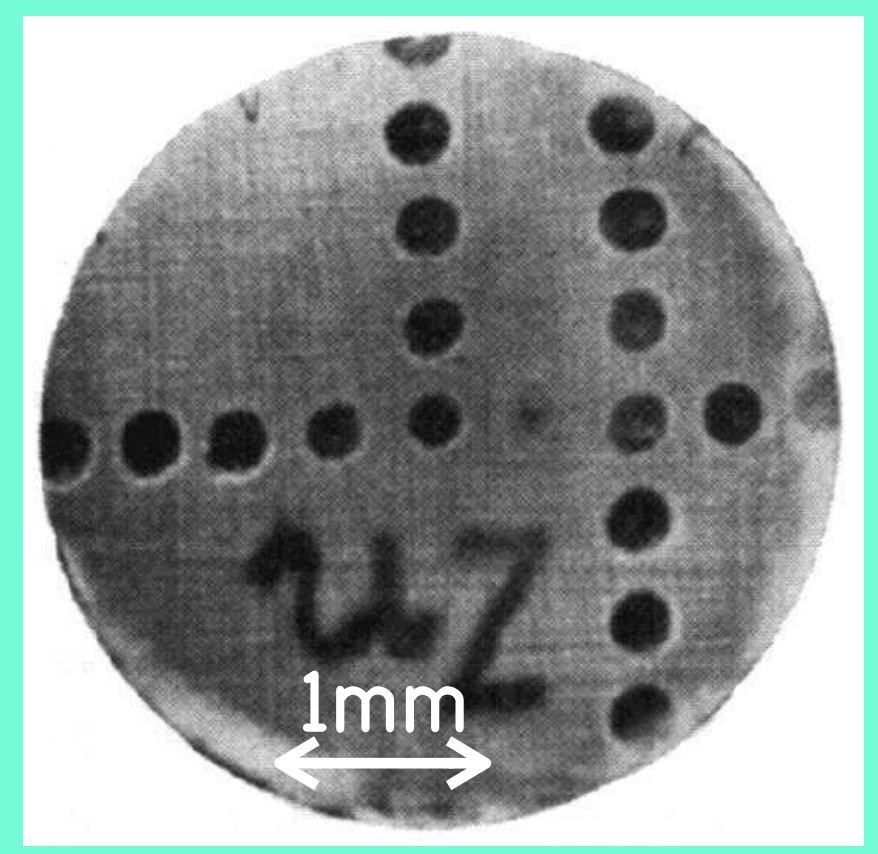
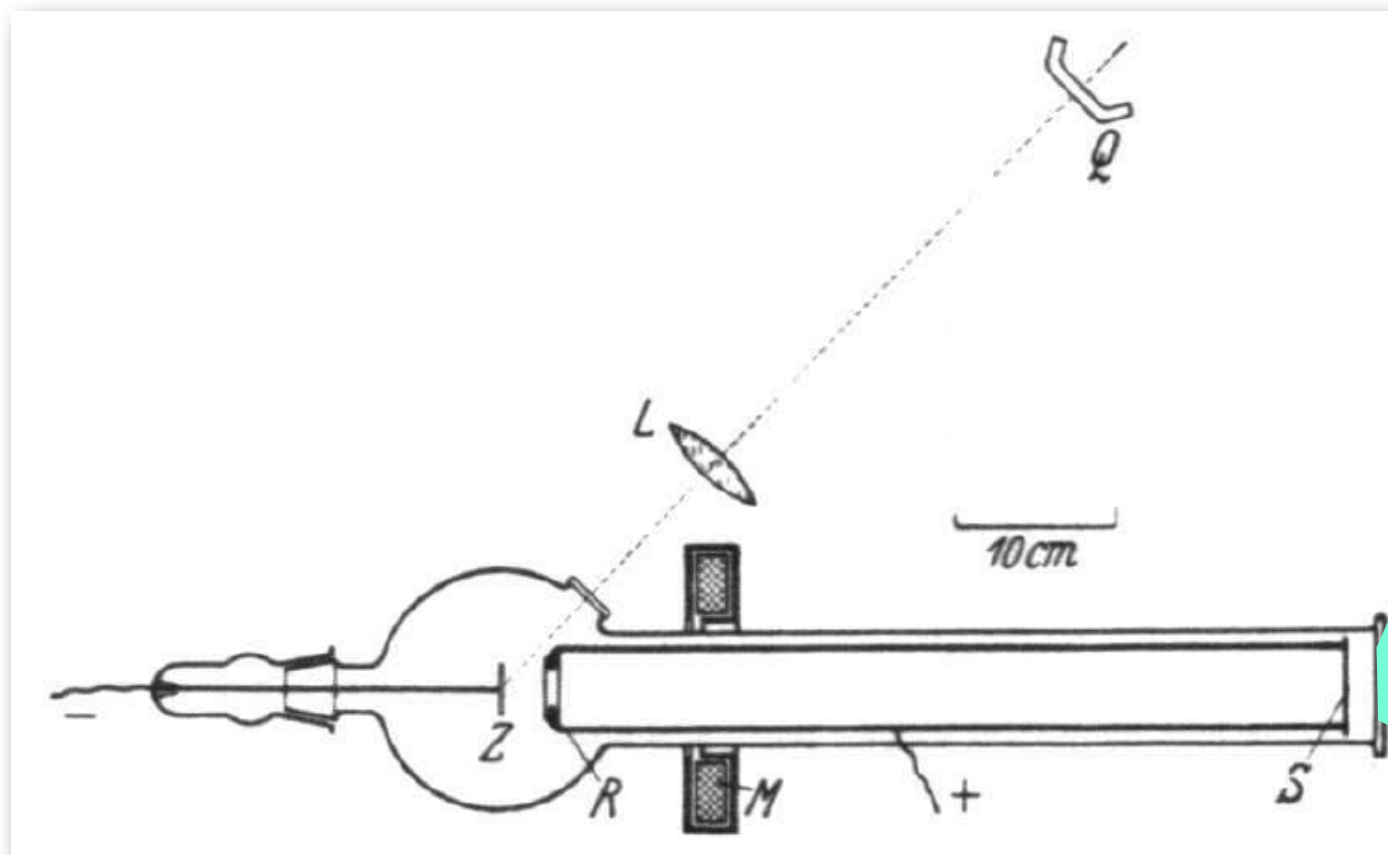
- immersion lens concept
- close distance, immersion fluid with high n
- increase of numerical aperture

(Aus dem Forschungs-Institut der AEG.)

Elektronenmikroskopische Abbildung mit lichtelektrischen Elektronen.

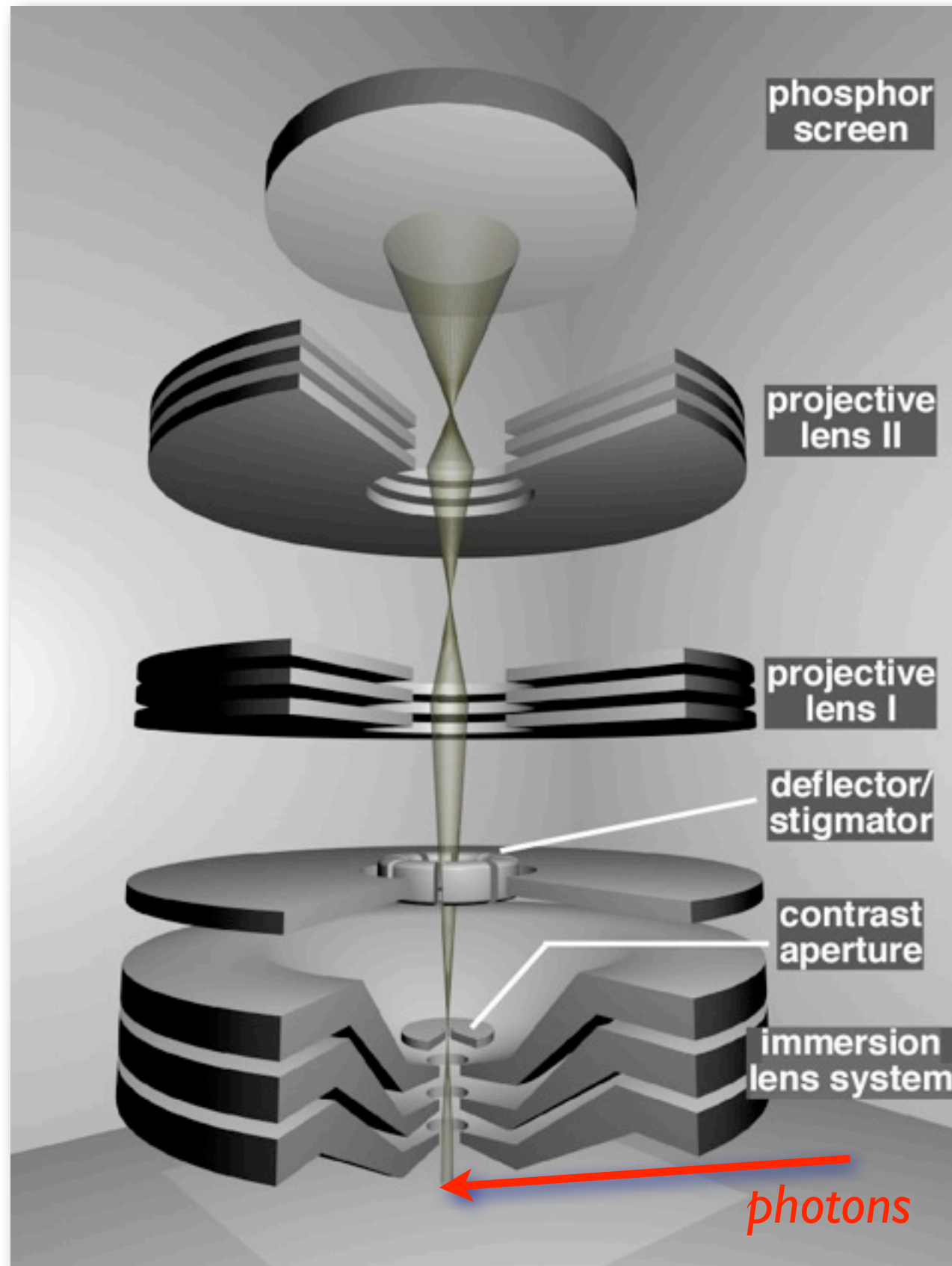
Von E. Brüche in Berlin-Reinickendorf.

E. Brüche, Z. Phys. 86, 448 (1933)

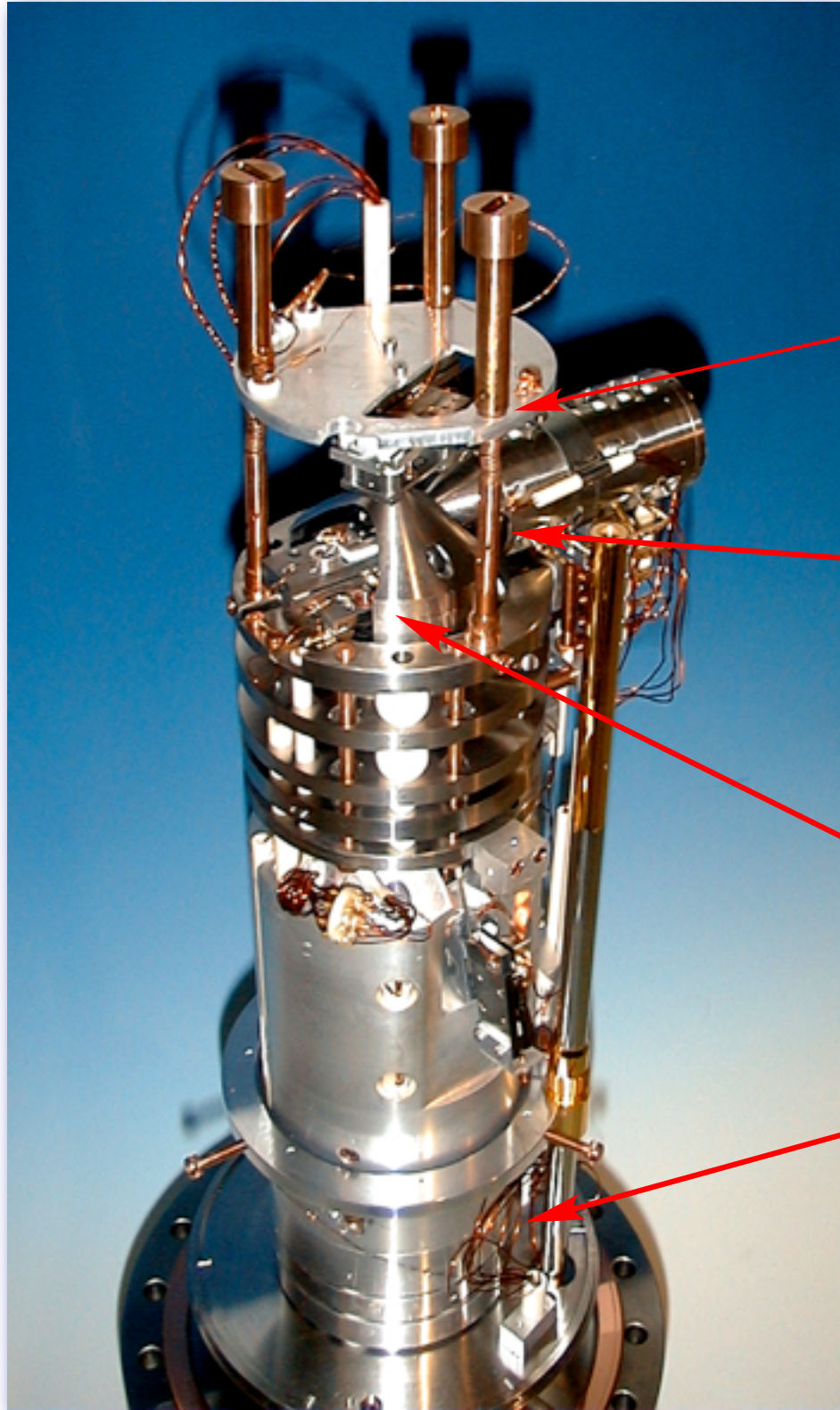


➤ holes in Zn metal plate

Immersion lens microscope II



PEEM column and objective lens

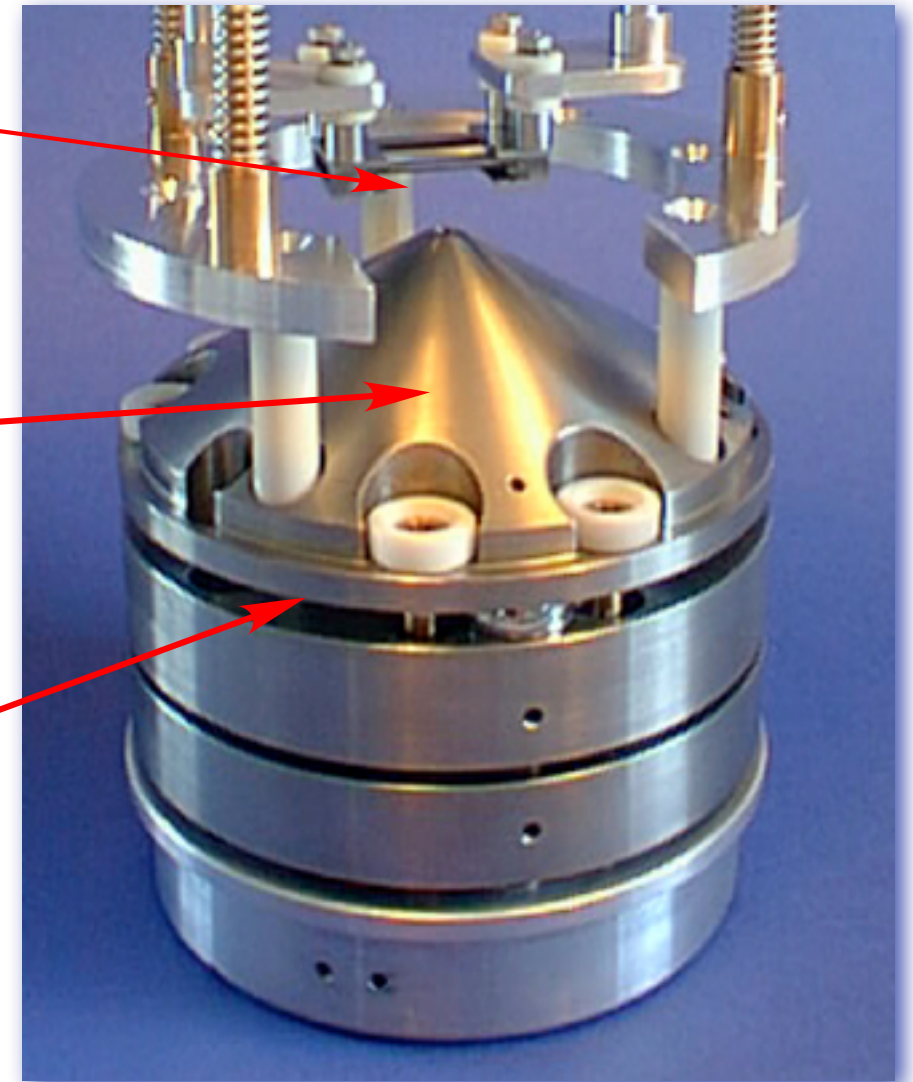


sample holder
with x,y table

objective lens

contrast
aperture
manipulator

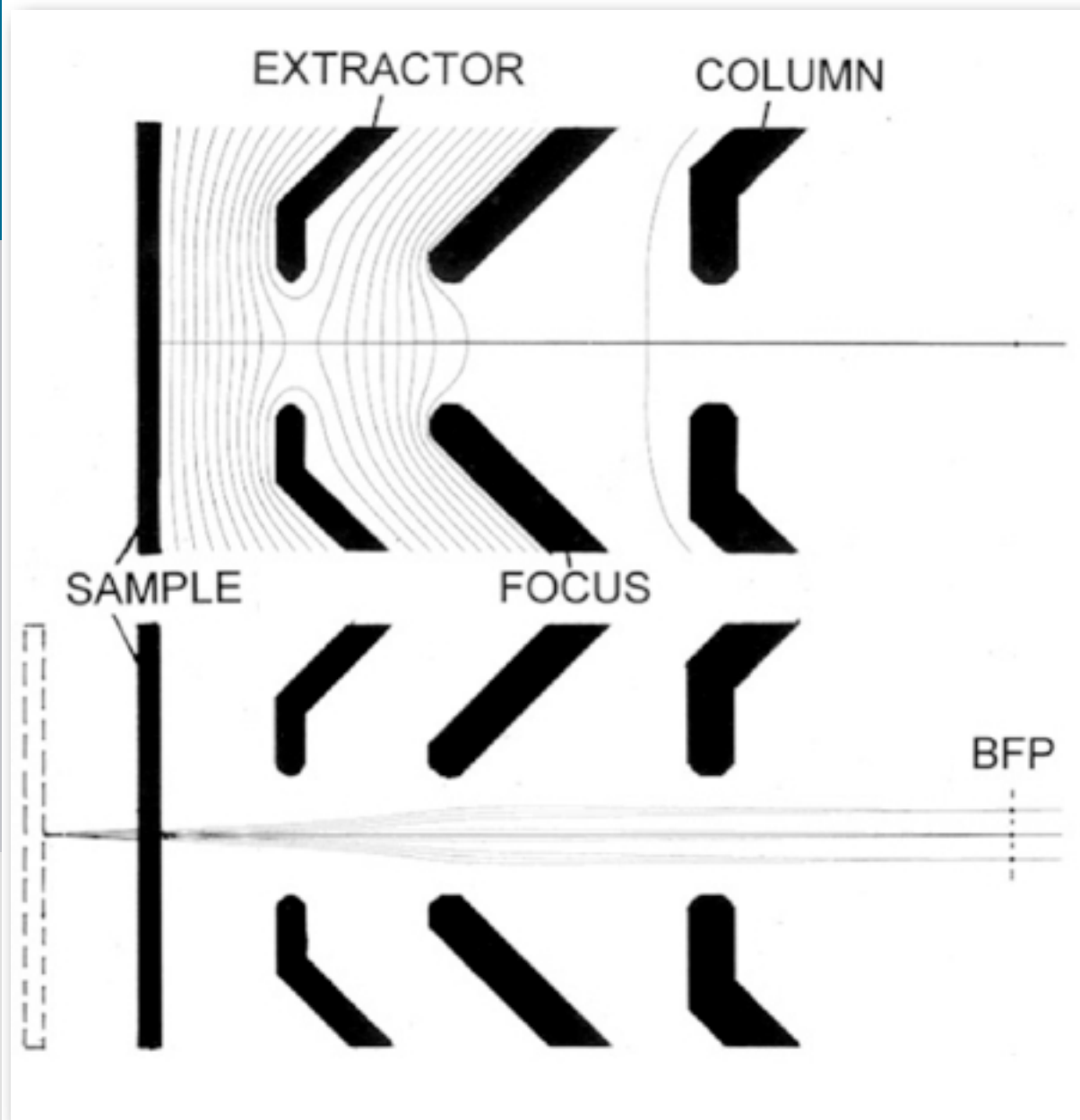
projective I



- modified PEEM set-up
- additional refraction lens
- additional electron gun with reflector crystal



high-resolution mode
(tetrode lens)

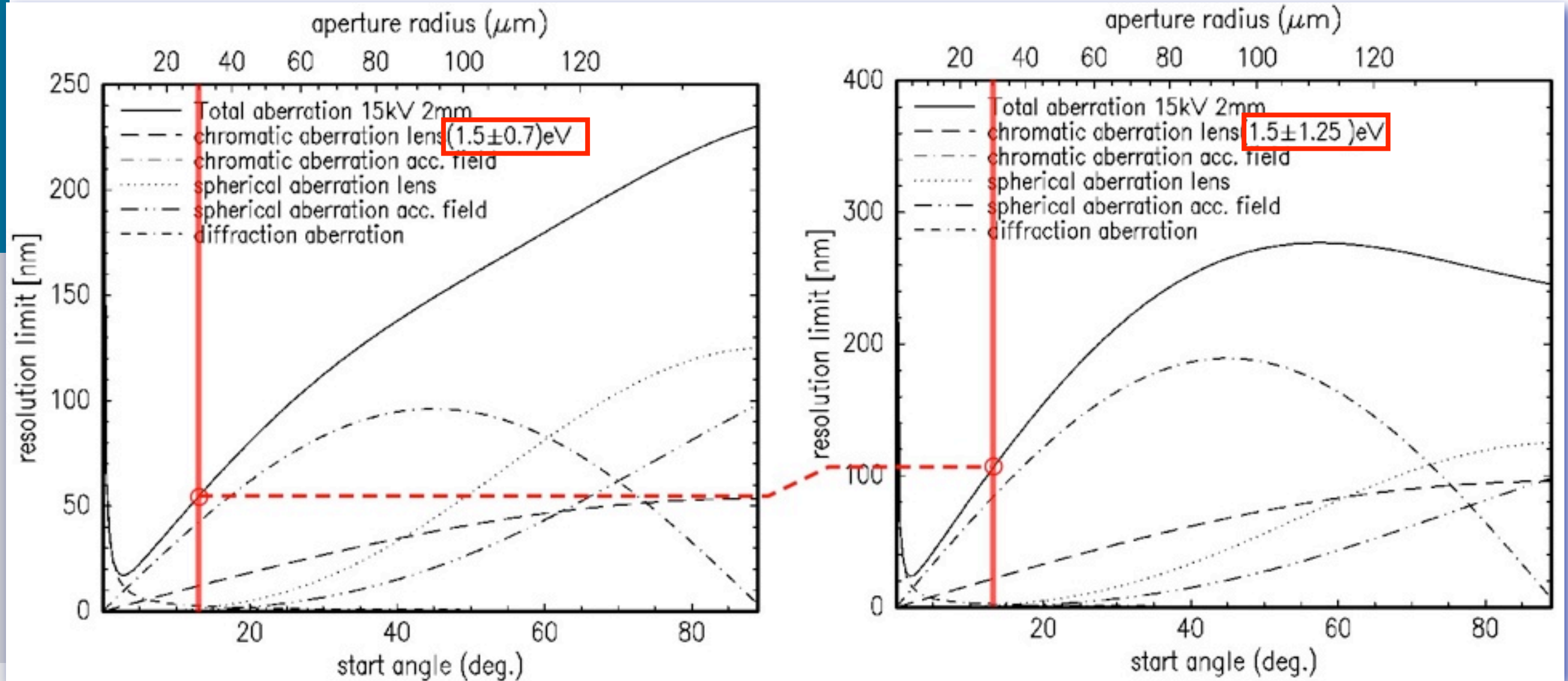


survey mode
(triode-like lens)

