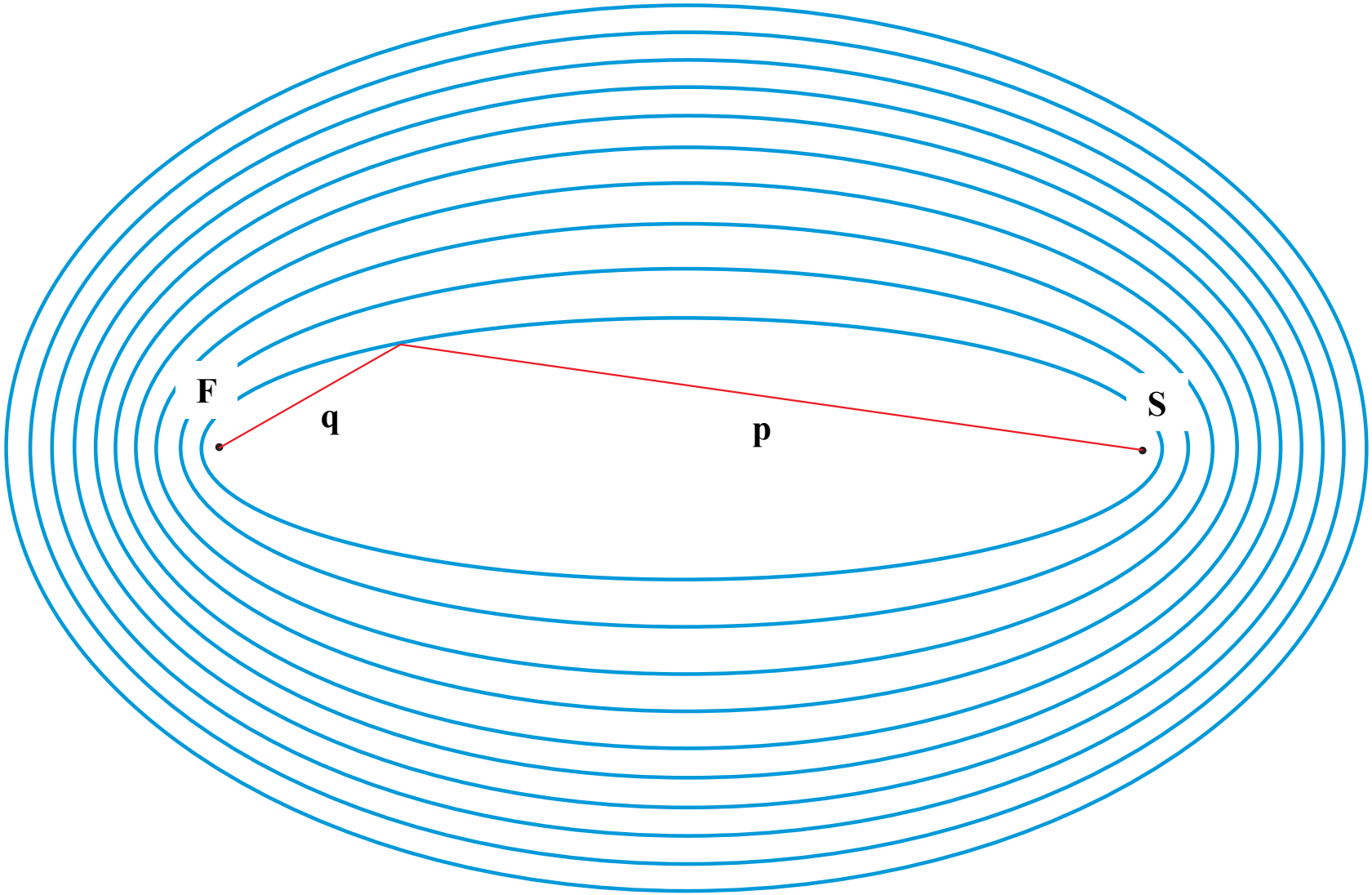
Mirror and multilayer x-ray optics

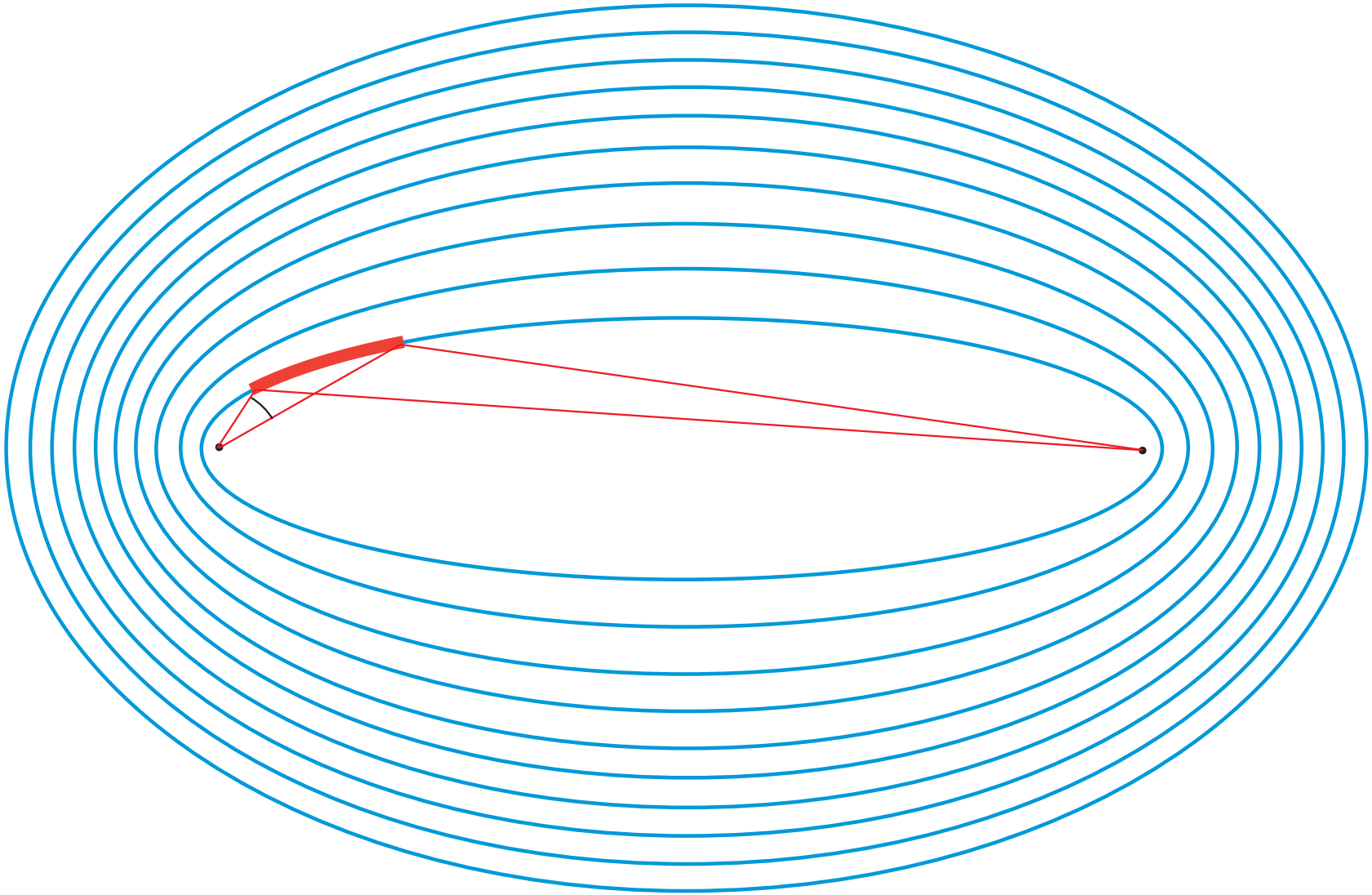
Ch. Morawe, ESRF Optics Group

- Background and theory
- Design, fabrication, and characterization
- Performance and limitations
- Applications
- Summary and perspectives

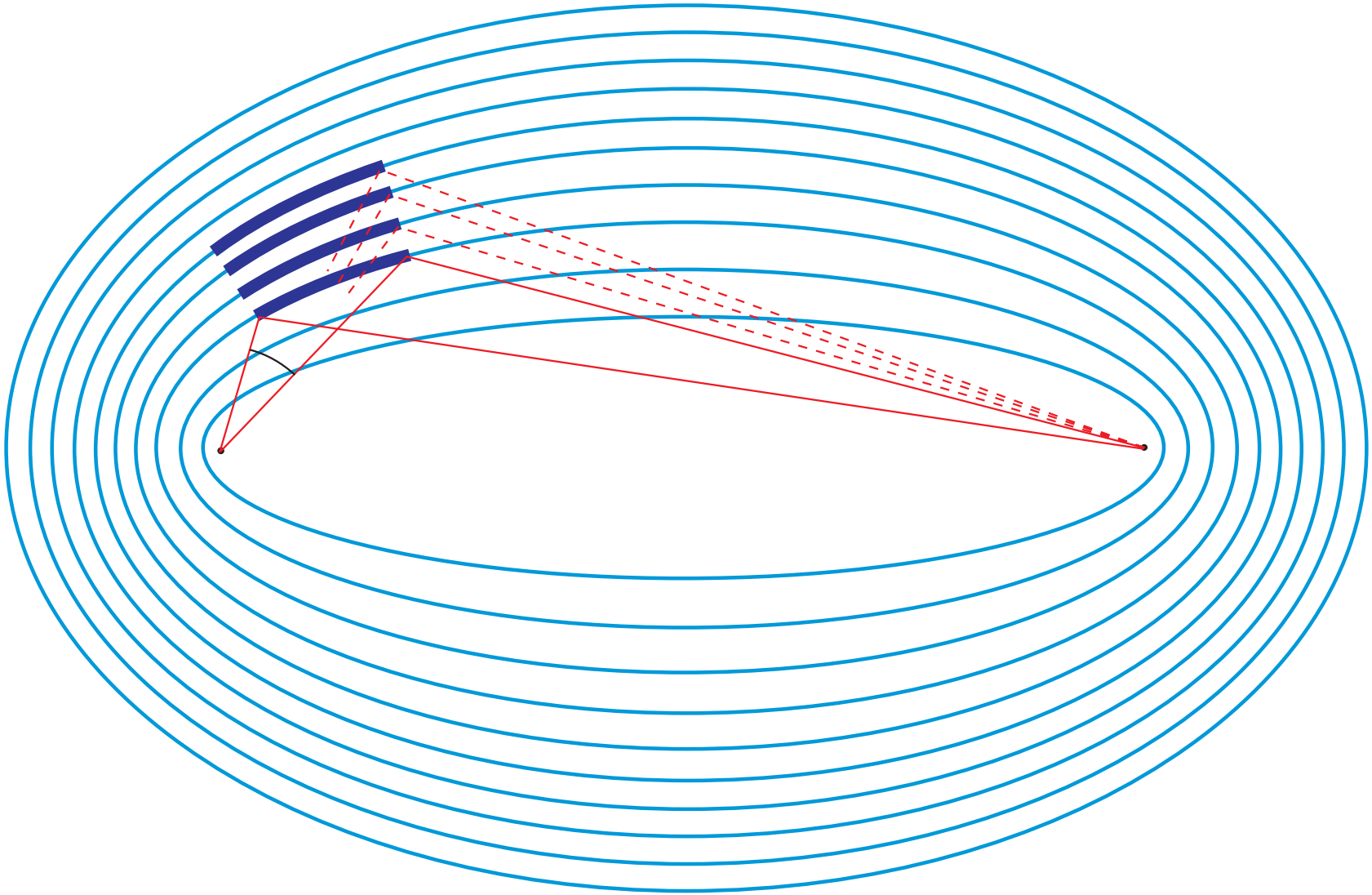
Basic geometry



Mirror optics



Multilayer optics



Interaction of x-rays with matter

Elastic (Thompson) scattering by a free electron

$$\sigma_{el} = \frac{8\pi}{3} \cdot r_e^{\,2}$$

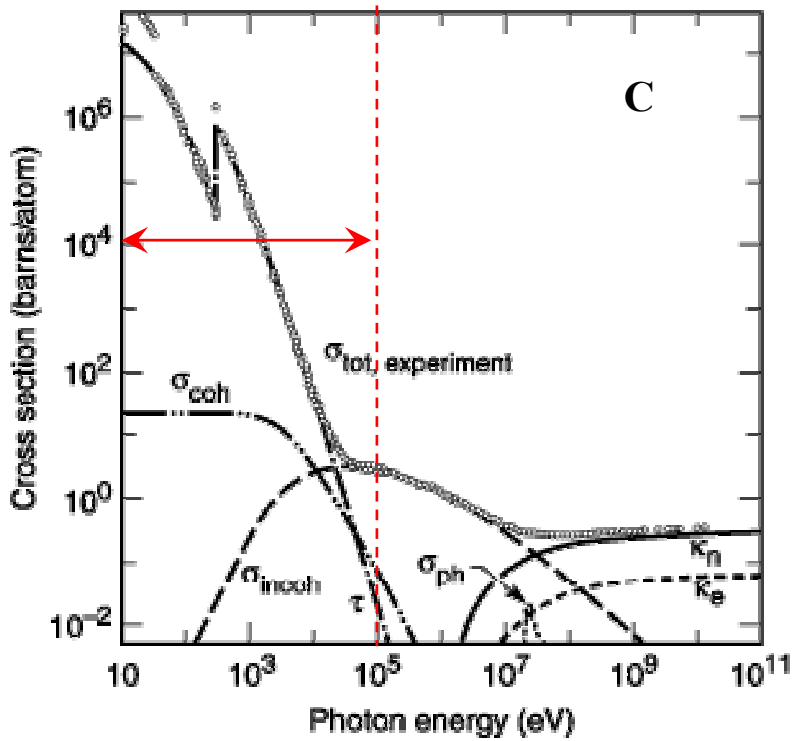
Coherent/elastic (Rayleigh) scattering from atoms

$$\sigma_{coh} = \pi \cdot r_e^{\,2} \int_{-1}^{+1} \left| f(\theta) \right|^2 \cdot \left(1 + \cos^2\theta\right) \cdot d(\cos\theta)$$

Total cross section

$$\sigma_{tot} = \sigma_{coh} + \tau + \sigma_{incoh} + \sigma_{ph} + \kappa_n + \kappa_e$$

- σ_{coh} : **Coherent elastic scattering**
- τ : **Atomic photo effect**
- σ_{incoh} : **Compton scattering**
- σ_{ph} : **Nuclear absorption**
- κ_i : **Pair production**



[1] J.H. Hubbel et al, J. Phys. Chem. Ref. Data 9, 1023 (1980)

Interaction of x-rays with matter

Definition of optical index for x-rays (E > 30eV)

Atomic form factor

$$f(\vec{q},E) = f_0(\vec{q}) + f_1(E) + if_2(E)$$

free electrons *bound electrons* *absorption*

Atomic cross section → Optical index n

Comparison between refraction and scattering description [2]

$$n = 1-\delta+i\beta \qquad e^{inkz} = e^{i(1-\delta)kz}\cdot e^{-\beta kz} \qquad \delta = \frac{2\pi\rho_a r_e}{k^2}(f_0+f_1) \qquad \beta = \frac{4\pi\rho_a r_e}{2k^2} f_2$$

In terms of total atomic scattering factor

$$k = \frac{2\pi}{\lambda}$$

$$n = 1-\frac{2\pi\rho_a r_e}{k^2}\left[f_0(\vec{q})+ f_1(E)+if_2(E)\right]$$

Typical value: n ~ 1 - 10^{-5} @ 10 keV < 1 !

Interaction of x-rays with matter

Practical aspects

Vast compilation of atomic scattering data e.g. by CXRO – ALS Berkeley (USA)
Data booklet and web site http://www-cxro.lbl.gov [3] – [4]
Dedicated area of research (theory and experiment)

VUV – EUV – Soft x-ray range:
Optical index very complex (many electronic states and transitions) and still under investigation

Hard x-rays:
Optical index well known and documented

Interaction of x-rays with matter

Experimental data

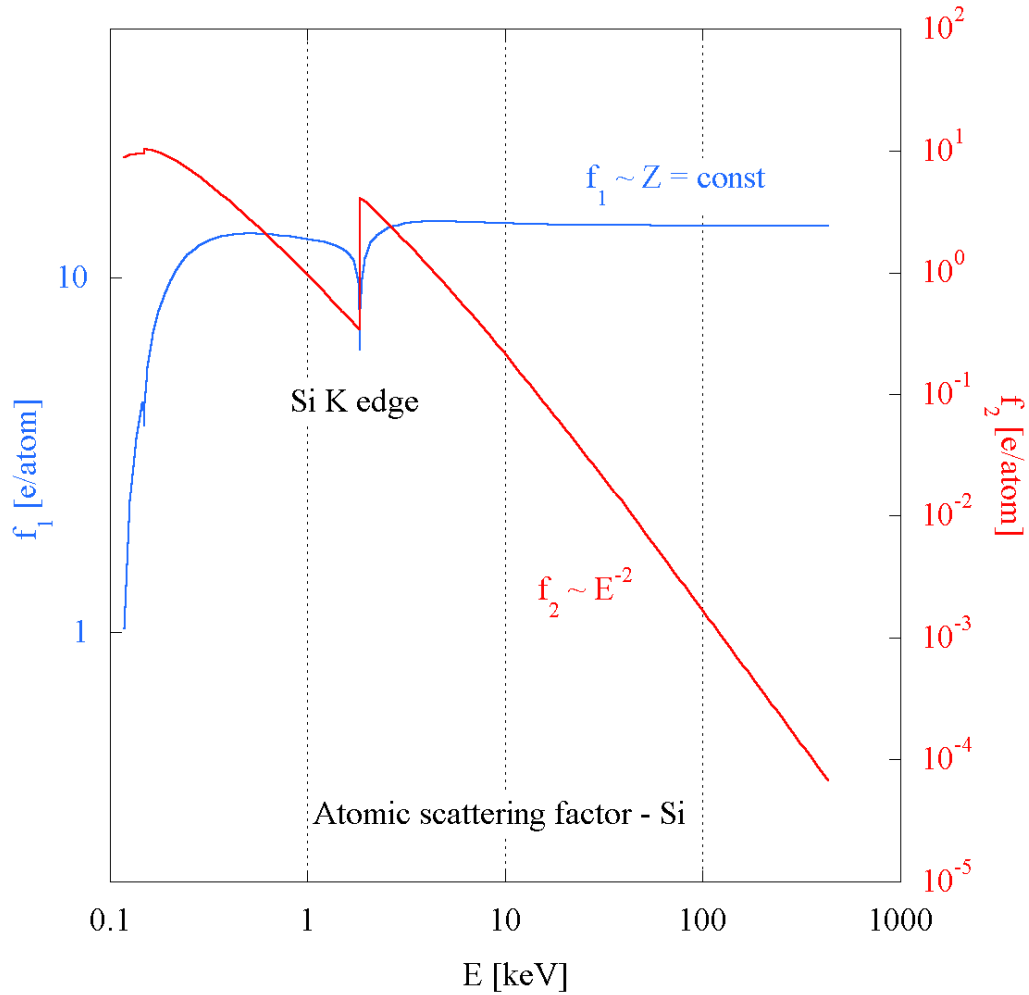
Asymptotic behaviour for E > E(K):

$$f_1 \approx const \qquad f_2 \approx 1/E^2$$

$$\delta \approx 1/E^2 \qquad \beta \approx 1/E^4$$

$$\frac{\delta}{\beta} \approx E^2$$

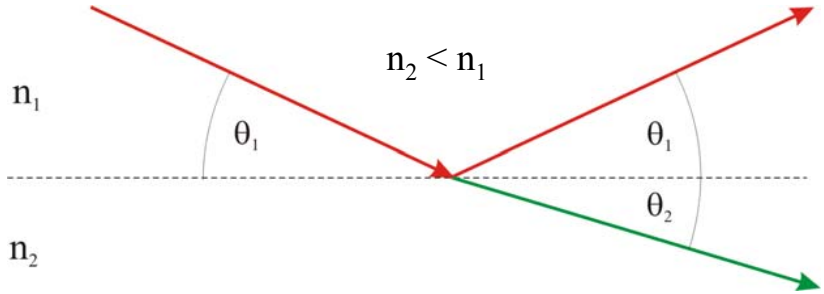
High energy applications !



Reflection and refraction

Snell's law $\frac{n_1}{n_2} = \frac{\cos\theta_2}{\cos\theta_1}$

Total reflection for $\theta_1 < \theta_C$ $\cos\theta_C = \frac{n_2}{n_1}$



Typical value: $\theta_C \sim 5$ mrad ~ 0.3° @ 10 keV

Wave propagation along interface, damped amplitude normal to it
No energy flux across interface!

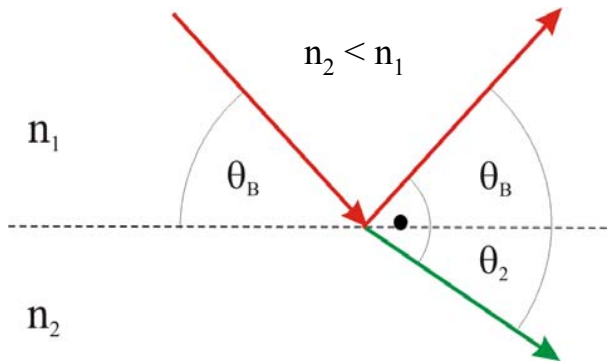
Total reflection x-ray mirrors !

