ESRF | The European Synchrotron

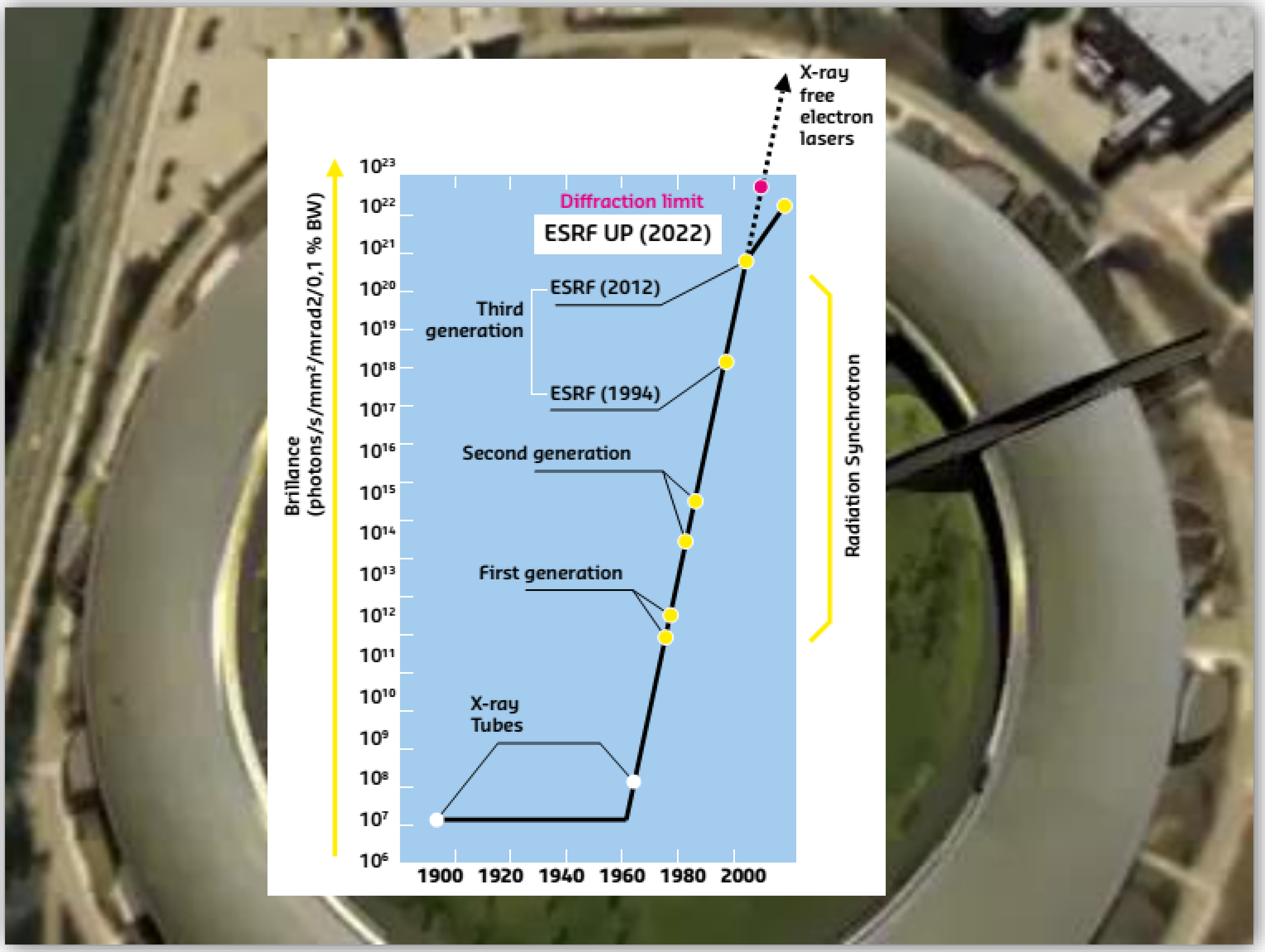
HARD X-RAY OPTICS FOR SYNCHROTRON BEAMLINES

- ***Synchrotron radiation***
- ***Principles of X-ray optics***
- ***Mirrors***
- ***Diffractive optics***
- ***X-ray micro-/nano-focusing***
- ***Summary***

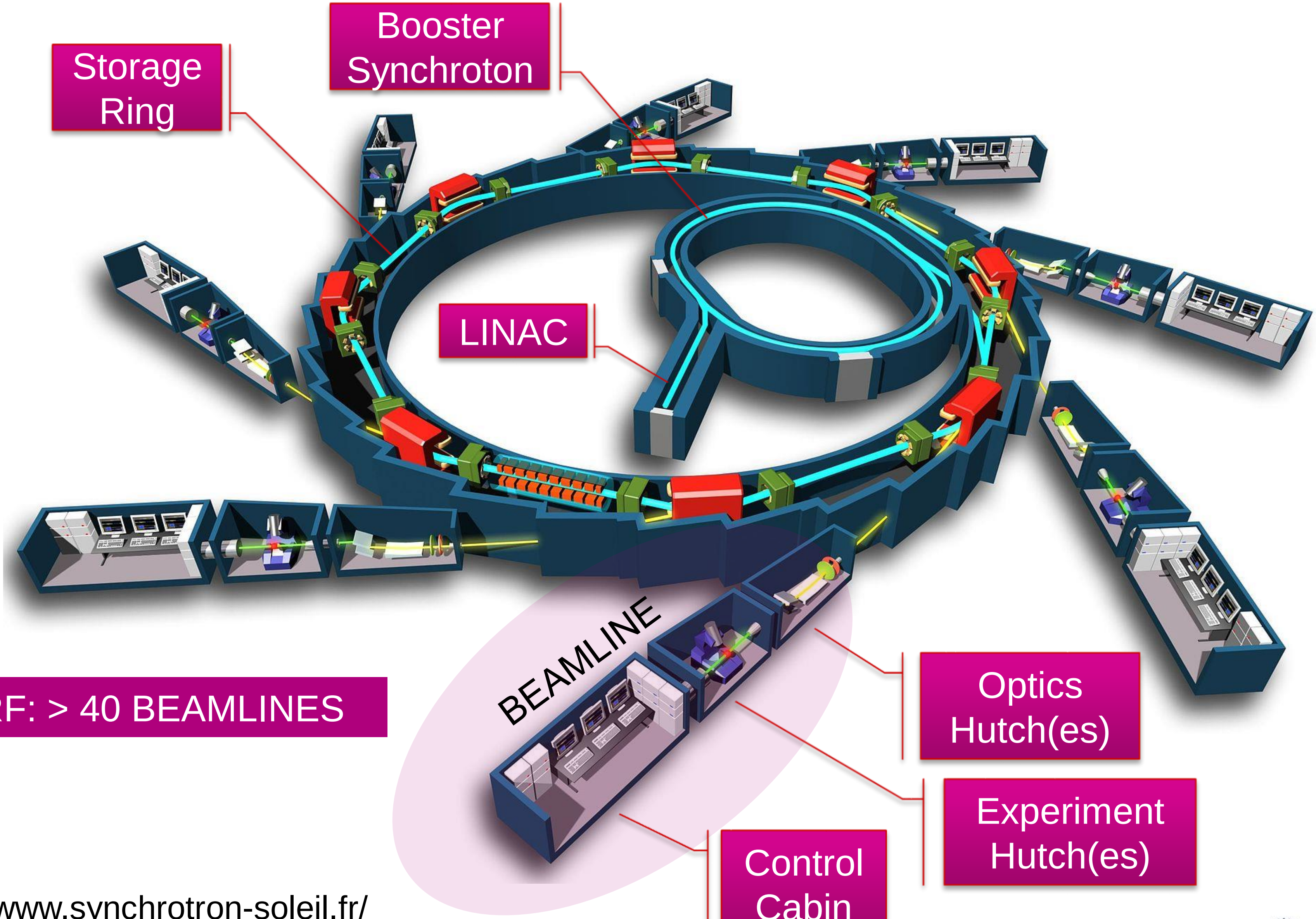
Ray Barrett
X-ray Optics Group Leader
European Synchrotron Radiation Facility
Grenoble, France

barrett@esrf.fr

A STORAGE RING BASED SYNCHROTRON SOURCE



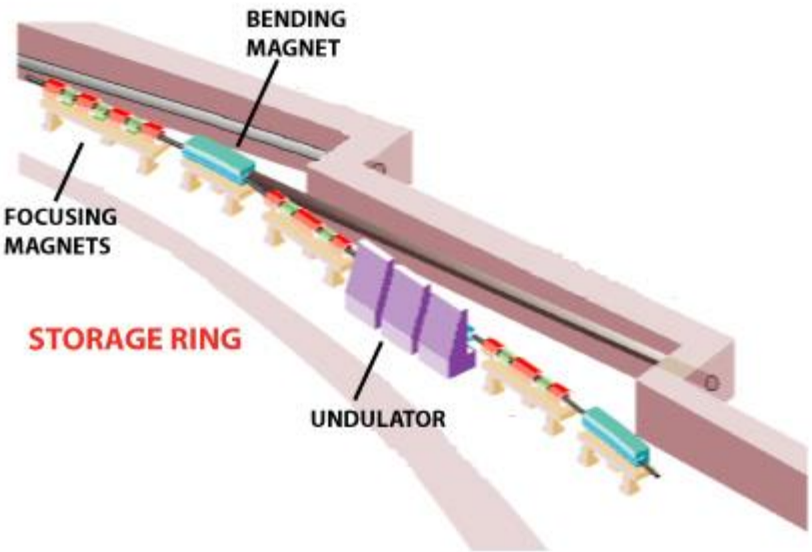
SCHEMATIC OF A SYNCHROTRON RADIATION (SR) LIGHT SOURCE

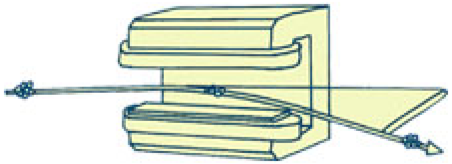


ESRF: > 40 BEAMLINES

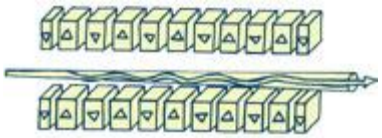
http://www.synchrotron-soleil.fr/

THE X-RAY SOURCES OF A SYNCHROTRON LIGHT FACILITY

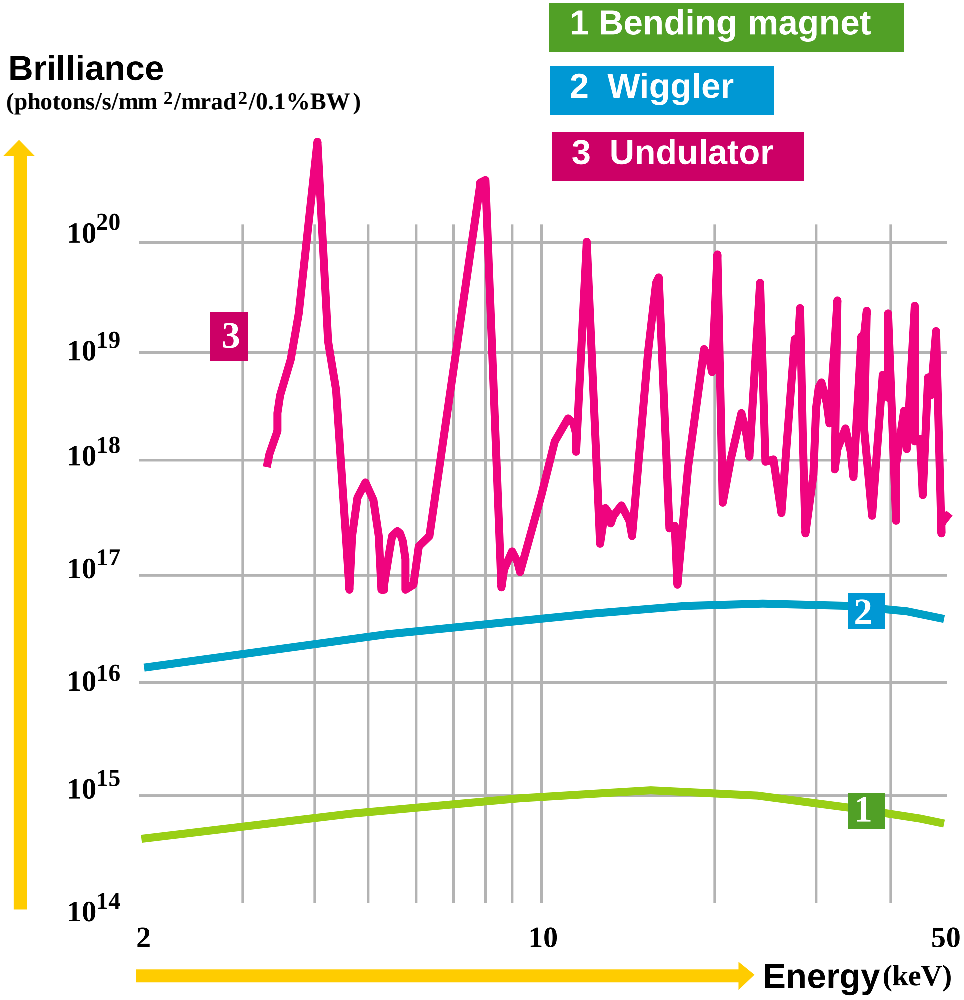




Bending magnet



Undulator/wiggler

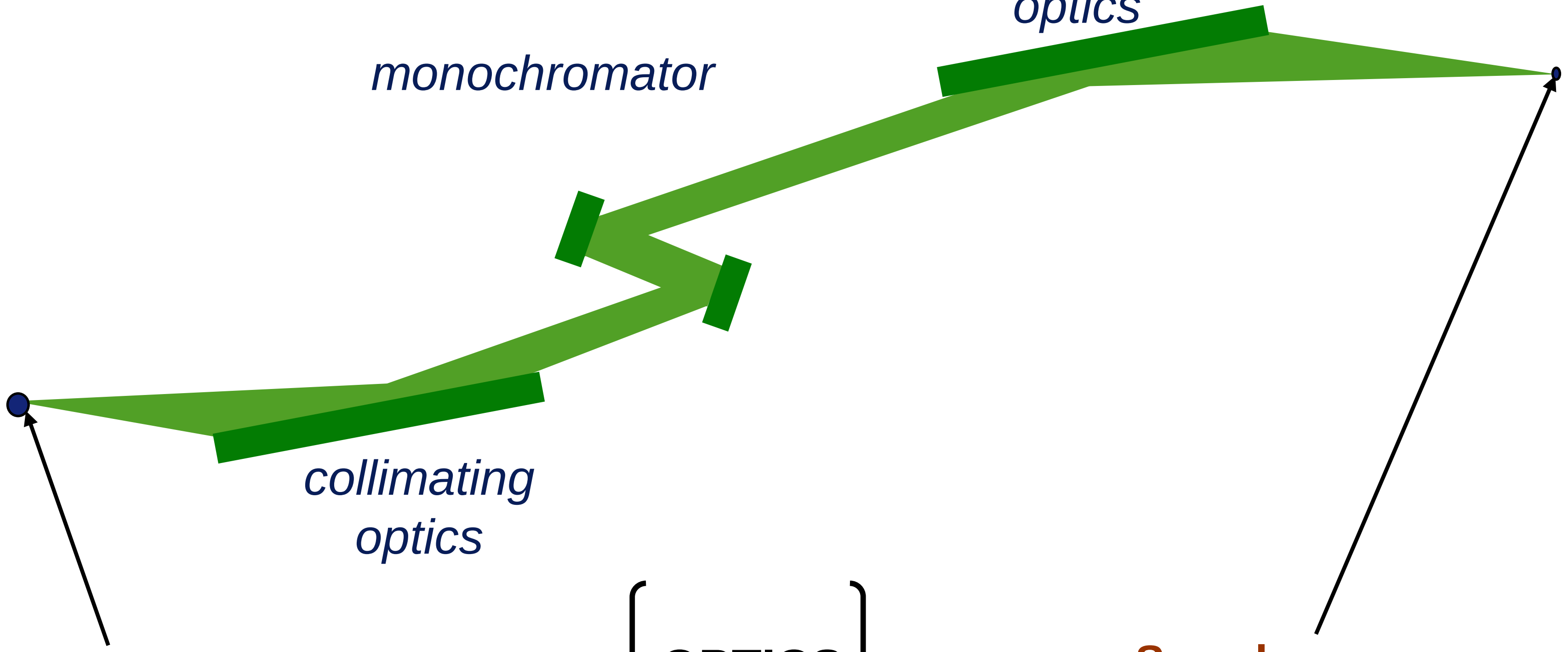


X-RAY BEAMS AT 3^{RD} GENERATION HARD X-RAY SR SOURCES

- Beam size
  - Unfocused: few mm to few cm (source is weakly divergent)
  - Focused beam: < 100 nm to ~10’s µm
- Energy range/tunability
  - 0.1eV < E < 0.5 MeV but mostly 2-100 keV
- Energy bandwidth (ΔE/E):
  - 10^{-2} to 10^{-8} at sample, typically ΔE ~ few eV @ 20keV
- Polarized radiation
  - 100% linear or circular or elliptical
- Pulsed radiation
  - 50 ps pulses every ns
- Power
  - several kW total power, several 100 W/mm^2 power density (white beam)
- High degree of coherence
- Photon Flux
  - Brilliance: 10^{22} ph/sec/mrad^2/mm^2/0.1%bw (10^{11} higher than conventional sources) $\Rightarrow$ photon flux (@ $\Delta E/E = 10^{-4}$): 10^9-10^{14} ph/s
  - Extremely variable photon rates on detectors (< 1 ph/s to full beam flux)

HARD X-RAY SYNCHROTRON BEAMLINES

Typical optical geometry



Source

- spectrum (ΔE/E)
- emittance (size x divergence)
- degree of spatial coherence
- brilliance (ph/s/mm²/mrad²/0.1%bw)
- polarisation (linear, circular, elliptic)

OPTICS

?