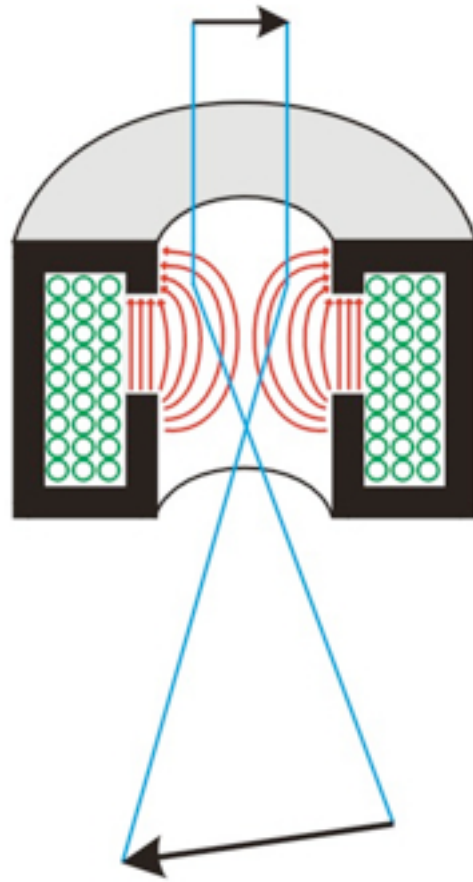


- sample on ground
- lateral resolution vs. field of view (FOV)
- survey mode: FOV $\sim 500\mu\text{m}$
- high-resolution mode: FOV $\sim 20\mu\text{m}$

G. Schönhense, *J. Phys.: Condens. Matter* **11** (1999) 9517



- ◆ 30 μm contrast aperture
- ◆ increase of energy window 0.7 eV to 1.25 eV
- decrease of lateral resolution by almost a factor of 2!
- main contribution: chromatic aberration



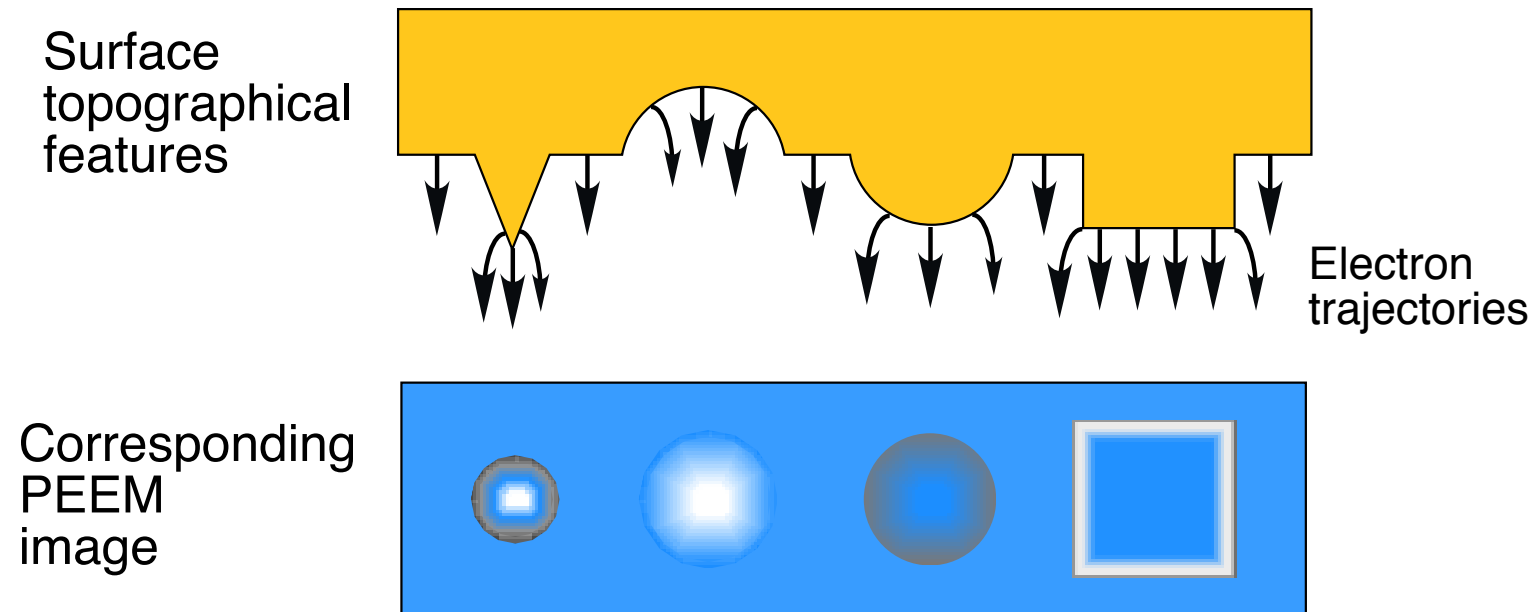
Elmitec PEEM III



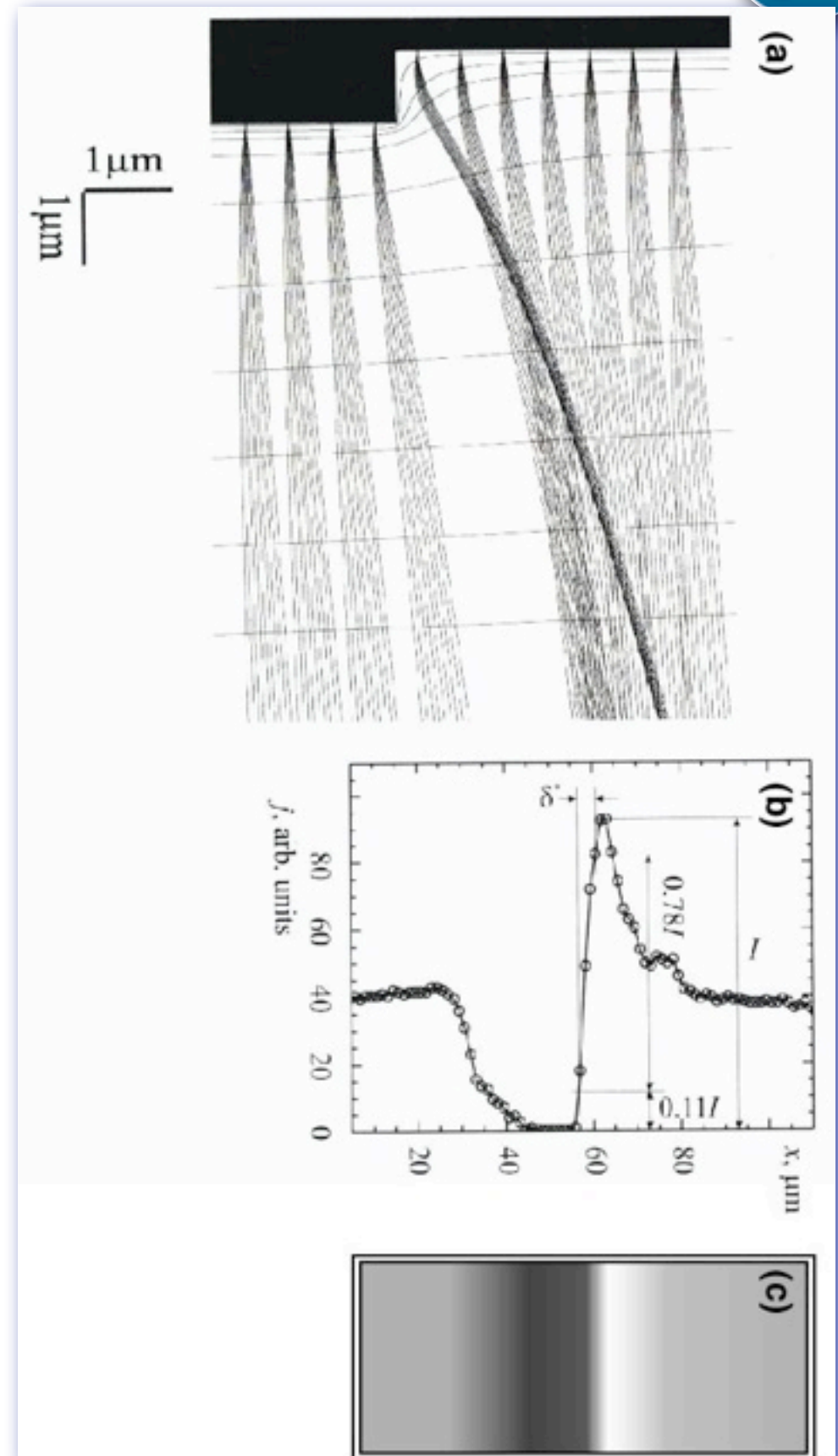
- more elaborate and expensive
- spherical aberration smaller by factor 4-10
- sample on -20kV

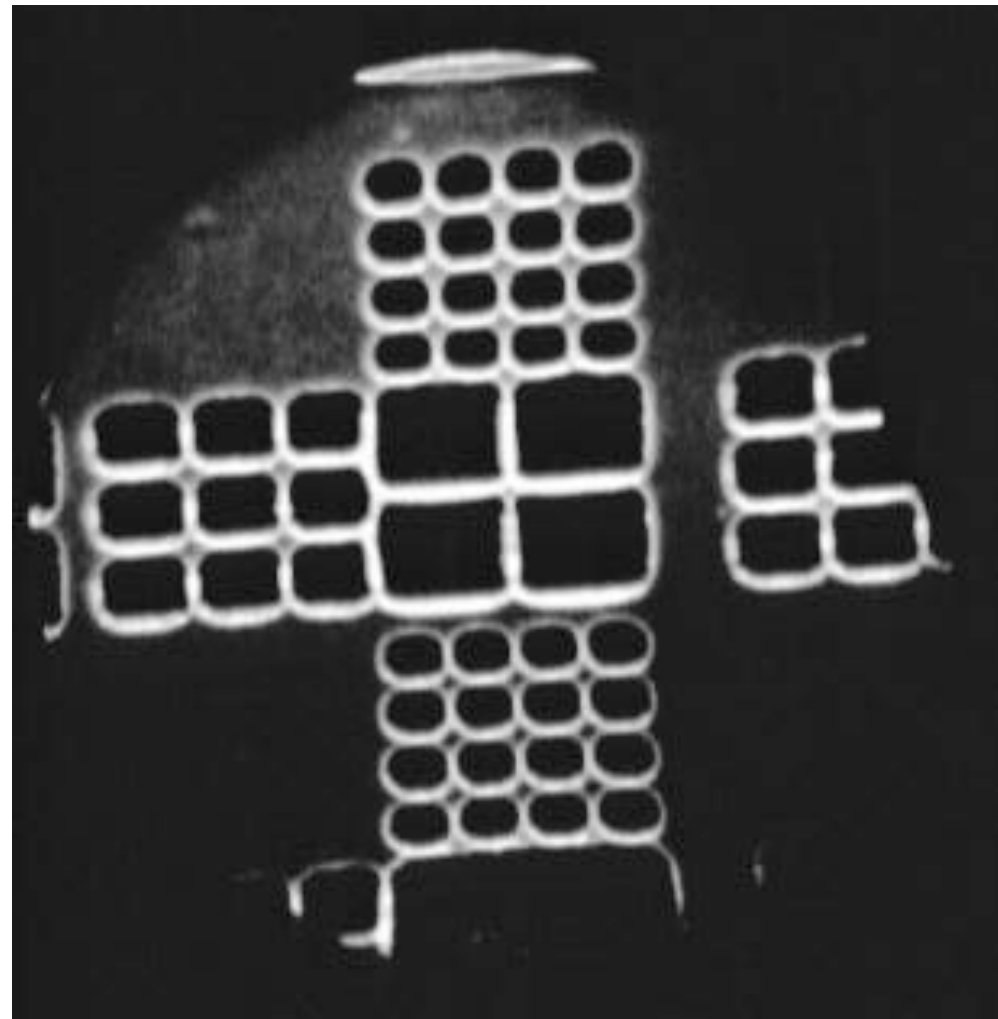


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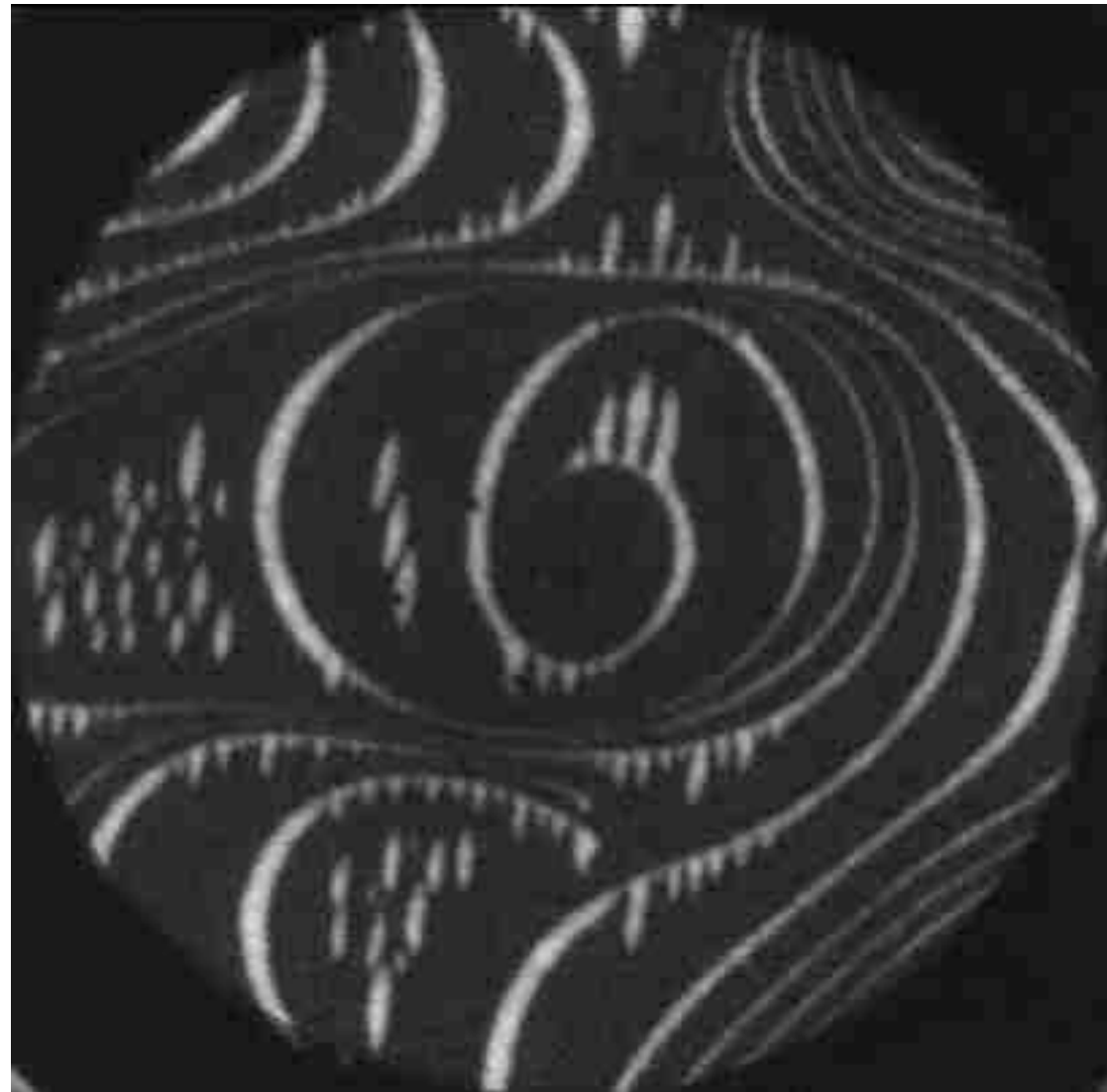


- topography contrast by steps and other geometrical features
- associated with local field distribution
- sharp variations of the topography may affect the lateral resolution field gradient

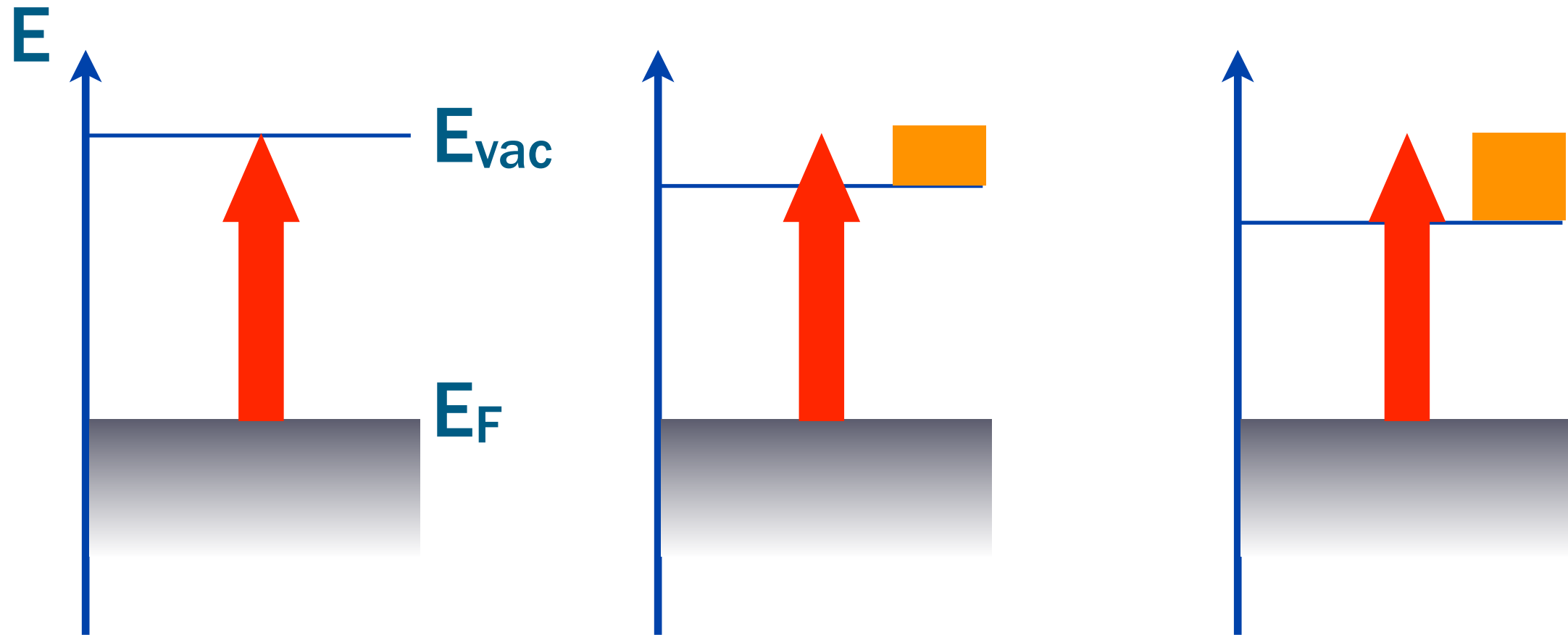




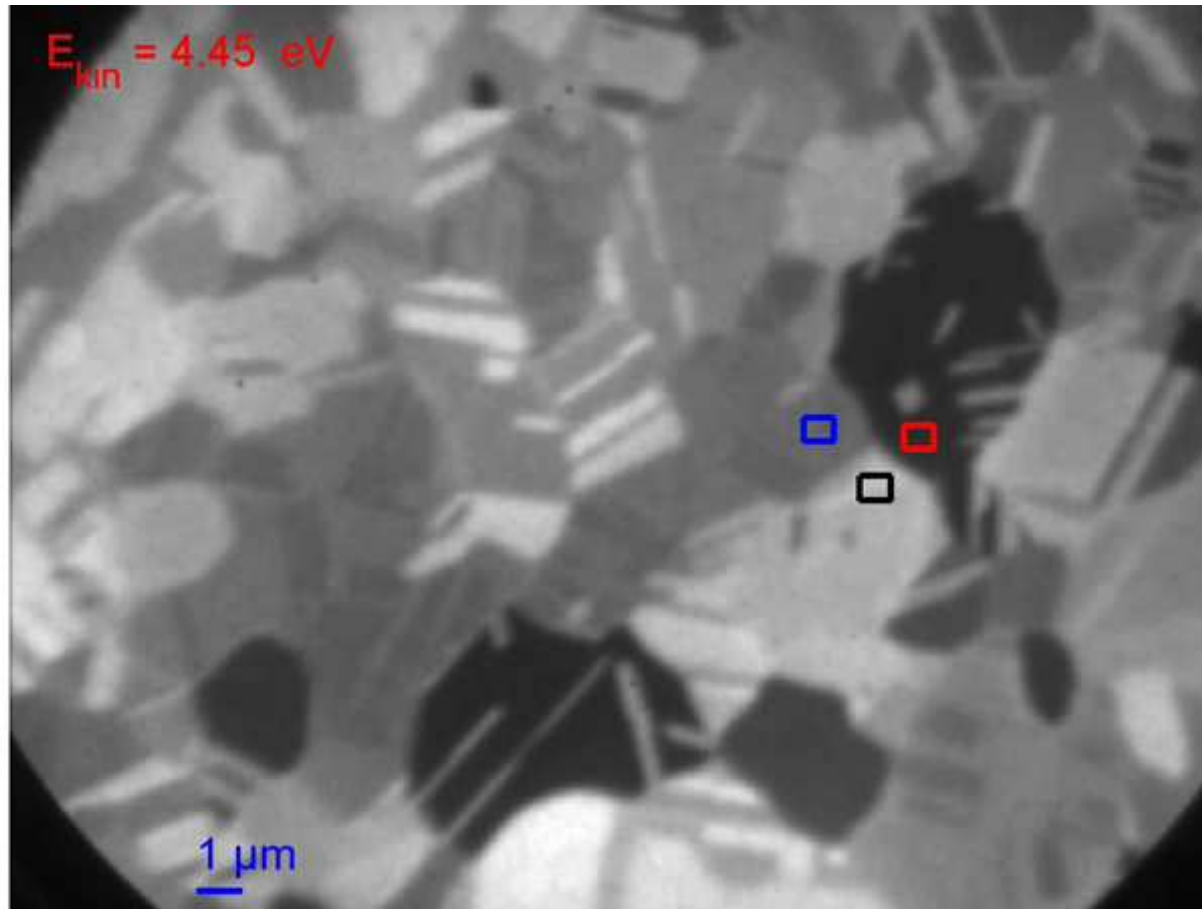
- field of view: 140 μm
- courtesy of Dr. Gary Kellogg, Sandia National Laboratories, Albuquerque, New Mexico



- field of view: $10\mu\text{m}$
- atomic steps on Mo(110)
- step edge decoration



- fixed photon energy
- band pass: $E_{vac} - E_F - h\nu$
- total photoemission yield depends on work function