Polarization

$E_\pi = 0 \Leftrightarrow \theta_1 + \theta_2 = 90°$

Brewster angle $\tan(\theta_B) = \frac{n_1}{n_2}$

Soft x-ray multilayer polarizers !

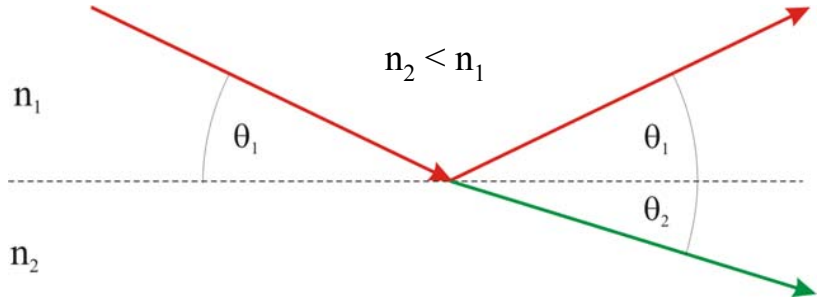


Reflection and refraction

Fresnel formulae for reflection and transmission amplitudes

$$r_\sigma = \frac{n_1 \sin\theta_1 - n_2 \sin\theta_2}{n_1 \sin\theta_1 + n_2 \sin\theta_2} \qquad r_\pi = \frac{n_1 \sin\theta_2 - n_2 \sin\theta_1}{n_1 \sin\theta_2 + n_2 \sin\theta_1}$$

$$t_\sigma = \frac{2n_1 \sin\theta_1}{n_1 \sin\theta_1 + n_2 \sin\theta_2} \qquad t_\pi = \frac{2n_1 \sin\theta_2}{n_1 \sin\theta_2 + n_2 \sin\theta_1}$$



Reflectivity amplitude as a function of external angle of incidence θ (vacuum)

$$r_\sigma = \frac{\sqrt{n_1^2 - \cos^2\theta} - \sqrt{n_2^2 - \cos^2\theta}}{\sqrt{n_1^2 - \cos^2\theta} + \sqrt{n_2^2 - \cos^2\theta}} \qquad r_\pi = \frac{n_1/n_2\sqrt{n_2^2 - \cos^2\theta} - n_2/n_1\sqrt{n_1^2 - \cos^2\theta}}{n_1/n_2\sqrt{n_2^2 - \cos^2\theta} + n_2/n_1\sqrt{n_1^2 - \cos^2\theta}}$$

Including graded interfaces (Gaussian density gradient, phase shift)

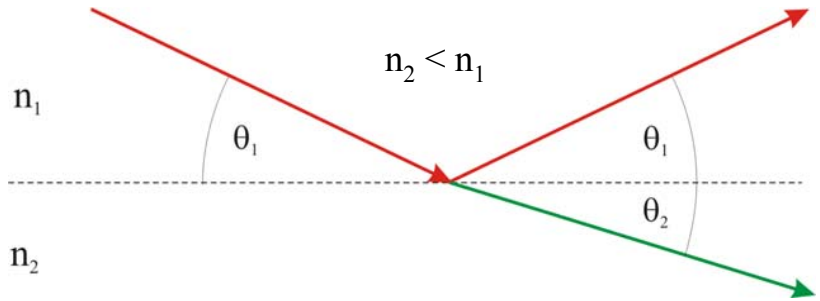
$$r = r_{ideal} \cdot e^{-\frac{8\pi^2}{\lambda^2}\sqrt{n_1^2 - \cos^2\theta}\sqrt{n_2^2 - \cos^2\theta}\,\sigma^2}$$

Reflection and refraction

Reflected and transmitted intensity

$$R = \frac{-\Phi_{ref}}{\Phi_{in}} = \frac{k_1 \cdot \sin\theta_1 \cdot |r|^2}{k_1 \cdot \sin\theta_1 \cdot |1|} = |r|^2$$

$$T = \frac{\Phi_{trans}}{\Phi_{in}} = \frac{k_2 \cdot \sin\theta_2 \cdot |t|^2}{k_1 \cdot \sin\theta_1 \cdot |1|} = \frac{n_2 \cdot \sin\theta_2}{n_1 \cdot \sin\theta_1} |t|^2$$



Graded interface: Lower reflectivity but enhanced transmission

See also [5] – [7]

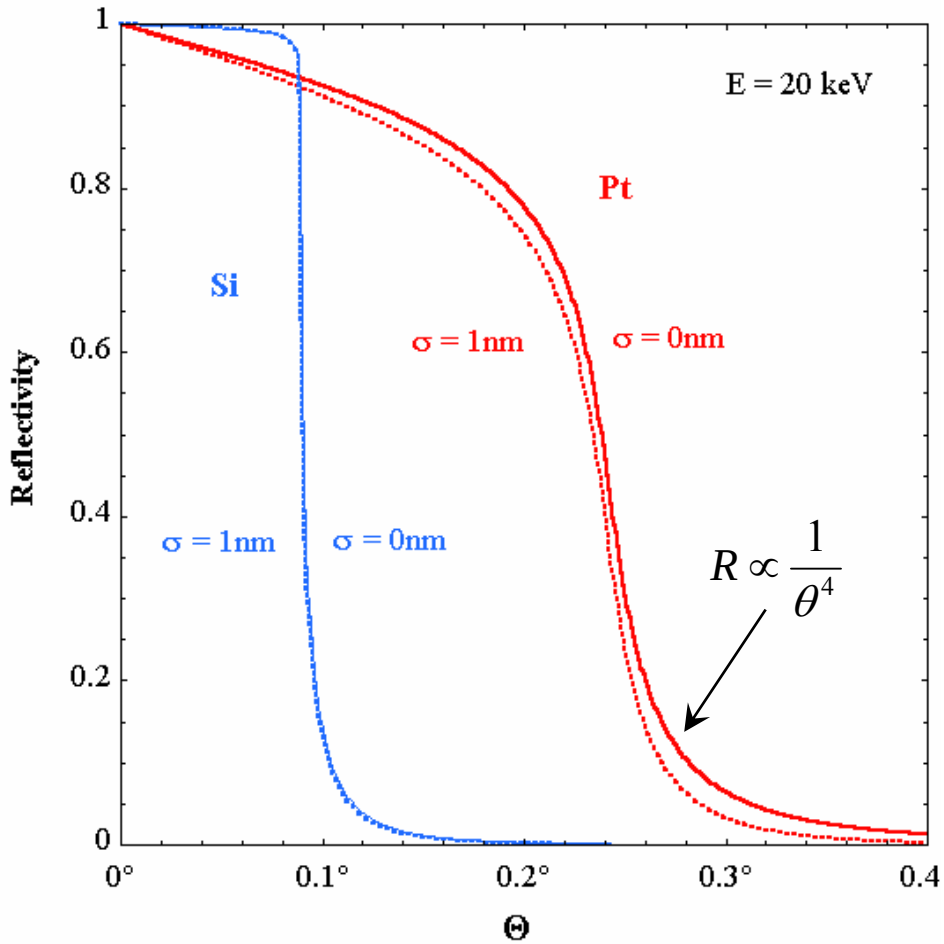
X-ray mirror reflectivity

Specular x-ray reflectivity at a surface

$\theta_C = \sqrt{2 \cdot \delta} \propto \sqrt{\rho_e}$ (critical angle)

Important parameters

- **Optical index** $n = 1 - \delta + i \cdot \beta$
- **Mass density** ρ
- **Interface width** σ



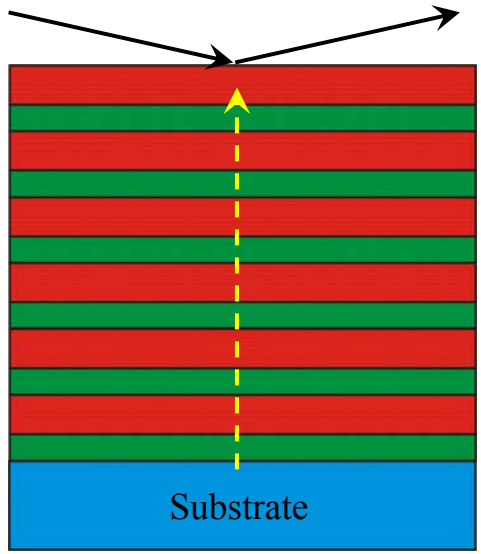
X-ray multilayer reflectivity

Recursive calculation of Fresnel coefficients and propagation

- **Parratt formalism (widely used in x-ray optics) [8]**

Principle

- **Start at semi-infinite substrate surface (no reflection from back side)**
- **Recursive construction of amplitudes and phases from layer to layer**



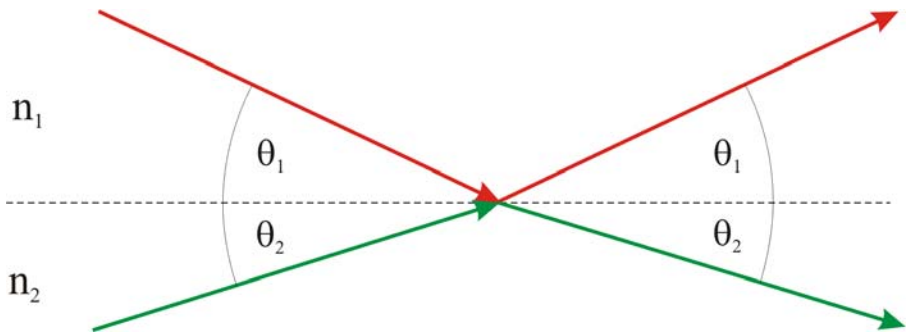
$$r_{n-1,n} = a_{n-1}^{4} \cdot \left[\frac{r_{n,n+1} + f_{n-1,n}}{r_{n,n+1} f_{n-1,n} + 1} \right]$$

$$r_{n,n+1} = a_n^{2} \frac{E_n^{R}}{E_n}$$

$$a_n = e^{-i\frac{\pi}{\lambda} \cdot t_n \sqrt{n_n^2 - n_0^2 \cos^2\theta}}$$

$$\longrightarrow \quad R = \left| r_{0,1} \right|^2$$

$f_{n-1,n}$: Fresnel coefficients
E_n: Electric field at centre of layer n
t_n: Thickness of layer n



X-ray multilayer reflectivity

Numerical calculations

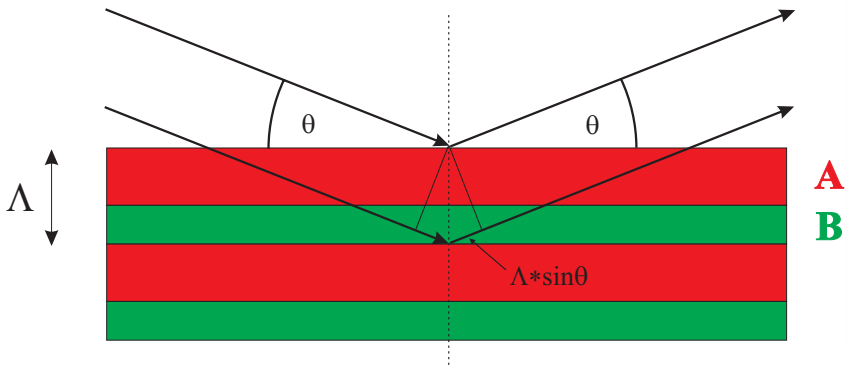
Main features

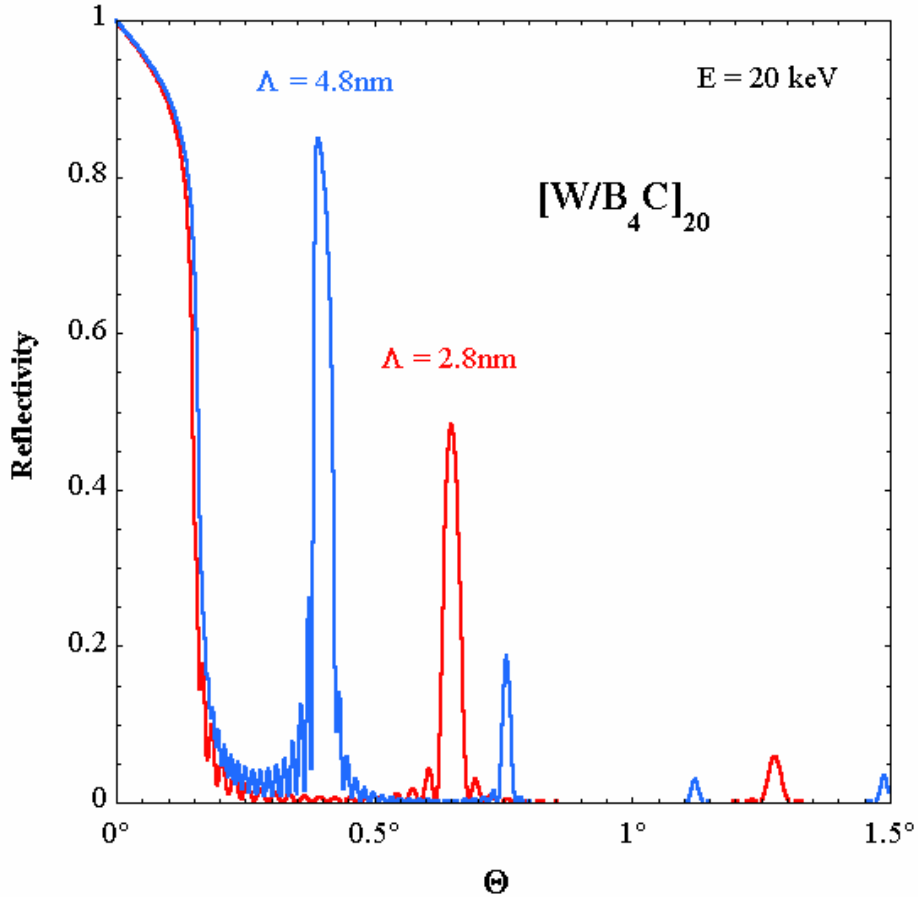
- **Bragg peaks and fringes due to interference**
- **Positions depend on E and Λ**
- **Intensities depend on Δρ, N, σ…**

Corrected Bragg equation

$$m \cdot \lambda = 2 \cdot \Lambda \cdot \sqrt{n_2^{\,2} - n_1^{\,2} \cos^2 \theta}$$

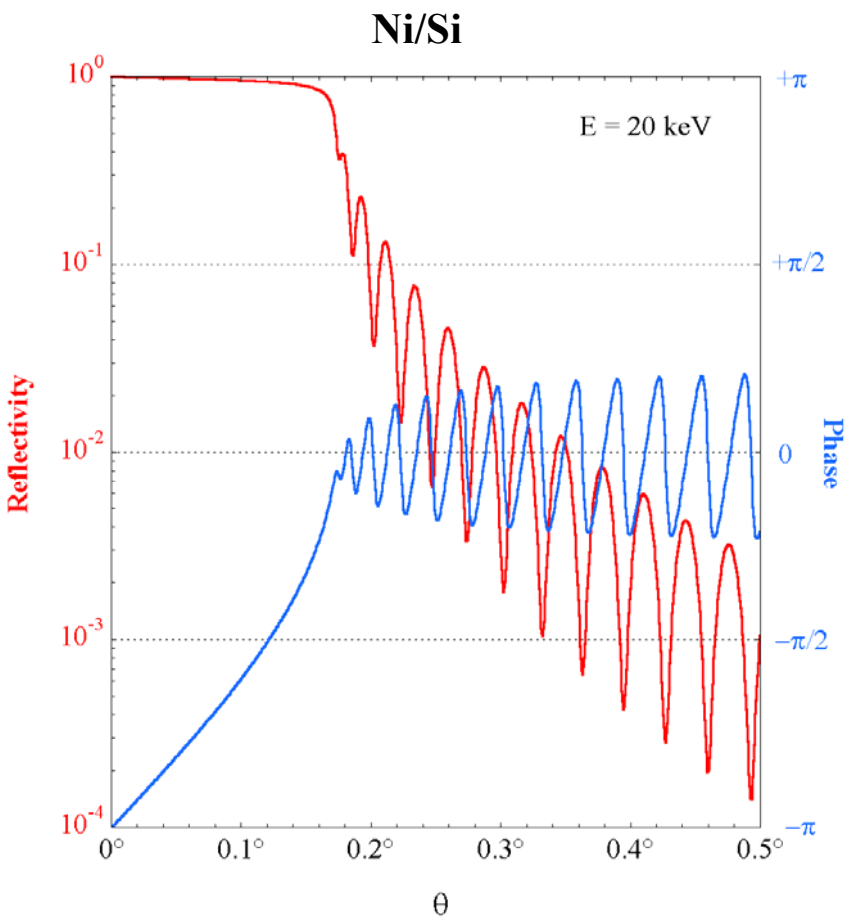
For θ >> θ_C → $m \cdot \lambda \approx 2 \cdot \Lambda \cdot \sin\theta$

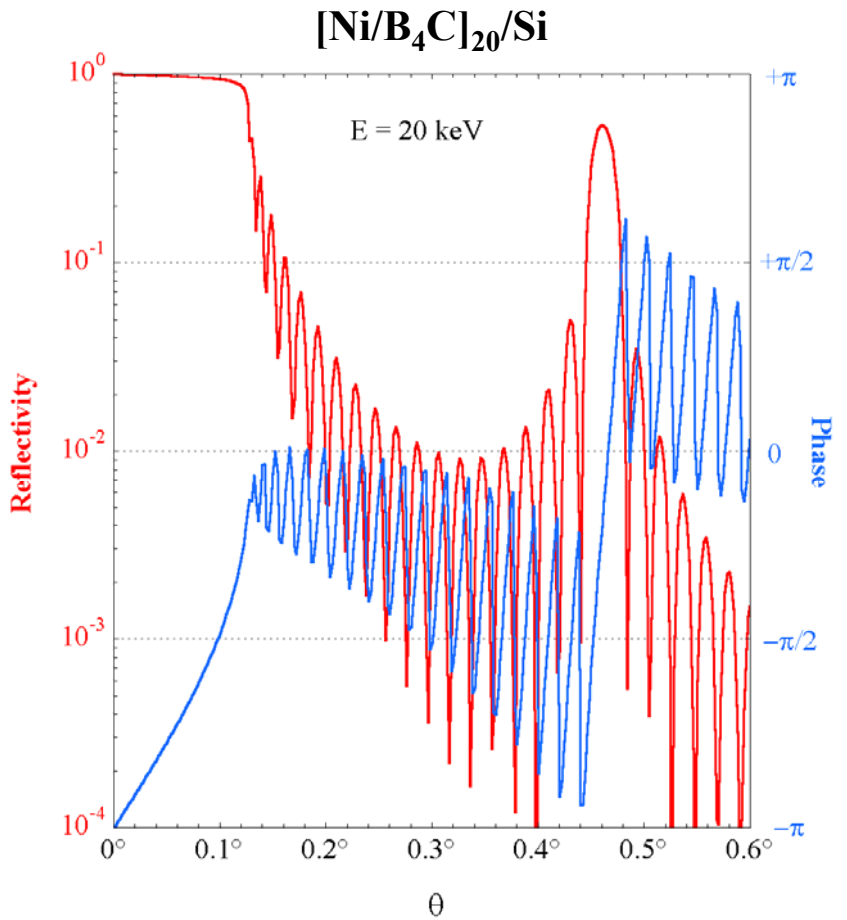




X-ray reflectivity

Reflectivity and phase





X-ray multilayer reflectivity - Imperfections

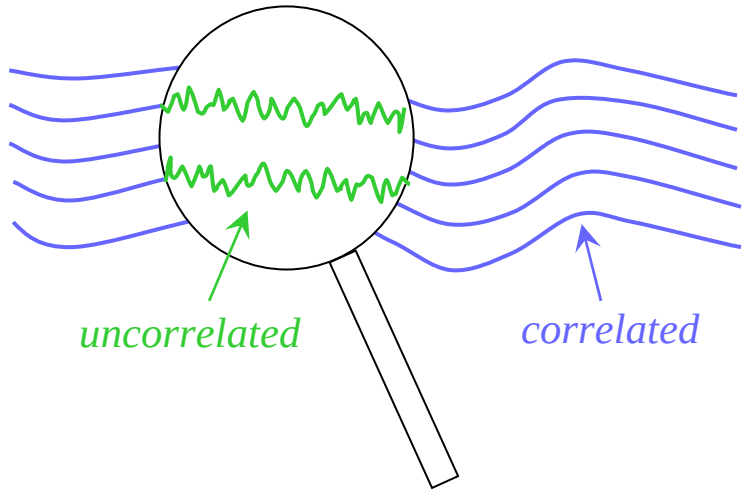
Interface roughness – Diffuse scattering

Kinematical (Born) Approximation (BA)

$$\frac{d\sigma}{d\Omega} = \left(\frac{r_e \rho}{q_z}\right)^2 \left(\frac{A}{\sin\theta_{in}}\right) \cdot \int e^{-q_z \cdot g(x,y)/2} \cdot e^{i(q_x x + q_y y)} dxdy$$

Height differences $g(x,y) = \left\langle (h(0,0) - h(x,y))^2 \right\rangle$

Uncorrelated interfaces $\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{Fresnel} \cdot e^{-q_z^2 \sigma^2}$



