Soft X-Ray Reflectivity: from quasi-perfect mirrors to accelerator walls

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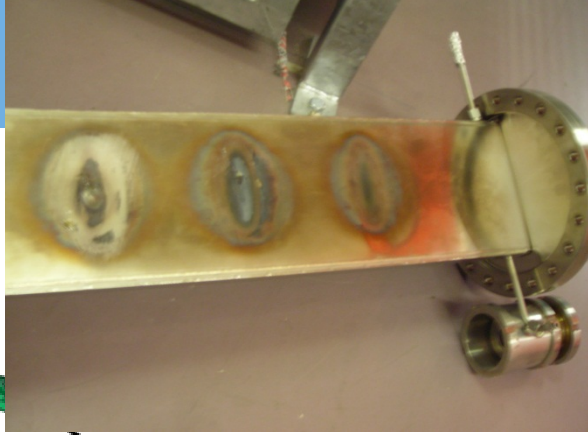
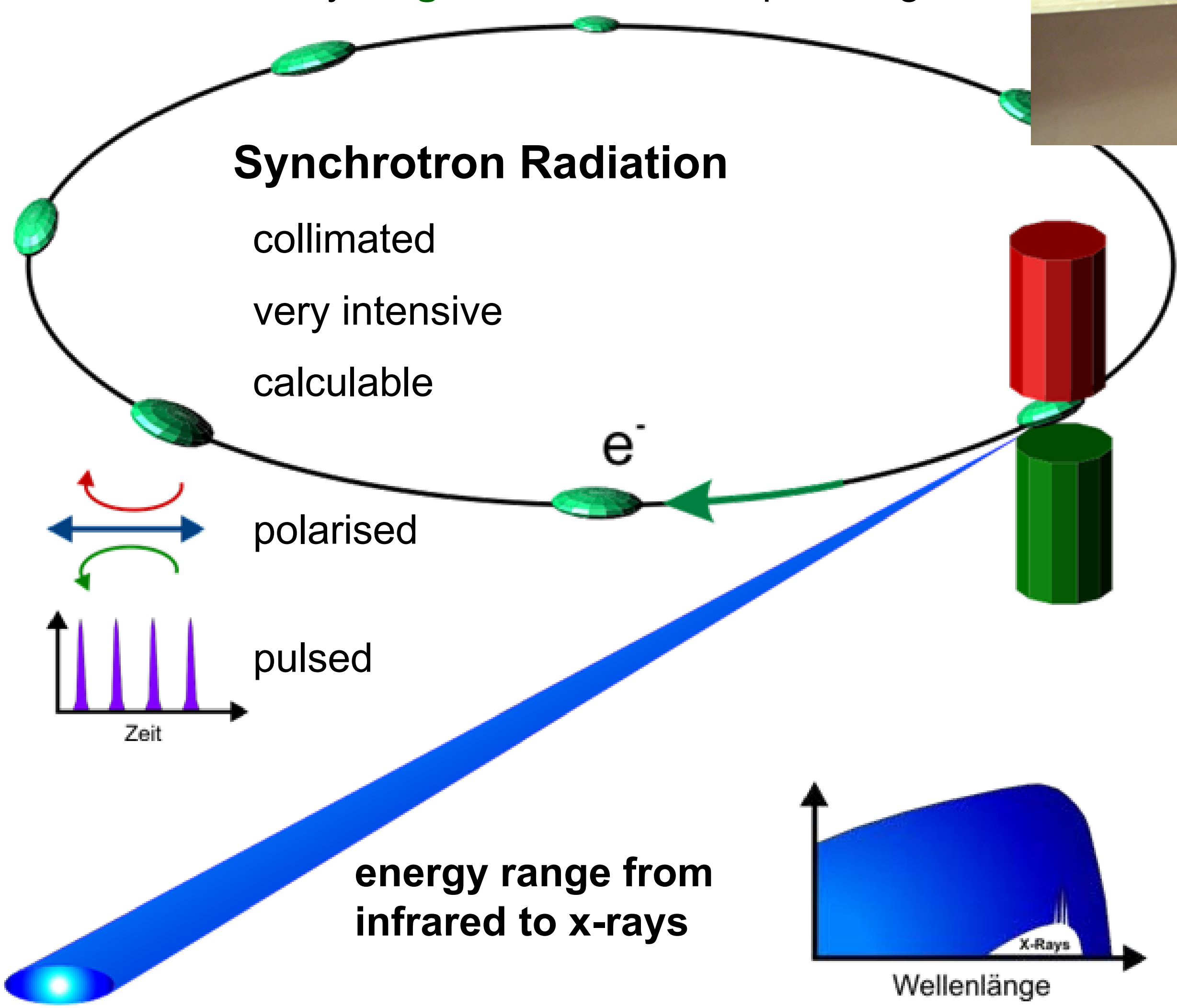
BESSY

Synchrotron Radiation in all colours



Charged particles,
moving close to the speed of light
when deflected by **Magnets** irradiate a "special light":



Synchrotron Radiation

collimated

very intensive

calculable

polarised

pulsed

energy range from infrared to x-rays

BESSY-II

15 Dip-beamlines

~50 mrad

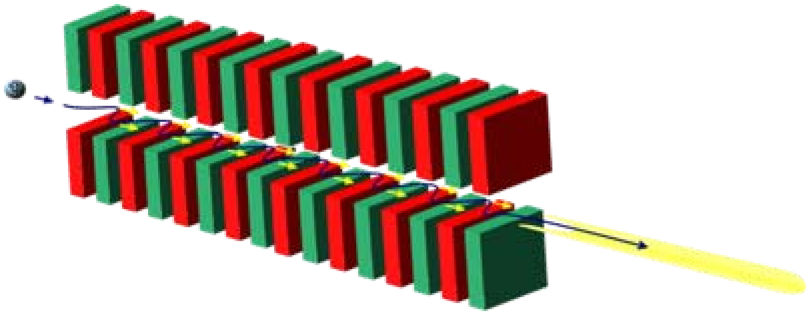
15 kW total power

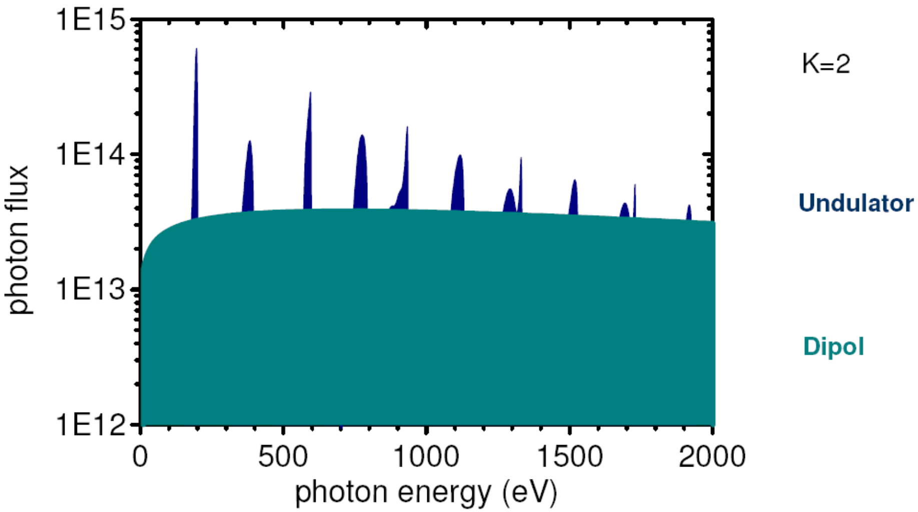
~ 1 % used

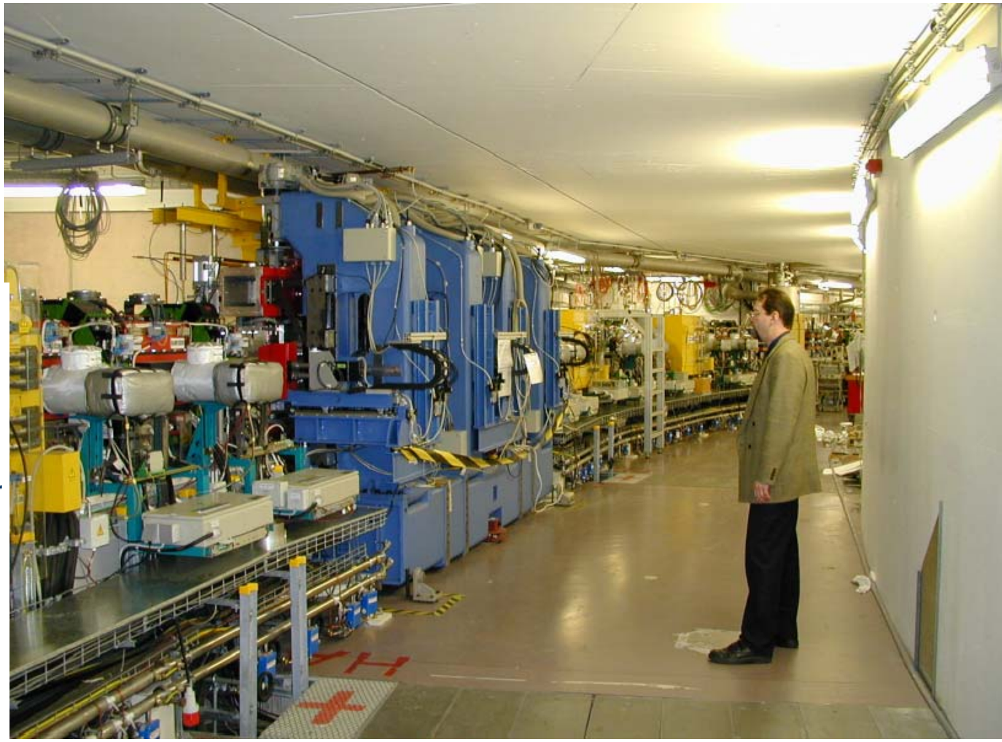
3rd Generation Light - our Product

Undulators and Wigglers

Devices with a periodic array of magnets (Undulators, Wigglers) implemented in the straight sections of the storage ring produce coherent, polarised radiation.







OUTLINE

Photon-matter interaction (basic optics)