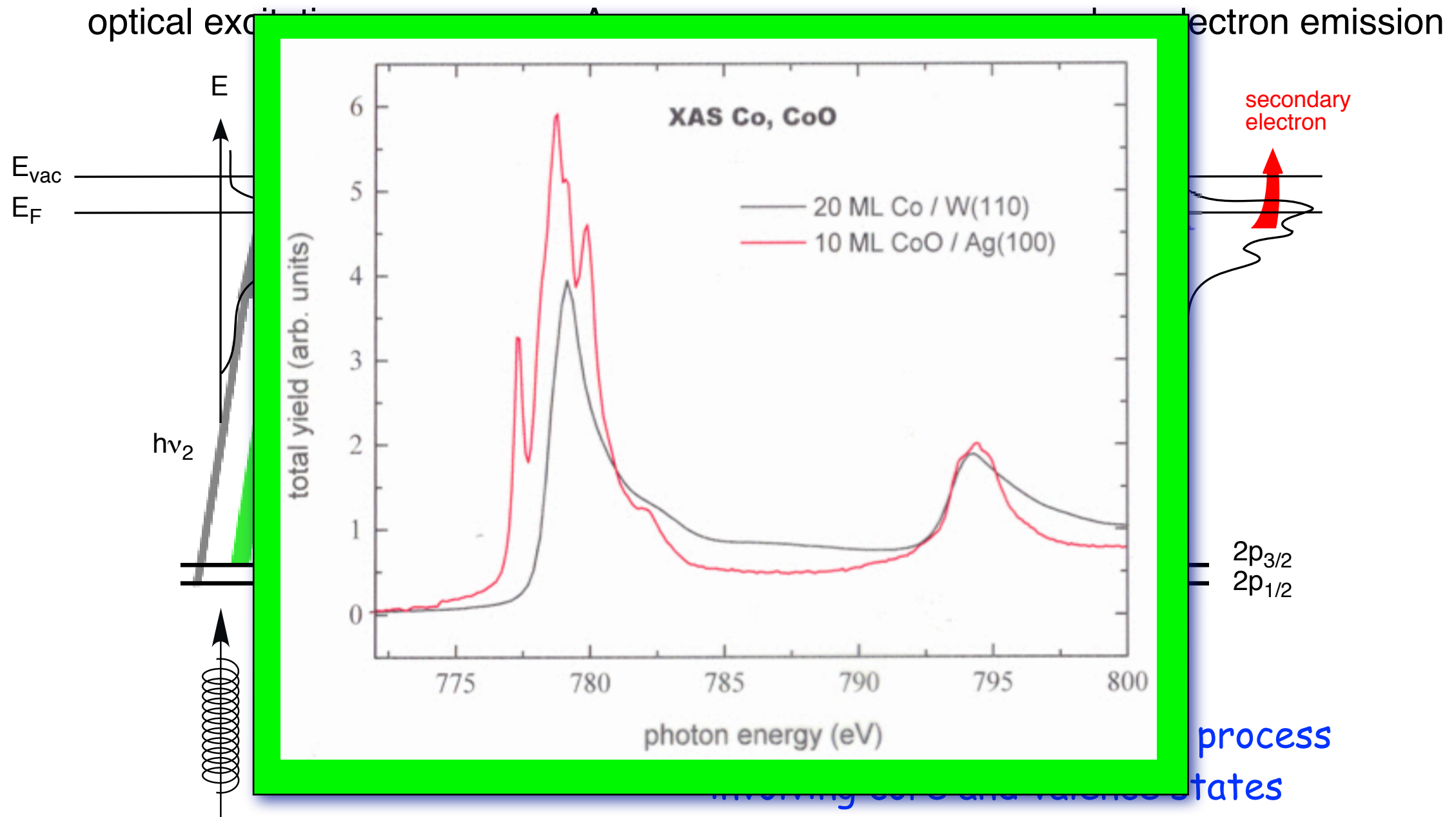


Region 4	<111>	4.85 eV
Region 2	<110>	4.55 eV
Region 1	<100>	4.40 eV

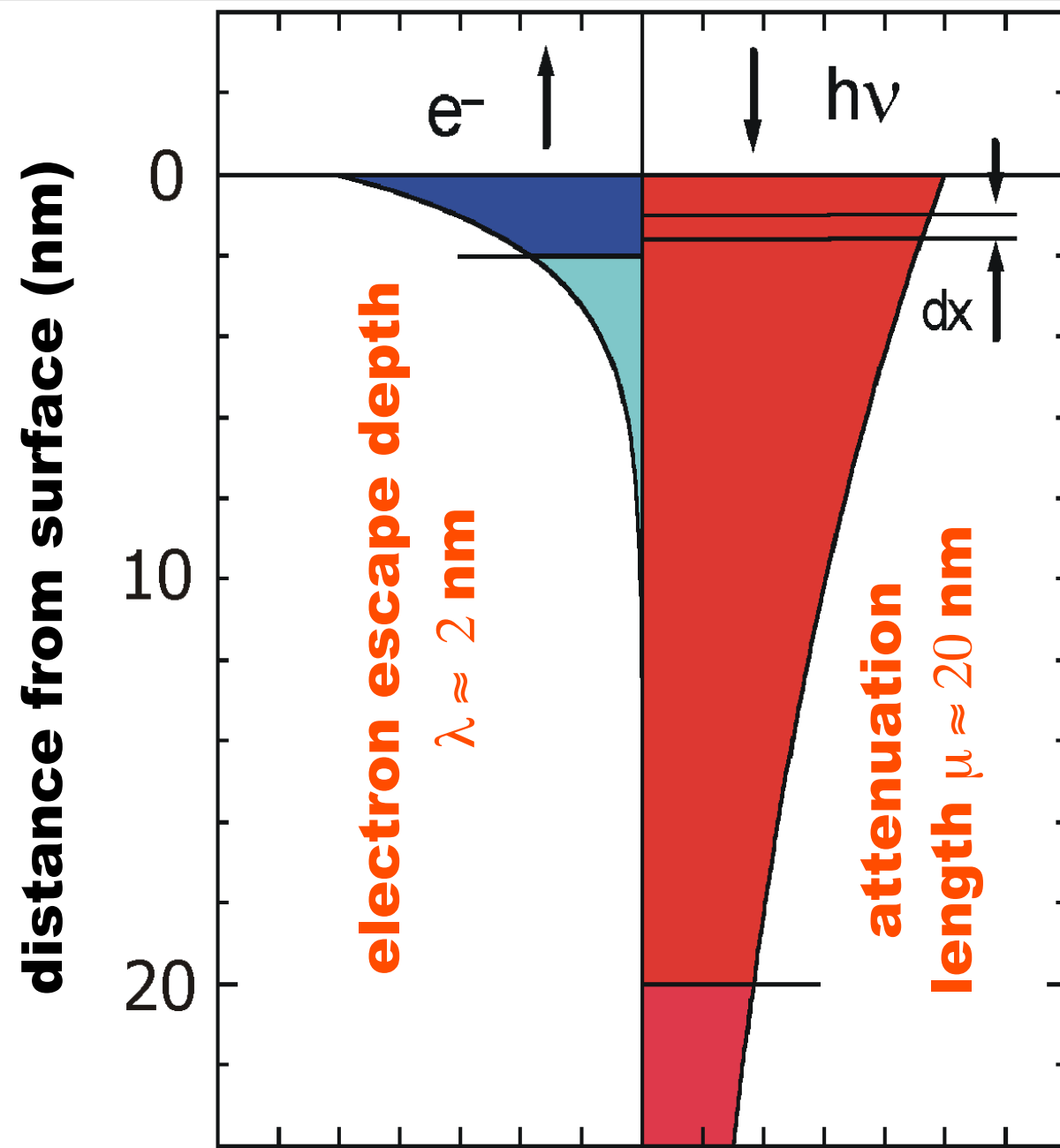
- polycrystalline copper
- work function depends on grain orientation
- photoemission yield depends on work function



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- sequential excitation process
- information depth is convolution of inelastic mean free paths of Auger and secondary electrons



assumption:

no. of secondary electrons
 $\propto$ no. of core vacancies

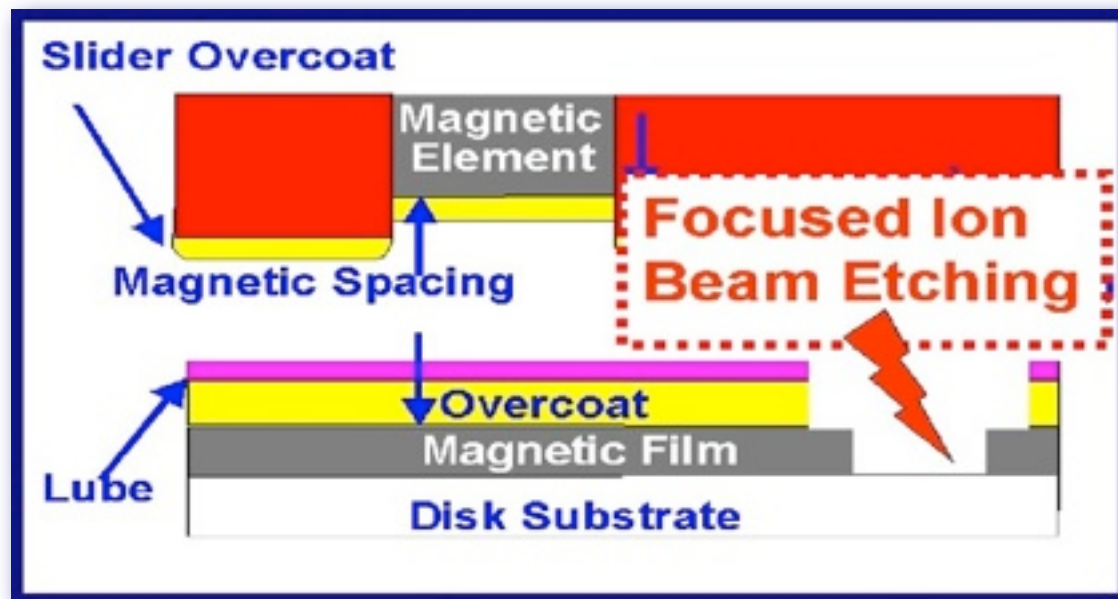
then the total yield is

$$n = c \left(\frac{\mu}{\mu + \lambda} \right) i_0$$

$$\mu \gg \lambda$$

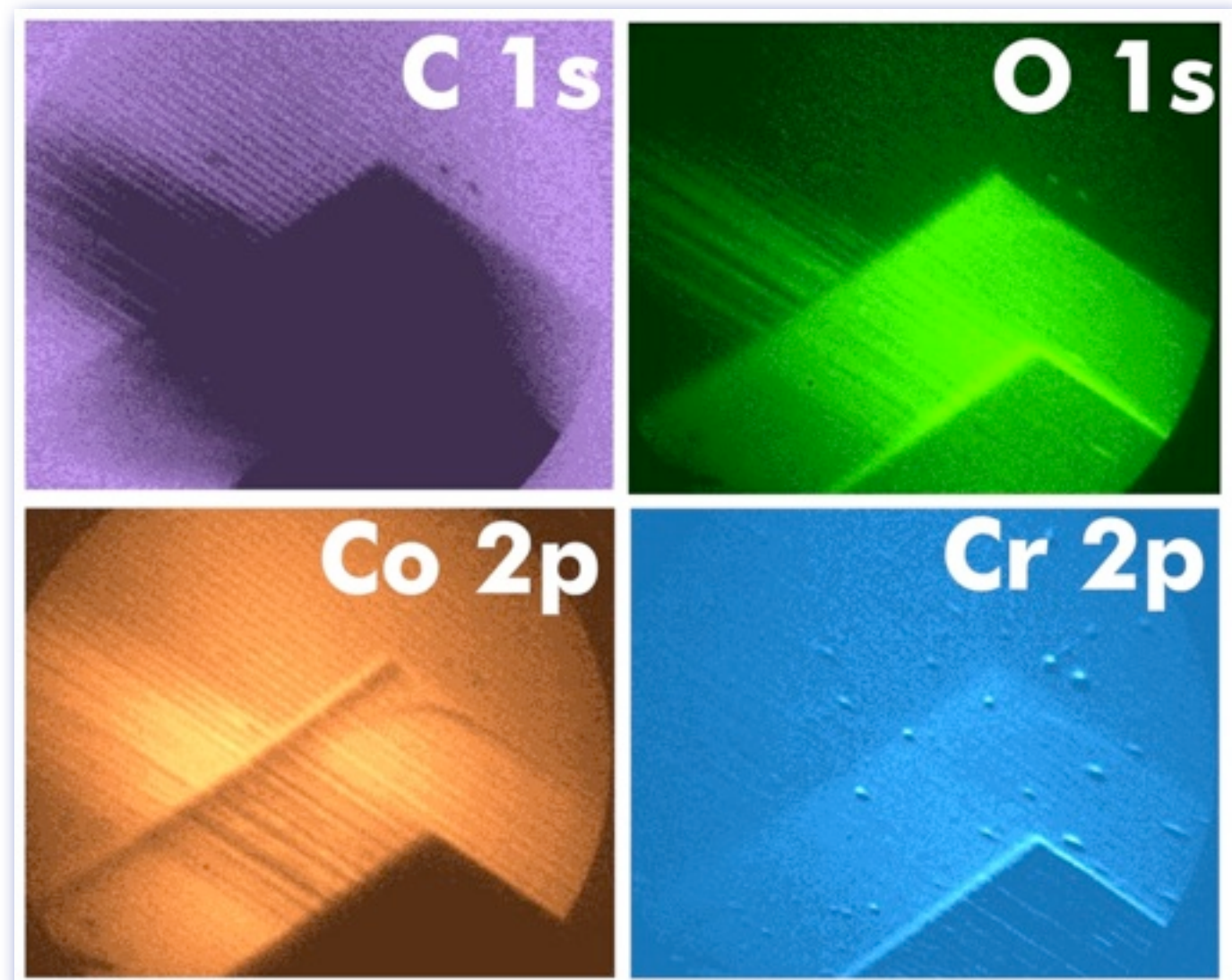
$$\rightarrow n = c \cdot \frac{\mu}{\lambda} \cdot i_0$$

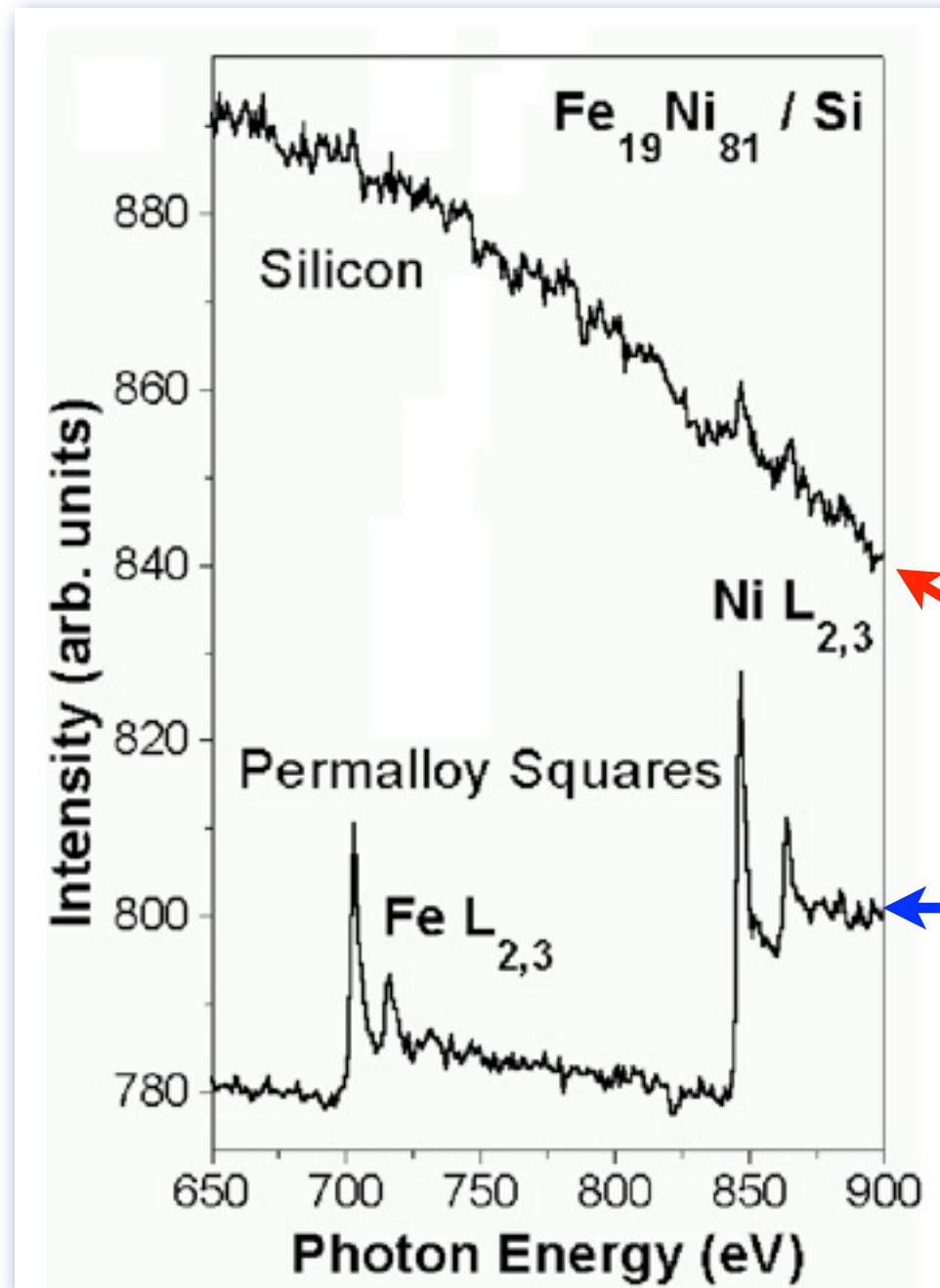
➤ total electron yield (TEY) proportional to μ



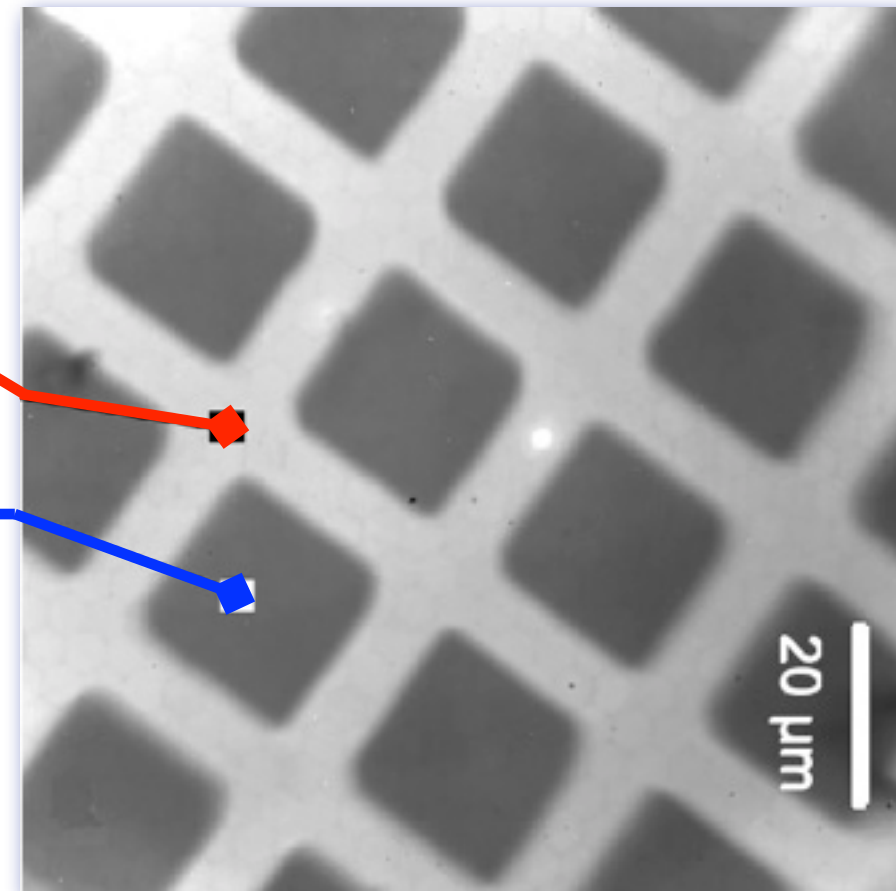
- head crash on hard disk
- ion beam etching
- CoCrPt intermetallic compound

- DLC overcoat destroyed
- Co signal seen through overcoat
- Cr signal weak (small content, possibly also used as seed layer)
- exposed area oxidized





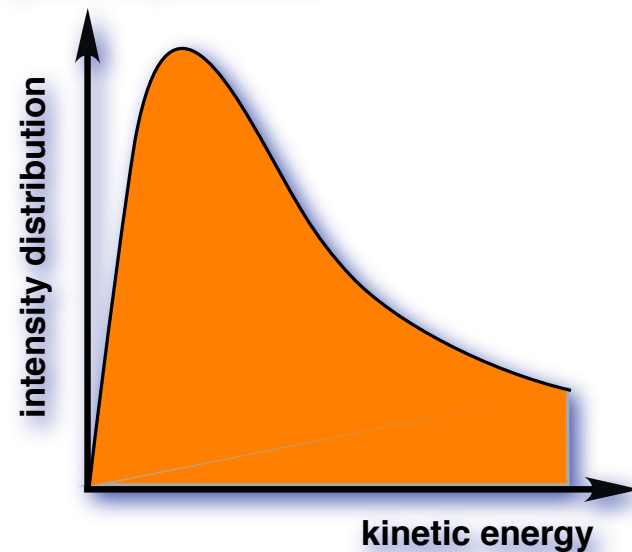
- 50nm FeNi/SiO₂
- 25 μm squares



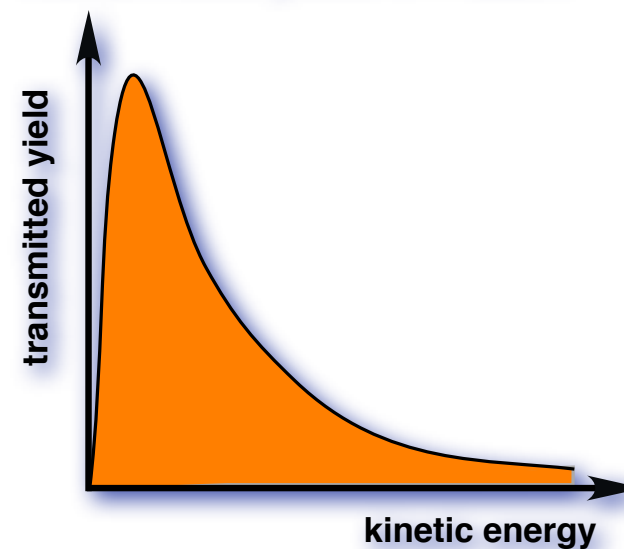
- chemical contrast “inverted”, since dominated by electron yield
- yield may be affected by topography and work function
- always check contrast mechanism (weak contrast)



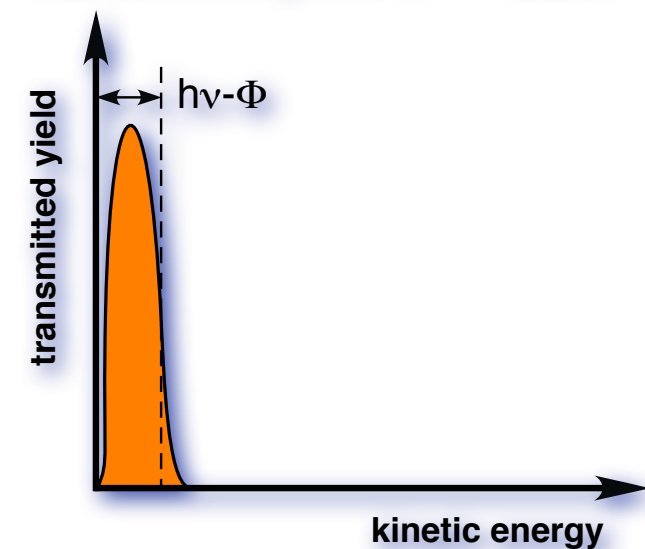
yield spectrum



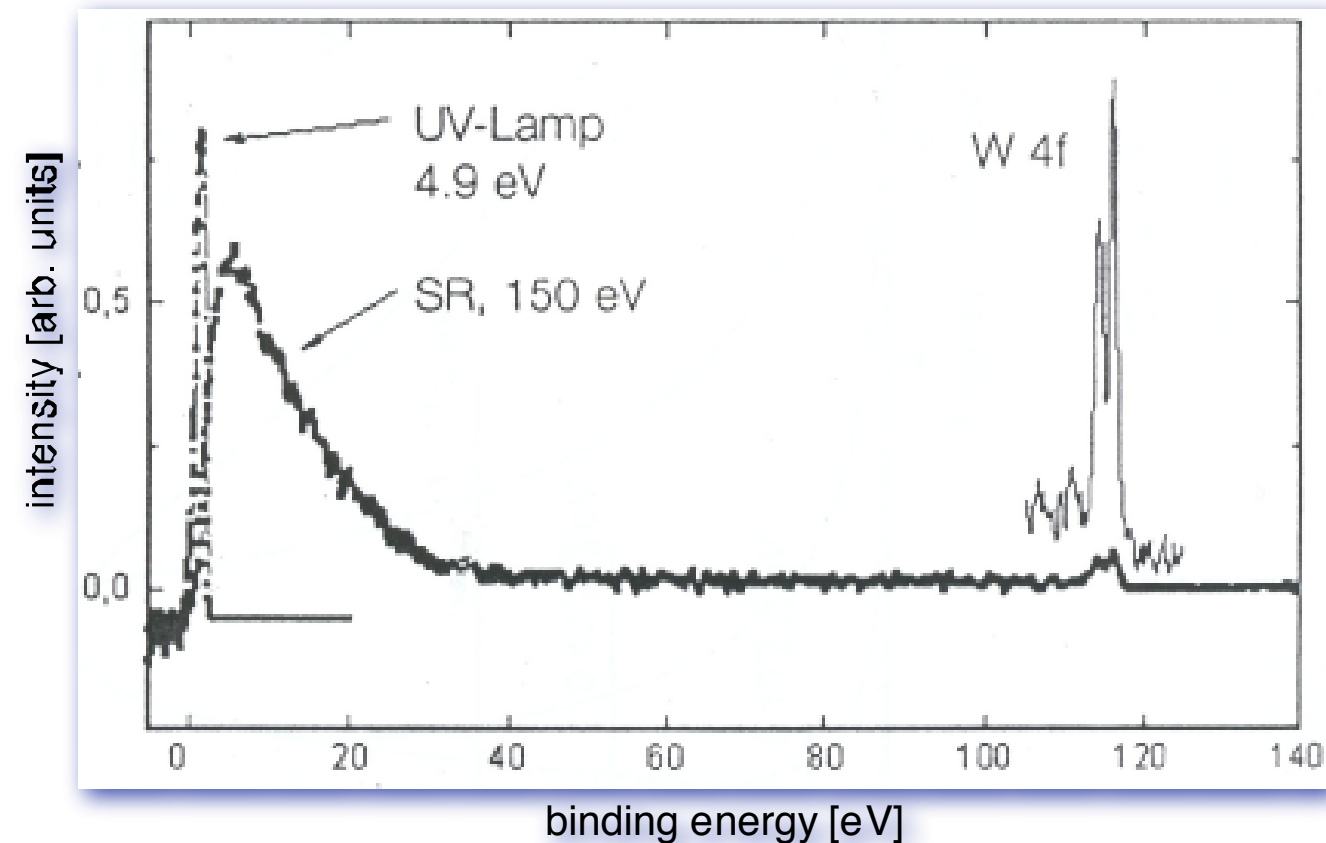
transmitted yield X-PEEM



transmitted yield UV-PEEM



- high-energy excitation generates broad electron energy distribution
- electron optics has sufficient transmission at higher energies
- chromatic aberration of lens system is more critical in X-PEEM