- **Scattering remains specular**
- **Reflectivity cannot distinguish density gradient from uncorrelated roughness**

Correlated interfaces

- **Generally numerical solutions, few analytical cases**
- **Non-specular scattering**
- **Information on lateral interface structure**

X-ray multilayer reflectivity - Imperfections

Interface roughness – Diffuse scattering

Distorted Wave Born Approximation (DWBA)

$$\frac{d\sigma}{d\Omega} = \frac{A}{\sin\theta_i}\frac{\pi^2}{\lambda^4}\left(1-n^2\right)^2 \cdot \left|t_i\right|^2 \cdot \left|t_f\right|^2 \cdot PSD(\vec{q})$$

Power spectrum density $PSD(\vec{q}) = \int C(\vec{r}) \cdot e^{i\vec{q}\vec{r}}\, d\vec{r}$

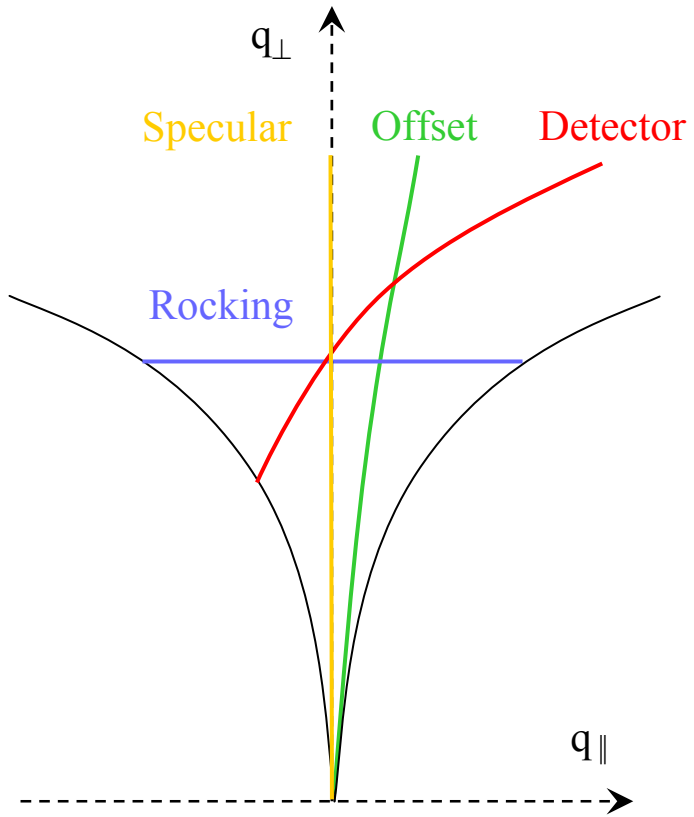
Height correlation function $C(\vec{r}) = \langle h(\vec{r}) \cdot h(\vec{r}') \rangle$

- **Refraction included → "Yoneda wings"**
- **Various approaches for PSD**
- **Complicated computation for multilayers**

Theory and software

- **S.K. Sinha, V. Holy, D.K.G. de Boer, T. Salditt**
- **IMD (D. Windt)**

Scattering geometries

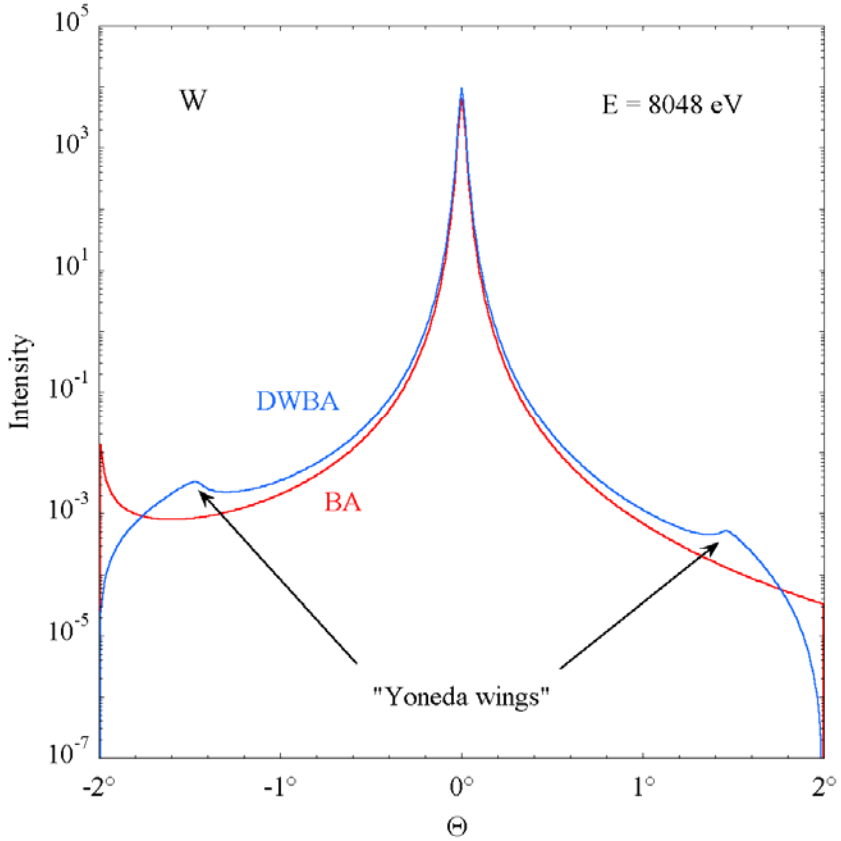


X-ray multilayer reflectivity - Imperfections

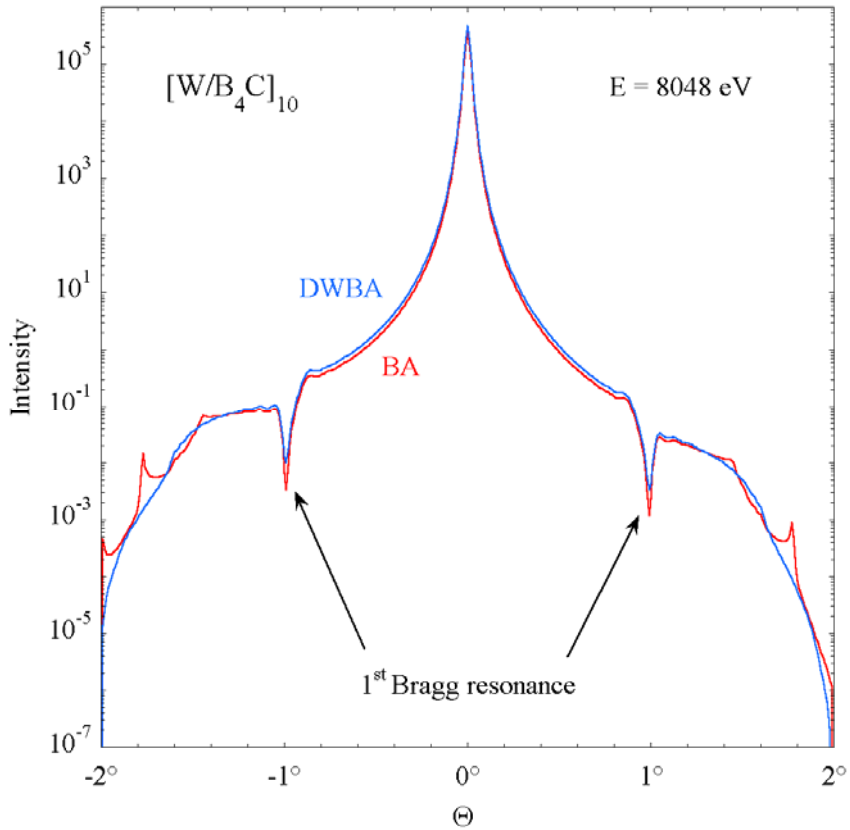
Diffuse scattering – Comparison: BA – DWBA

IMD (D. Windt)

Single surface



Multilayer 2nd Bragg peak



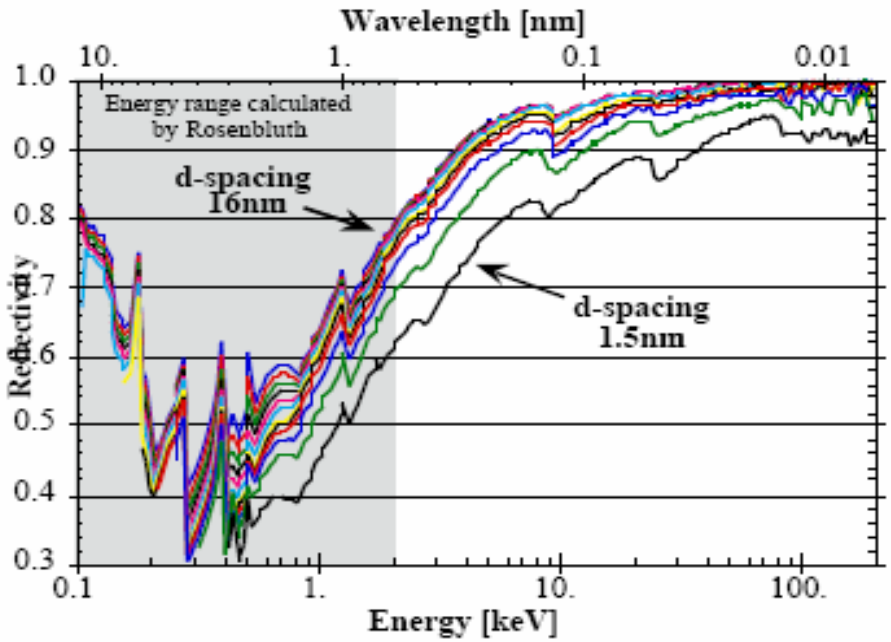
X-ray multilayer design

Materials choice – Basic rules:

1. Select low-Z spacer material with lowest absorption (β_{spacer})
2. Select high-Z absorber material with highest reflectivity with spacer ($\delta_{abs} - \delta_{spacer}$)
3. In case of multiple choices select high-Z material with lowest absorption (β_{abs})
4. Make sure that both materials can form stable and sharp interfaces (lower d-spacing limit)

Computational search algorithms

- Soft X-rays: A.E. Rosenbluth (1988)
- Hard X-rays: K. Vestli (1995)



[9] K. Vestli, E. Ziegler, Rev. Sci. Instr. 67, 3356 (1996)

X-ray multilayer design

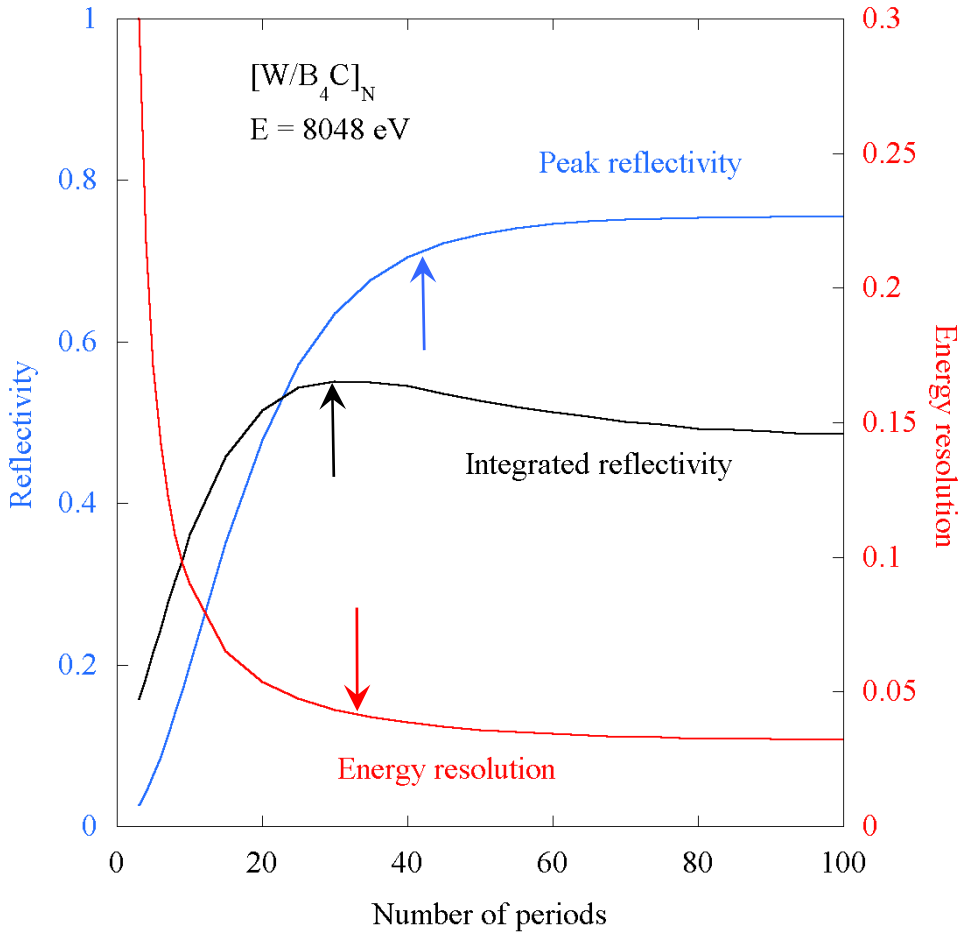
Period number N:

Peak versus integrated reflectivity:

- **R_{peak} increases with N up to extinction**
- **$\Delta E/E$ decreases ~ 1/N in kinematical range**
- **R_{int} is maximum before extinction**

High and low resolution MLs

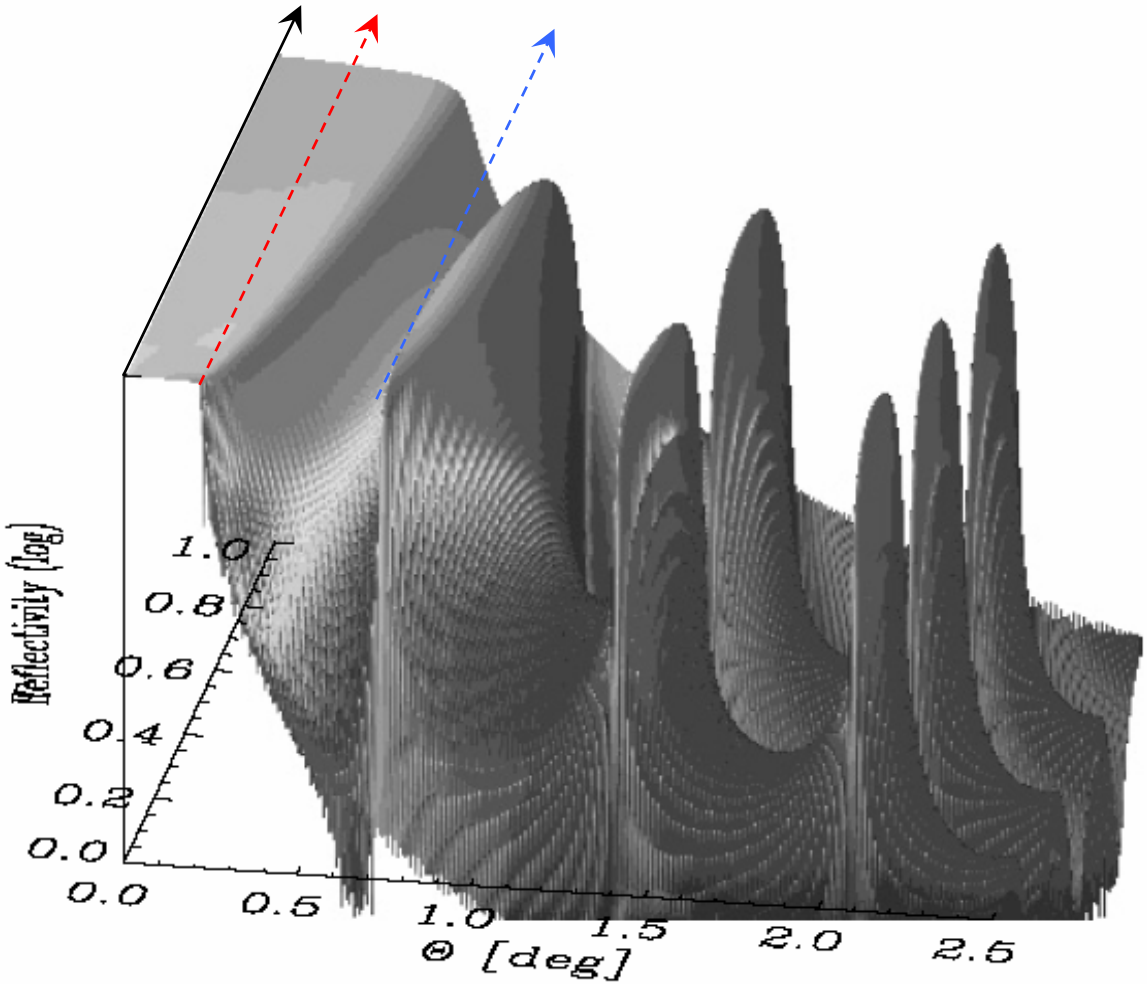
Optimize N according to needs !



X-ray multilayer design

Filling factor $\Gamma = t_{abs}/\Lambda$

- **Harmonics suppression**
- **Reflectivity enhancement**

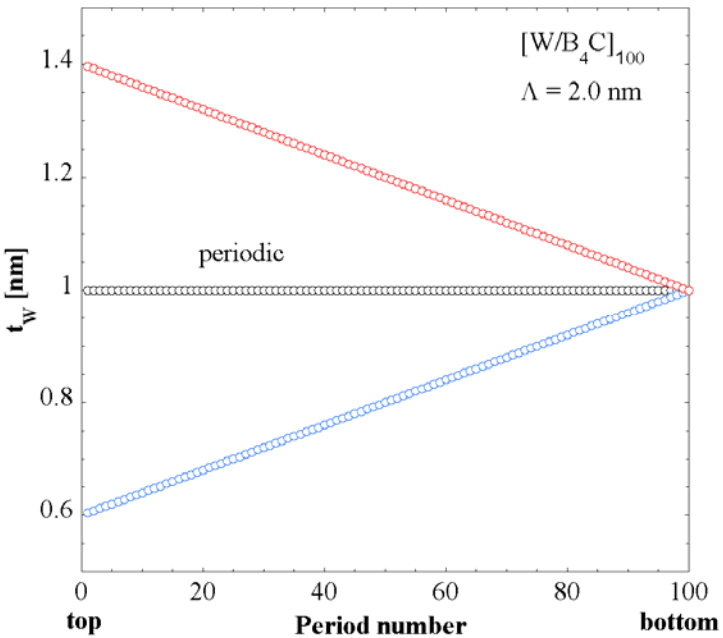


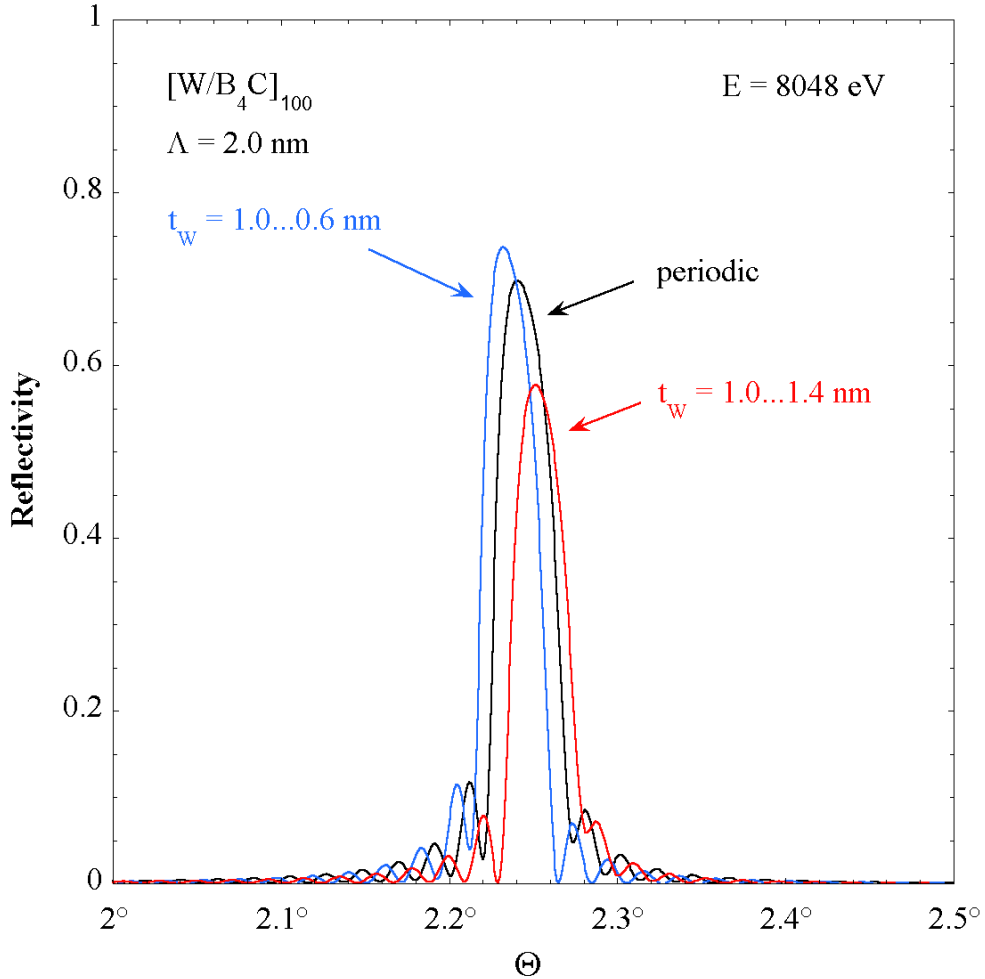
X-ray multilayer design

Quasi-periodic design:

Simple approach

- **Constant d-spacing**
- **Decreasing Γ from 0.5 at bottom to top**





X-ray multilayer design

Aperiodic design:

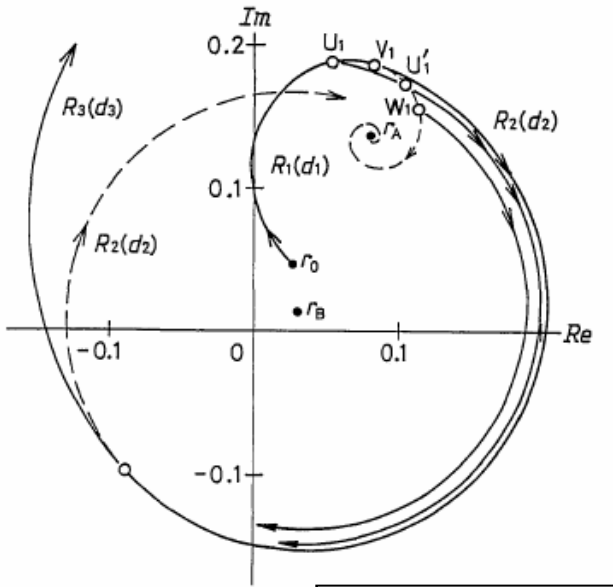
[10] P.H. Berning, *Physics of Thin Films*, J. Hass, ed. (Academic, New York, 1963)

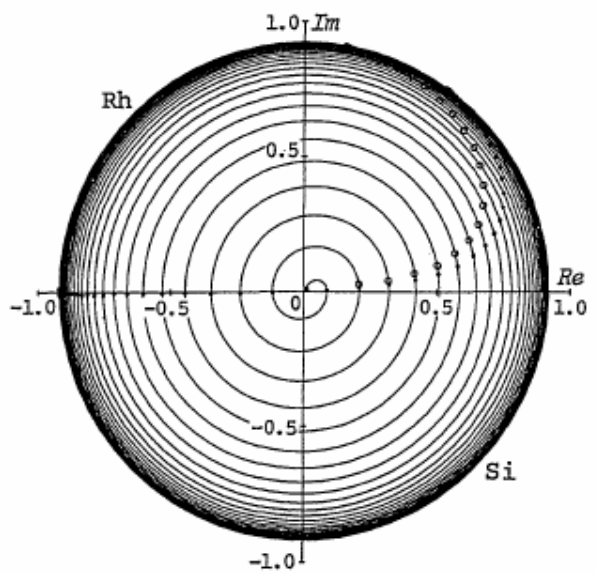
Layer-by-layer design (M. Yamamoto)

- **Amplitude maximization with respect to vacuum**
- **Berning's recursive formula**
- **Non-periodic structure**

$$r_n = \frac{f_n\left(1 - f_n r_{n-1}\right) + \left(r_{n-1} - f_n\right)e^{-i\varphi_n}}{1 - f_n r_{n-1} + f_n\left(r_{n-1} - f_n\right)e^{-i\varphi_n}}$$

$$\varphi_n = e^{-i4\pi\frac{t_n}{\lambda}\sqrt{n_n^2 - n_0^2\cos^2\theta}}$$





[11] M. Yamamoto, T. Namioka, Appl. Opt. 31, 1622 (1992)

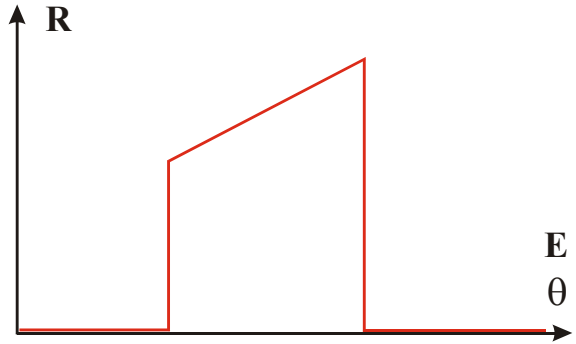
X-ray multilayer design

Aperiodic design:

Goal: ML with particular reflectivity profile

- **R = R(θ) for E = const**
- **R = R(E) for θ = const**

Find vertical composition profile



Method:

- **Derive analytical expression for reflectivity**
- **Do inversion to obtain 1st estimate for layer sequence**
- **Apply fit algorithm to optimize the structure**

[12] I.V. Kozhevnikov et al, Nucl. Instr. And Meth. A 460, 424 (2001)

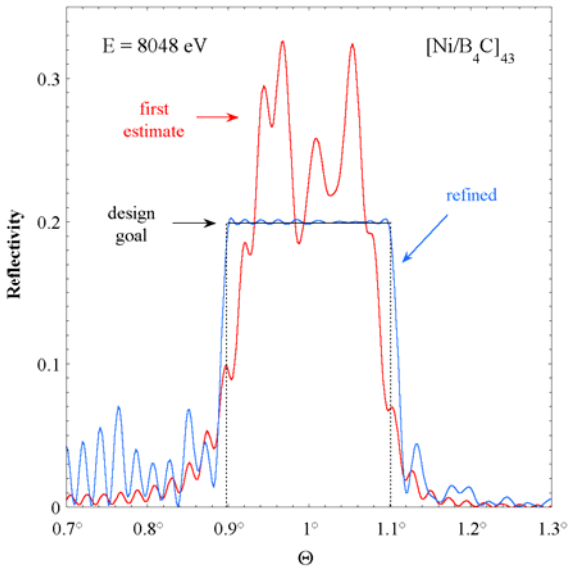
X-ray multilayer design

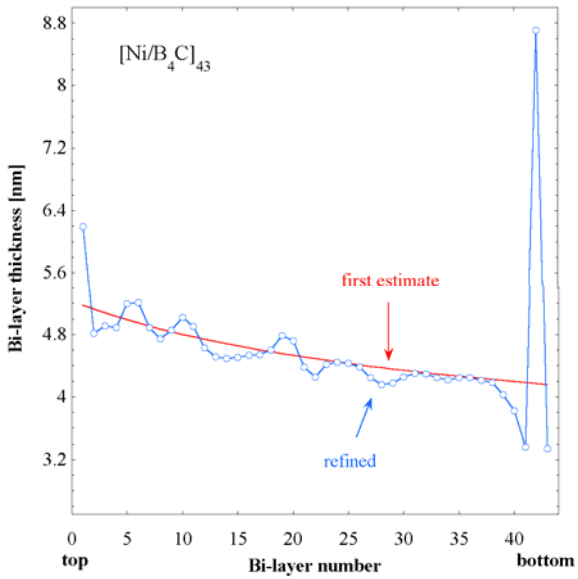
Example:

- **Ni/B_4C structure**
- **R(θ) = const over 20% bandwidth**

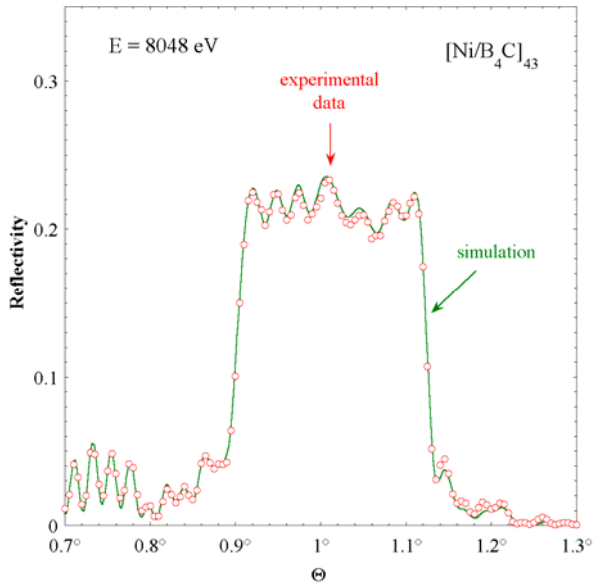
[13] Ch. Morawe et al, Nucl. Instr. And Meth. A 493, 189 (2002)

Theoretical design

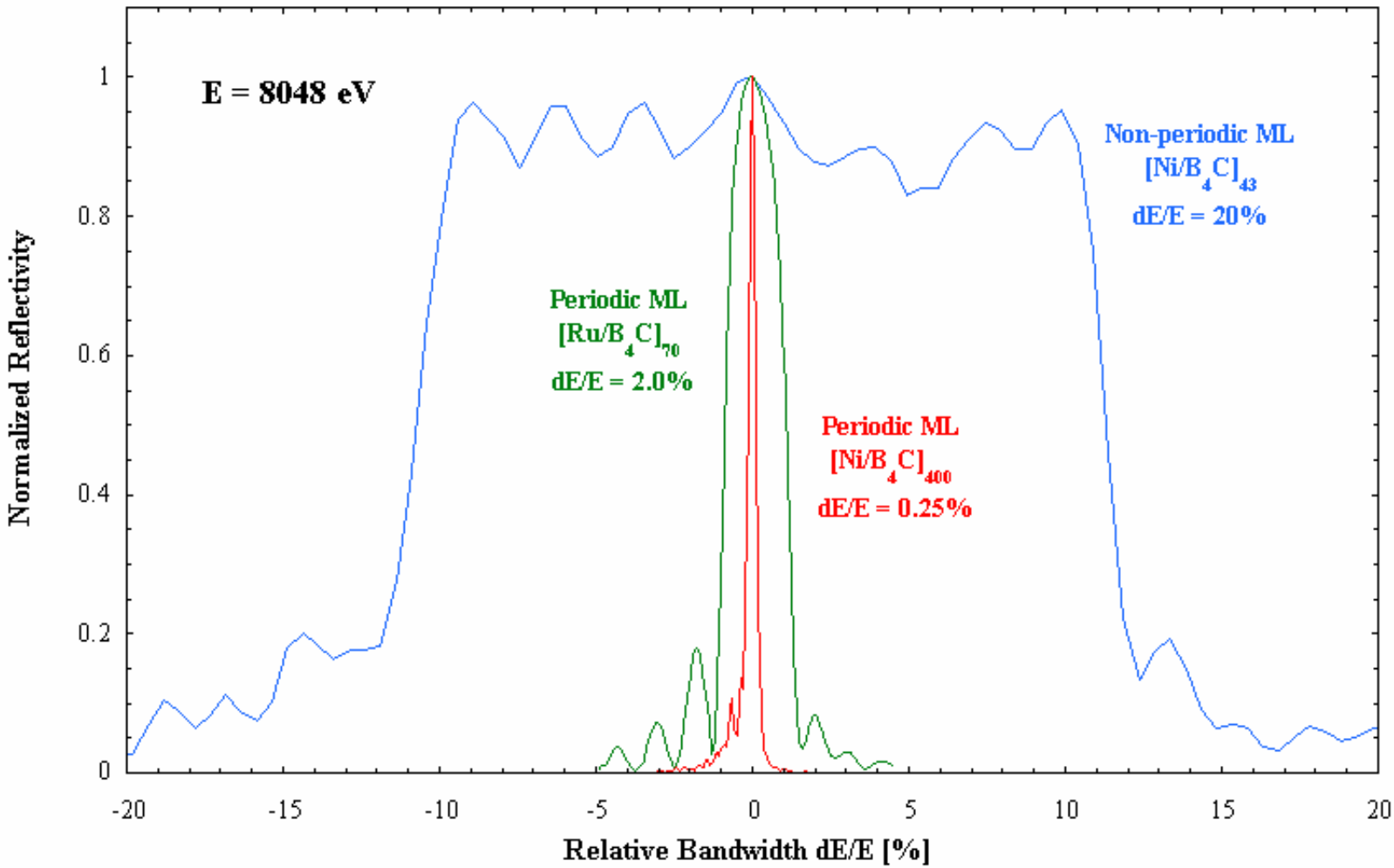




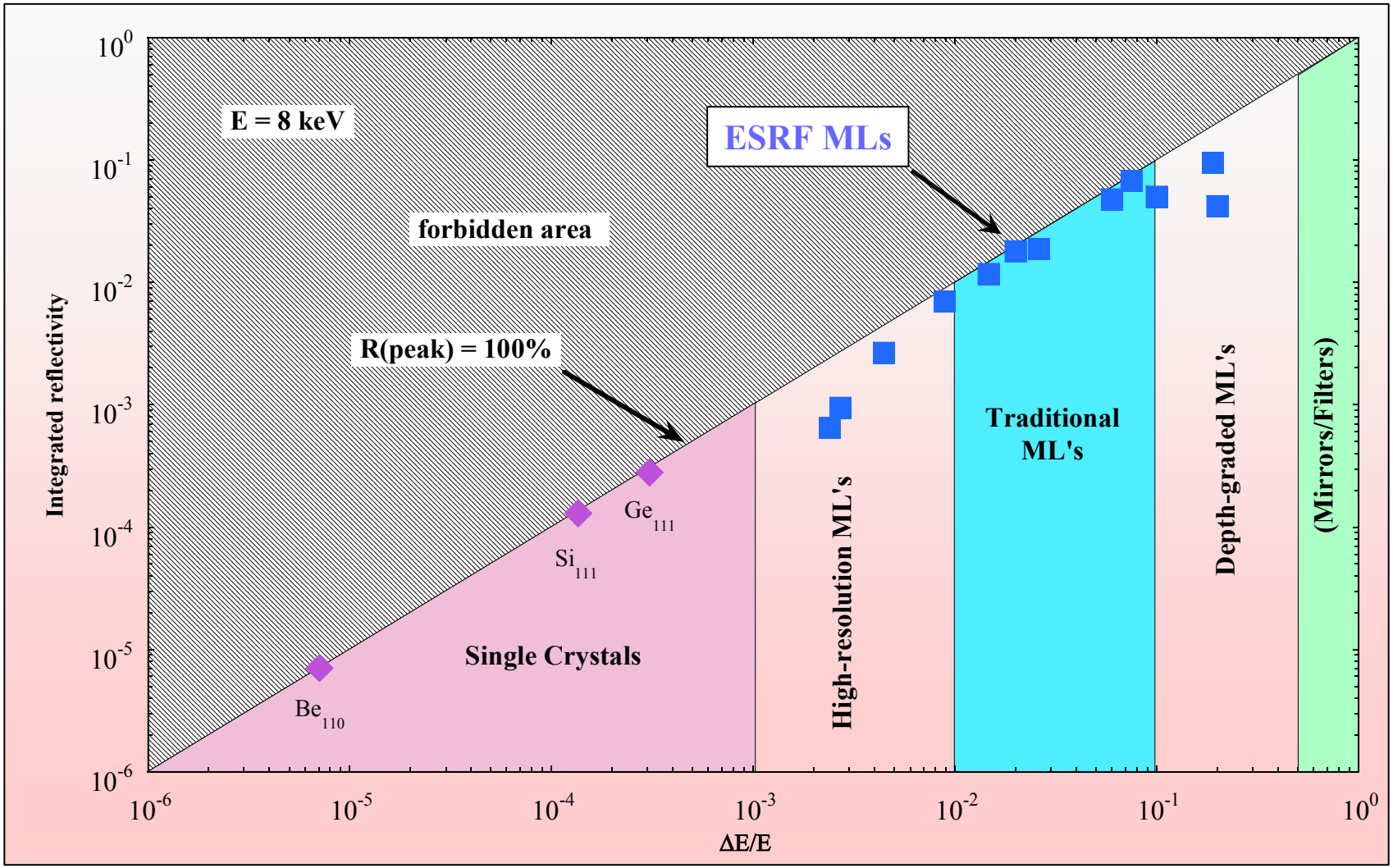
Experimental result



Energy resolution of multilayers

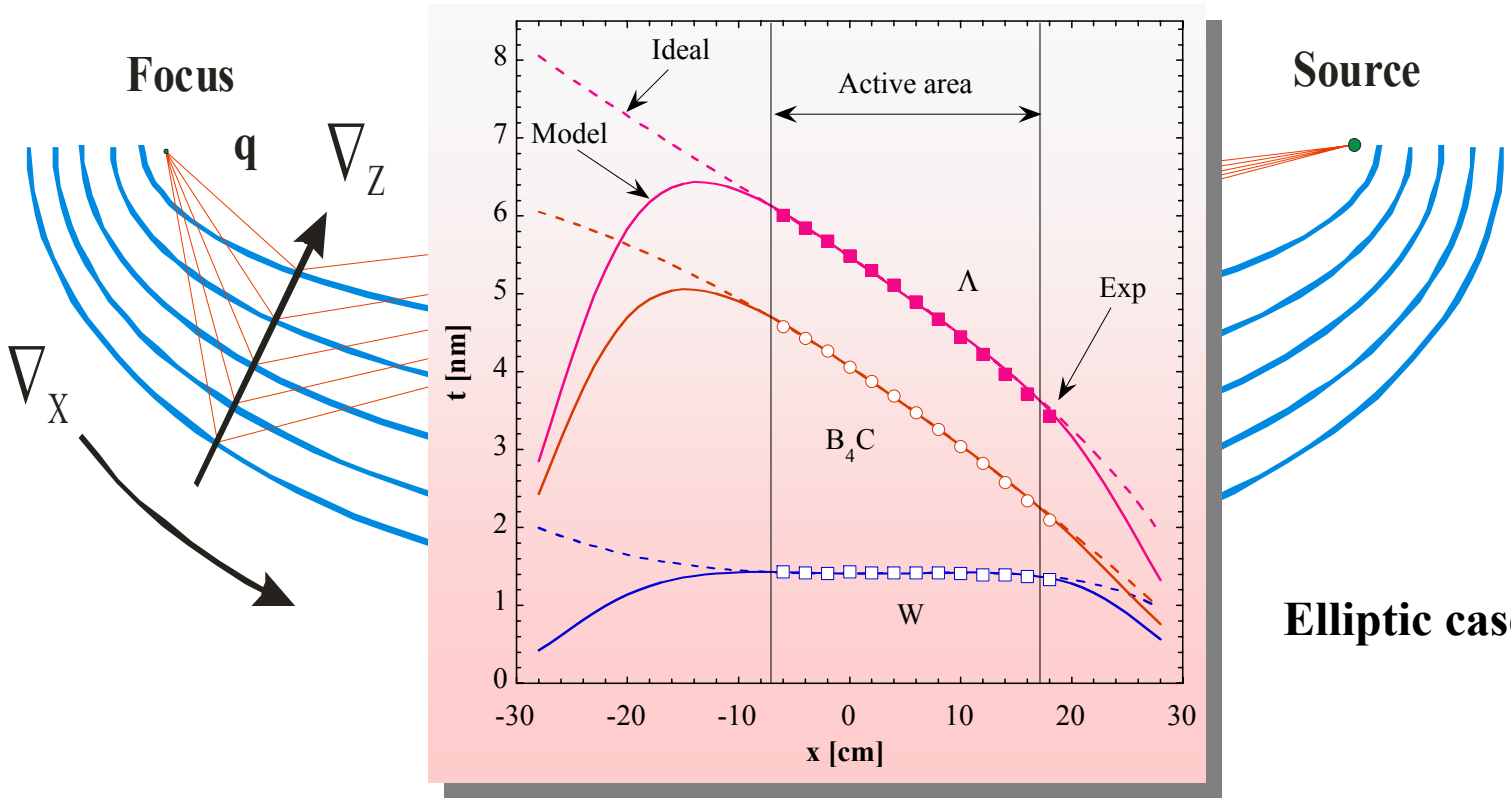


Reflecting X-ray optics – Overview



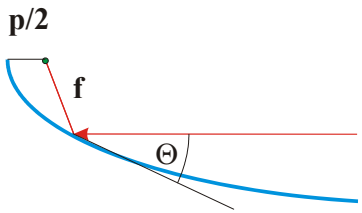
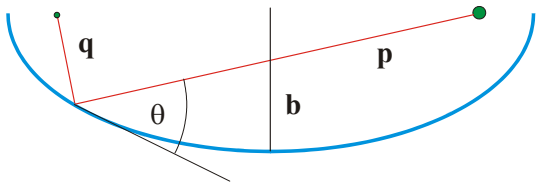
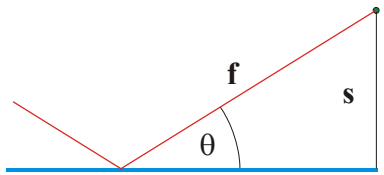
Laterally graded multilayers

- Divergent beam, focusing applications with curved substrates
- Incidence angle variation → laterally graded multilayers
- Additional depth gradient negligible (< 10^{-5})