- Power management
- Ease of use
- Lifetime
- Price

Sample

- beam size (µm)
- beam divergence (µrad)
- flux (ph/s)
- temporal coherence: ΔE/E
- spatial coherence
- polarisation

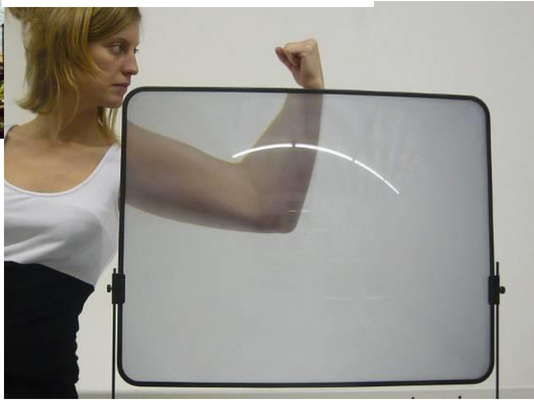
- *Synchrotron radiation*
- *Principles of X-ray optics*
- *Mirrors*
- *Diffractive optics*
- *X-ray micro-/nano-focusing*
- *Summary*

VISIBLE LIGHT OPTICS

Refractive lenses

Polarising Optics

Fresnel lenses



Diffractive optics

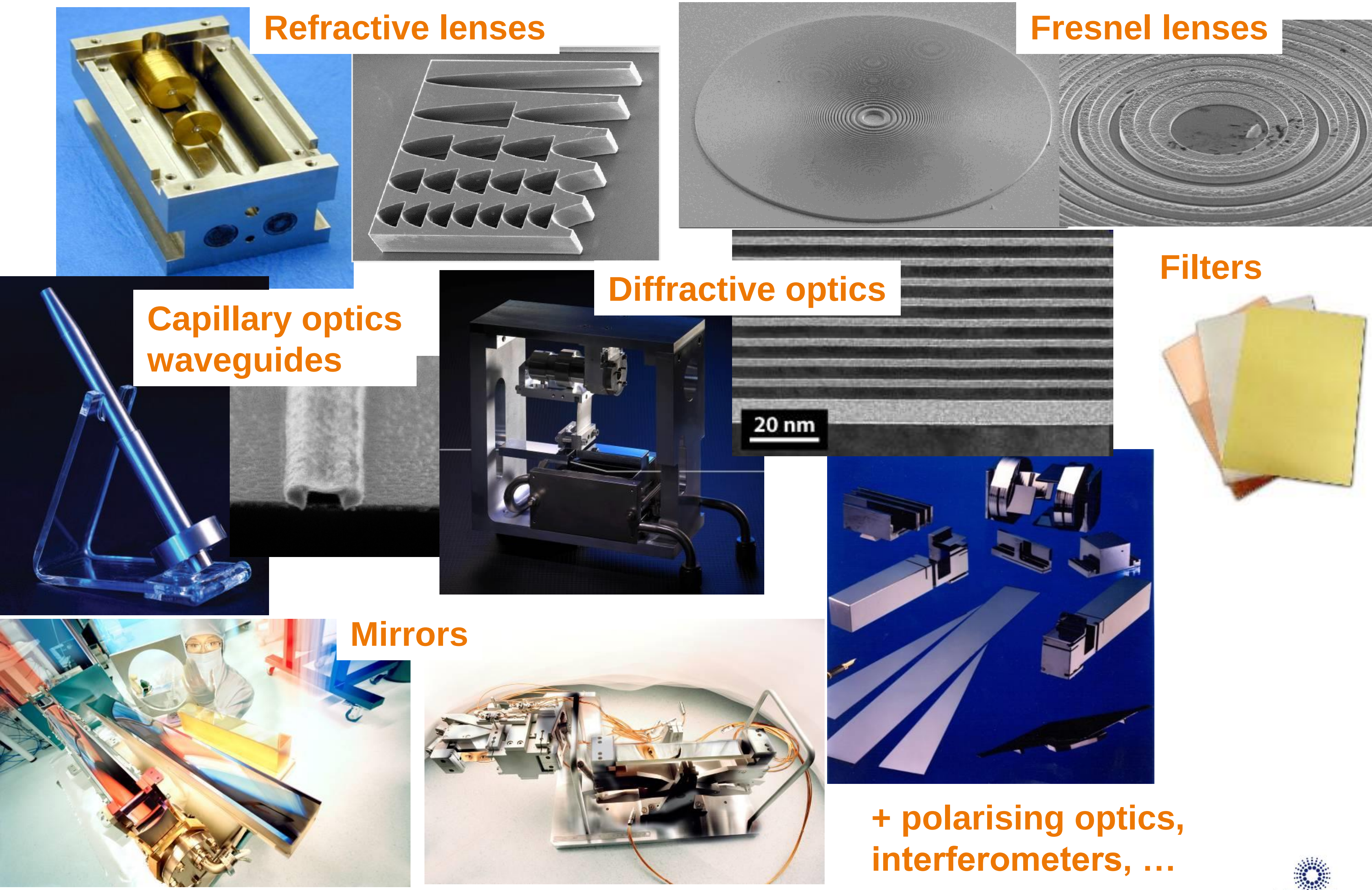
Fibre optics/ waveguides

Filters

Mirrors

+ interferometers, …

X-RAY OPTICS



Refractive lenses

Fresnel lenses

Filters

Capillary optics waveguides

Diffractive optics

Mirrors

+ polarising optics, interferometers, …

X-RAY INTERACTIONS WITH UNIFORM MATTER

plane wave in vacuum:

$\Psi(z) = \Psi_0 exp(-ik_0 z)$ where $k_0=2\pi/\lambda$

wave in medium ($n=1-\delta-i\beta$):

$\Psi(z) = \Psi_0 exp(-ink_0 z)$

$= \Psi_0 exp(-ik_0 z)\, exp(i\delta k_0 z)\, exp(-\beta k_0 z)$

δ: phase change

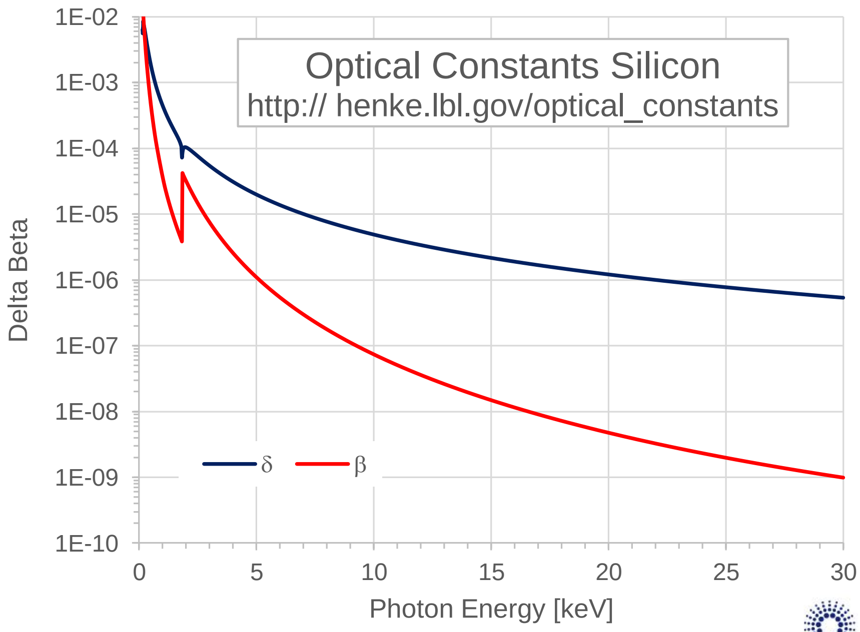
β: attenuation

intensity: $|\Psi(z)|^2$

$I/I_0 = exp(-2\beta k_0 z) = exp(-\mu z)$

phase change in distance *z*:

$\varphi(z)=2\pi\delta z/\lambda$



e.g. Kirz et al.,*Quart. Rev. Biophys* 28, [1] (1995): 33–130. doi:10.1017/S0033583500003139.

X-RAY OPTICS: MANY APPROACHES

"... The refractive index.... cannot be more than 1.05 at most....
….X-rays cannot be concentrated by lenses..."

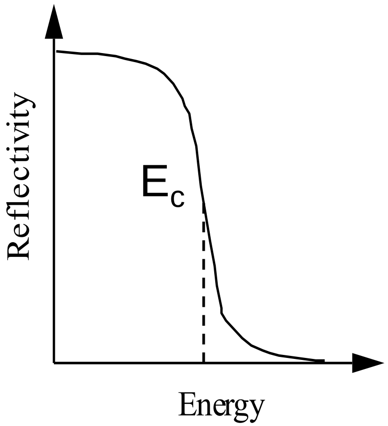
W.C. Röntgen
Über eine neue art von Strahlen.
Phys.-Med. Ges., Würzburg, **137**, p. 41, (1895)
English translation in Nature ***53****, p. 274*

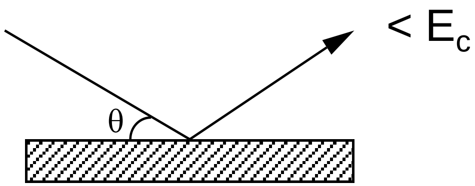
$n=1-\delta-i\beta$ with $\delta, \beta <<< 1$

δ (phase-shift), β (absorption), materials (and energy) dependent optical constants

- Very weak refraction
- Quite high absorption

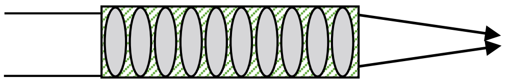
REFLECTION





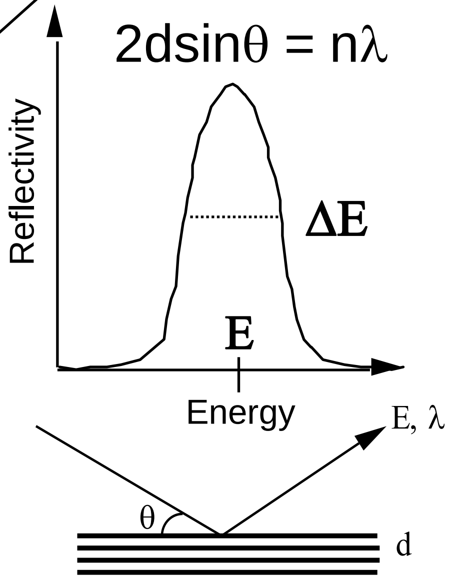
- X-ray mirrors
- Capillaries
- Waveguides

REFRACTION



- Refractive lenses

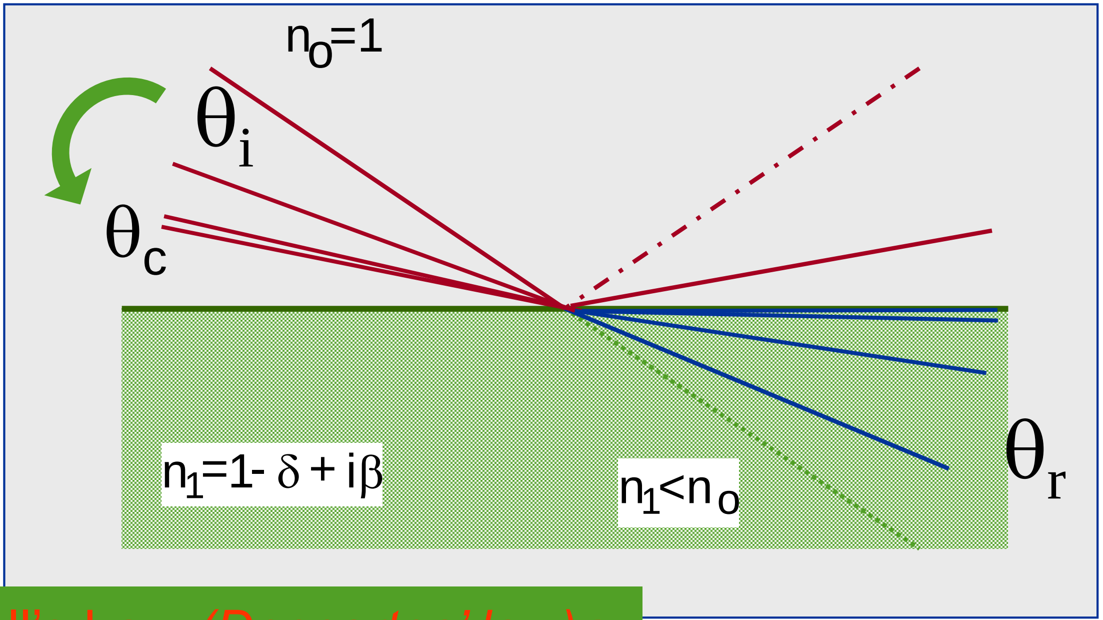
DIFFRACTION



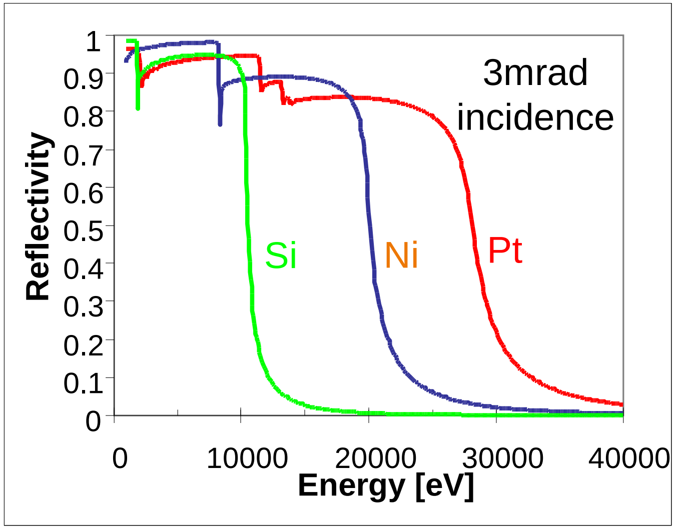
- Crystals & multilayers
- X-ray gratings
- Fresnel zone plates
- Bragg-Fresnel lens

- *Synchrotron radiation*
- *Principles of X-ray optics*
- ***Mirrors***
- *Diffractive optics*
- *X-ray micro-/nano-focusing*
- *Summary*

TOTAL EXTERNAL REFLECTION: X-RAY MIRRORS



‘real’ materials



Snell’s Law *(Descartes’ law)* :

$$n_o \cos\theta_i = n_1 \cos\theta_r$$

for $\delta << 1$ and $\beta << \delta$

$$\boxed{\theta_{c_{[mrad]}} E_{c_{[keV]}} = 19.83\sqrt{\rho_{[g/cm^3]}}}$$

$$\boxed{\theta_c \approx \sqrt{2\delta} \propto \lambda\sqrt{Z}}$$

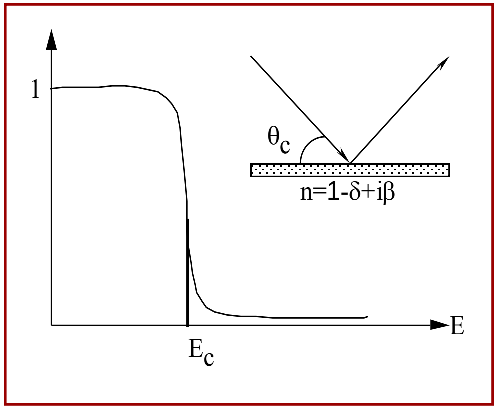
The critical angle for total external reflection.

E=10keV

Gold	9 mrad
Nickel	6 mrad
Silicon	3 mrad

See also: http://www.coe.berkeley.edu/AST/sxreuv/

X-RAY MIRRORS : MAIN FUNCTIONS



- ***Deflection***

  beam steering (different experiments, Bremsstrahlung)

- ***Power filter***

  lower incident power on sensitive optical components

- ***Spectral shaper***

  energy low-pass filter (harmonic rejection)

  mirror+filter = spectral window

- ***Focusing***

  wiggler & bending magnet : spherical, cylindrical, and toroidal mirrors

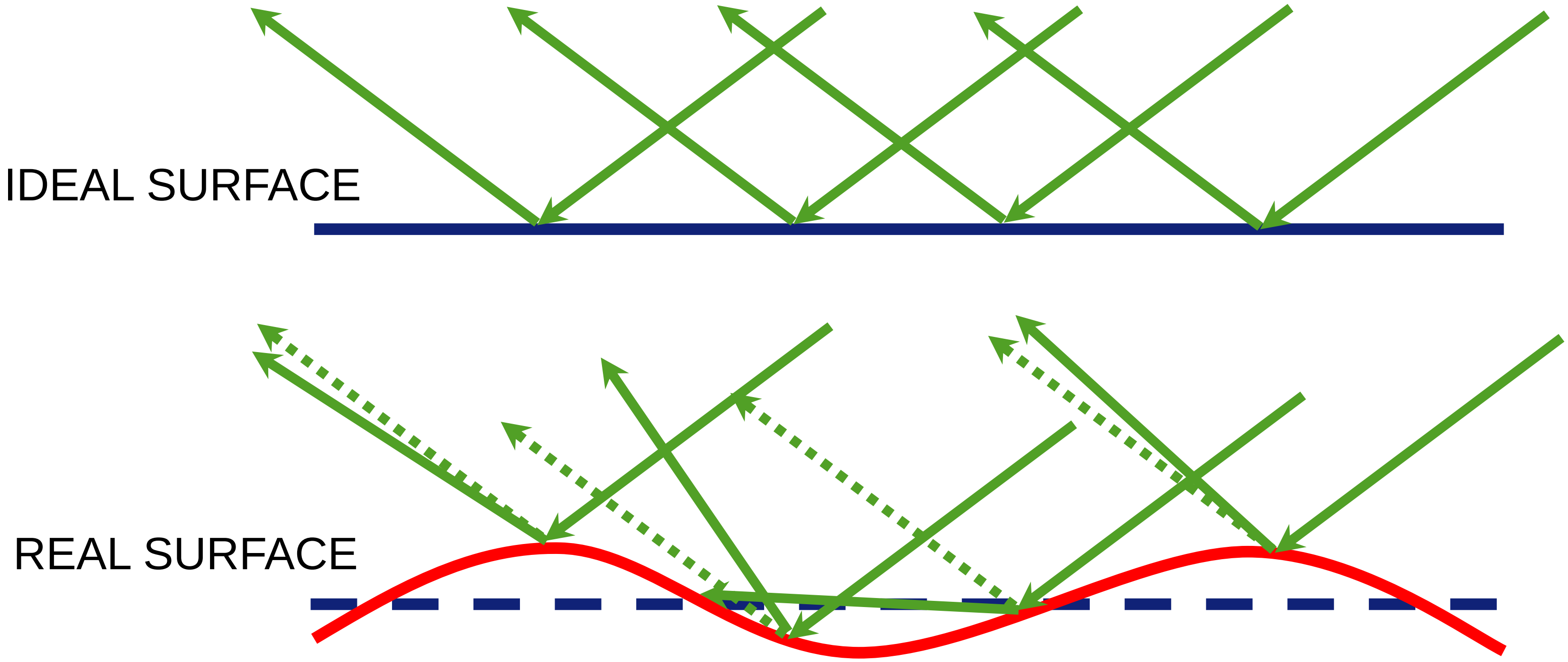
  microscopy & microprobe : source demagnification (ellipsoidal mirror, KB ……)

- ***Collimation***

  parabolic mirror : matching the monochromator angular acceptance with the beam divergence

J. Susini, Optical Engineering, 34(2), (1995)

REFLECTIVE X-RAY OPTICS



Topography of surface typically described by:

1) Slope error (orientation of local surface compared with ideal surface). Distinguish between meridional/tangential (along mirror) and sagittal slope error. Usual units for X-ray mirrors: µradian or arcsecs (1” ≈ 5 µrad)
2) Figure error (height of local surface compared with ideal surface). Usual units for X-ray mirrors: nm.

X-RAY MIRROR QUALITY

•Typical Requirements

micro-roughness < 3Å rms and *slope error* < 1 µrad rms for blur 10% source size

Ultra-precise shaping, figuring and super-polishing

Very accurate and stable mechanical mounting, bending mechanisms, UHV environment

Efficient cooling scheme

Technically limiting parameters

- gravity sag $$\Delta_g \propto \frac{5g}{32}\frac{L^3}{t^2}\frac{\rho}{E}$$
- vibration $$f_o \propto \sqrt{\frac{E}{\rho}}$$
- thermal deformation $$\Delta_t \propto \frac{\alpha}{\kappa} P_s$$
- thermal bending $$F_b \propto E\frac{\alpha}{\kappa} P_t\, w\, t^3$$

→ $\frac{\rho}{E} \searrow \quad E\frac{\alpha}{\kappa} \searrow \quad \frac{\alpha}{\kappa} \searrow$

+

"Polishability"