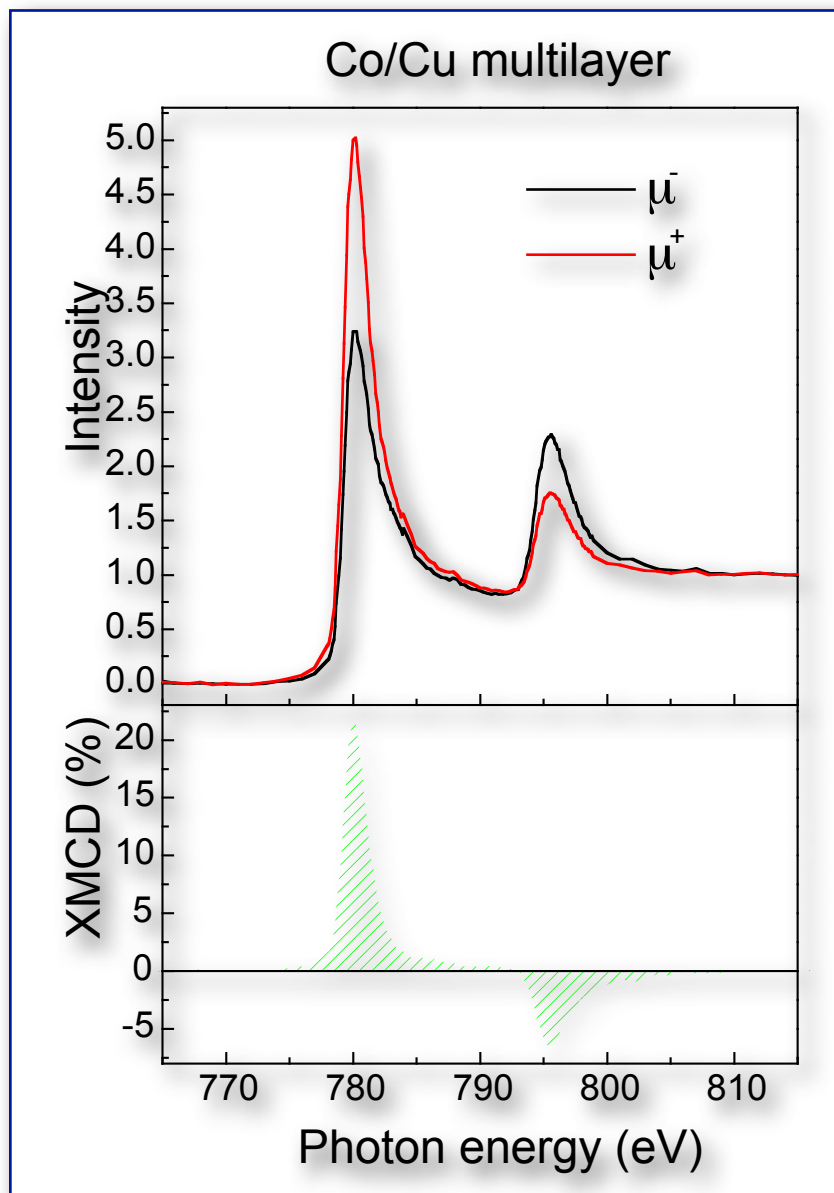




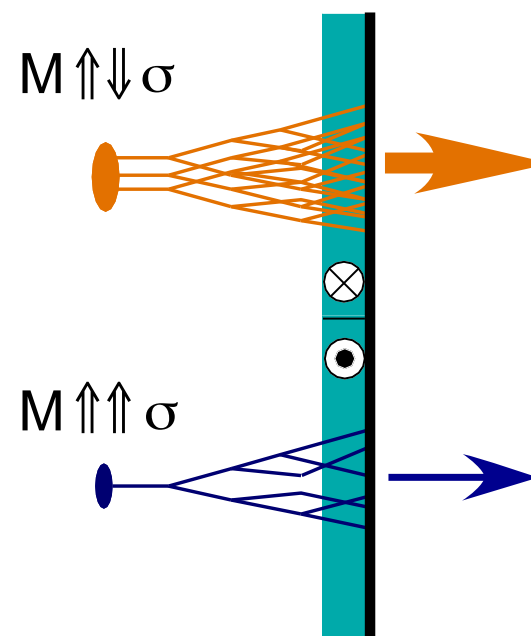
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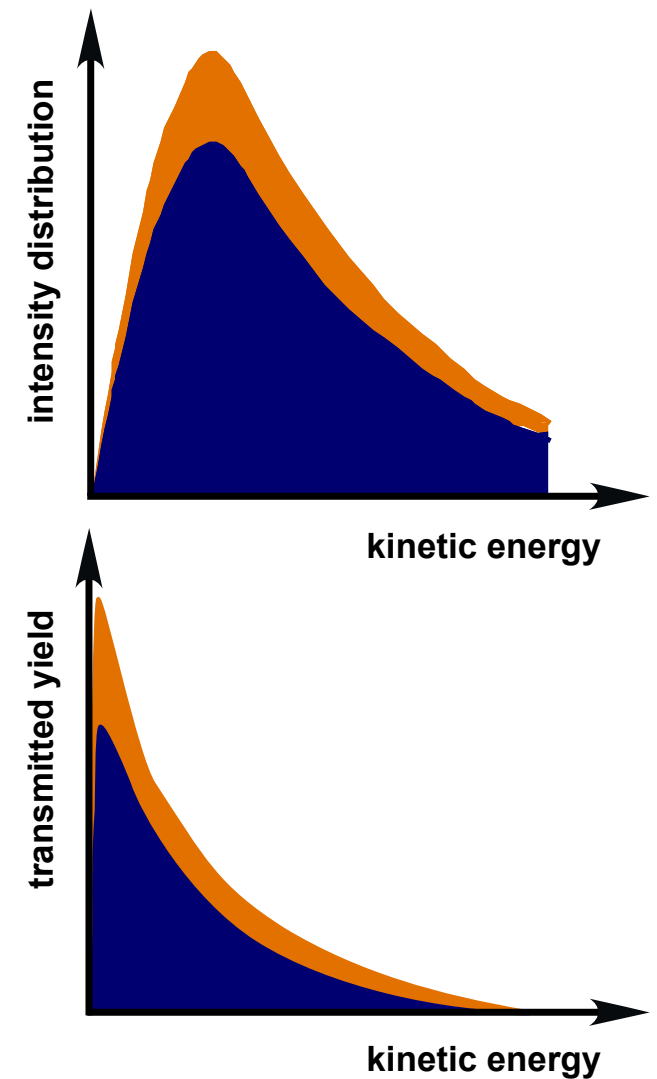
1. Auger electron excitation



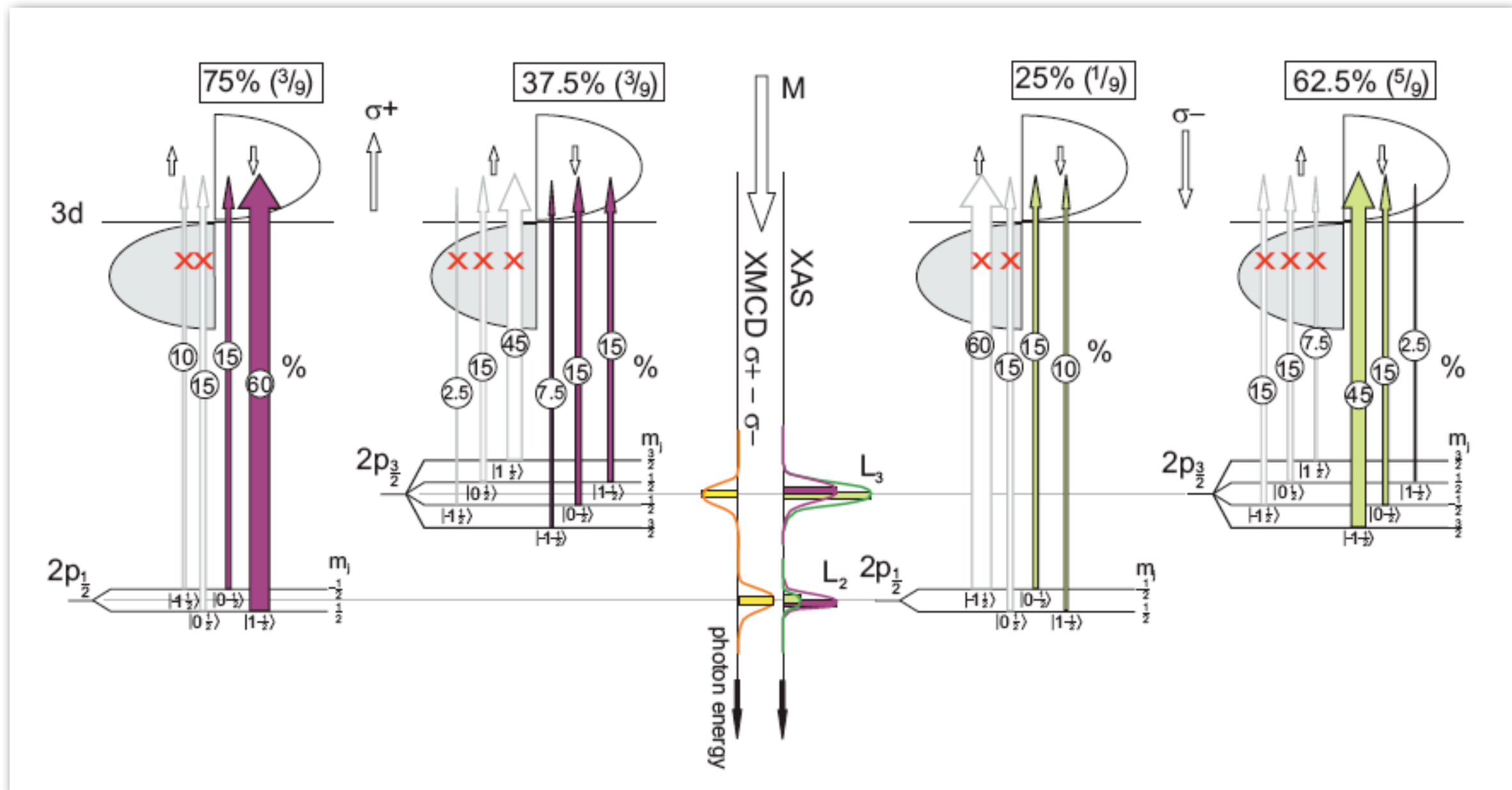
2. Inelastic scattering cascade transmission



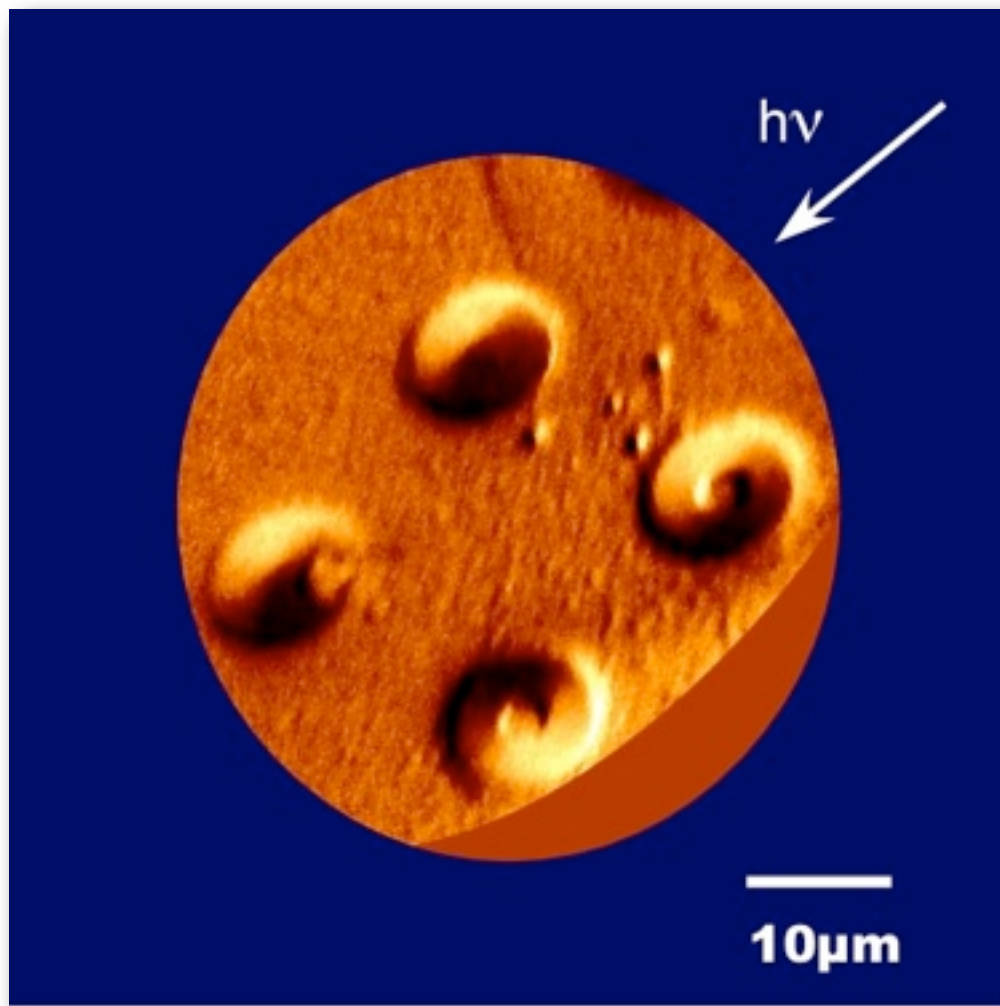
3. "Low pass"



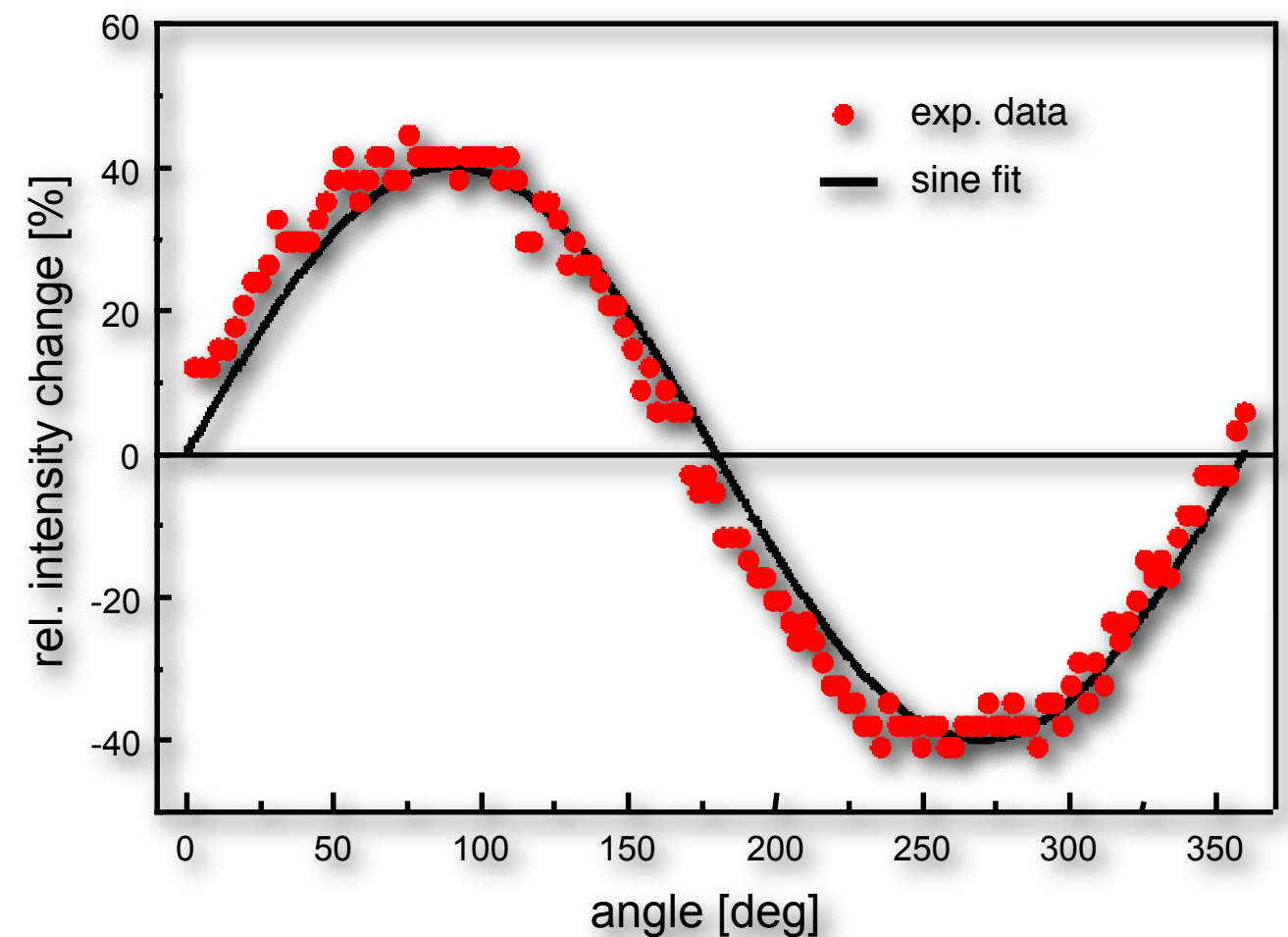
➤ XMCD in total or partial (low energy) electron yield



- MXCD occurs without invoking exchange splitting in the core states
- sum over subshell transitions unequal for σ^+ and σ^-

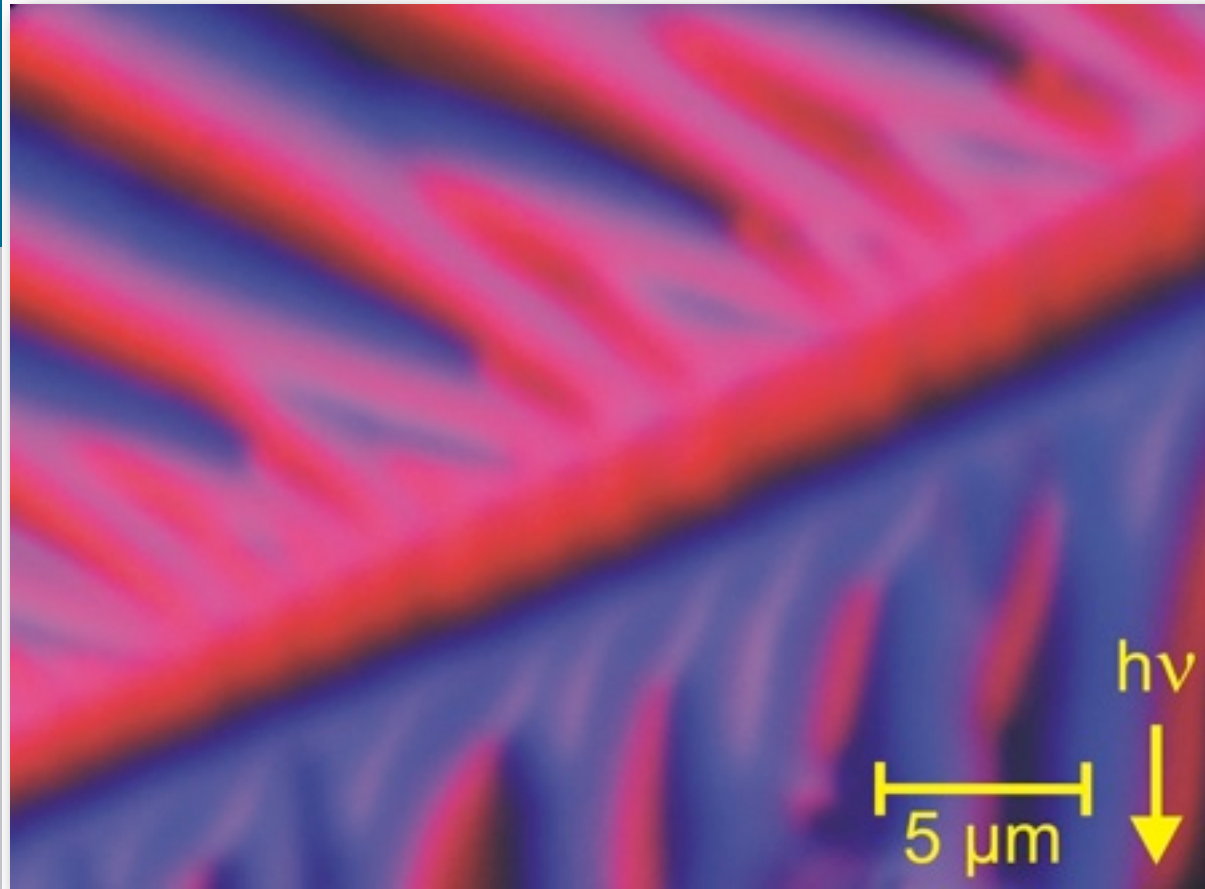


- continuous rotation of the magnetization vector
- MXCD scales as $A \sim M \cdot \zeta$ or $A \sim M \cdot q$
- no magnetic contrast for $M \perp q$

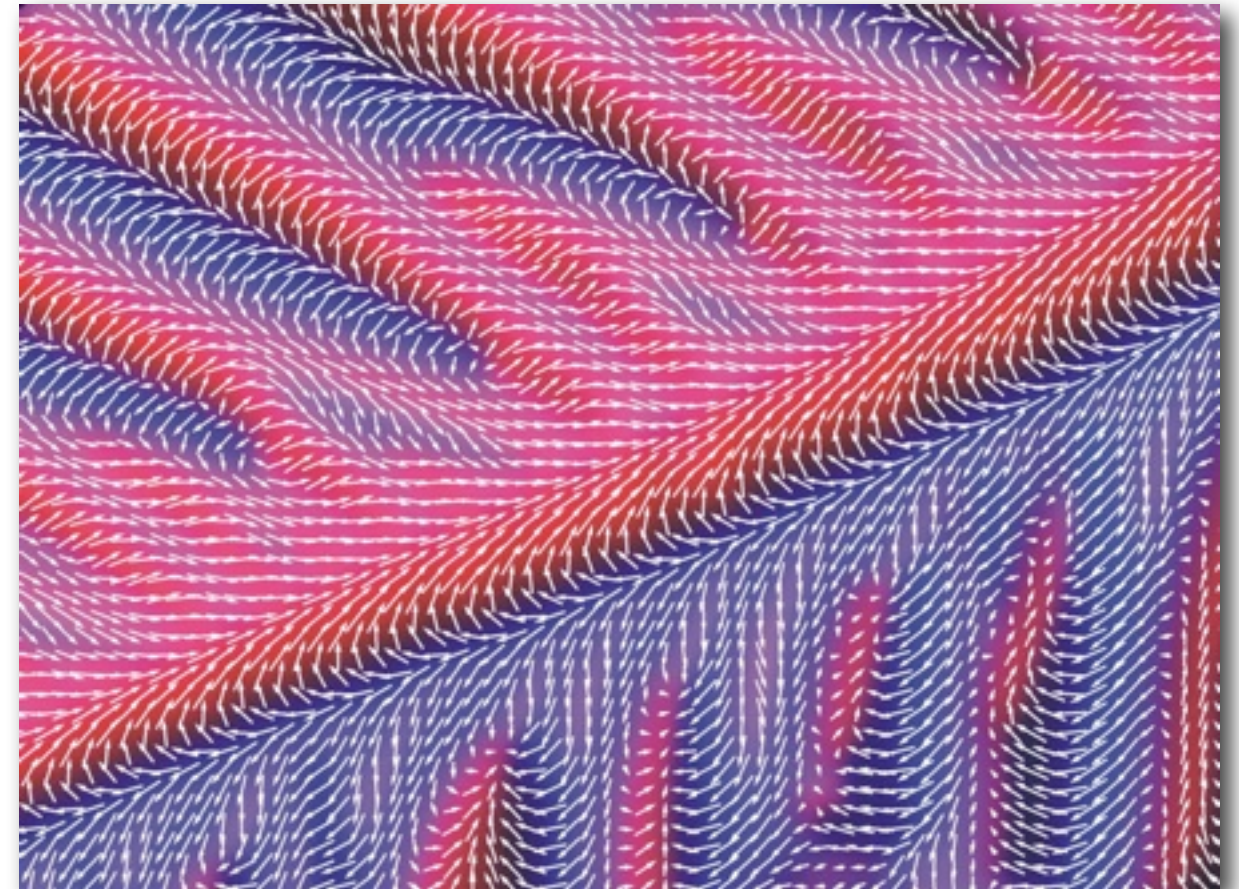


- $\text{Ni}_{80}\text{Fe}_{20}/\text{Cu}/\text{SiO}_2$
- lithographically micropatterned
- Ni L_3 XMCD