From mirrors to accelerator walls

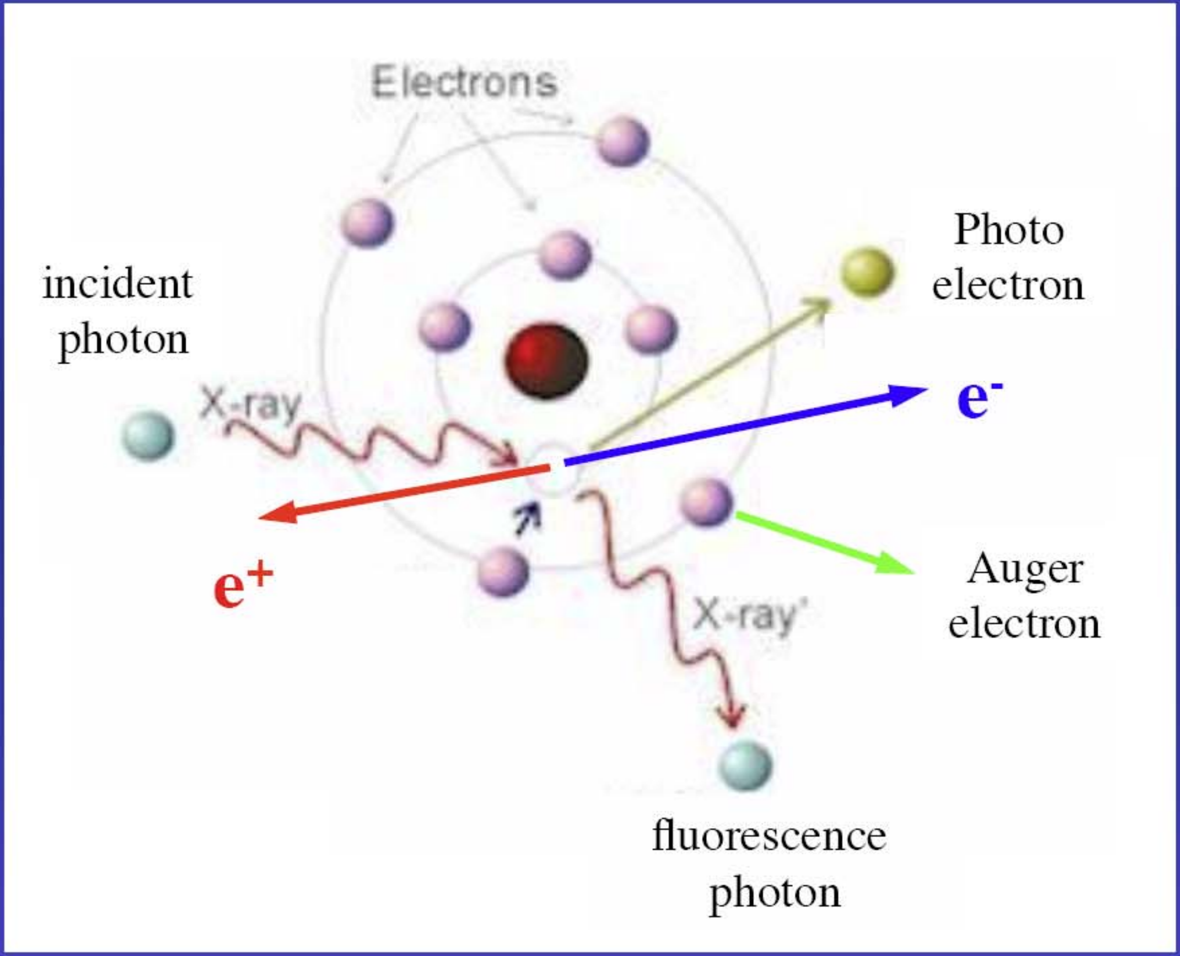
Reflectometry

Experimental data at BESSY-II

Photon-matter interaction

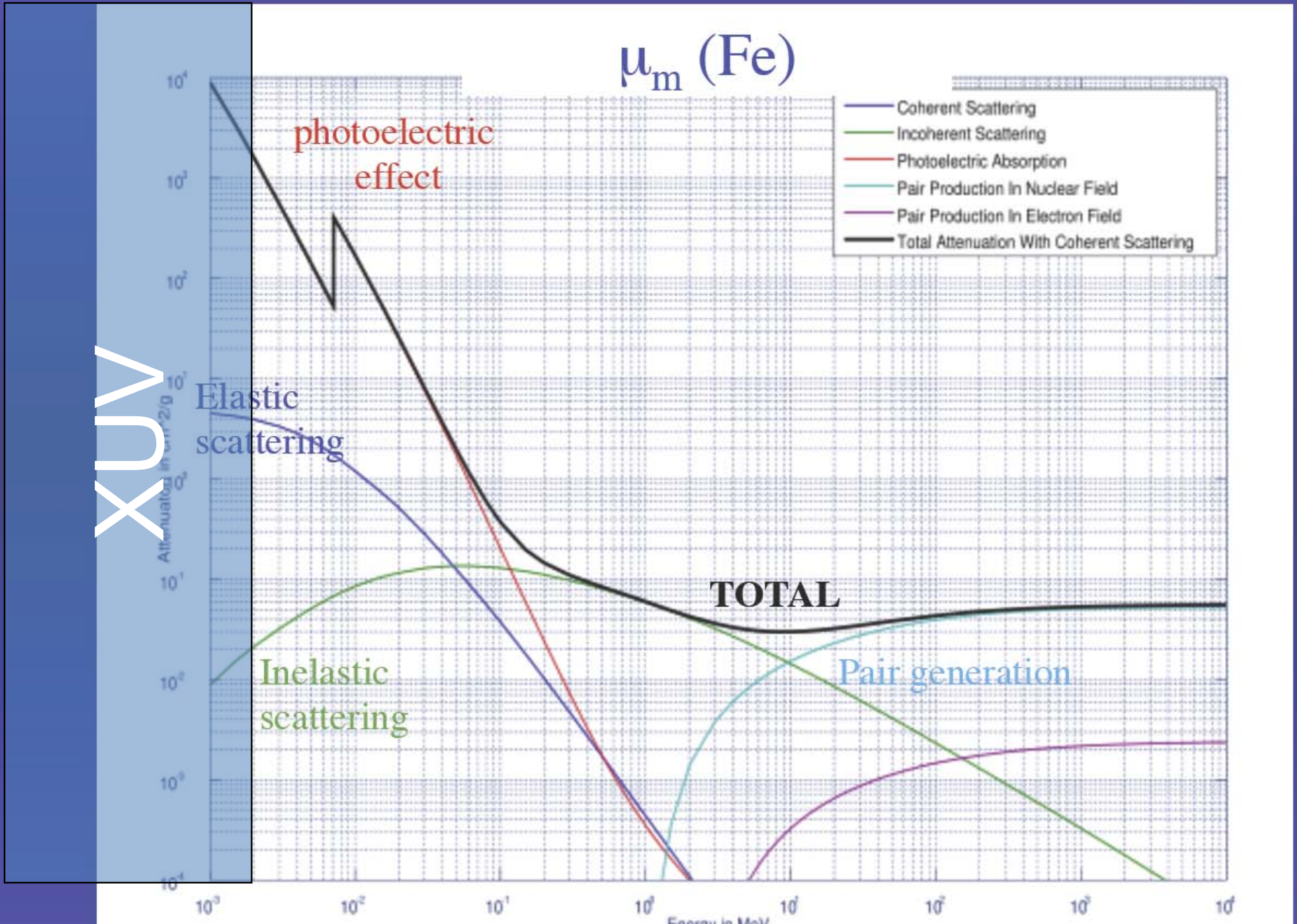
1^{er} order processes:

- Photo-electric effect then:
  - **radiative** decay (photon)
  - **non-radiative** (electron)
- Scattering
  - elastic ($E=E_0$)
  - inelastic ($E<E_0$)
- Pair generation e^+e^-
  ($E> 2 \times 0.511$ MeV)



A. Simionovici SAS Berlin 1/2012

Interaction processes



A. Simionovici SAS Berlin 1/2012

Augustin Fresnel
1788 - 1827

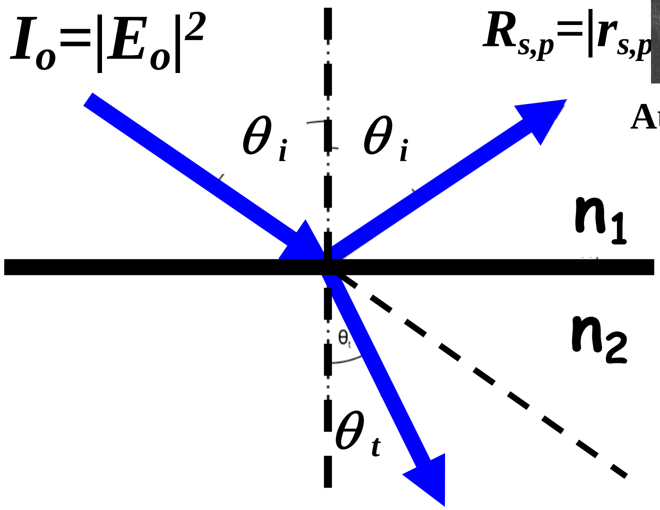
$$E_{s,p}(r,t)=E_{o_{s,p}}e^{i(\omega t-kr-\phi_{s,p})}$$

$$r_s=\frac{E_{rs}}{E_{is}}=\frac{n_1\cdot\cos\theta_i-n_2\cdot\cos\theta_t}{n_1\cdot\cos\theta_i+n_2\cdot\cos\theta_t}$$

$$t_s=\frac{E_{ts}}{E_{is}}=\frac{2n_1\cdot\cos\theta_i}{n_1\cdot\cos\theta_i+n_2\cdot\cos\theta_t}$$

$$r_p=\frac{E_{rp}}{E_{ip}}=\frac{n_2\cdot\cos\theta_i-n_1\cdot\cos\theta_t}{n_1\cdot\cos\theta_t+n_2\cdot\cos\theta_i}$$

$$t_p=\frac{E_{tp}}{E_{ip}}=\frac{2n_1\cdot\cos\theta_i}{n_1\cdot\cos\theta_t+n_2\cdot\cos\theta_i}$$



$T_{s,p}=|t_{s,p}|^2$

$r_{s,p}=|r|e^{-i\delta_{s,p}}$

Willebrord von Ruijen Snell
1580 - 1626

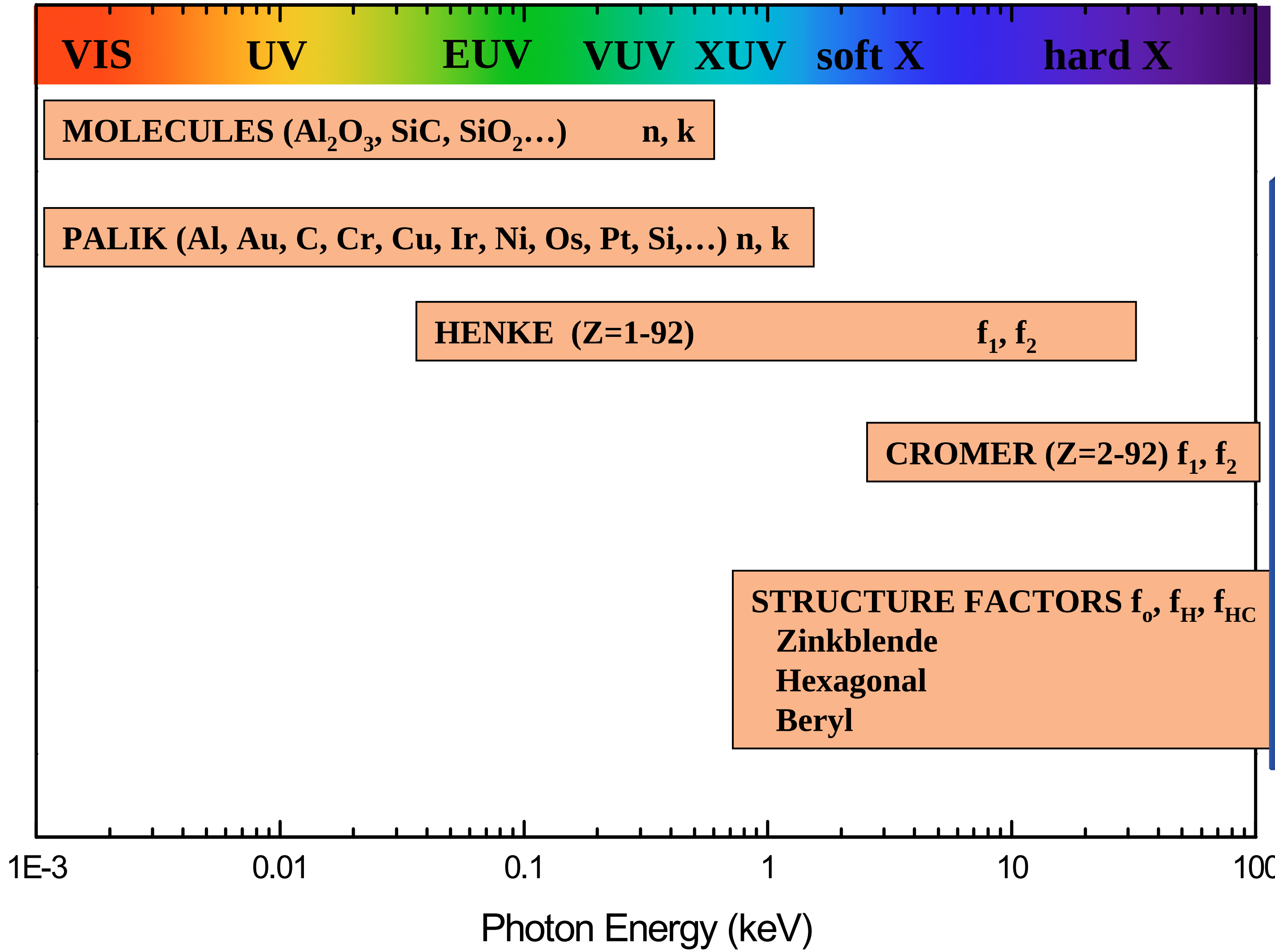
Snells law:

$\sin\theta_i / \sin\theta_t = n_1/n_2$

Index of refraction:

$n(\lambda) = 1 - \delta - ik$

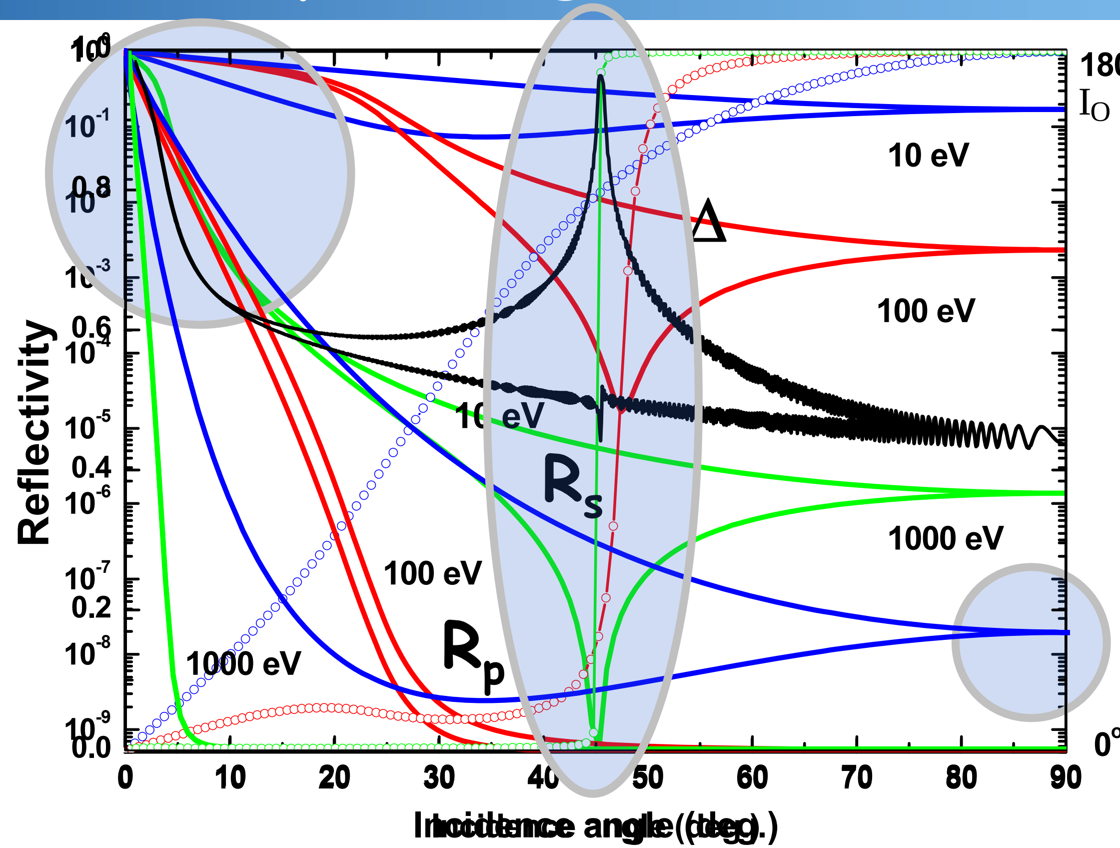
OPTICAL DATA TABLES

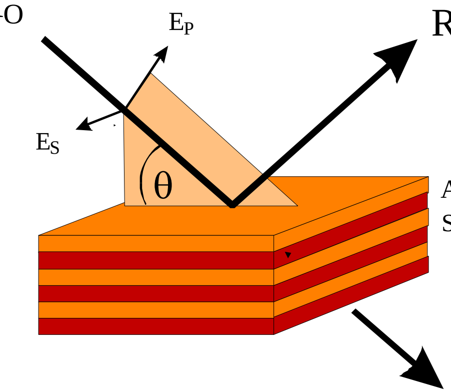


Calculation of

- Reflectivity
- Efficiency
- Transmission
- Rocking curves
- Photon Flux
- Resolving power
- Polarisation

