Photo **emission** electron microscopy

Outline

Introduction

Electron optics:
Resolution
Transmission

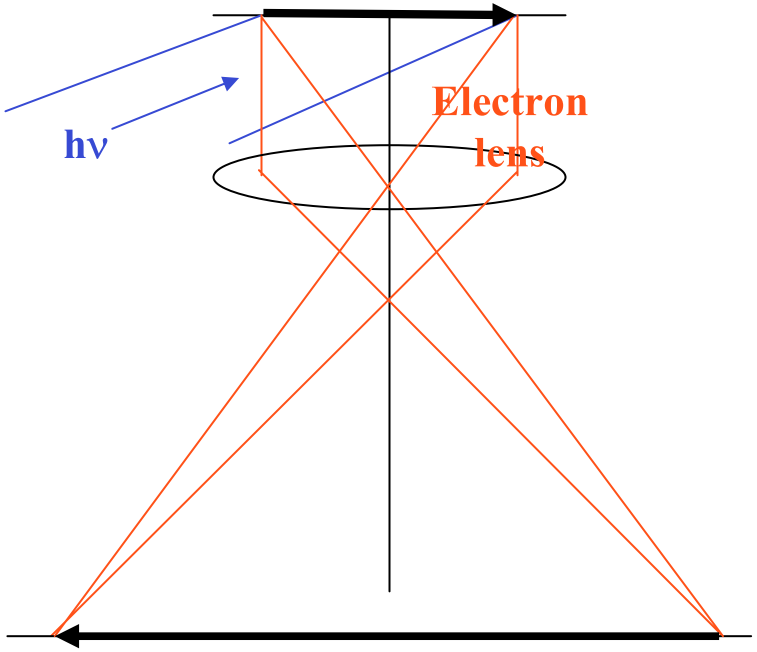
Instruments:
PEEM
PEEM + LEEM
SPELEEM

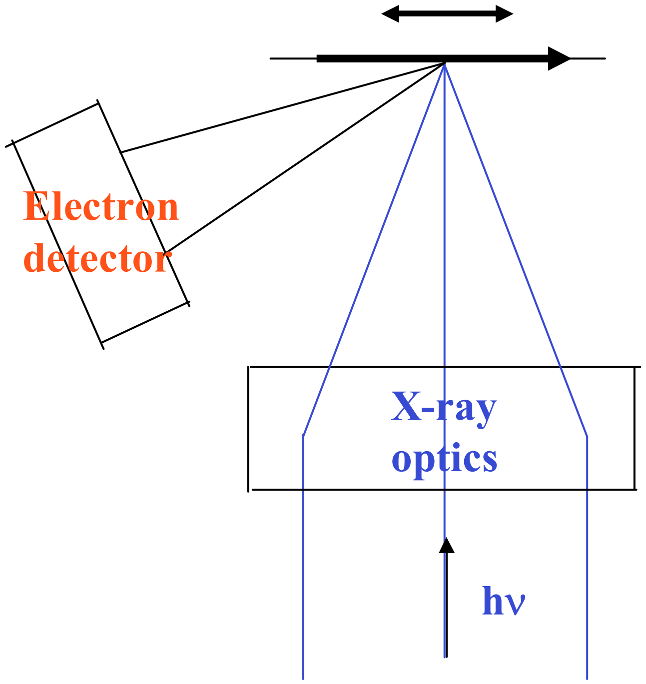
Methodic

Applications:
Magnetic imaging

Photo Emission Electron Microscopy (PEEM)

2 types





broad illumination

Full field

sample fixed

Bauer, Locatelli

PEEM

focused illumination

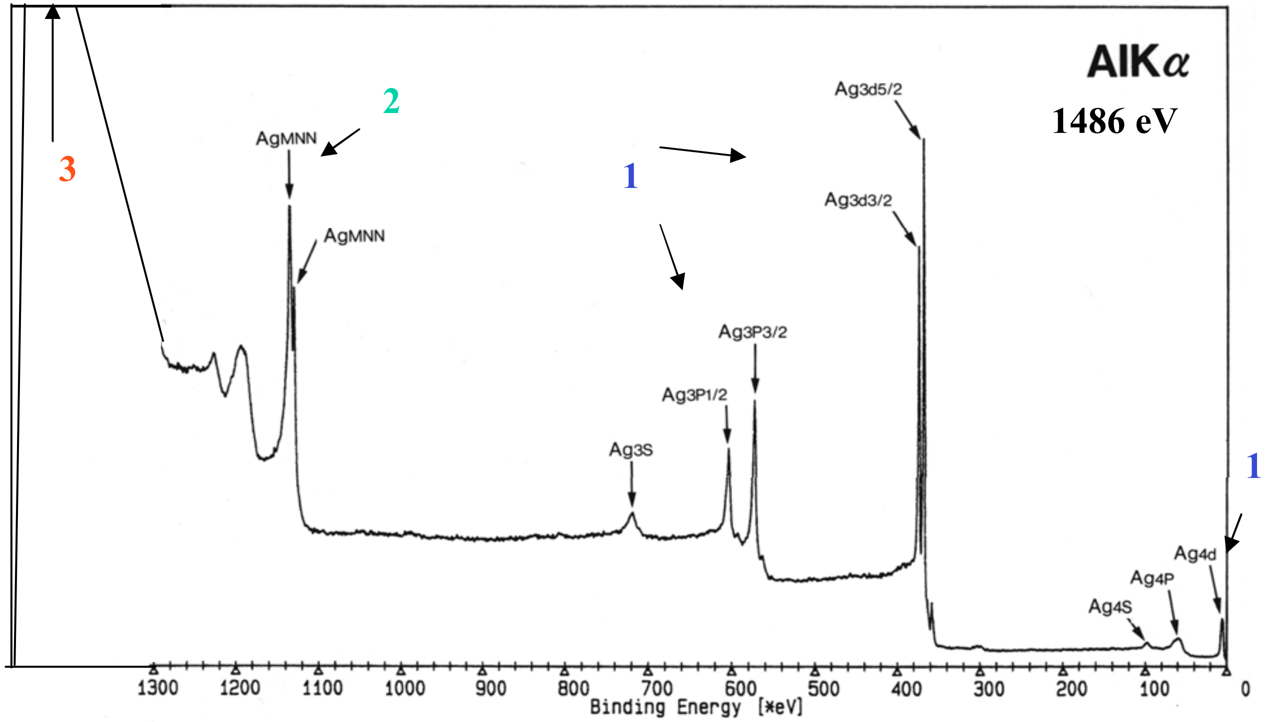
Scanning

sample scanned

Kiskinova

3 imaging modes

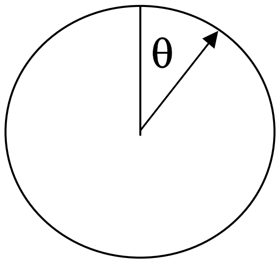
1	XPEEM	Photo electrons PE	with energy filter
2	XAEEM	Auger electrons AE	with energy filter
3	XSEEM	Secondary electrons SE	



Angular distribution

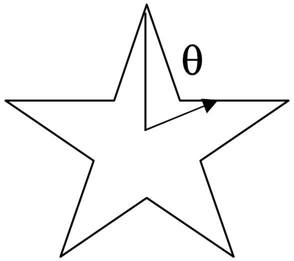
Internal

Amorphous, polycrystalline, SE



$I_i(\theta)$ = const.

single crystalline, PE, AE

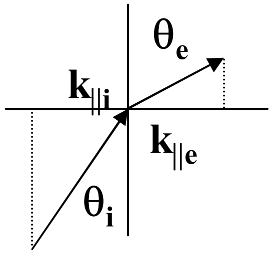


$I_i(\theta)$ due to diffraction

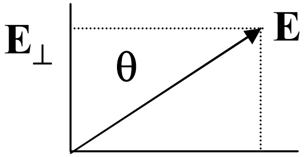
Internal (i) → External (e)

$n \sim \frac{\sqrt{E}}{\sqrt{E+V_0}}$

Refraction



$k_{||}$ conservation $k_{||e} = k_{||i}$

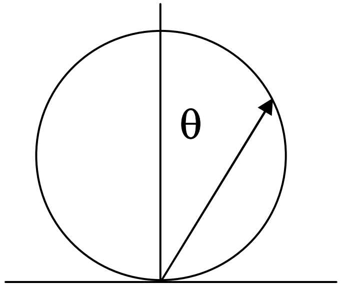


$E_\perp = E \cos\theta$

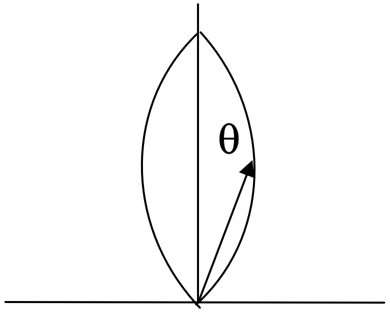
For escape necessary:

$E_\perp > \Phi$ (work function)
I (ionization energy)
U (HOMO)

External



$I_e(\theta) = \cos\theta$



Electron optics

The cathode lens

In emission microscopy $\theta \equiv \alpha_0$ is large

Electron lenses can accept only small $\theta \equiv \alpha_0$ because of large chromatic and spherical aberrations

Solution of problem: accelerate electrons to high energy before lens

↓

Immersion objective lens = cathode lens

$$n \sin\theta = \text{const}$$

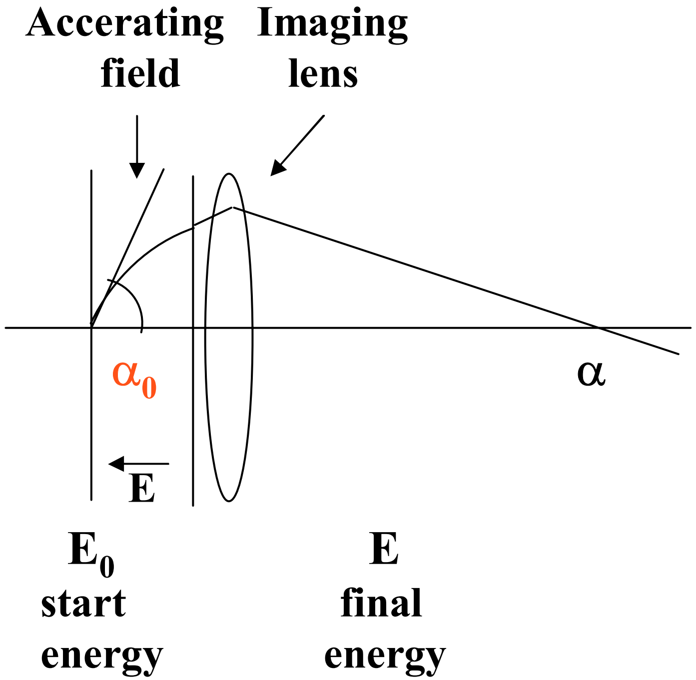
$$n \sim v \sim \sqrt{E}$$

$$\theta \rightarrow \alpha$$

$$\boxed{\sin\alpha / \sin\alpha_0 = \sqrt{E_0/E}}$$

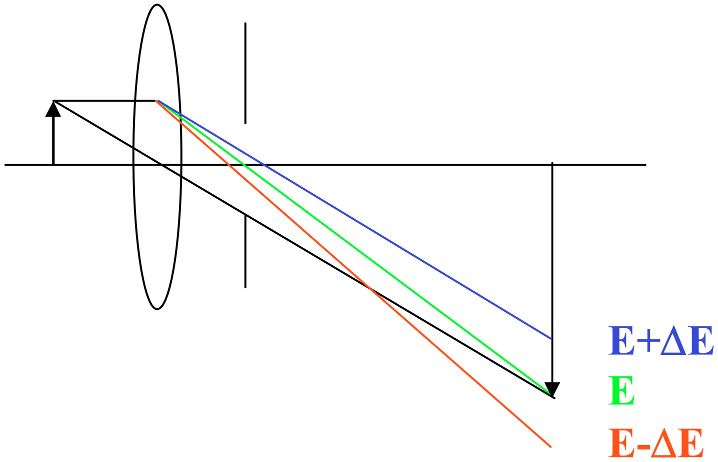
Example for E = 20000 eV:

E_0	2 eV	200 eV
α for $\alpha_0 = 45^\circ$	0.4°	4.5°



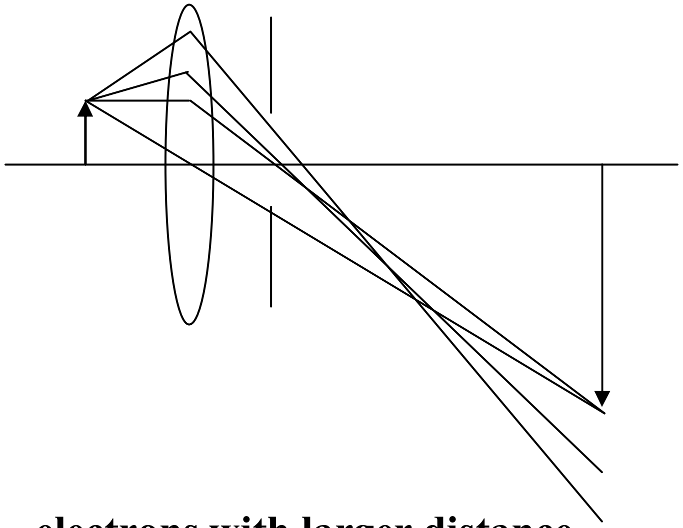
Aberrations

chromatic



slower (faster) electrons
are more (less) deflected

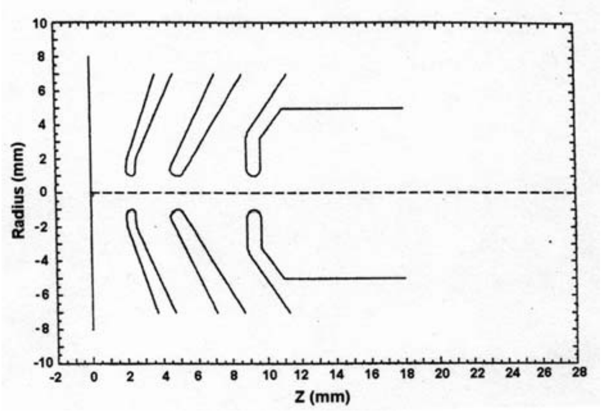
spherical



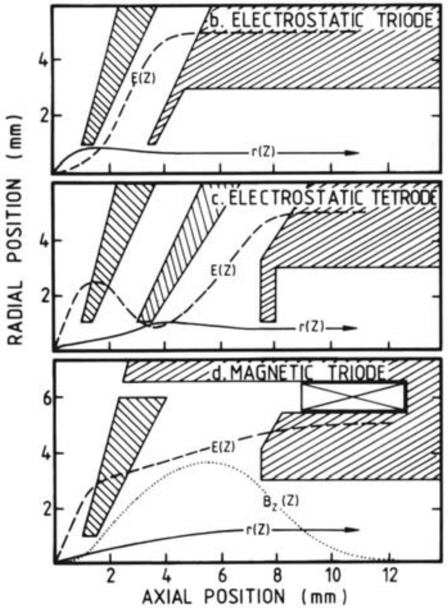
electrons with larger distance
from axis are more deflected
(stronger field!)