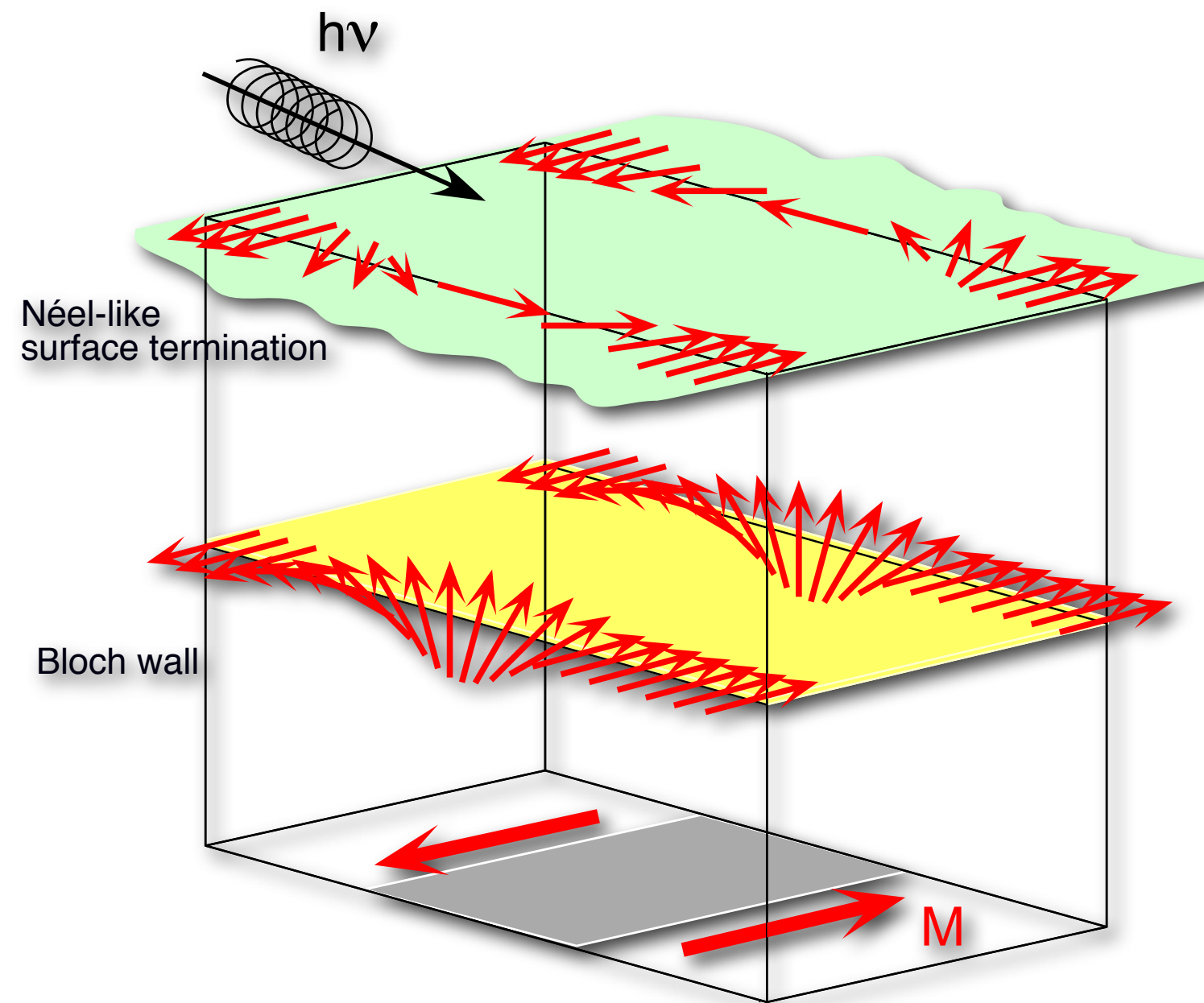
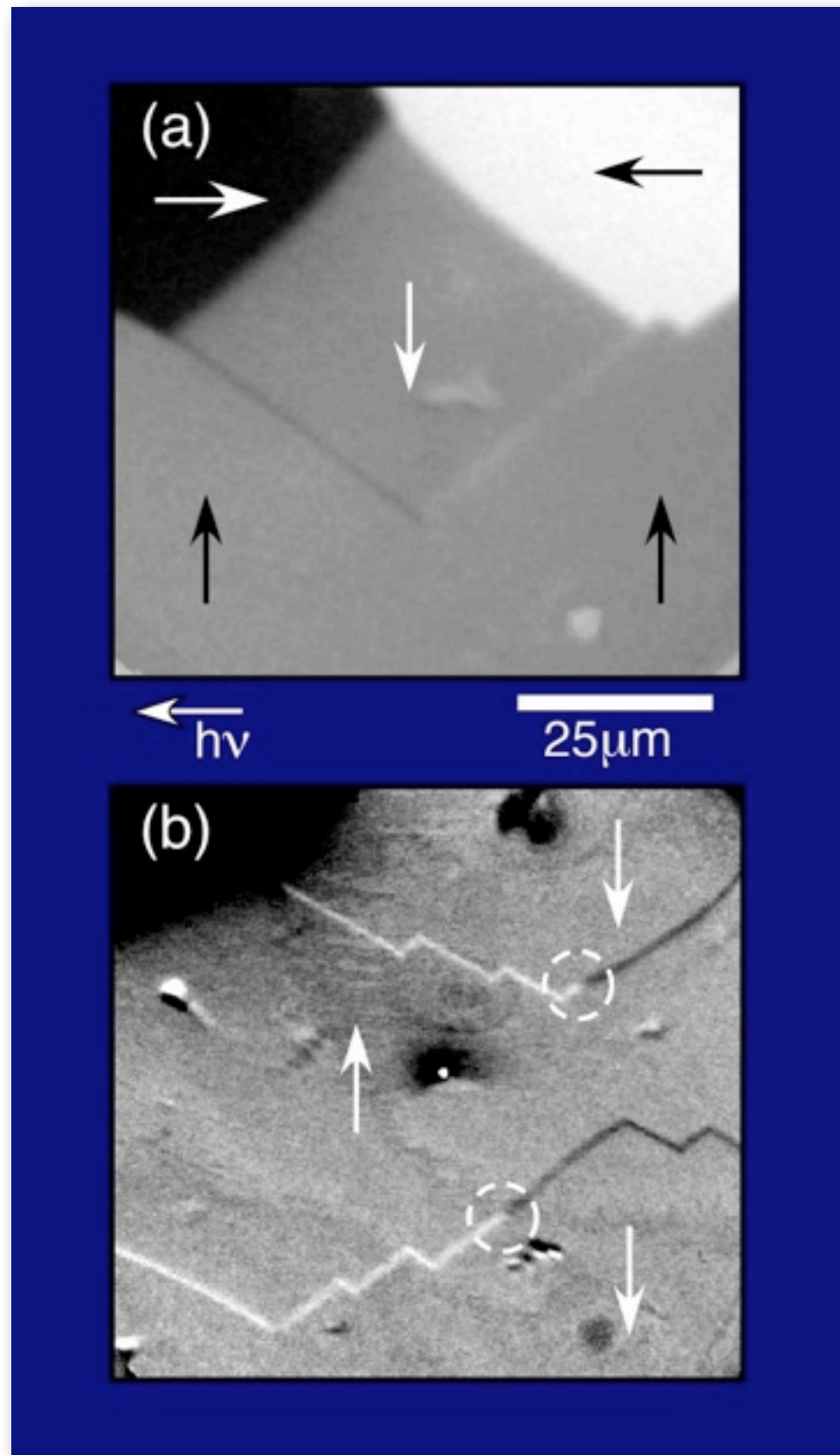
Fir-tree pattern



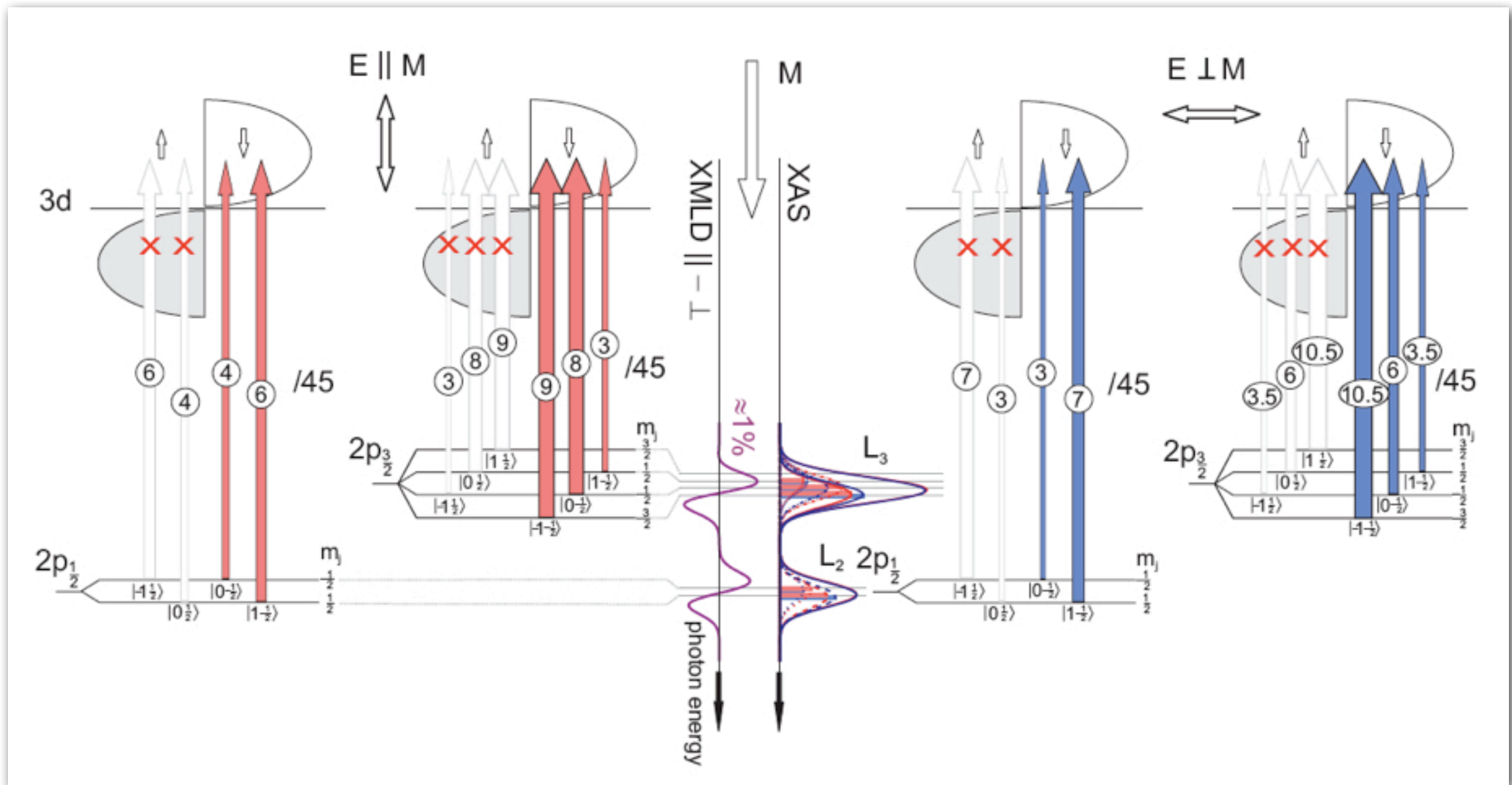
spin configuration



- ◆ MXCD images reveal complicated magnetic surface structure
- ◆ formation of quasi-domains at the surface
- ◆ no sufficiently large surface areas with a homogeneous magnetization!



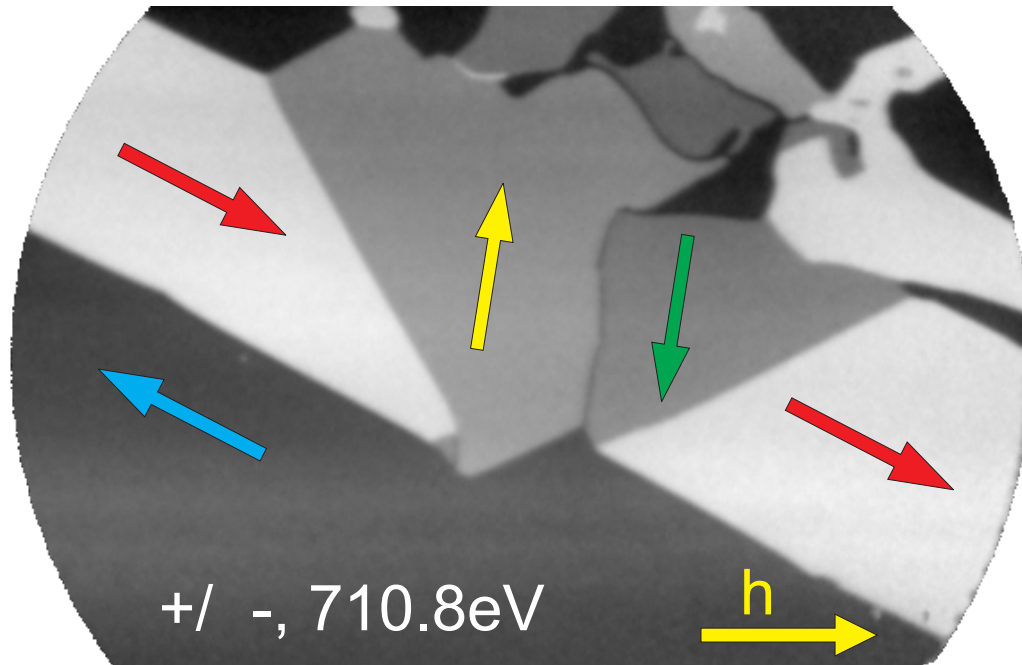
➤ selective imaging of Néel-type domain walls



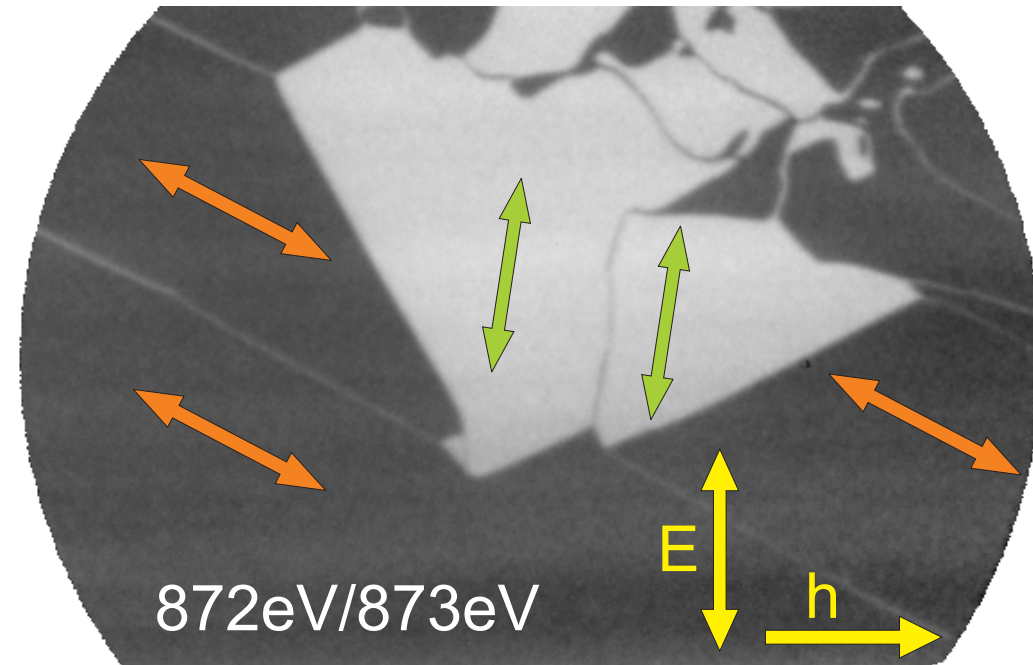
- MXLD relies on exchange-splitting of the core states
- sum of subshell transitions equal for $E \parallel M$ and $E \perp M$



$\text{Fe}_3\text{O}_4(110)$ XMCD

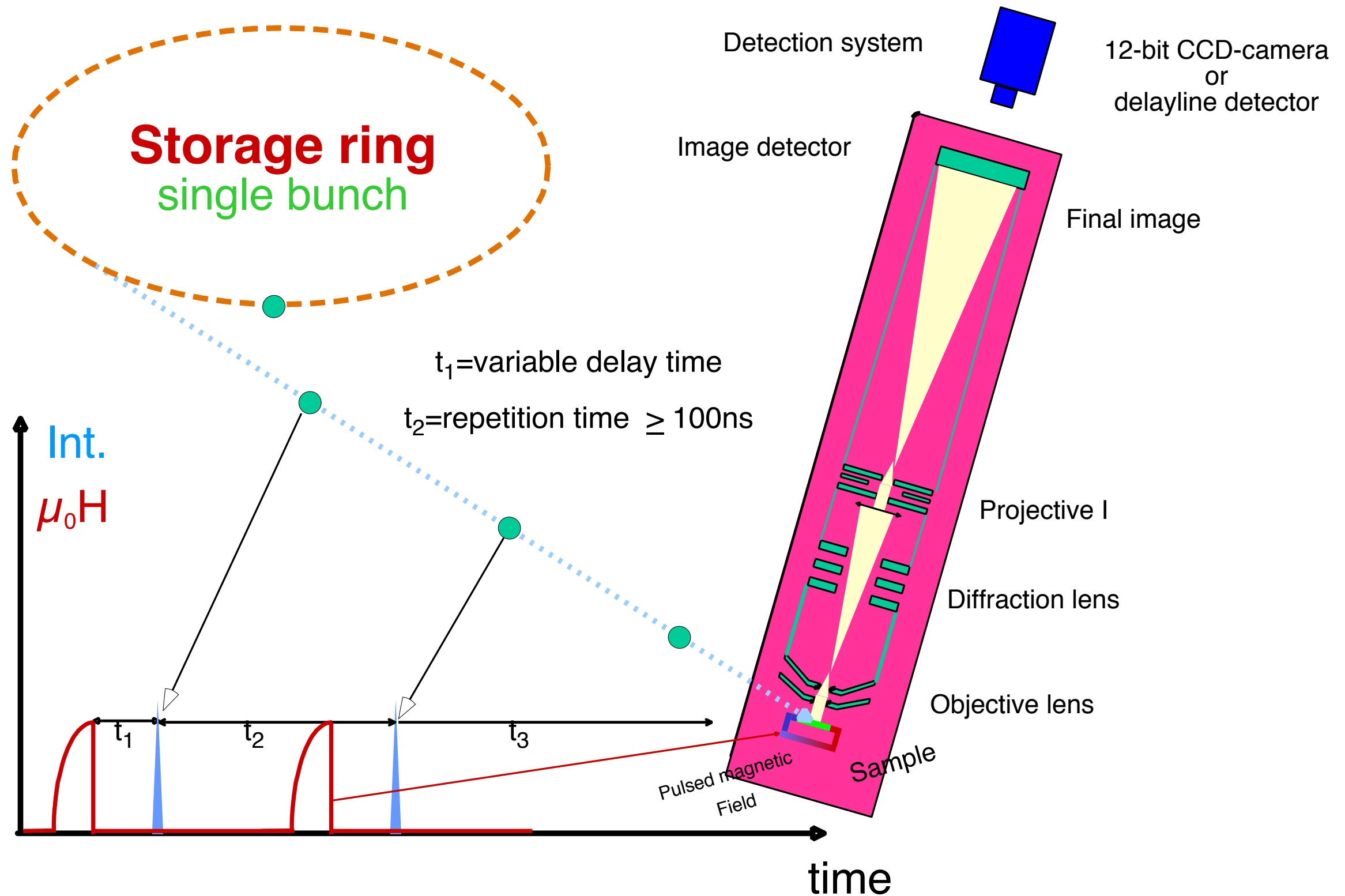


NiO XMLD s-polarized



- ◆ XMLD has a more complicated angular variation
- ◆ XMLD has anisotropic components
- ◆ breakdown of the simple angular dependence!
- ◆ careful analysis yields collinear coupling

Time-resolved XPEEM: Principle

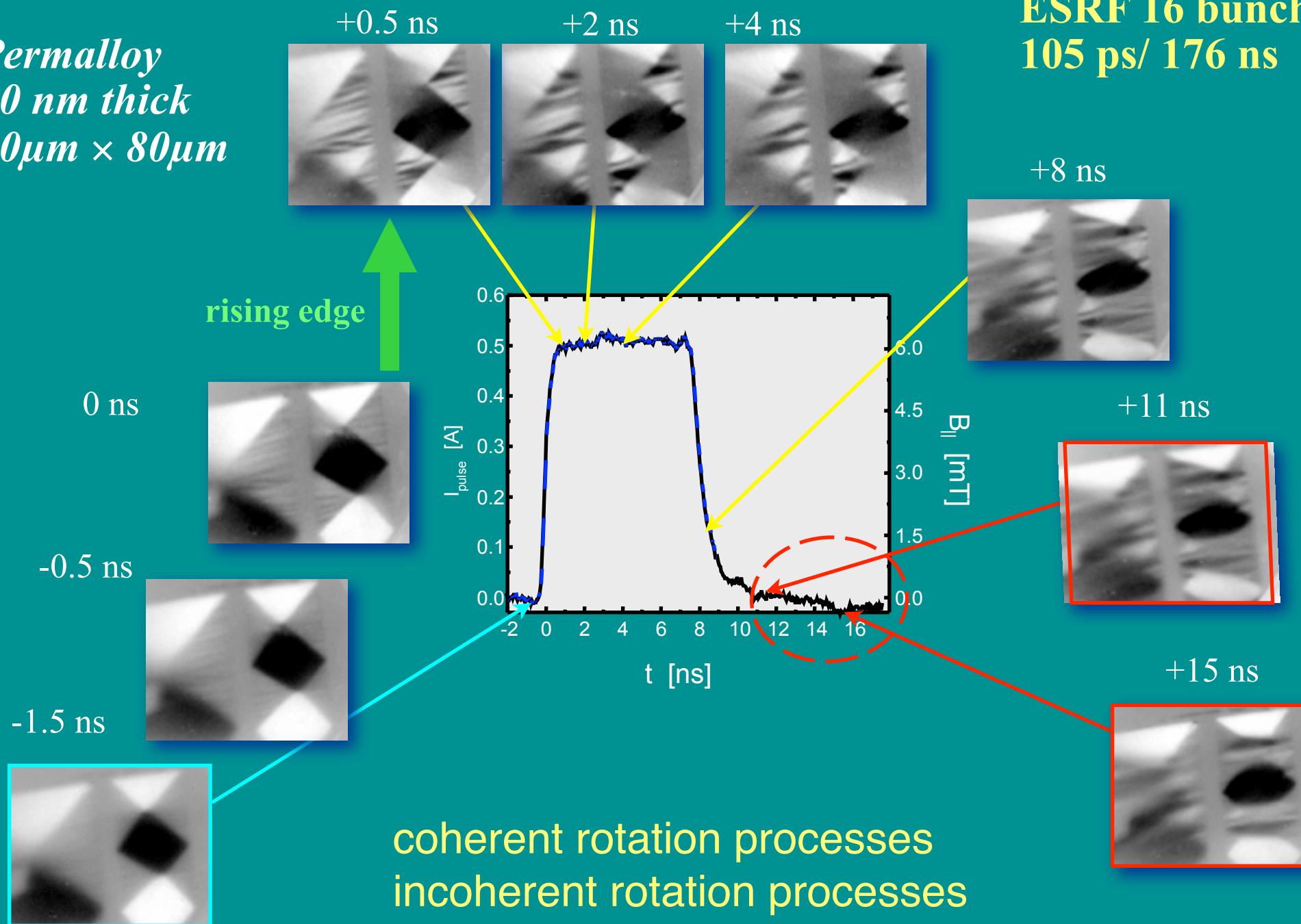
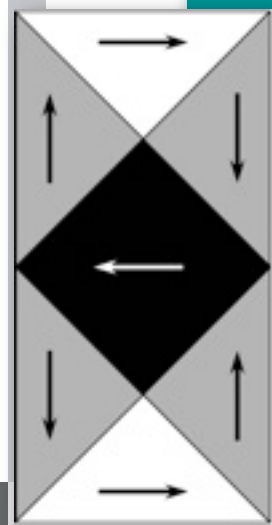