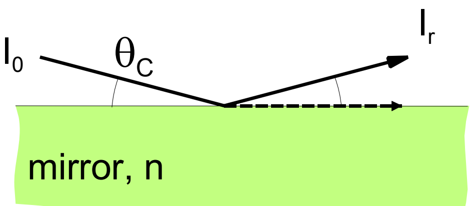
Reflectometry for beginners: Fresnel Equations





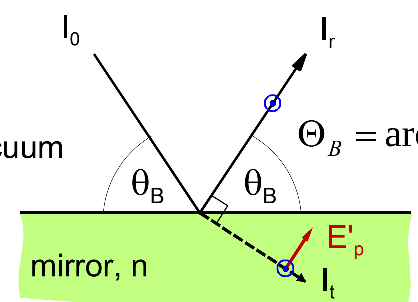
Multilayer
$n\lambda = 2d\sin\theta$

Total external reflection



$\Theta_C = \arccos n$

Brewster angle



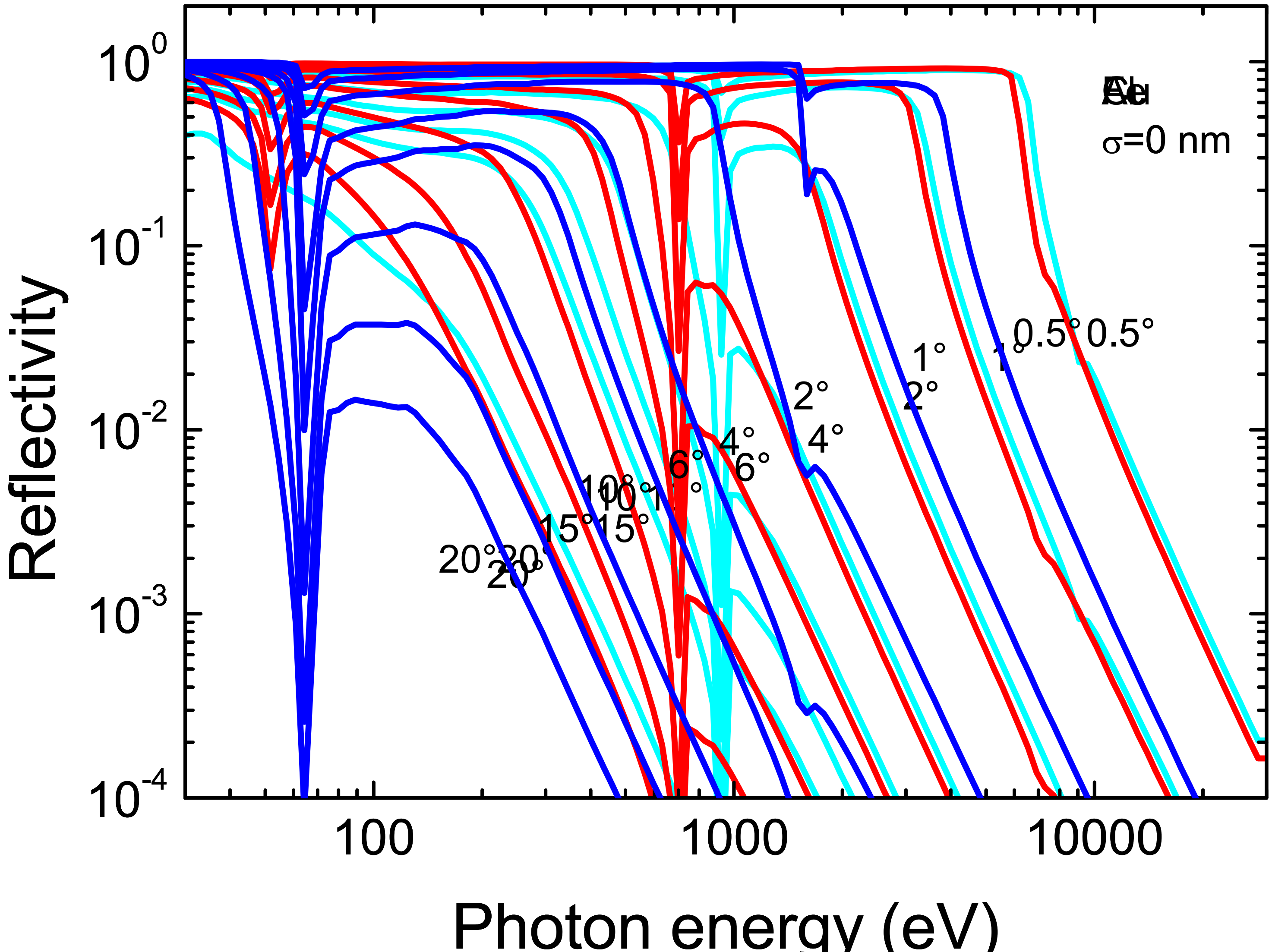
$\Theta_B = \arctan\left(\frac{1}{n}\right)$ ~45°

Normal incidence

$Rs,p = \frac{1}{4}(\delta^2+\beta^2)$

$\ll 1$

Fresnel reflectivity Al, Cu, SS



OUTLINE

Photon matter interaction (basic optics)

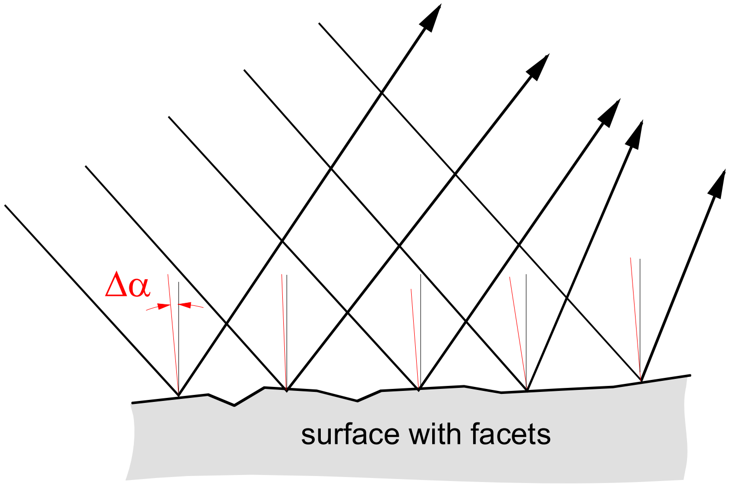
From mirrors to accelerator walls

Reflectometry

Experimental data at BESSY-II

Real Optics: Slope errors, Surface roughness

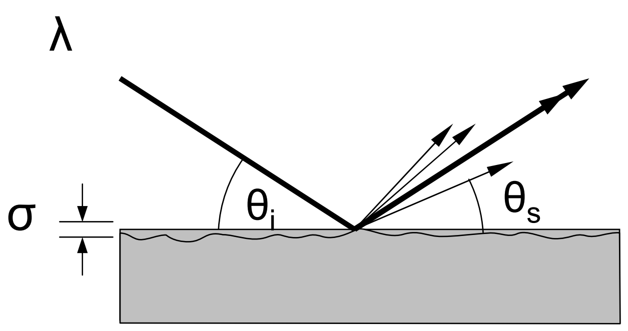
- **Surface composed of facets with angle $\Delta\alpha_i$**
- **beams are deflected by $2 \cdot \Delta\alpha_i$**
- **Slope error is the rms-value of the (gaussian) angular distribution of the surface facets $\Delta\alpha_i$**
- **Slope error gives rise to a blurring of the image**



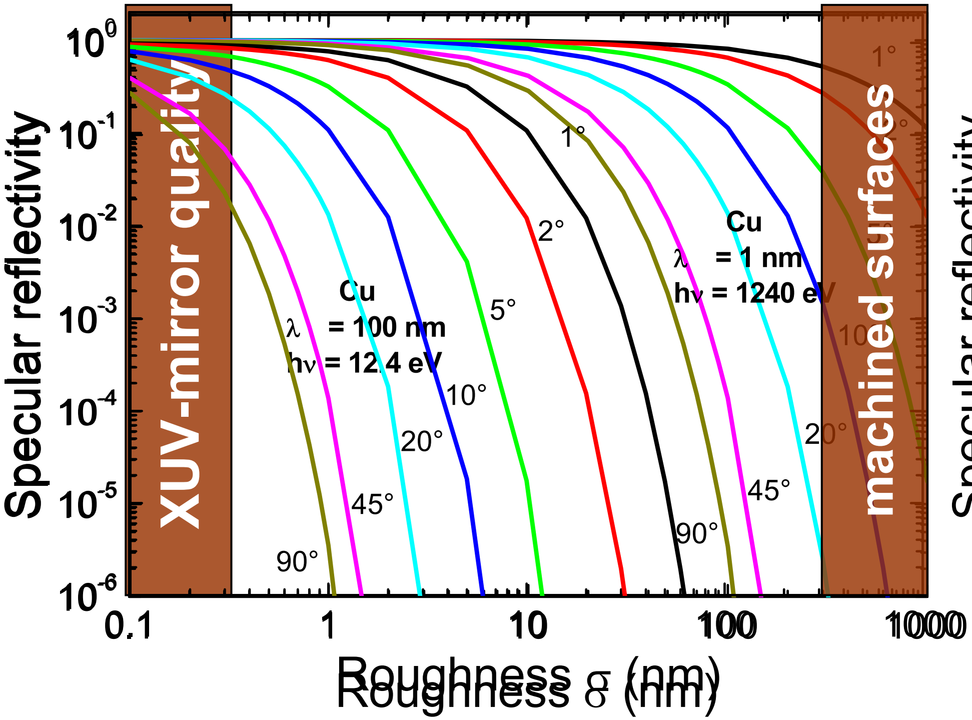
- **Reduction of specular intensity**
- **Debye-Waller factor reduces reflectance R_0**

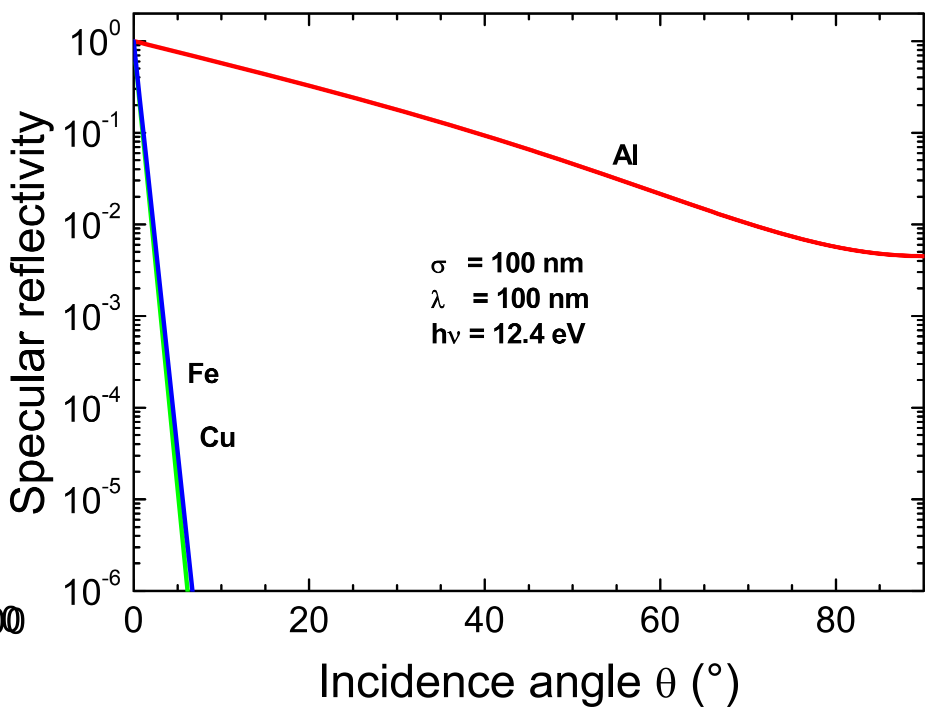
$$R = R_0\, e^{-\left(\frac{4\pi\sigma \sin\theta_i}{\lambda}\right)^2}$$

σ: rms value of the height deviation



Note that FWHM = 2.3·σ

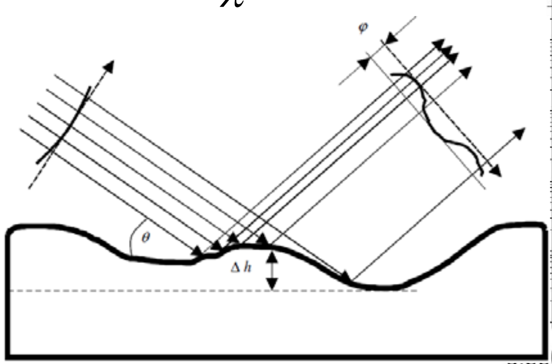

Specular reflectivity
XUV-mirror quality
machined surfaces
Cu
λ = 100 nm
hν = 12.4 eV
Cu
λ = 1 nm
hν = 1240 eV
1°
2°
5°
10°
20°
45°
90°
Roughness σ (nm)