Most SR Mirrors are manufactured from Si

X-RAY MIRRORS FOR SYNCHROTRON RADIATION

Grazing incidence => rectangular optical aperture

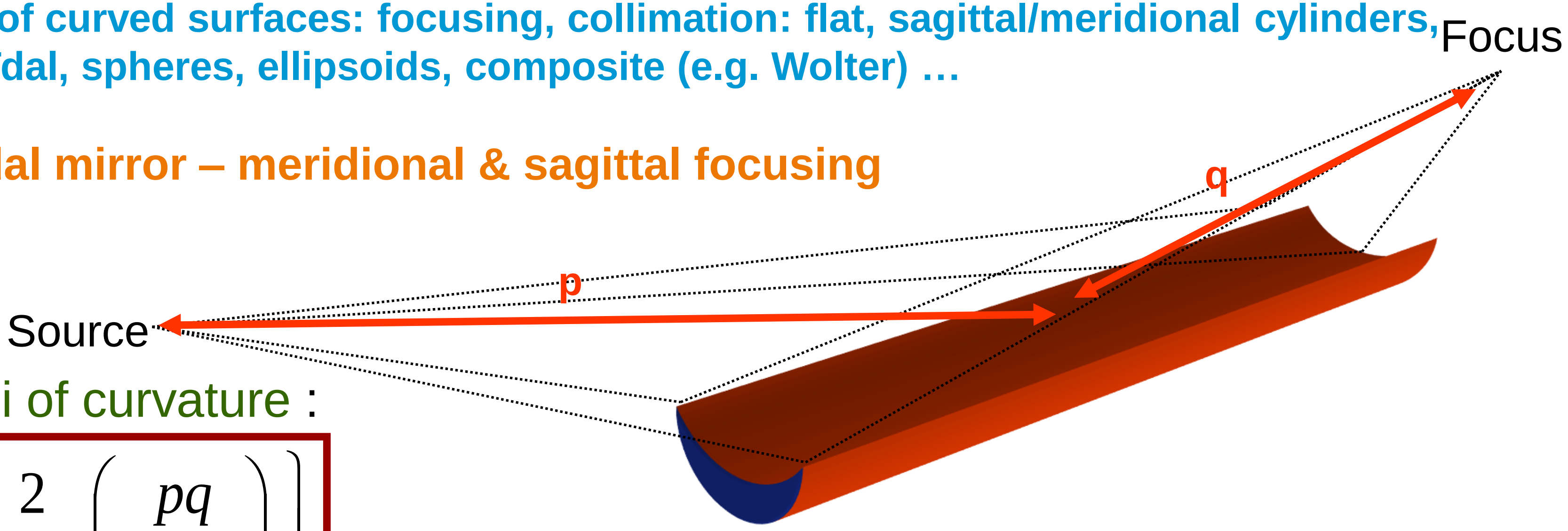
Long mirrors (up to 1.5m): gravity sag

Typically Si with surface coatings (Rh, Pt, …) to tailor X-ray reflectivity, E_c

Intense X-ray beams: thermal deformation, cooling

Use of curved surfaces: focusing, collimation: flat, sagittal/meridional cylinders, toroïdal, spheres, ellipsoids, composite (e.g. Wolter) …

e.g. toroïdal mirror – meridional & sagittal focusing

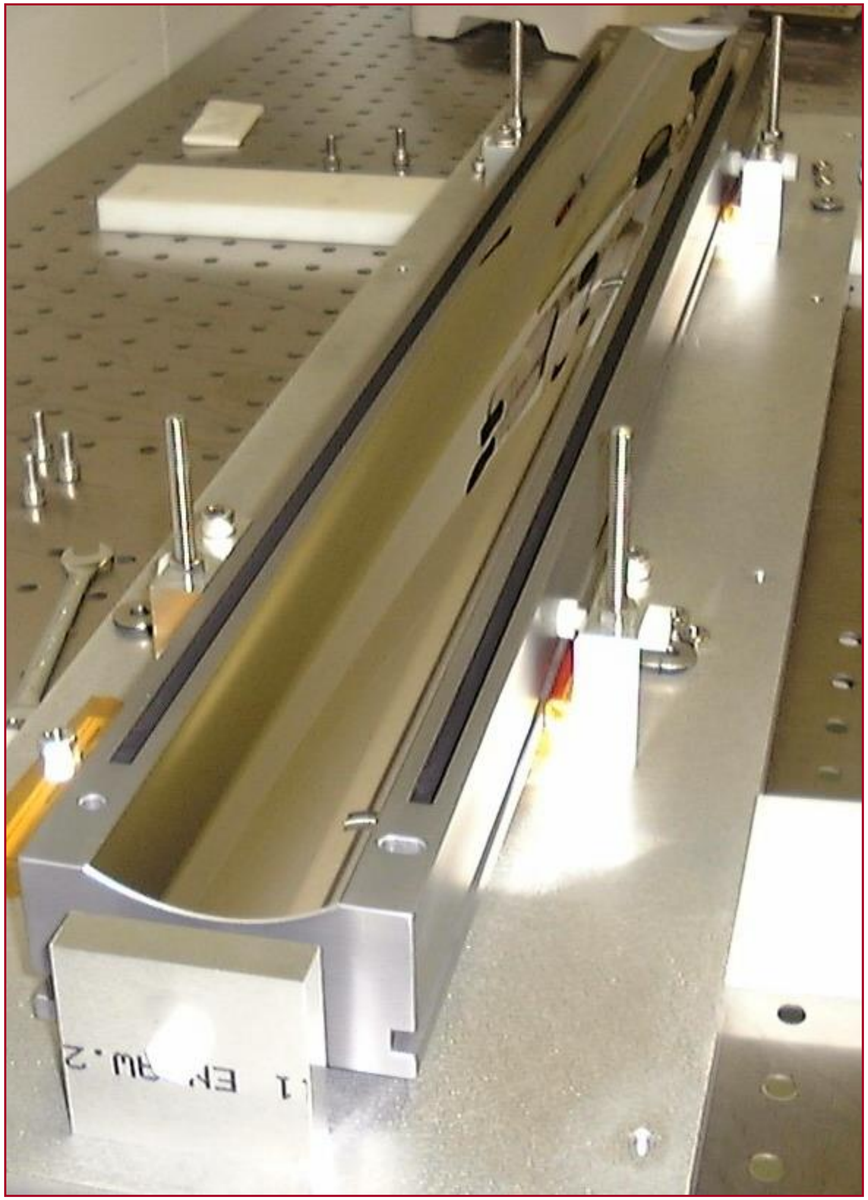


Radii of curvature :

$$\left.\begin{aligned} R_m &= \frac{2}{\sin\theta_i}\left(\frac{pq}{p+q}\right) \\ R_s &= 2\sin\theta_i\left(\frac{pq}{p+q}\right) \end{aligned}\right\} \rightarrow \boxed{R_s \approx R_m\theta^2} \xrightarrow{\theta = 10\text{mrad}} \boxed{\begin{aligned} R_s &\sim mm \\ R_m &\sim km \end{aligned}}$$

May be obtained by bending

TOROIDAL MIRROR (ID09 ESRF)

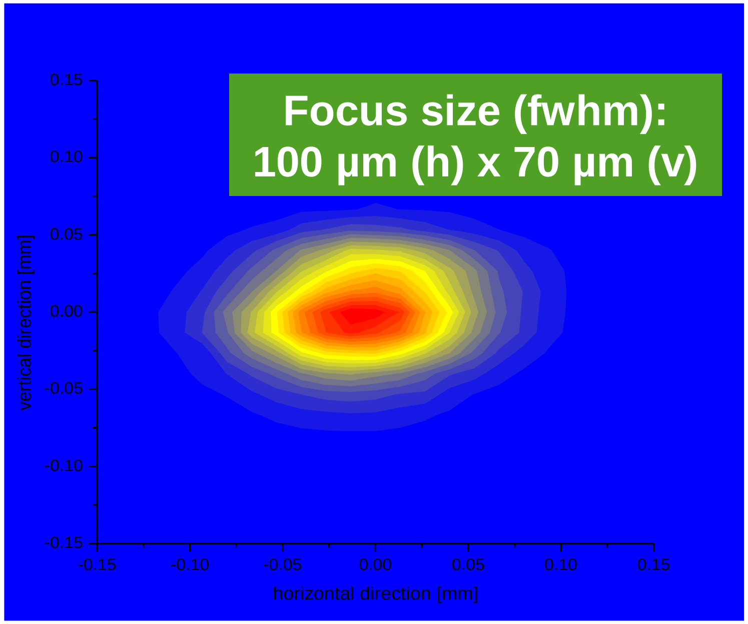


Material-coating: Silicon-Pt
Supplier: SESO (France)
Roughness ≤ 2Å rms
Radii of curvature:

- Sagittal: 71.60 mm
- Meridional: 25 km

Slope error (RMS)

- 0.7 µrad over 450 mm
- 1.0 µrad over 900 mm



Focus size (fwhm):
100 µm (h) x 70 µm (v)

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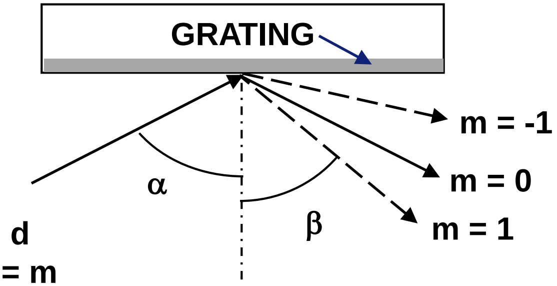
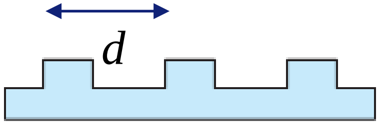
X-RAY REFLECTION GRATINGS: SOFT X-RAYS

surface reflection and diffraction to disperse X-rays according to energy:

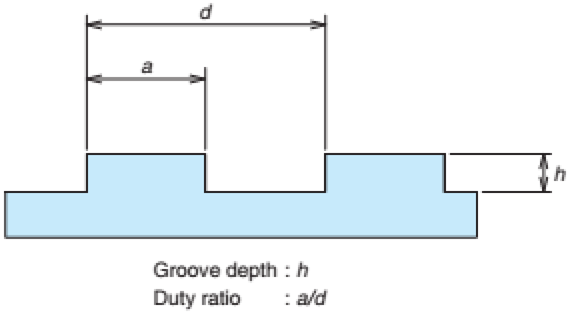


Grating period = d
Diffracted order = m



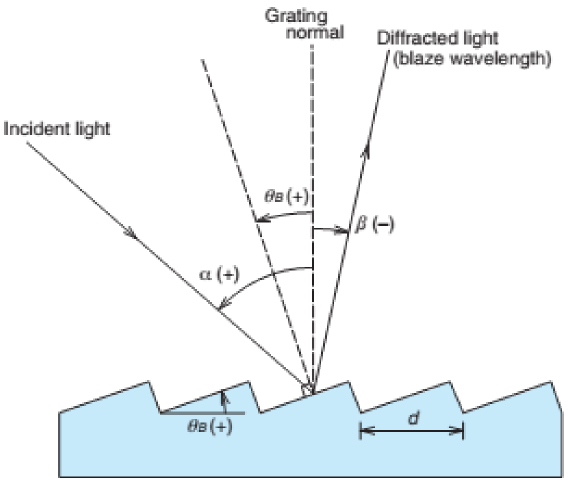
$$d(\sin\alpha + \sin\beta) = m\lambda$$

- **surface grating structures - mechanical ruling or masked etching**
- **monochromators or energy analysers**
- **Grating line densities (lines/mm) either constant or variable (VLS – variable line spacing) - latter have a focusing effect**
- **Substrates flat, spherical, (toroïdal)**
- **Groove profile important for efficiency**



Laminar: rectangular grooves

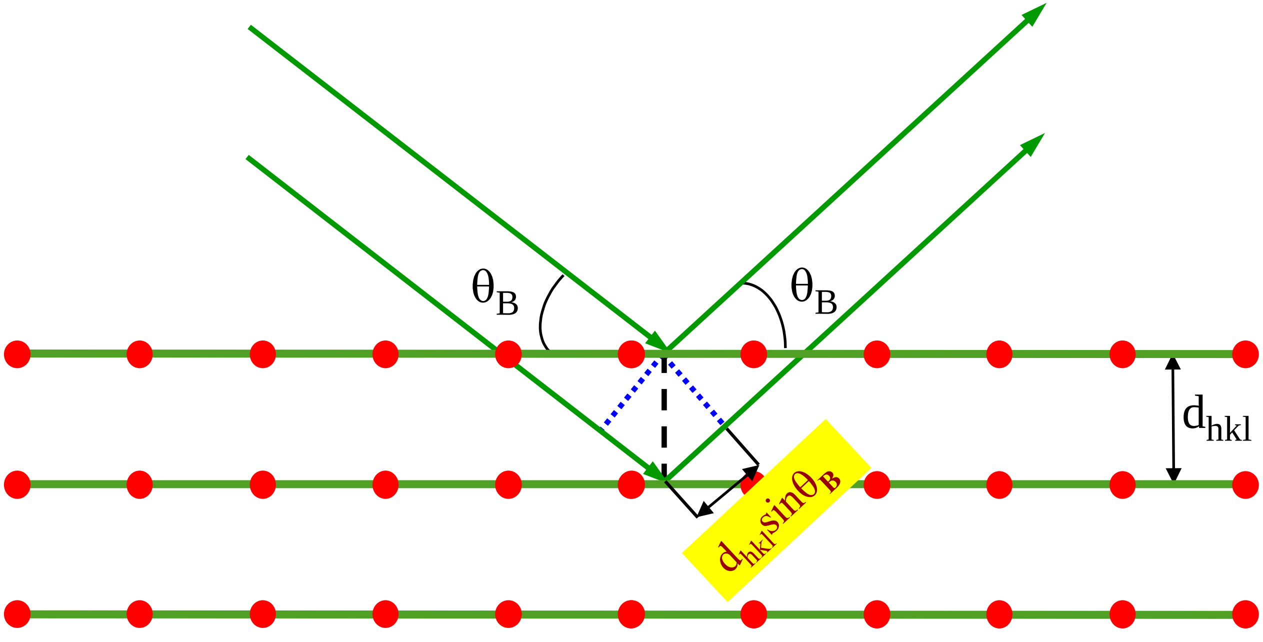
Courtesy:Shimadzu



Blazed: saw-tooth grooves

X-RAY DIFFRACTION: HARD X-RAYS

X-ray diffraction results from elastic scattering of X-rays from structures with long-range order. For X-ray optics generally concerned with highly perfect single crystals (typically Silicon) *cf* neutron mosaic crystals



Bragg equation: $2d_{hkl}\sin\theta_B = n\lambda$

- Incident X-rays are “reflected” at atomic planes in the crystal lattice (bulk effect)
- Path difference of the rays $2d_{hkl}\sin\theta_B$
- Constructive interference if the path difference amounts to λ ($n\lambda$?)
- Use of curved, elastically deformed crystals allows focusing

CRYSTAL MONOCHROMATORS

Energy, E, determined by incidence angle, θ_B, of X-ray beam onto crystal planes according to Bragg equation:

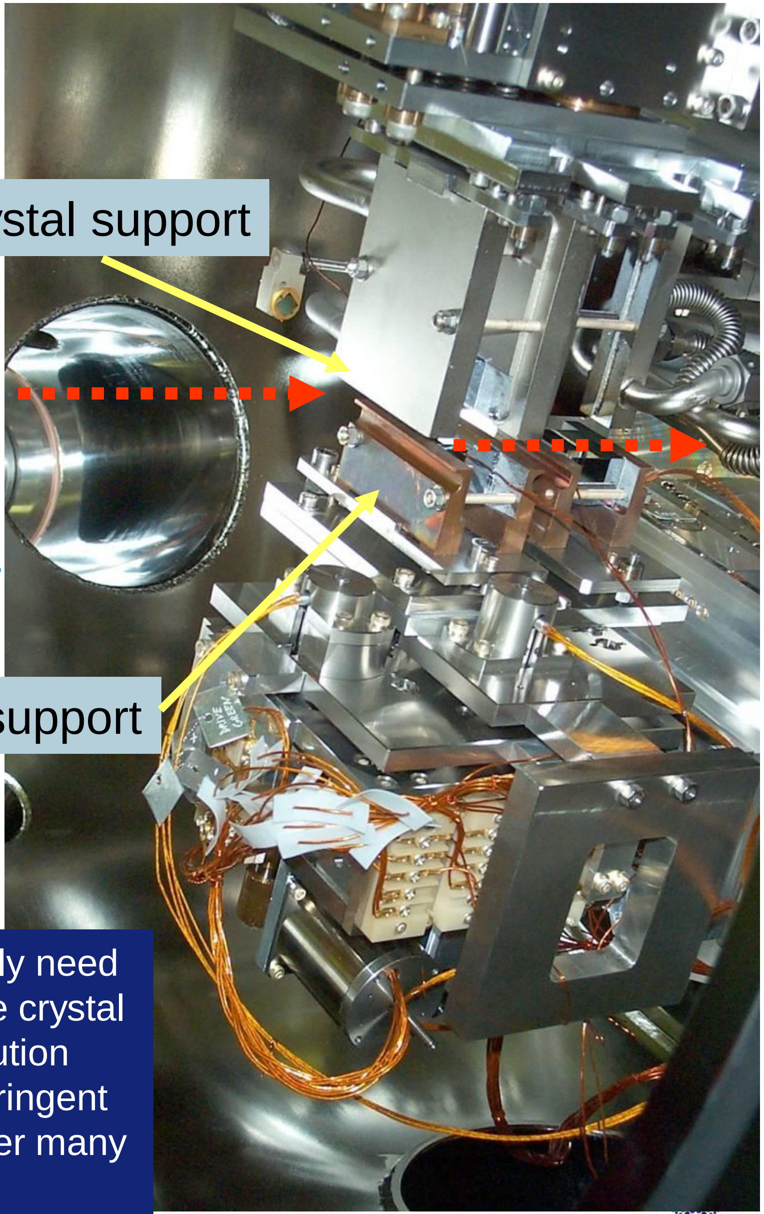
$$E=\frac{hc}{\lambda}=\frac{hc}{2d_{hkl}\sin\theta_B}$$

c = light velocity
h = Plancks constant

Energy resolution depends upon type of crystal and reflecting planes used (described by angular Darwin width ω_s) & divergence of incident beam,

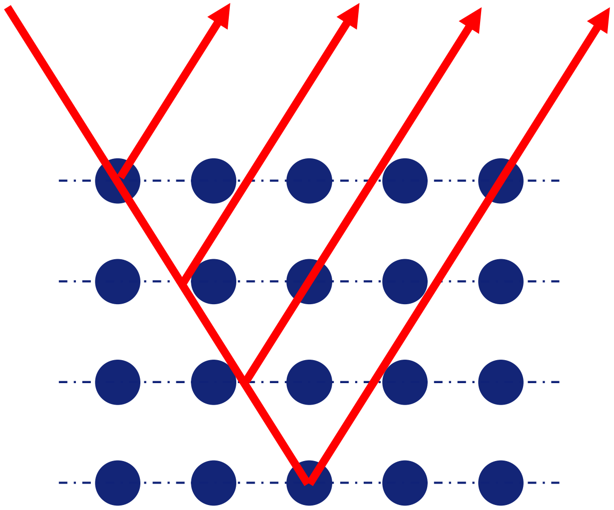
$$\frac{\Delta E}{E}=\frac{\Delta\lambda}{\lambda}=\sqrt{\omega_s{}^2+\psi_0{}^2}\cot\theta_B$$

e.g. **Si 111 reflexion**,
d_{hkl}= 3.1355Å
ω_s = 10.7 µrad (@ 8keV):
θ_B = 14°
with a parallel incident beam:
$\Delta E/E = 1.4.10^{-4}$, ΔE=1.1eV

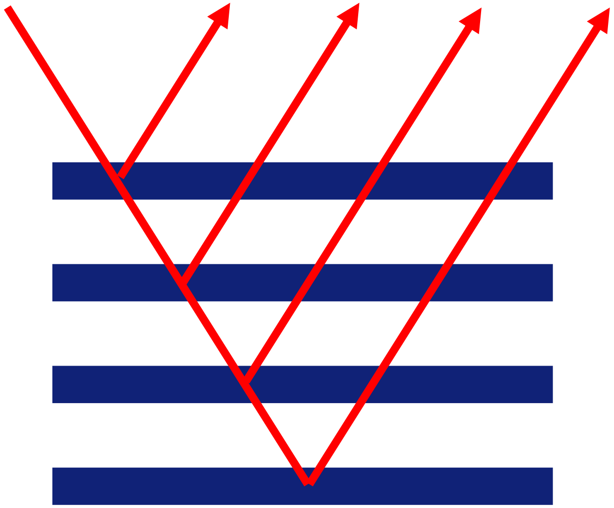


Monochromators typically need to be able to position the crystal planes with <µrad resolution over ~90° particularly stringent demands on stability over many hours:

X-RAY MULTILAYERS

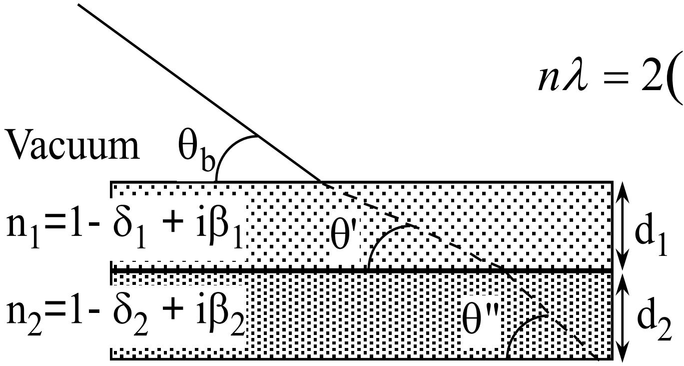


Crystal
(3-dimensional)



Multilayer (Synthetic crystal)
(1-dimensional)

X- region : *inside the multilayer, as a result of refraction, modified Bragg's law needed*

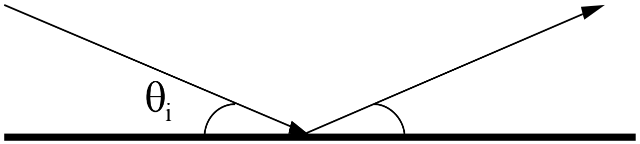


$$n\lambda = 2(d_1+d_2)\sqrt{1-\frac{\bar{\delta}}{\sin^2\theta_b}}\,\sin\theta_b$$

$$\begin{cases} \gamma = d_1/(d_1+d_2) \\ \bar{\delta} = \gamma\delta_1+(1-\gamma)\delta_2 \\ \bar{\beta} = \gamma\beta_1+(1-\gamma)\beta_2 \\ P(\theta_b)=1(s) \quad or \quad \cos(2\theta_b)(p) \end{cases}$$

X-RAY MULTILAYERS

high reflectivity x-ray mirrors…
or 'synthetic crystals'



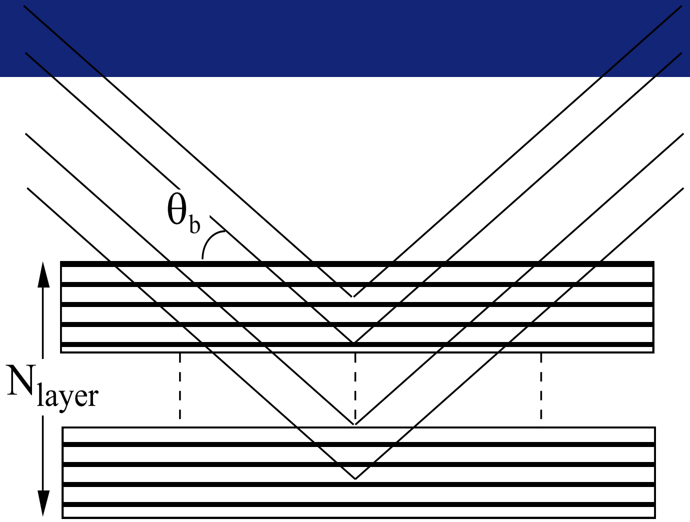
single boundary

For $\theta_i > \theta_c$

$E_r = rE_0$ where E_r, E_0 are reflected and incident wave amplitudes, r is the amplitude reflectivity

