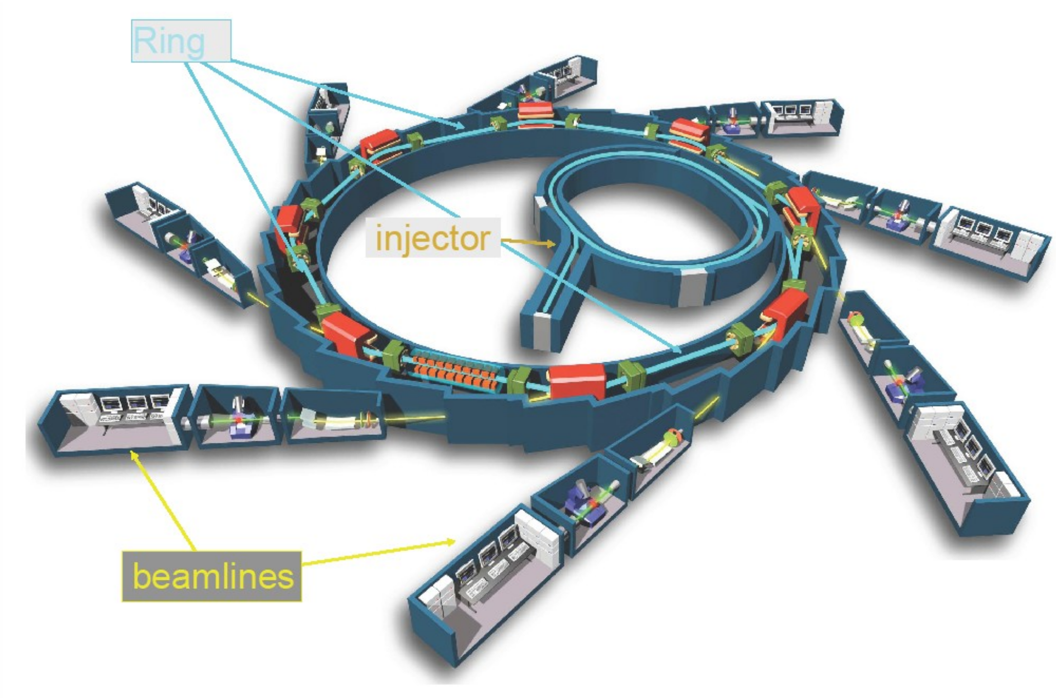
IAEA training workshop on synchrotron technologies and techniques and their applications

Beamlines

Outline

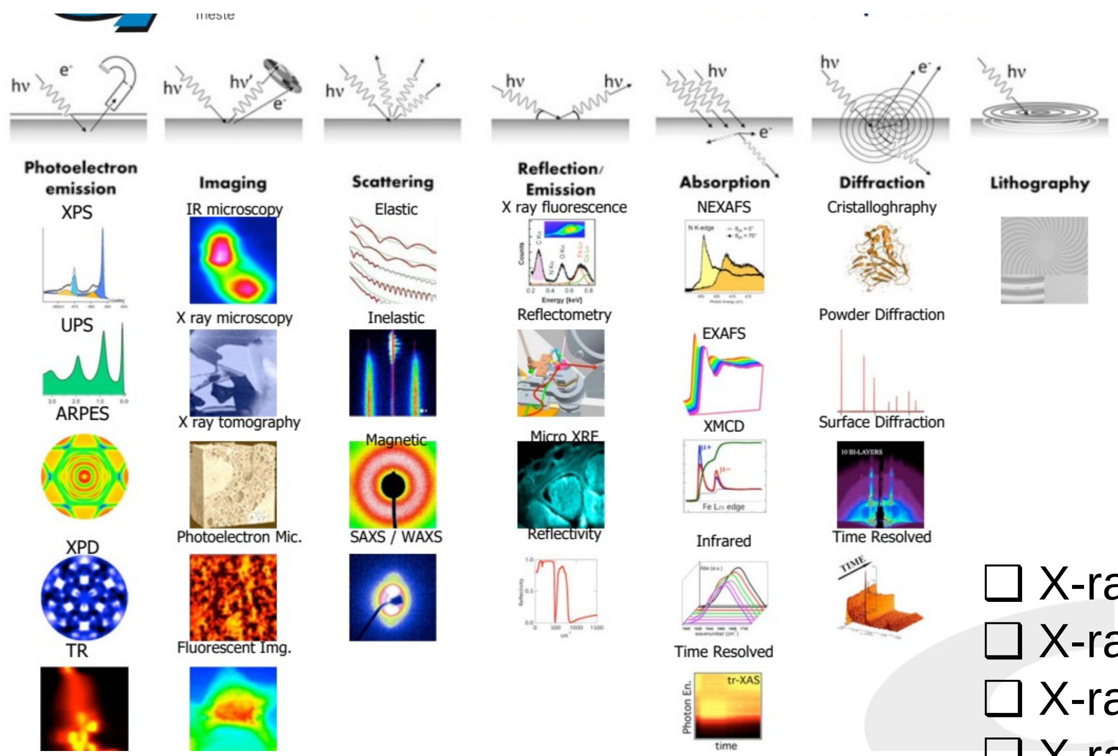
- Beamline Definition
- Beamline Components
  - Vacuum system
  - Safety system
  - Radiation Sources and spectra
  - Optics
    - Monochromators
    - Mirrors
    - Focusing Optics
  - Experimental setup

Beamline Definition



A beamline is the "equipment" required to transport SR from the source (BM/ID) to the sample
and to condition the radiation for the experiment.

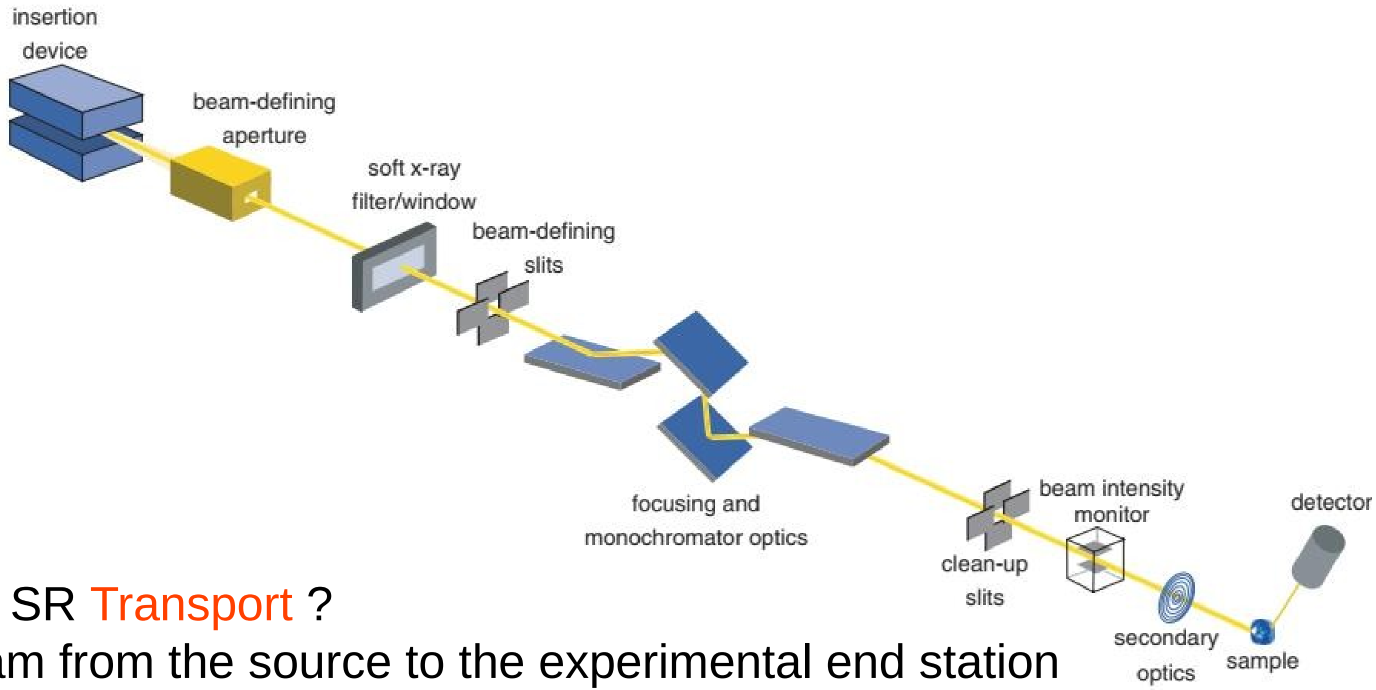
Beamline Definition



- ❑ X-ray powder diffraction - MCX
- ❑ X-ray single crystal diffraction - XRD1/2
- ❑ X-ray absorption - XAFS
- ❑ X-ray Fluorescence - XRF

CERTIFIED MANAGEMENT SYSTEM
CERTIQUALITY
UNI EN ISO 9001:2015
UNI ISO 45001:2018
UNI CEI EN ISO 50001:2018

Beamline Definition



What does SR Transport ?

- Steer beam from the source to the experimental end station
- Steer beam in an efficient manner **preserving flux**
- Steer beam in a **safe manner** both for equipment and personnel

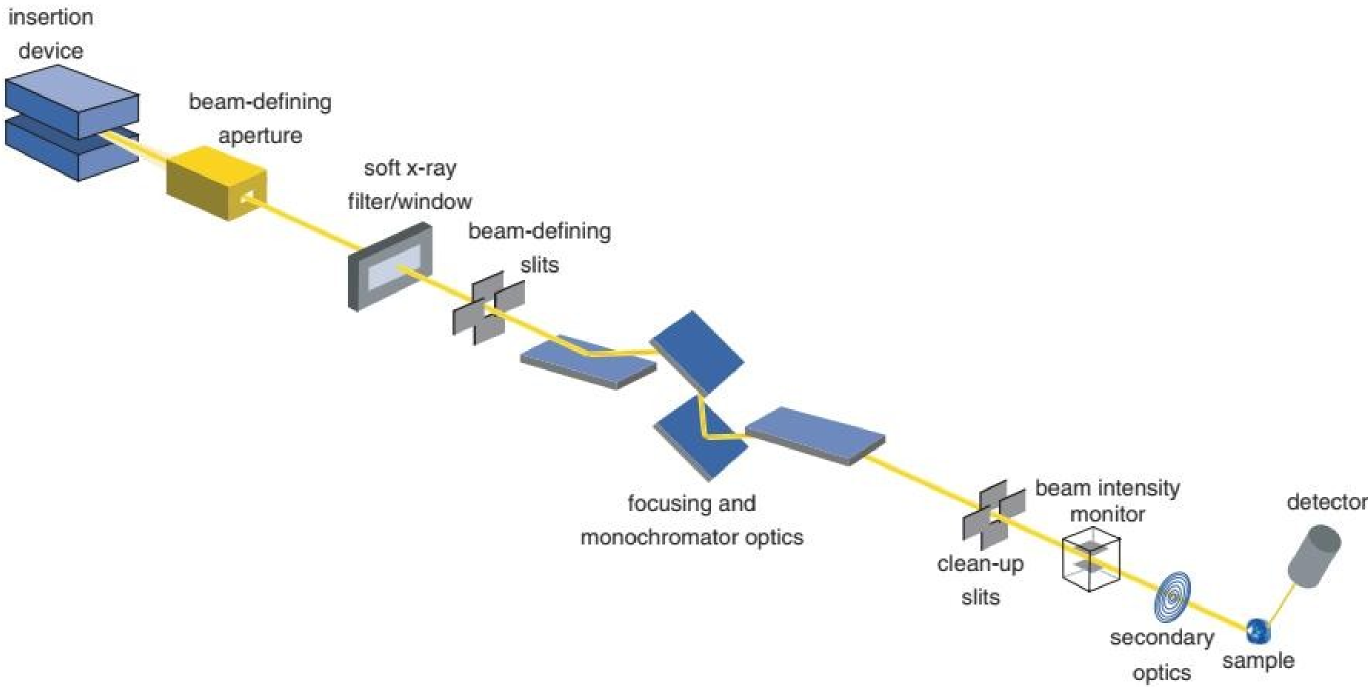
Elettra Sincrotrone Trieste

Beamline Definition

What does condition mean?