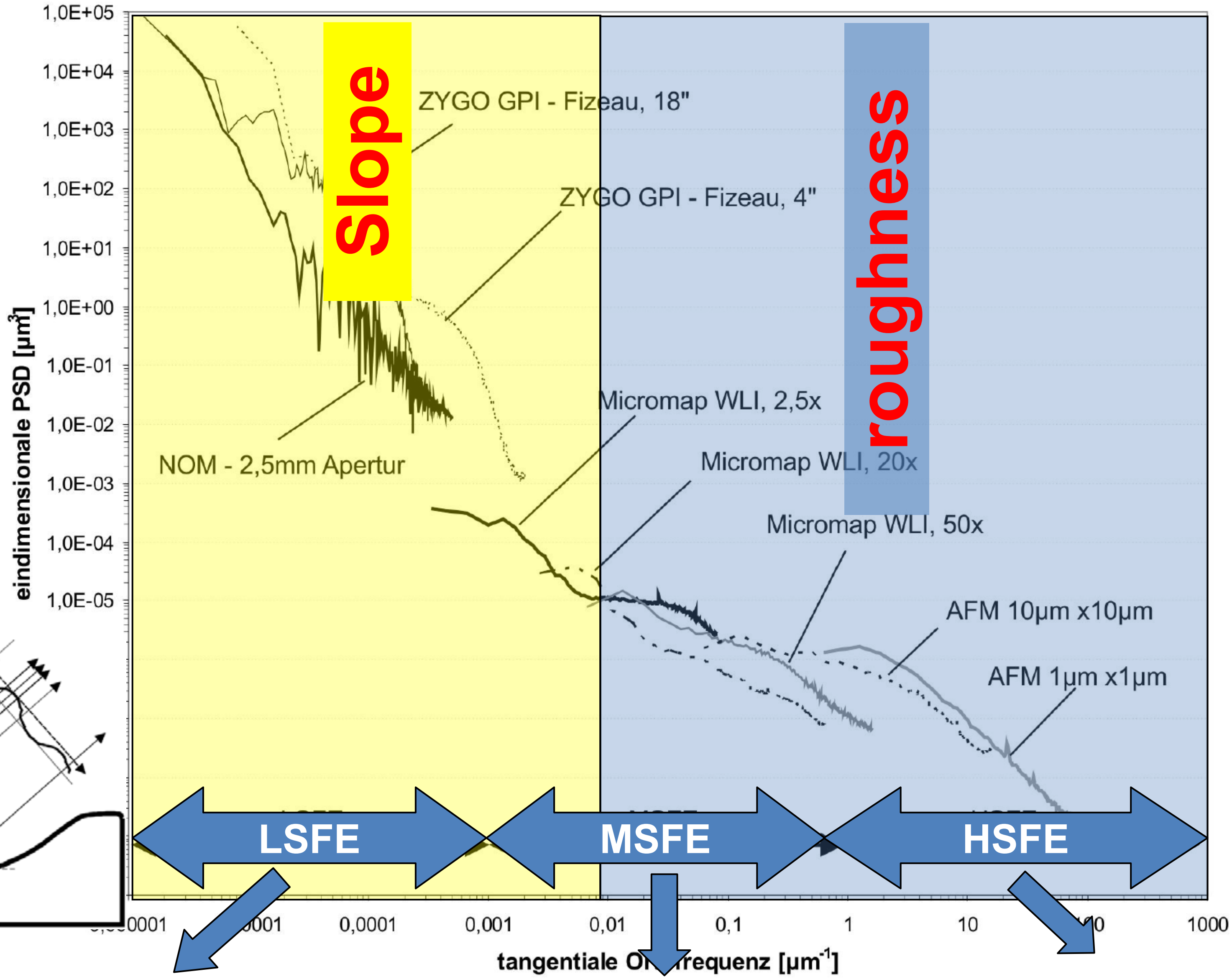

Specular reflectivity
Al
Fe
Cu
σ = 100 nm
λ = 100 nm
hν = 12.4 eV
Incidence angle θ (°)

Metrology on surfaces: PSD - Power spectral density

Courtesy of V. Yashchuk, ALS

$$\varphi = \frac{2\Delta h \sin\theta}{\lambda}$$





wavefront distortion

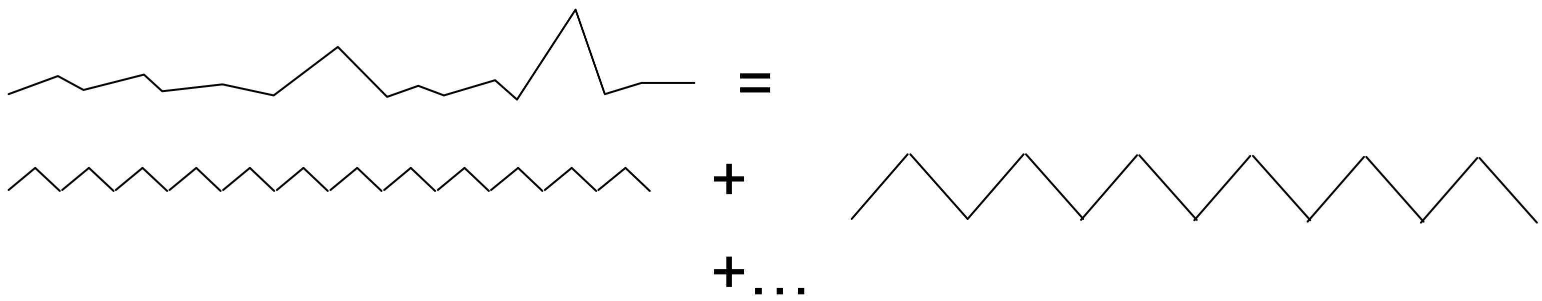
small angle scatter

wide angle scatter

Angular distribution of scattered power

Courtesy of V. Yashchuk, ALS

Surface is sum over gratings



$$\frac{1}{P_0}\frac{dP}{d\omega} = \left(\frac{16\pi^2}{\lambda^4}\right)\left(R\right)\left(\sin^3\theta_i\right)\left(PSD_{2D,\,2\,\mathrm{sided}}\left(\mathbf{f}\right)\right)$$