Mapping response to unipolar pulse



Permalloy
30 nm thick
20 μm $\times$ 80 μm

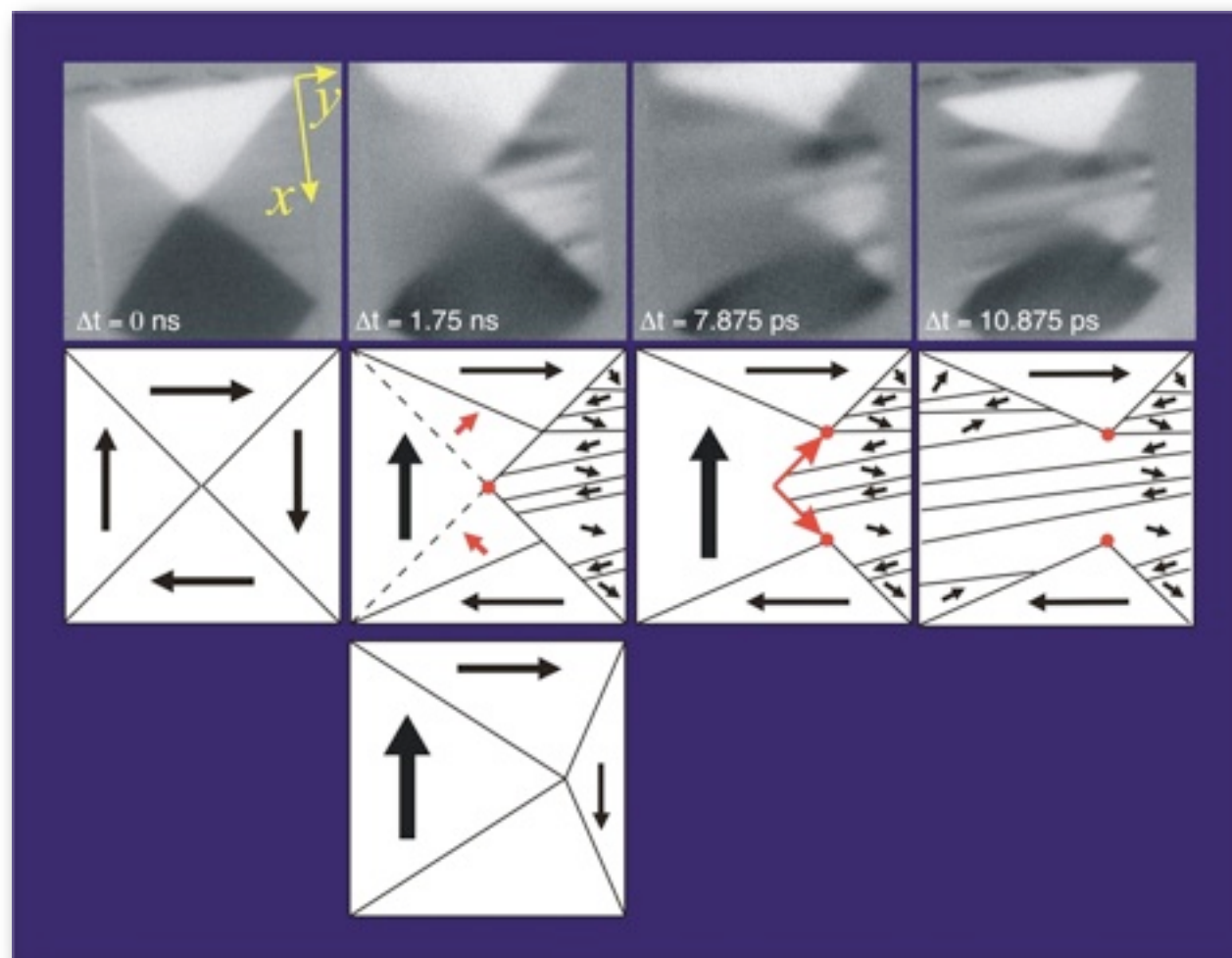
ESRF 16 bunch mode
105 ps/ 176 ns



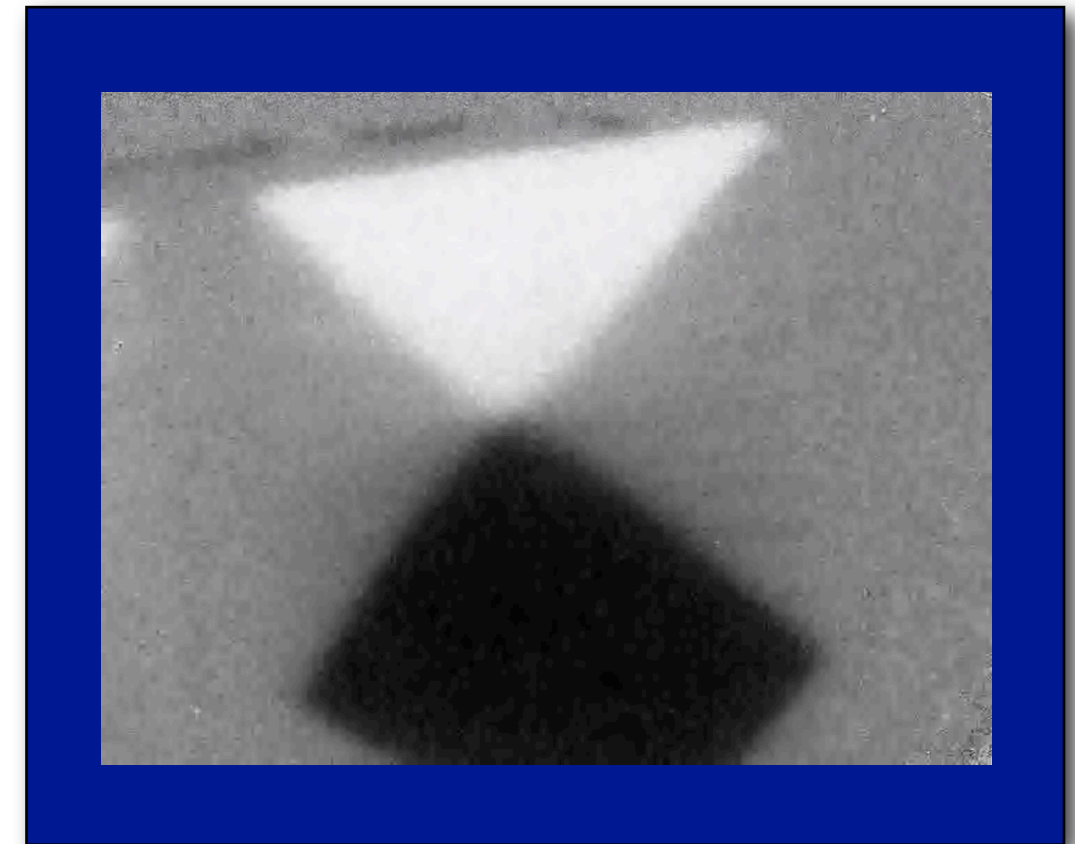
coherent rotation processes
incoherent rotation processes
slow relaxation



- ◆ 40 nm Permalloy
- ◆ top end of $20 \times 80 \mu\text{m}$
- ◆ Ni L_3 edge
- ◆ 0.125 ns (!) time slices
- ◆ 176 ns (!) repetition time



125 ps steps

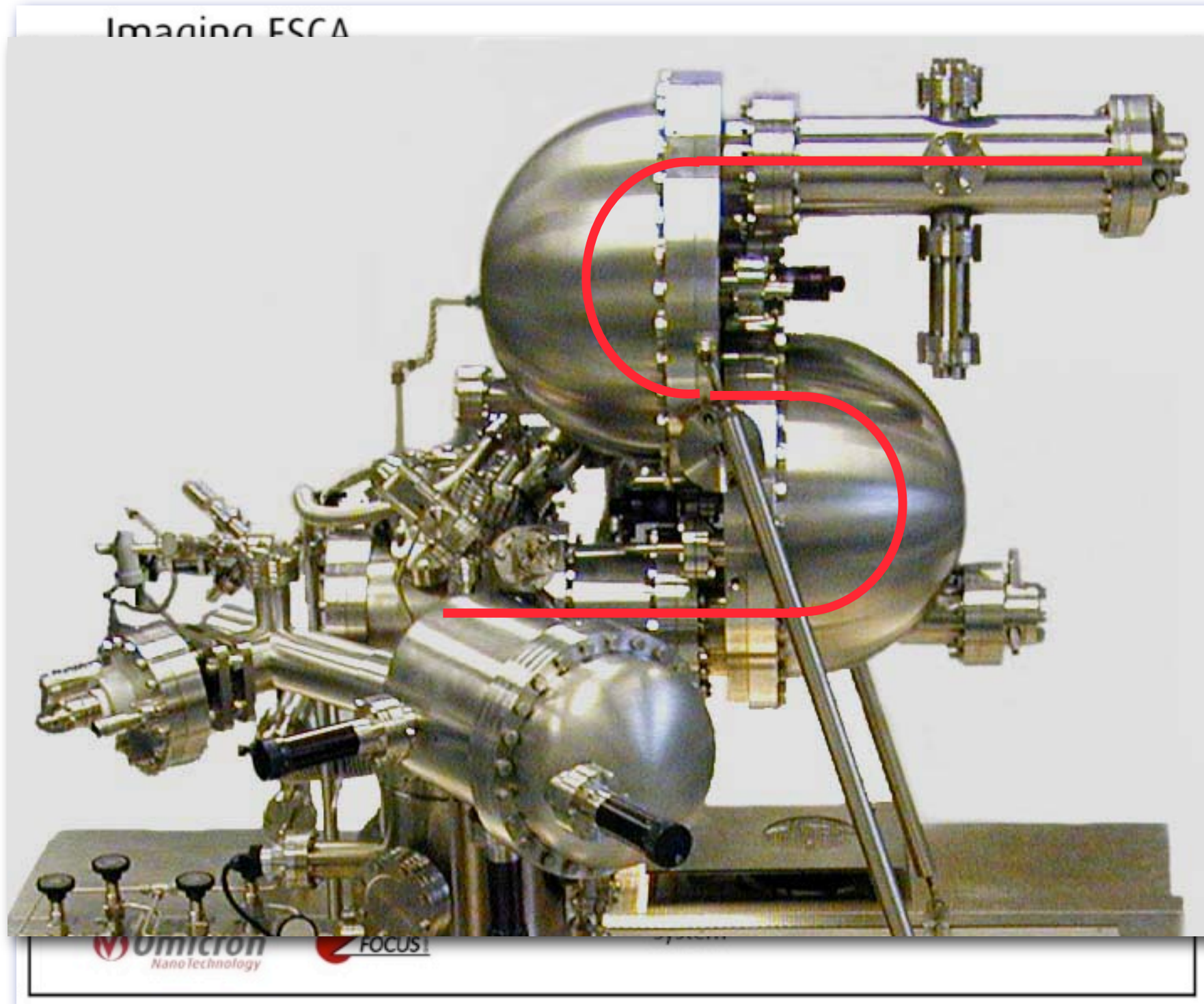


C.M. Schneider et al., Appl. Phys. Lett. **85** (2004) 2562

- initial Landau-Lifshitz state
- formation of stripe-like structures
- incoherent magnetization rotation
- vortex formation and motion



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3 modes:

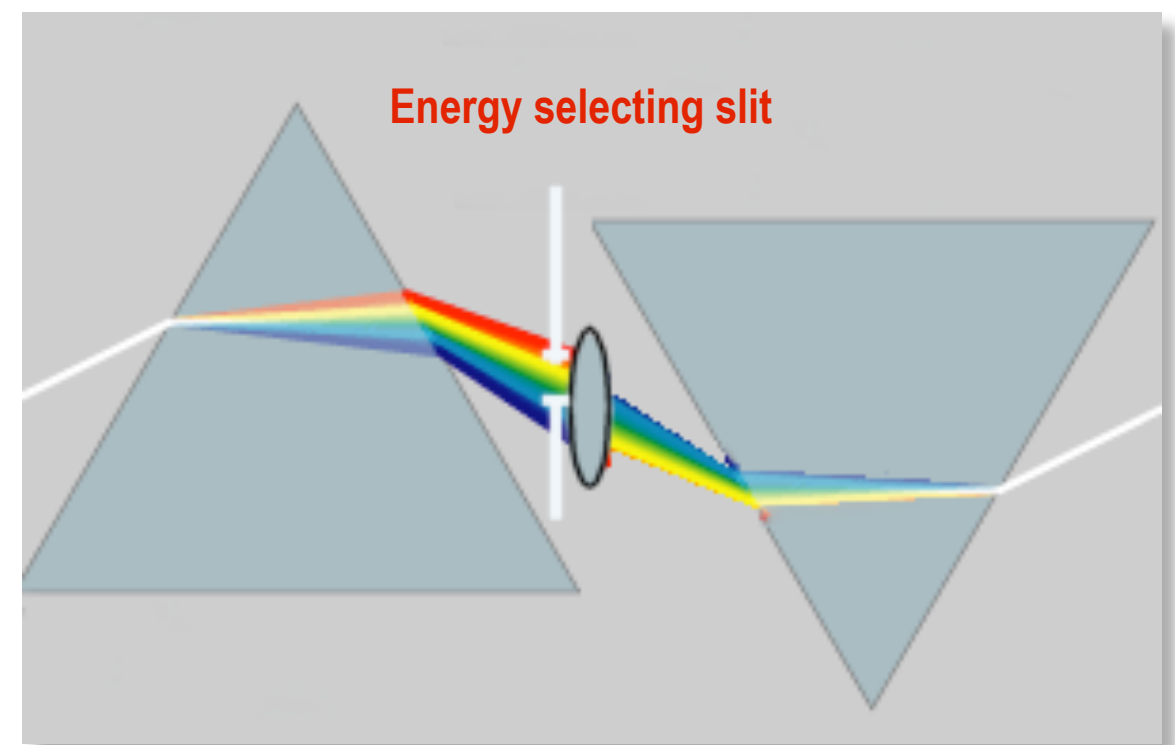
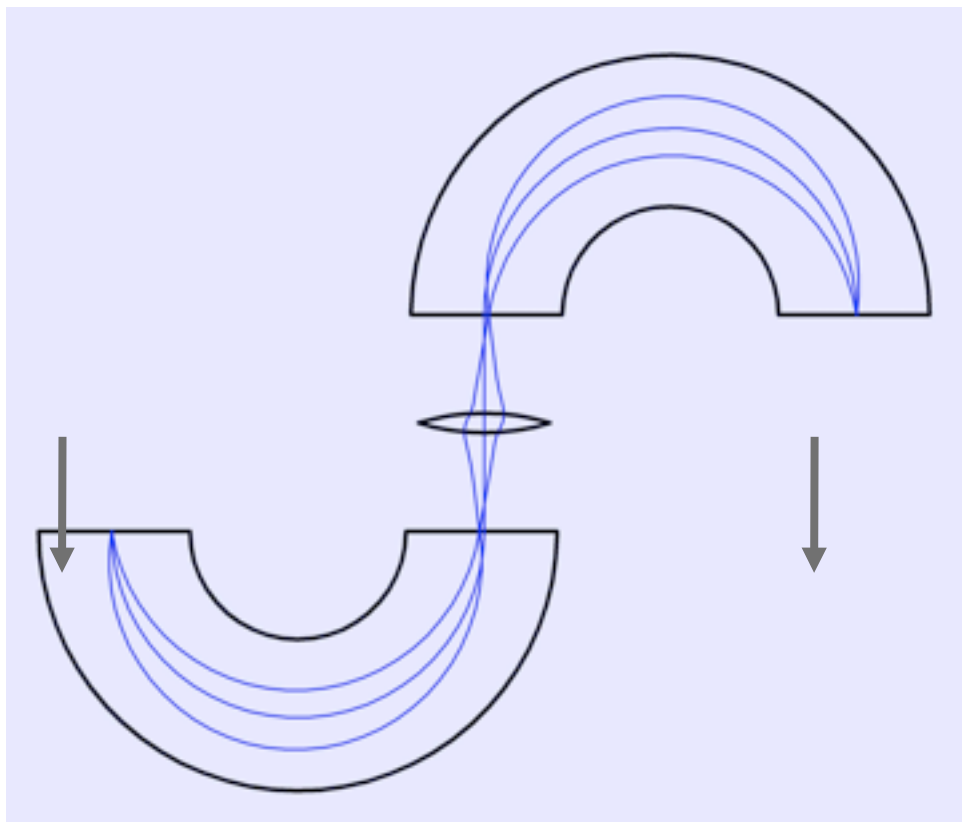
1. **PEEM**
*direct SE-imaging
without energy
filter*
2. **Imaging XPS**
*imaging with
energy filter*
3. **Spectroscopy**
*with area selection
aperture and
channeltron*

➤ dual imaging mode system



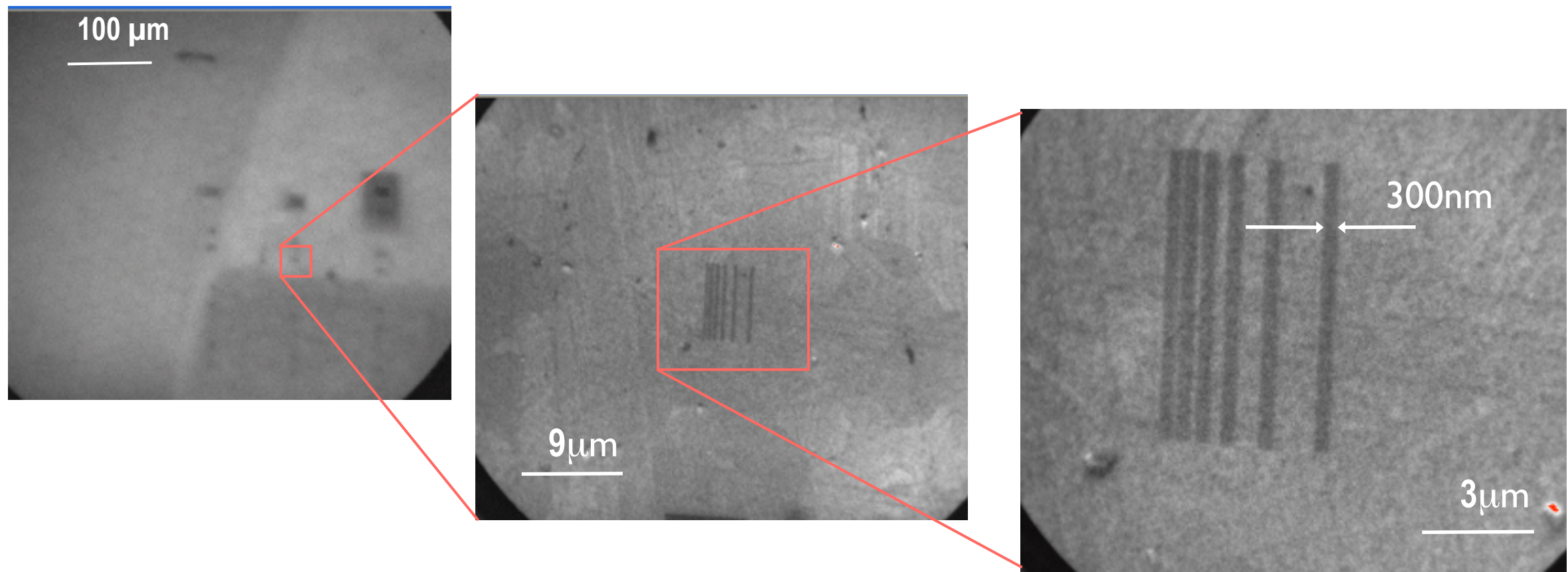
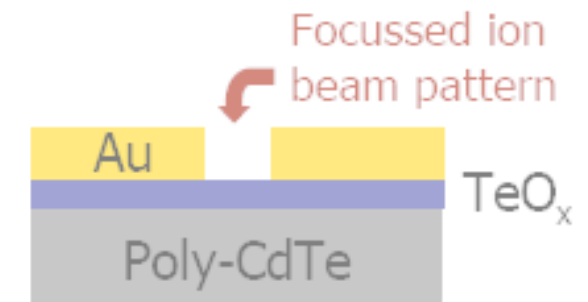
➤ Patented concept of NanoESCA

- IDEA aberration corrected band pass energy filter
- Compensation of first analyser by second analyser allows large slits (1-2mm) and small pass energy
- No intermixing of spatial and energy information
- Result: high transmission imaging energy analyser



➤ Synchrotron results (ESRF ID08)

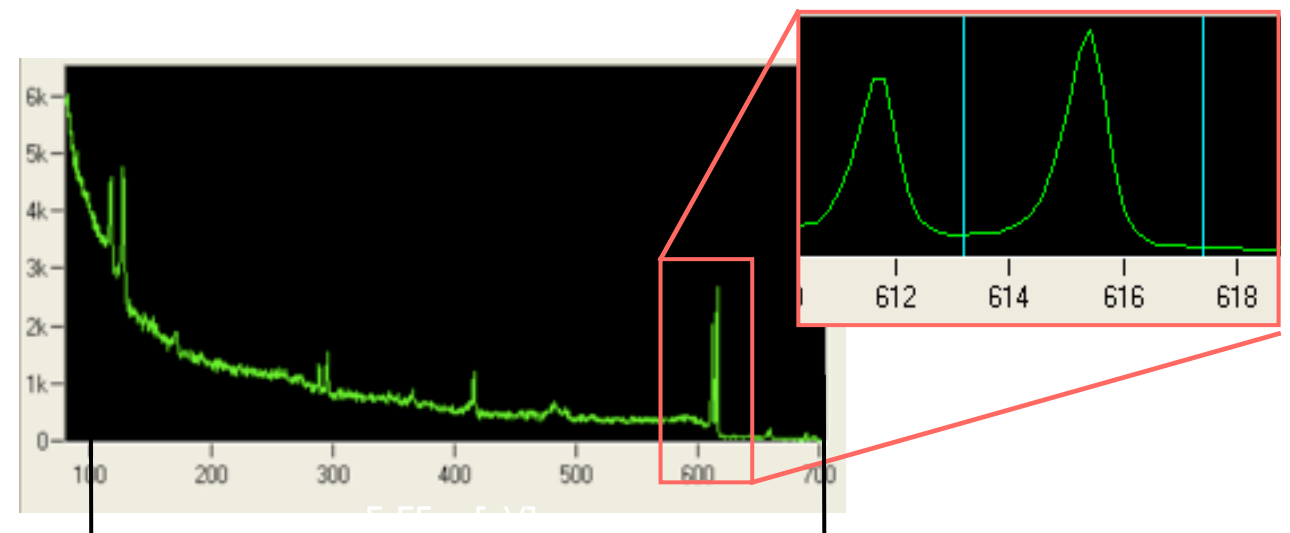
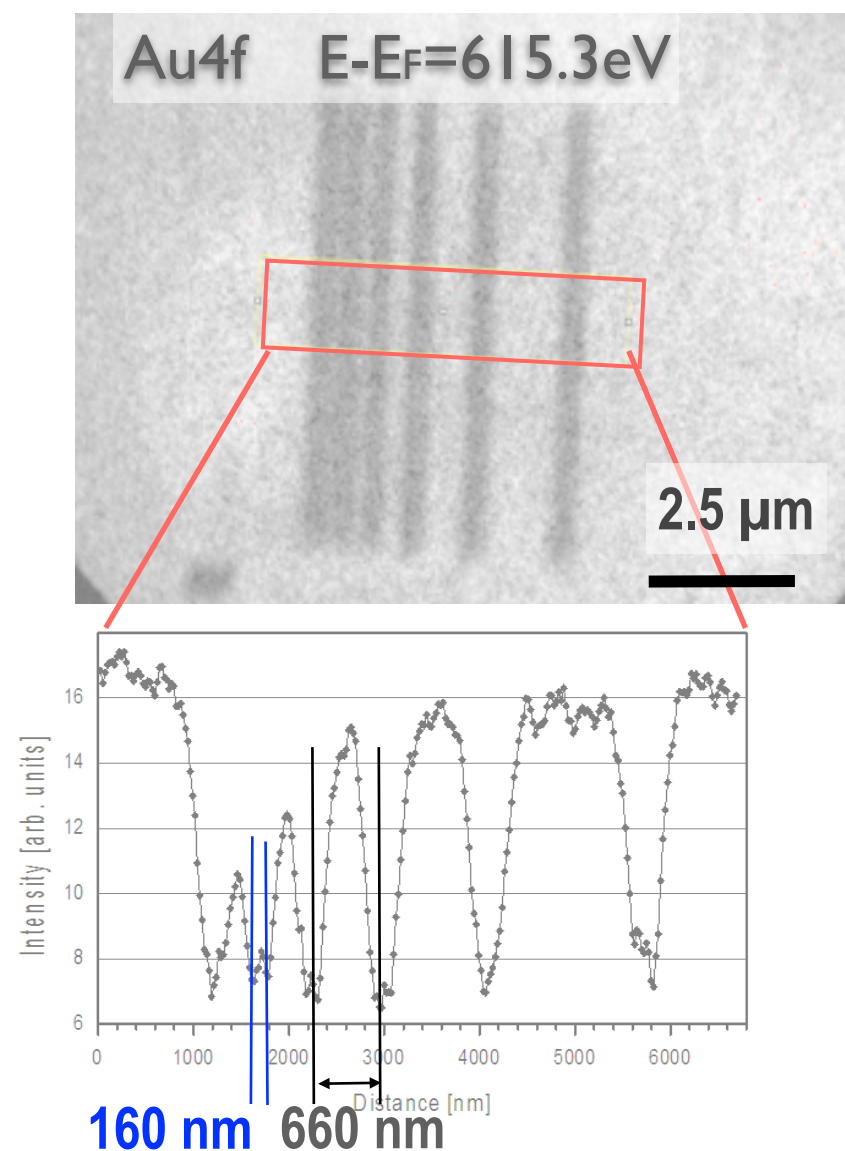
- **Select suitable pattern for XPS imaging: 300nm structures**
- **Secondary electron imaging with high resolution**
- **Microstructured sample (FIB ion milled) Au on CdTe**
- **Mercury arc lamp illumination**



Commissioning at LETI

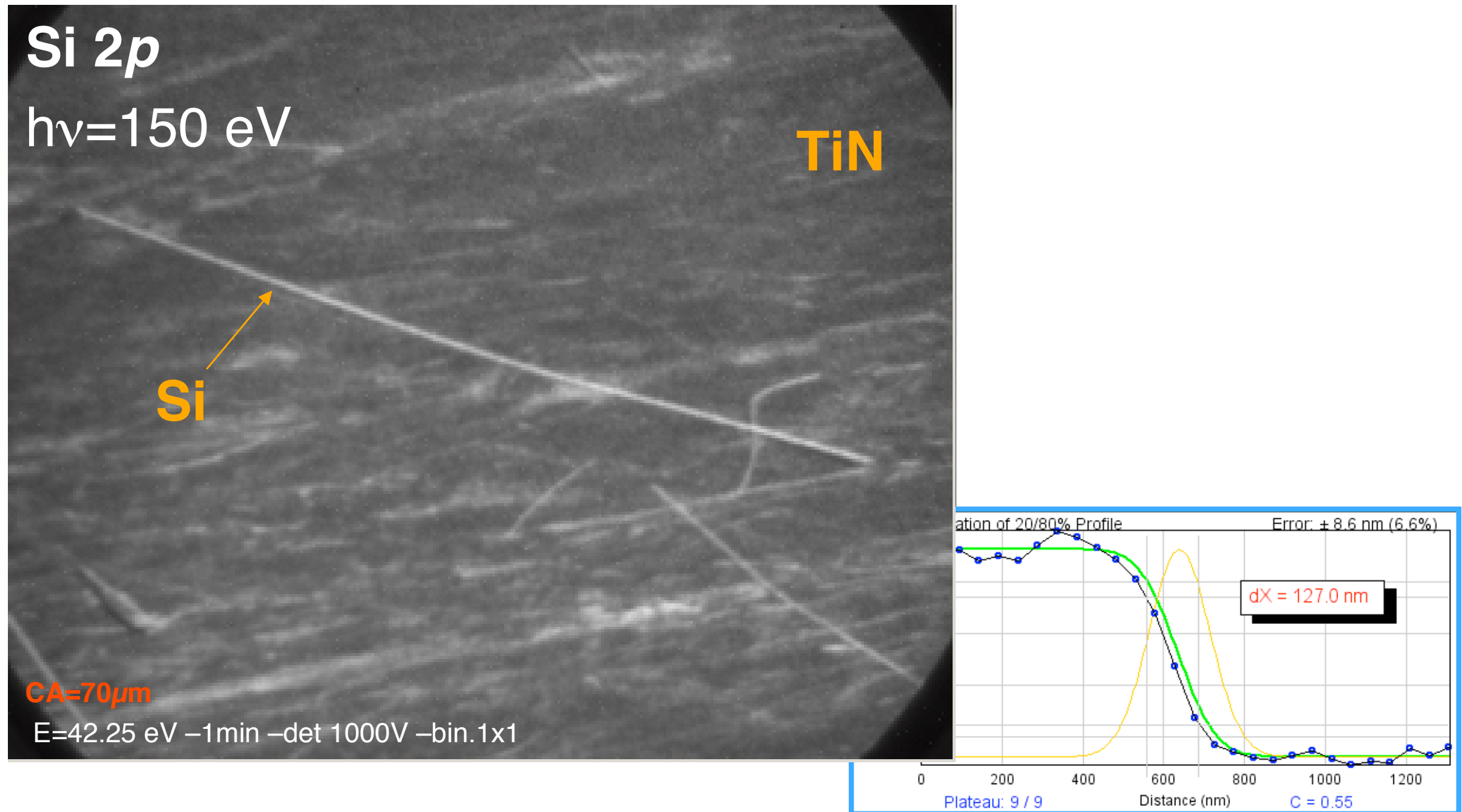
➤ Synchrotron Results (ESRF ID08)

- Synchrotron illumination $h\nu = 700\text{eV}$
- Fast overview spectrum with channeltron® to locate Au4f peak



- **Ultimate XPS resolution: 160nm**
- **15 min per image**

Commissioning at LETI!