- Control energy (E) and bandwidth (ΔE) of the beam
  - Monochromatic beam (ΔE = 1-2 eV @ 10KeV; ΔE /E = 10-4)
  - Polychromatic beam (ΔE = 1-2 KeV @ 10KeV; ΔE /E = 10-1)
  - High resolution beams (ΔE a few meV @ 10KeV; ΔE /E = 10-7)
- Control size/divergence of the beam
  - Micro or nano beams
  - Highly collimated beams
- Control polarization of the beam
  - Linear
  - Circular
- Remove unwanted power

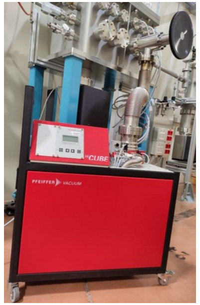
Beamline Components → Vacuum system



Elettra Sincrotrone Trieste

Beamline Components → Vacuum system

<u>Ring pipe is maintained in ULTRA HIGH VACUUM (< 10^{-9} mbar)</u>

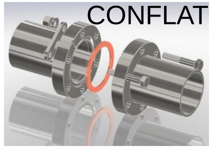



LOW VACUUM

- Roughing pumps ~10^{-3} mbar
- Mechanically noisy, lubricants → contamination

HIGH VACUMM (HV)

- Turbo pumps ~10^{-8} mbar
- Mechanically quiet, magnetically suspended, needs low vacuum pumps

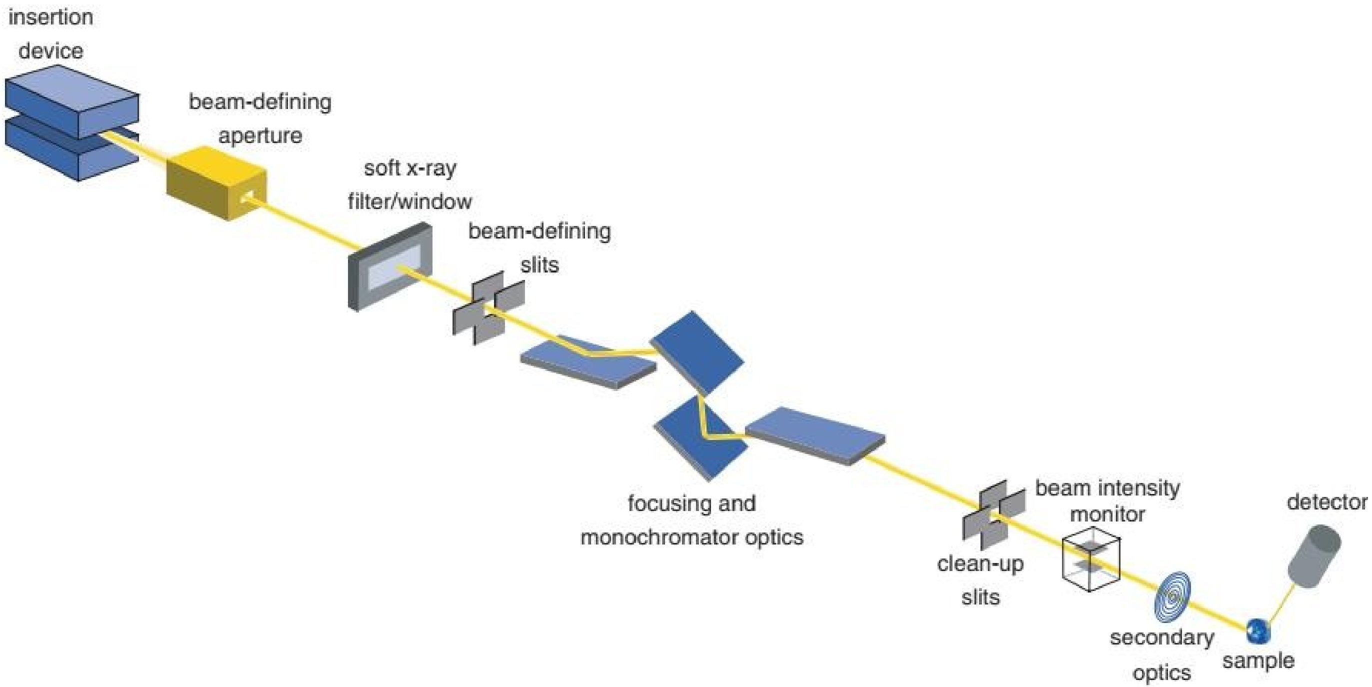


HIGH and ULTRA HIGH VACUUM (UHV)

- Ion pumps ~10^{-11} mbar
- No moving parts, no lubricants. Molecular casting.

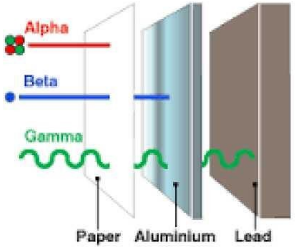
Low absorbing windows are placed along a beamline to separate different vacuum sections with the ultimate function to save ring vacuum in case of vacuum break at the beamline.


Beamline Components → Safety system



Beamline Components → Safety system

A radiation is defined as **ionizing** if it carries enough energy for ionizing atoms and/or molecules

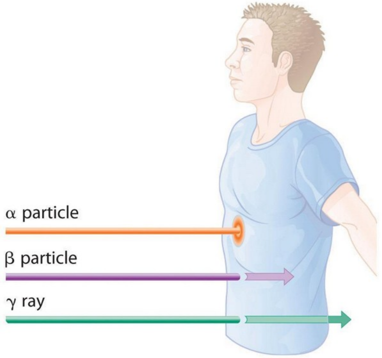


DIRECT IONIZATION

- Massive charged particles traveling at relativistic speed: α-particles , β-particles

INDIRECT IONIZATION

- High energy photons that exert ionization through photoelectron, Compton effect or pair production (γ-rays, X-rays and Higher Energy UV)
- Uncharged fast neutrons can dislodge a proton upon collision the “recoil proton” may induce secondary ionization effects



Beamline Components → Safety system

Radiation sources at Synchrotron Facility

X-ray and UV **synchrotron radiation** produced by Bending Magnets and Insertion Devices

Bremsstrahlung produced by electromagnetic cascade or shower due to e-beam *loss*

Prompt radiation sources at electron accelerators are generated by e-beam loss

❖ All the electron injected into the ring pipe are lost naturally:
during ring revolution ➔ due to Columbian *friction* / scattering with residual gas particles

Shielding structures (lead)

Very good vacuum for electrons!

Beamline Components → Safety system

X-ray and UV **synchrotron radiation** produced by Bending Magnets and Insertion Devices

Bremsstrahlung produced by electromagnetic cascade or shower due to e-beam *loss*

X – Rays

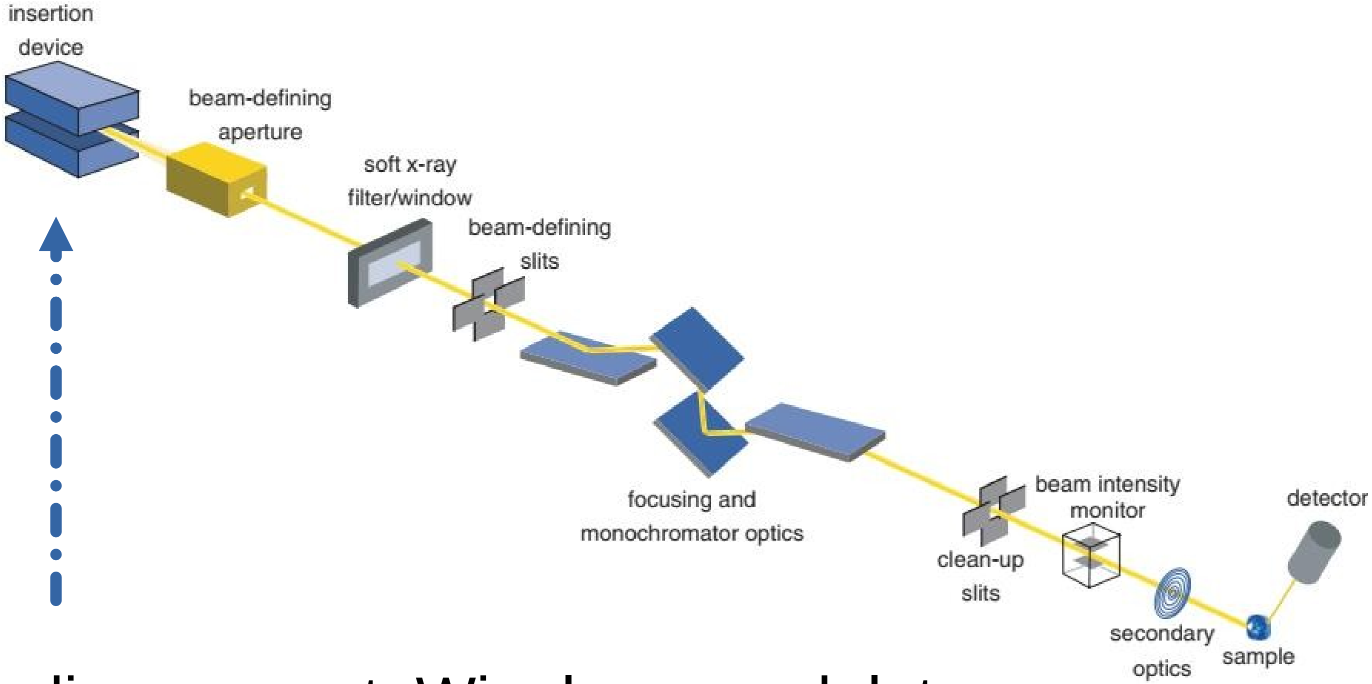
γ – Rays

Shielding structures (lead) in case of presence of hard X-rays

Very good vacuum for electrons is requested

Shutters (Cooled copper blocks to manage beam power) and stoppers (high density materials, e.g. Tungsten) to protect users in case of e^--beam loss (**Bremsstrahlung)**