Rayleigh scattering ‚blue sky' factor

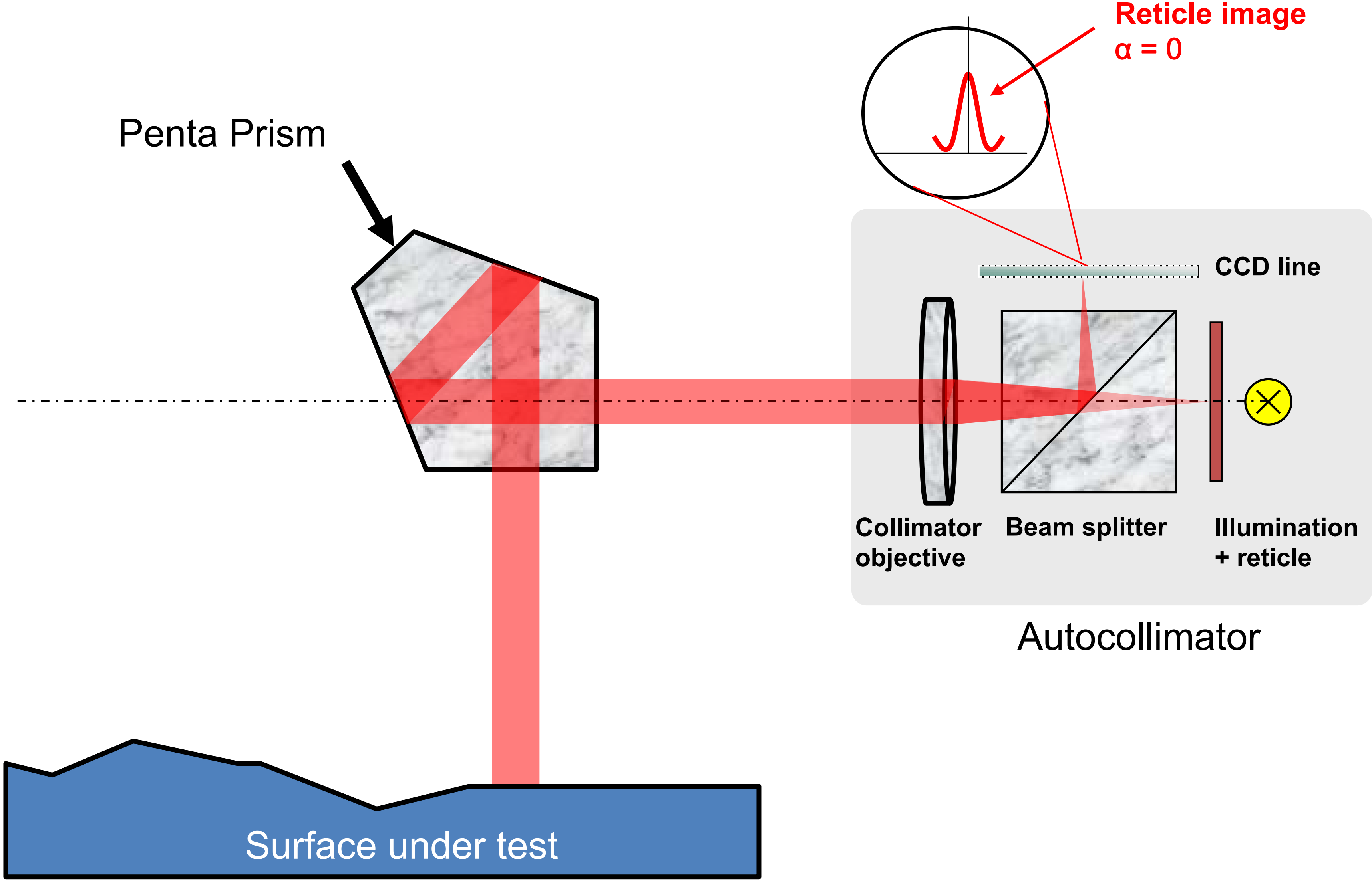
Material properties

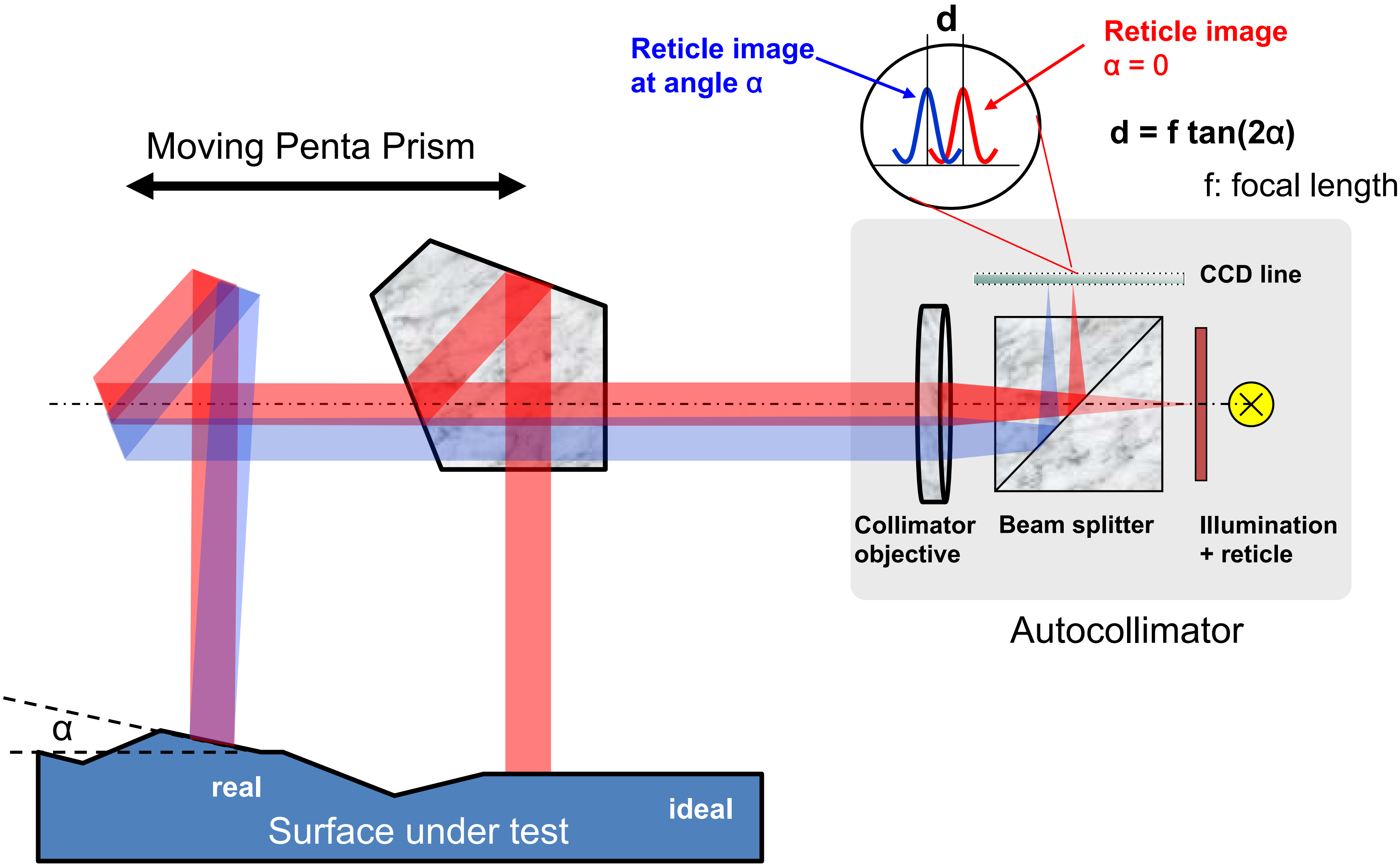
Grazing incidence

Power spectral density

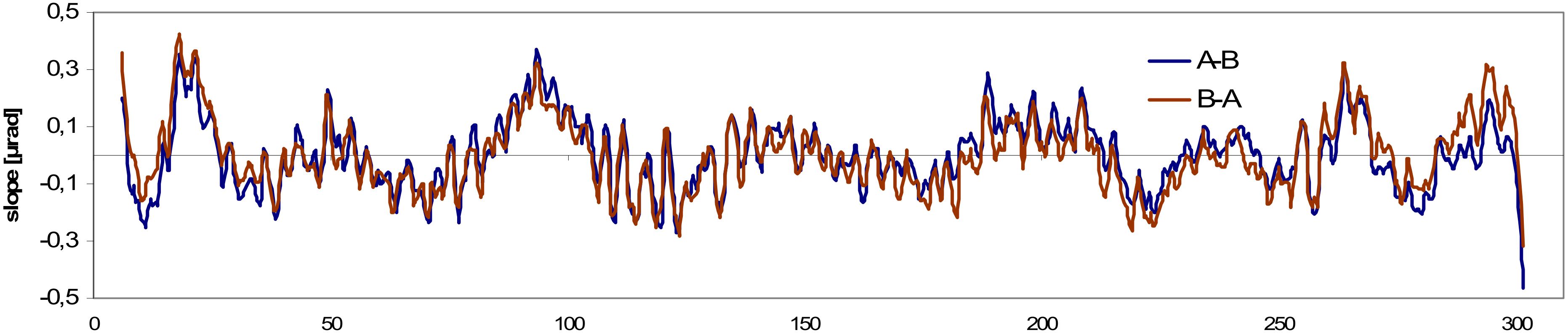
- Scattering goes up with energy of the light--fast
- Scattering goes down with higher incidence angle
- Valid in the 'smooth surface' limit!!!

NOM - The Nanometer Optics Measuring Machine



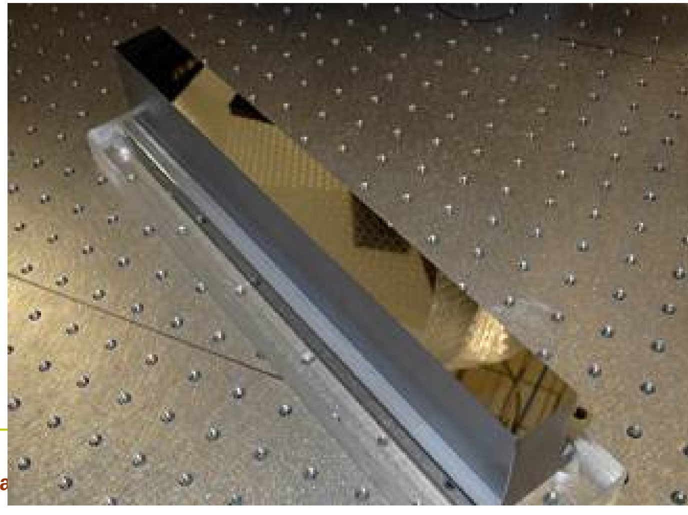

d
Reticle image
at angle α
Reticle image
α = 0
d = f tan(2α)
f: focal length
Moving Penta Prism
CCD line
Collimator
objective
Beam splitter
Illumination
+ reticle
Autocollimator
α
real
ideal
Surface under test

Mirrror Requirements for todays X-Ray Optics



achieved:	BESSY-II	Plane mirrors	300 mm	0.1 µrad	(0.02“)
	LCLS	Refoc. mirror	350 mm	0.05 µrad	<1 nm rms
goal:	XFEL	Plane mirror	800 mm	0.05 µrad	(2 nm pv)
	XFEL	Refoc. mirror	800 mm	0.05 µrad	

the tip of the needle, not the head!



OUTLINE

Photon matter interaction (basic optics)

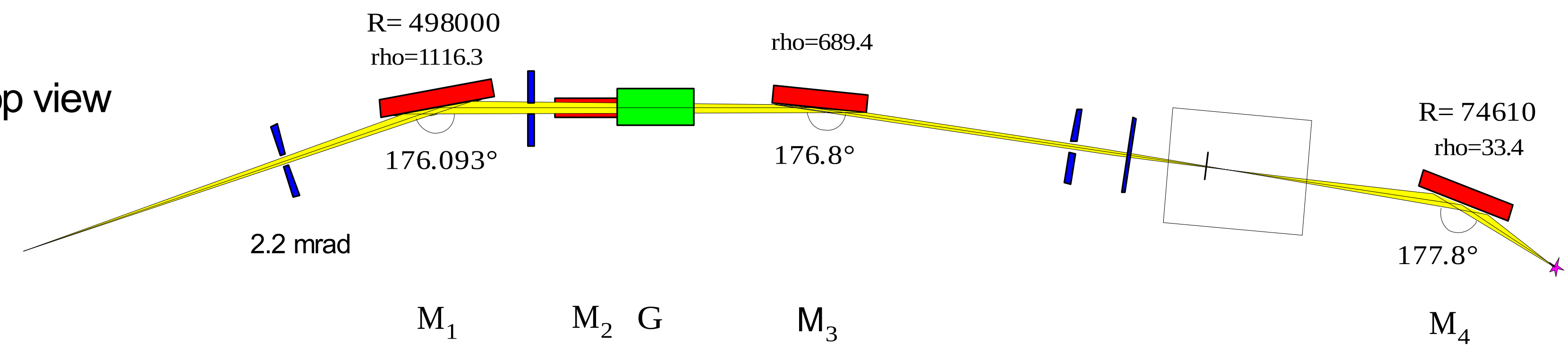
From mirrors to accelerator walls

Reflectometry

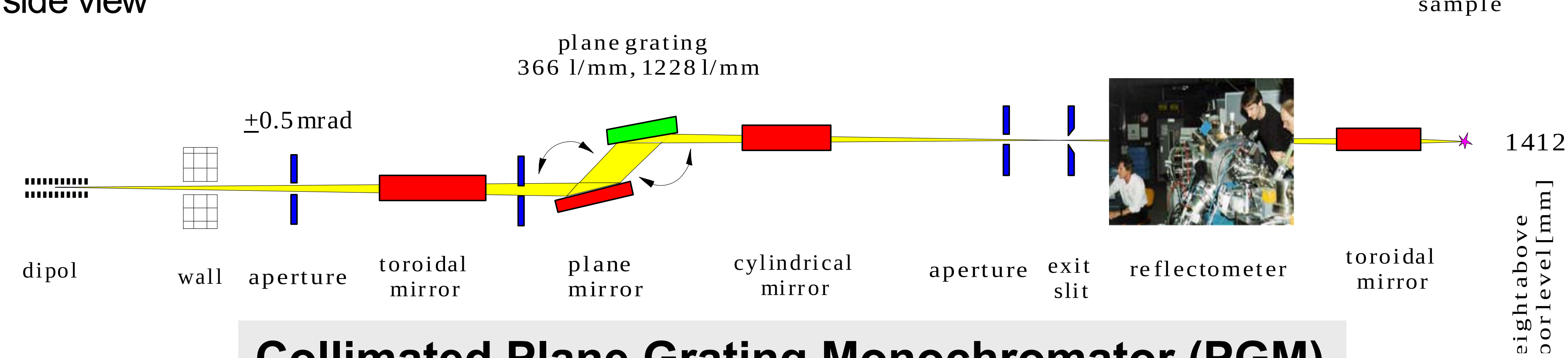
Experimental data at BESSY-II

At-wavelength Metrology - Optics Beamline @BESSY-II

top view



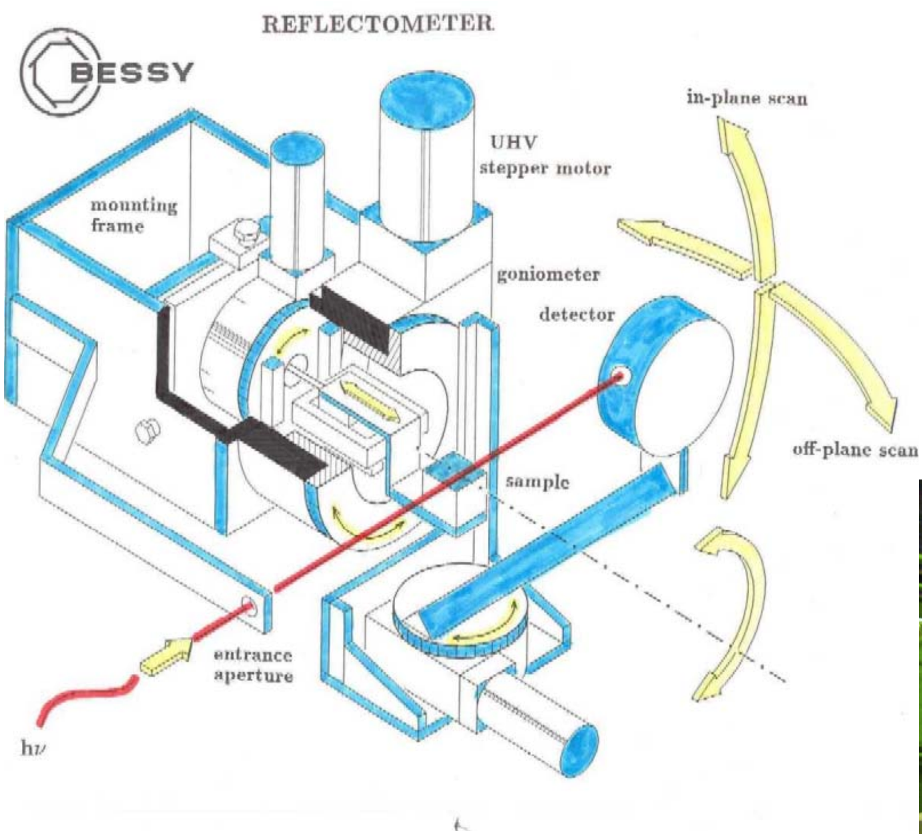
side view

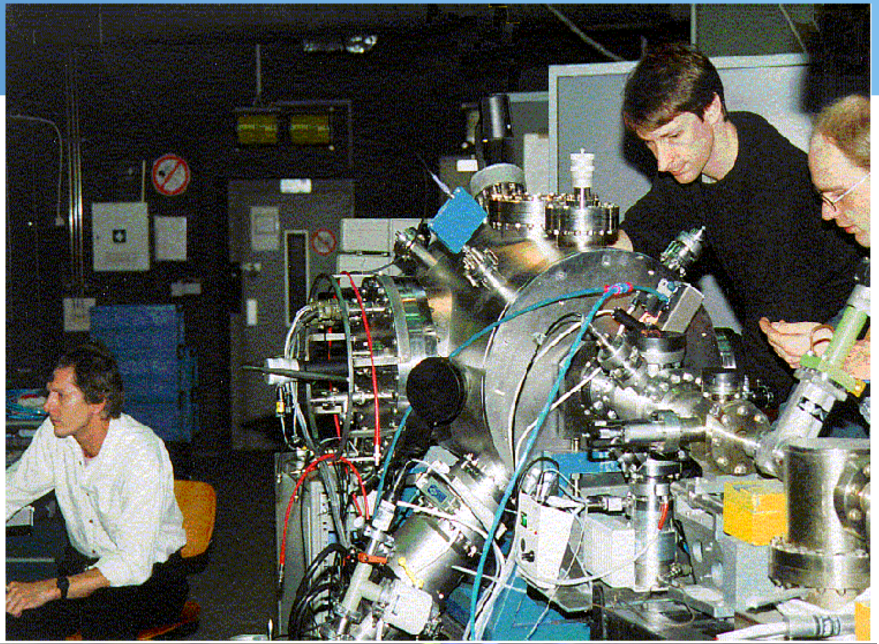


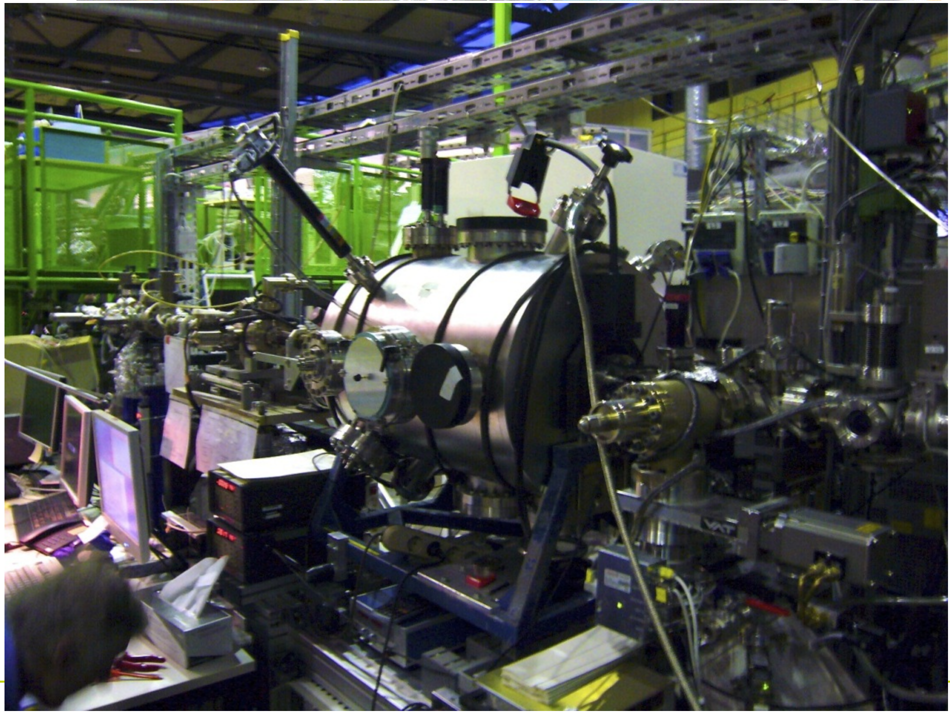
Collimated Plane Grating Monochromator (PGM)