$r < 10^{-2}$ and $R = |r|^2 < 10^{-4}$

$$\boxed{R \propto \frac{1}{\sin^4 \theta_i}}$$



multiple boundaries

ideally $|r| \times N_{layer} \Rightarrow R \to 1$

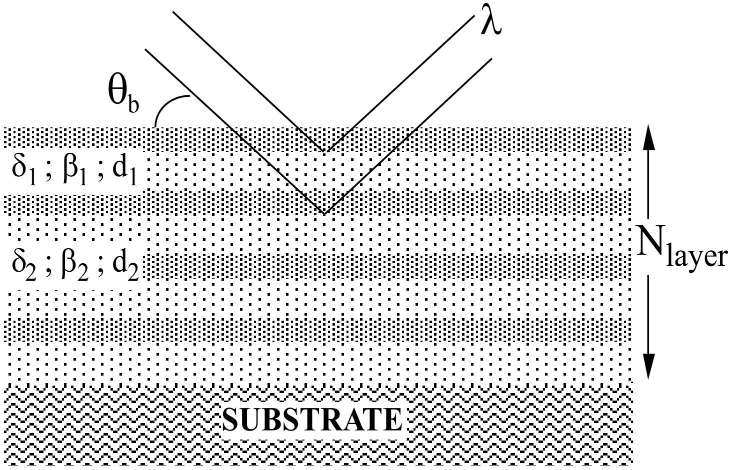
$n_l = 1 - \delta_1 + i\beta_1$ and $n_2 = 1 - \delta_2 + i\beta_2$

$$\boxed{R \propto \frac{\Delta\delta^2 + \Delta\beta^2}{4} \frac{N_{layer}^2}{\sin^4 \theta_b}}$$

X-RAY MULTILAYERS : MAIN FEATURES

1 - Materials : *highest contrast*

$$R \propto \frac{\Delta\delta^2 + \Delta\beta^2}{4} \frac{1}{\sin^4 \theta_b}$$



2 - Gamma parameter : *order suppression*

$$\gamma = d_1 / (d_1 + d_2)$$

$\gamma = 1/n \Rightarrow$ ~~order n~~

3 - Number of layers : *energy resolution*

$$FWHM = \frac{0.888\,\lambda}{N_{layer}\, d \cos \theta_b} \Rightarrow \frac{\Delta E}{E} = \frac{1.776}{N_{layer}}$$

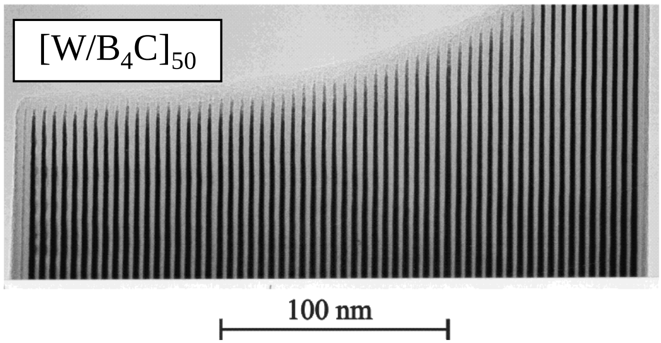
Typically $N_{layer/max} \sim 100$

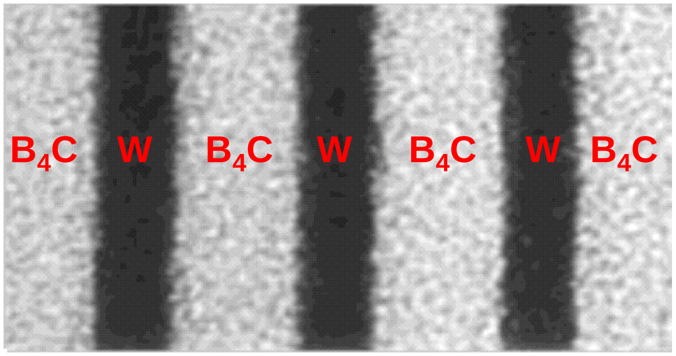
$$\Rightarrow \frac{\Delta E}{E} \sim 10^{-2}$$

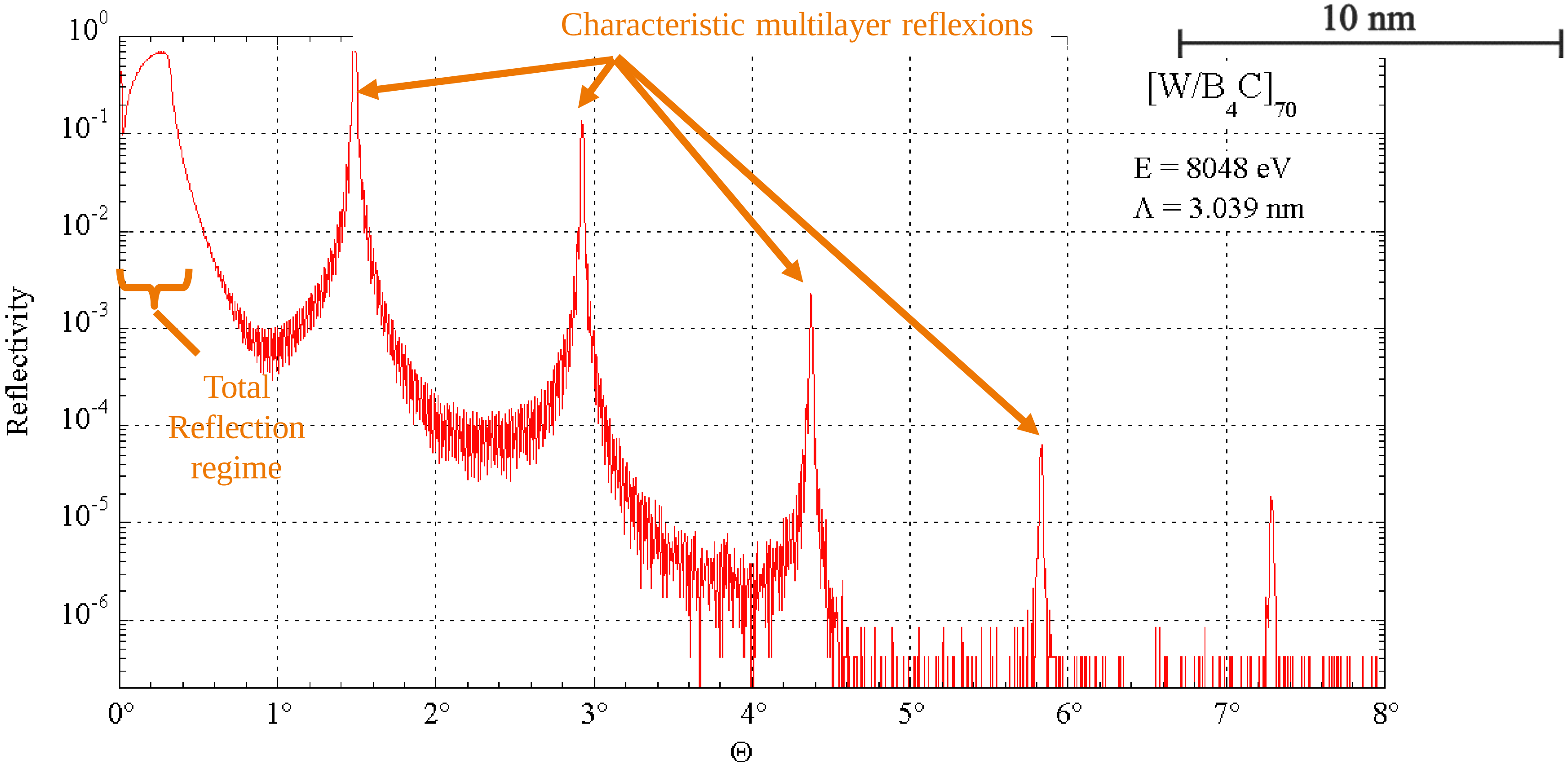
N_{layer} limited by : $N_{\max} = \dfrac{\sin^2 \theta_b}{2\pi\beta} = \dfrac{2\sin^2 \theta_b}{\lambda\mu}$

X-RAY MULTILAYER CHARACTERIZATION

Typical X-ray reflectivity scan of a multilayer







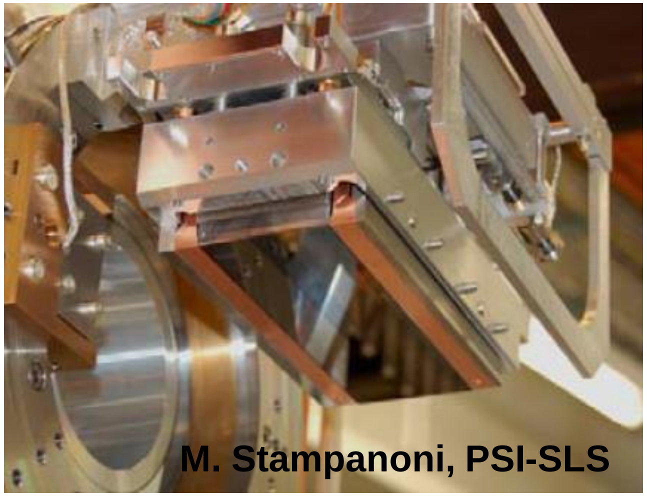
Characteristic multilayer reflexions

Total Reflection regime

X-RAY MULTILAYERS : MAIN APPLICATIONS

- **Power filter**
  - θ_b multilayer << θ_b crystal ⟶ crystal length << multilayer length

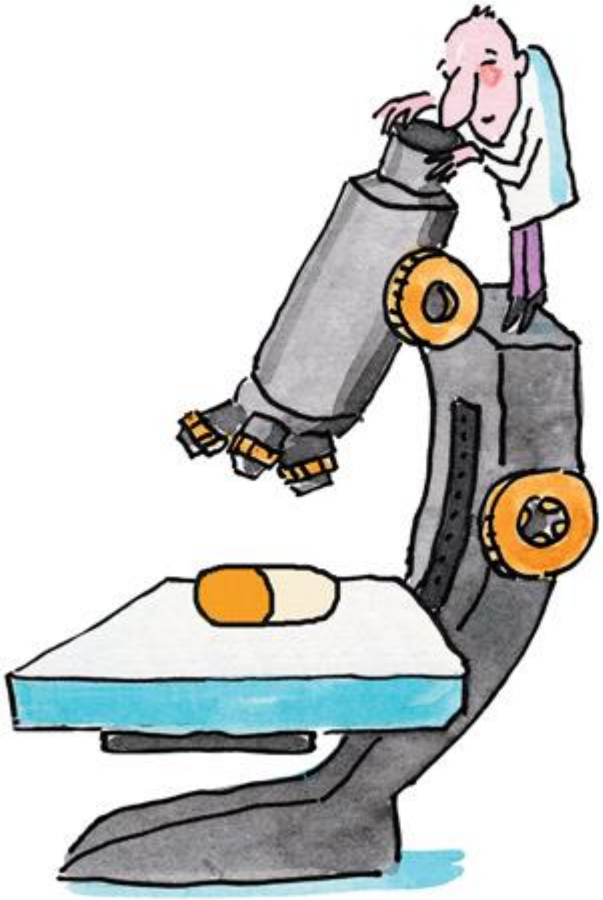
  → *lower power density*


M. Stampanoni, PSI-SLS

- **Wide band-pass monochromator - analyser**
  - $5\ 10^{-3} < \Delta E/E < 5\ 10^{-1}$
- **Harmonic rejection**
  - $\gamma = 1/n$
- **Monochromator for soft(er) X-rays**
  - d-spacing >2nm cf 3-4Å for radiation hard crystals
- **Focussing**
  - θ_b multilayer >> θ_c mirror ⟶ multilayer length << mirror length

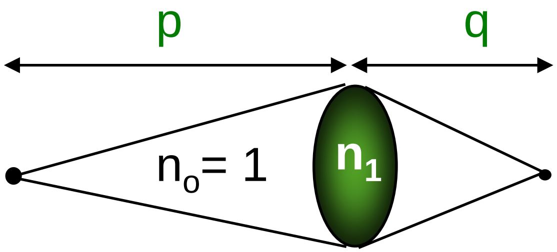
  → *lower spherical aberrations* (~L^2), *increased numerical aperture*

- **Super-mirror (depth graded ML) : extending total reflection**
  - R > 40% at 60keV : not possible with a mirror



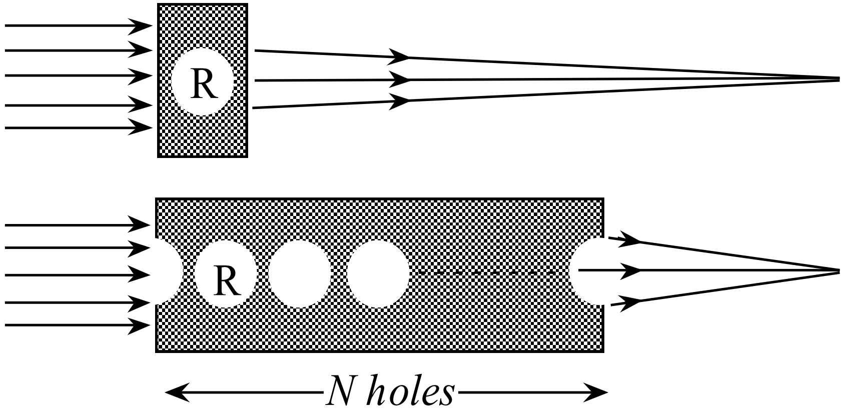
- *Synchrotron radiation*
- *Principles of X-ray optics*
- *Mirrors*
- *Diffractive optics*
- *X-ray micro-/nano-focusing*
- *Summary*

COMPOUND REFRACTIVE LENS



Gaussian lens equation: $\frac{1}{f} = \frac{2(n_1 - 1)}{R}$

Thin lens equation : $\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$



$$\frac{1}{f} = \frac{2\delta}{R}$$

$$\boxed{\frac{1}{f} = N\frac{2\delta}{R}}$$

X-rays : $n = 1 - \delta + i\beta$

$n_1 < 1$: concave lens

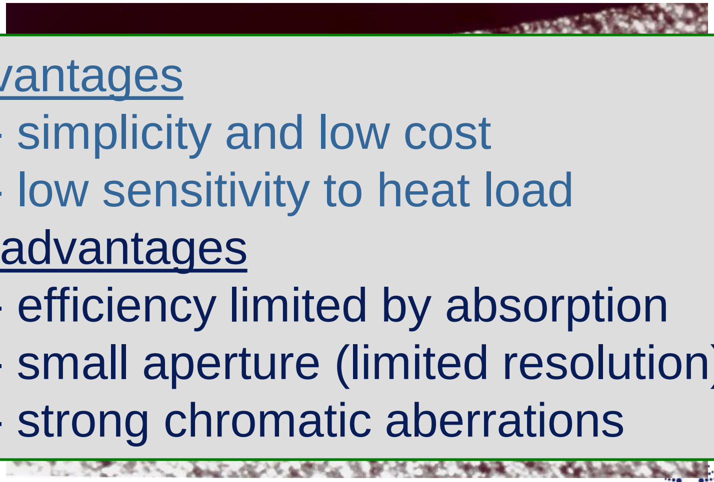
Typically Be or Al lenses –e.g.

Aluminium @ 10keV $\delta = 5.5\ 10^{-6}$

1 hole 100 µm radius : f = 9 m

15 holes 100 µm radius: f = 60 cm

A. Snigirev et al. Nature, 384 (1996)



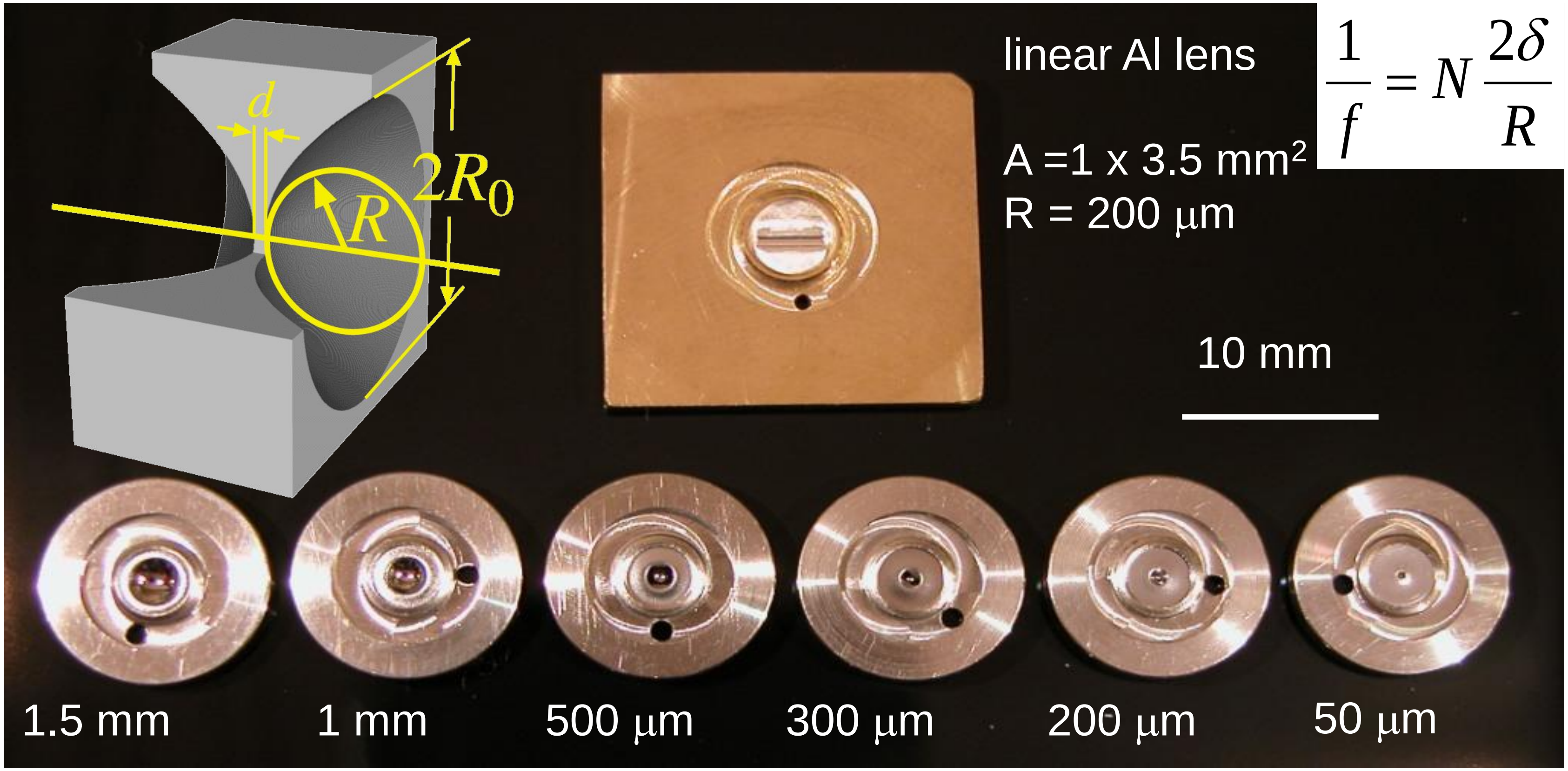
Advantages
- simplicity and low cost
- low sensitivity to heat load

Disadvantages
- efficiency limited by absorption
- small aperture (limited resolution)
- strong chromatic aberrations

PARABOLOIDAL & PARABOLIC CYLINDER X-RAY LENSES

- Parabol-ic/oidal profile ⇒ no spherical aberration
- Be ~2-40 keV ⇒ absorption↓
- Al ~40-80 keV
- Ni ~80-150 keV