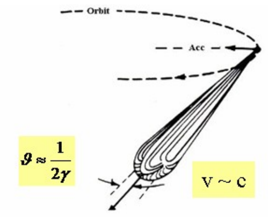
Beamline Components → Radiation Sources

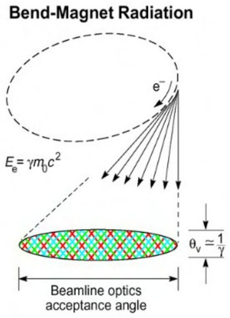


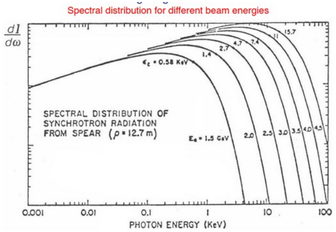
Bending magnet, Wiggler or undulator

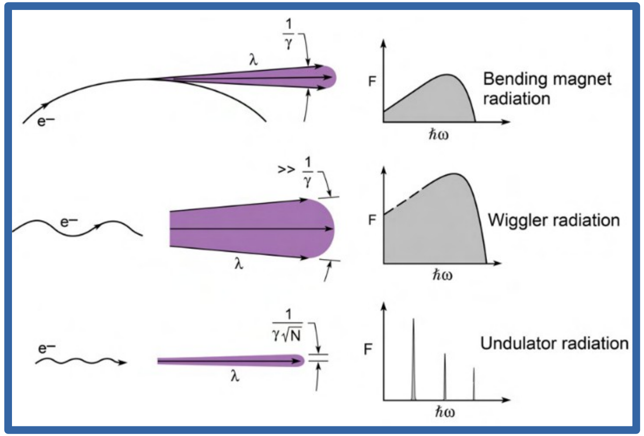
Beamline Components → Radiation Sources/spectra

BENDING MAGNETS and WIGGLERS

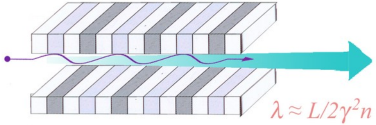








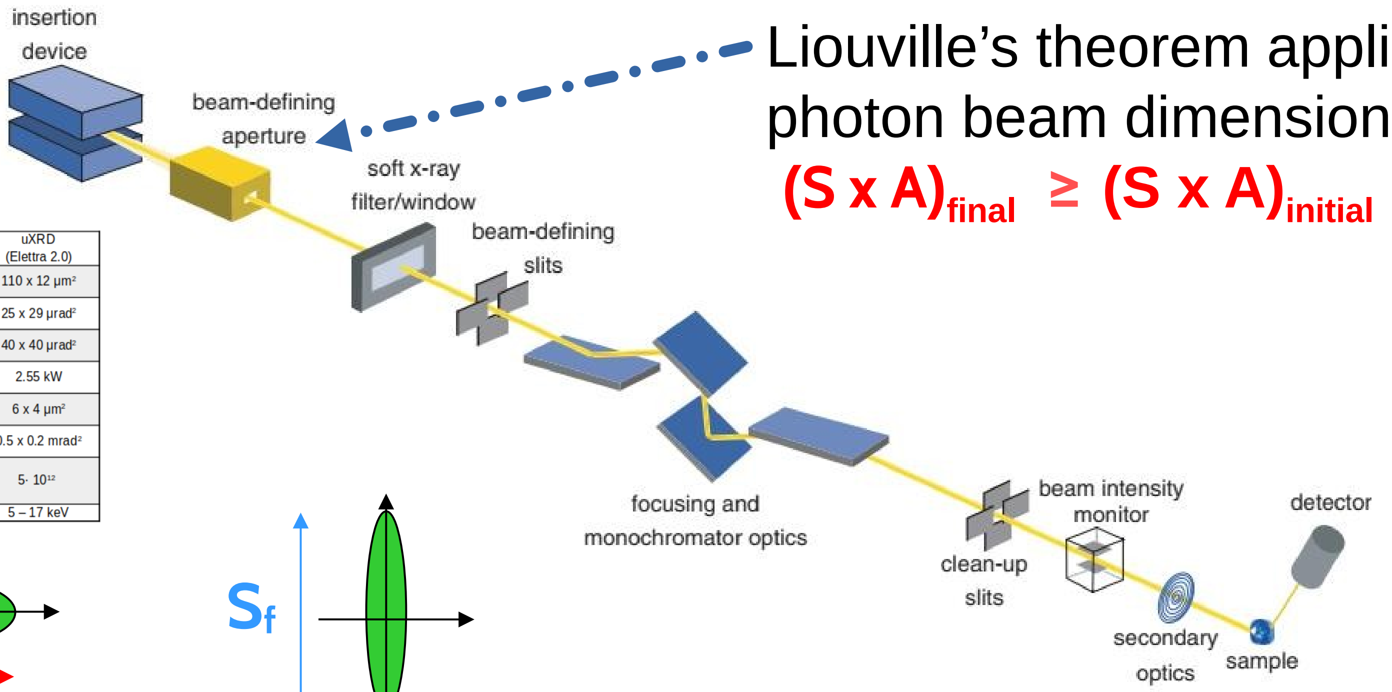
UNDULATORS



$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

	XRD2 (Elettra 1.0)	uXRD (Elettra 2.0)
Source Size FWHM	660 x 60 μm²	110 x 12 μm²
Source angular emission FWHM	11000 x 200 μrad²	25 x 29 μrad²
Angular acceptance	1000 x 180 μrad²	40 x 40 μrad²
Total emitted power	19 kW	2.55 kW
Final spot at sample (minimum)	300 x 100 μm²	6 x 4 μm²
Final divergence at sample (minimum)	2.3 x 0.3 mrad²	0.5 x 0.2 mrad²
Final photon flux at sample (ph/sec) at 12.4 keV	$2\cdot 10^{13}$	$5\cdot 10^{12}$
Energy range	7 – 36 keV	5 – 17 keV

Beamline Components → Radiation Sources/spectra



Liouville's theorem applied to photon beam dimensions:

$(S \times A)_{final} \geq (S \times A)_{initial}$

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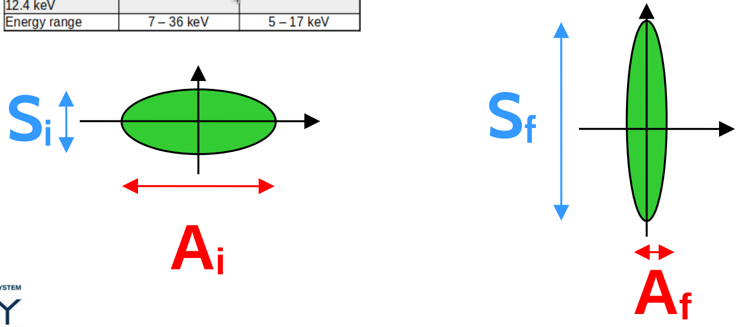
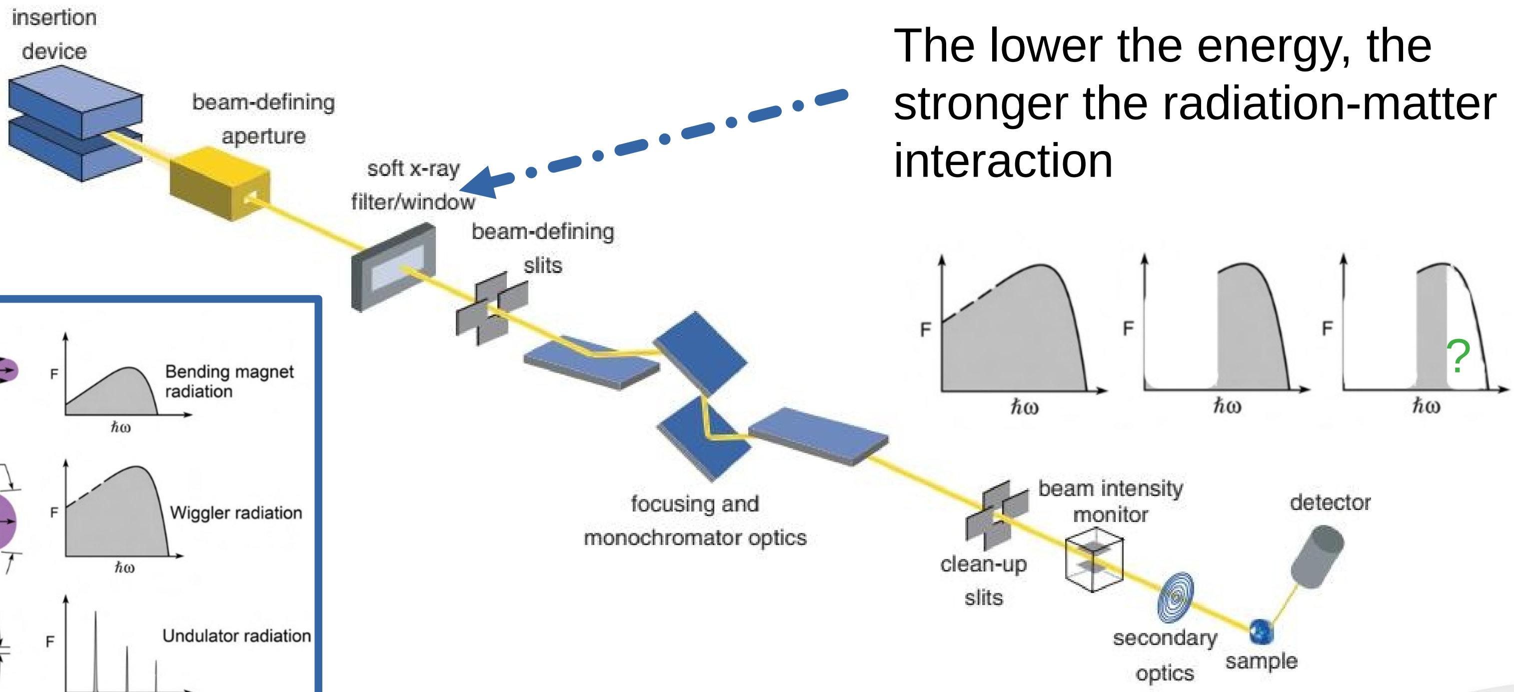
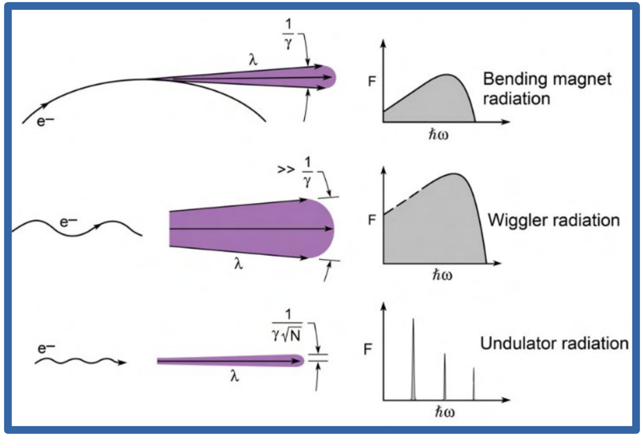