Cathode lens types

Electrostatic tetrode

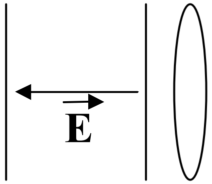


Lens comparison



Magnetic diode

Estimation of aberrations:
Separate lens into acceleration and imaging regions



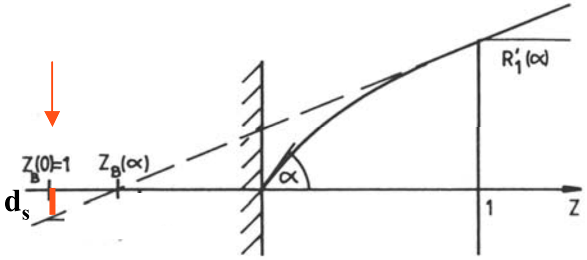
At low energies the aberrations of the accelerating region dominate

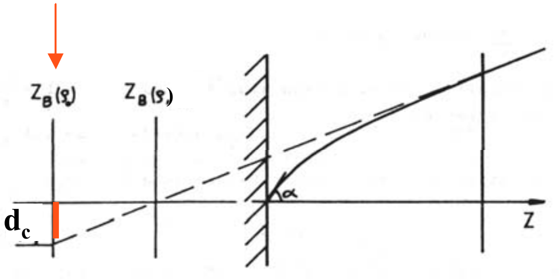
Aberrations of homogeneous acceleration field

$\rho_0 = E_0/E \quad \varepsilon = \Delta E_0/E \quad \rho = \rho_0 + \varepsilon$

Spherical aberration d_s

Chromatic aberration d_c





Analytical solution

Approximation: ρ_0 and $\varepsilon << 1/\cos \alpha^2 > 1$

Example: $E_0 = 100$ eV, $\Delta E_0 = 1$ eV, $E = 20000$ eV

$\varepsilon = \rho_0 /100, \; \rho_0 = 1/200$

$d_s \approx 2 \rho \sin \alpha \, (1 - \cos \alpha)$

$\approx \rho \, \alpha^3$ **for small α**

$d_c \approx 2 \rho \sin \alpha \, (\sqrt{\ } \rho_0 / \rho - 1)$

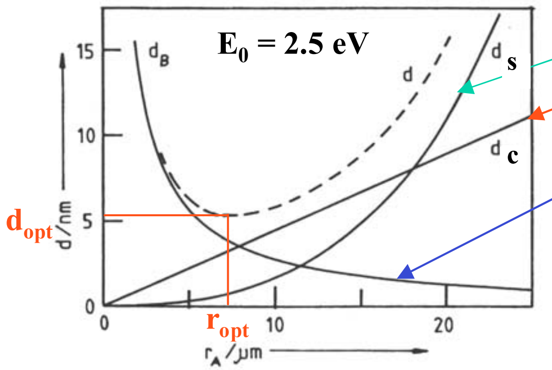
$\approx \varepsilon \sin \alpha$ **for $\varepsilon << \rho_0 \approx \rho$**

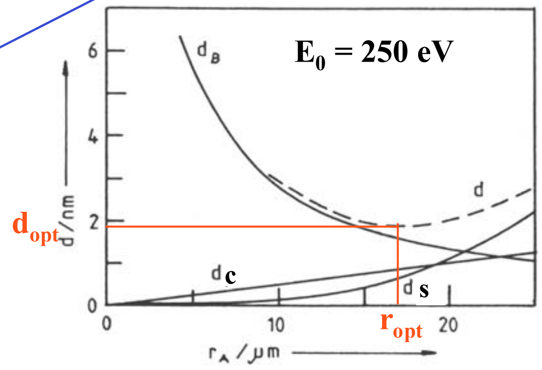
$\approx \varepsilon \, \alpha$ **for small α**

α-dependent aberrations require α-limitation by angle-limiting aperture (“contrast aperture”) with radius r_A

Diffraction by aperture: diffraction disc of confusion $d_B = 0.6\ \lambda / r_A$

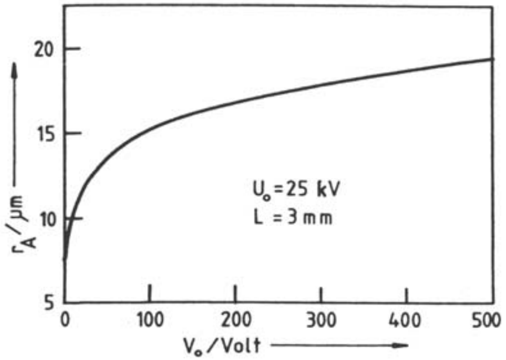
Approximate resolution $d = \sqrt{d_s^2 + d_c^2 + d_B^2}$



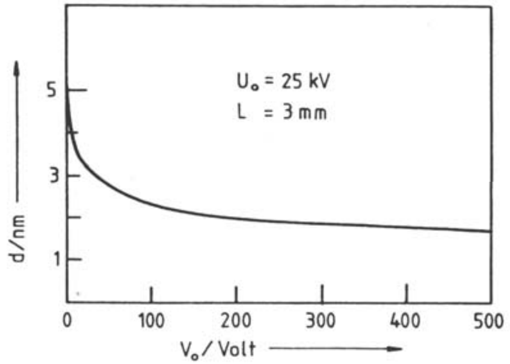


L = 3 mm   E = 25000 eV ΔE_0 = 0.25 eV

Optimum aperture radius



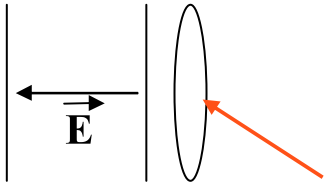
Optimum resolution



Note: small angle approximation sin α ≈ α ~ r

Complete lens

Combine acceleration and imaging regions



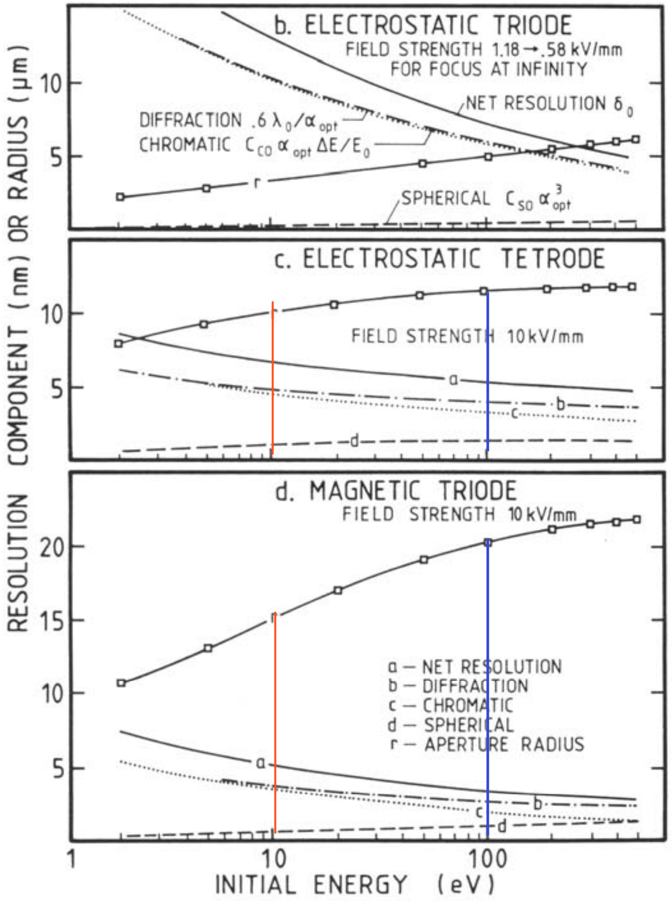
At low energies aberrations of accelerating region dominate

but

at high energies the spherical aberration of second part of lens becomes important

Resolution and optimum aperture of real lenses

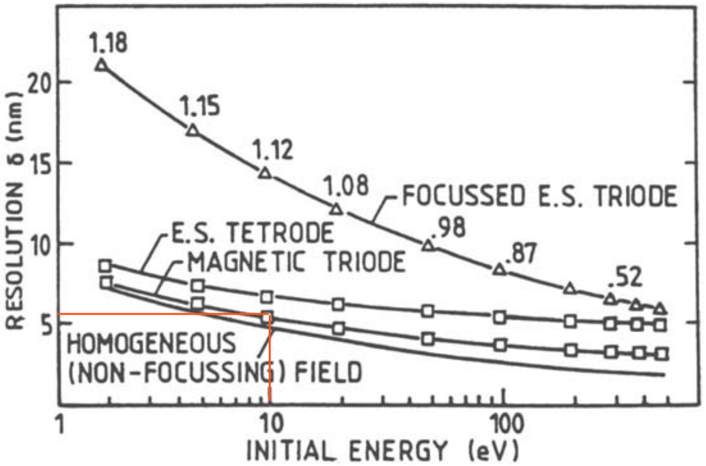
Optimum aperture r and resolution-limiting contributions



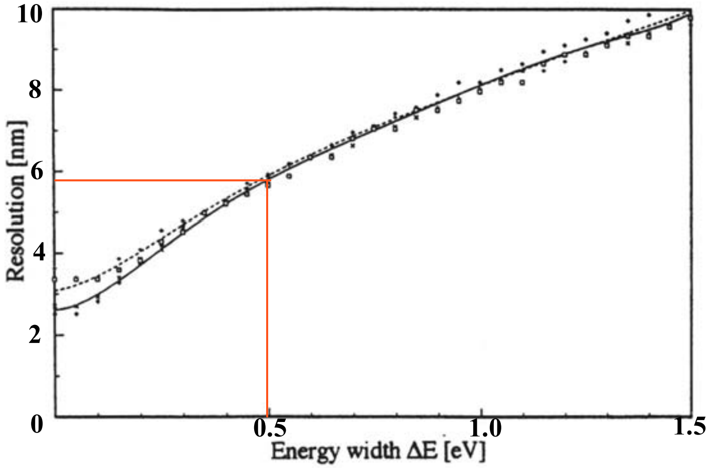
J. Chmelik et al, Optik 83 (1989)155

T. Müller, M.S. thesis, TU Clausthal 1995

Resolution with optimum aperture
E-dependence at fixed ΔE = 0.5 eV, U_0 = 20 keV



ΔE-dependence at fixed E = 10 eV, U_0 = 18 kV magnetic triode



Transmission

limited by angle accepted by contrast aperture (r_A)

Axial distance (in back focal plane) of electron starting at angle α

$r \approx f \sin\alpha \sqrt{E_0/E}$ (f focal length)

↓

$\sin\alpha \approx (r/f) \sqrt{E_0/ E}$

Examples for $f = 10$ mm, $E = 20000$eV, $r_A = 10$ μm

E_0	2 eV	200 eV
$\sin\alpha$	0.2	0.02
α	11.5°	1.15°

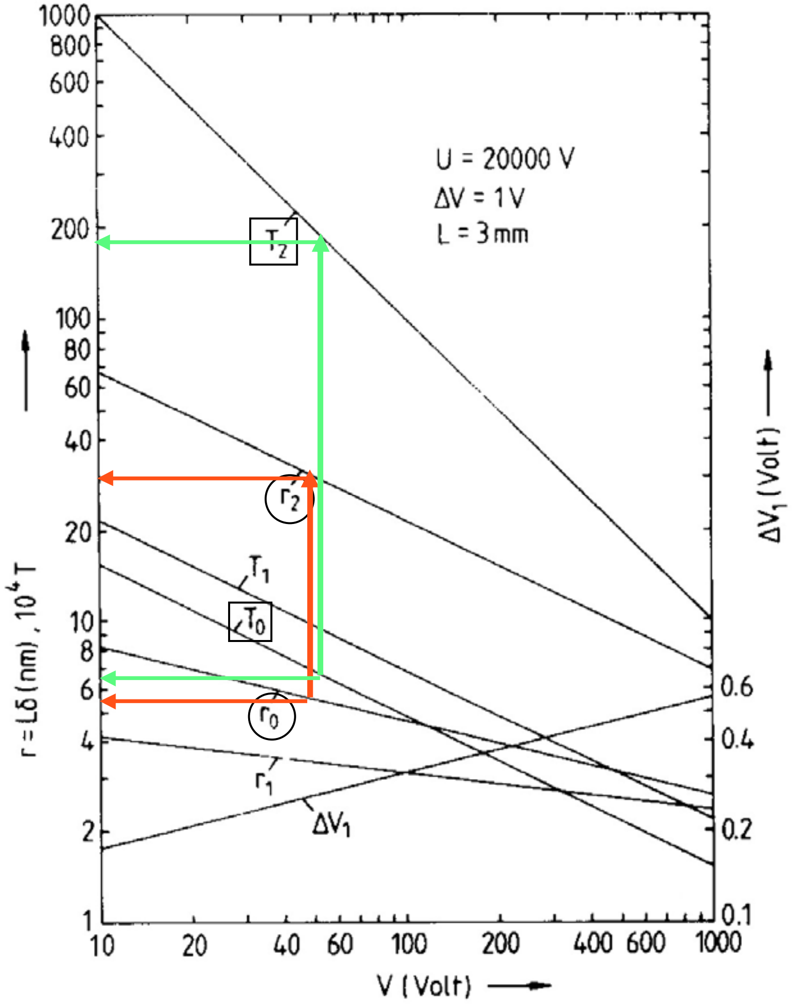
In emission microscopy (wide α range) optimum resolution condition reduces transmission T, therefore

optimize T^n/d^2 instead of $1/d^2$

For $\cos\alpha$ distribution $T = \pi \sin^2\alpha$

$T^n/d^2 = \pi \sin^{2n}/d^2$

Transmission T_n, resolution r_n of homogeneous field



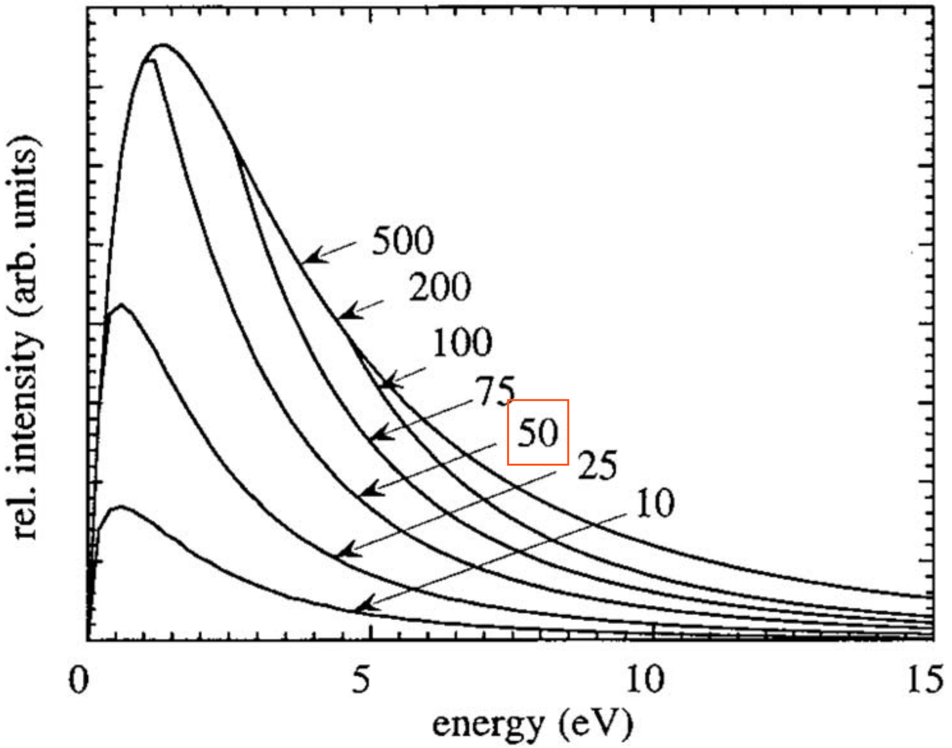
T_2

T and d equally weighted:

50 eV:
$\Delta T \cong 30$
$\Delta d \cong 5$

E. Bauer, Ultramicroscopy 36 (1991) 52

Influence of angle-limiting aperture on the energy distribution of secondary electrons

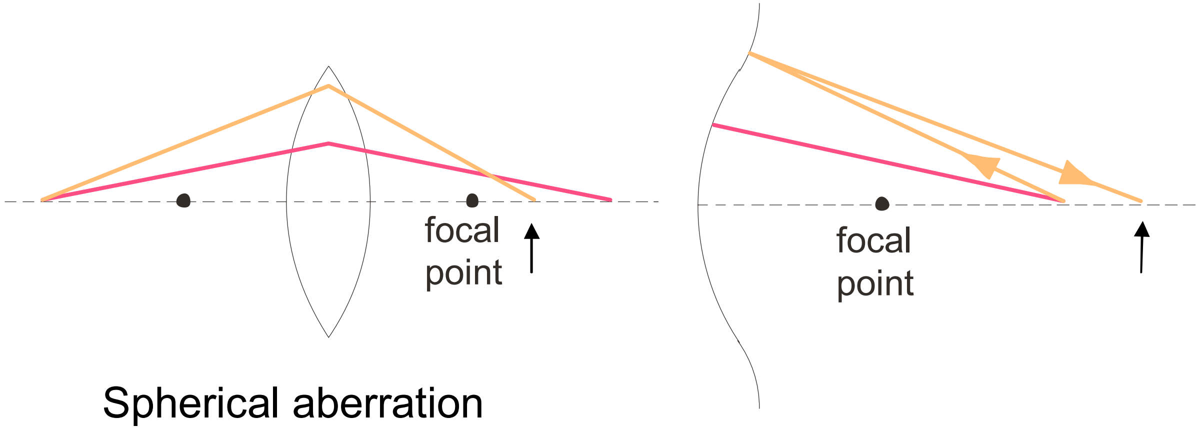


Work function $\Phi = 4$ eV, accelerating voltage $V = 20$ kV
Parameter: aperture diameter in μm, ALS PEEM

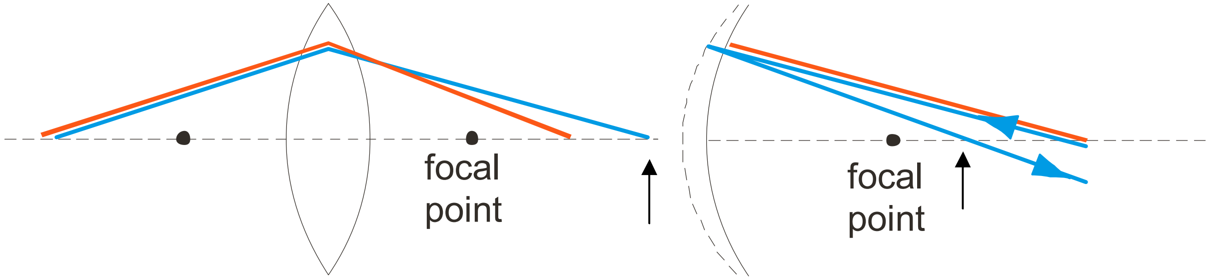
S. Anders et al, Rev. Sci. Instrum. 70 (1999) 3973