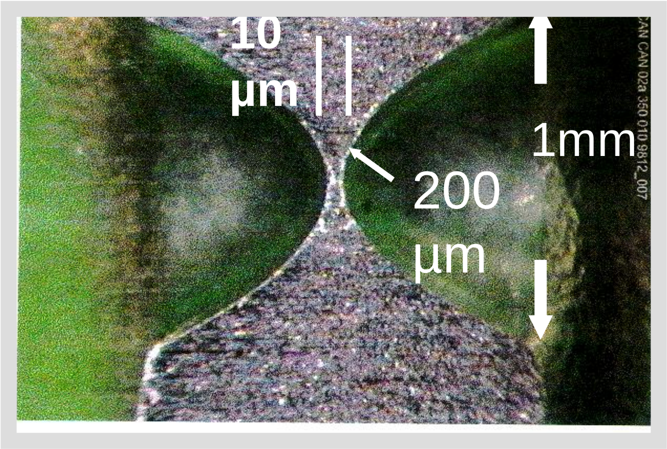
Typical parameters :
R = 50 to 1500 µm
$2R_0$ = 0.45 to 2.5 mm
d < 30µm



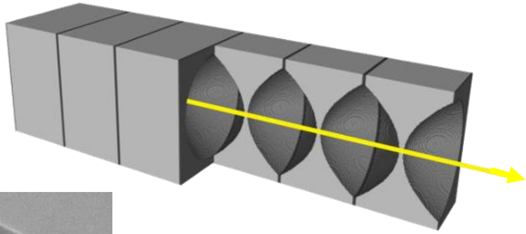
$$\frac{1}{f} = N\frac{2\delta}{R}$$

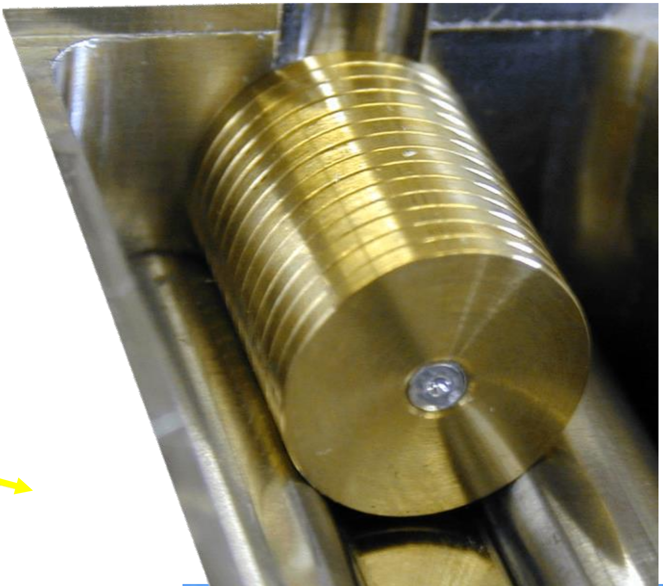
Be / Al parabolic lenses (Aachen) courtesy Prof. B. Lengeler

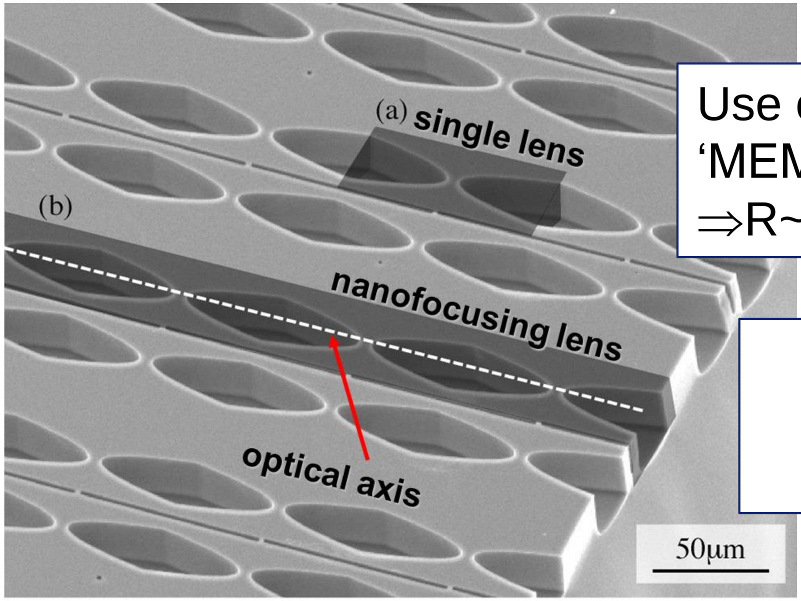
PARABOLIC REFRACTIVE LENSES



Materials:
low Z, high density
Al, Be, B, Si, …

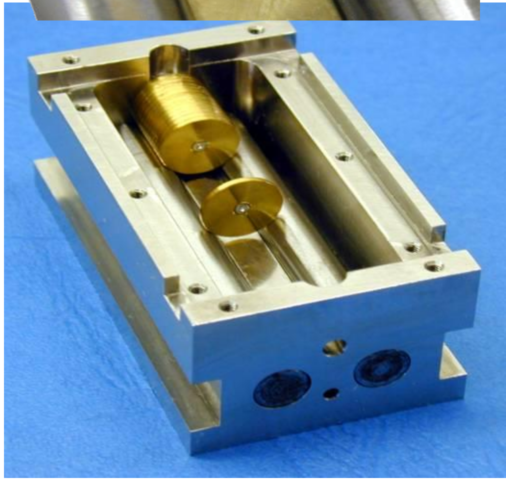






Use of planar ‘MEMS’ technologies
⇒R~2µm

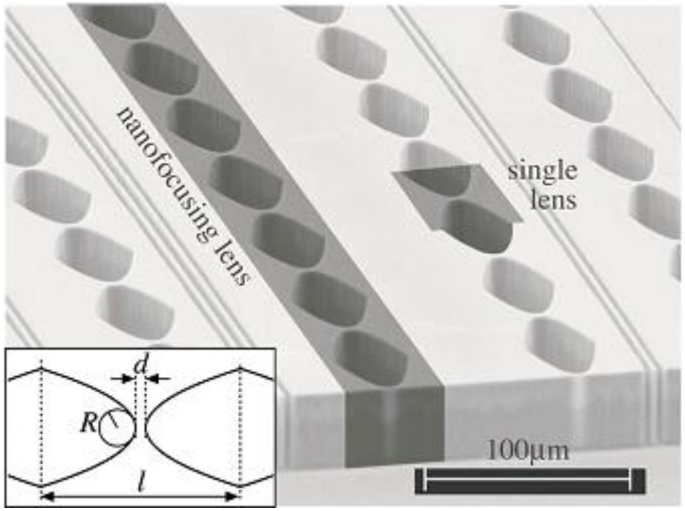
Si lens (e-beam lithography & deep trench RIE

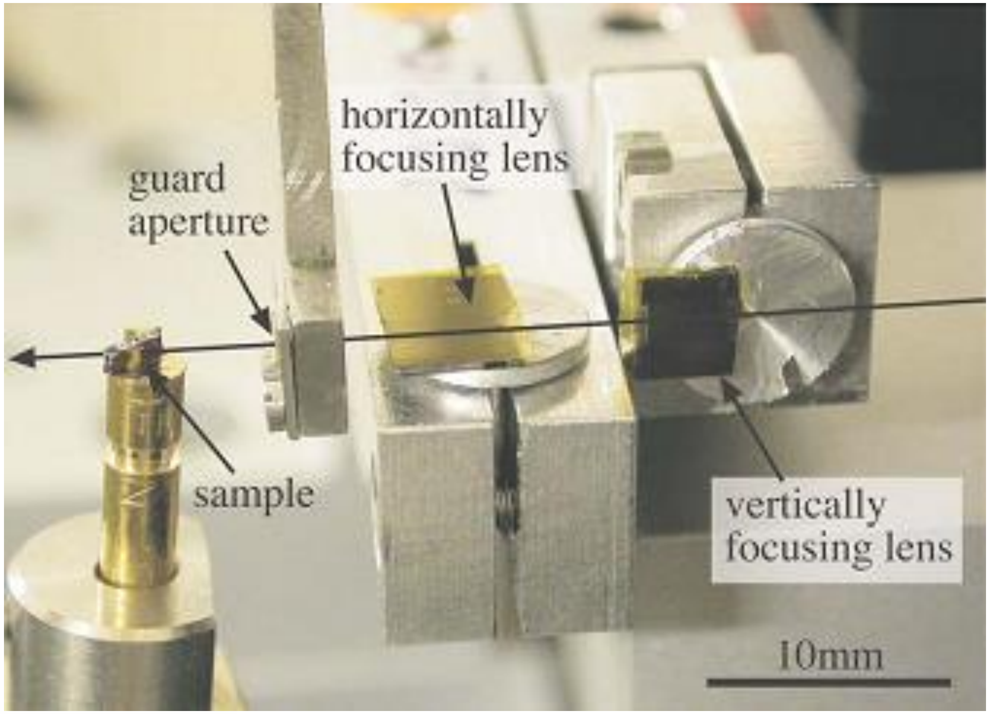


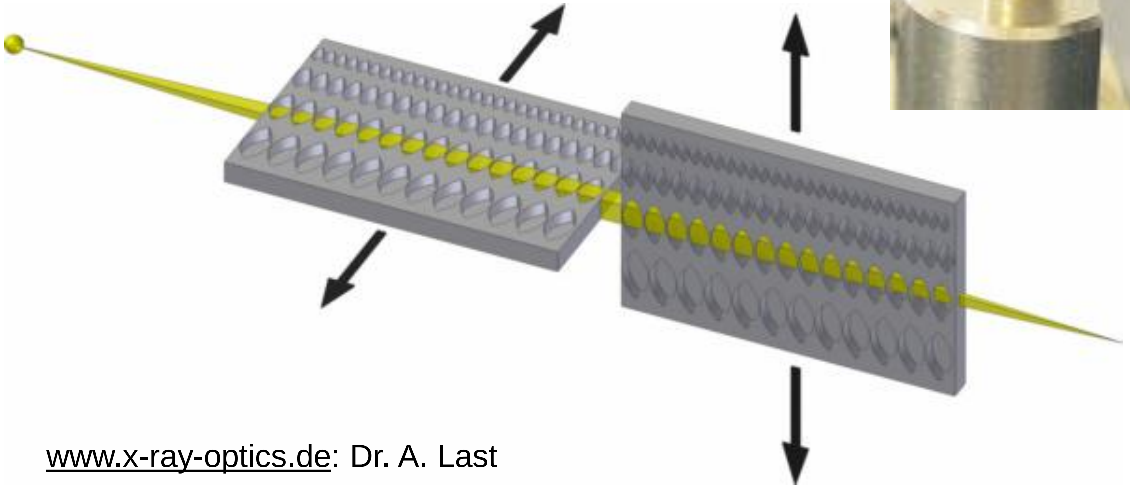
B. Lengeler, C. Schroer, M. Richwin,
RWTH, Aachen, Germany

C. Schroer *et al*, *Applied Physics Letters*, 82(9), 2003

2D FOCUSING WITH PLANAR REFRACTIVE LENSES



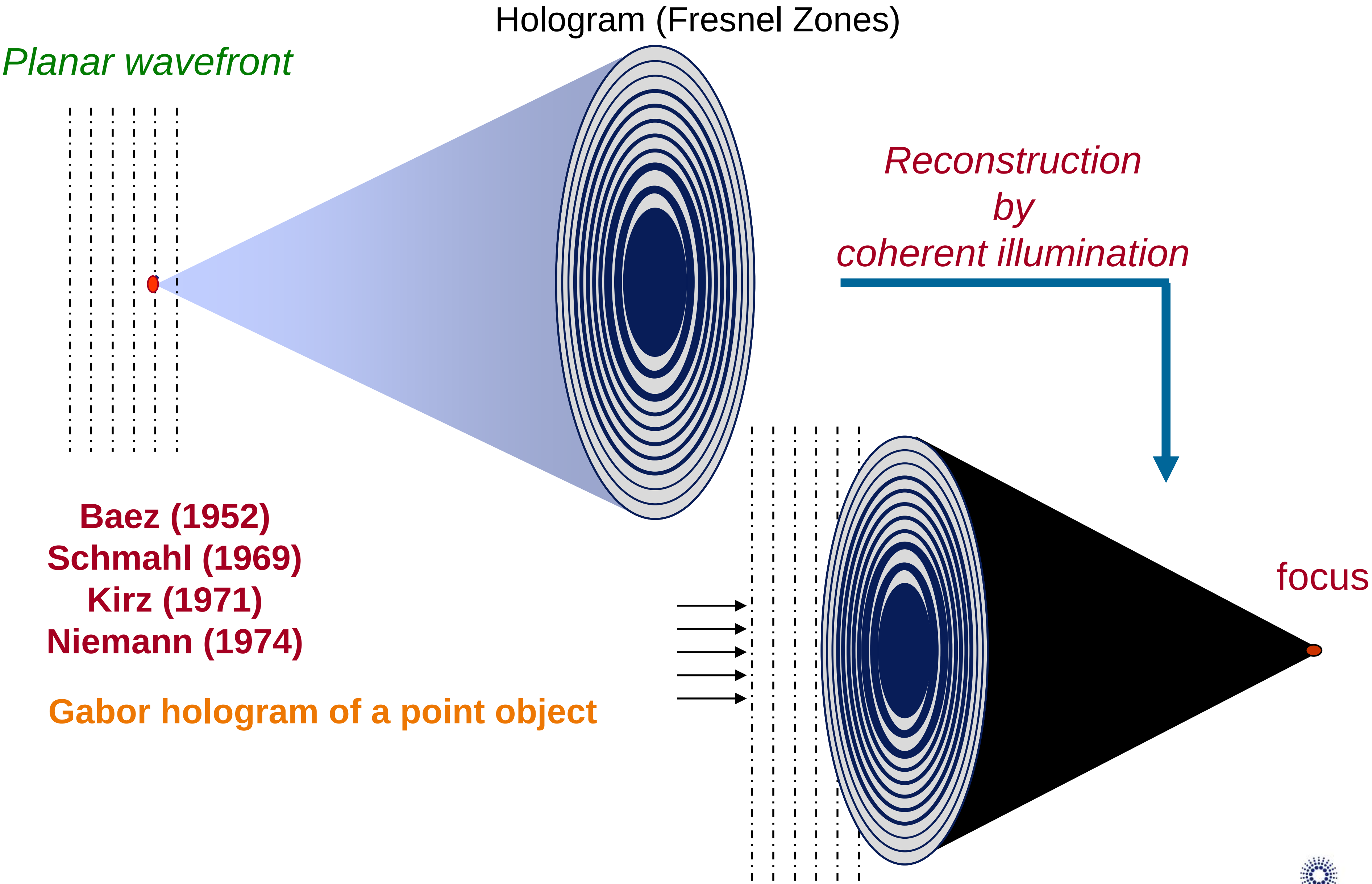




www.x-ray-optics.de: Dr. A. Last

47 x 55 nm^2 beam focus @21keV
Schroer et al.,Appl. Phys. Lett. 87, 124103 (2005)
Aperture limited by absorption

FRESNEL ZONE PLATES

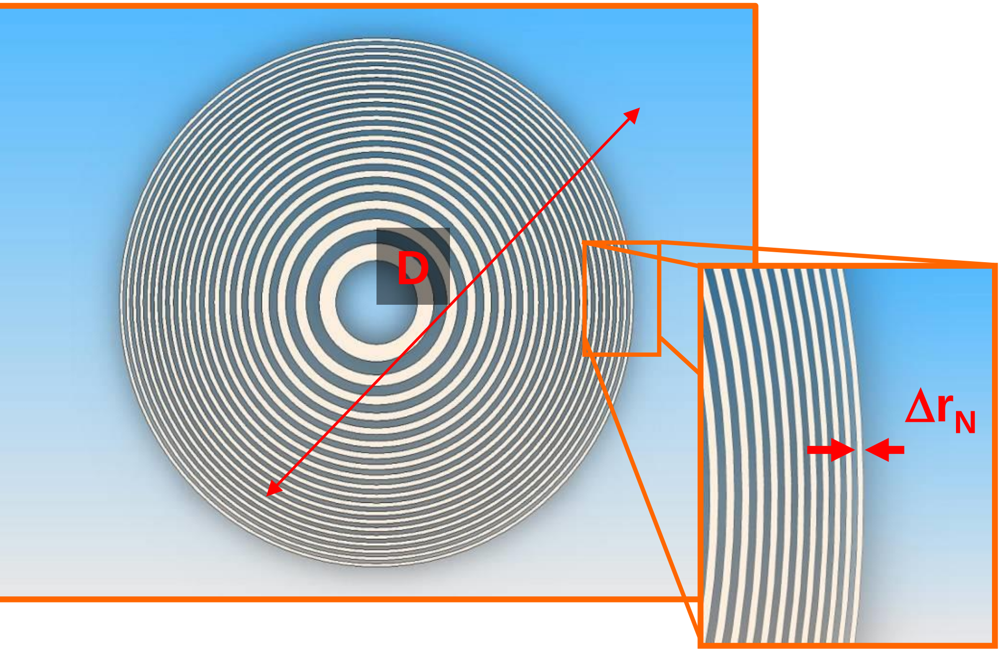


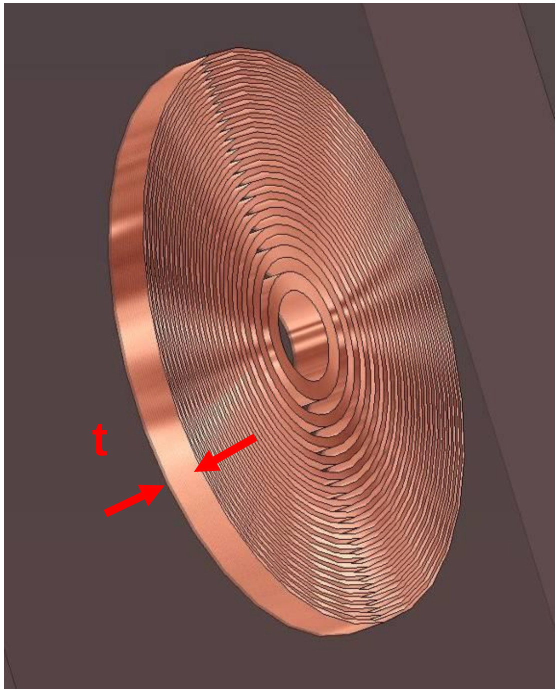
Baez (1952)
Schmahl (1969)
Kirz (1971)
Niemann (1974)

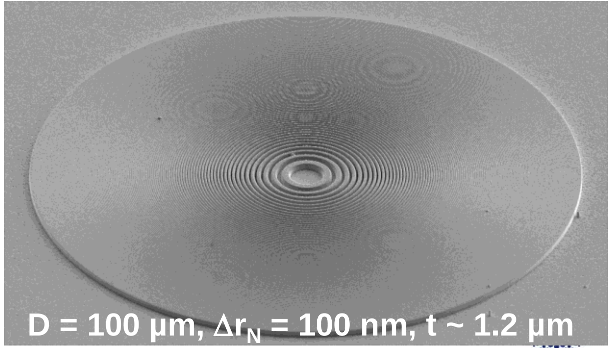
Gabor hologram of a point object

FRESNEL ZONE PLATES

Diffractive X-ray Lenses: Circular transmissive diffraction gratings with radially decreasing line width giving focusing effect