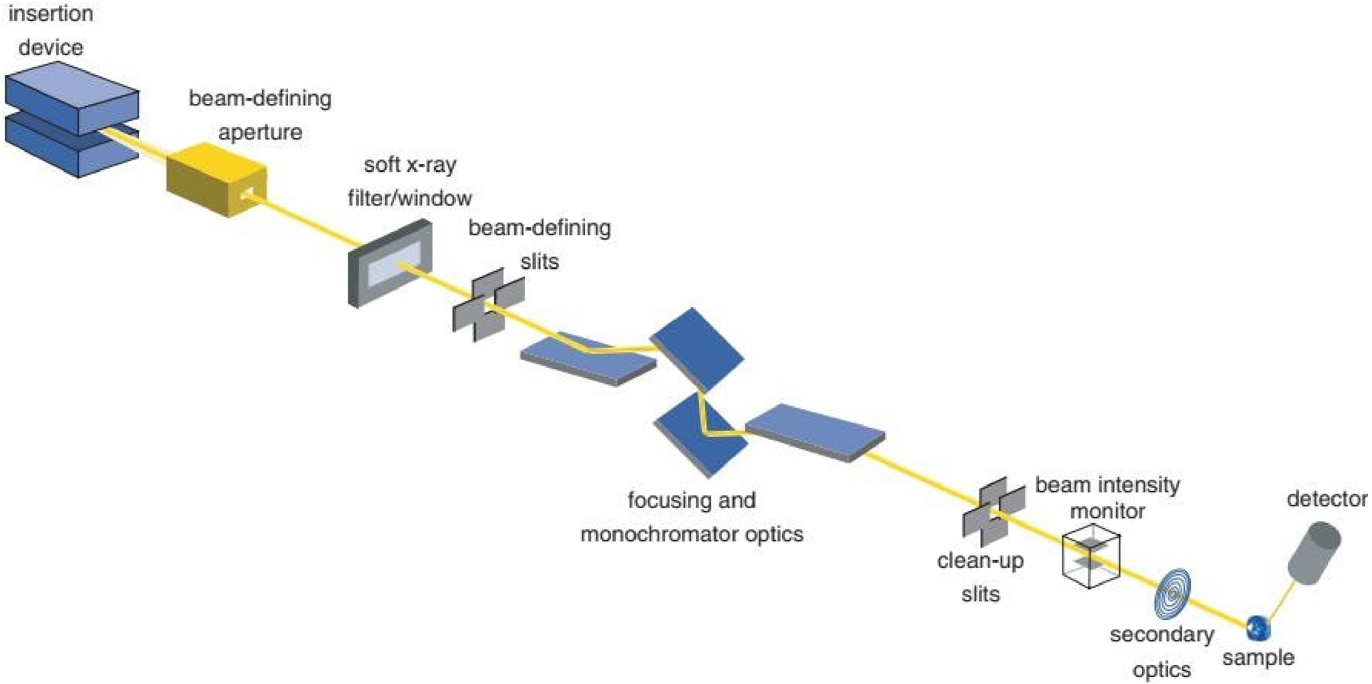
Beamline Components → Radiation Sources/spectra



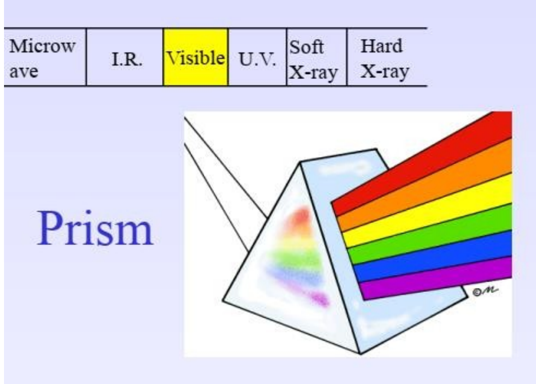
The lower the energy, the stronger the radiation-matter interaction

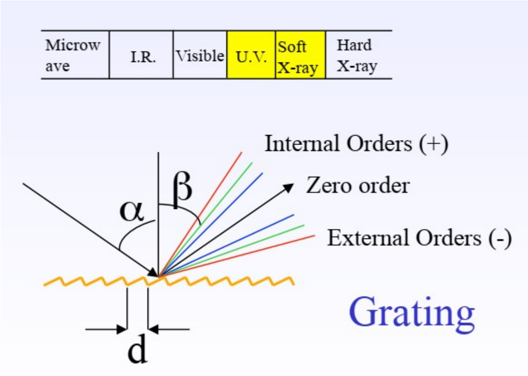


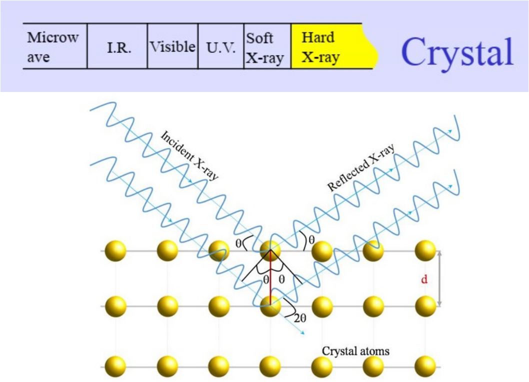
Beamline Components → Monochromator



Beamline Components → Monochromator

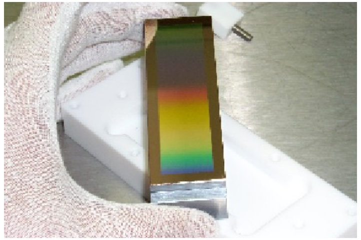




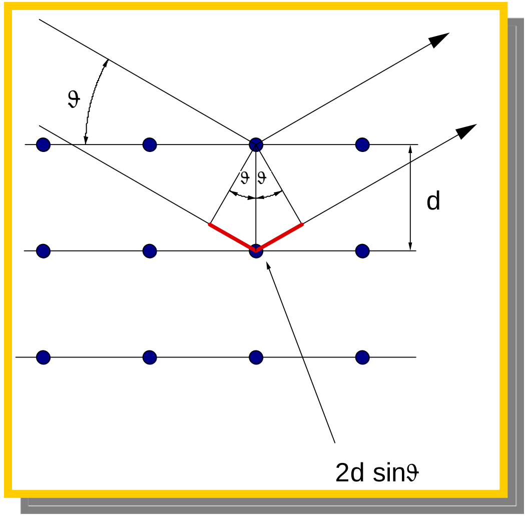


$$\sin\alpha + \sin\beta = Nk\lambda$$

$$2d\sin\vartheta = n\lambda$$



Beamline Components → Monochromator



Radiation of wavelength is reflected by the lattice planes. The outgoing waves interfere. The interference is constructive when the optical path difference is a multiple of λ :

$$2d\sin\vartheta = n\lambda$$

d is the distance between crystal planes.

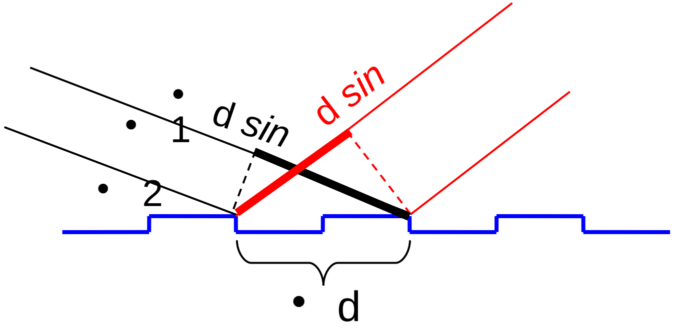
Si(111), d=3.13 Å, Emin ~ 2 KeV
Si(220), d=1.92 Å, Emin ~ 3.2 KeV
Si(311), d=1.64 Å, Emin ~ 3.8 KeV
InSb(111), d=3.74 Å, Emin ~ 1.7 KeV
Ge(111), d=3.27 Å, Emin ~ 1.9 KeV

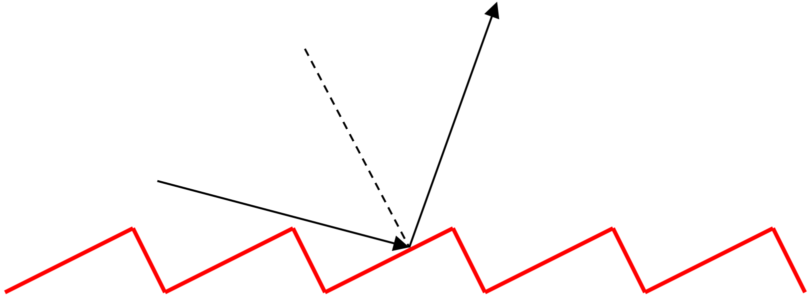
Multilayers:
W/Si, Mo/Si, W/B4C
Ru/B4C, Rh/C, Ni/C

Beamline Components → Monochromator

- The diffraction **grating** is an artificial periodic structure with a well defined period d. The diffraction conditions are given by the grating equation:

$$\sin\alpha + \sin\beta = Nk\lambda$$





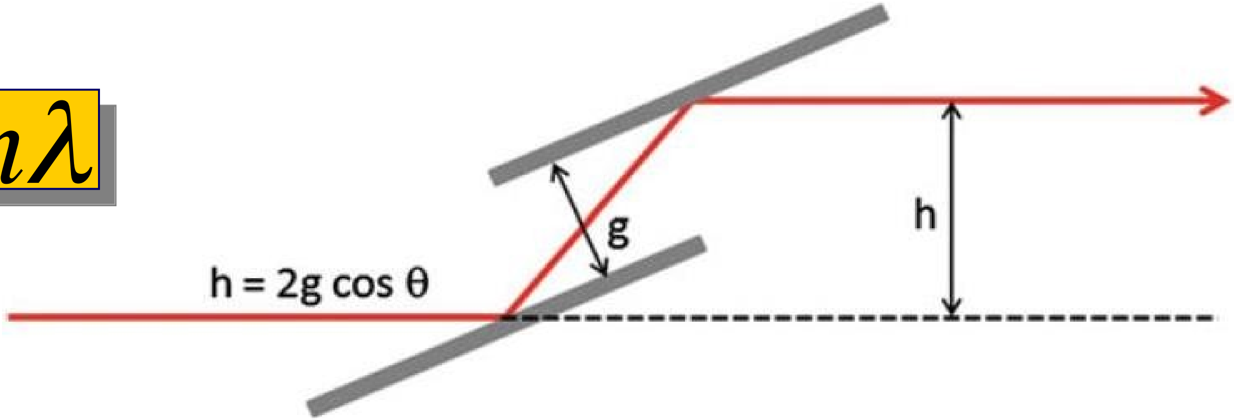
Laminar gratings: higher spectral purity

Blaze gratings: higher efficiency

Beamline Components → Monochromator

❖ Monochromator is made by two parallel crystals (usually with same hkl exposed face) and produces a monochromatic beam running parallel to the incident X-ray beam
❖ The whole system is mechanically designed in order to rotate the pair of crystals to change the incident angle corresponding to a given energy
❖ Maintaining the perfect parallelism is crucial for maximizing the throughput of the system