Laterally graded multilayers

Surface curvature and beam divergence define lateral gradient dΛ /dx

Shape	Parabolic	Elliptic	Flat
Angle θ	$\sin\theta = \sqrt{\frac{p}{2f}}$	$\sin\theta = \frac{b}{\sqrt{pq}}$	$\sin\theta = \frac{s}{f}$
Geometry			

d-spacing including refraction correction (modified Bragg equation)

$$\Lambda = \frac{\lambda \cdot m}{2\sqrt{n^2 - \cos^2\theta}}$$

Double graded multilayers

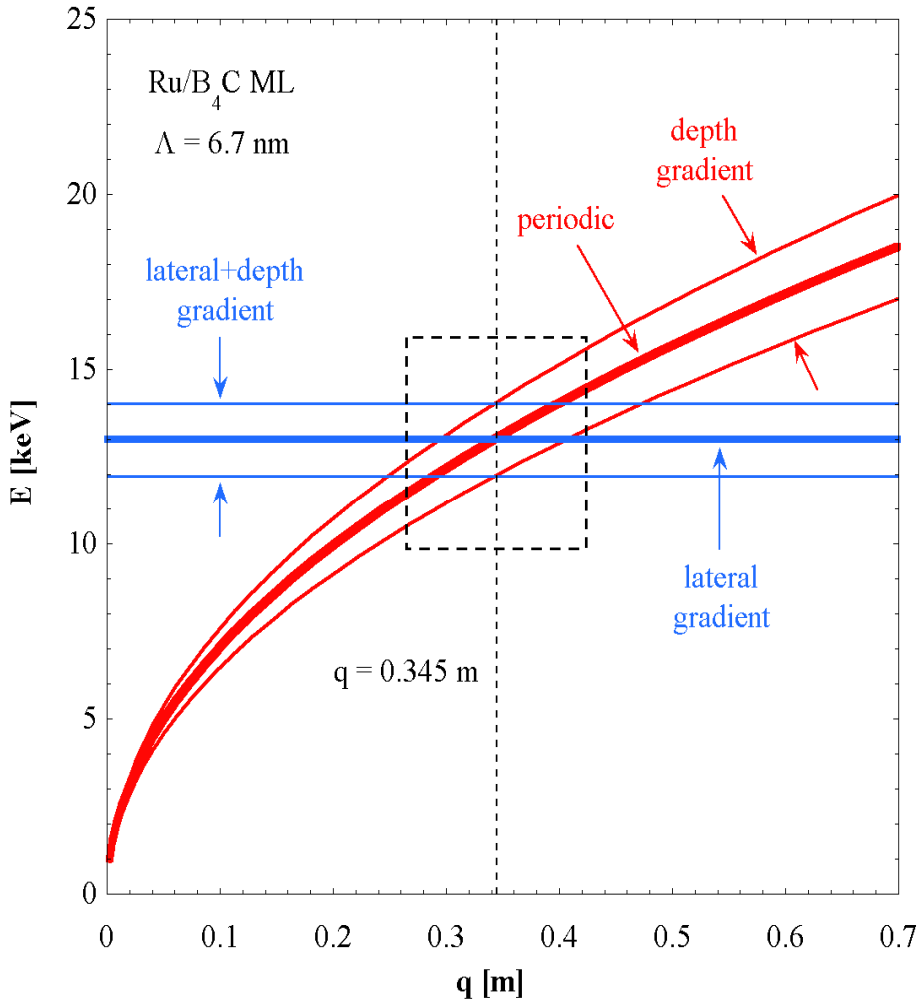
Energy dispersion:

Bragg equation: $E(\theta) = \dfrac{h \cdot c}{2\Lambda\sqrt{n^2(E) - \cos^2\theta}}$

Elliptic mirror: $\sin^2\theta = \dfrac{b^2}{p \cdot q} \qquad p + q = 2 \cdot a$

$$E(q) = \frac{h \cdot c}{2\Lambda\sqrt{n^2(E) - 1 + \dfrac{b^2}{(2a - q)q}}}$$

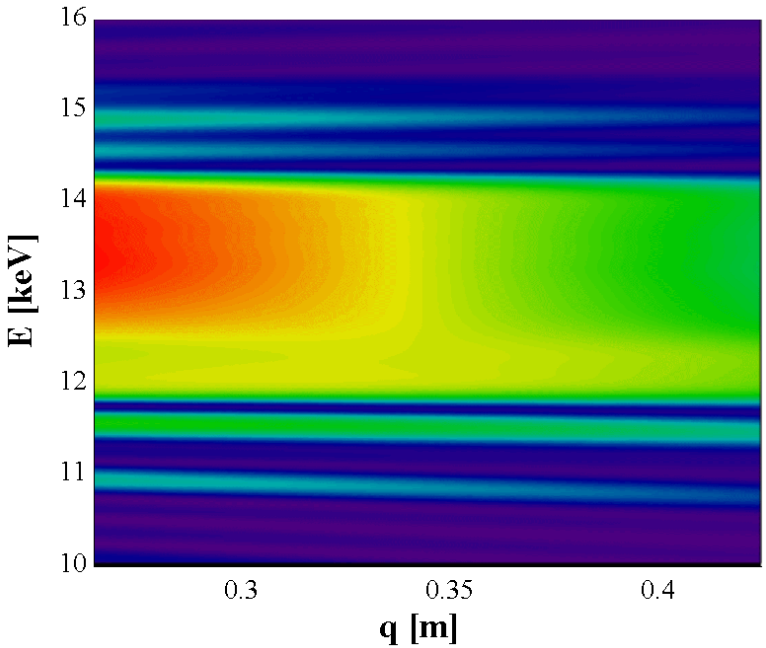
Dispersion "along ML mirror"



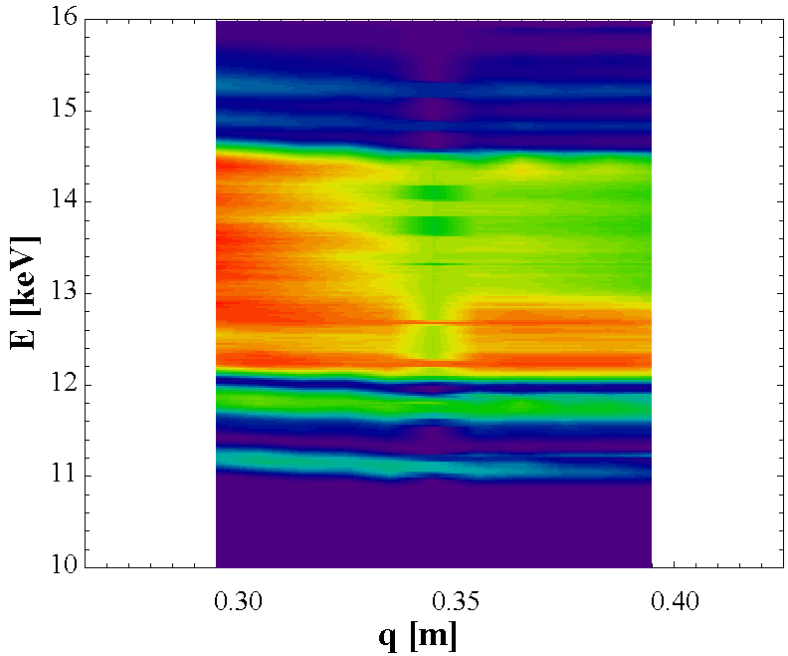
Double graded multilayers

Intensity profiles: (Kirkpatrick-Baez multilayer optics on ESRF BM05)

Theory



Experiment



[14] Ch. Morawe, Ch. Borel, E. Ziegler, J-Ch. Peffen, Proc SPIE 5537, 115 (2004)

X-ray multilayer fabrication

Deposition techniques	Vacuum	Particle energy	Deposition rate	Deposition area
Thermal evaporation	HV (UHV)	Low	Low	Small
E-beam evaporation	UHV	Low	Low	Small
Magnetron sputtering	HV (+Gas)	High	High	Large
DECR sputtering	HV (+Gas)	High	Low	Medium
Ion beam sputtering	UHV (+Gas)	Very high	High	Medium
Pulsed laser deposition	HV	Very high	High	Medium

- **Characteristics may vary depending on equipment and application**
- **Magnetron sputtering most widely used for X-ray multilayer fabrication**
- **Vacuum and purity important for EUV and soft X-rays**
- **High particle energy favors very thin and uniform layers**

X-ray multilayer fabrication

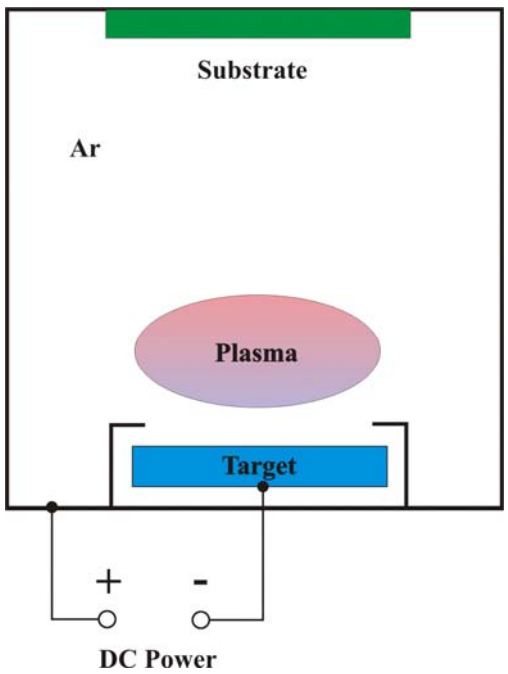
History

1923	Koeppe	Cd/Ag	electrolysis	unstable
1930	Deubner	Au/Ag	electrolysis	unstable
1935	Dumond	Au/Cu	thermal evaporation	1 week life time
1963	Dinklage	Me/Mg	thermal evaporation	stable
1972	Spiller	Au/MgF_2	thermal evaporation	UV MLs
1976	Haelbich	Me/C	thermal evaporation	XUV MLs
1978	Barbee	W/C	magnetron sputtering	X-ray MLs
1983	Gaponov	Me/C	pulsed laser deposition	X-ray/VUV MLs

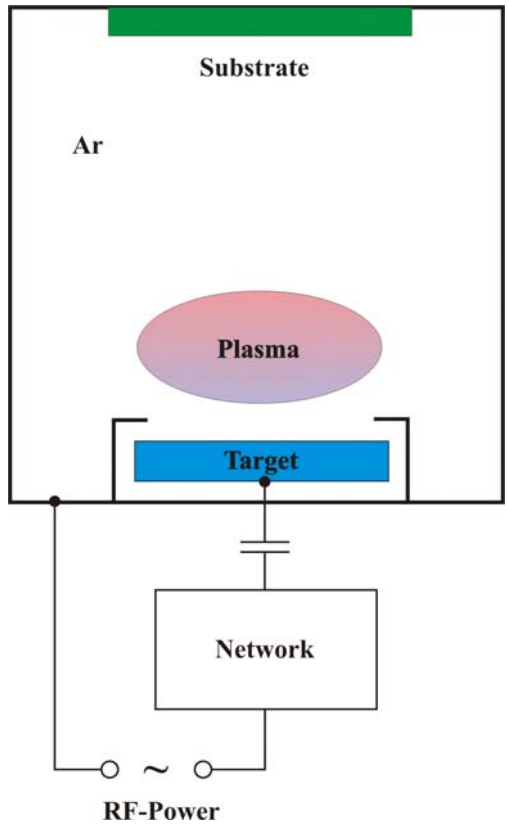
X-ray multilayer fabrication

Sputtering techniques

DC (conductors)



RF (insulators)

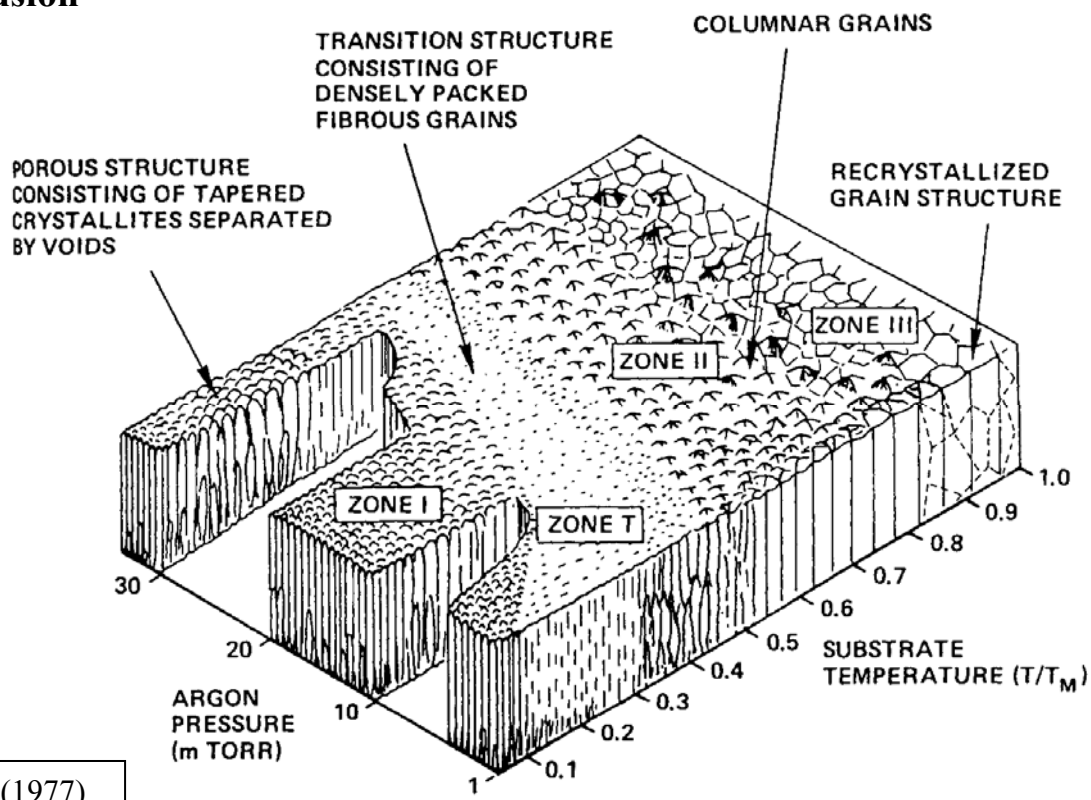


X-ray multilayer fabrication

Thin film growth

- Good adhesion
- Trade-off: in- and out-of-plane diffusion
- Preference for amorphous layers
- Low working gas pressure
- Low substrate temperature
- Consider interface chemistry

Thornton zone model for sputtering

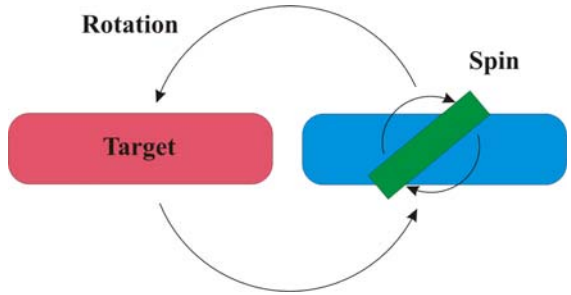


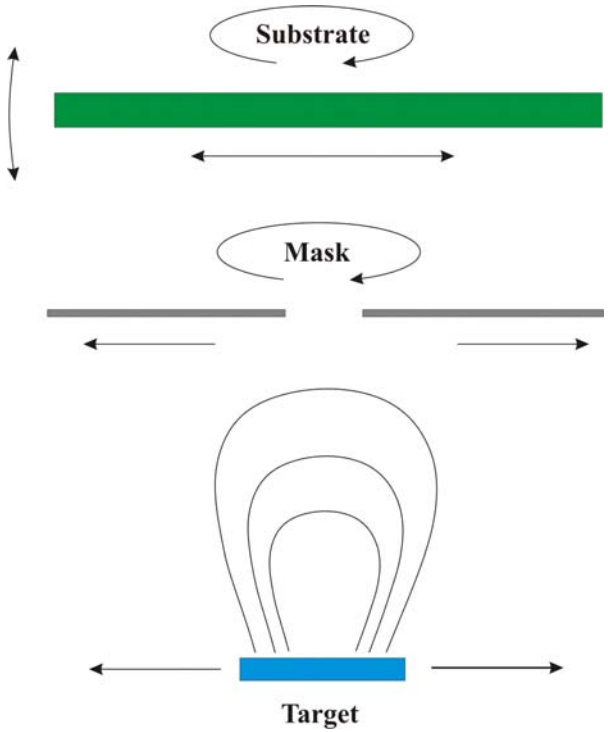
[15] J.A. Thornton, Ann. Rev. Mater. Sci. 7, 239 (1977)

X-ray multilayer fabrication

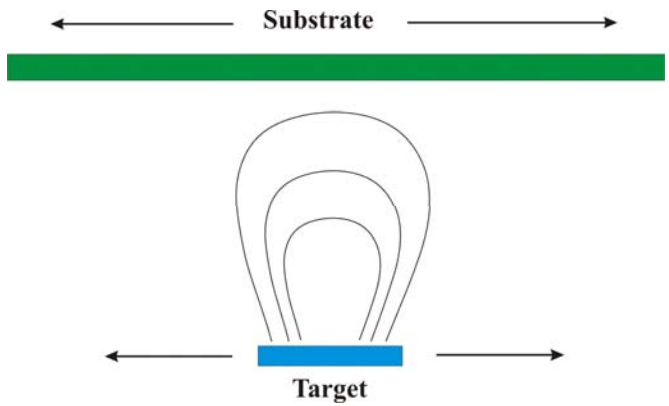
Large area coatings (uniform, gradient)

- **Relative motion source - substrate**
- **Masking techniques**



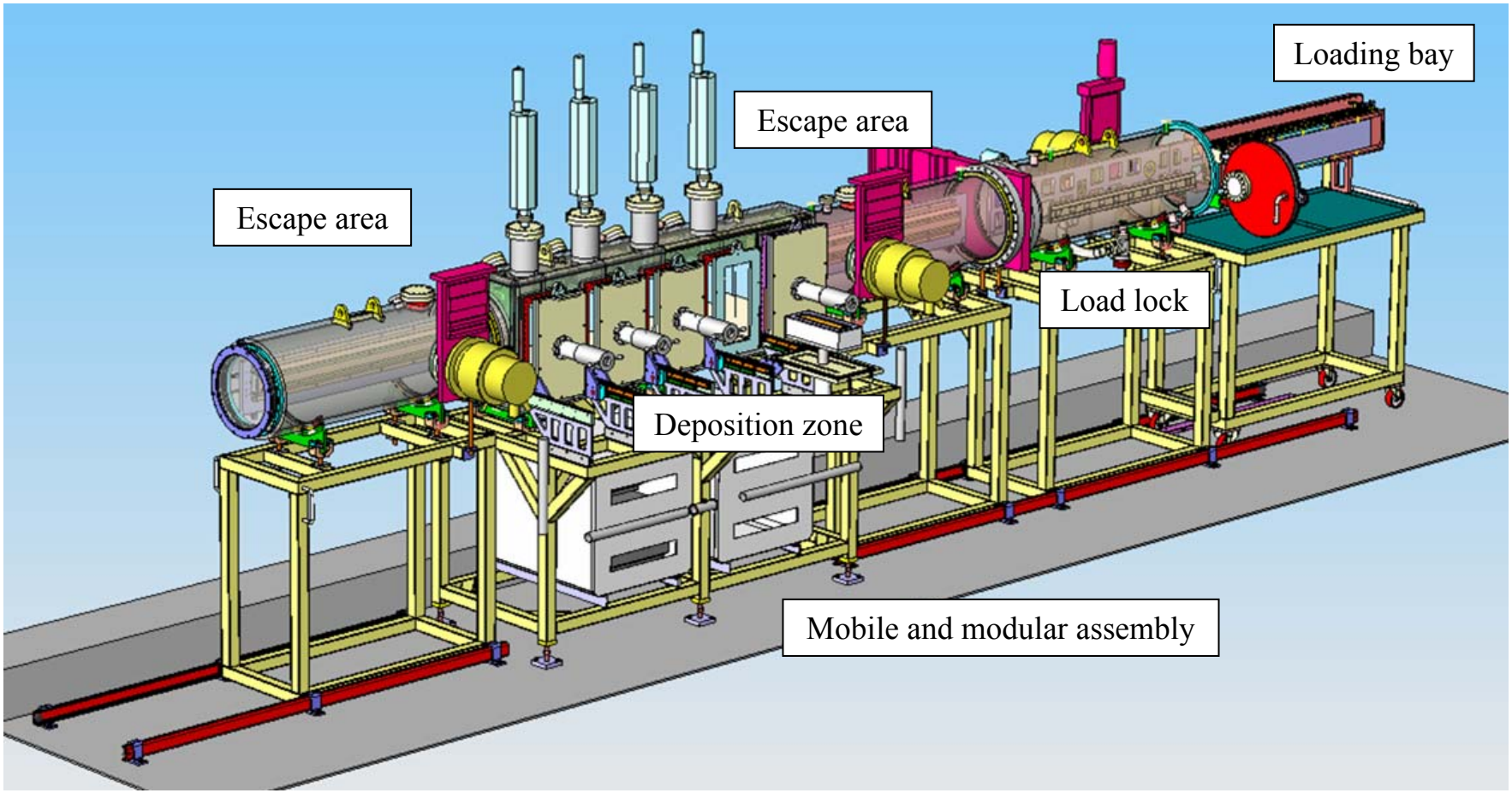


$$t(\vec{r}) = \int \varphi(\vec{r}, \vec{r}') \frac{d\vec{r}'}{v(\vec{r}')}$$



X-ray multilayer fabrication

ESRF magnetron sputter deposition system



X-ray multilayer fabrication

Technology and engineering

Curved MLs

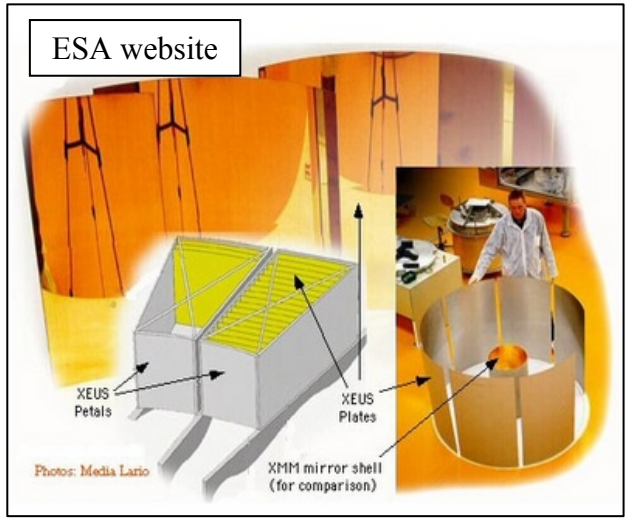
- Figured substrates or bending techniques ?
- Surface finishing (deterministic polishing/etching/coating)
- Weight and aperture (astronomy)