- 10 - 2000 eV
- polarization linear/elliptical
- higher order light suppression
- low divergence

Reflectometer @ Optics Beamline

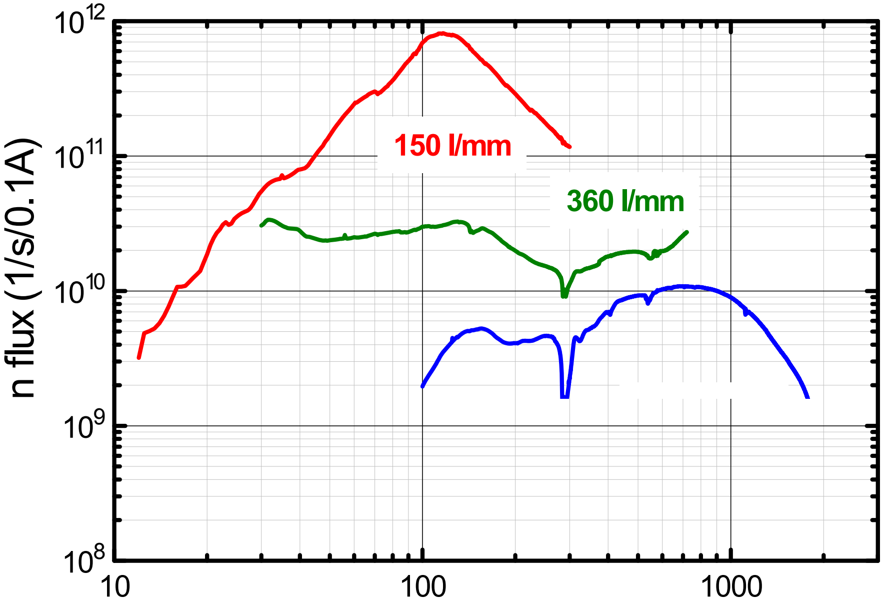




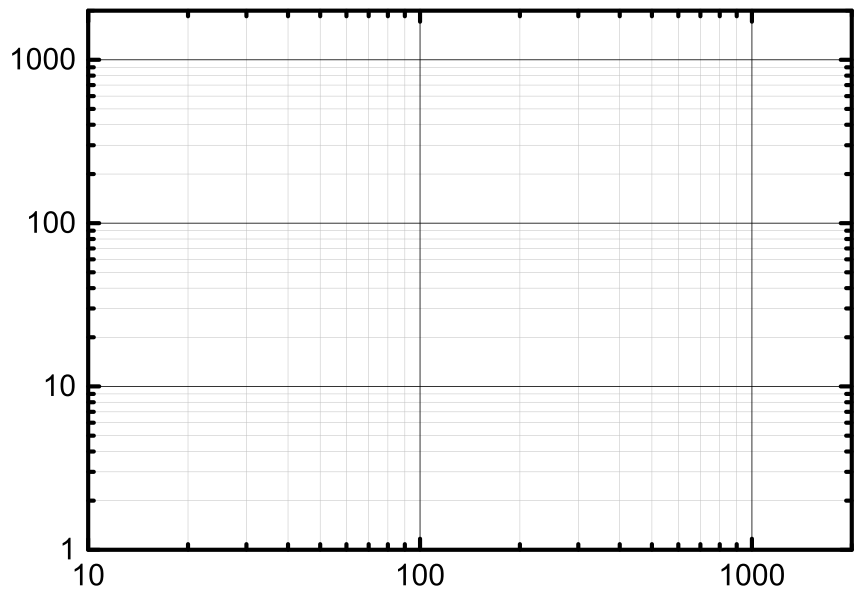


- 3 axis goniometer
- Vertical reflecion (s-pol)
- In sitù ´sample in-out´: R=I/Io
- Incidence angle 0°- 87.5°

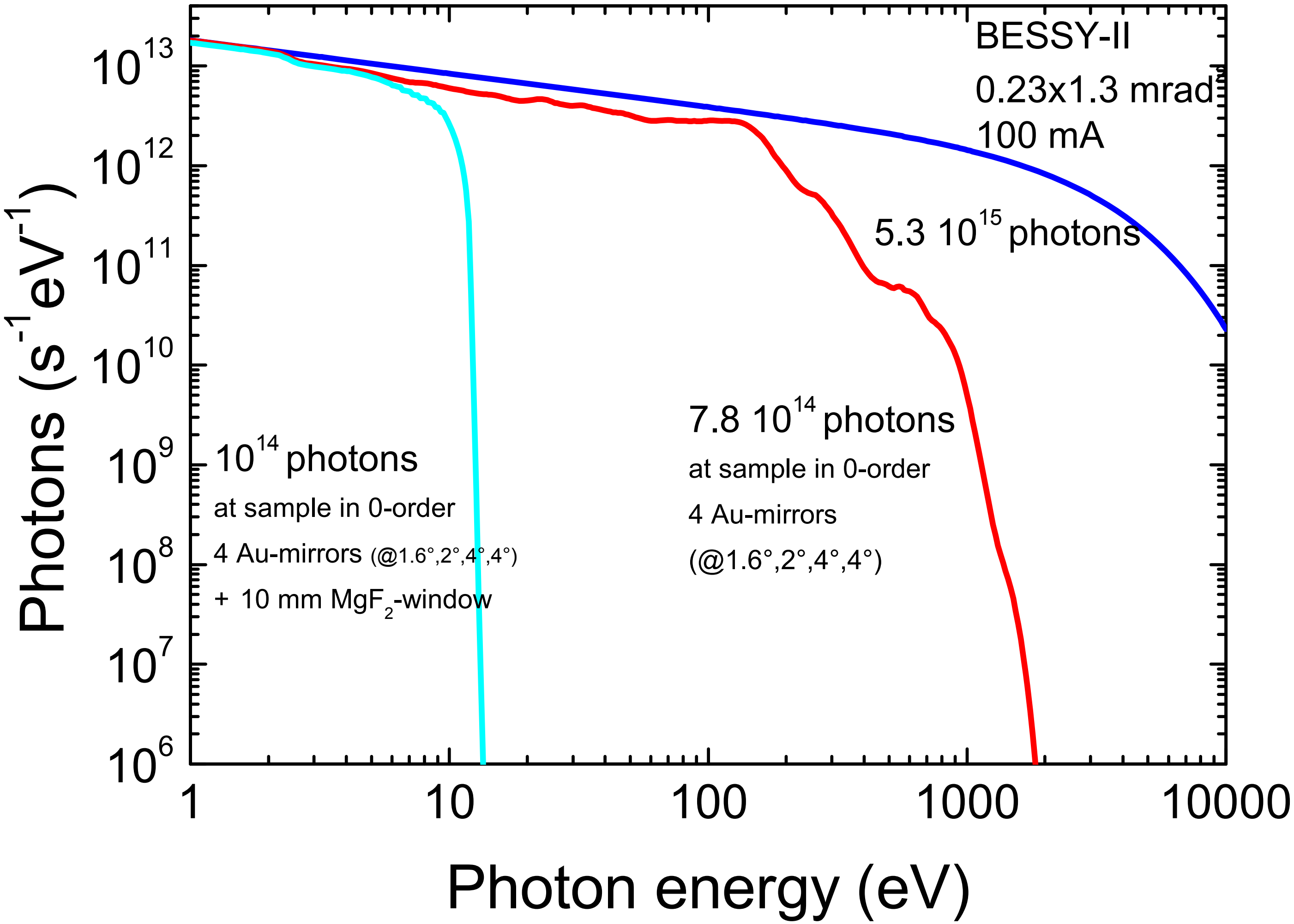
Photon flux



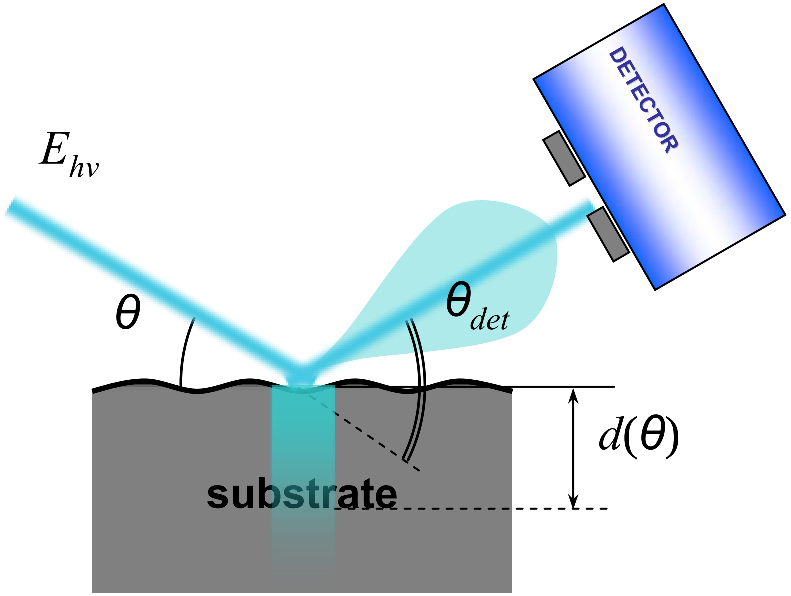
Energy resolution



White light irradiation tests

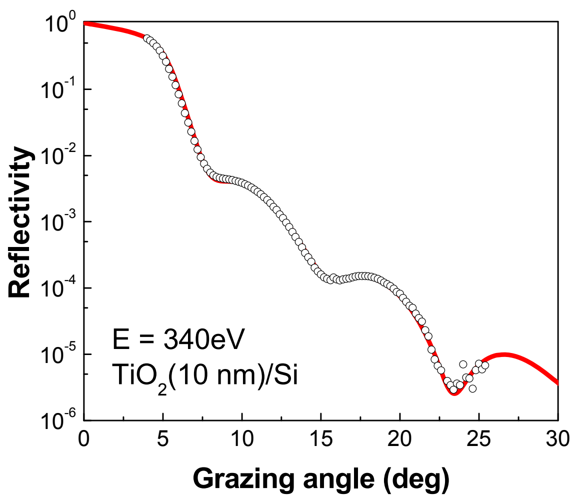


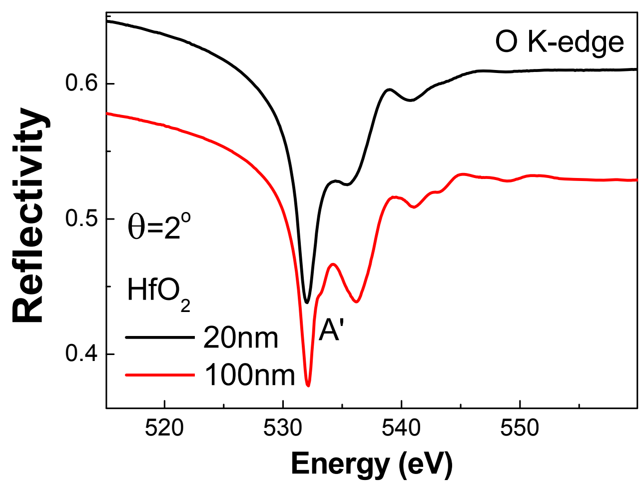
Reflectometry

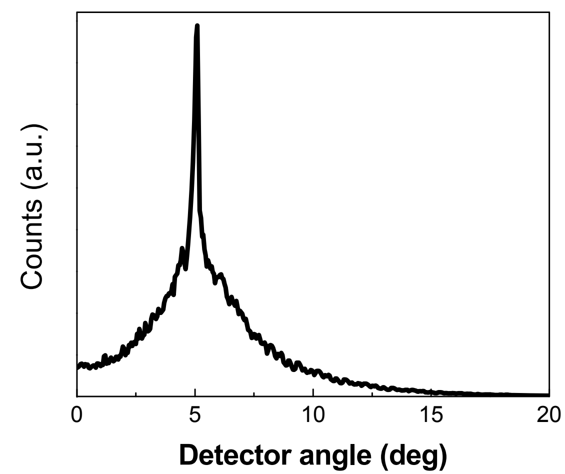


- **Reflectivity**
- **surface roughness**
- **interface quality**
- **layer thickness**
- **chemical composition**
- **optical constants**