Aberration correction in electron optics

Round **convex** lenses **electrostatic mirror**

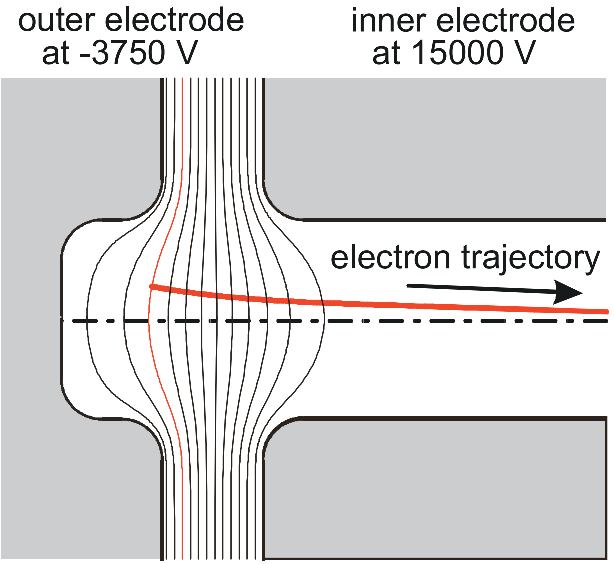


Spherical aberration



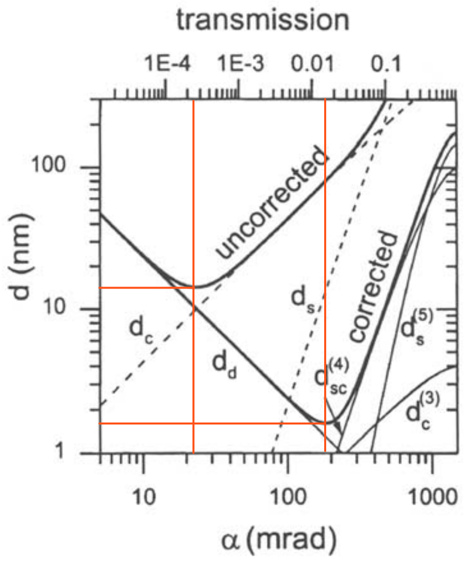
Chromatic aberration

Equipotential surfaces
in a diode mirror



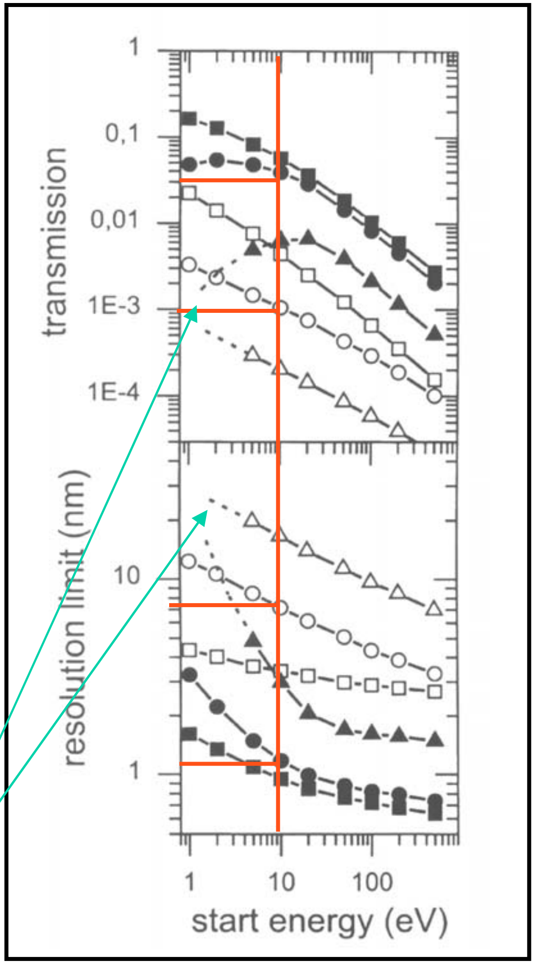
Resolution and transmission improvement with aberration correction

Example: SMART



E_0 = 10 eV, ΔE = 2 eV, F = 5 kV/mm

ΔE (eV)	without correction	with correction
0.1	□	■
1.0	○	●
5.0	△	▲

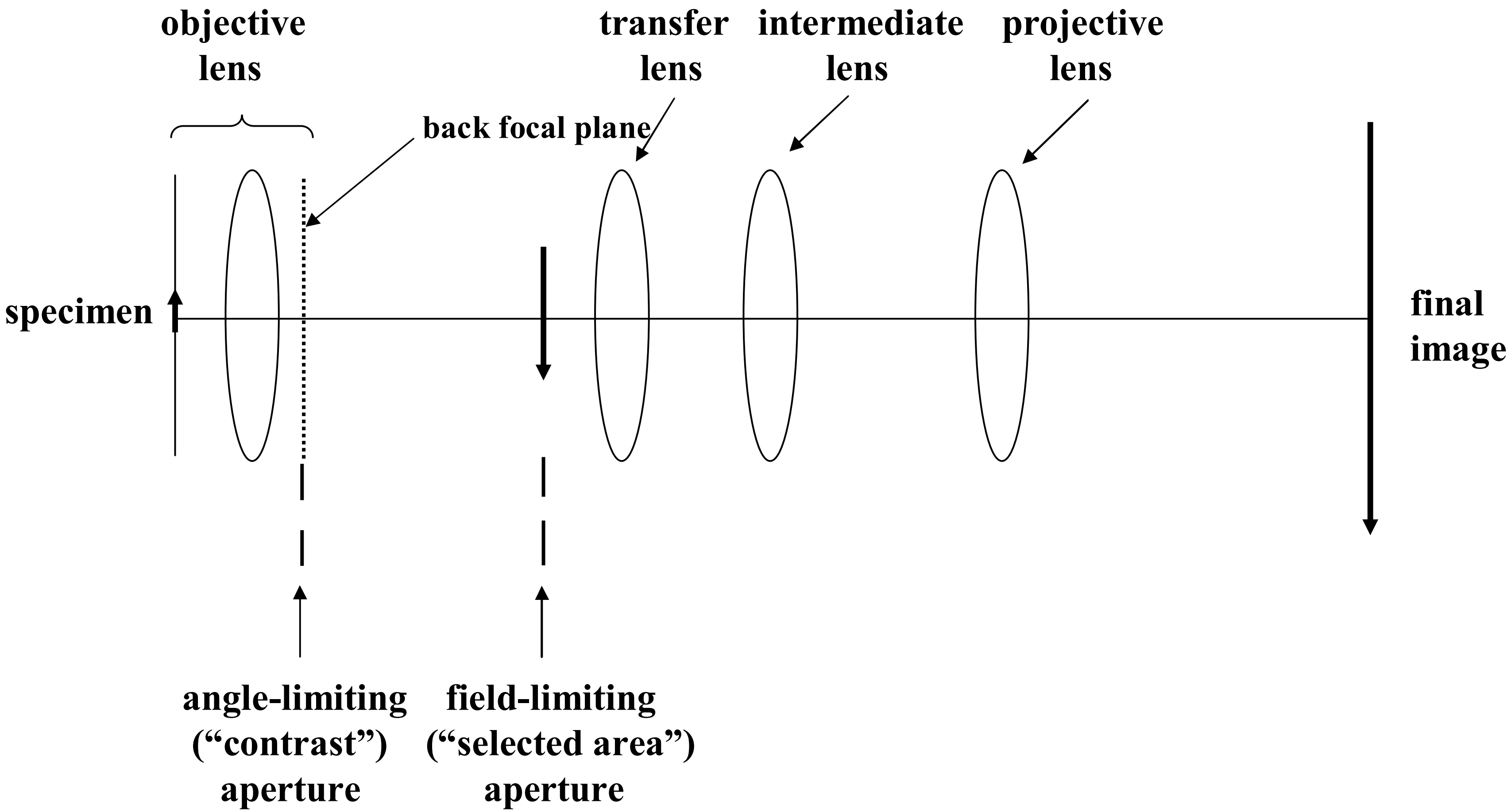


Energy filter needed for secondary electrons

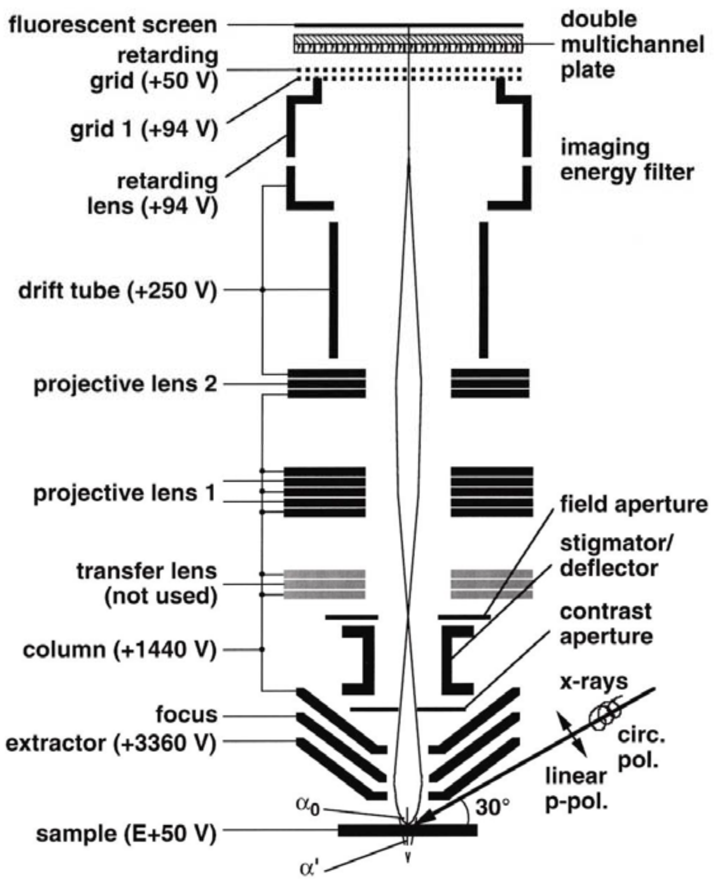
Calculations: D. Preikszas
From Th. Schmidt et al,
Surf. Rev. Lett. 9 (2002) 223

Instruments

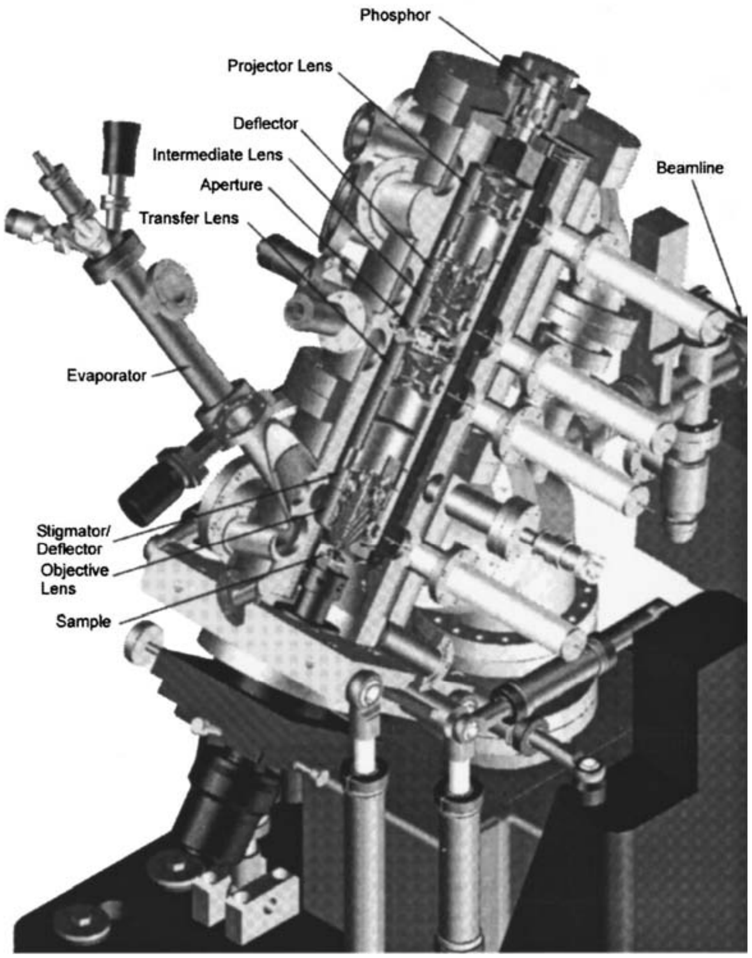
Basic PEEM schematic



Electrostatic PEEM examples

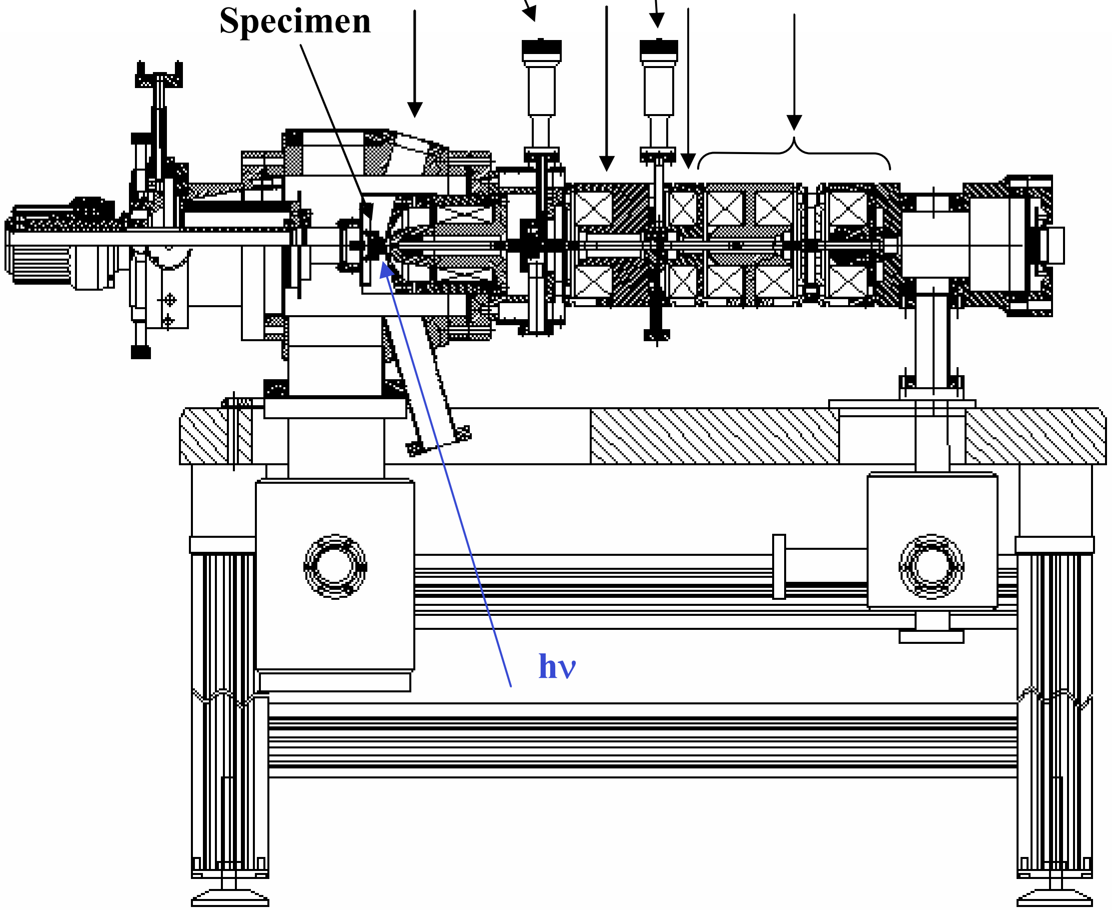


Focus PEEM
with high pass filter



ALS PEEM II

Magnetic PEEM (ELMITEC)



Field-lim.

Angle-lim. aperture

Obj.

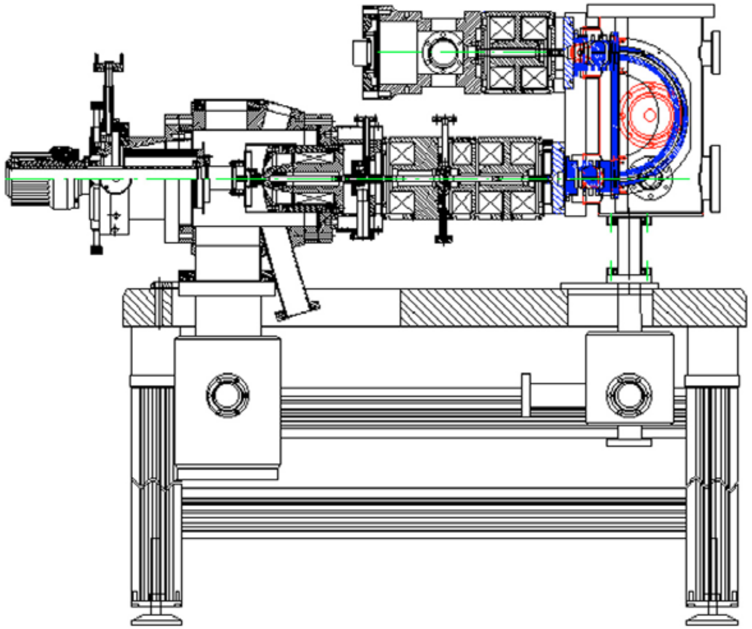
Transf. Interm. Proj. lens

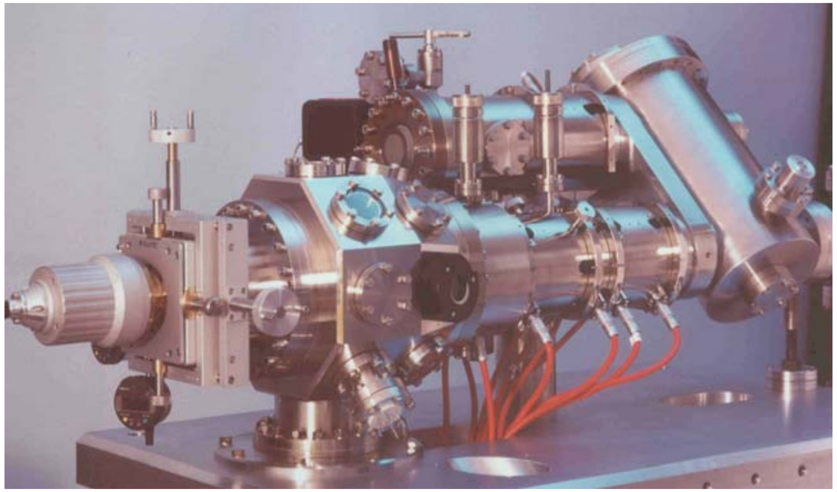
Specimen

hν

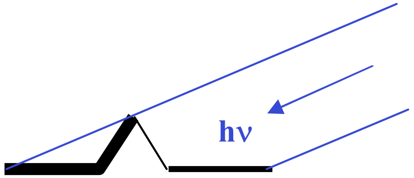
Spectroscopic PEEM with band pass filter

ELMITEC





Contrast mechanisms



1 Topographic contrast due to oblique illumination and field distortion
2 Work function contrast at low E_0 (escape probability!)