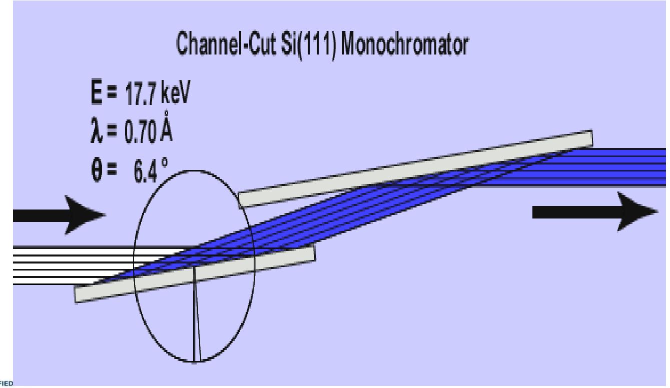
$$2d\sin\vartheta = n\lambda$$

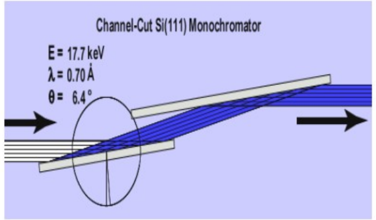


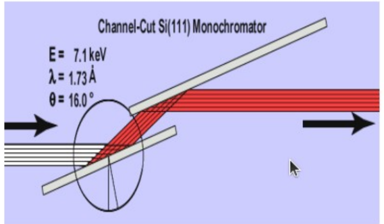
Beamline Components → Monochromator

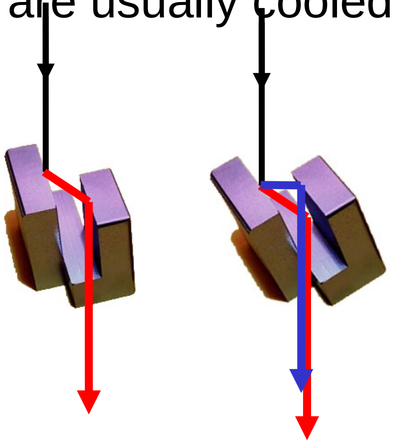
❖ Channel cut or Double crystal monochromator (DCM) :In order to make h fix (that is important for properly illuminating the downstream optics), g should be changed accordingly to the selected energy

Deformation of the crystal due to the thermal load can severely affect the performances of the monochromator. Monochromators are usually cooled



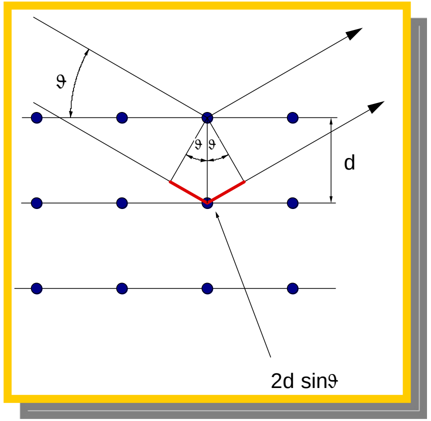






Beam moves!

Beamline Components → Monochromator



$$2\,d\,\sin\vartheta = n\lambda$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta E}{E} = \Delta\vartheta\,\frac{\cos\vartheta}{\sin\vartheta}$$

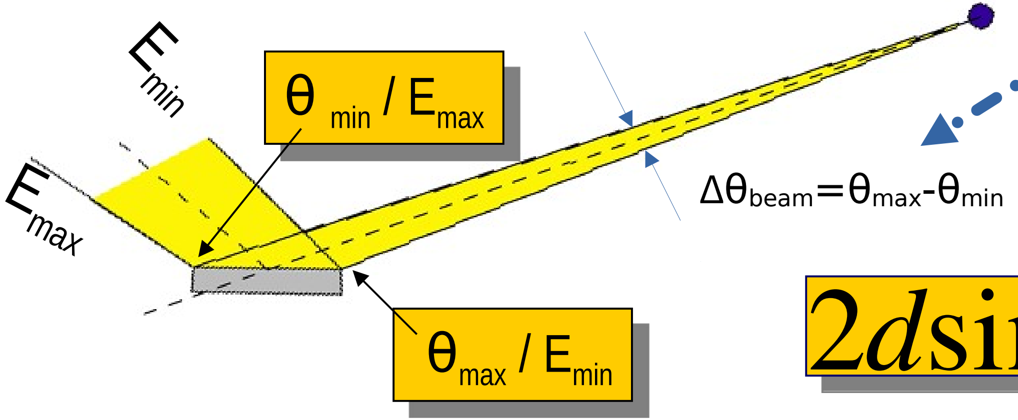
- The energy resolution of a crystal monochromator is determined by the angular spread ° of the diffracted beam and by the Bragg angle .

° has two contributions :

$°_{beam}$: **angular divergence of the <u>incident</u> beam**

$°_{crystal}$: intrinsic width of the Bragg reflection

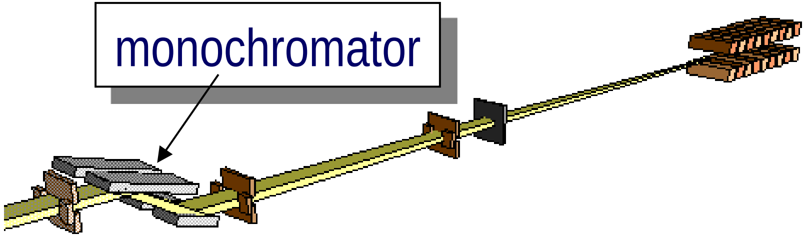
Beamline Components → Monochromator



It could be quite large for W/BM, or comparable with the intrinsic Bragg width (O)

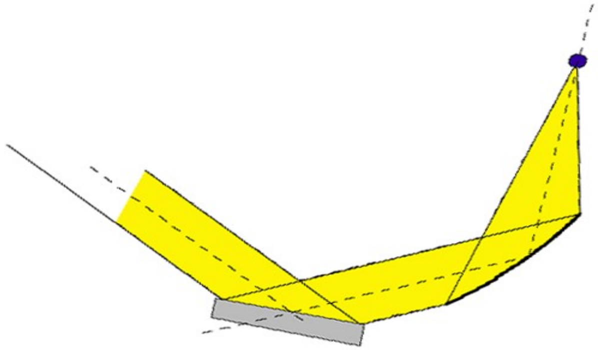
$$2d\sin\vartheta = n\lambda$$

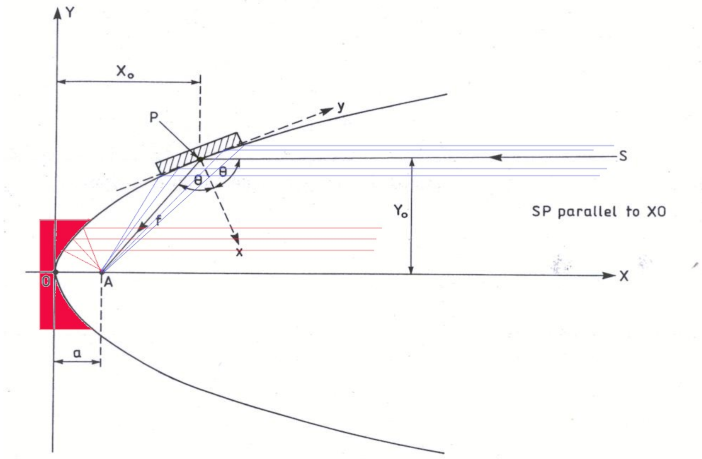
- A slit at the exit of the monochromator can select a narrower energy range.

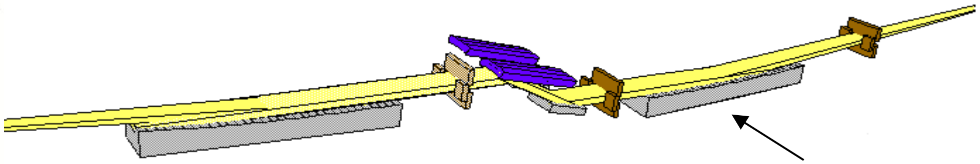


Beamline Components → Monochromator

- A collimating mirror in front of the crystal reduces the angular divergence $\Delta\theta_{beam}$ of the incident beam, improving the monochromator energy resolution.







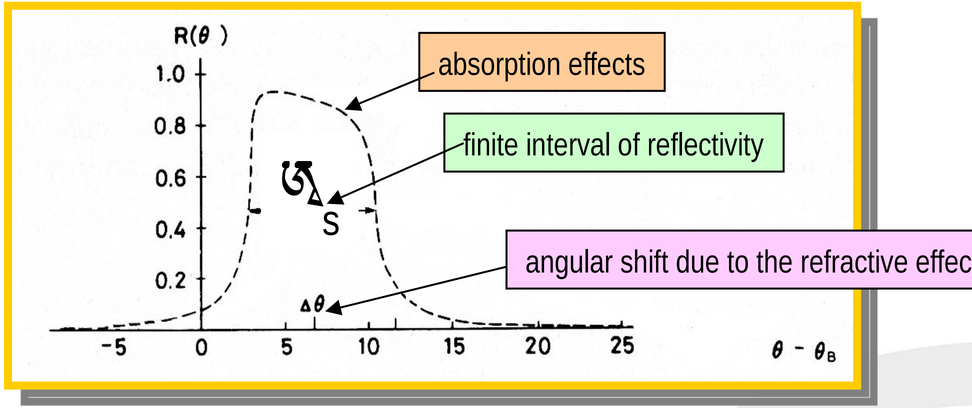
Collimating pre-mirror

Beamline Components → Monochromator

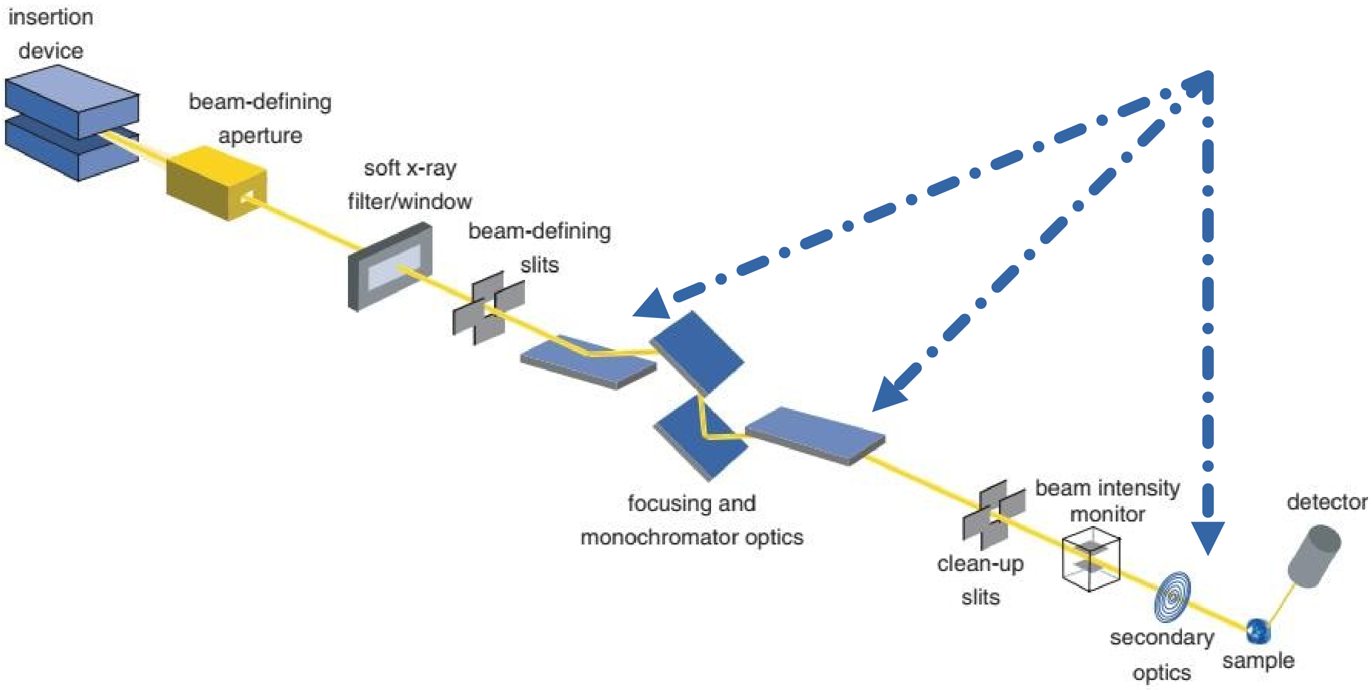
Intrinsic width of the Bragg reflection (maximum energy resolution)