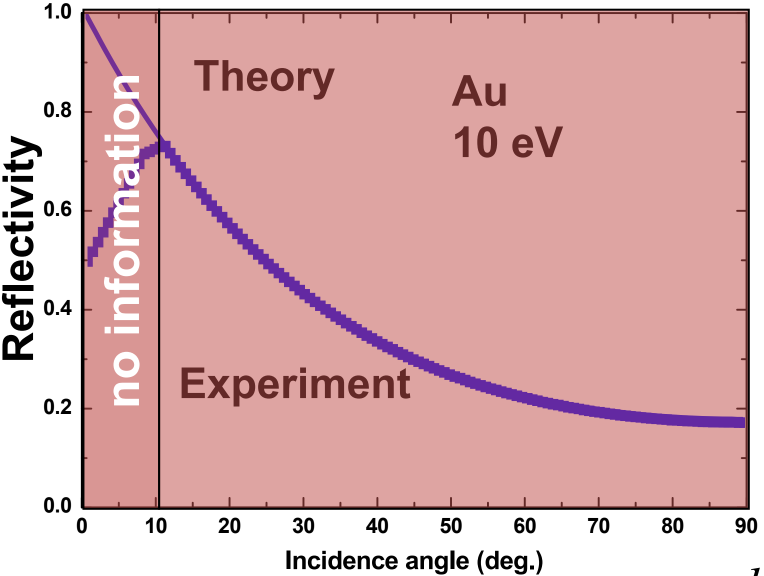
- **TEST DRIVE for Optics**



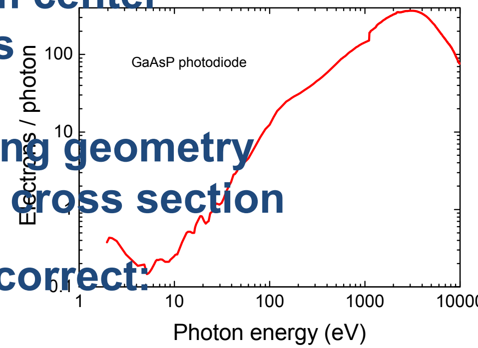




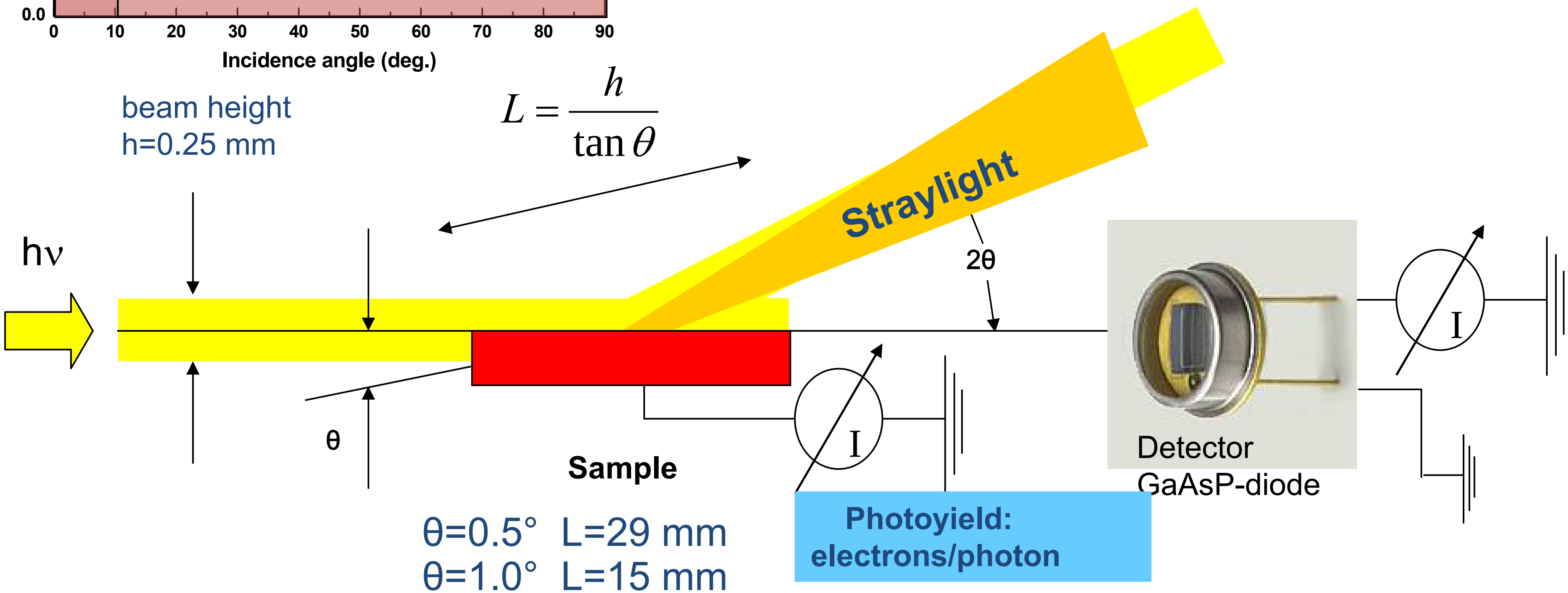
Reflectometry facing reality



- θ–rotation axis not in beam center
- Sample not in rotation axis
- Both
- Sample too short for grazing geometry
- Detector larger than beam cross section



- Angular coupling θ – 2θ incorrect: problems at small angles
- Sample tilt: problems at large angles



Photon matter interaction (basic optics)

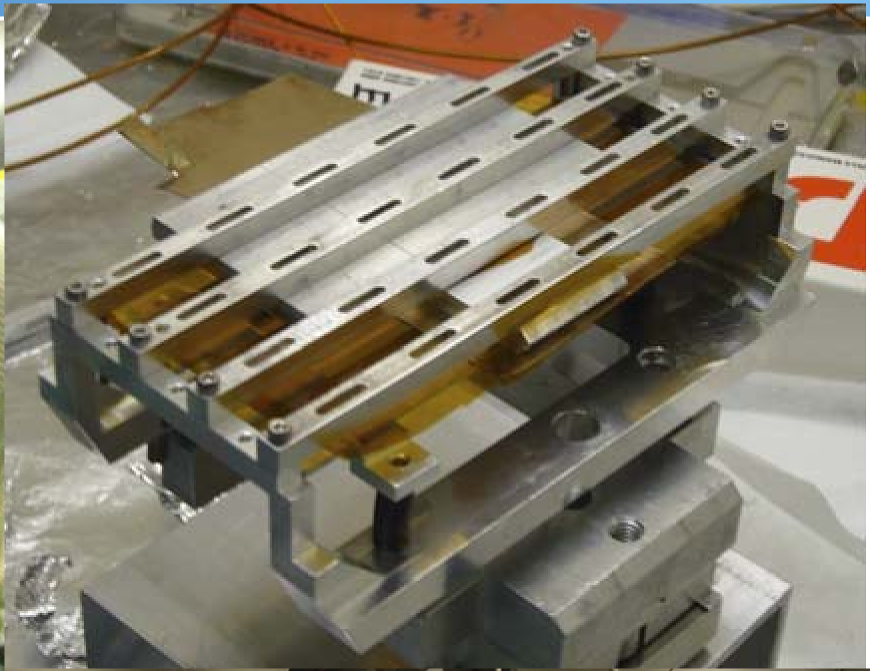
From mirrors to accelerator walls

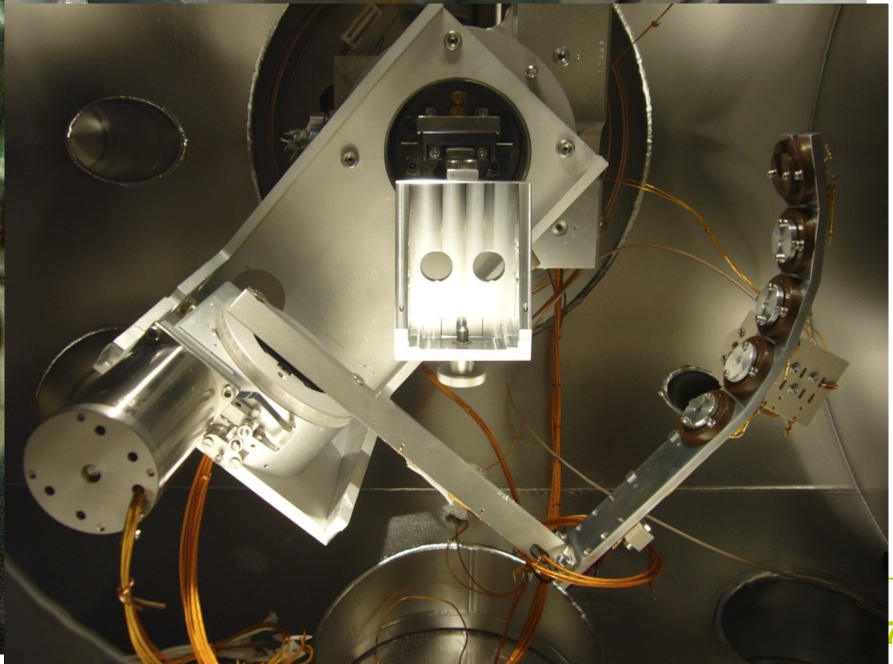
Reflectometry

Experimental data at BESSY-II

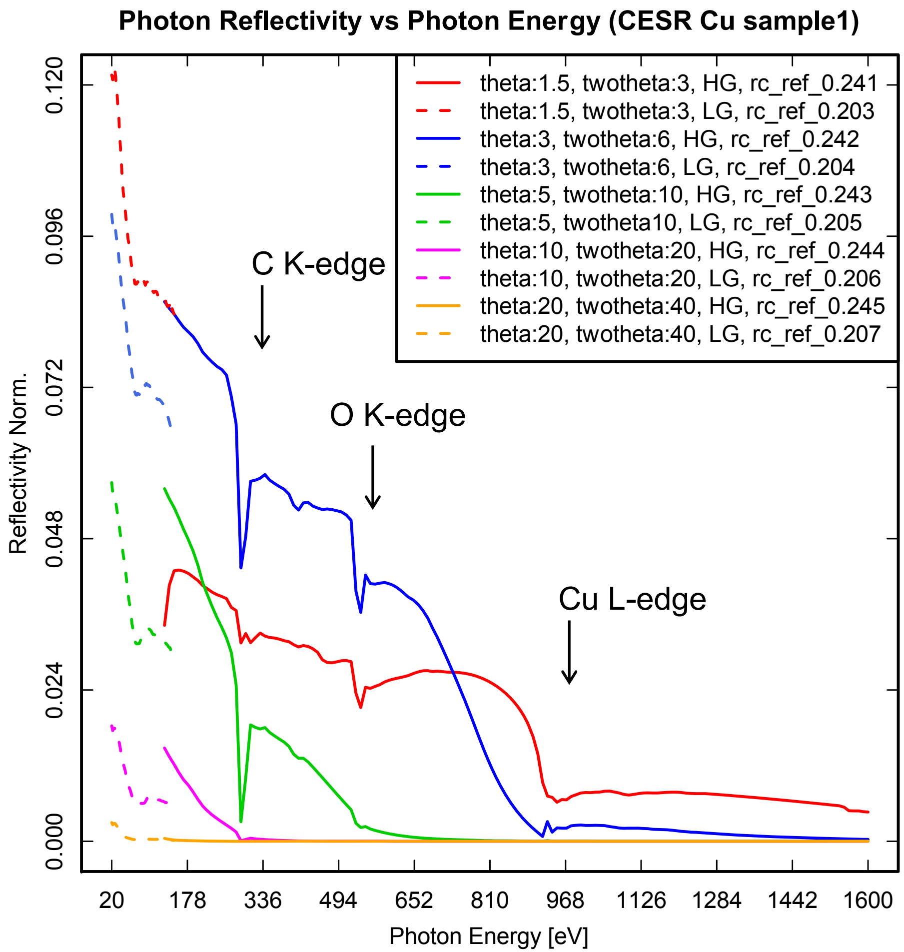
(Roberto, Takuya, Laura)