3 Chemical contrast due to inner shell ionization

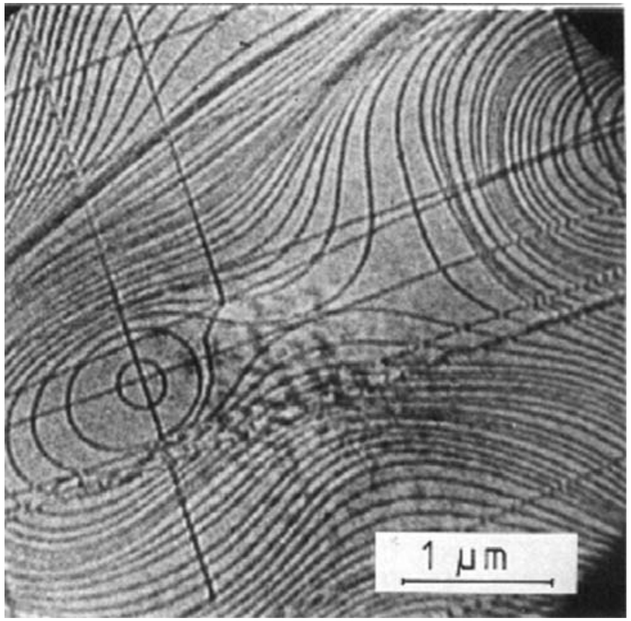
4 Magnetic contrast via XMCD and XMLD

No structural contrast, therefore combination with Low Energy Electron Microscopy (LEEM)

The usefulness of LEEM

Properties not visible with PEEM, but with LEEM

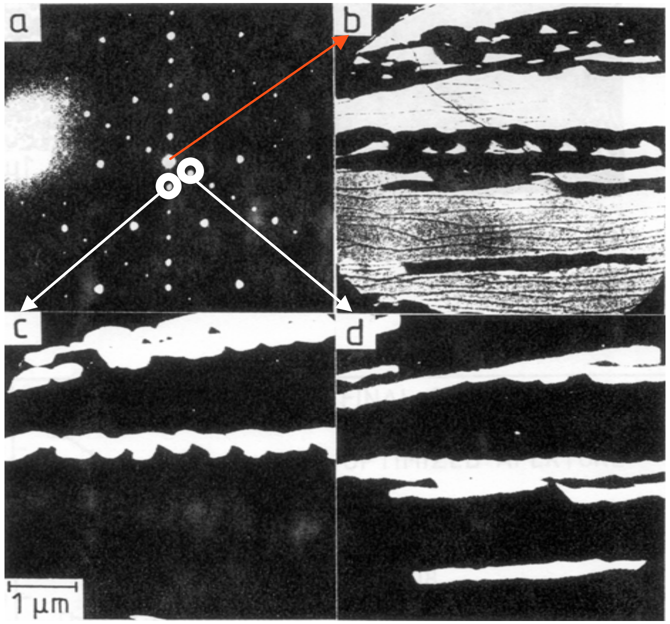
atomic steps



Mo(110)

Interference contrast

domain orientations



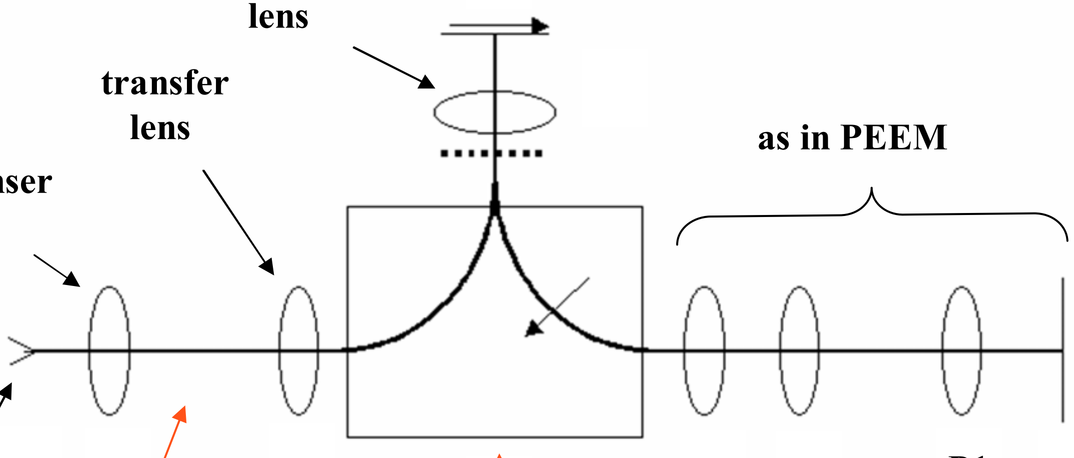
Au(√3×√3)-R30° + Au(5 ×2) on Si(111)
b c,d

Diffraction contrast

LEEM also much brighter and better resolution ⇒ use for focusing in XPEEM

LEED much easier to interpret than PED ⇒ use for structure analysis

Basic LEEM schematic



objective lens

specimen

transfer lens

condenser lens

as in PEEM

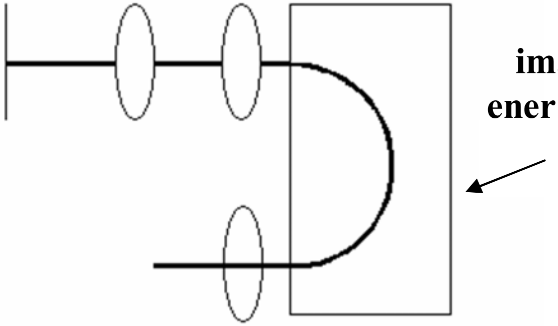
final image

P1

electron gun

Illumination system

Magnetic beam separator



image

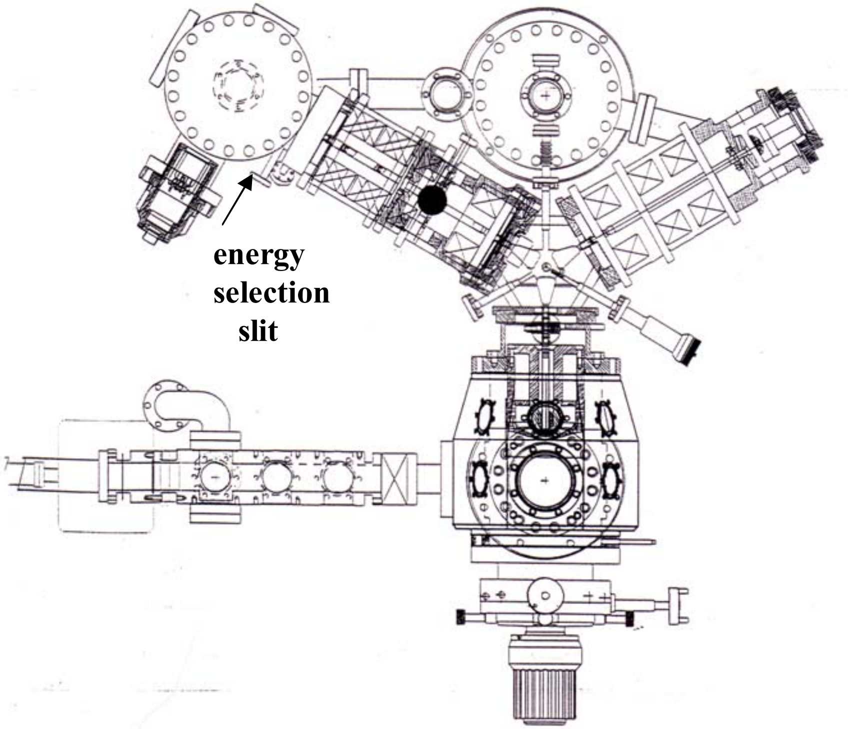
imaging energy filter

P1

Spectroscopic Photo Emission and Low Energy Electron Microscope

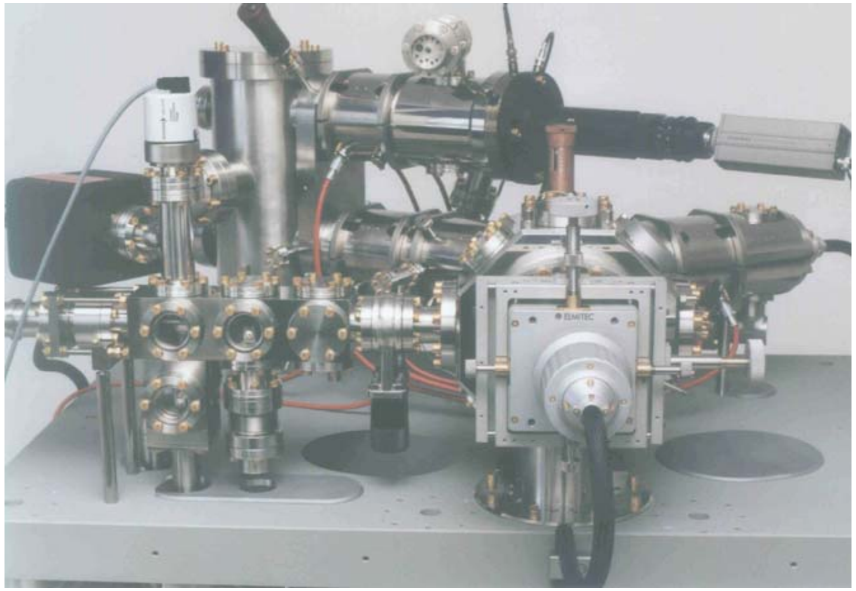
SPELEEM

ELMITEC

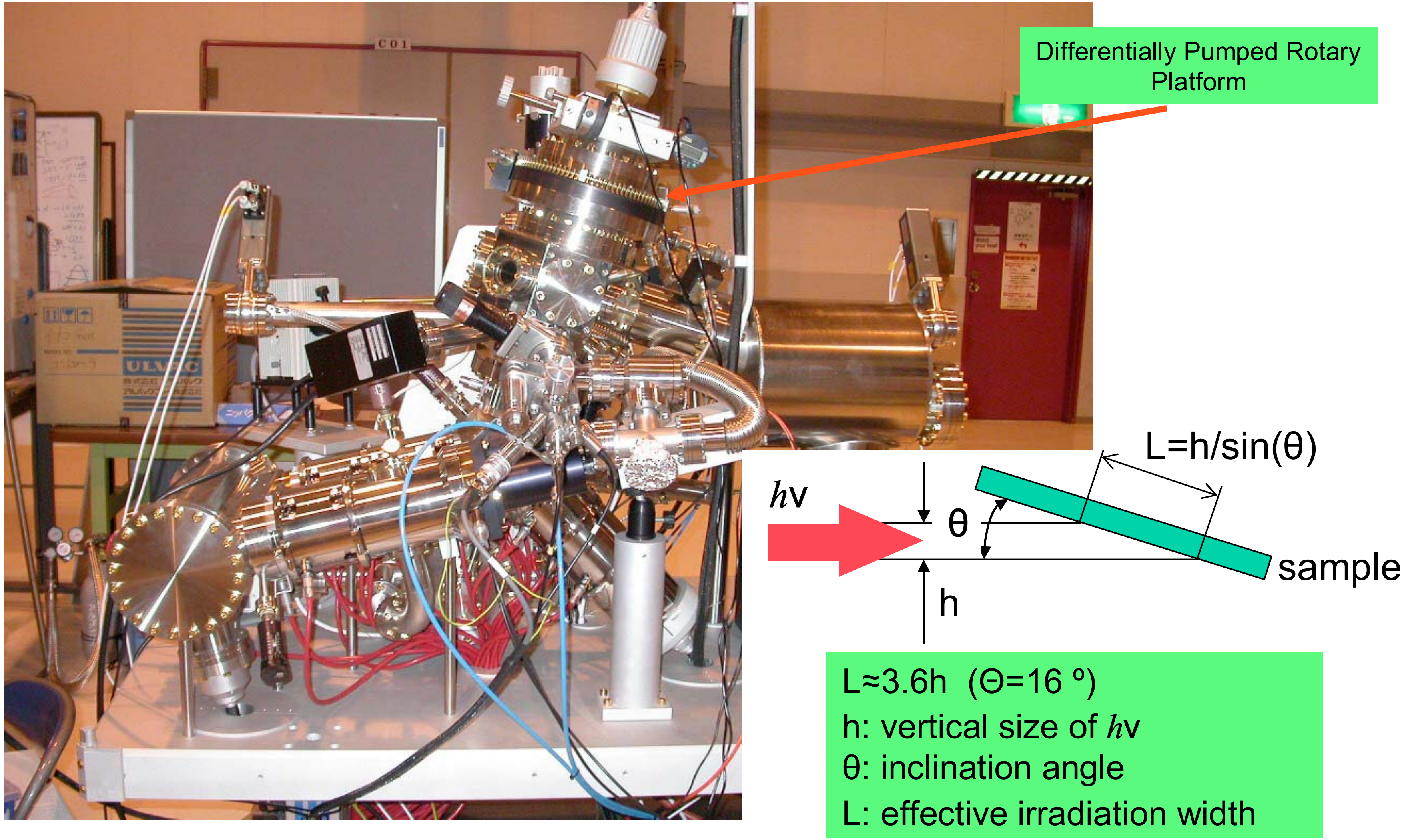


energy
selection
slit

energy
selection
slit

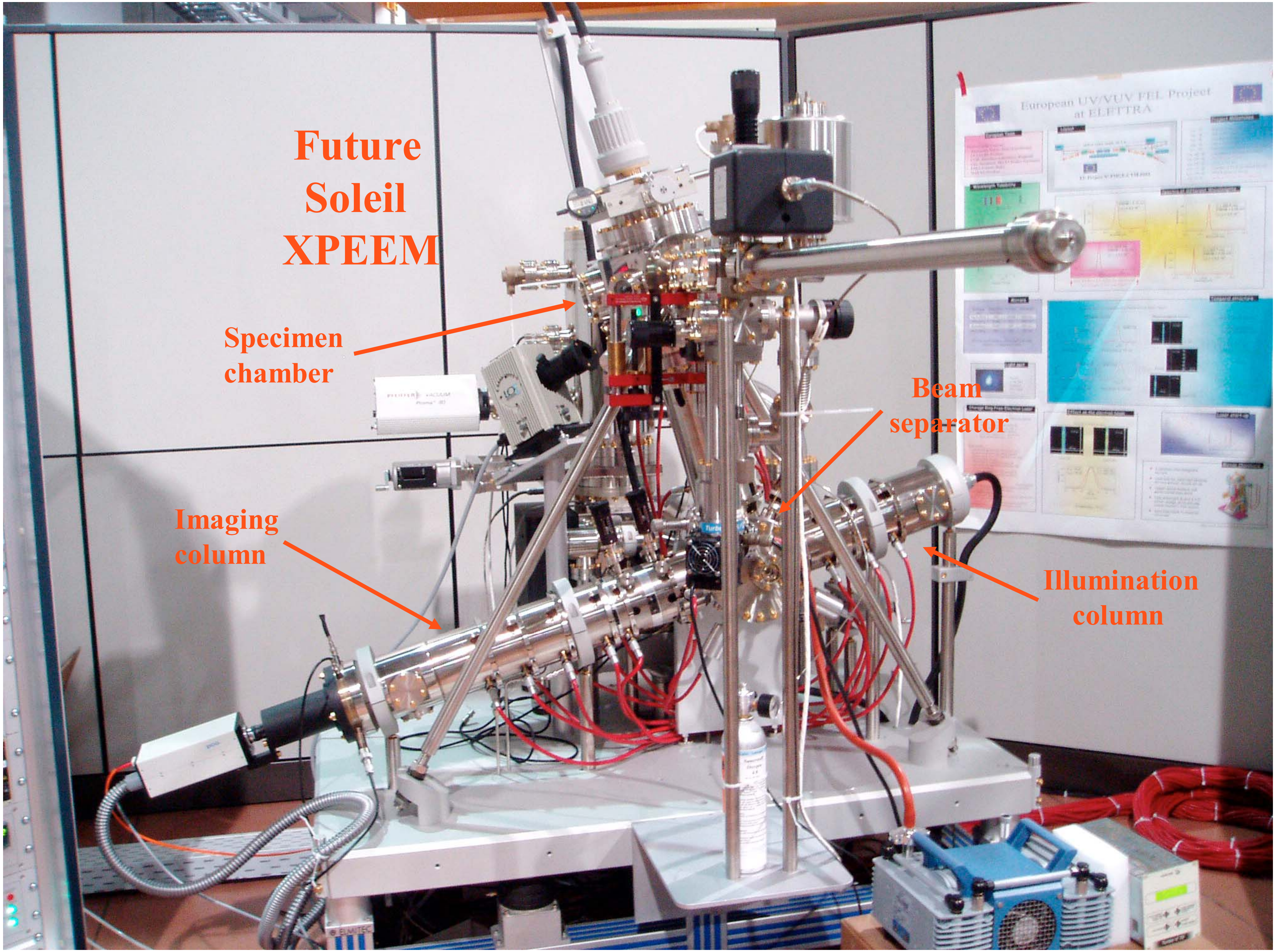


SPELEEM side view



L≈3.6h (Θ=16 °)
h: vertical size of *h*ν
θ: inclination angle
L: effective irradiation width