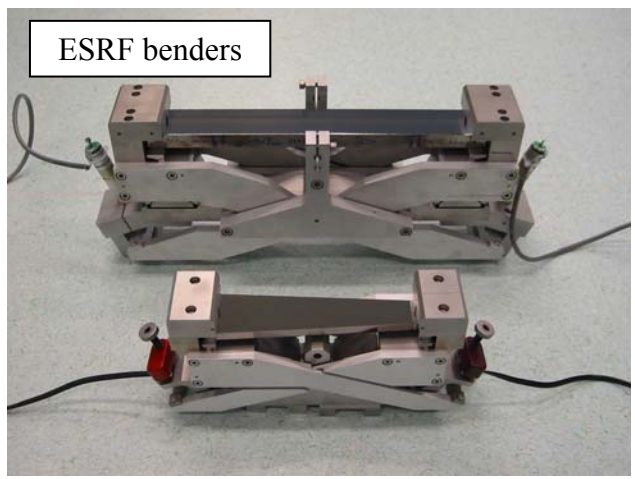
Stability and stress

- Intrinsic stress after coating (mainly compressive)
- Thermal and radiation load (white beam)
- Protection against debris (EUV, laser plasma, astronomy)
- Sample environment (vacuum/He/N_2)

Interface engineering

- Cap and barrier layers (EUV)

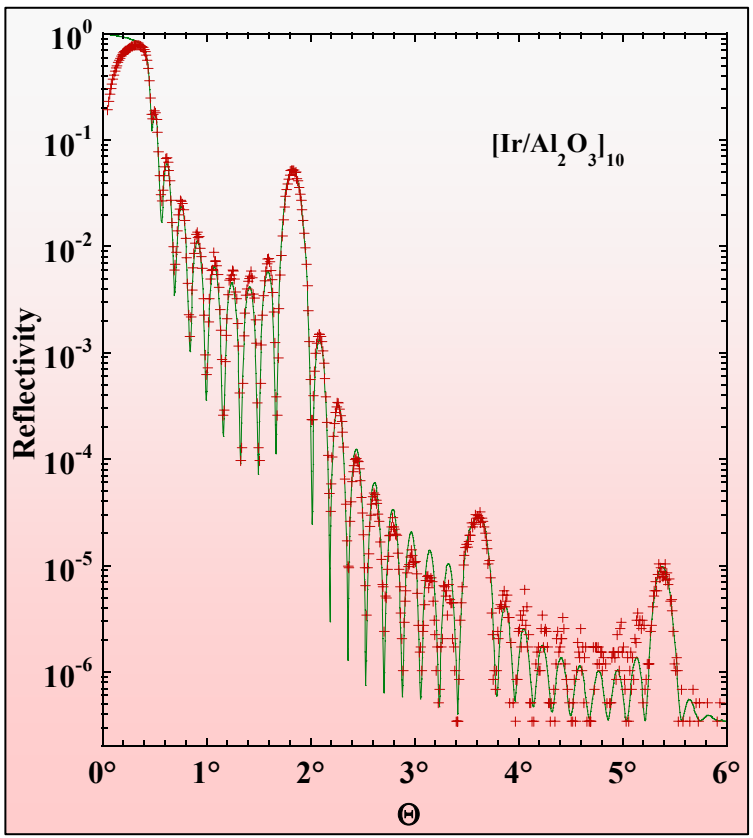




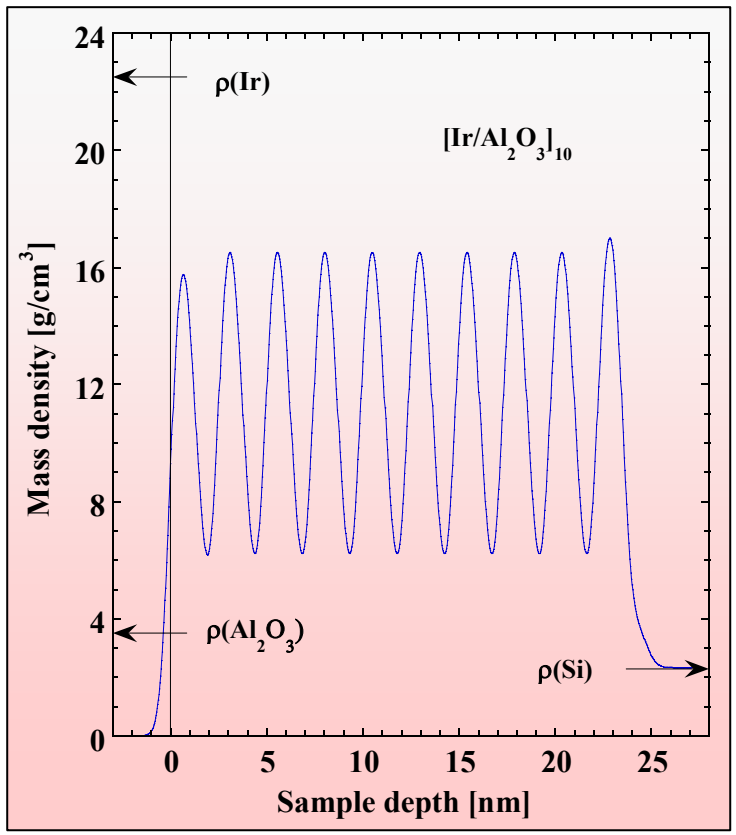
X-ray multilayer characterization

X-ray reflectivity

Simulation of x-ray reflectivity



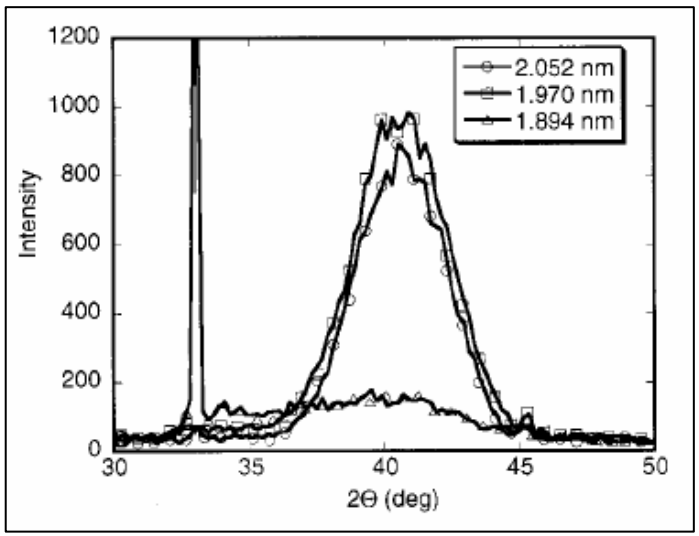
Vertical density profile



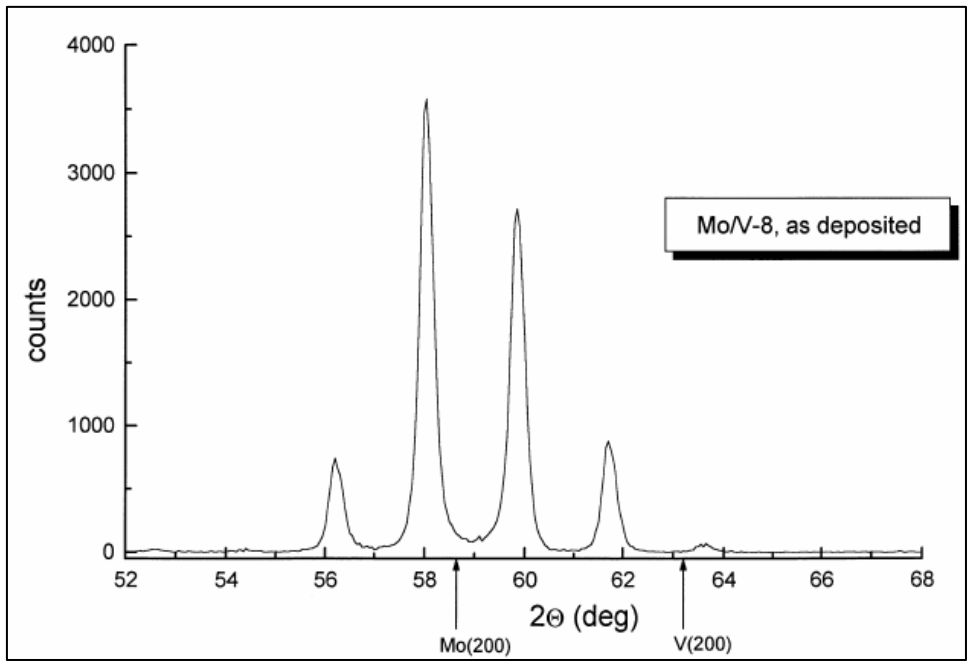
X-ray multilayer characterization

X-ray scattering

- Access to atomic structure
- Phase transitions
- Coherence lengths
- Superlattice formation



[16] S. Bajit et al, J. Appl. Phys. 90, 1017 (2001)



[17] D.L Beke et al, Vacuum 50, 373 (1998)

X-ray multilayer characterization

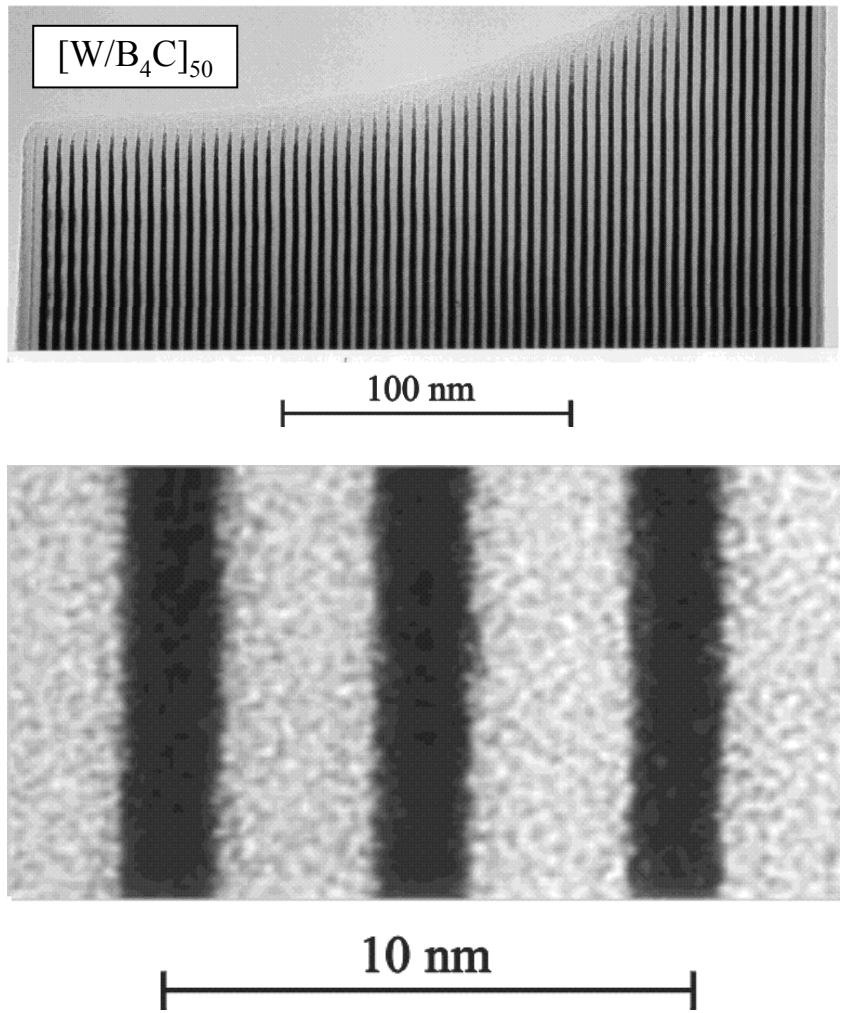
Transmission electron microscopy (TEM)

- **Fabrication errors**
- **Roughness evolution**
- **Crystallinity**
- **Interface diffusion**

↓

Complementary to x-ray measurements !

R. Scholz, MPI Halle, Germany

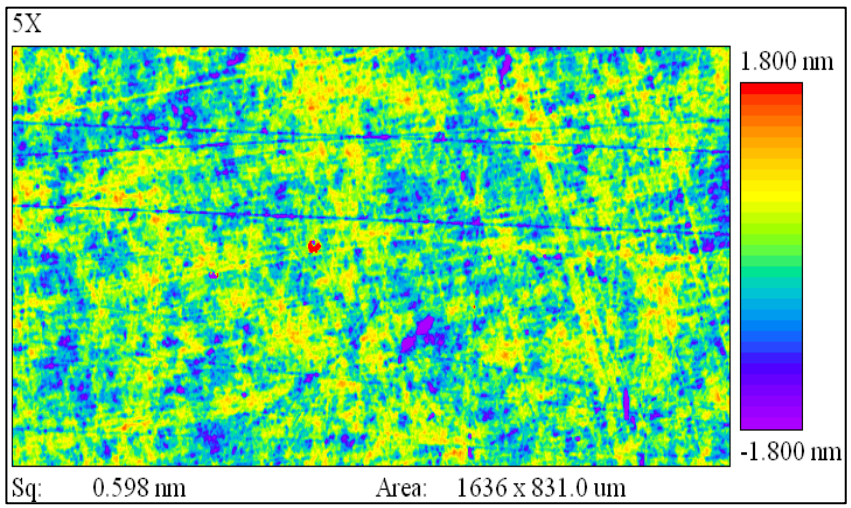


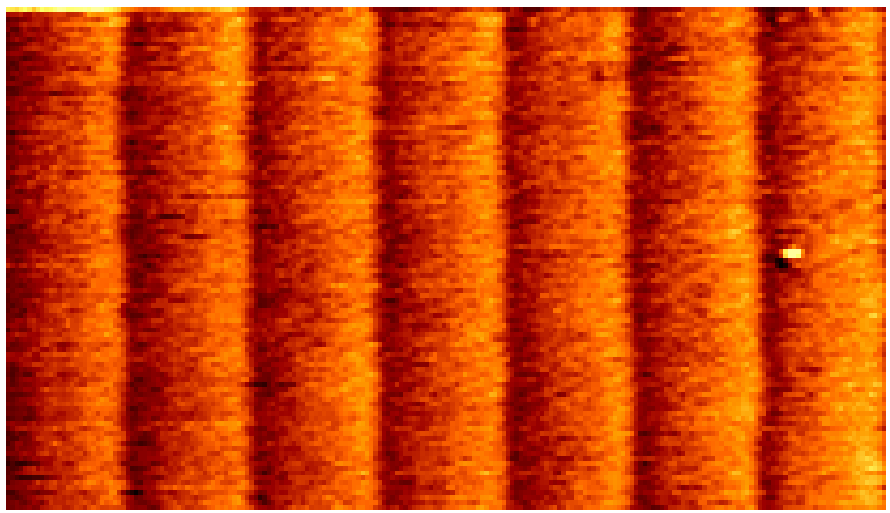
X-ray multilayer/mirror characterization

Surface metrology

- **Atomic Force Microscopy (AFM)**
- **Interferometry**
- **Long Trace Profiler (LTP)**
- **From nm to m scale**
- **No depth information !**

A. Rommeveaux, ESRF Optics Group

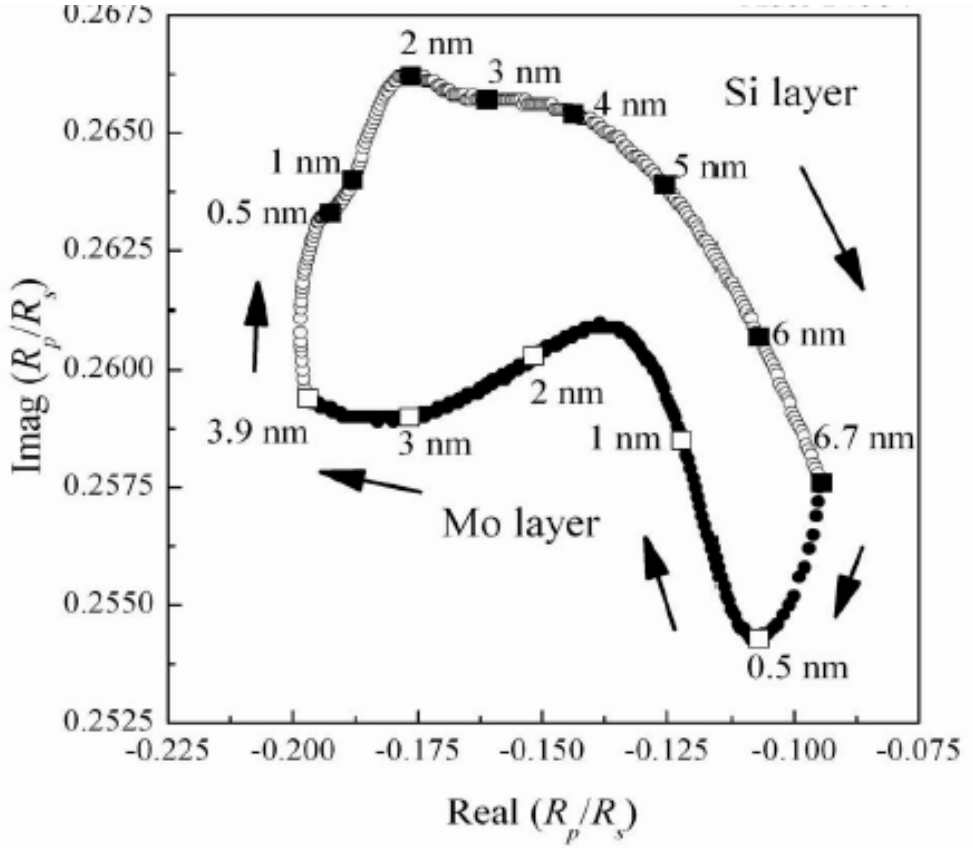




X-ray multilayer characterization

Ellipsometry

- **Complex field amplitude**
- **In-situ tool during growth**
- **Based on growth models**
- **Access to nucleation/coalescence**
- **Limited penetration depth !**

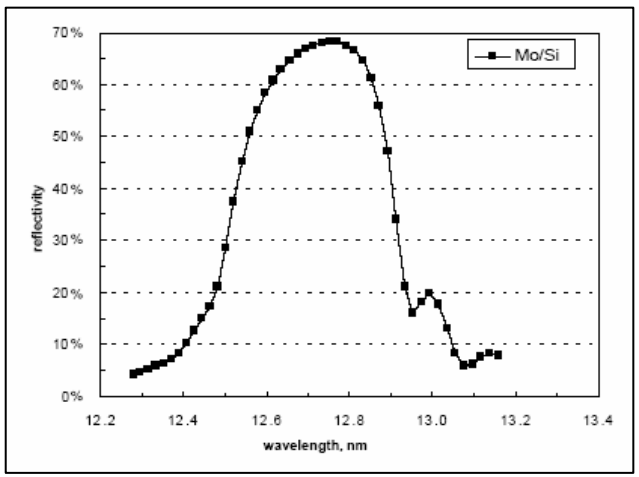


[18] T. Tsuru, T. Harada, M. Yamamoto, IPAP Conf. Series 7, 168 (2006)