- The intrinsic reflection width of the crystal, $\boldsymbol{\omega_s}$, can be obtained measuring the crystal reflectivity for a perfectly collimated monochromatic beam, as a function of the difference between the actual value of the incidence θ angle and the ideal Bragg value: $\Delta\theta = \theta - \theta_B$.

This reflectivity is derived by the dynamic diffraction theory, which includes multiple scattering **Darwin curve**:



Beamline Components → Mirrors (and more)

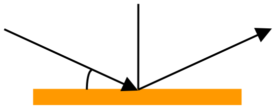


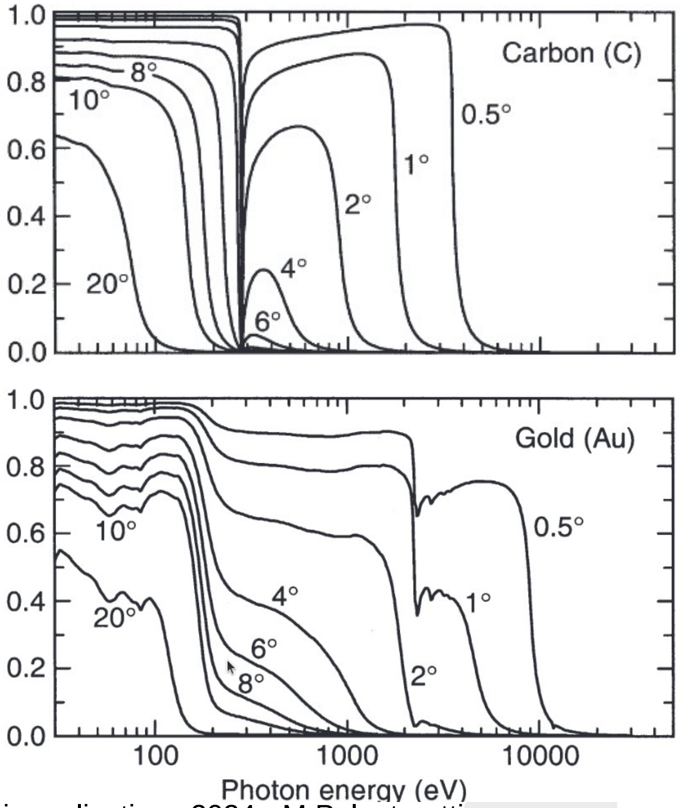
Beamline Components → Mirror Reflectivity

Reflectivity drops down fast with the increasing of the grazing incidence angle

→ only reflective optics at grazing incidence angles

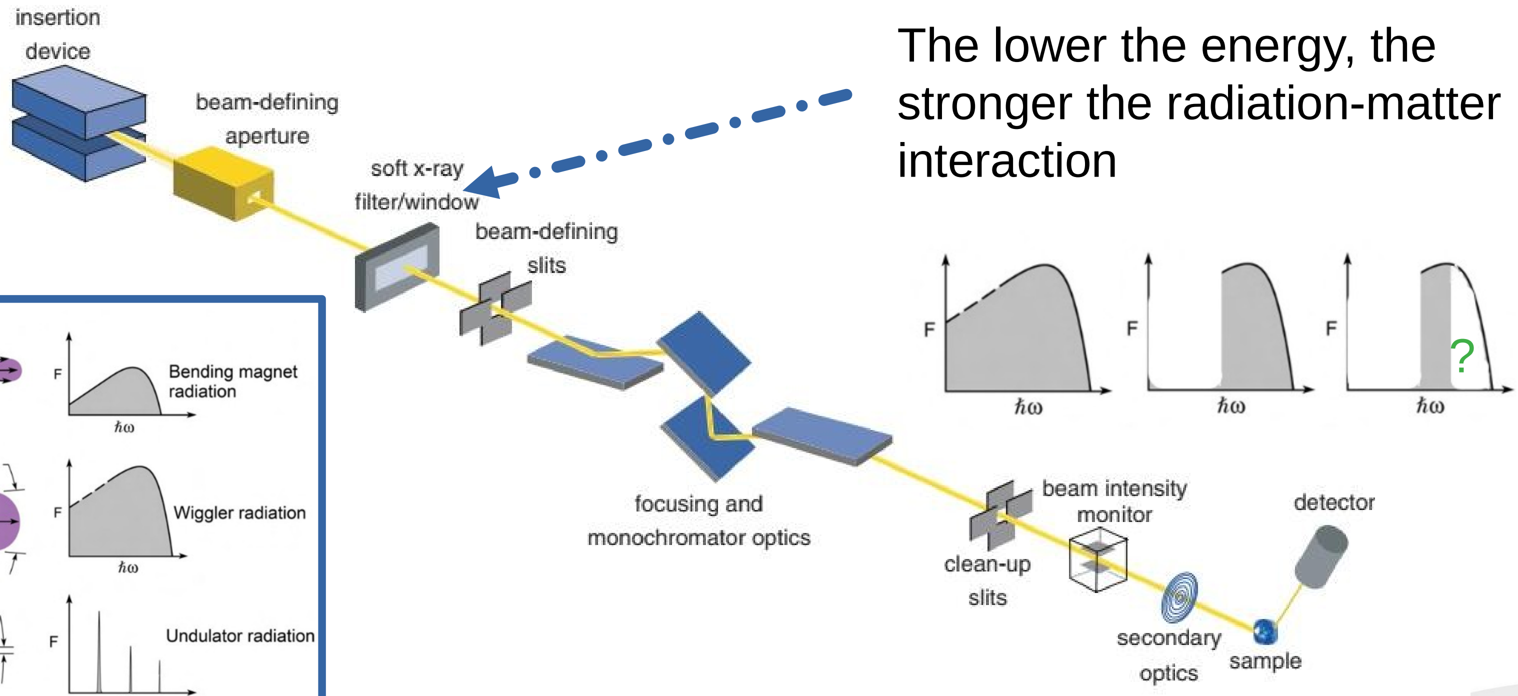
Typically 1°-2° for soft x-rays, few mrad for hard x-rays, 1 mrad= 0.057°



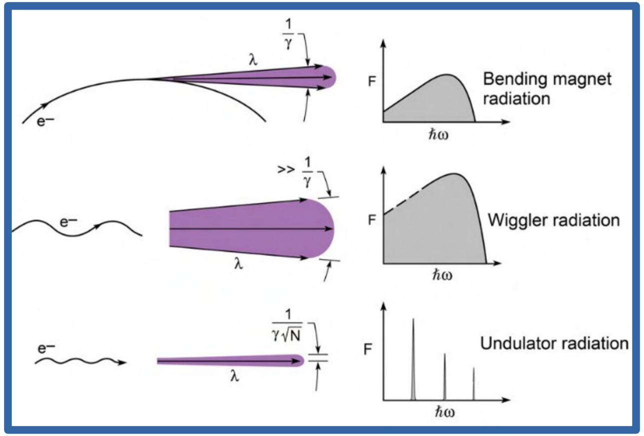


Reflectivity depends on photon energy… let's make a step back!

Beamline Components → Radiation Sources/spectra

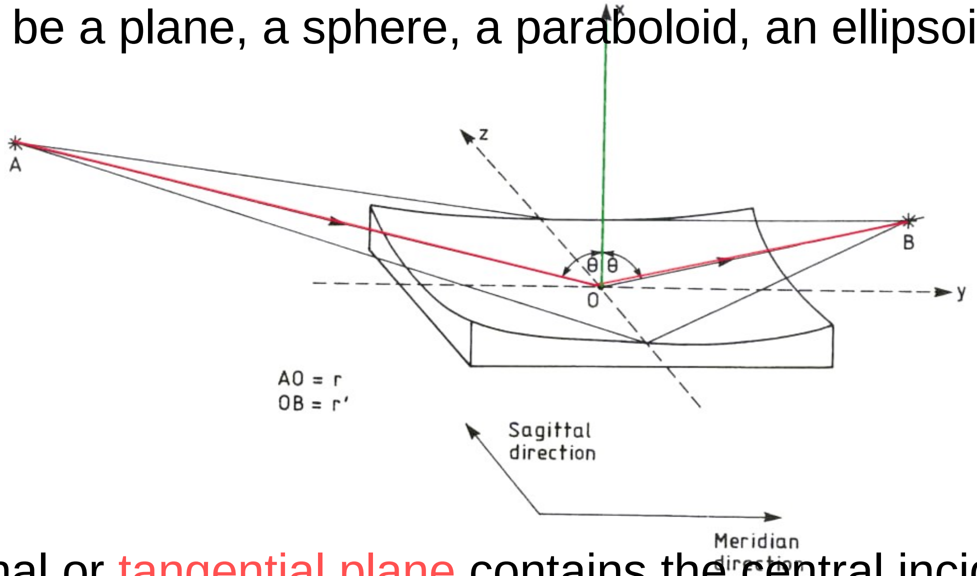


The lower the energy, the stronger the radiation-matter interaction



Beamline Components → Mirrors, focusing properties

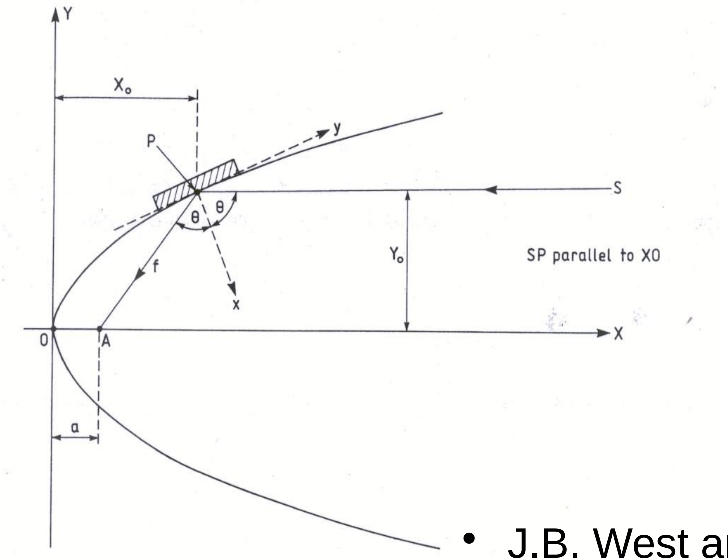
X-rays mirrors can have different geometrical shapes, their optical surface can be a plane, a sphere, a paraboloid, an ellipsoid and a toroid.