SPring8



Future Soleil XPEEM

Specimen chamber

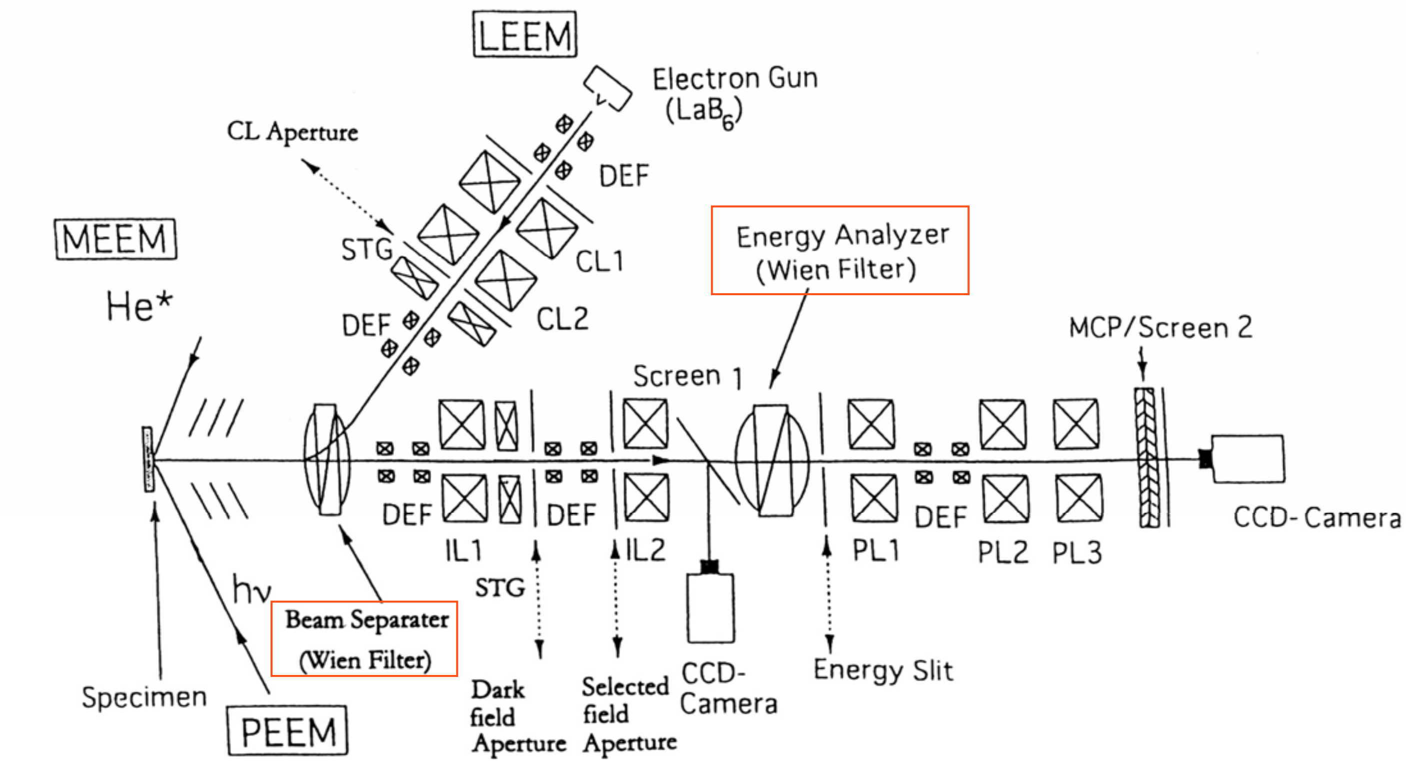
Beam separator

Imaging column

Illumination column

LEEM with energy filter

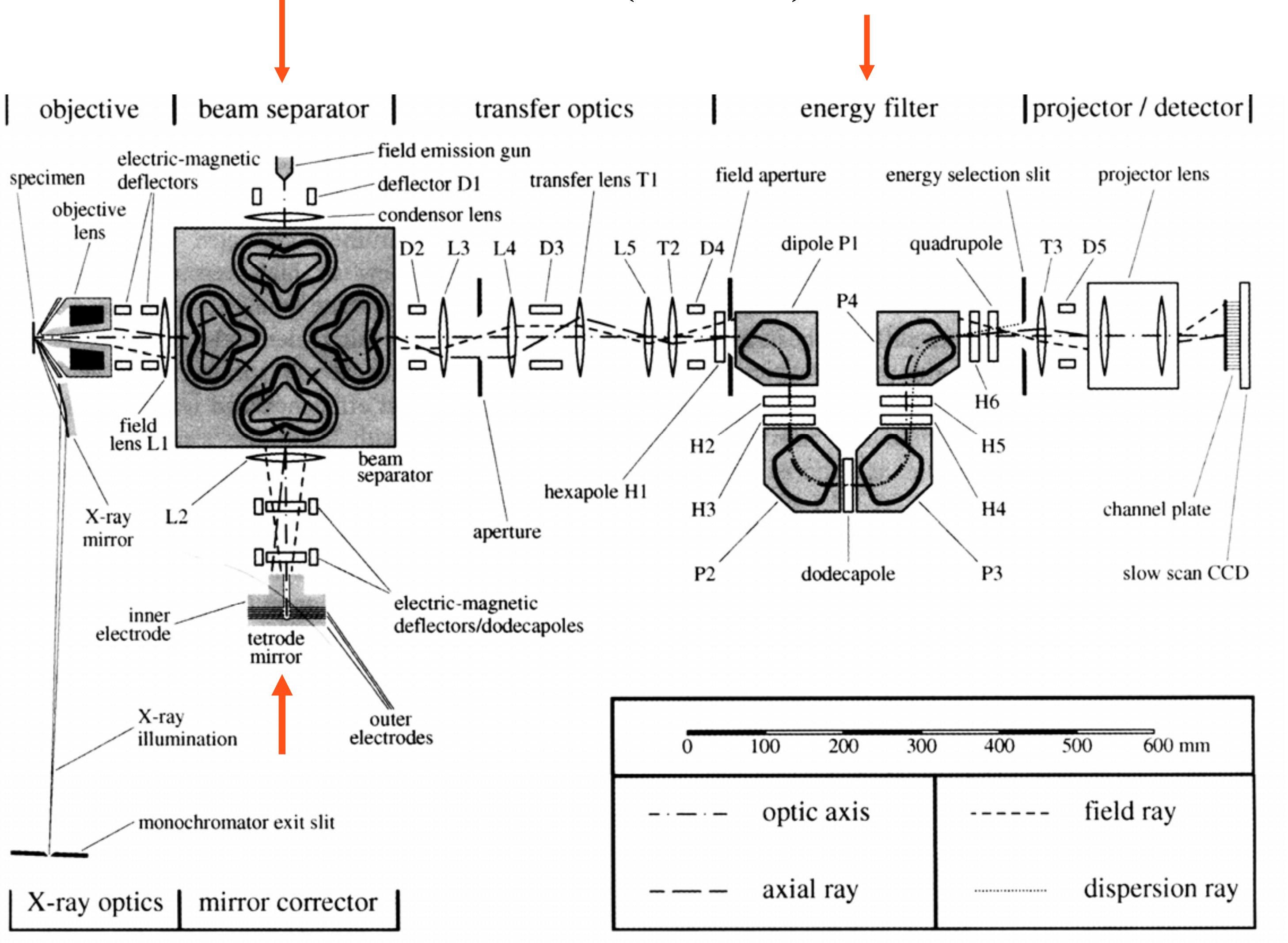
JEOL



Y. Sakai et al, Surf. Rev. Lett. 5 (1998) 1199

Aberration-corrected SPELEEM

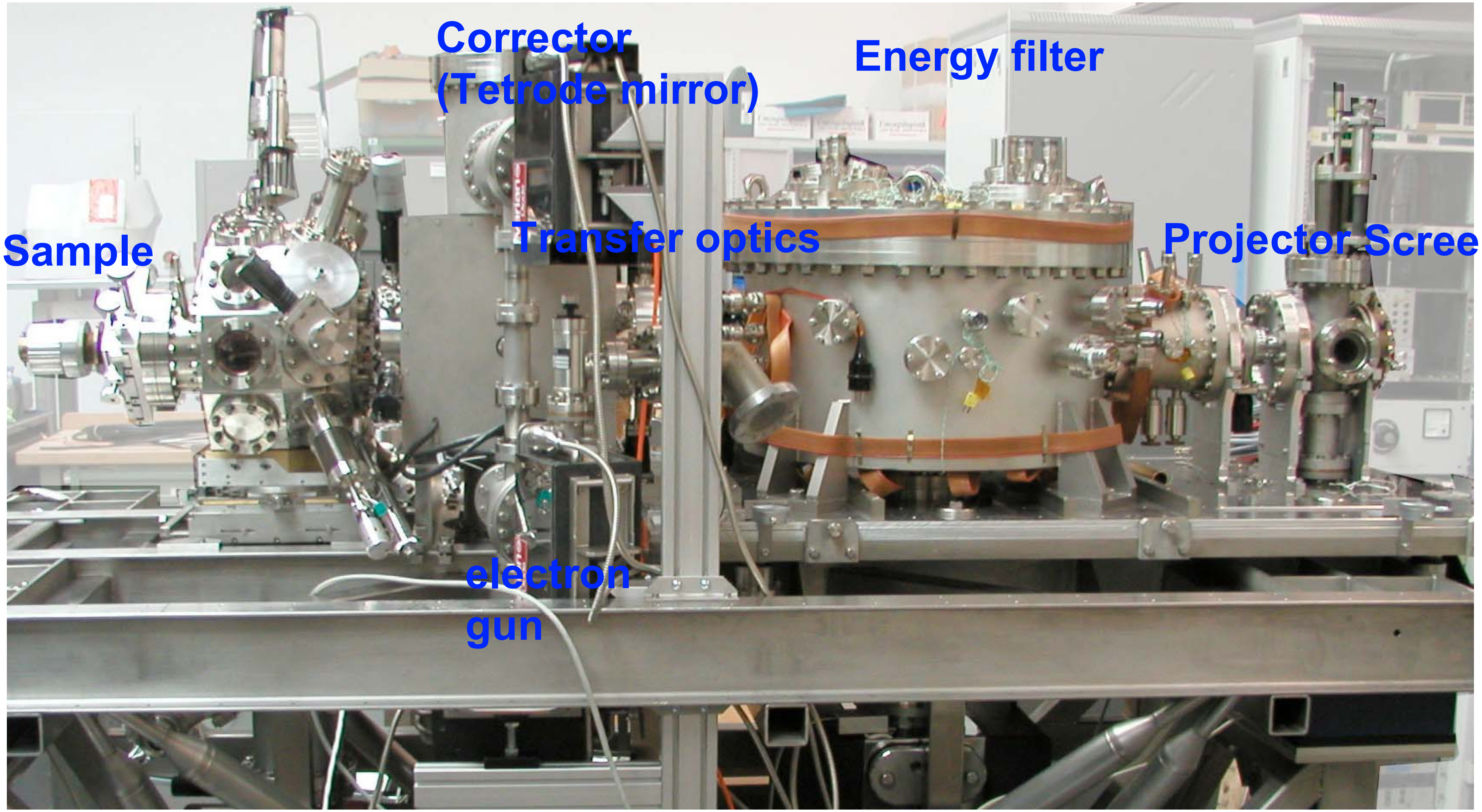
SMART (BESSY II)