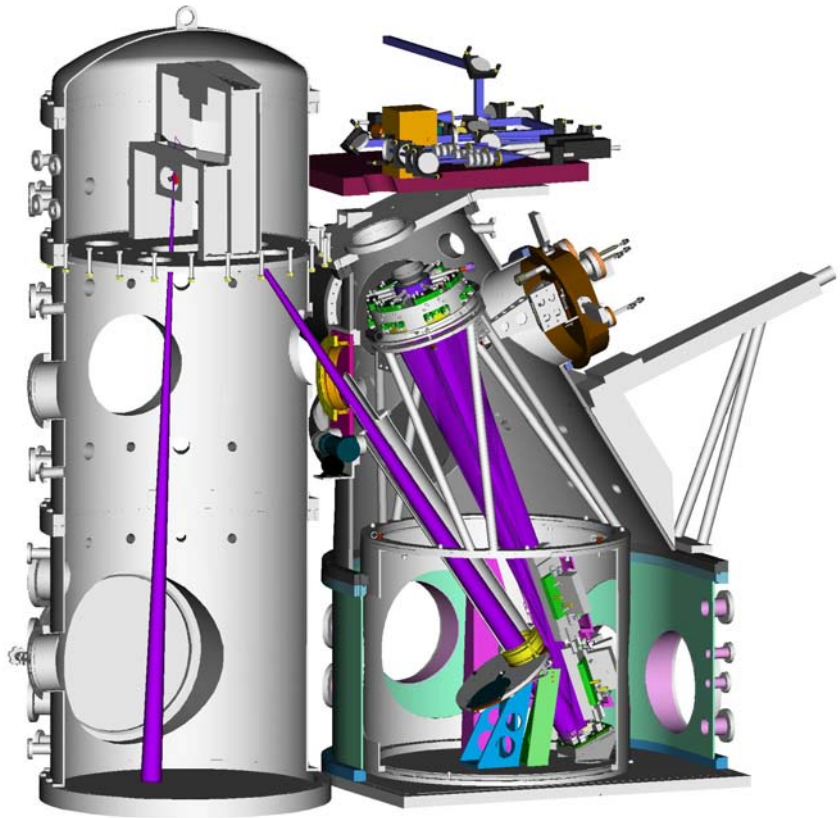
Applications

EUV lithography

- Vast projects in U.S. and Europe
- Achieve 30 nm structures on chips
- Illumination at $\lambda = 13.4$ nm
- Multilayer based optics
- Near normal incidence
- ≈ 10 reflections $\rightarrow R = R_i^{10}$!
- Mo/Si and derivatives most promising



Sandia National Laboratory website

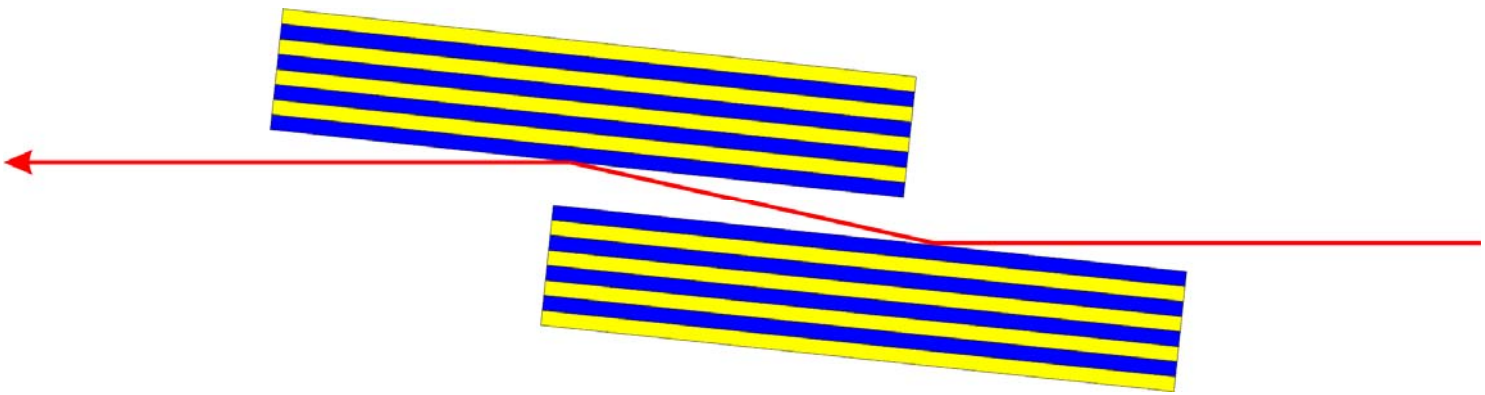


[19] T. Feigl et al, Jpn. J. Appl. Phys. 41, 4082 (2002)

Applications

Synchrotron optics: Multilayer high flux monochromators

- **Two bounce optics**
- **100x larger bandwidth compared with Si(111)**
- **Harmonics suppression due to refraction and filling factor**
- **Radiation and heat load issues !**

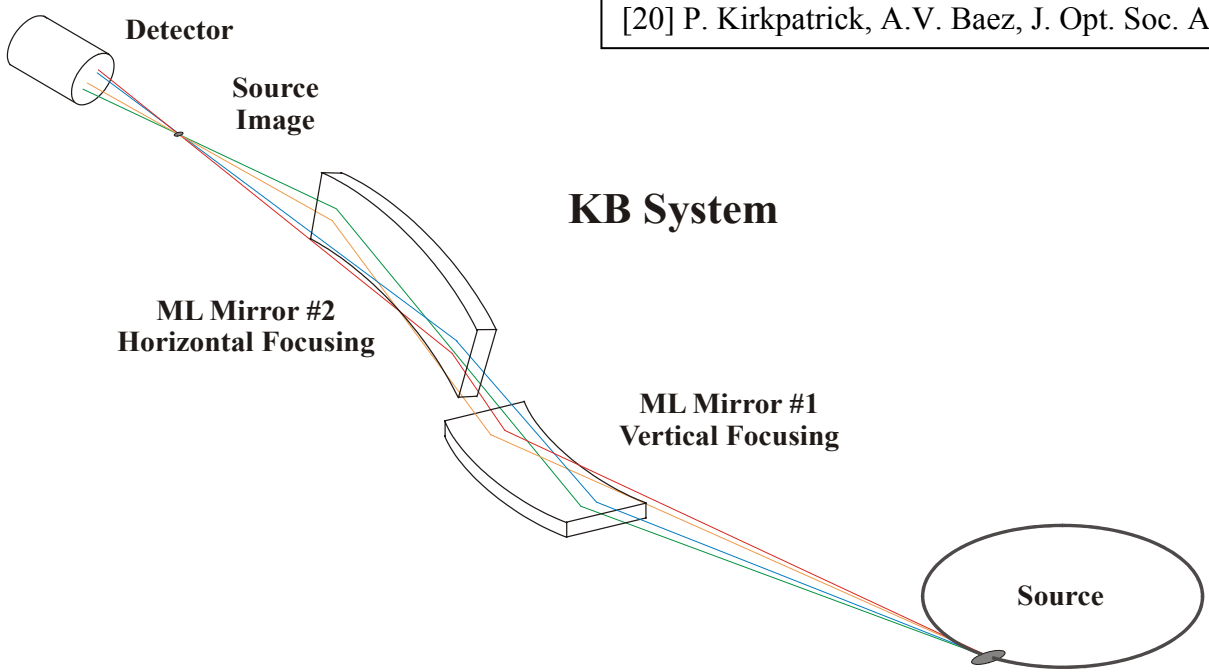


Applications

Synchrotron optics: Kirkpatrick-Baez (KB) focusing devices

- **Separate vertical and horizontal focusing (non-circular source)**
- **Technologically easier than single reflection ellipsoid + increased field of view**
- **Metal or graded ML coatings**

[20] P. Kirkpatrick, A.V. Baez, J. Opt. Soc. Am. 38, 766 (1948)



Applications - Limitations

Diffraction limit $D_{FWHM} = C\frac{\lambda}{NA}$

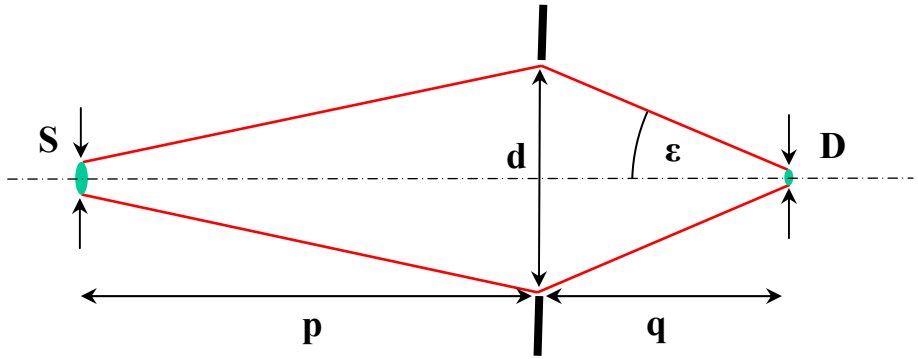
Numerical aperture $NA = n \cdot \sin\varepsilon$

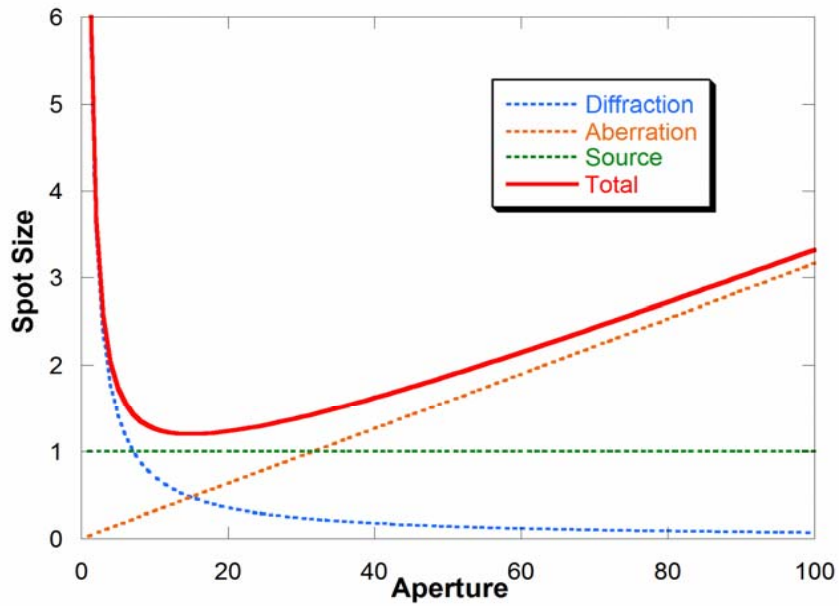
Straight aperture $C = 0.44$

Source size limit $D = \frac{q}{p} \cdot S$

Further limitations

- Volume diffraction
- Scattering
- Non-trivial design
- Fabrication accuracy
- Alignment





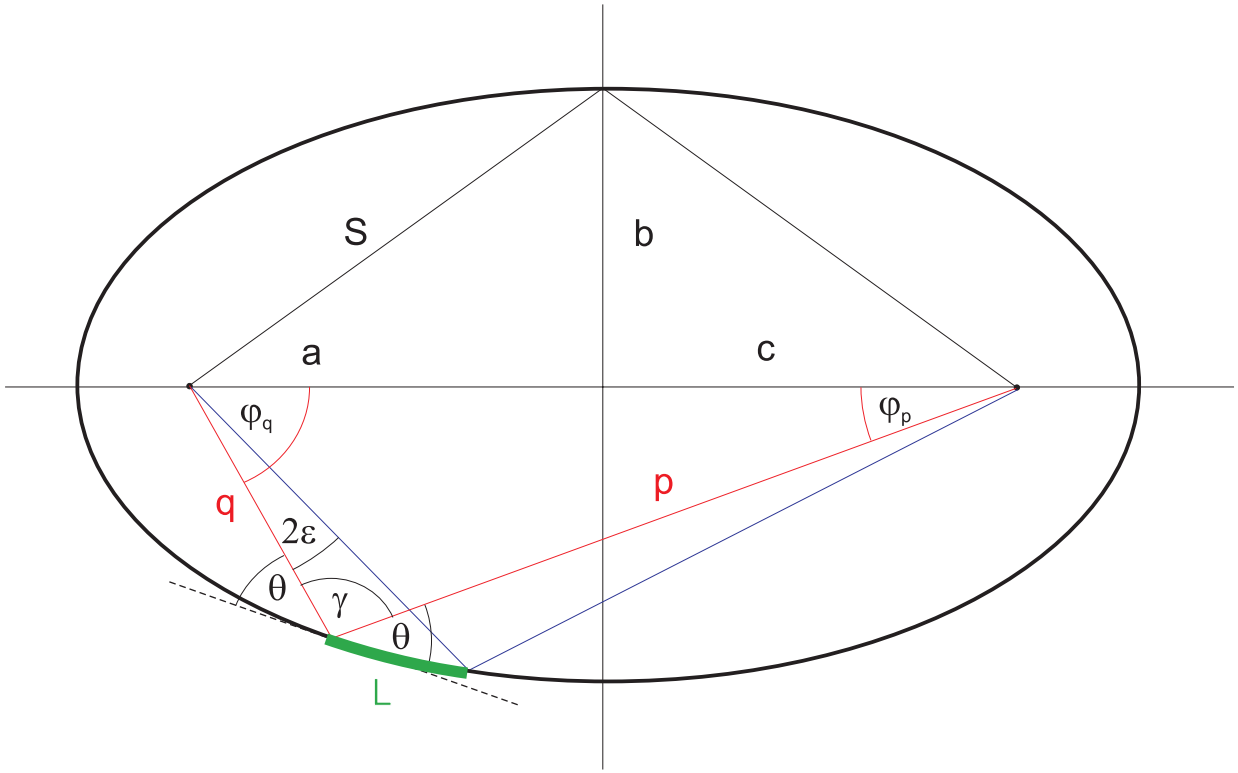
Applications

Ellipse geometry

$$2\varepsilon = \varphi_q(\theta_2) - \varphi_q(\theta_1)$$

$$\sin\varphi_q = \frac{p \cdot \sin 2\theta}{2 \cdot c}$$

$$NA = n \cdot \sin\varepsilon$$



Attention: Depth of aperture! → Wave front calculations

Applications

Simple approximation

Total reflection mirror

$$\sin\varepsilon \approx \frac{1}{4}\sin\theta_c = \frac{\sqrt{2\cdot\delta}}{4} = \frac{\lambda}{4}\sqrt{\frac{r_0\rho_e}{\pi}}$$

$$\Rightarrow D_{FWHM} \approx 1.76\cdot\sqrt{\frac{\pi}{r_0\rho_e}}$$

$D_{FWHM} \approx 25$nm (Pt)

Multilayer mirror

$$\sin\varepsilon = \frac{1}{4\cdot c}\left(p_2\cdot\sin 2\theta_2 - p_1\cdot\sin 2\theta_1\right)$$

$$\sin 2\theta \approx 2\cdot\sin\theta \approx \frac{\lambda}{\Lambda},\ p \approx 2\cdot c$$

$$\Rightarrow \sin\varepsilon \approx \frac{\lambda}{2}\left(1/\Lambda_2 - 1/\Lambda_1\right)$$

$$\Rightarrow D_{FWHM} \approx \frac{0.88}{1/\Lambda_2 - 1/\Lambda_1}$$

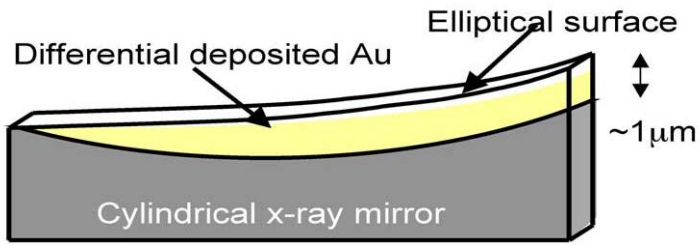
$D_{FWHM} \approx 5$nm

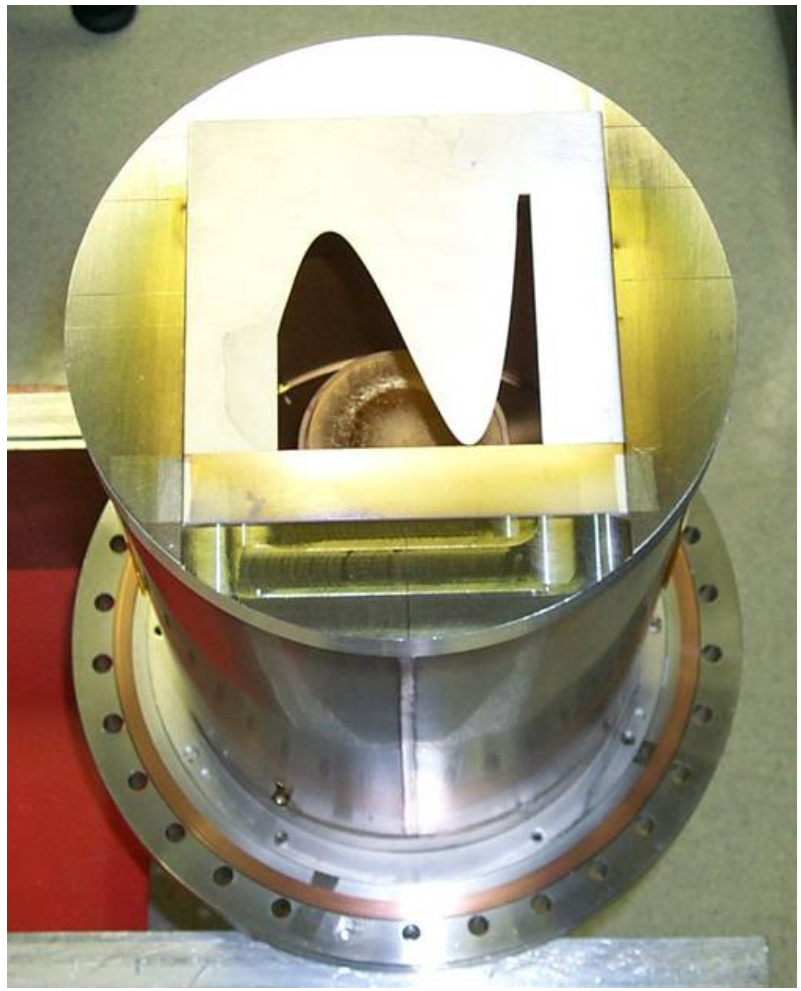
No explicit energy dependence !

Applications

APS KB development

- **Static total reflection mirrors**
- **Correct figure by thick Au coating**
- **Differential deposition along beam footprint**
- **Profile coating by masking along beam footprint**



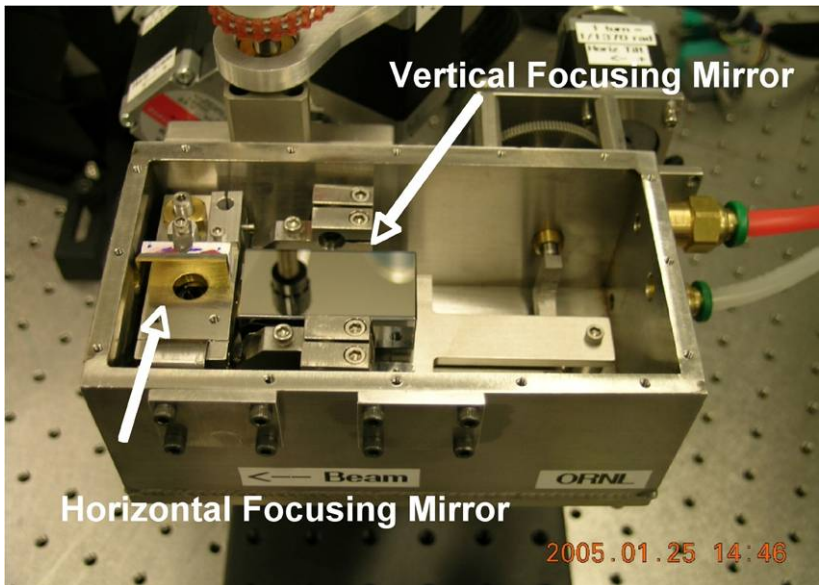


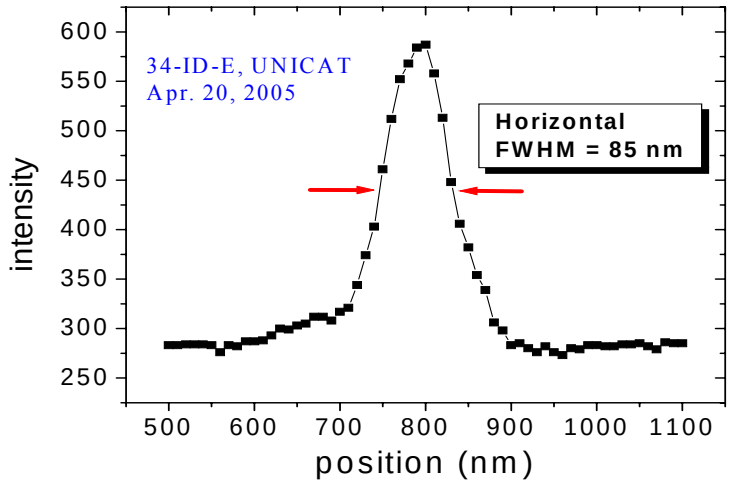
[21] G. Ice et al, Rev. Sci. 71, 2635 (2000)