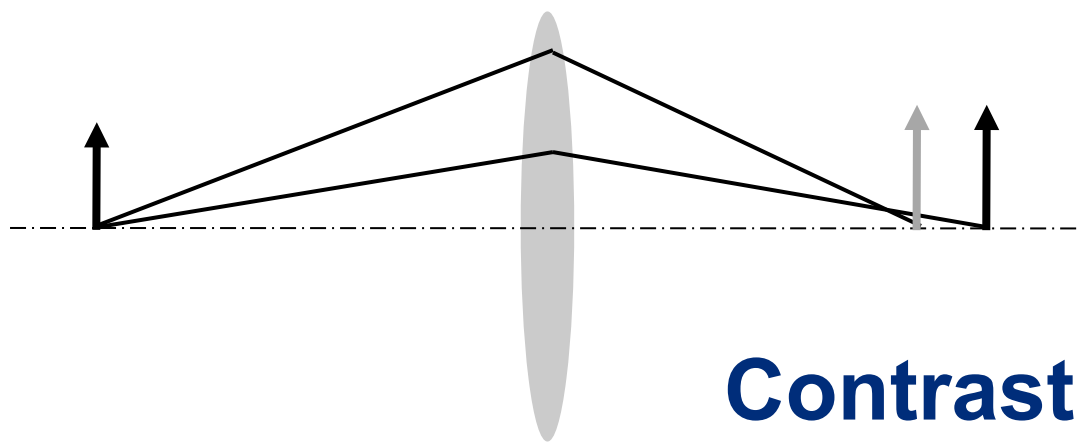


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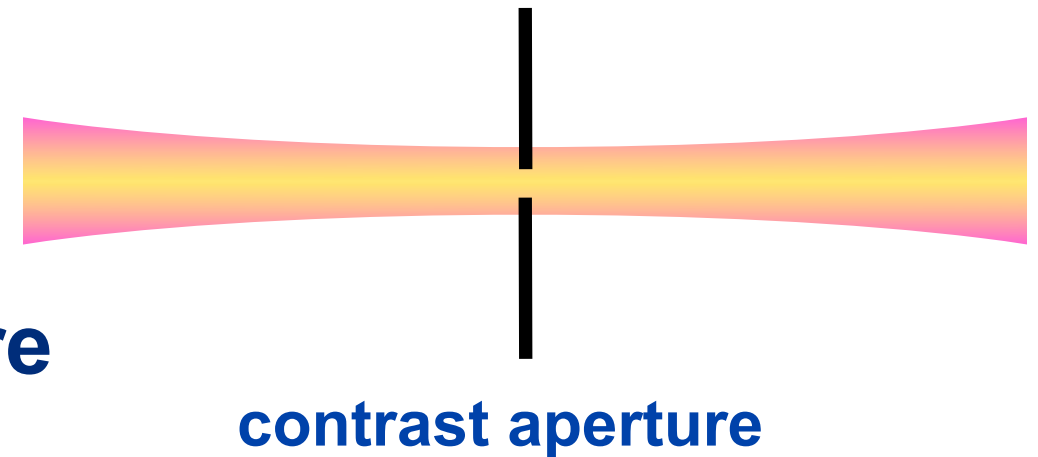
- imaging with Si 2p photoelectrons
- width of wire <127 nm



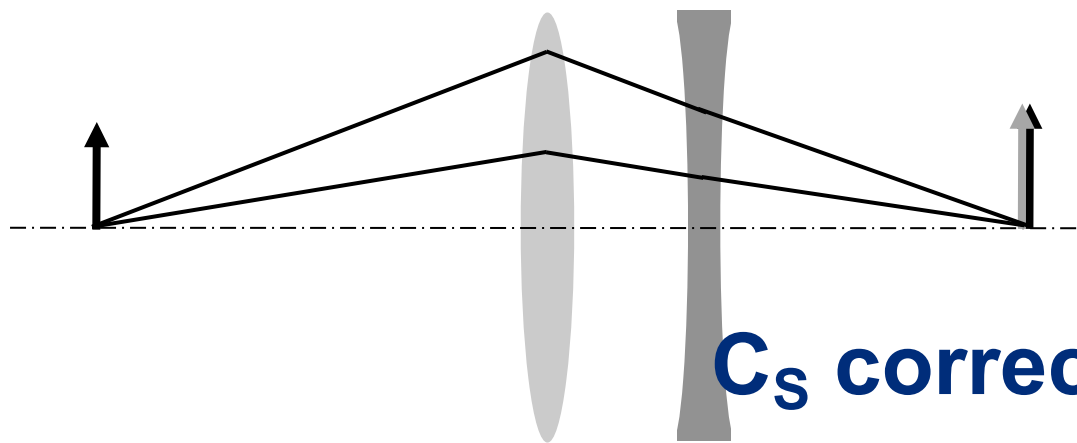
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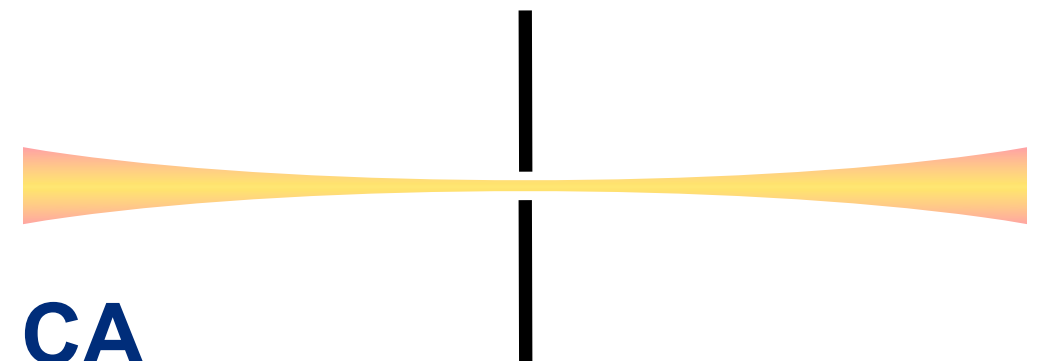
Contrast aperture



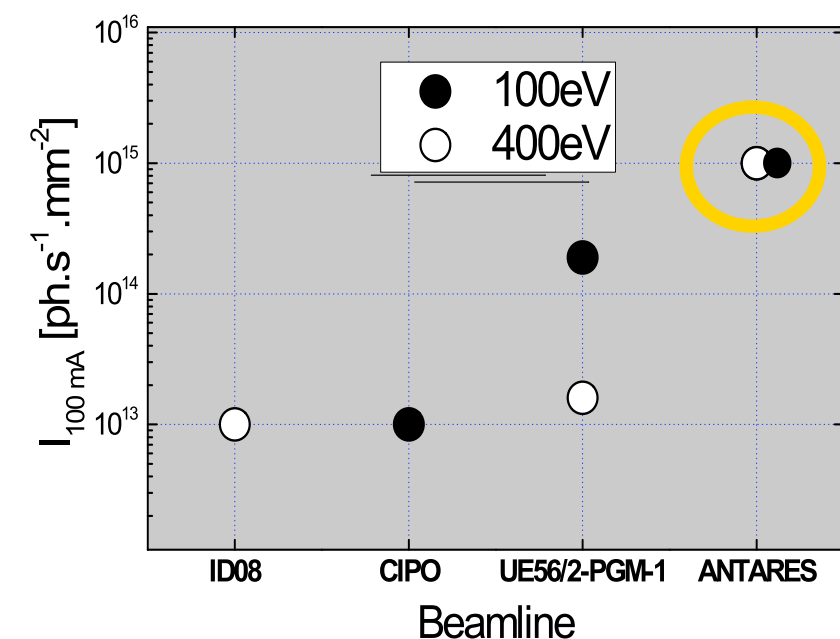
contrast aperture

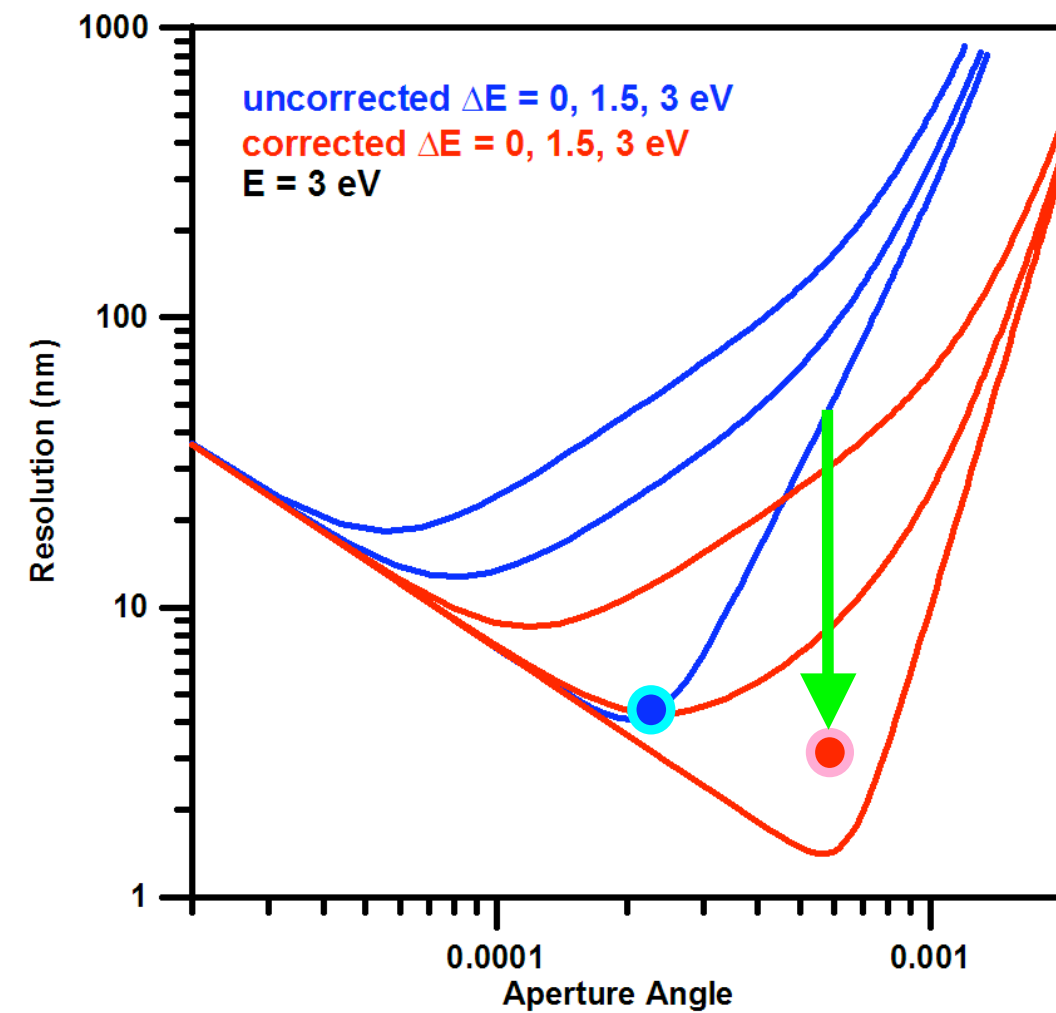
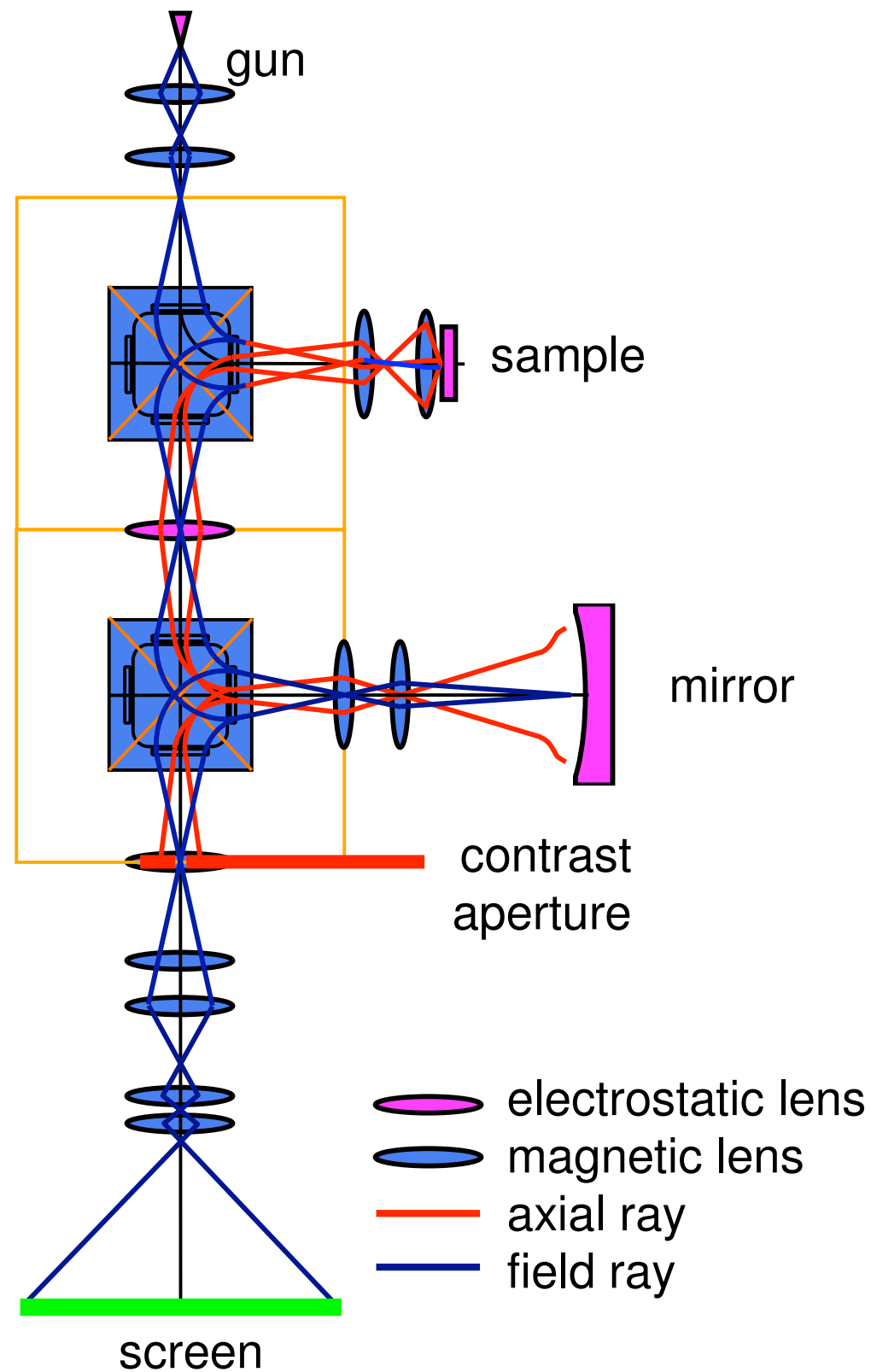


C_s corrector and CA

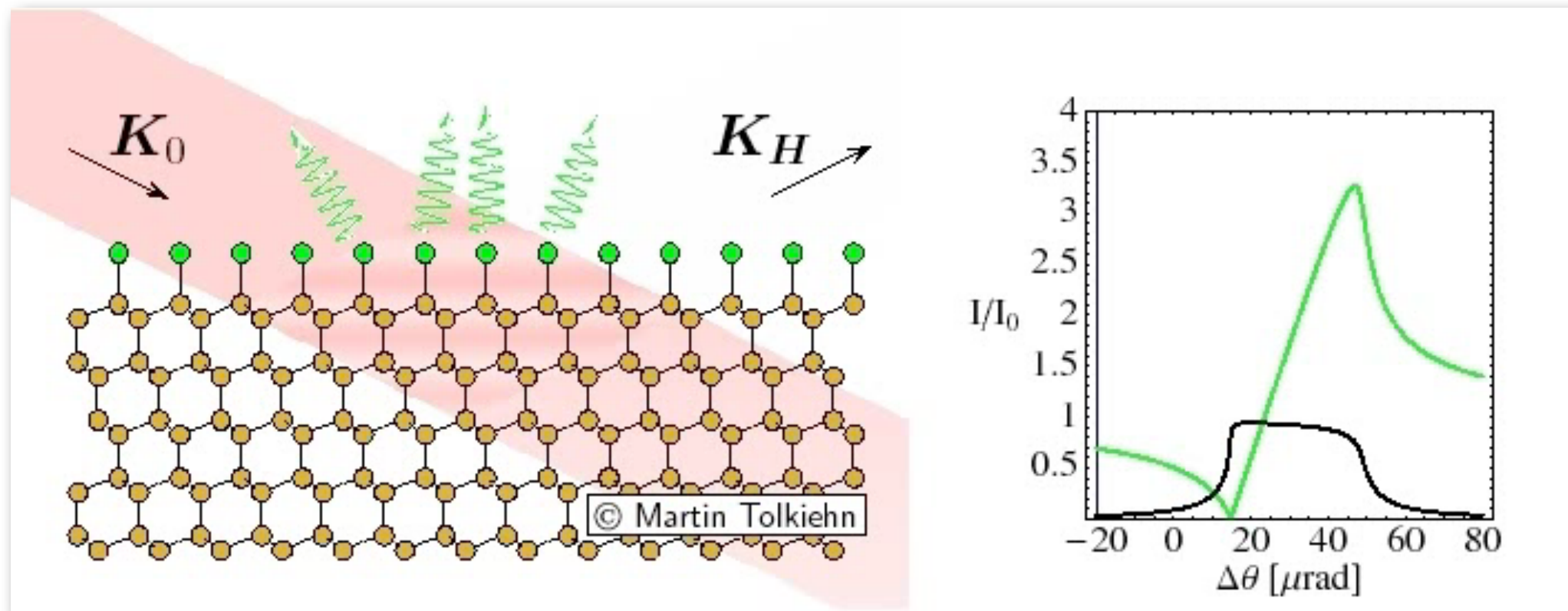


Increase transmission ~ factor 5
Attention: *space-charge at surface or in bfp of PEEM...*

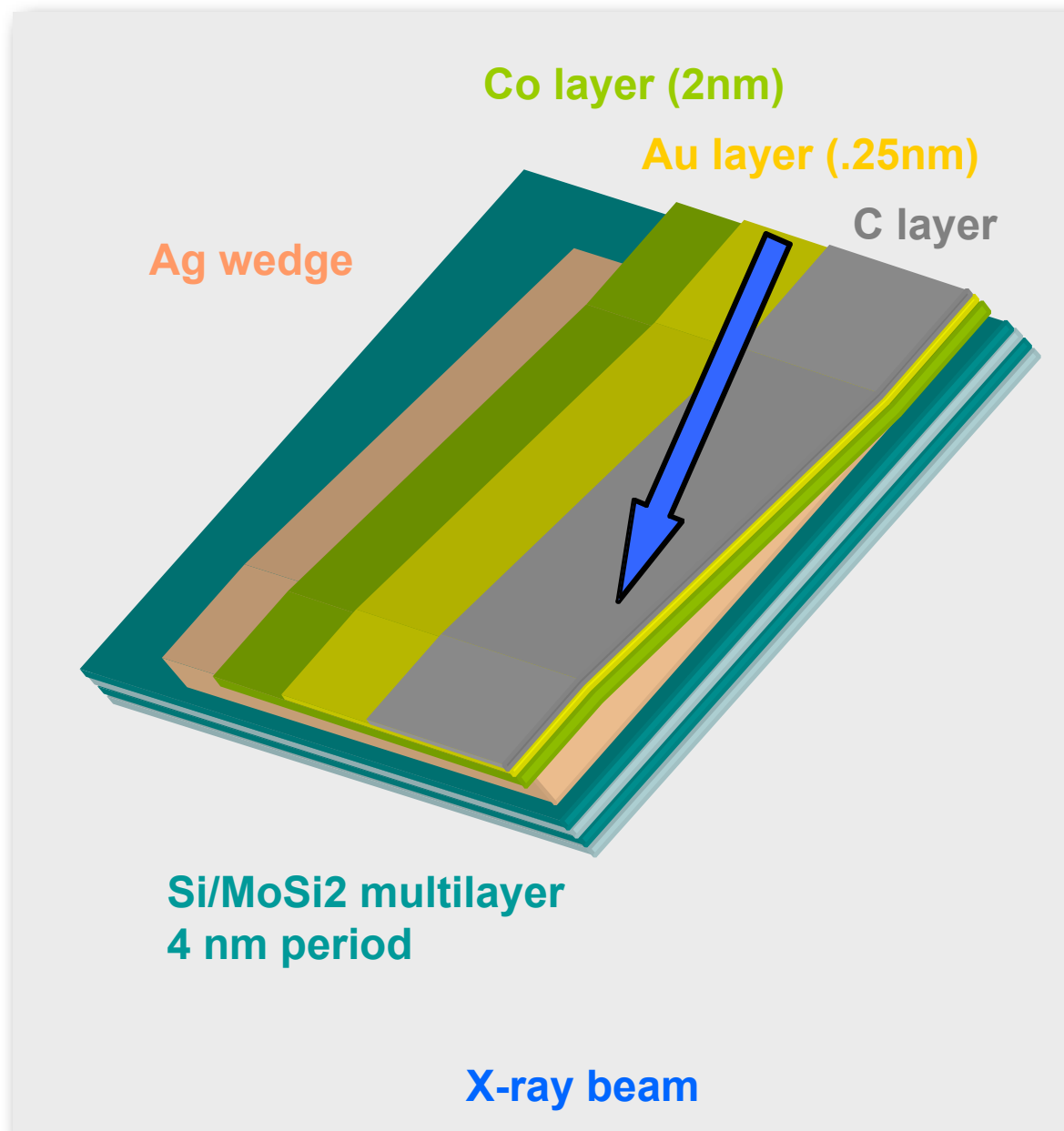




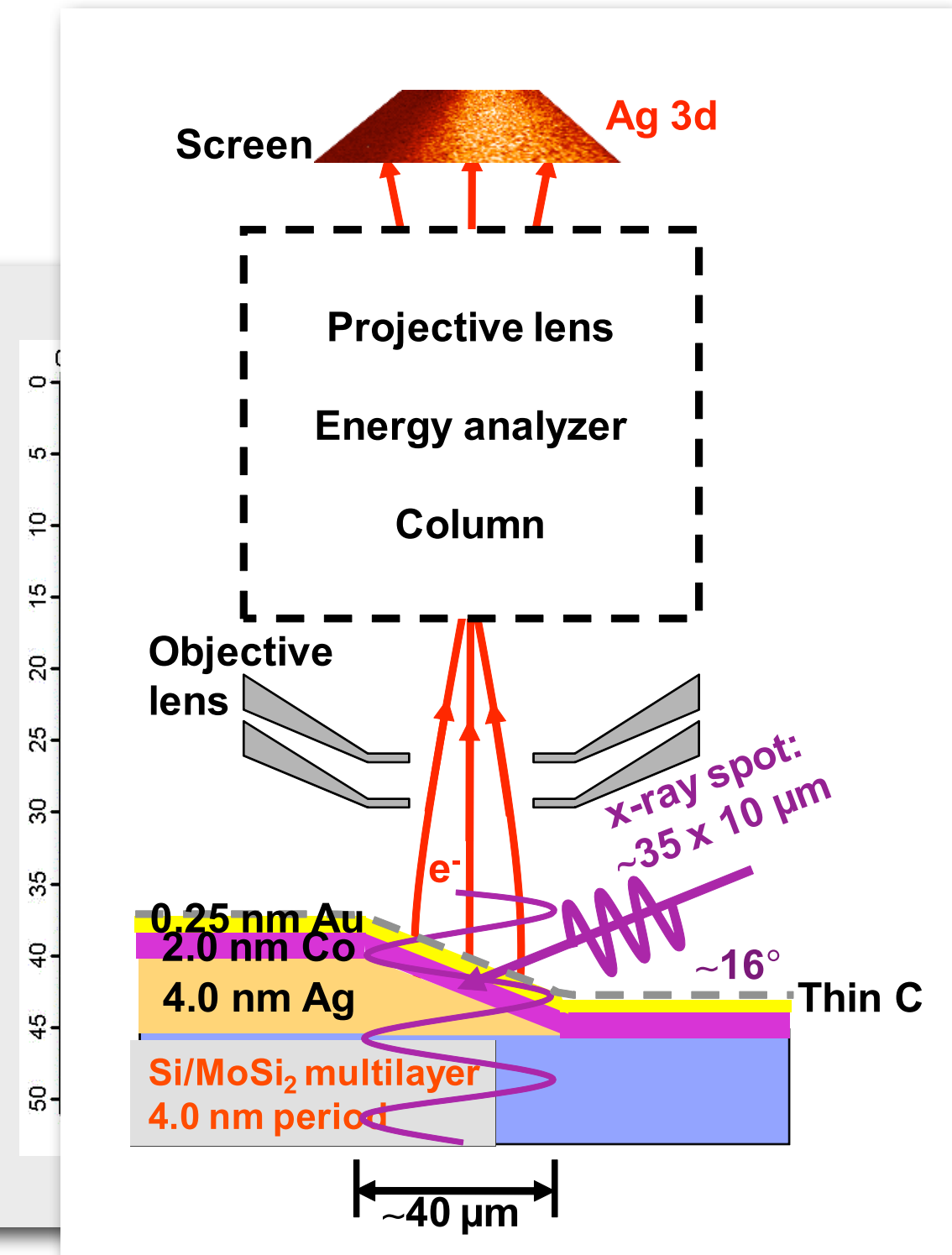
- resolution tested in LEEM
- improvement (Jun 2009) by a factor of 2
- improvement of transmission by a factor of 10!