H. Rose, D. Preikszas, Nucl. Instr. & Meth. A363, 201 (1995)

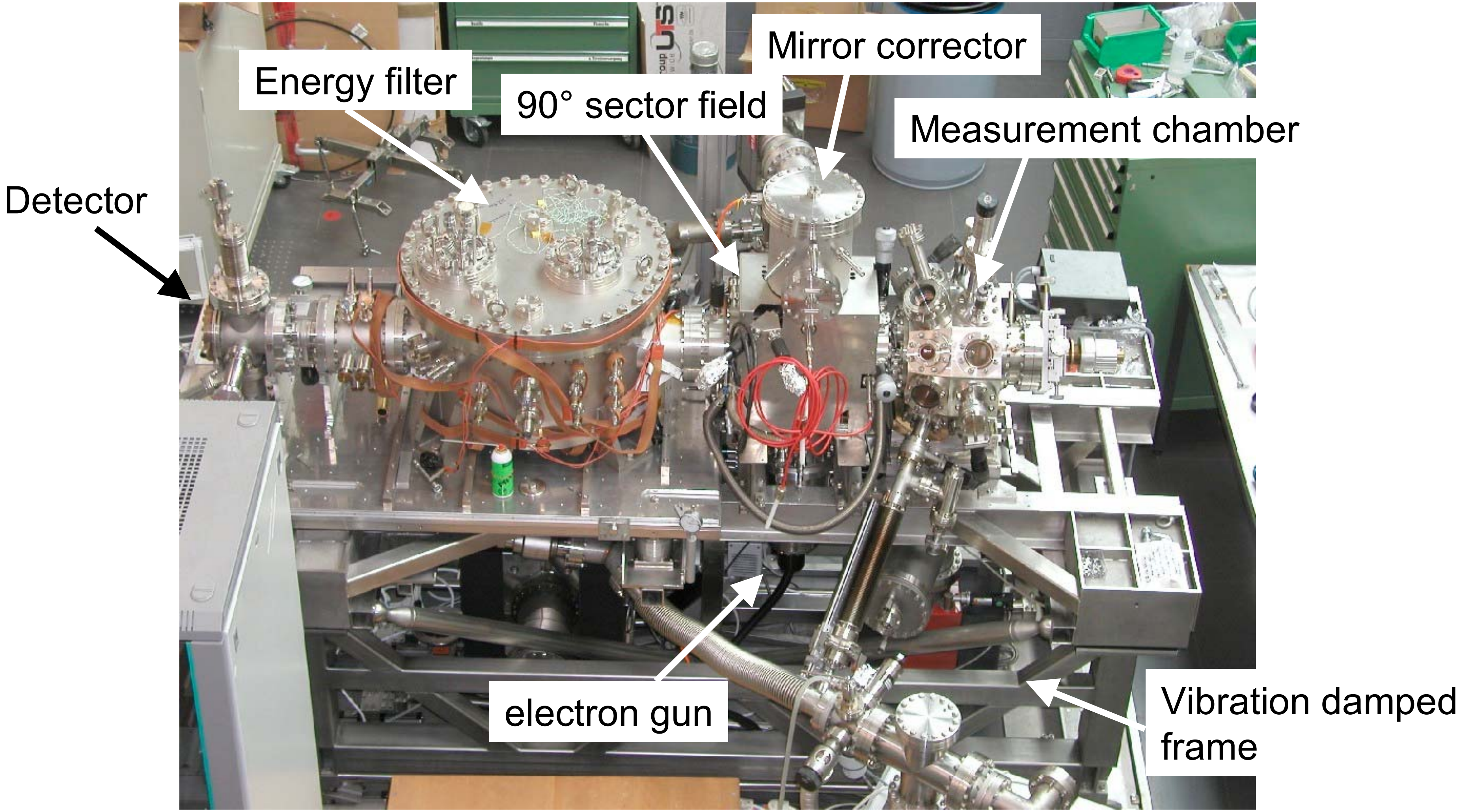
SMART side view

Aberration corrected PEEM/LEEM with energy filtering



Th. Schmidt April 2004

SMART top view

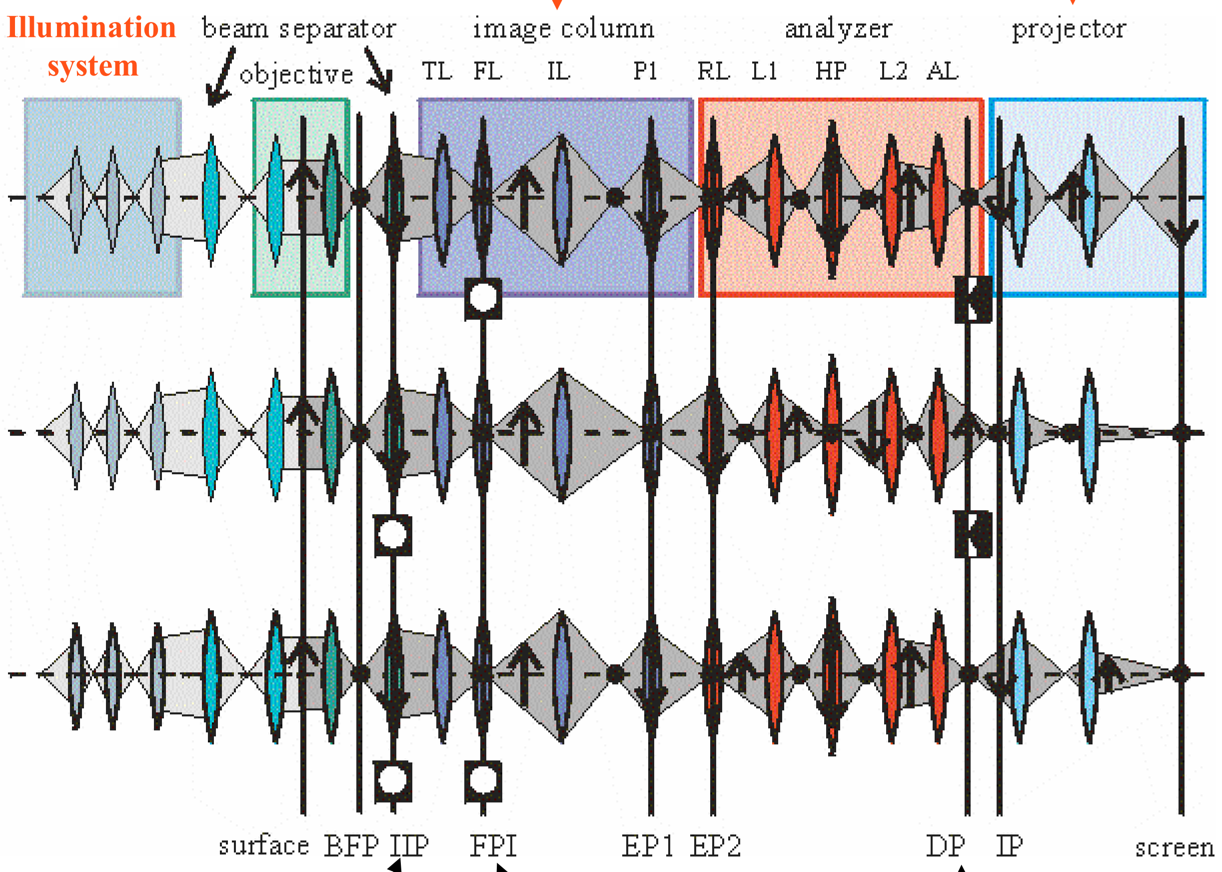


Th. Schmidt April 2004

Methodic

Operation modes of a SPELEEM

LEEM



imaging — **LEEM**

diffraction — **LEED**

spectroscopy — **AES**
ELS

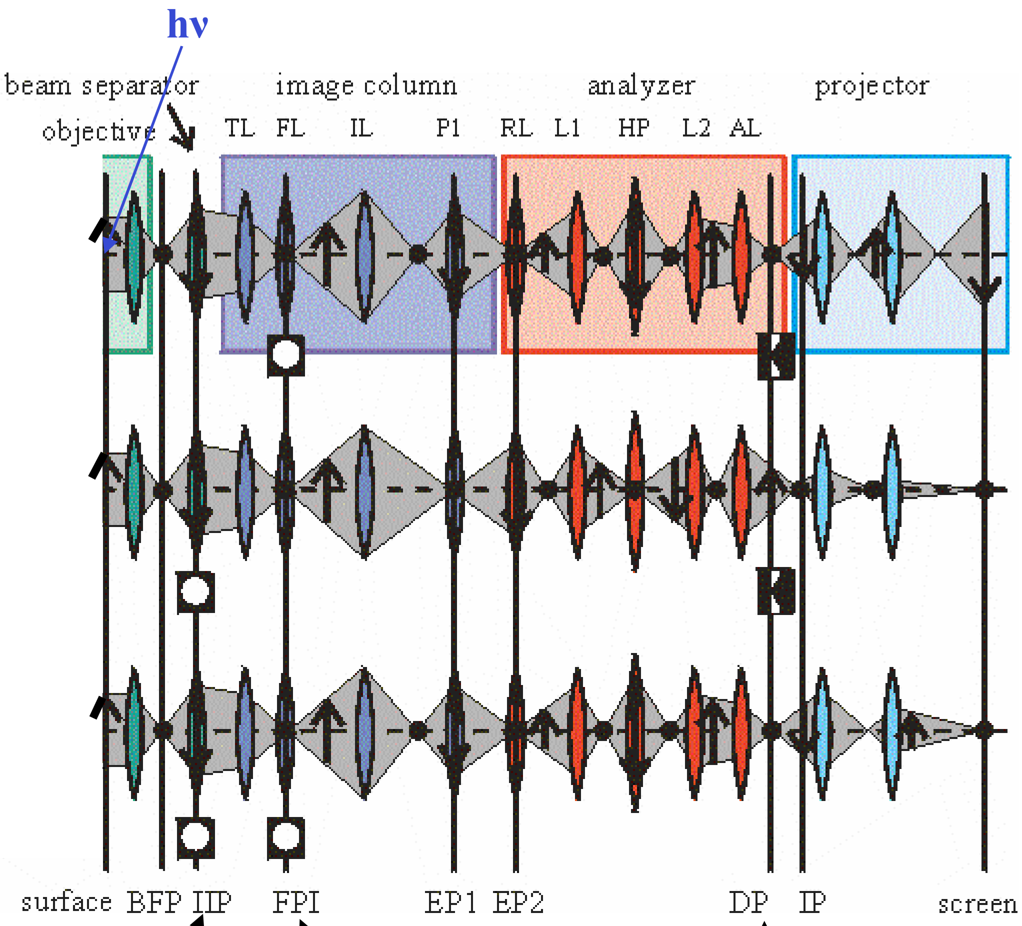
field limiting aperture

angle limiting aperture

energy selection slit

Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

Operation modes of a SPELEEM with photons



imaging — **XPEEM**

diffraction — **XPD (PED)**

spectroscopy — **XPS (PES)**
AES

field **angle**
limiting aperture

energy selection
slit

Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

PEEM practice

Ultrahigh vacuum (low 10^{-10} torr range)
but experiments up to 10^{-5} torr range possible

Surface cleaning: heating, sputtering or chemical reactions, e.g with oxygen for carbon removal

Choice of optimum photon energy:

Secondary electron imaging: $h\nu \approx E_i$ in:
XANES, NEXAFS, XMCD, XMLD

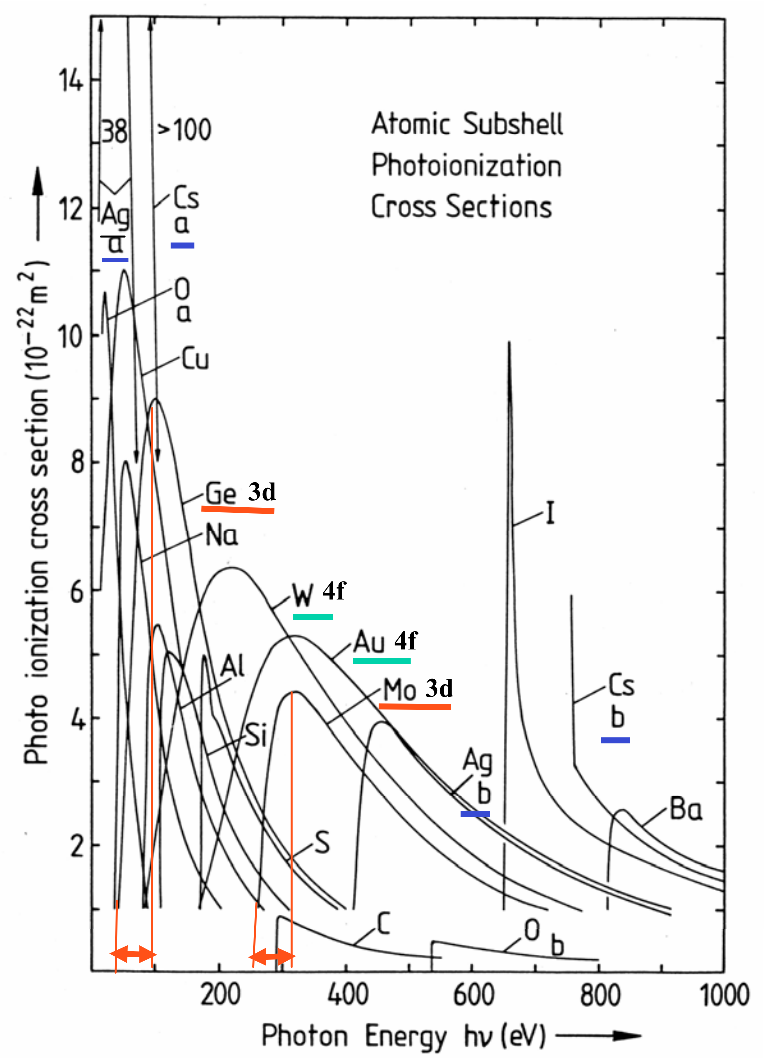
Photo electron imaging: $E_i + 50\ \text{eV} < h\nu < E_i + 200\ \text{eV}$

to minimize
secondary electron
background

to maximize
transmission
and
photo electron yield

Photo ionization cross sections

Photon energy selection

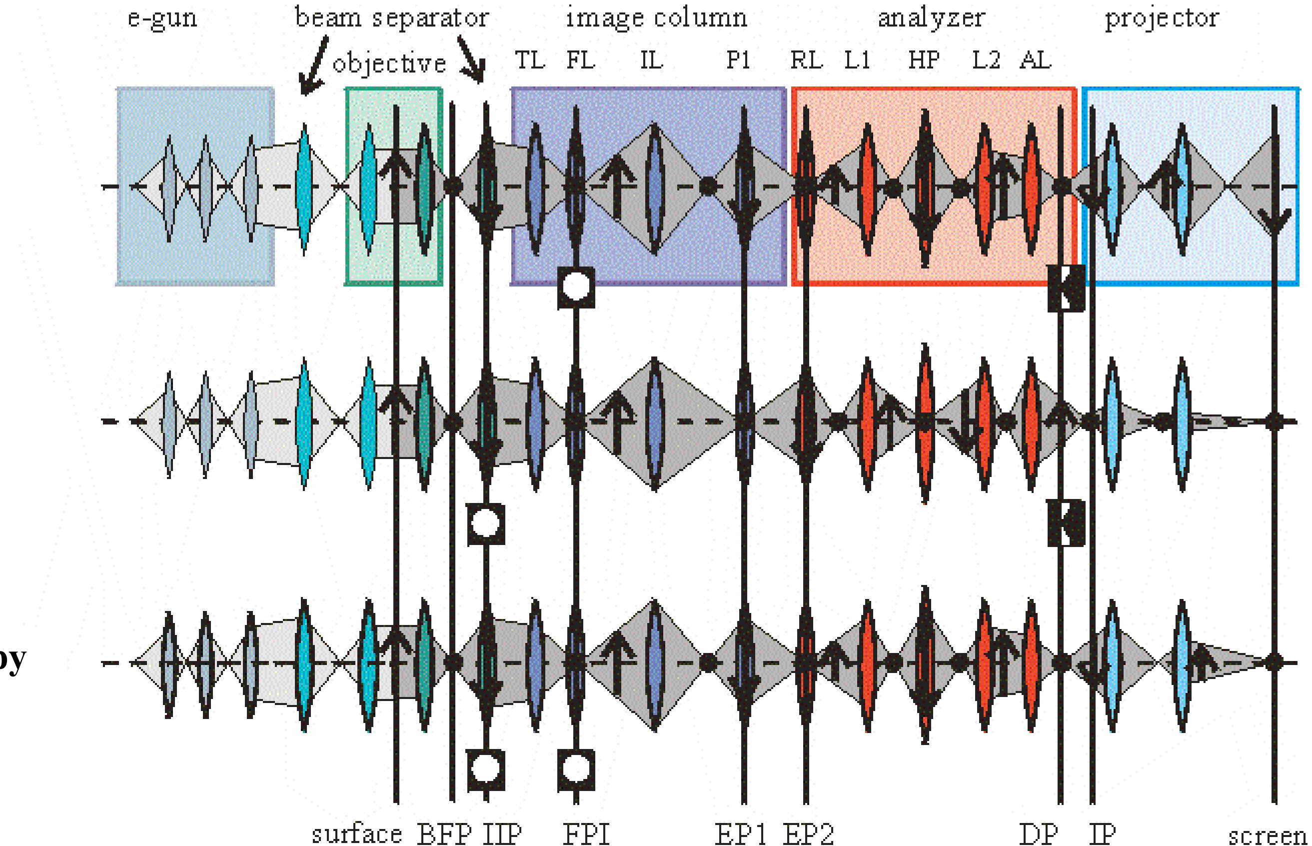


Binding energies (eV)

Ge 3d	29.8, 29.2
Mo 3d	231.1, 227.9
W 4f	33.6, 31.4
Au 4f	87.6, 84.0
Ag	
a 4d	≈ 5
b 3d	374.0, 368.3
Cs	
a 4d	79.8, 77.5
b 3d	740.5, 726.6

J.J. Yeh and I. Lindau,
Atomic Data 1985

Operation modes of a SPELEEM



imaging

mode 1

XPEEM
LEEM

diffraction

XPD (PED)
LEED

spectroscopy

XPS (PES)
AES
ELS

field **angle**
limiting aperture

energy selection
slit

Image plane

Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

Chemical imaging (mode 1)

secondary electrons
spatial resolution
$\sigma_{Ag4d} \approx 5\,\sigma_{W5d}$
$h\nu = 65\ \text{eV} \gg E_i < 10\ \text{eV}$
$\Delta E_F \leq 1\ \text{eV}$

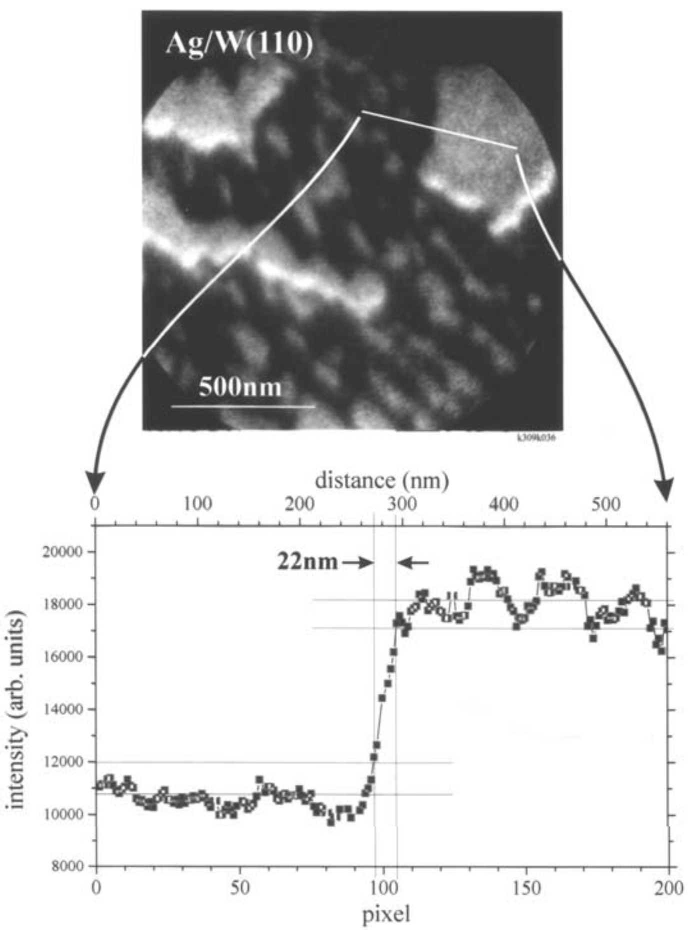
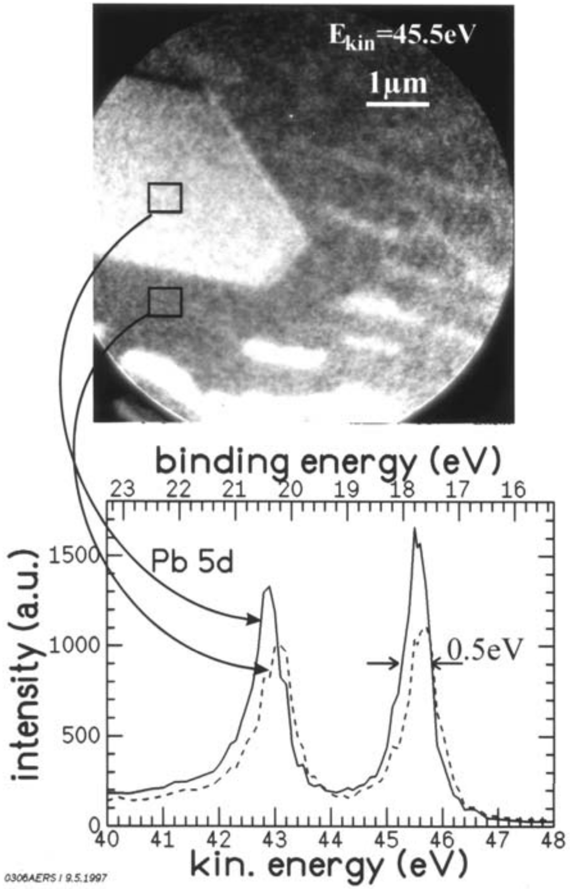