- The meridional or tangential plane contains the central incident ray and the normal to the surface. The sagittal plane is the plane perpendicular to the tangential plane and containing the normal to the surface.

Beamline Components → Mirrors (paraboloid)

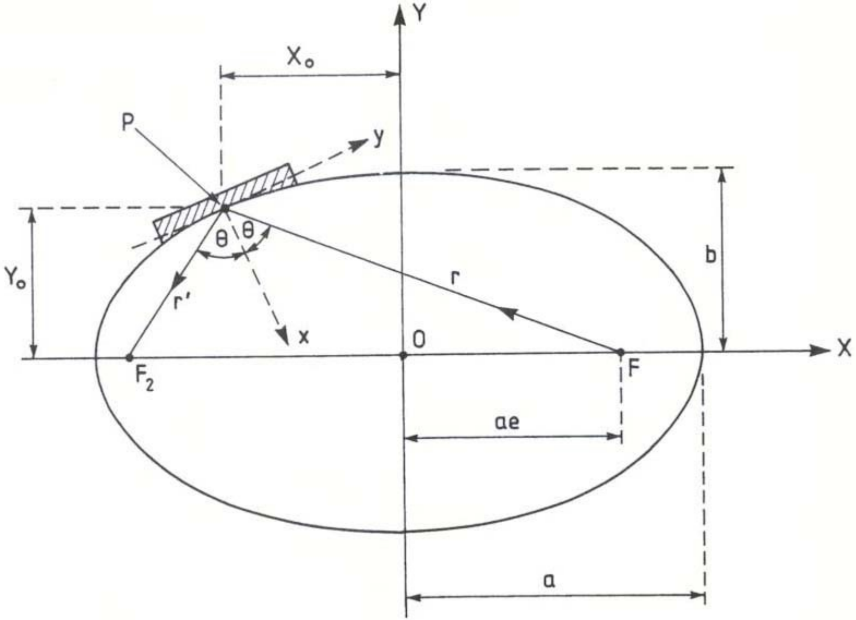
- Rays traveling parallel to the symmetry axis OX are all focused to a point A.
- Conversely, the parabola collimates rays emanating from the focus A.



- J.B. West and H.A. Padmore, Optical Engineering, 1987

Beamline Components → Mirrors (ellipsoid)

- Rays from one focus F_1 will always be perfectly focused to the second focus F_2.



- J.B. West and H.A. Padmore, Optical Engineering, 1987

Beamline Components → Mirrors (toroid)

Elettra Sincrotrone Trieste

- The bicycle tyre toroid is generated rotating a circle of radius   in an arc of radius R.
- In general, a toroid produces two non-coincident line images: one in the tangential focal plane and one in the sagittal focal plane
  - Tangential focus T:

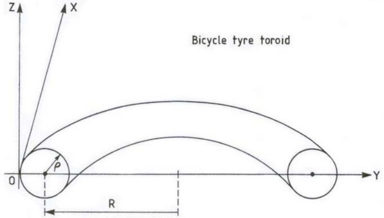
$$\left(\frac{1}{r}+\frac{1}{r'_t}\right)\frac{\cos\vartheta}{2}=\frac{1}{R}$$

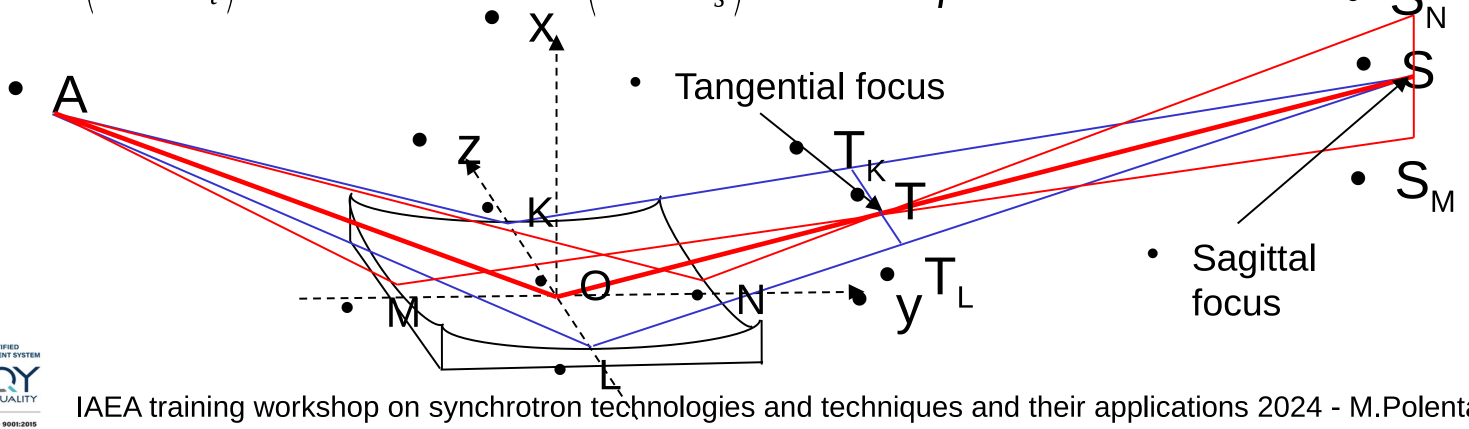
  - Sagittal focus S:

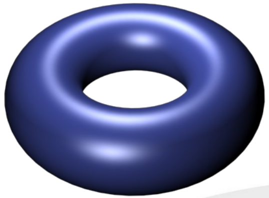
$$\left(\frac{1}{r}+\frac{1}{r'_s}\right)\frac{1}{2\cos\vartheta}=\frac{1}{\rho}$$

  - Stigmatic image:

$$\frac{\rho}{R}=\cos^2\vartheta$$

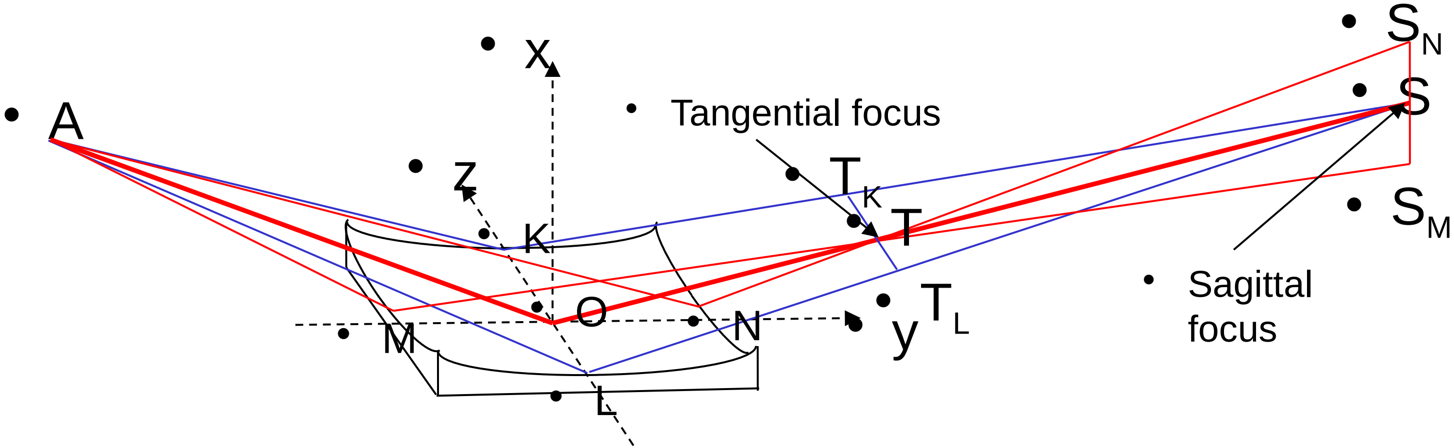


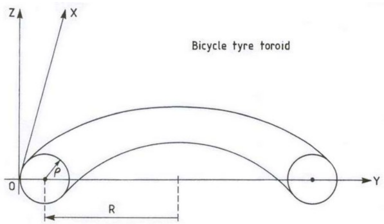


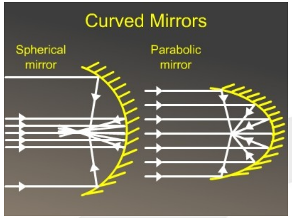


Beamline Components → Mirrors (spherical)

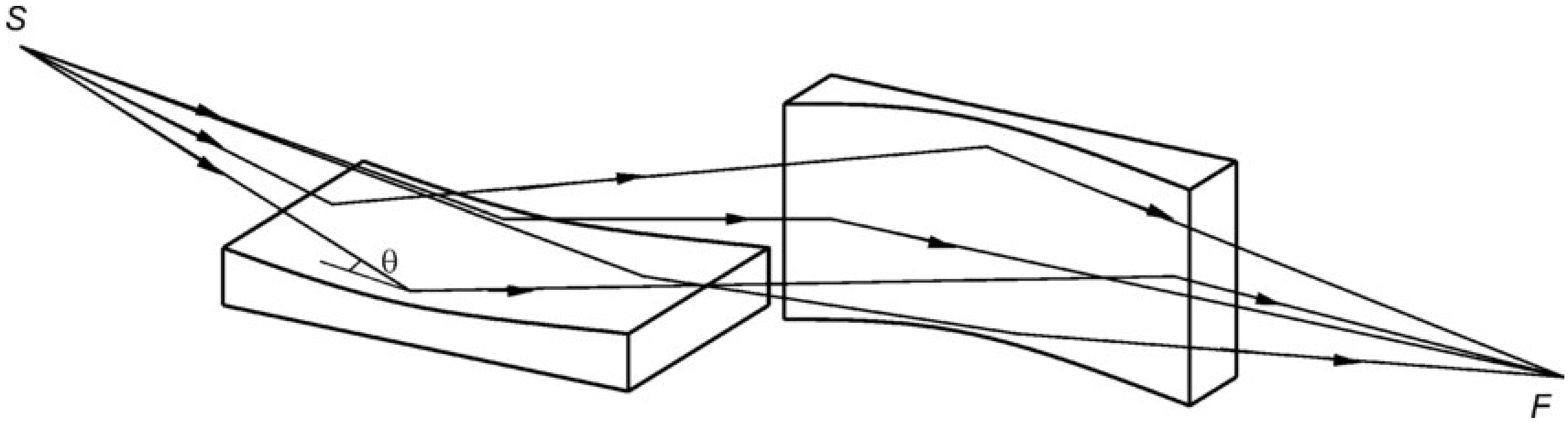
- For =R toroid becomes spherical.
- A stigmatic image can only be obtained at normal incidence.
- For a vertical deflecting spherical mirror at grazing incidence the horizontal sagittal focus is always further away from the mirror than the vertical tangential focus. The mirror only weakly focalizes in the sagittal direction.