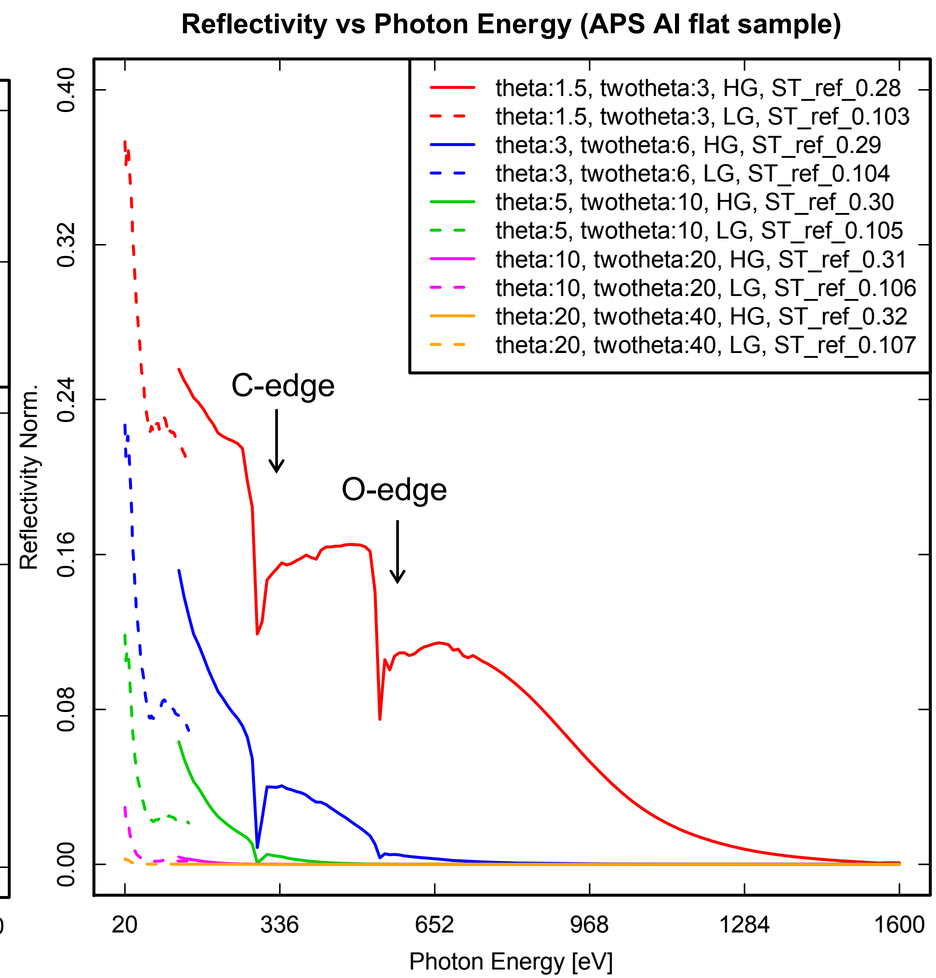
Samples and Sample holder





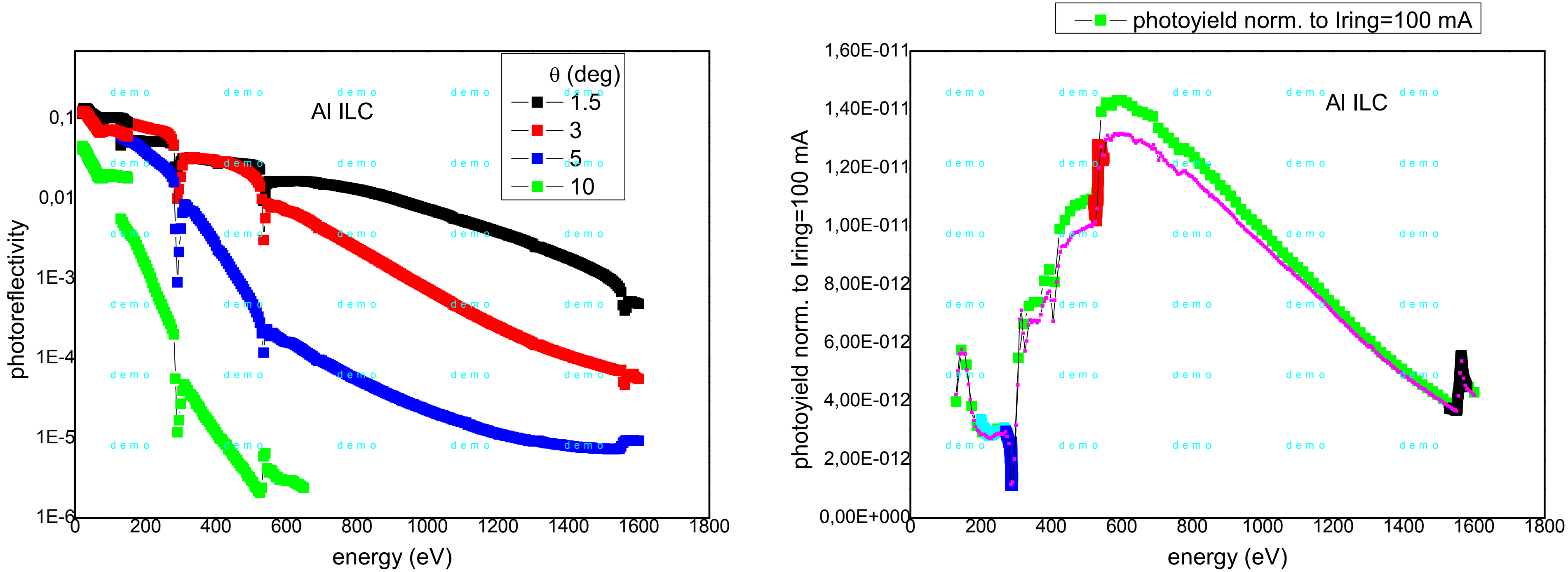
Energy dependence of Reflectivity





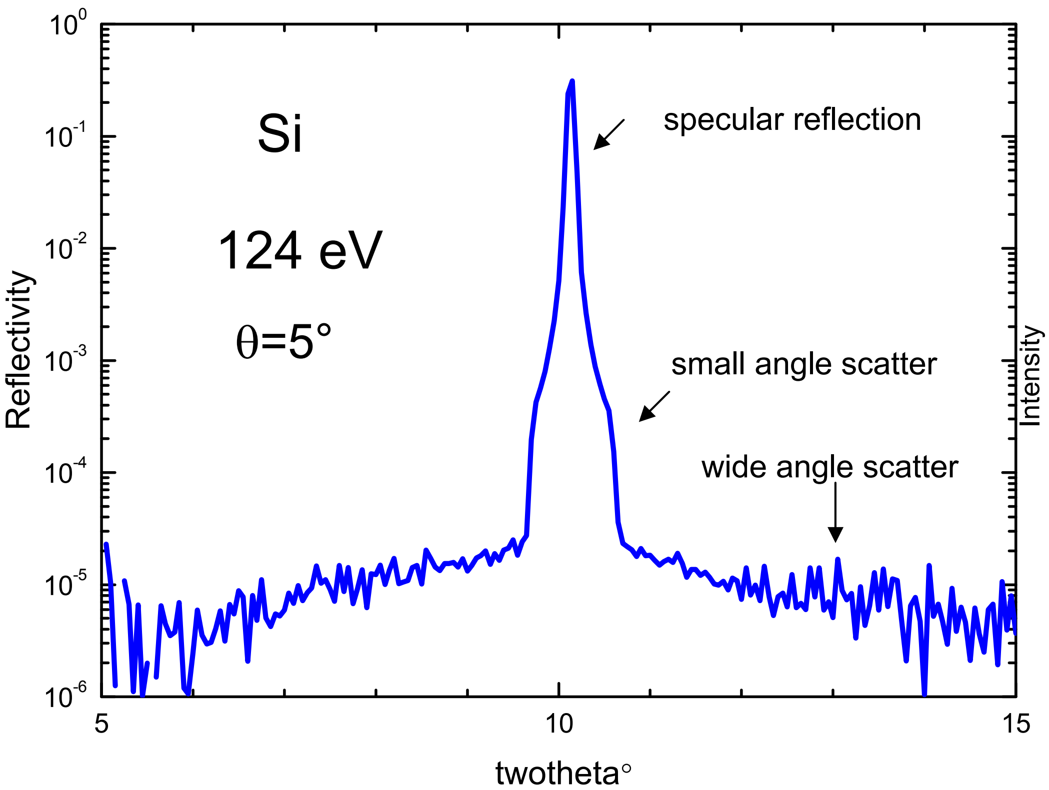
data from Takuya Ishibashi

Al (ILC) Specular reflectivity - Photoyield

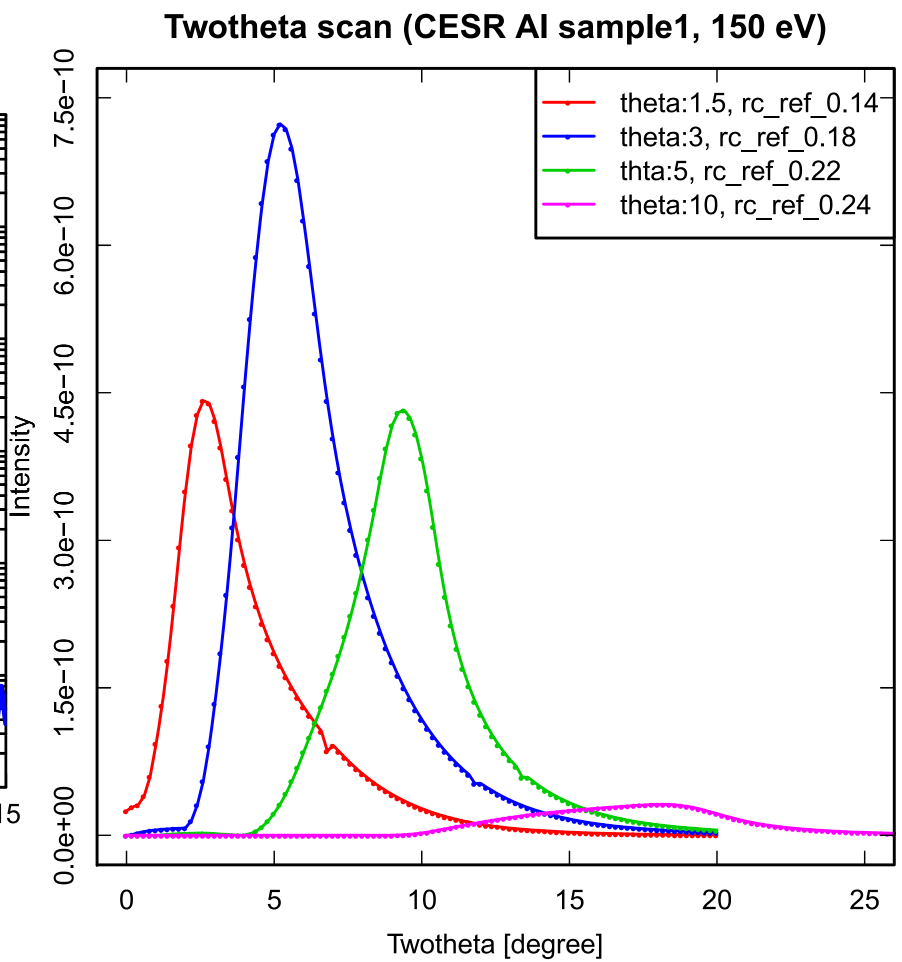


Straylight distribution (twotheta scans)

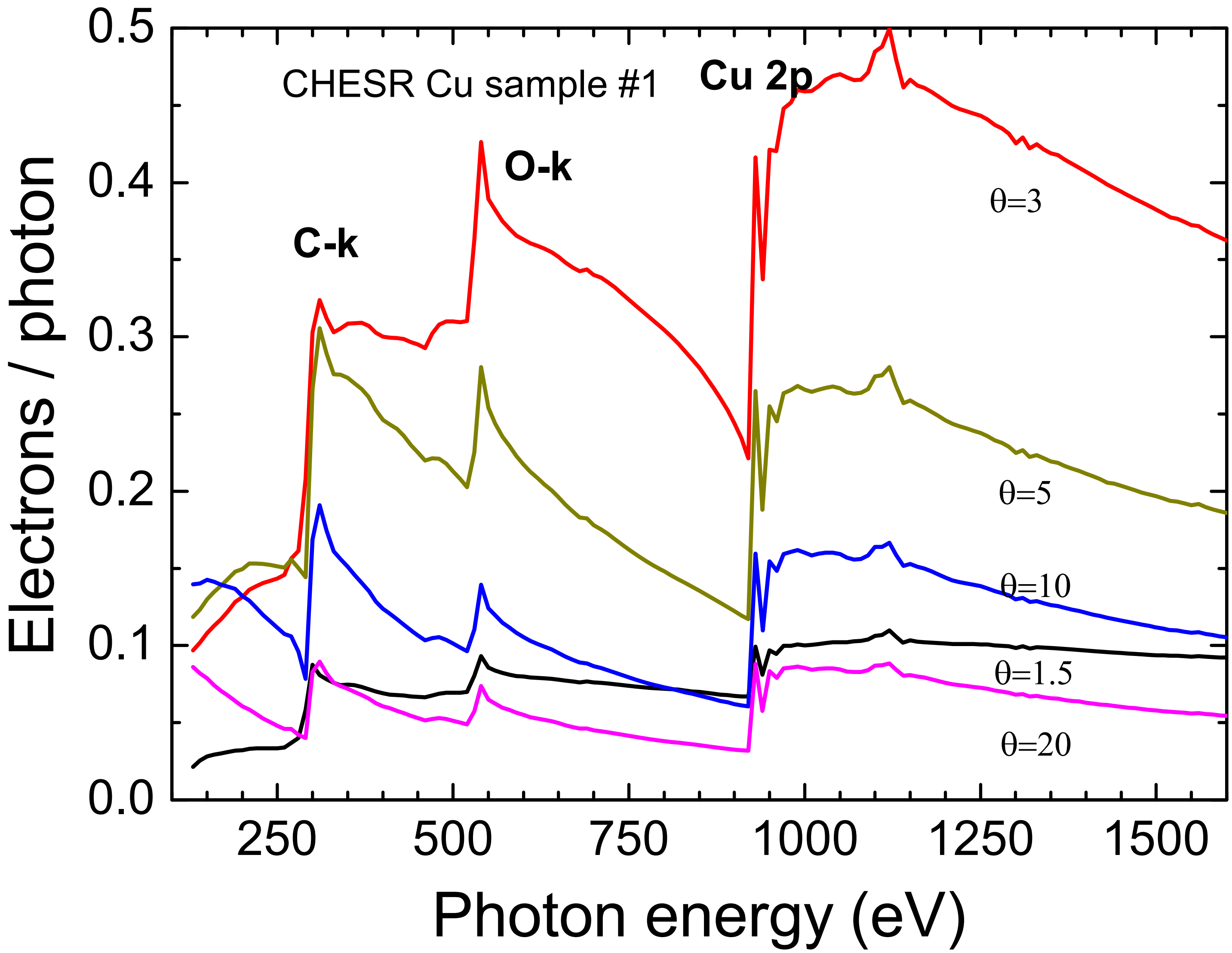
quasi-perfect mirror



accelerator wall



Photoyield



CHESR Cu sample #1
Cu 2p
O-k
C-k
θ=3
θ=5
θ=10
θ=1.5
θ=20
Electrons / photon
0.0
0.1
0.2
0.3
0.4
0.5
250
500
750
1000
1250
1500
Photon energy (eV)

Conclusion

- Reflectometry is a multi-dimensional experimental challenge: photon energy, angle, substrate, contamination, non-perfect surfaces (up to sandpaper quality)
- Reflectometry is a nice and indispensible tool for a quality check of optical elements
- It delivers information on the slope and roughness of the surface and the optical properties - at the design wavelength
- Scattering is difficult to be treated mathematically - just on a statistical basis
- Sample alignment is always a serious issue - a source of misinterpreting the measured data
- Nevertheless we've measured photon reflectivity and photoyield for some samples (Al, Cu, and SS) of vacuum chambers at BESSY II
- Photoyield data can be transformed quantitatively (electrons/photon)
- We need to analyze all the data (total 630 data sets) and see how it compares with theory

Acknowlegement

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