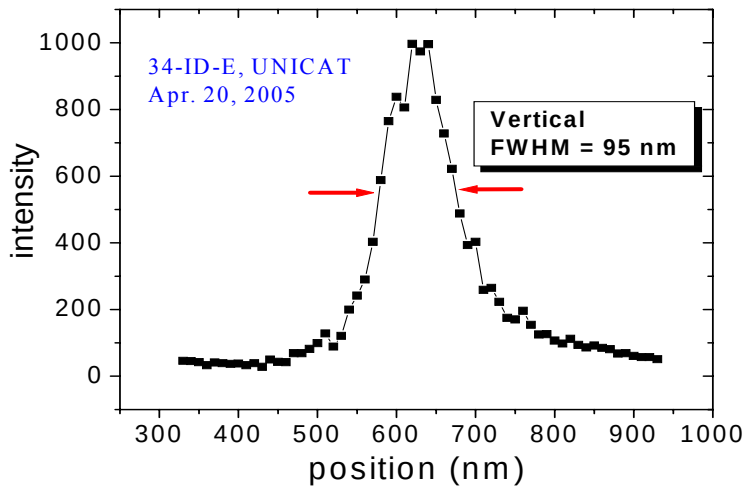
Applications

APS KB development

- White beam focusing experiment at sector 34
- Spot size below 100 nm





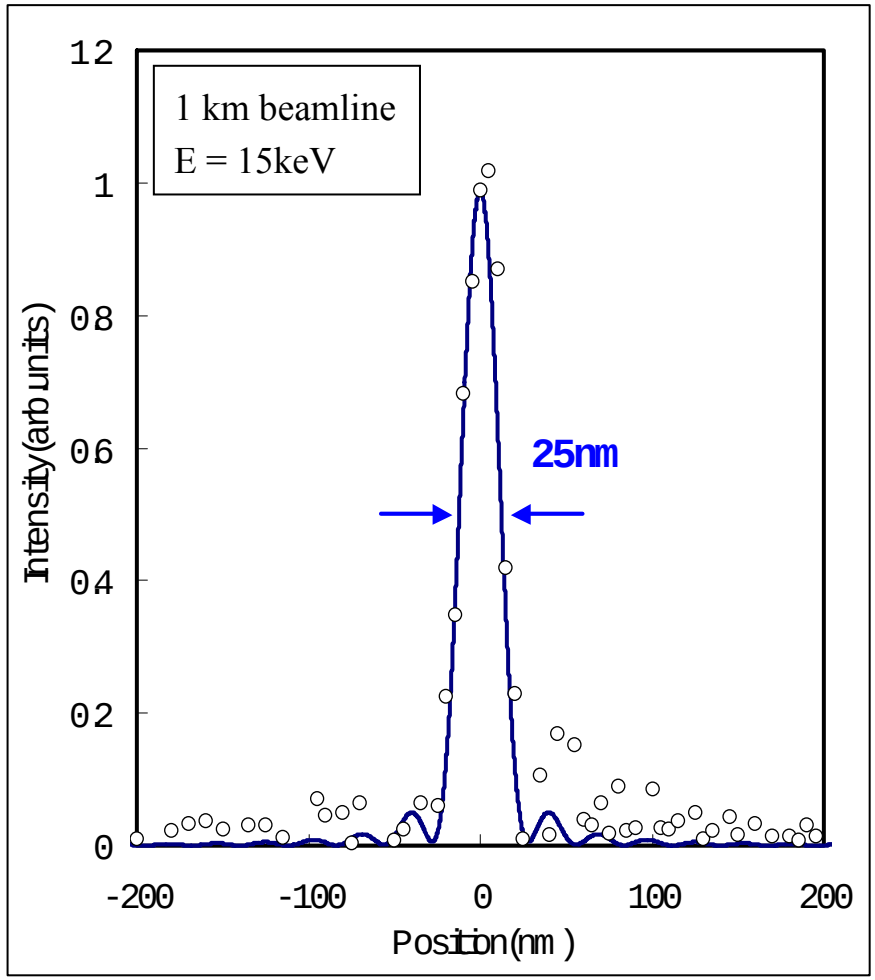


[22] C. Liu et al, Ref. Sci. Instr. 76, 113701 (2005)

Applications

Spring-8/Osaka KB development

- **Static and figured Si substrates**
- **Plasma Chemical Vapour Machining (PCVM)**
- **Elastic Emission Machining (EEM)**
- **Pt coating + thickness correction**
- **Focal spots below 30 nm**
- **Aiming less than 10 nm using multilayers**

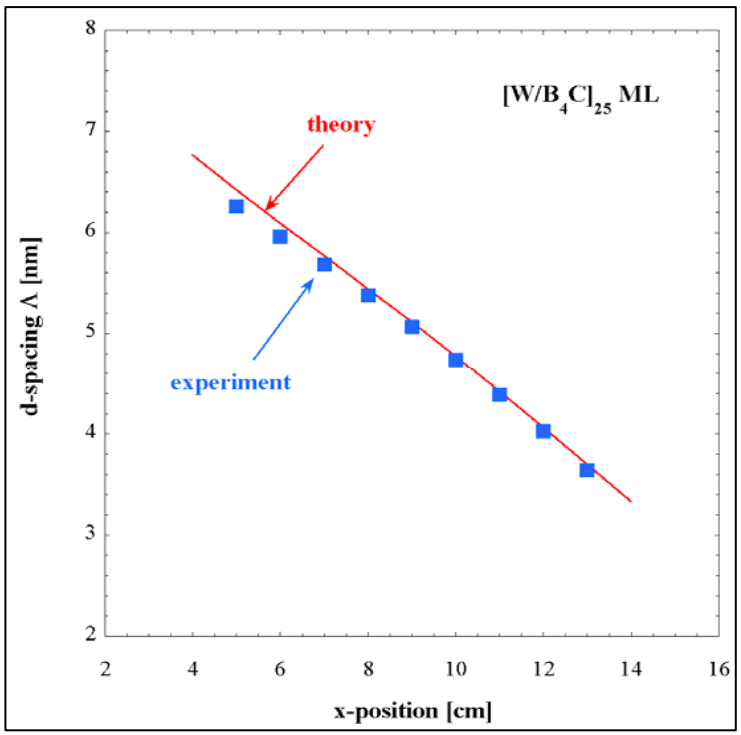


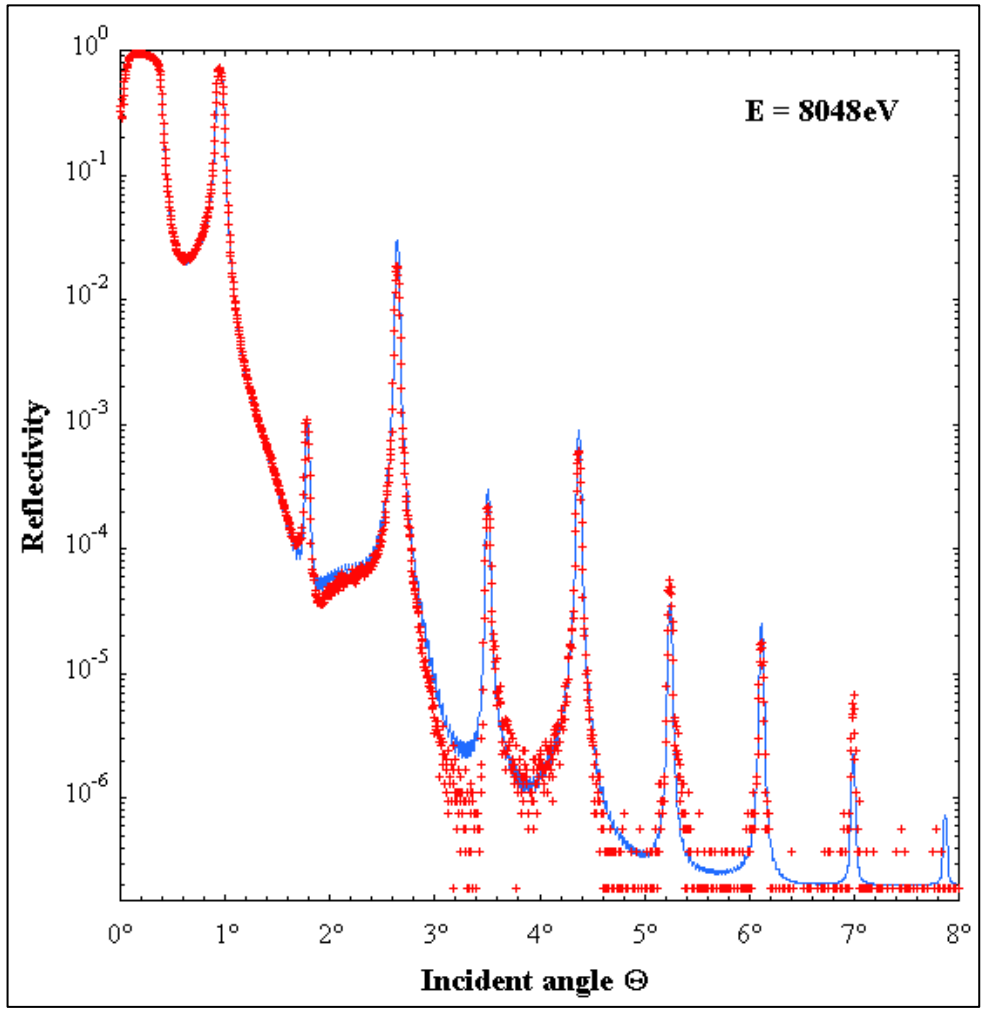
[23] H. Mimura et al,
Jpn. J. Appl. Phys. Part 2 44, 18539 (2005)

Applications

ESRF KB development

- Laterally graded multilayers
- Flat Si substrates

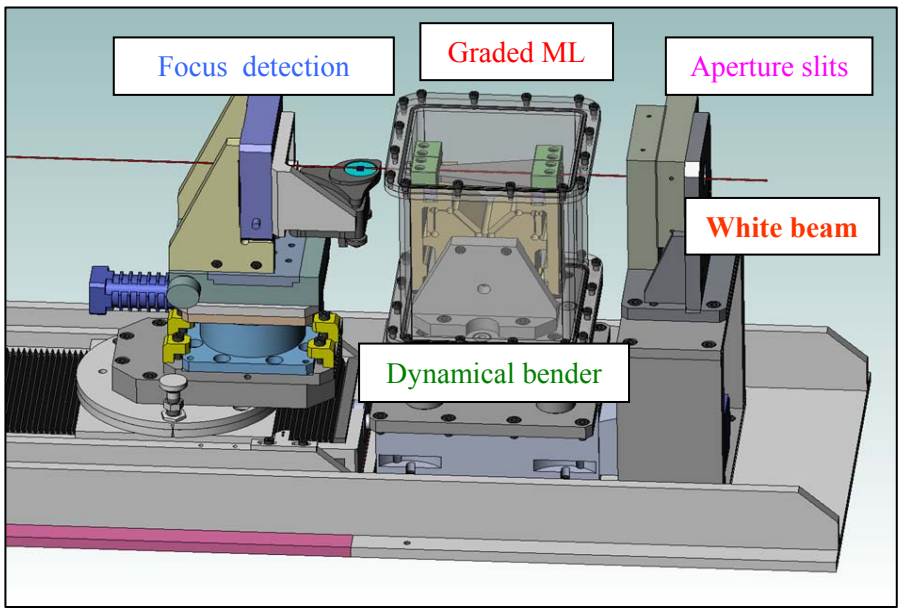


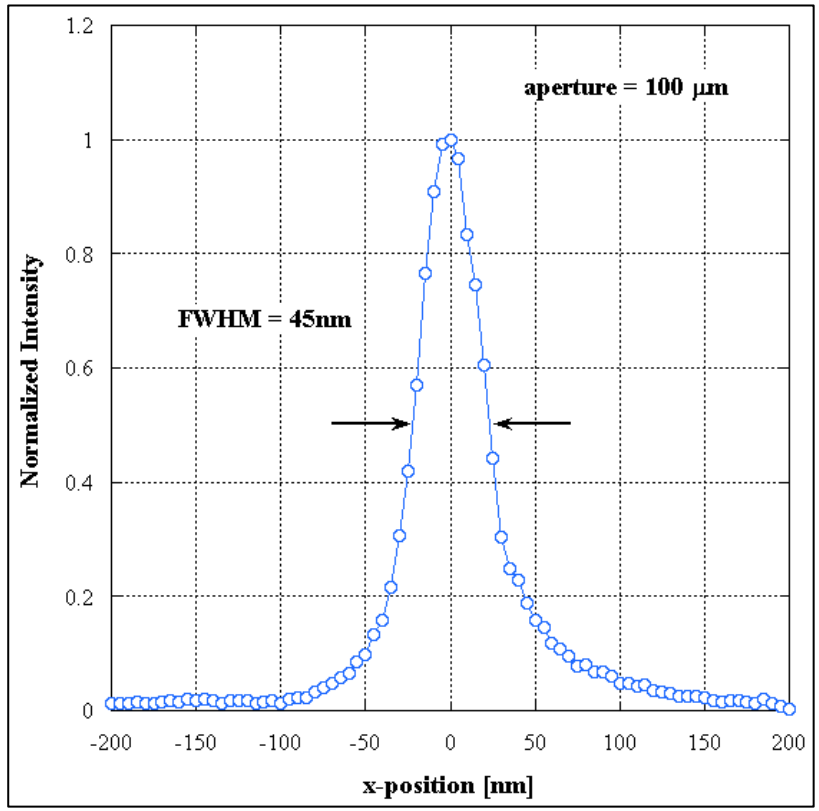


Applications

ESRF focusing experiment

- Full undulator spectrum
- Vertical line focus
- Dynamical bender
- Raw data 45 nm FWHM @ 100 µm aperture





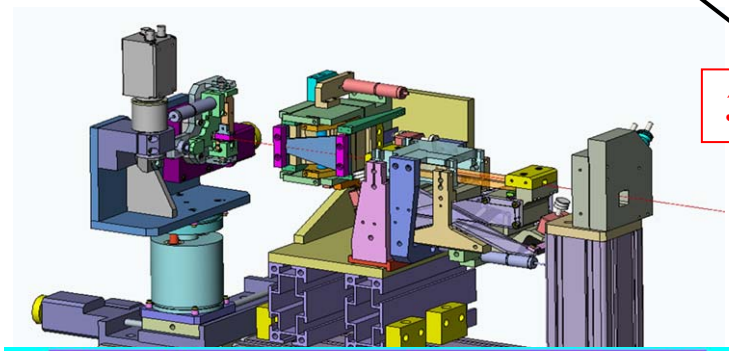
[24] Ch. Morawe et al, Proc. SPIE 6317 (2006)

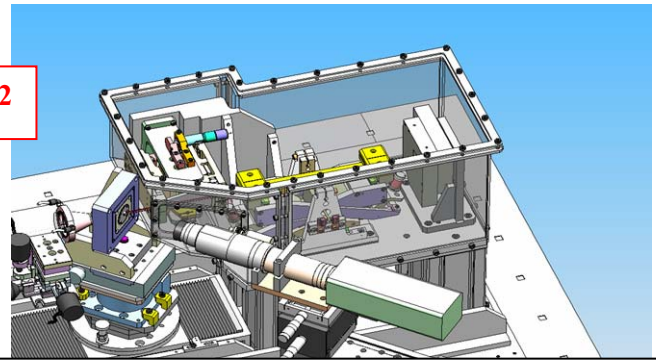
Applications

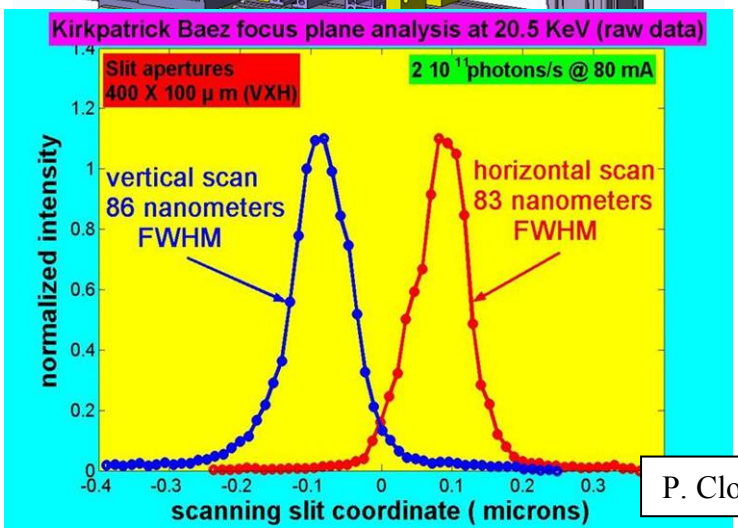
ID19: low β @ 150 m, E = 15…24 keV
86*83 nm^2: 2*10^{11}ph/s @ 80mA

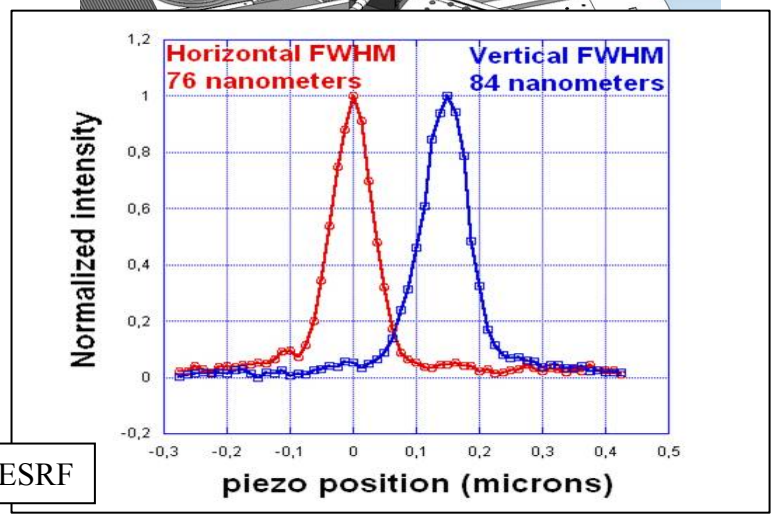
ID22: high β @ 60 m, slit source, E = 17 keV
76*84 nm^2: 10^{9}ph/s @ 200mA
150*100 nm^2: 10^{12}ph/s @ 200mA

3*10^5 ph/s/mA/nm^2









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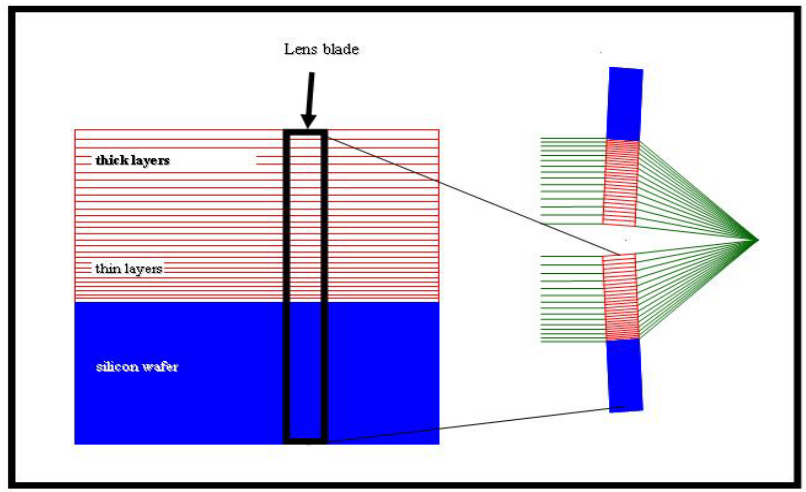
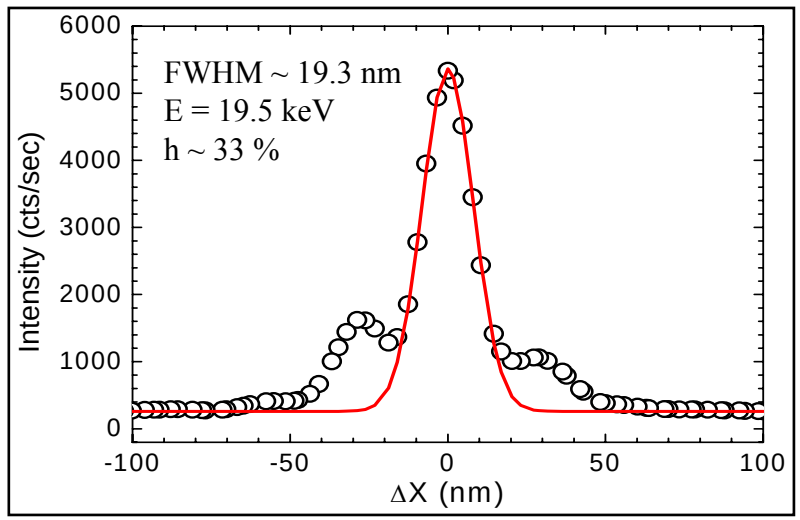
Applications

Multilayer Laue Lenses (APS)

- High aspect ration linear zone plate
- Transmission multilayer optics
- Bragg reflection to enhance efficiency
- Very thick depth graded coatings
- Starting with thinnest layer
- Crossed KB geometry possible
- Line focus below 20 nm





[25] H.C. Kang et al, Phys. Rev. Lett. 96, 127401 (2006)

Applications

Further mirror/multilayer based optics

- **X-ray astronomy (normal and grazing optics)**
- **Water window microscopy (Wolter)**
- **Plasma spectroscopy**
- **Laboratory X-ray instrumentation (commercial)**
- **Free Electron Lasers (FEL)**
- **…**

Summary - Perspectives

Past achievements

- Theoretical treatment of flat multilayers well established
- Inclusion of experimental artifacts possible
- Tools for design and analysis available
- Advanced fabrication and characterization instrumentation
- Vast areas of application from visible light to hard X-rays

Areas of ongoing research and development

- Full wave optical treatment of curved multilayers
- Diffraction limited high aperture optics
- Improved understanding of radiation impact
- …

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Thank you !