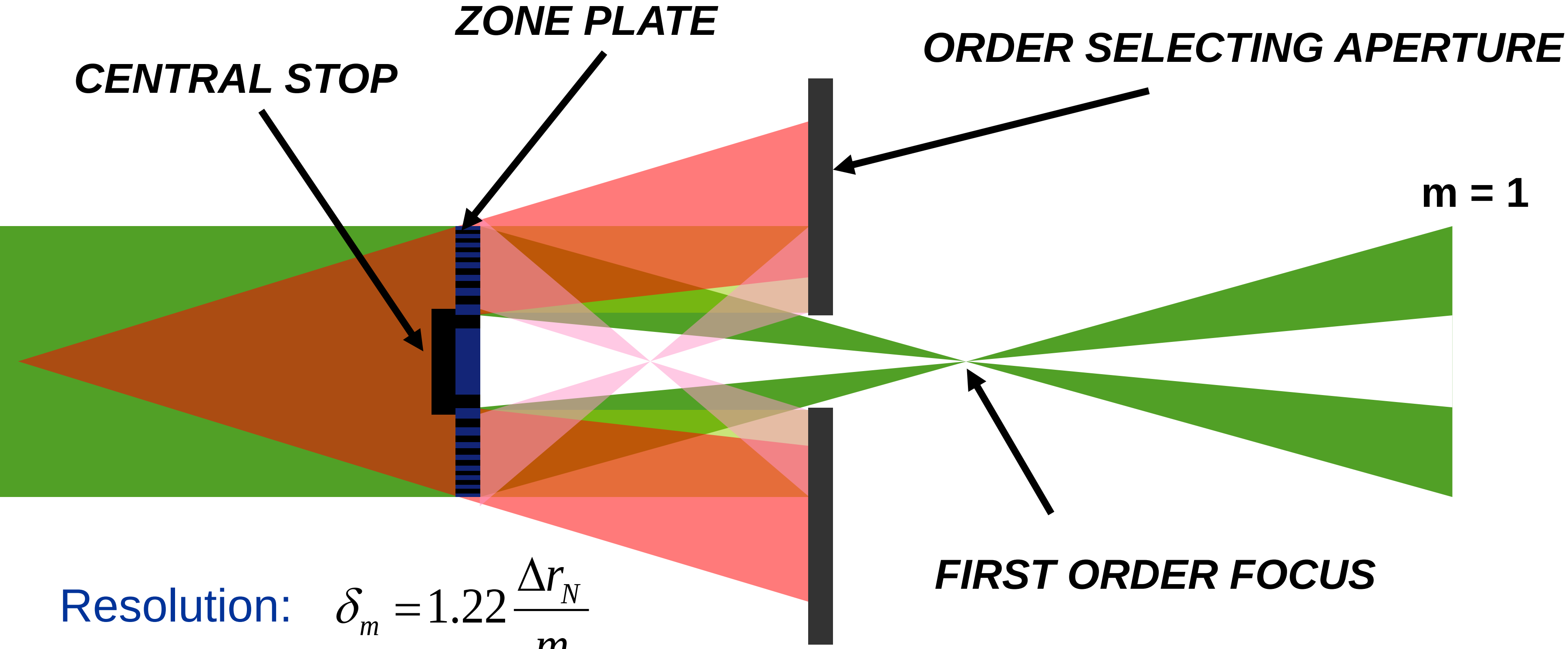
D = 100 µm, Δr_N = 100 nm, t ~ 1.2 µm

Alternate ‘zones’ modify phase/amplitude of incident wavefront: for material of thickness, t, wavelength, λ, refractive index 1-δ-iβ, phase shift, Δϕ, is:

$$\Delta\phi = \frac{2\pi\delta t}{\lambda}$$

FOCUSING BEHAVIOUR OF FRESNEL ZONE PLATE LENSES

Rejection of unwanted diffraction orders requires central stop & OSA



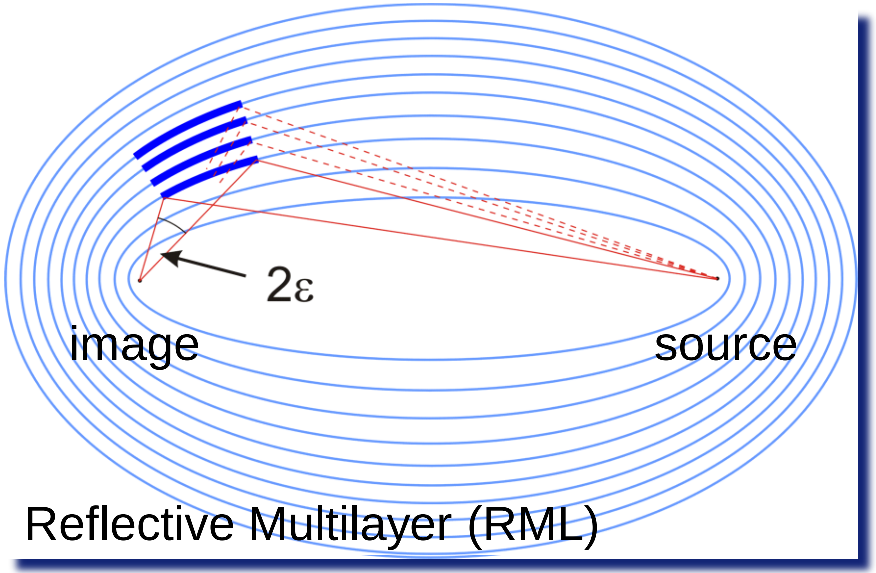
Resolution: $\delta_m = 1.22 \frac{\Delta r_N}{m}$

Focal length: $f_m = \frac{D \, \Delta r_N}{m \, \lambda}$

Depth of focus: $DOF = \pm \frac{2 \Delta r_N^{\,2}}{m \, \lambda}$

- best zone plates Δr_N ~10nm
- zone aspect ratio limits efficiency (often just a few %): better adapted to lower energies <10keV

FOCUSING WITH ELLIPTICAL MIRROR SURFACES



Reflective Multilayer (RML)

Diffraction limited focusing:

$$D_{diff} = \frac{0.44 \cdot \lambda}{NA} = \frac{0.44 \cdot \lambda}{\varepsilon}$$

$$\varepsilon_{\max} \approx \frac{\theta_c}{4}, \quad D_{diff}(TRM) \approx \frac{1.76 \cdot \lambda}{\sqrt{2 \cdot \delta}}$$

Pt mirror:
25 nm

$$D_{diff}(RML) \approx \frac{0.88}{1/\Lambda_2 - 1/\Lambda_1}$$

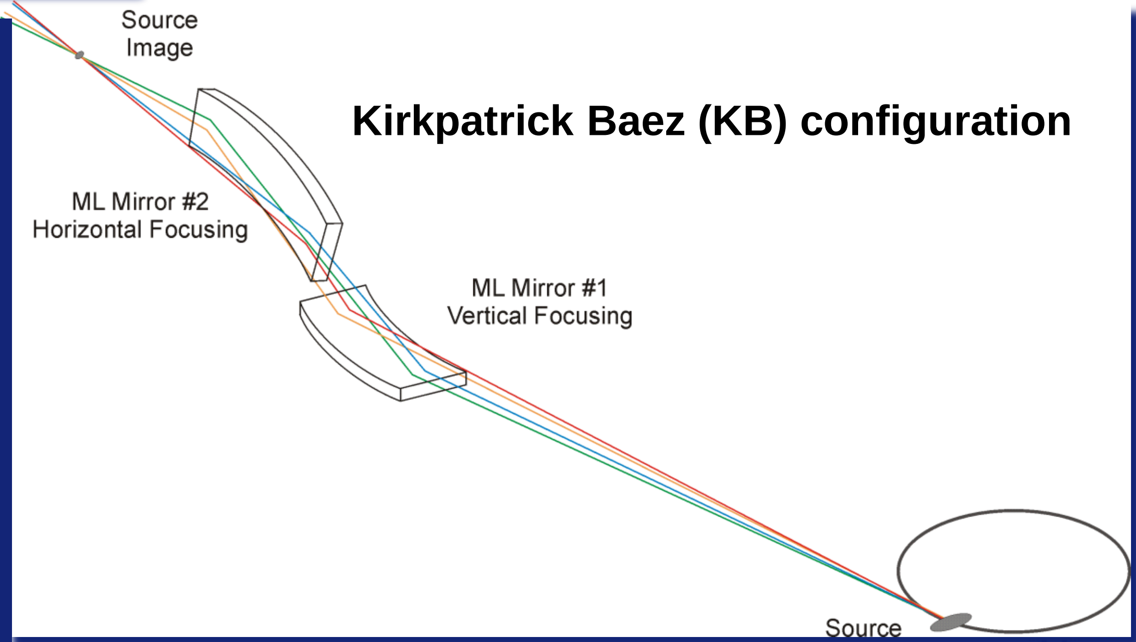
7 nm focus
Mimura et al,(2010)

Use of MLs => increased aperture →flux!

Elliptical Mirrors for micro- & nano-focusing

- Dynamic figure
  - Adapt figure to focusing requirements (f, λ, multilayers)
  - Increased figure errors
- Static figure
  - Fixed focusing configuration
  - Better figure – less flexible operation

Kirkpatrick Baez (KB) configuration



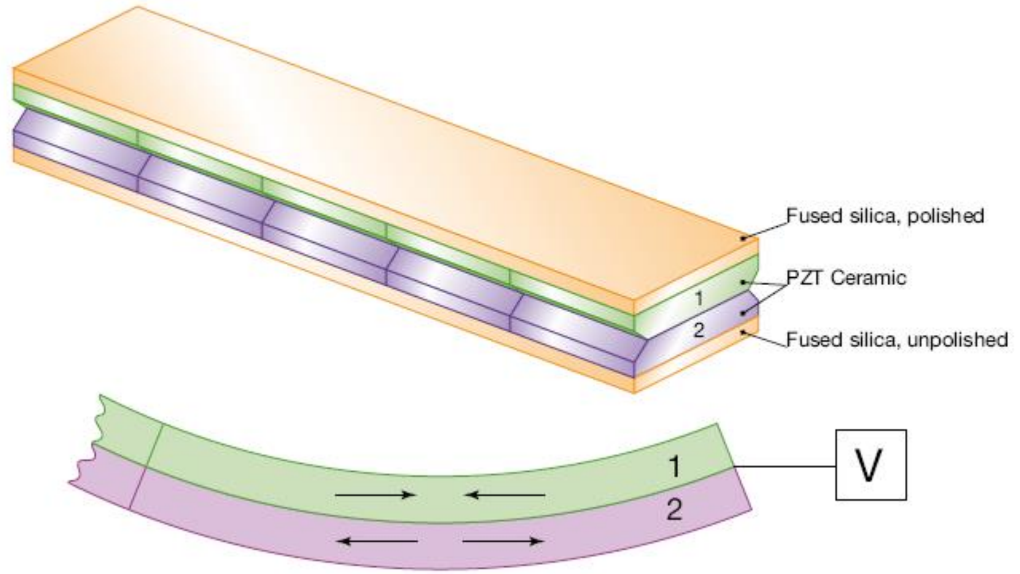
DYNAMICALLY BENT MIRRORS

2 major classes:

- **Piezoelectric bimorph systems**
- **Mechanically actuated systems**

Extension of these technologies – increase number of actuators to correct local figure errors – active optics (several projects)

2 independent bending moments: Elliptical Figure



Principle of Bimorph Mirror (from FMB-Oxford)

2 independent actuators

ESRF mirror bender based on monolithic flexure hinge technology

ESRF NANOFOCUSING KB SYSTEM: ID16B

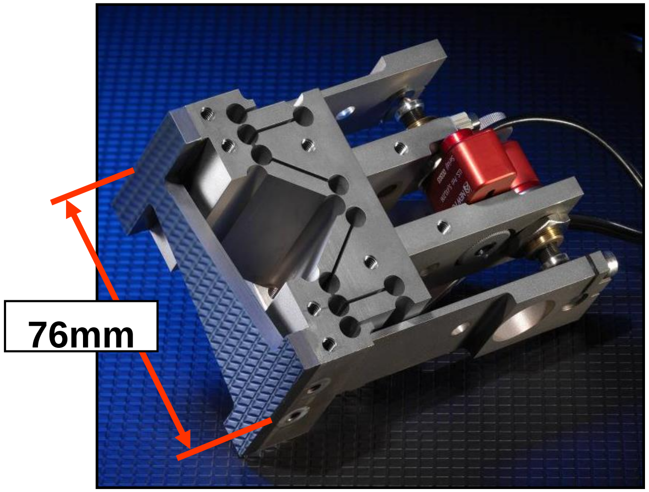
Smallest ESRF dynamic bending system

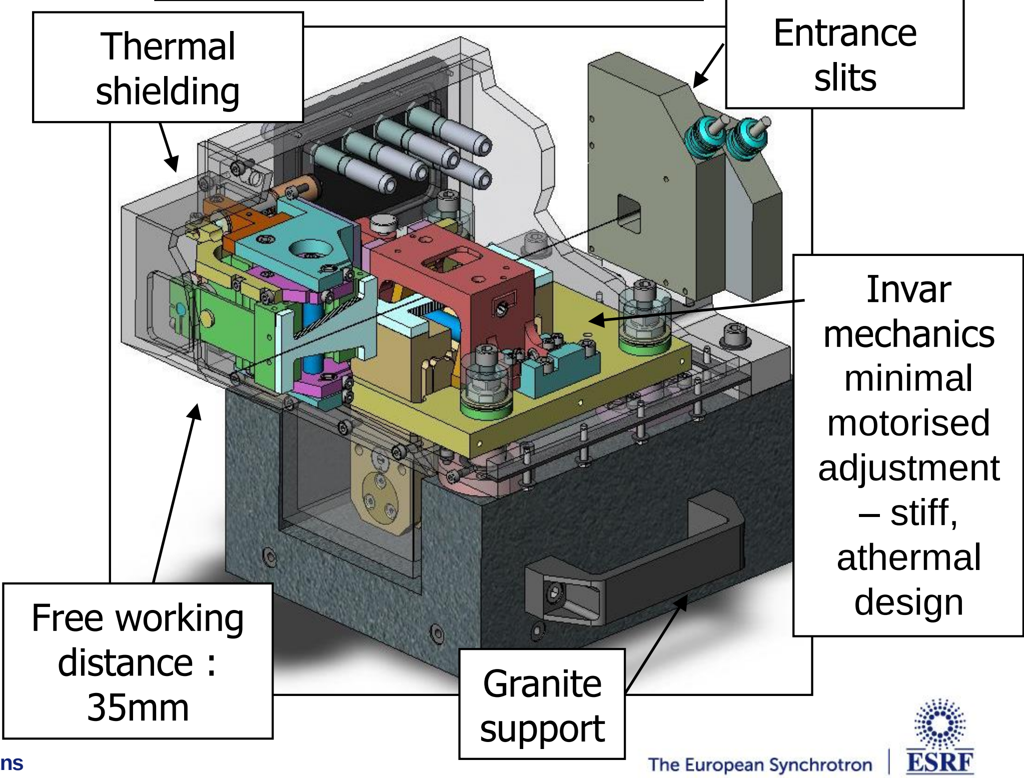
HF Mirror focal distance ~83 mm

Close to the current limits of bending technology:

- Local bending radius down to 10 m
- Mirror stress up to 30 MPa

Optimised figure at 17keV: 8 mrad (25keV 5.5 mrad)		
	slope error [µrad rms]	figure error [nm rms]
HF (40 mm)	0.15 (0.11)	0.38 (0.16)
VF (70 mm)	0.09 (0.06)	0.32 (0.16)