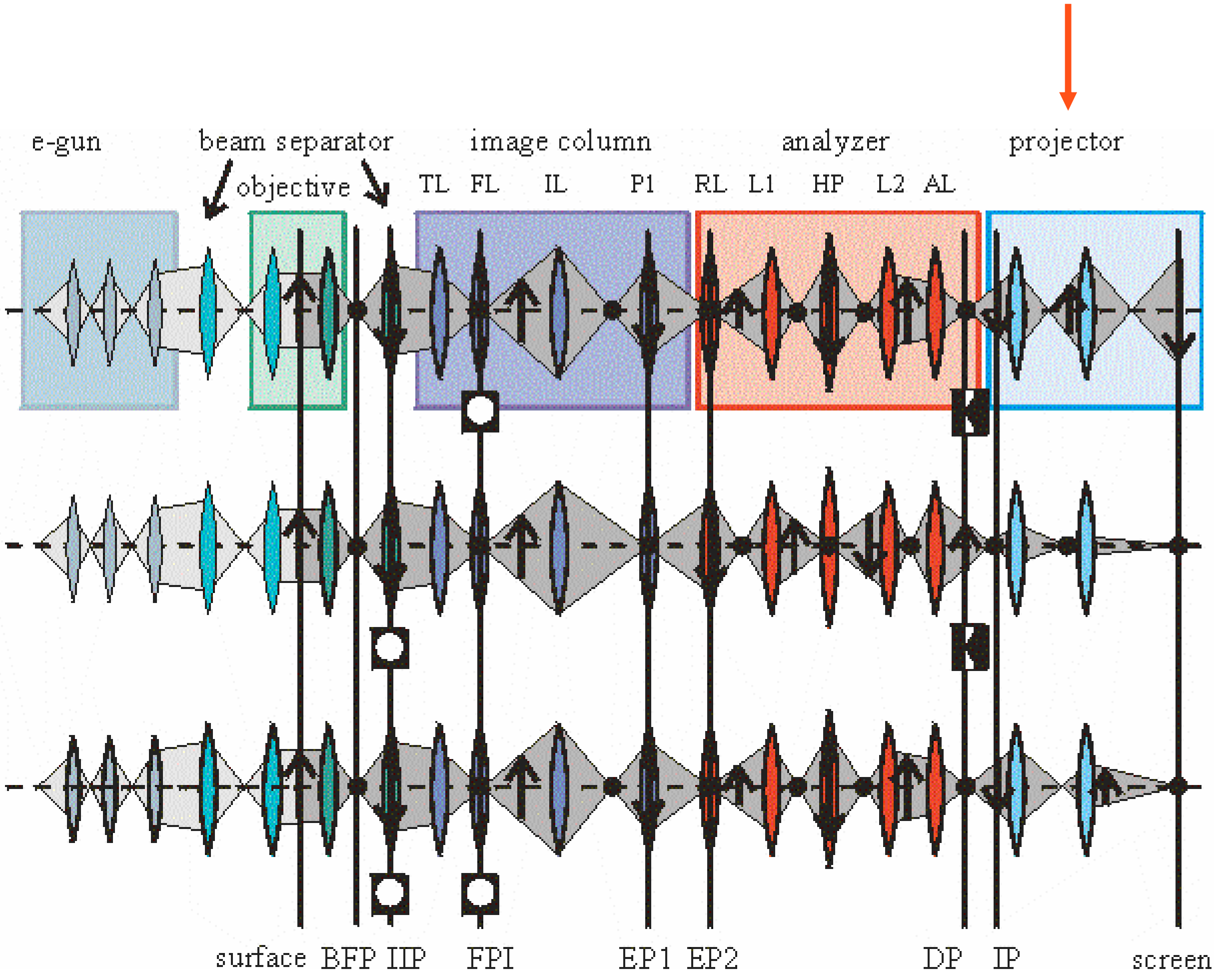
photo electrons
energy resolution
$h\nu = 65$ eV, images in 0.2 eV steps
10-60 sec/image 0.25 μm^2 areas
$\Delta E_F \leq 0.5\ \text{eV}$, $\Delta E_{chem} \approx 0.15\ \text{eV}$



Pb/W(110)

Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

Operation modes of a SPELEEM



imaging

XPEEM
LEEM

diffraction

XPD (PED)
LEED

spectroscopy

mode 3

XPS (PES)
AES
ELS

field **angle**
limiting aperture

energy selection
slit

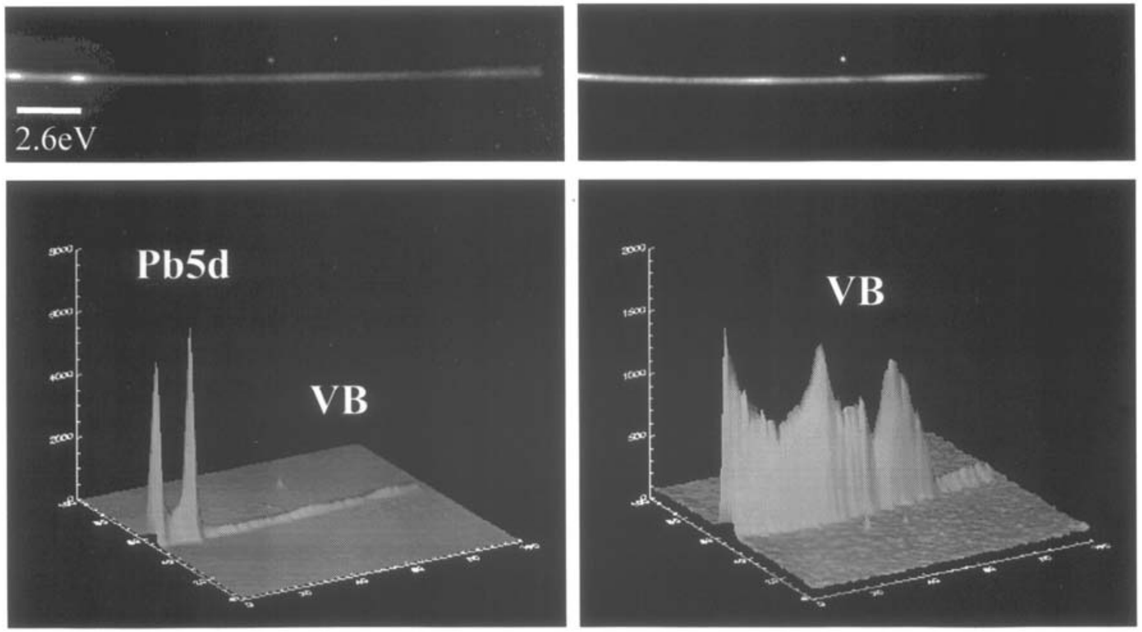
Dispersive plane

Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

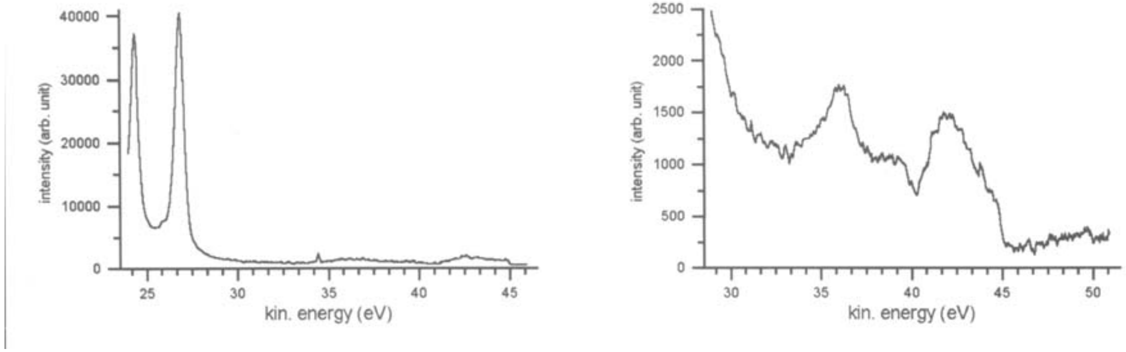
Fast local spectroscopy
by imaging the dispersive plane (mode 3)

$\alpha = 8^{o}$ (contrast aperture), 0.8μm^2 area (selected field aperture)
20 eV full dispersion, 60 sec
hν = 48 eV

8 monolayers Pb on Si(111)-√3× √3-Ag



Dispersive plane



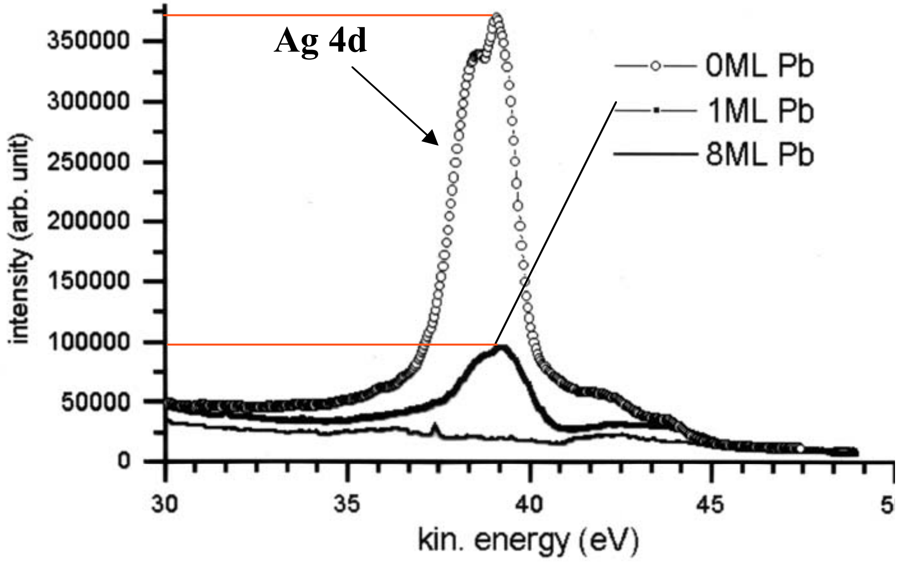
Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

Surface sensitivity of photo electrons

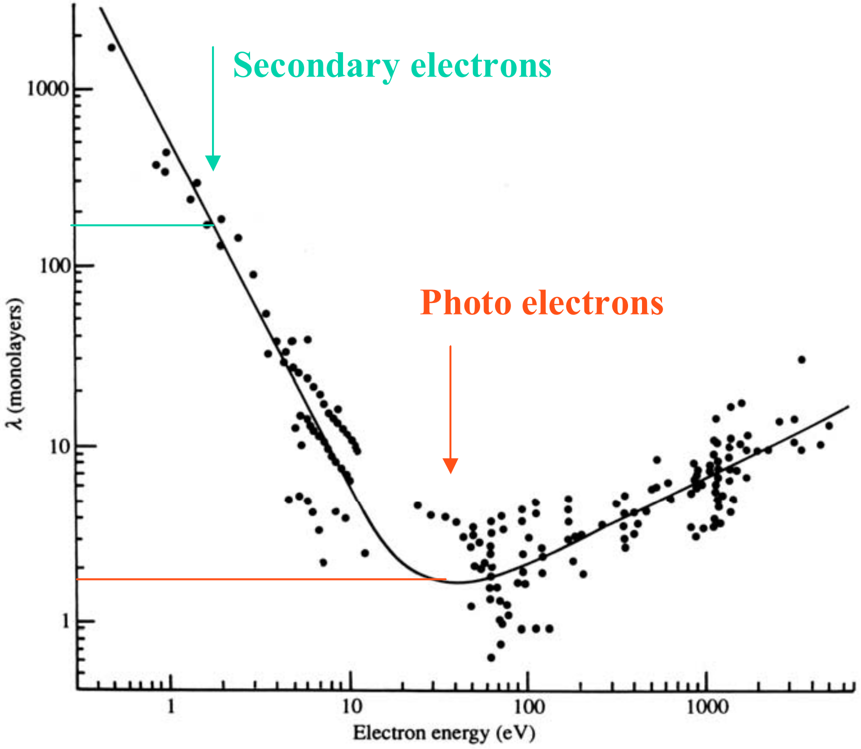
versus secondary electrons

valence band region

hν = 48 eV



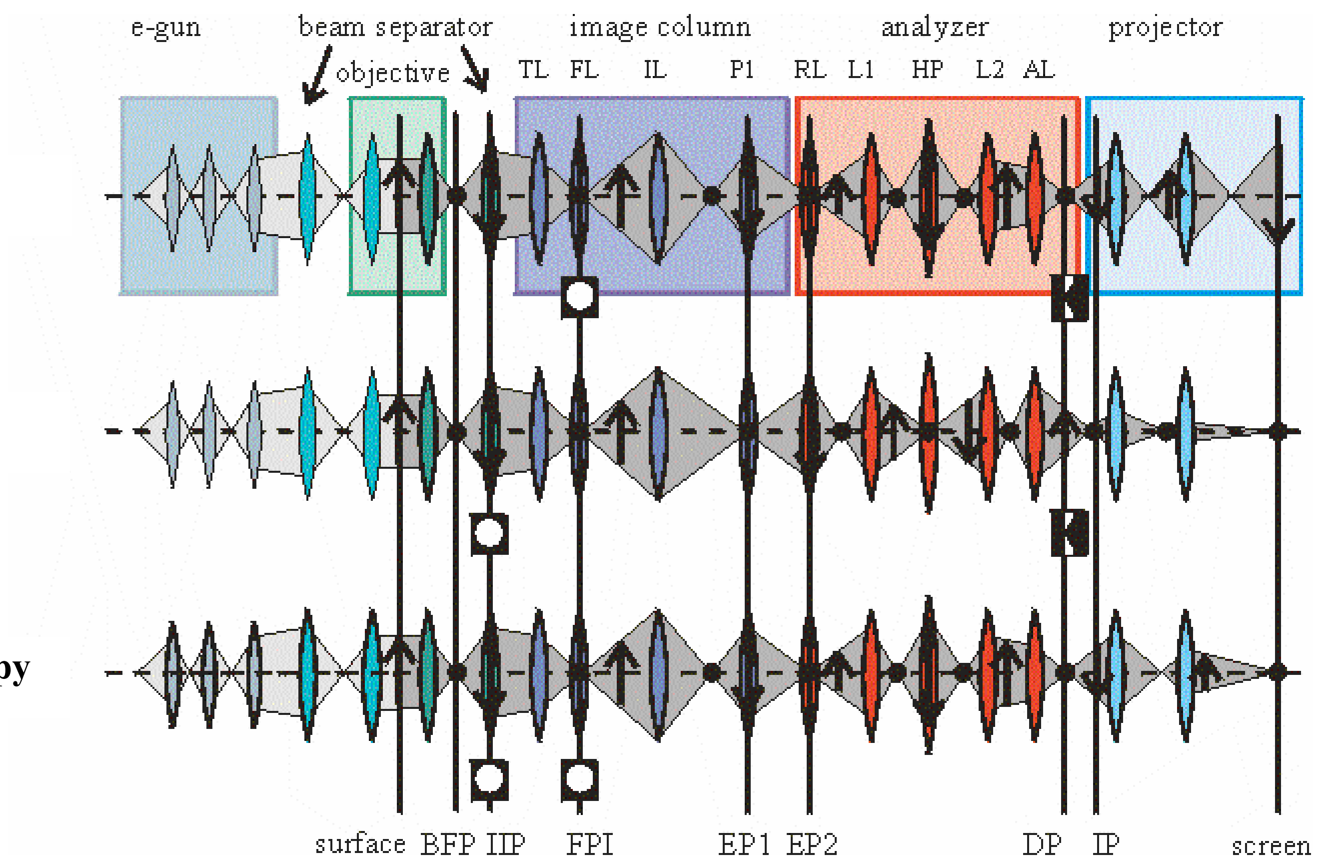
Pb on Si(111) – Ag (√3×√3) – R30°
(1 monolayer Ag)



Inelastic mean free path
("universal curve")
determines sampling depth

Th. Schmidt et al, 1998

Operation modes of a SPELEEM



imaging

XPEEM
LEEM

diffraction

mode 2

XPD (PED)
LEED

spectroscopy

XPS (PES)
AES
ELS

field angle
limiting aperture

energy selection
slit

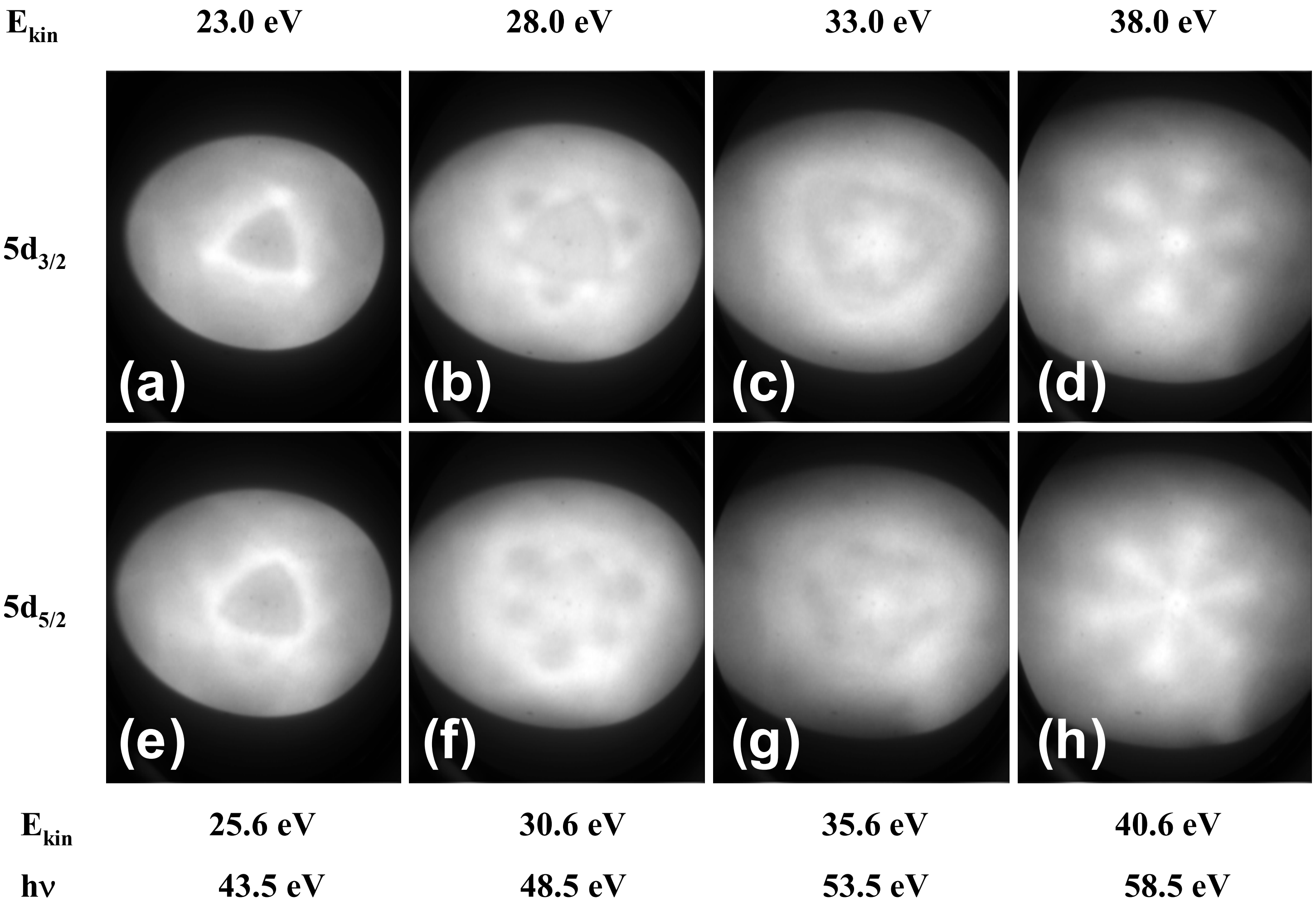
Image plane

Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

Local photo electron diffraction (mode 2)