- standing wave field at the surface at Bragg angle
- modulation of wave field intensity via photon energy or the angle of incidence
- multilayer mirror transposes XSW approach into the soft x-ray regime

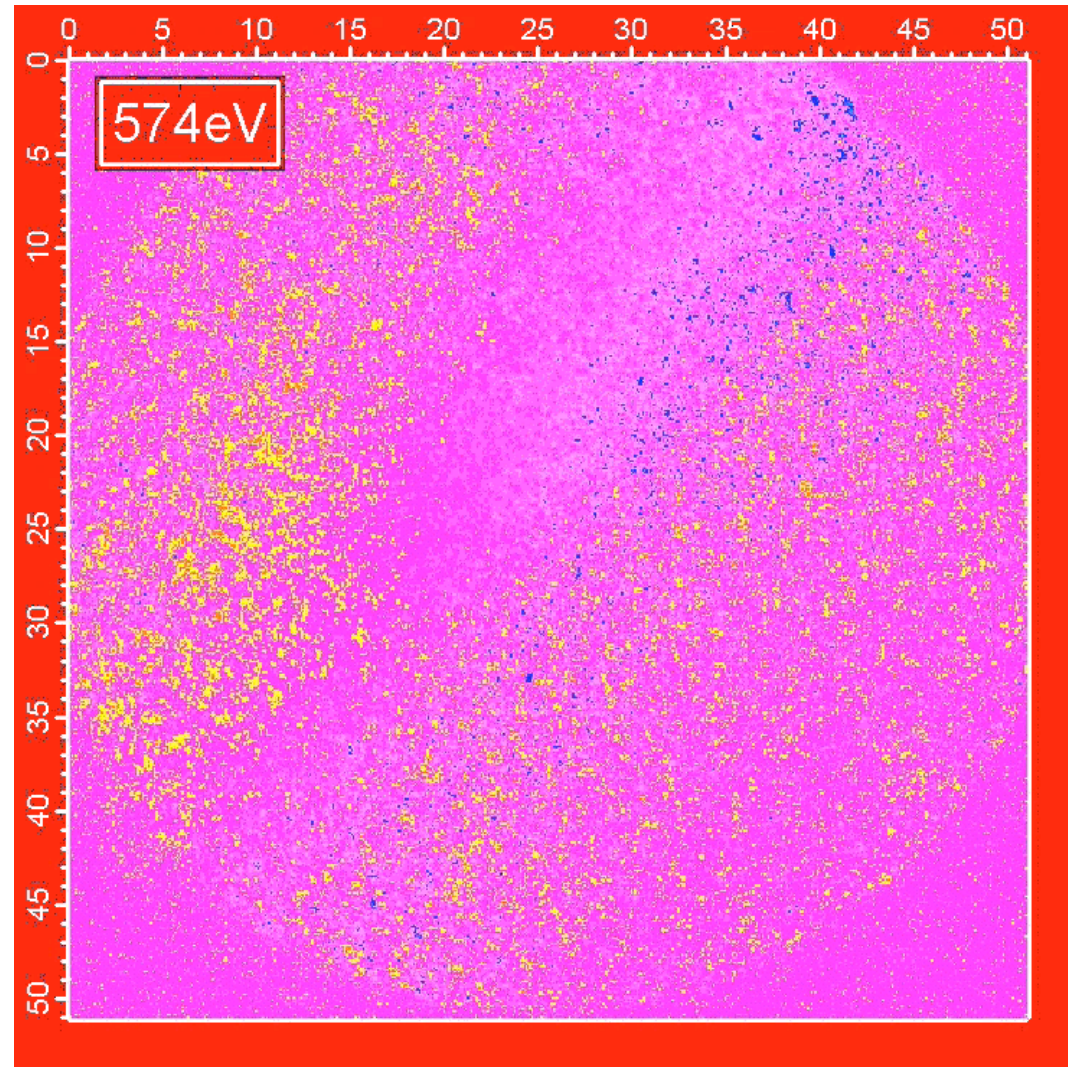


- Si/MoSi₂ multilayer
- Ag wedge 0 ... 17 nm
- PEEM with energy filtering ⇒ direct photoemission
- imaging the Ag intensity distribution

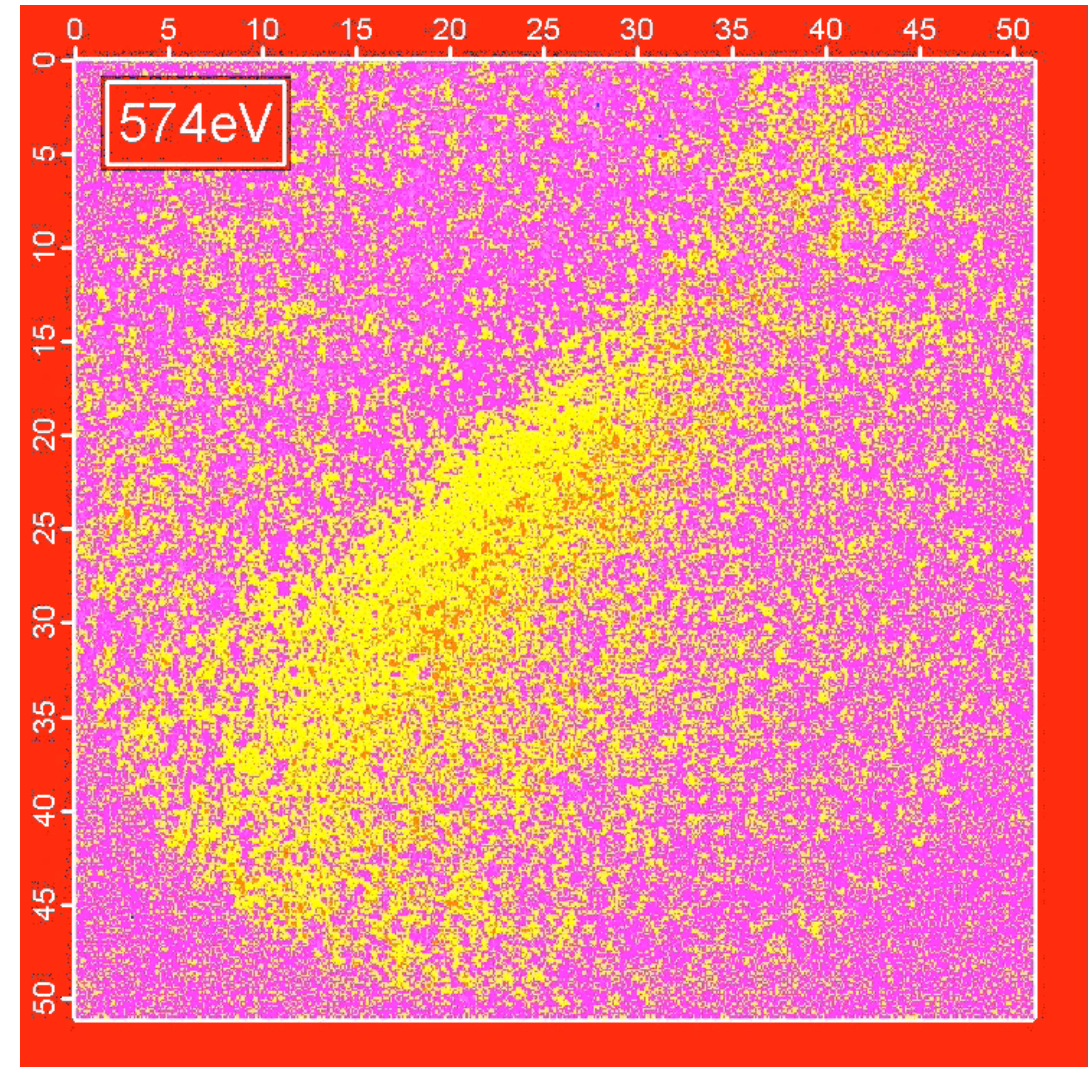




Ag 3d



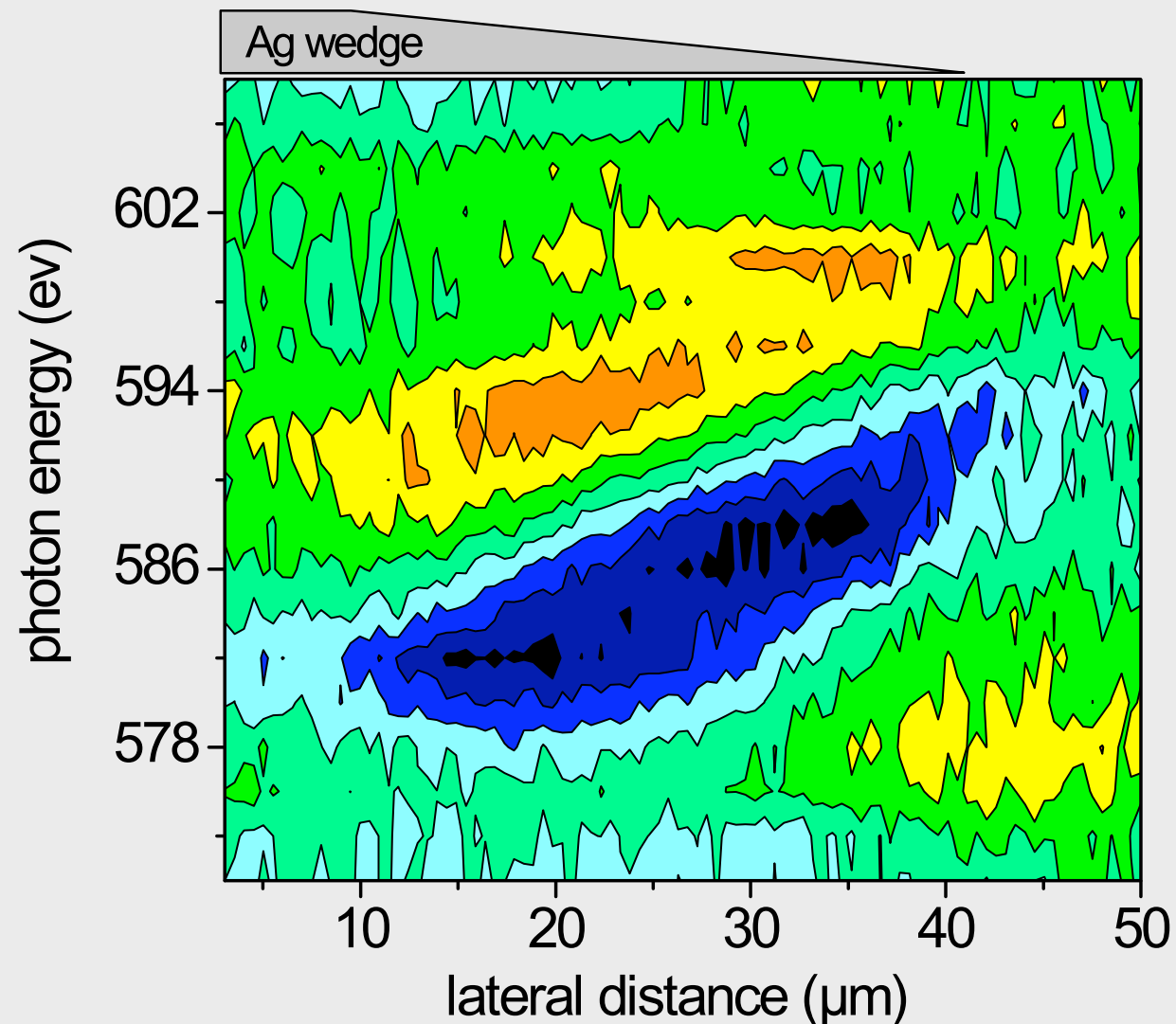
C 1s



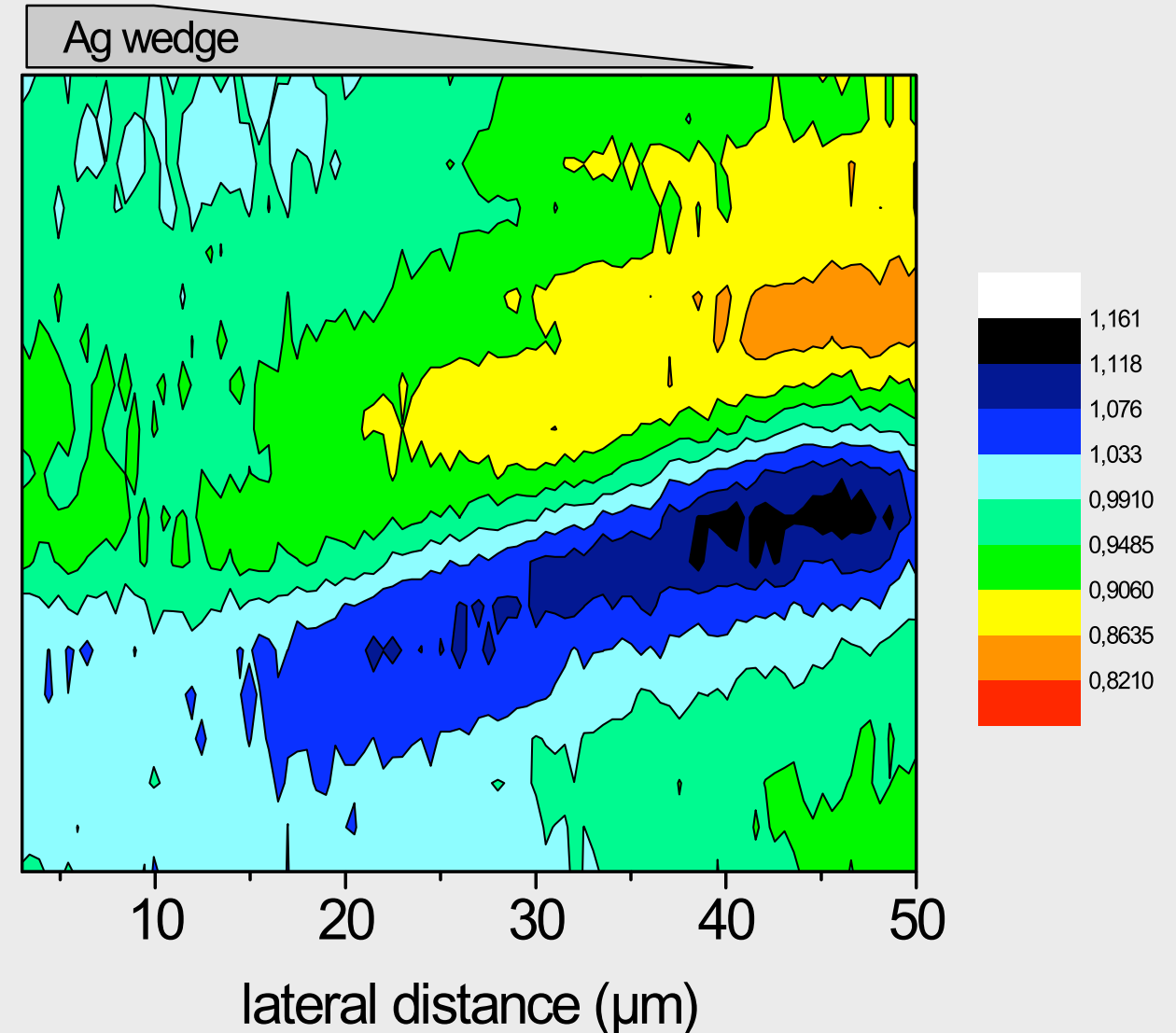
- spectral mapping of the intensity distribution along the wedge
- lateral shift of the photoemission maximum Ag 3d and C 1s as a function of photon energy
- clear indication of the standing wave character



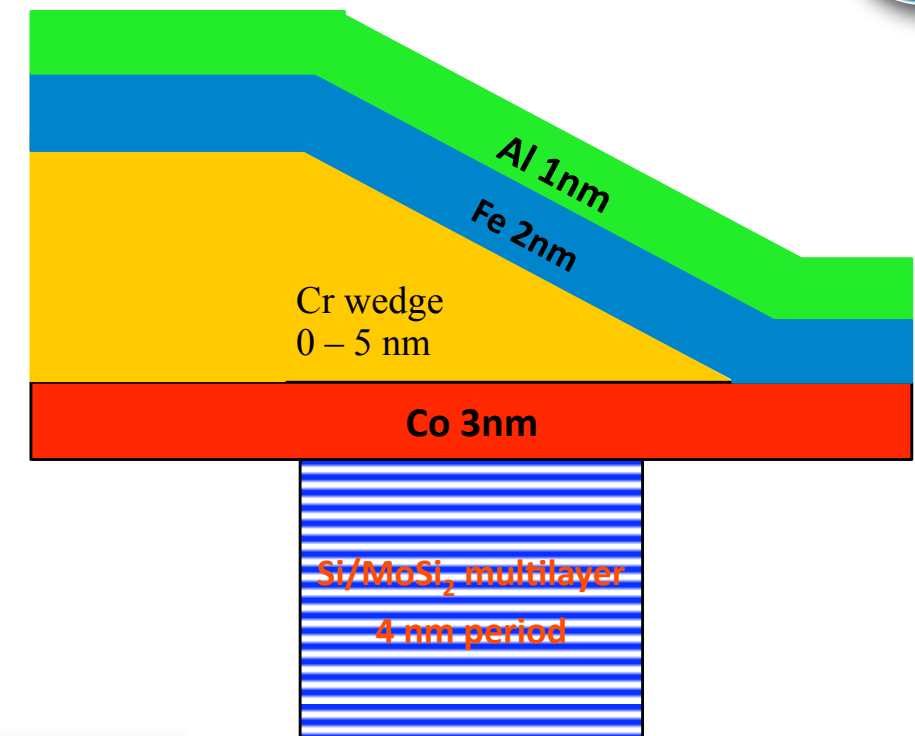
Ag 3d intensity



C 1s intensity

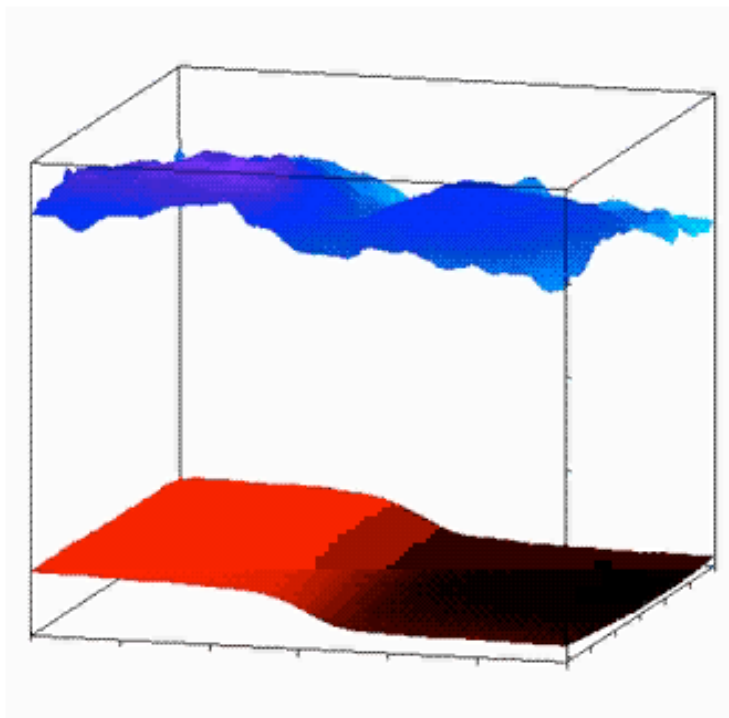


- maximum and minimum of the XSW depending on photon energy
- lateral shift of the photoemission maximum Ag 3d and C 1s as a function of photon energy

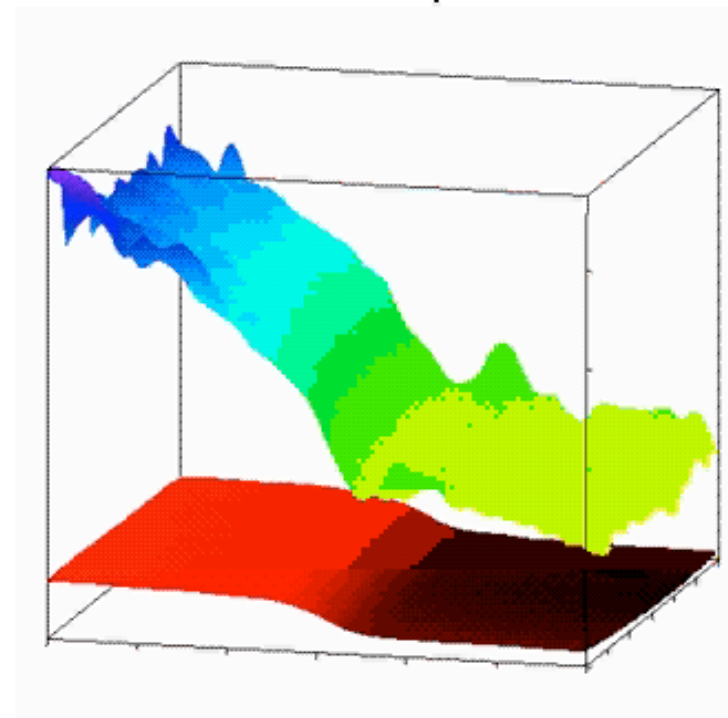


580eV

C 1s



Fe 3p



Cr wedge

5μm

What you should take home!



- ★ XPEEM = special case of electron emission microscopy (EEM)
- ★ chemical selectivity $\Rightarrow$ spectroscopic imaging
- ★ information depth = several nanometers
- ★ current lateral resolution $\sim 50\text{nm}$ with x-rays
- ★ ideally suited for investigation of complex systems
- ★ access to ferromagnetism via XMCD
- ★ access to antiferromagnetism via XMLD
- ★ intrinsic time-resolution via time structure of the synchrotron radiation