Thermal shielding

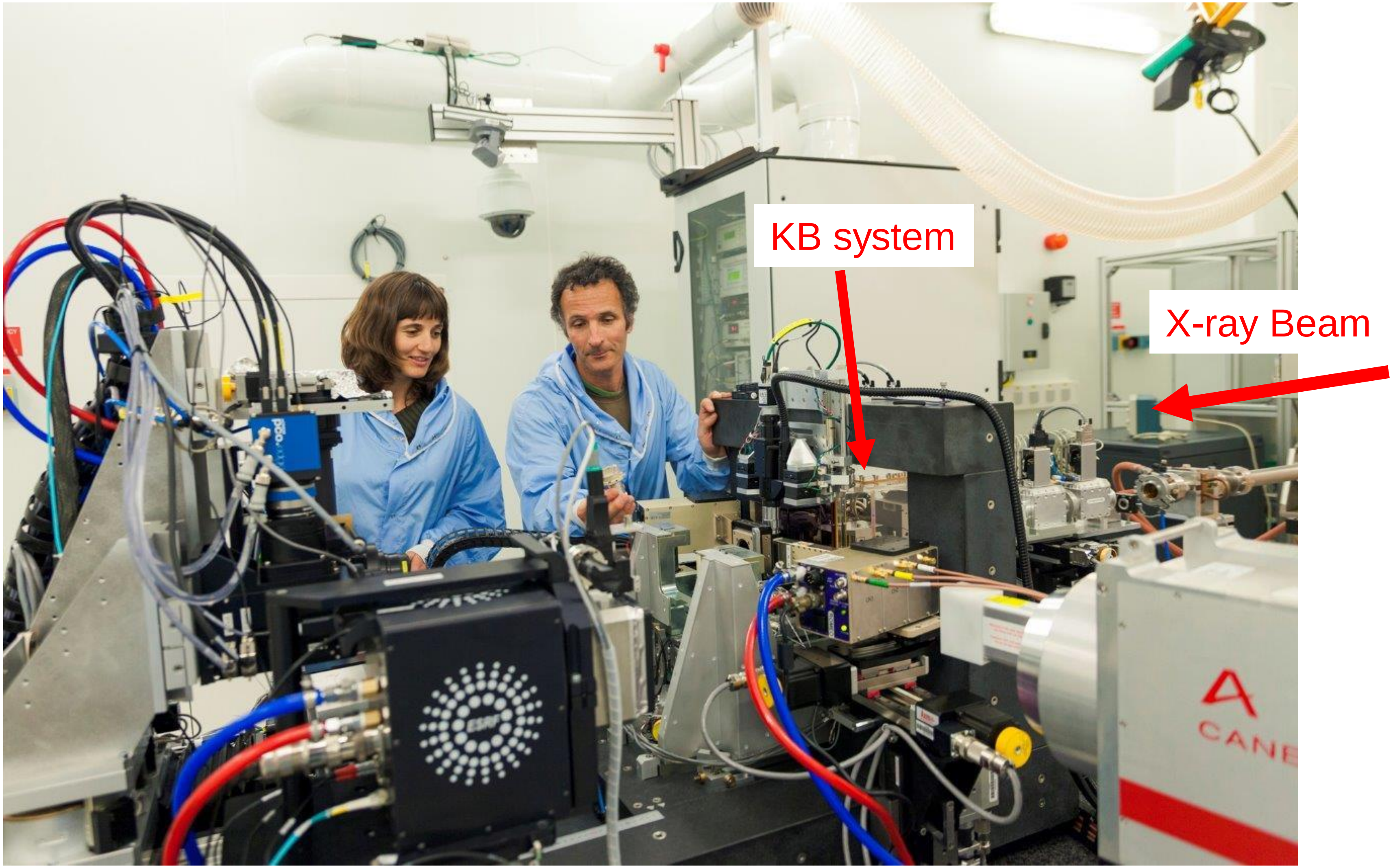
Entrance slits

Invar mechanics minimal motorised adjustment – stiff, athermal design

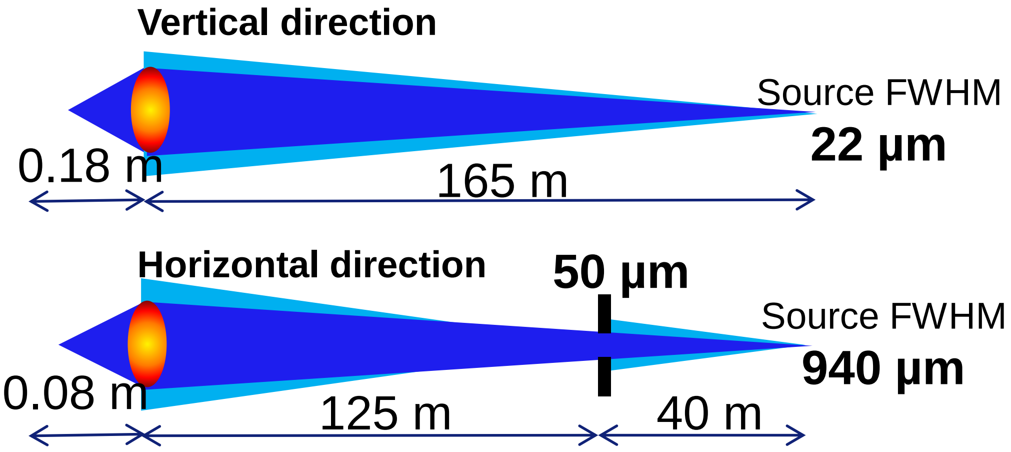
Free working distance : 35mm

Granite support

ID16B END STATION

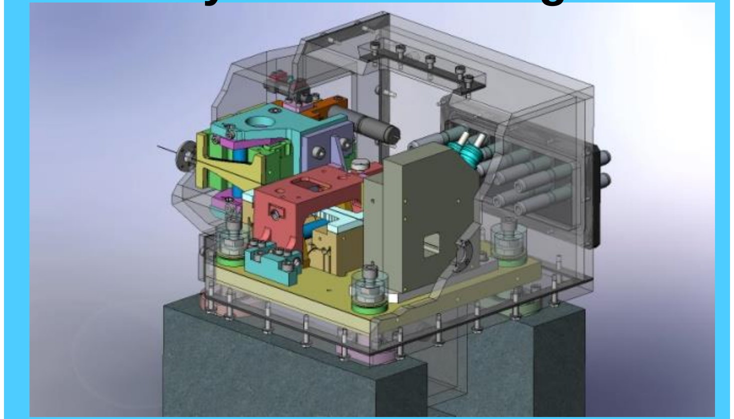


FOCUSING OPTICS PERFORMANCE ON ID16B

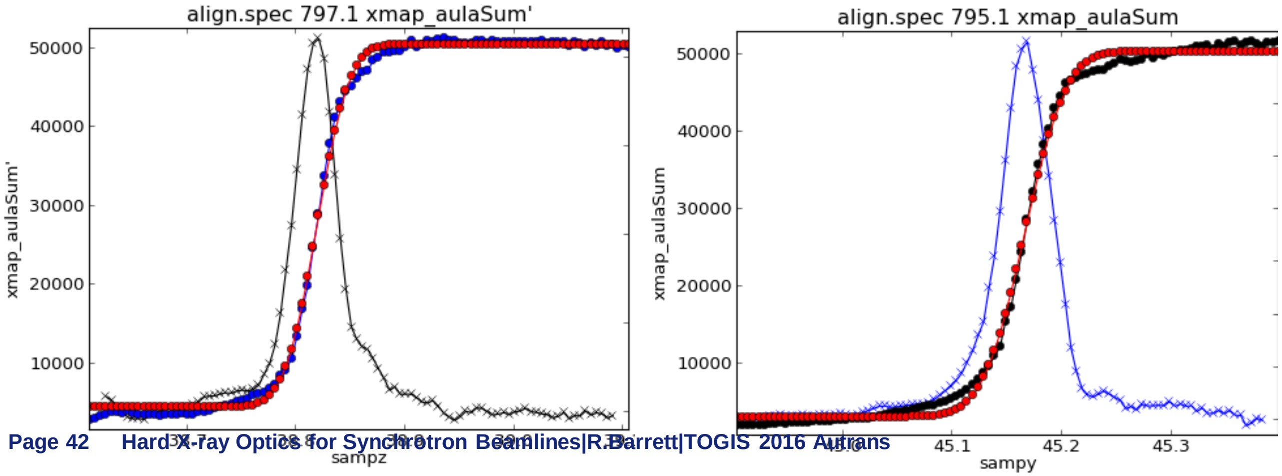


Knife-edge scans:
FWHM horiz. = 50 nm
FWHM vert. = 48 nm

KB mirrors + Multilayers +dynamic bending

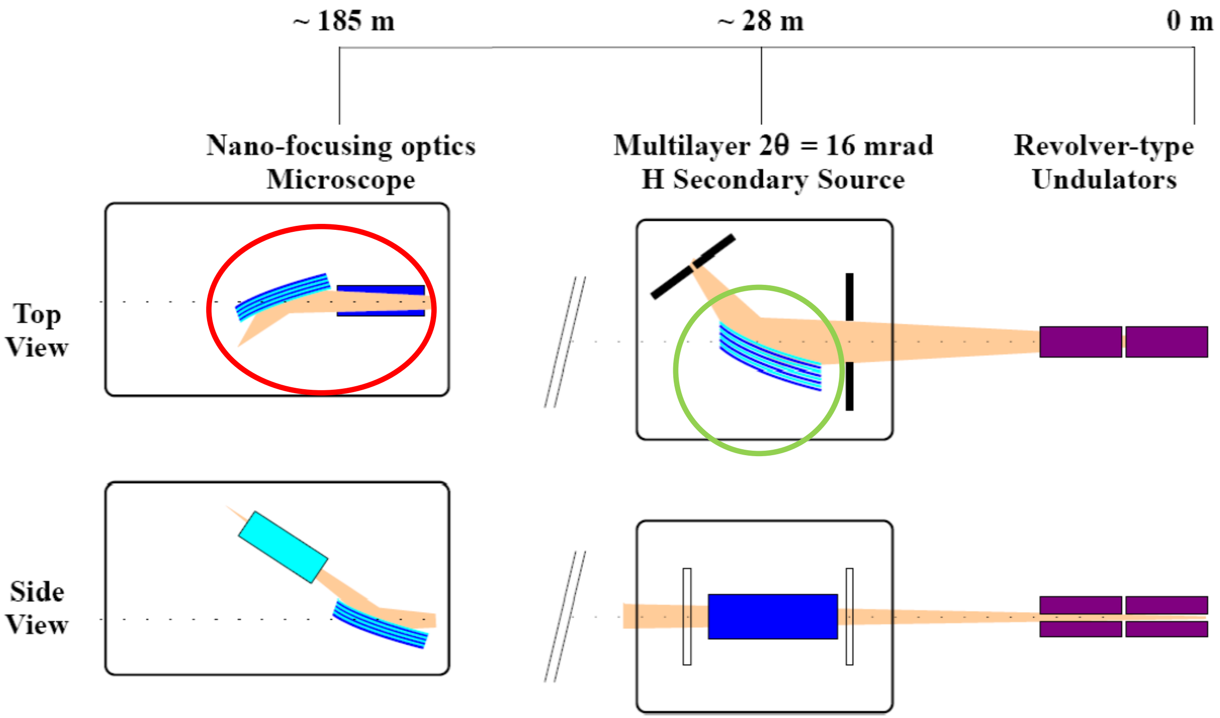


- **High Flux**
- **High numerical aperture**
- **Achromaticity**



E= 17.5 keV
Pink beam mode
Flux = 5 10^{11} ph/s
Energy range: 17-29 keV
Tunable bandwidth:
ΔE/E ~ 1.5 - 7 %

ID16A “NI” OPTICAL SCHEME



Nano-imaging applications:

- **17 and 34 keV**
- **High throughput**
- **Pink beam (full undulator peak)**
- **Target fwhm spot size ~20-25 nm**

•Horizontal: Secondary source by **focusing ML**

•Three ML stripes for E = 11.2 / 17.0 / 33.6 keV

•**2 sets of static figured KBs** with graded ML coatings

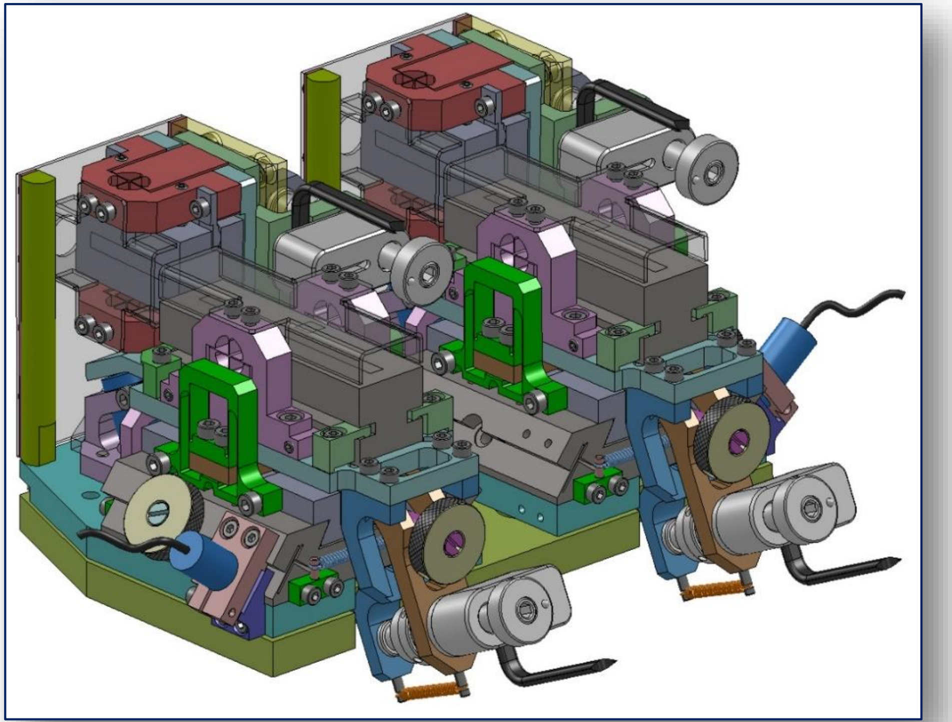
•KB1: 17.0 keV, KB2: 33.6 keV

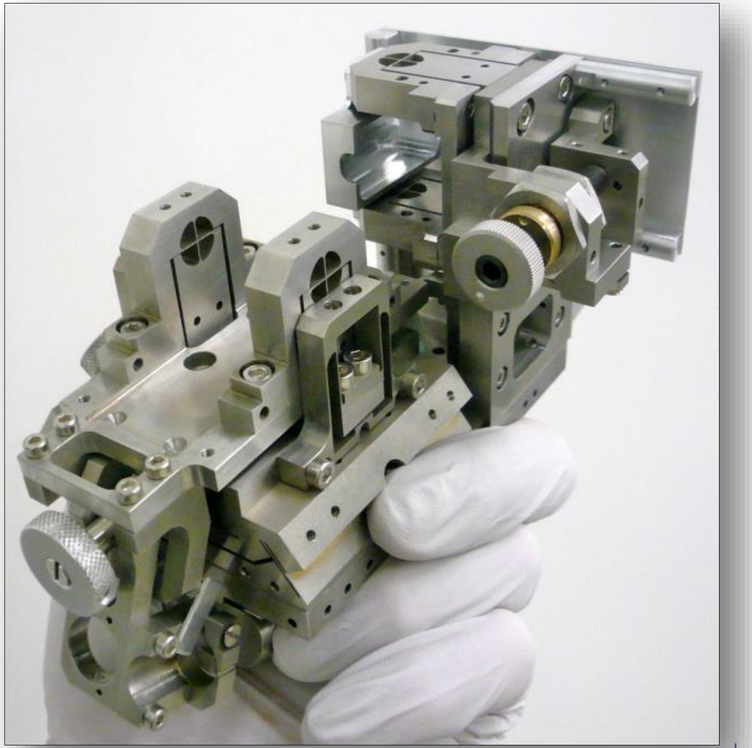
STATICALLY FIGURED NANOFOCUSING KB MIRROR SYSTEM

Radius of curvature and figure specifications too severe for bending ⇒ Fixed curvature KB mirrors (JTEC, Japan)
ML coating at ESRF and integrated into in-house designed mechanics

2 mirror pairs KB1:17 keV, KB2: 33.6 keV
Extreme asphericity:
VFM: 22 to 7 m over 70 mm
HFM: 10 to 2.7 m over 36 mm (for KB1)

Target figure errors < 1 nm p.v.
Surface roughness < 1 Å rms

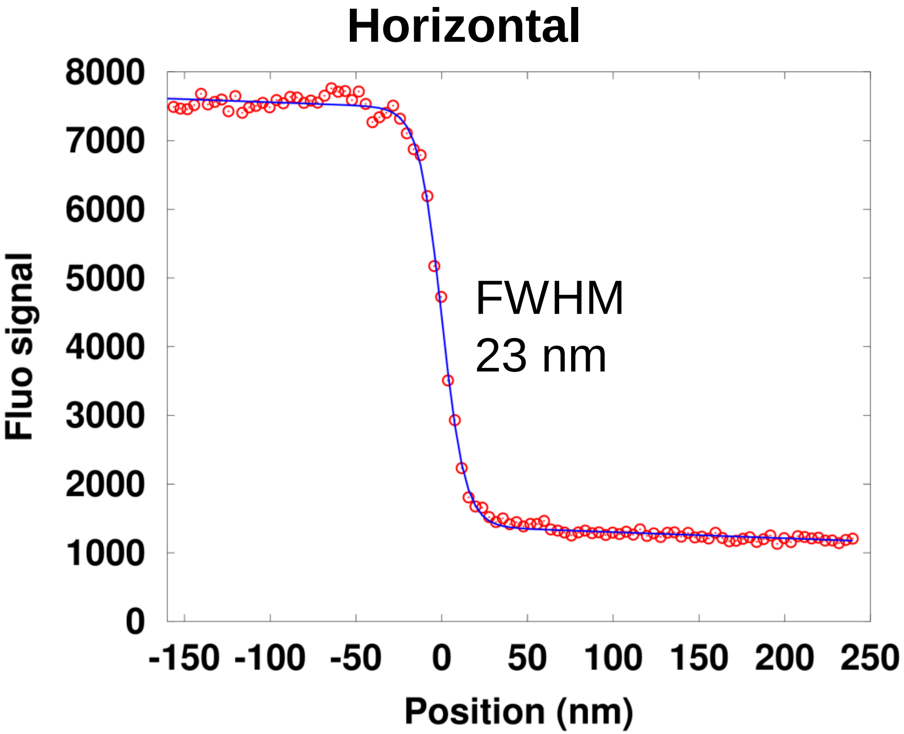


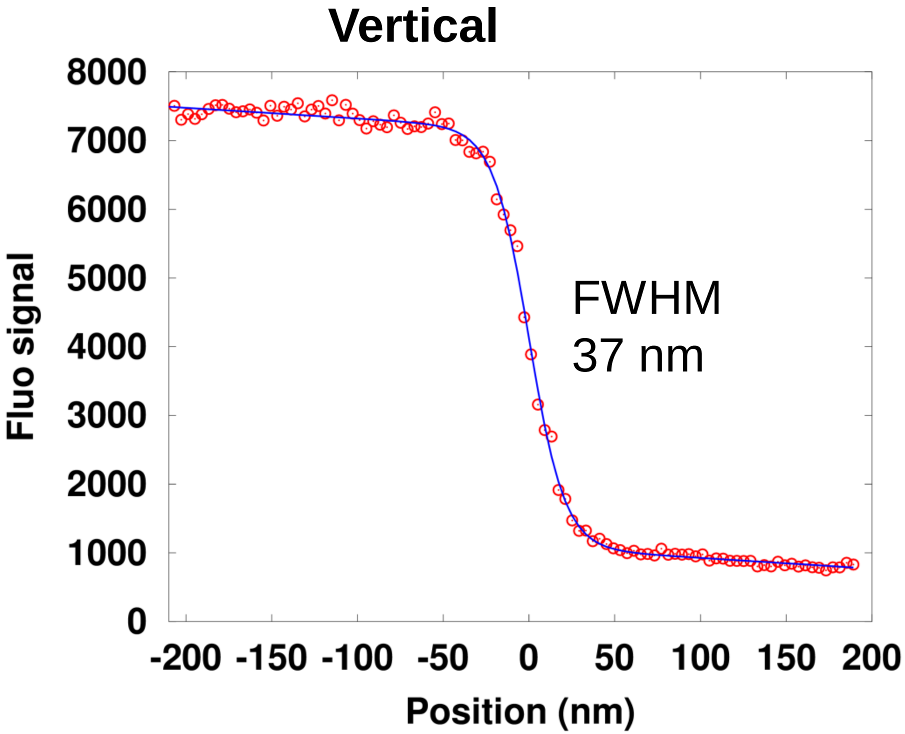


ID16A-NI: KB OPTICS 17KEV

Focus size: **75 nm** (July 2014) → **50 nm** (August)
→ **30 x 40 nm** (September) → **23 x 37 nm** (October)

Acceptance:550µm x 300µm





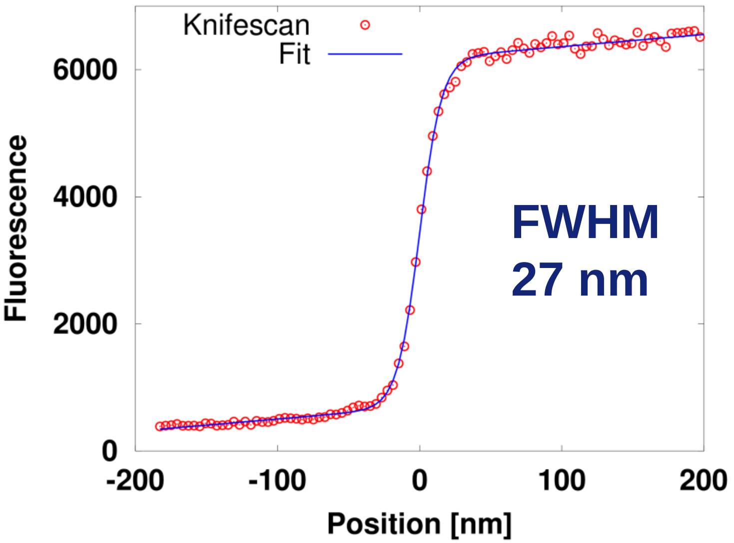
Flux (in smallest beam): **7 10^{11} ph/s with single undulator!**

A. Pacureanu, Y. Yang, F. Fus, P. Cloetens

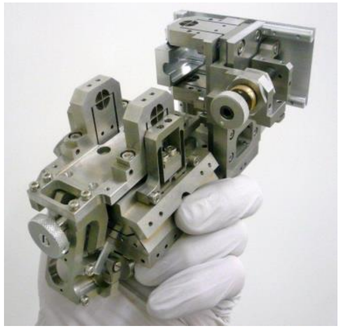
ID16A / UPBL04: KB OPTICS 34 KEV

Focus size: 27 x 21 nm (July 2015)

Horizontal

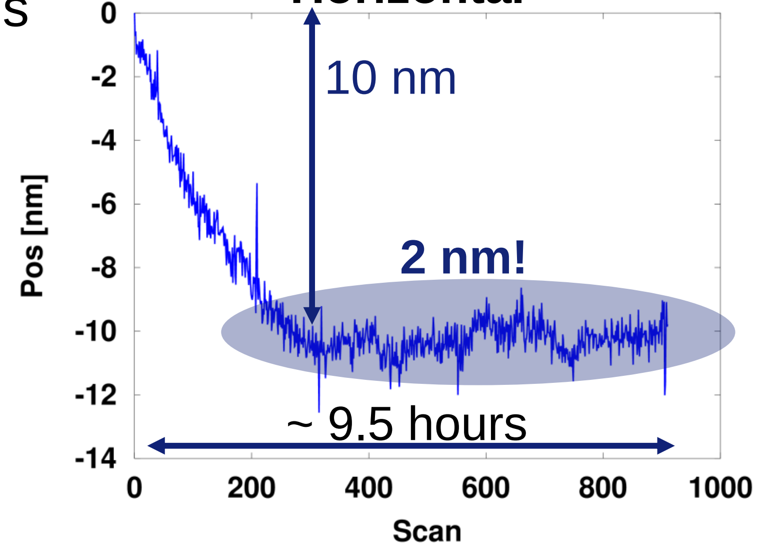


Flux 6.10^{10} ph/s

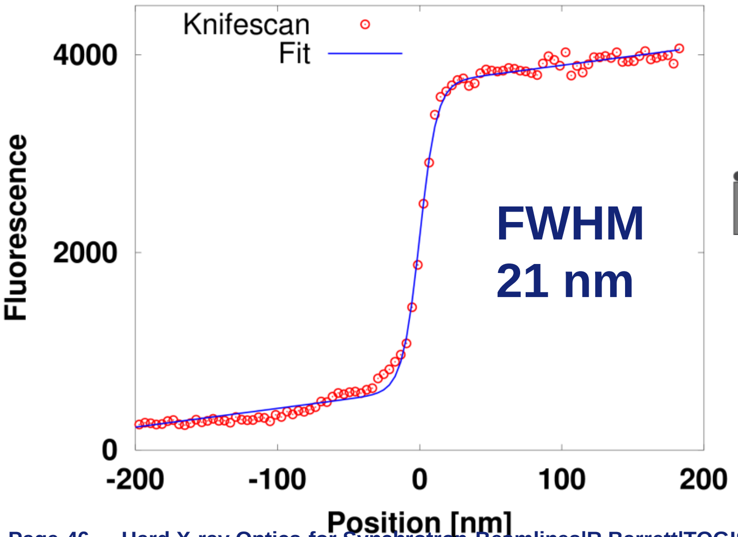


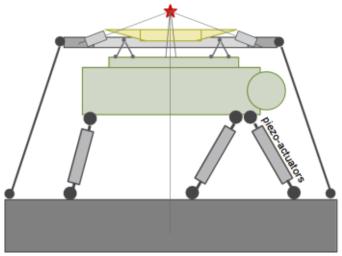
Stability (Sept 2015, 4-bunch)

Horizontal



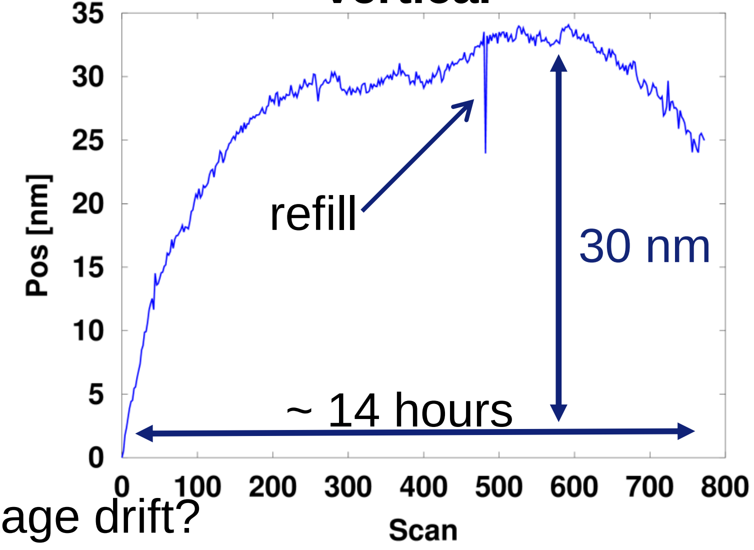
Vertical





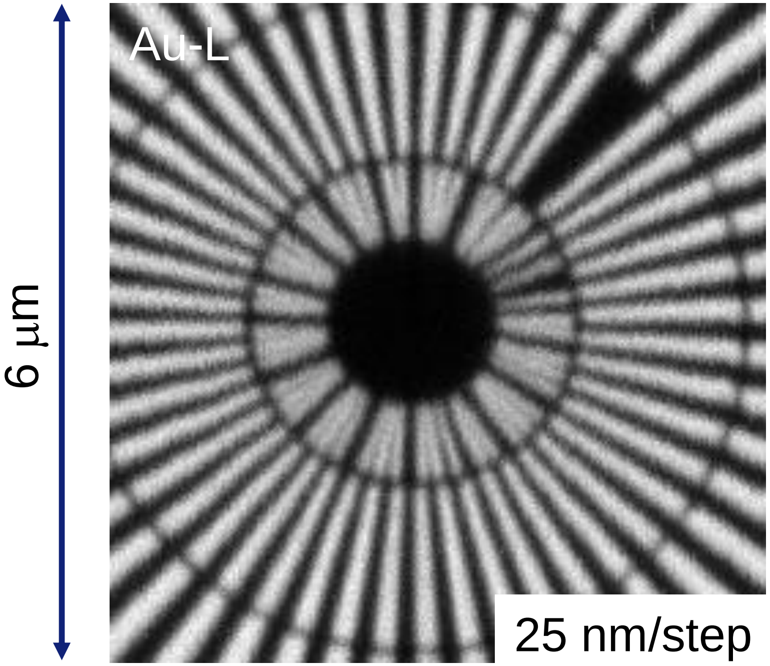
4-bunch mode,
KB or sample stage drift?