Pb 5d photo electrons

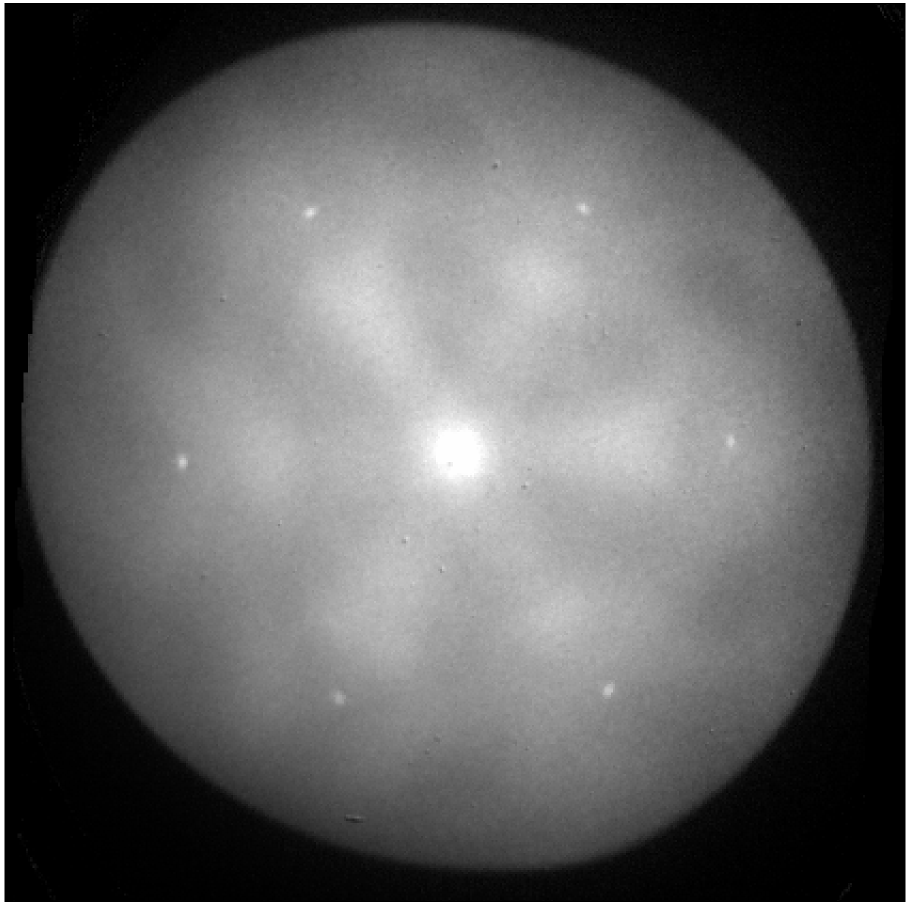
from 0.8µm^2 area (selected field aperture)



Th. Schmidt et al, Surf. Rev. Lett. 5 (1998) 1287

Simultaneously acquired PED and LEED pattern

Pb 5d 38 eV

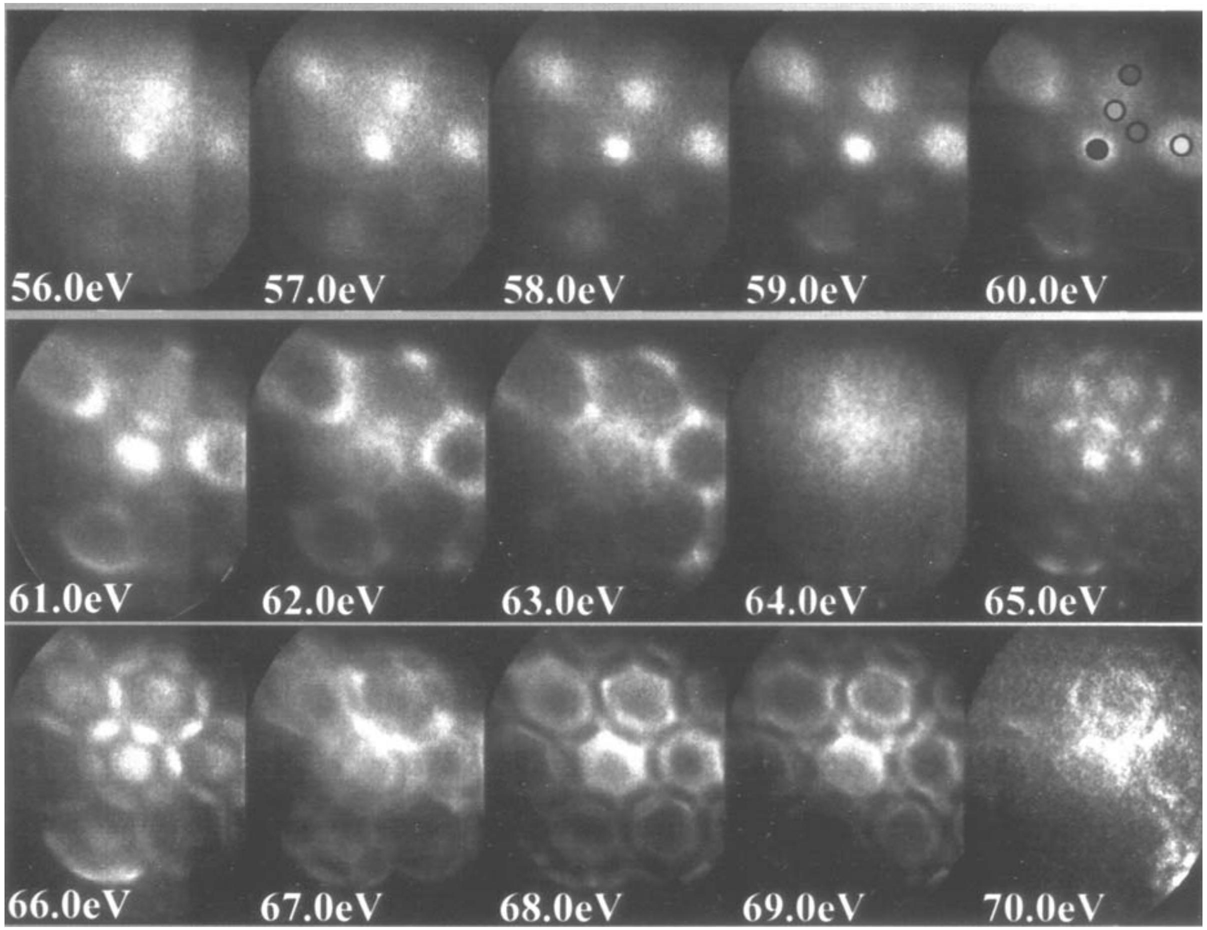


Local band structure analysis (mode 2)

Conduction band of Pb(111)

5 Pb monolayers on Si(111) – Au √3×√3 – R30°

hν = 73 eV, 0.8 μm² area (selected field aperture)



Parameter: E_{kin}

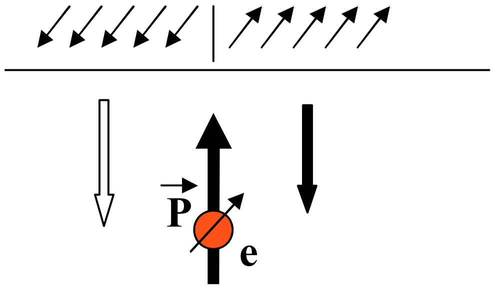
Th. Schmidt, 1997

Magnetic imaging

XMCD, XMLD

Methods

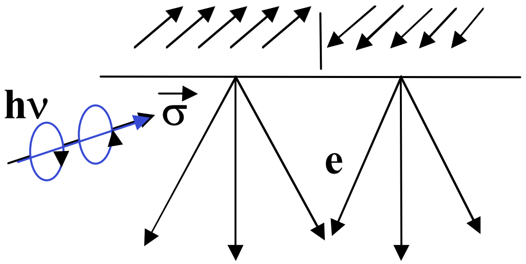
SPLEEM



$E_i = E_r = 0 – 20$ eV

$I = I_{0r} + c\,\vec{P} \bullet \vec{M}$

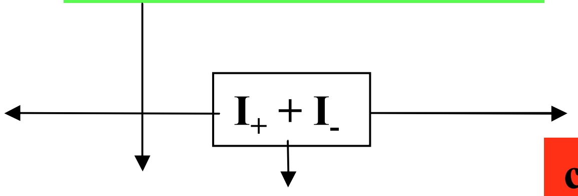
XMCDPEEM



$E_e = 0 – 20$ eV (SE)

$I = I_{0e} + c\,\vec{\sigma} \bullet \vec{M}$

2 images with opposite $\vec{P}$ or $\vec{\sigma}$: I_+, I_-



$I_+ – I_- =$ magnetic image

$I_+ + I_-$

$2\ I_{0r}$

structural image

$|\vec{P}|$ typical 20%

$(I_+ – I_-) / (I_+ + I_-)$

asymmetry image

$2\ I_{0e}$

chemical
topographic
image

$|\vec{\sigma}|$ typical 80%

Basic mechanisms

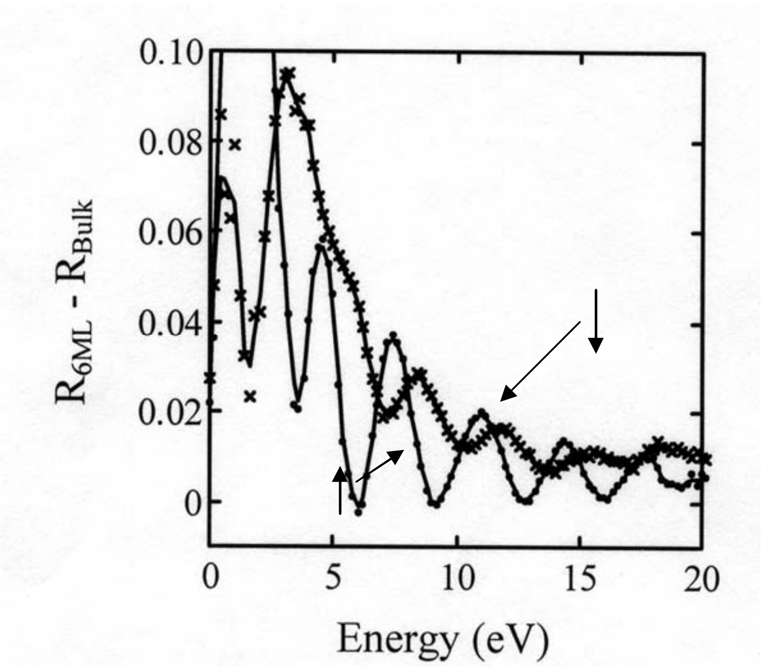
SPLEEM

Spin-dependent scattering cross-section due to exchange interaction

↓

Spin-dependent reflectivity

6 ML Fe on W(110)



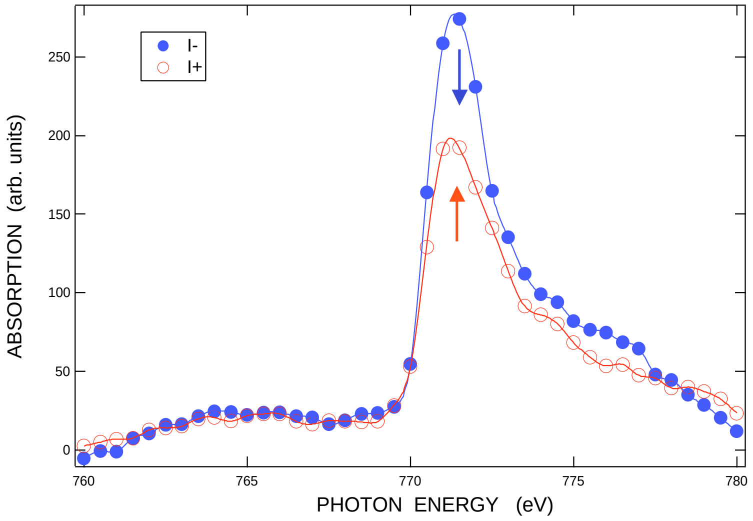
XMCDPEEM

Helicity-dependent transition probability from 2p to unoccupied 3d (↑↓) states

↓

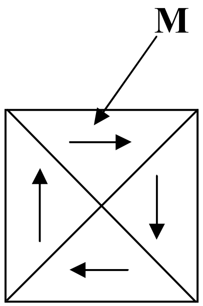
Spin-dependent secondary electron emission

Secondary electron yield around Co $2p_{3/2}$ edge



Closure domains in permalloy squares

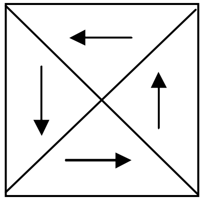
Ion beam milled from permalloy film

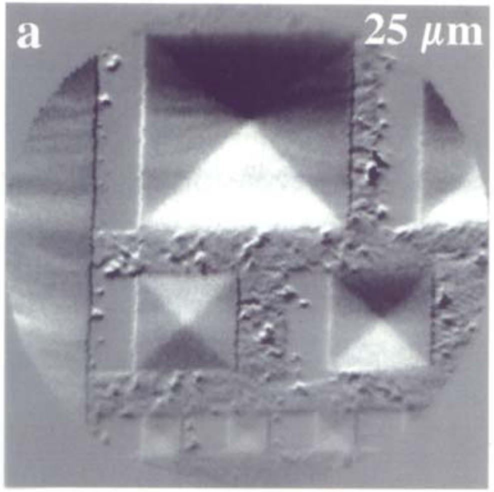


hν

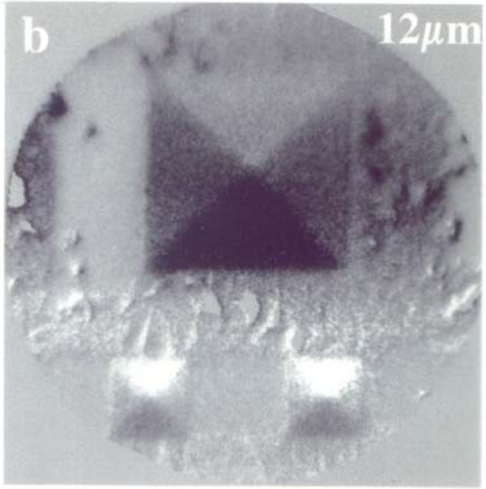
→ σ

Fe L_3 edge

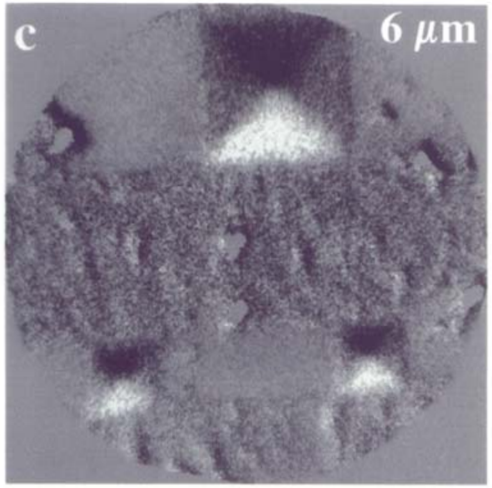




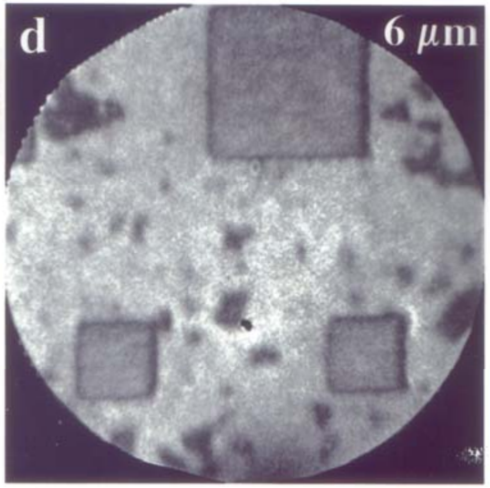
10 μm and 5 μm



5μm and 2 μm



2 μm and 1μm



2 μm and 1μm (LEEM)

A. Locatelli et al, Surf. Rev. Lett. 9 (2002) 171

Conclusion

Full field XPEEM is one of the most important applications of the high brilliance of third generation synchrotron light, in particular when combined with a band pass energy filter and with LEEM because it allows a complete characterization of surfaces and thin films, presently on the 10 nm lateral resolution scale, with aberration correction in the future on the 1 nm scale (hopefully).

The main benefit of aberration correction, however, will be the strong increase of the transmission of the system which will reduce image acquisition time considerably. This will allow dynamical studies, which are presently limited to LEEM, also with XPEEM.

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