Vertical



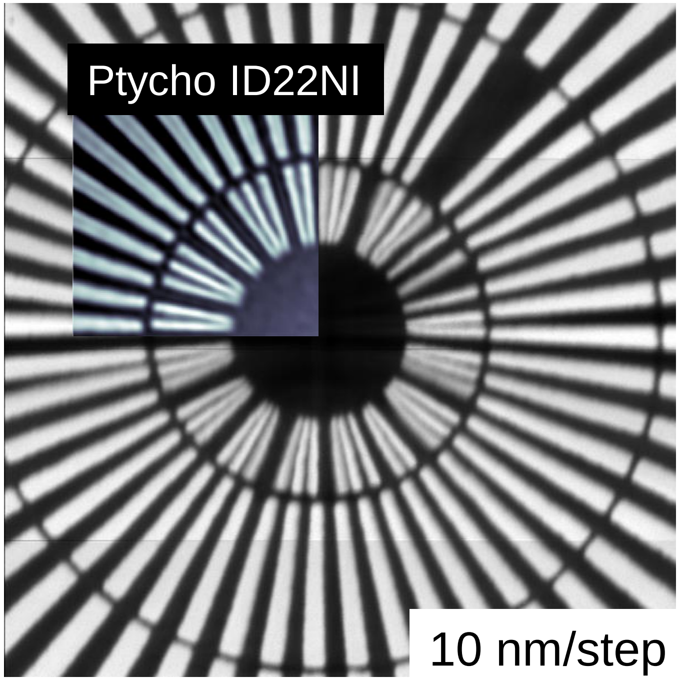
DYNAMIC VS STATIC KB SYSTEM

XRF: Dynamic bending

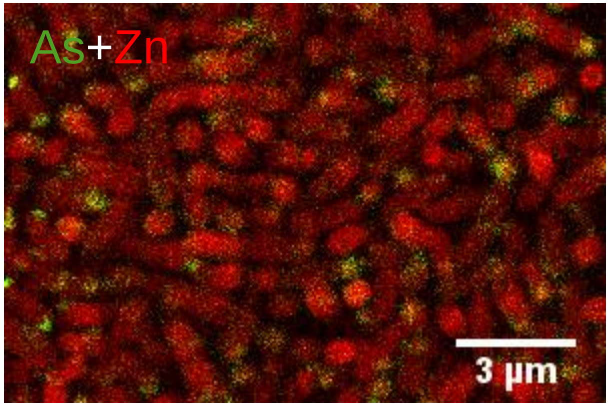


25 nm/step

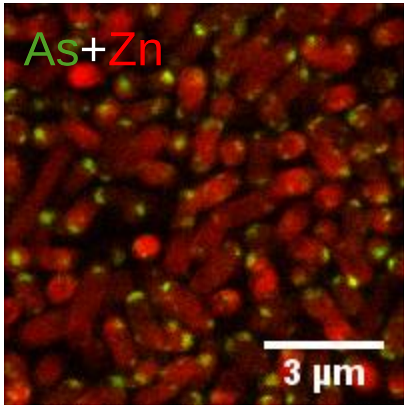
XRF: Static figure



10 nm/step



50 nm/step
100ms
exposure



Study of As metal uptake within bacteria populations.

S.Kirchen, IFG, Karlsruhe Institute of Technology

A. Pacureanu, Y. Yang, F. Fus, S. Bohic, P. Cloetens

REQUIRED QUALITY OF X-RAY OPTICS (DIFFRACTION LIMITED FOCUSING)

Strehl ratio: > 80% (i.e. <20% of intensity outside spot)

Maréchal Criterion: rms wavefront error λ/13 (but λ ~ 1 Å!)

Reflective Optics: Any deviation *h* from the ideal surface introduces a phase distortion φ. At grazing angle θ, $\varphi = (4\pi/\lambda)\cdot h\cdot \sin\theta$

X-ray energy (keV)	Coating material	Incidence angle θ (mrad)	Figure specification σ (nm, rms)
8	Rhodium	6.0	1.0
20	Platinum	3.0	0.8
50	Multilayer (W/B_4C)	5.9	0.15

e.g. O. Hignette *et al*., Proc. SPIE 4501:43–53. San Diego 2001

Refractive Optics: Cumulated thickness errors, t, of lenses introduce phase distortion φ. For material with $n=1-\delta-i\beta$, $\varphi = 2\pi\delta t/\lambda$

X-ray energy (keV)	Lens material	delta	Figure specification σ (nm, rms) (full stack)	Figure specification σ (nm, rms) (per lens *)
8	Be	5.3E-06	2200	980
20	Be	8.5E-07	5600	1000
50	Al	2.2E-07	8700	810

*** Assumes focal length of 1m with lenses R=50µm**

Fresnel Zone Plates: Zone placement accuracy ~ 1/3 zone width (3-4 nm!)

e.g. A.G. Michette, *Optical Systems for Soft X Rays*. Plenum Press, 1986

DEFECTS ON COHERENTLY ILLUMINATED MIRRORS

Ideal Focus (15keV)

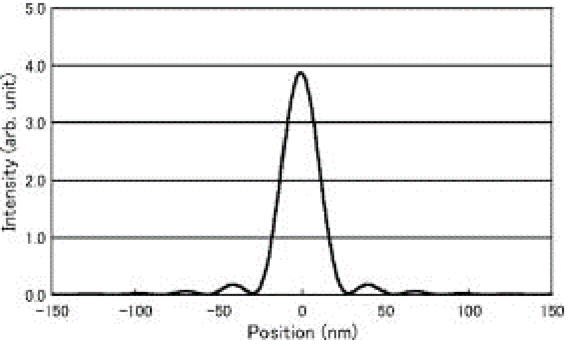
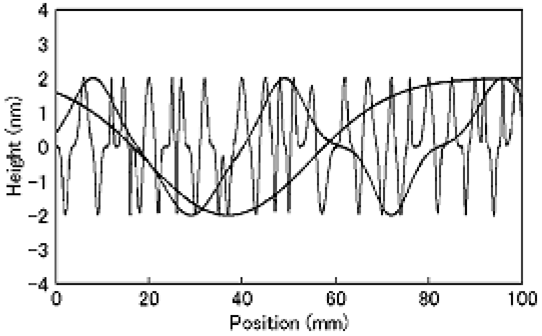
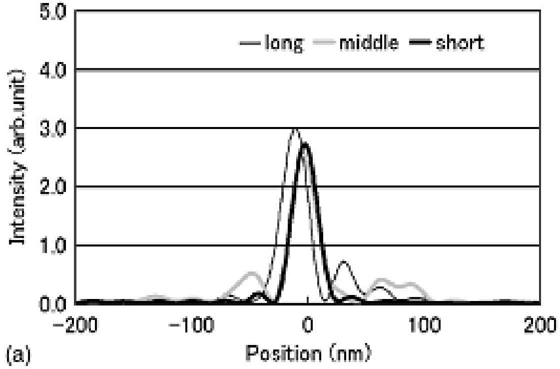


Figure Errors

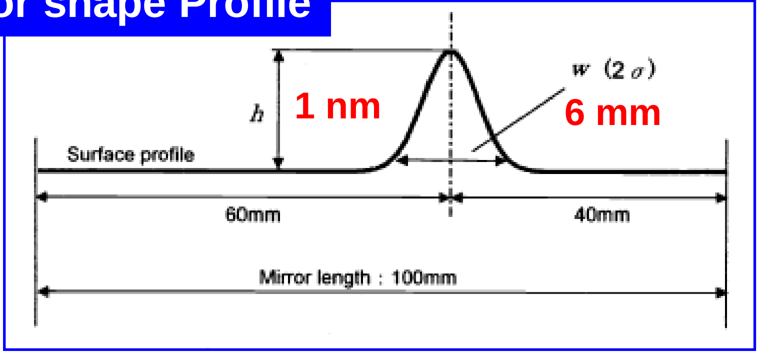


Aberrated focus

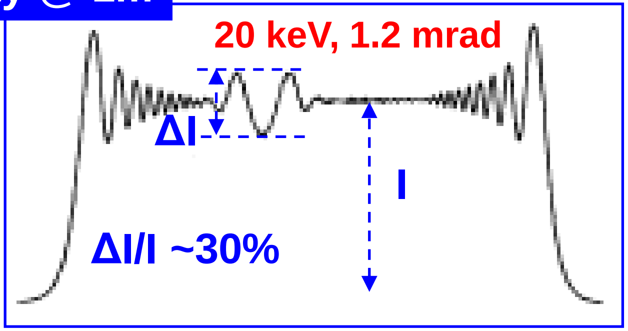


H. Mimura et al, *Rev. Sci Inst* 76, [4] (2005) 045102–6 doi:10.1063/1.1868472.

Mirror shape Profile



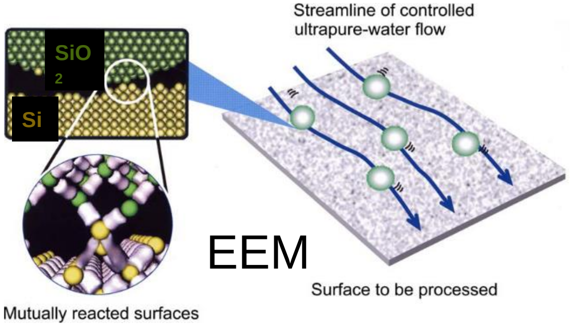
Intensity @ 1m



Current state of the art of X-ray mirror quality is for slope errors ~0.1urad rms, figure errors ~1nm p.v. - both still limit optimal source exploitation

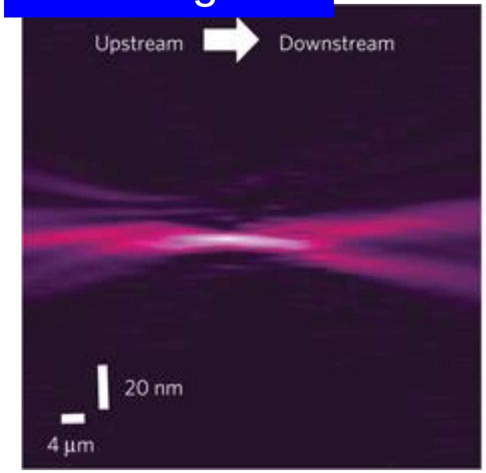
CURRENT BEST FOCUSING PERFORMANCE

Deterministic Polishing

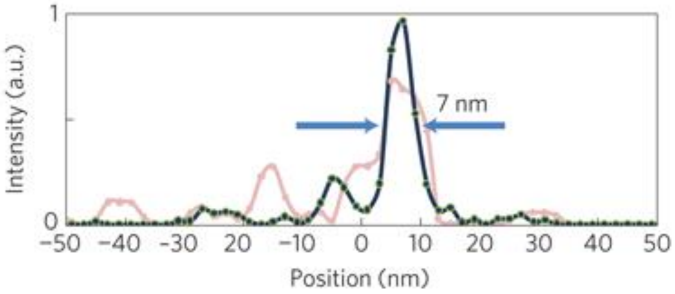


Advanced Metrology Techniques

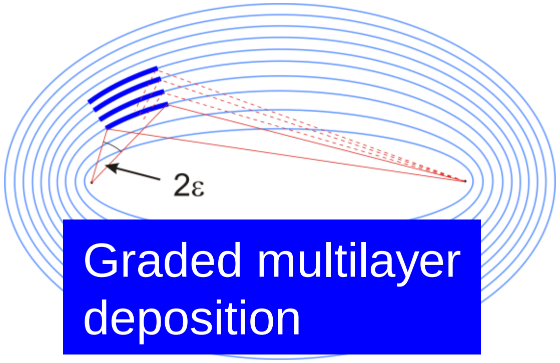
Wave-optical Modeling



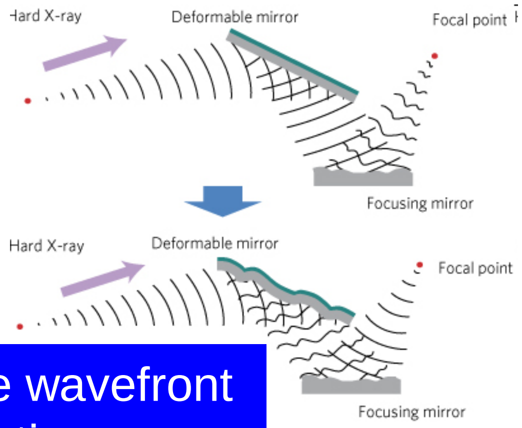
20keV: 7 nm measured focal spot



Coherent illumination



Graded multilayer deposition



Active wavefront correction

H. Mimura et al., “Breaking the 10 nm barrier in hard-X-ray focusing,” *Nat Phys* **6**, (2010): 122-125

PROGRESS IN HARD X-RAY FOCUSING

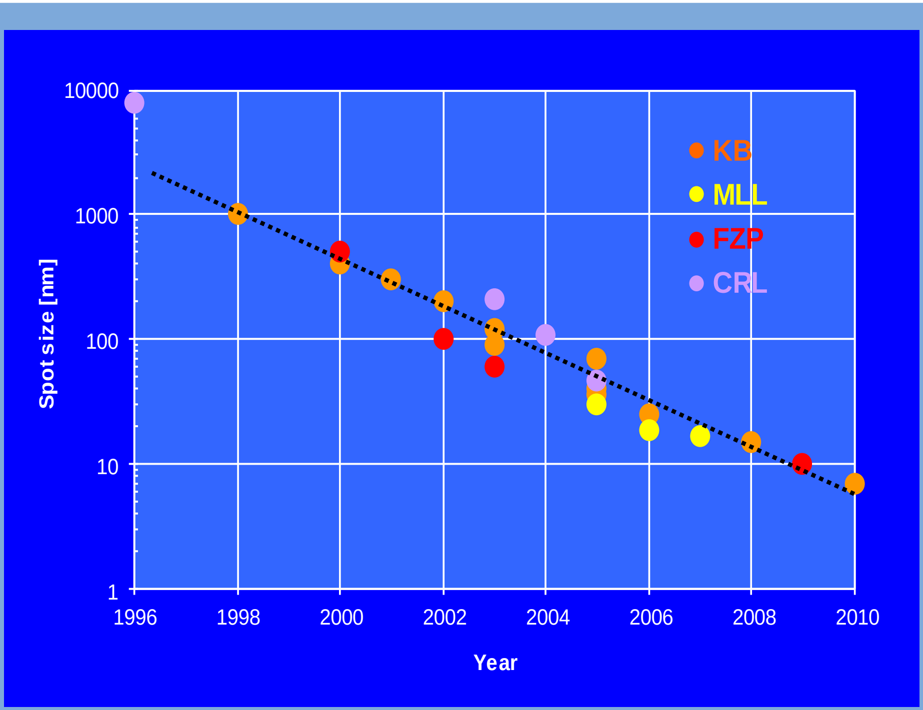
Moore’s law adapted to the X-ray world:

ESRF Red Book (1987): very few beamline projects aiming even for 10 micron sized beams

Now optics exist for 10nm beams

Routine application of sub-micron beams still complicated

Also many engineering issues in implementing stable, reliable X-ray nanofocusing systems



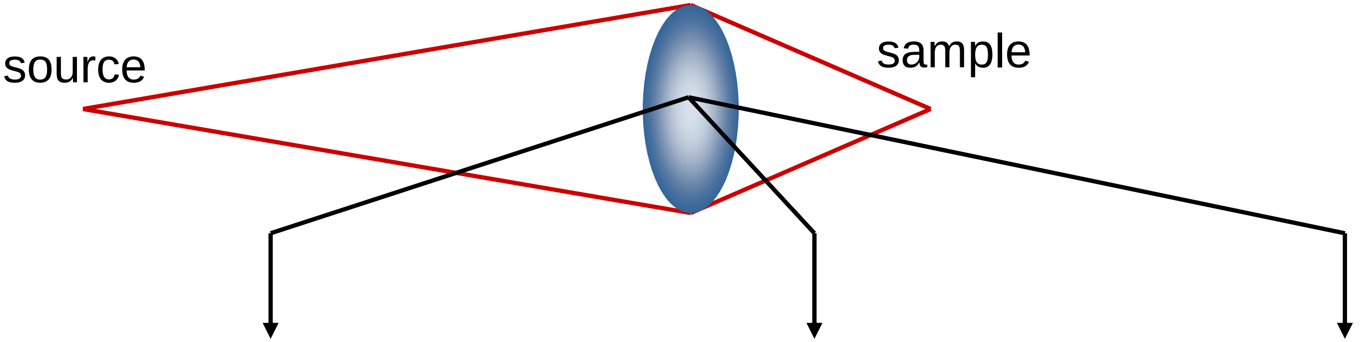
Historical evolution of the measured spot size for different hard x-ray focusing elements *(courtesy C. Morawe)*

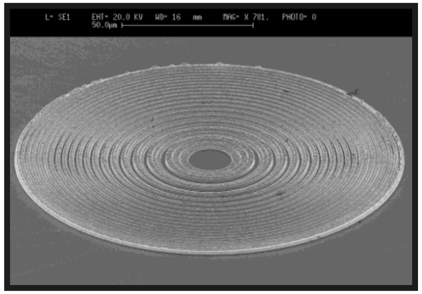
- H. Mimura *et al. Nature Physics*, **6**, 122-125 (2010).
- J. Vila-Comamala et al., Ultramicroscopy,**109**,1360–1364 (2009)
- H. Kang *et al., Physical Review Letters*, **96**:127401 (2006)
- C. Schroer *et al., Physical Review Letters*, **94**:054802 (2005)

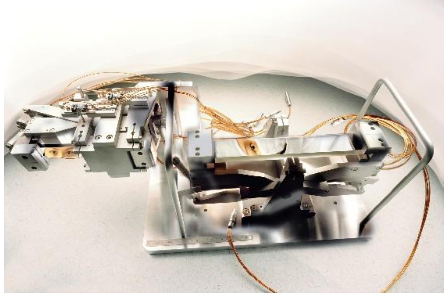
Best focus Experiments

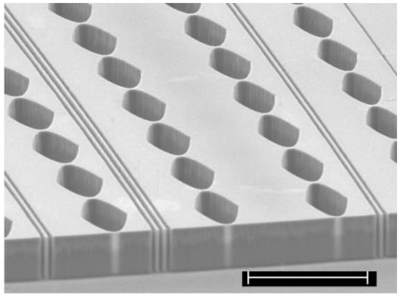
Ultimate resolution Theory

COMPARISON OF DIFFERENT MICRO/NANOFOCUSING OPTICS









Energy ↗

	Zone plates	Mirrors	Refractive lenses
• **Resolution**	++++	++	++
• **Achromaticity**	-(-)	+++	--(-)
• **Efficiency**	+	+++	++
• **Imaging (MTF)**	++++	+	++

SUMMARY & CONCLUSION

The advent of 3rd generation synchrotron X-ray sources has encouraged the development of new hard X-ray optics

- Modern beamline design can draw on a toolbox of optical components based on diffraction, reflection and refraction of X-rays
- dramatic improvement in manufacturing and preparation techniques
  - low roughness, high-accuracy figuring, perfect crystals (Ge, Si), diamond, ...
- improved power management strategies
- focusing optics (spot size ~ 50- 0.01µm)
  - zone-plate and refractive lenses, elliptically figured mirrors
- wide range of experimental requirements – no one ideal optic

- ***R&D programs continuously in progress****: current hot-topics*
  - preservation of the wave-front quality – especially important for anticipated use of fully coherent XFEL sources
  - routine sub-10nm focusing