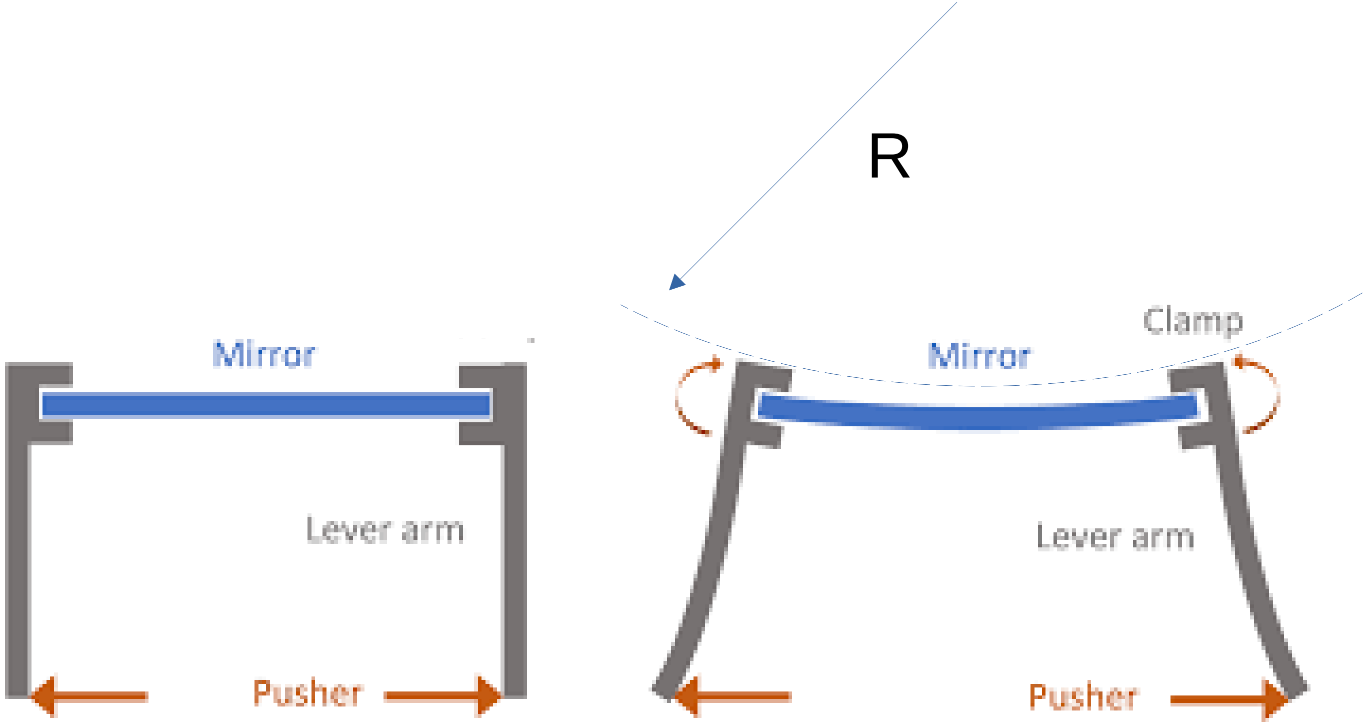


Beamline Components → Mirrors (Kirkpatrick-Baez)

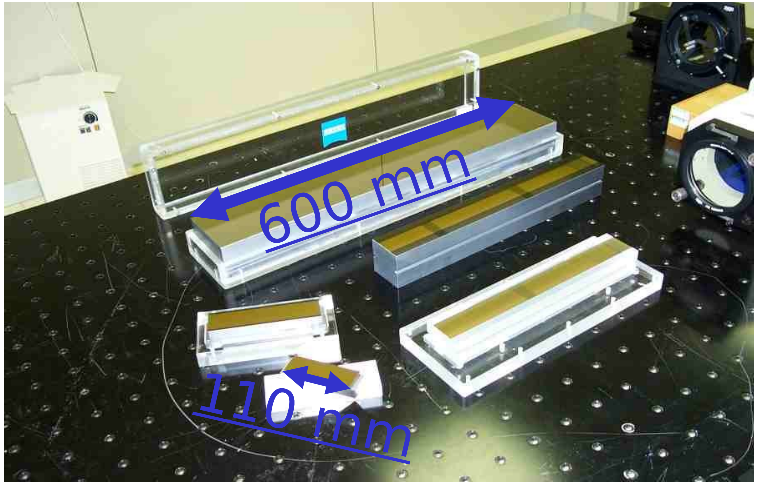


- This configuration, originally suggested by Kirkpatrick and Baez in 1948, is based on two mutually perpendicular concave spherical mirrors.

Beamline Components → Mirror bender



Beamline Components → Mirror defects



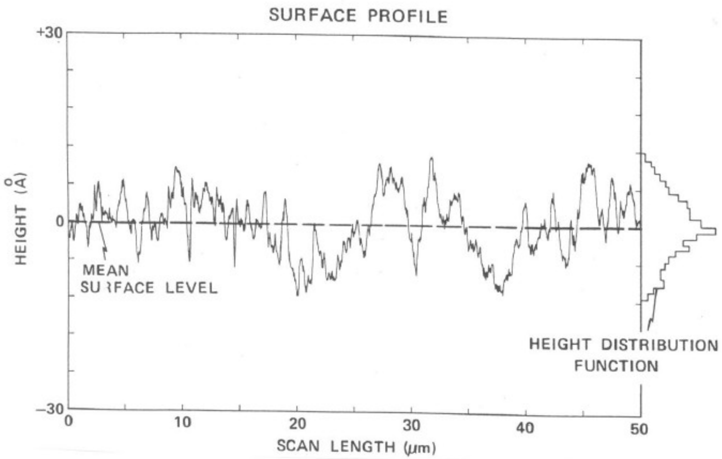
Manufacturing imperfections on a mirror surface:

- **Micro roughness** spatial period <1 mm
- **Slope errors** spatial period >1 mm

Beamline Components → Mirror defects, Microroughness

Micro roughness, Spatial period <1 mm

Characterized by the rms value of the surface height measured with respect to the mean surface level. **Usual range: 1-5 Å**



$$\sigma = \sqrt{\frac{1}{n}\sum_{x=0}^{n}\left[s(x) - \overline{s(x)}\right]^2}$$

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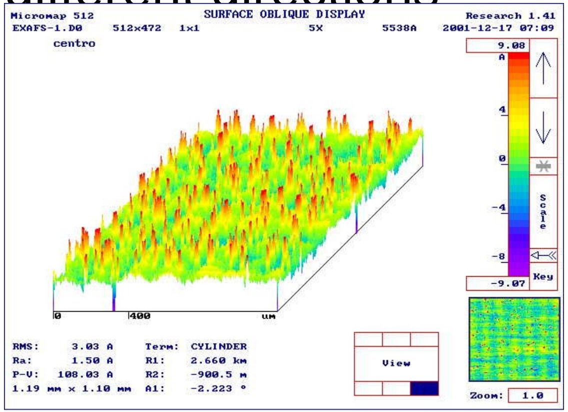
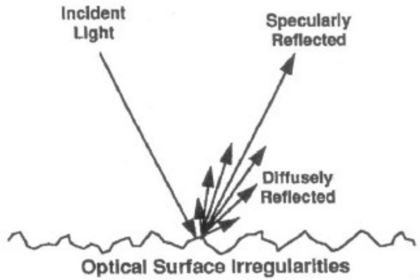
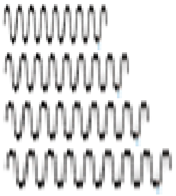
Beamline Components → Mirror defects, Microroughness

- produces a **diffuse background**: light is scattered at random directions
- superposition of diffraction gratings, each diffracting the light in different directions

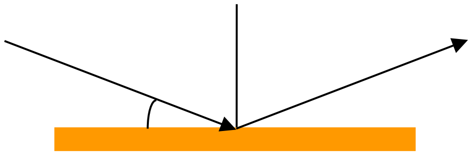




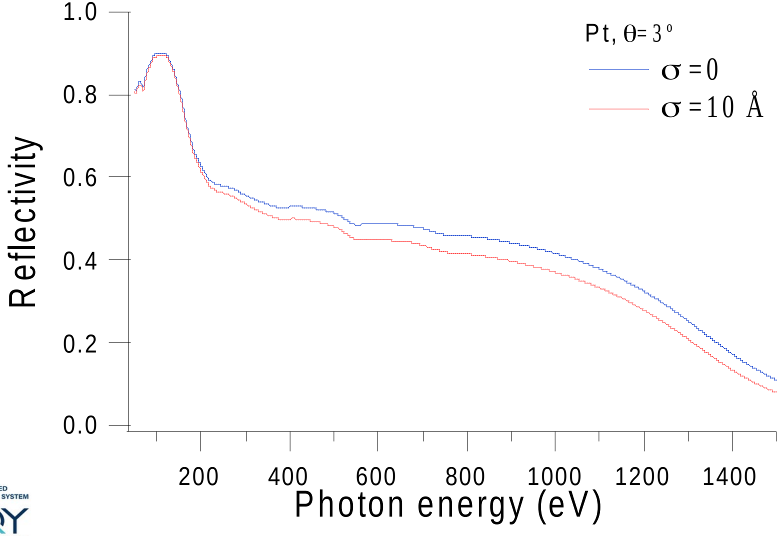


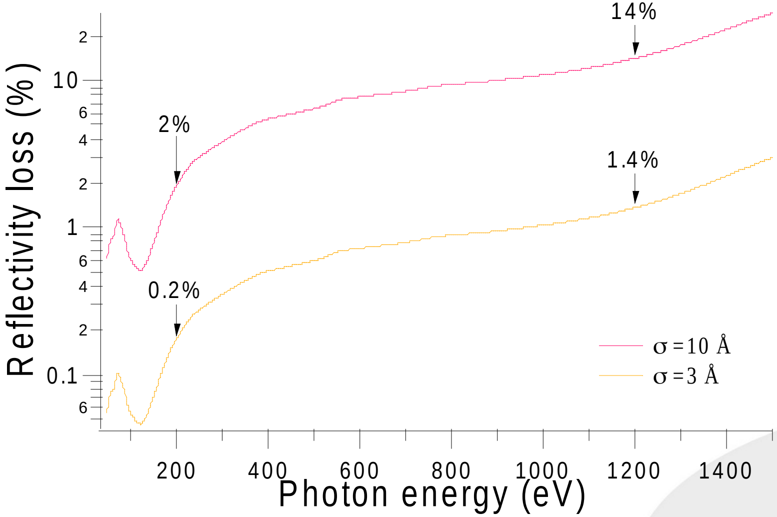
Beamline Components → Mirror defects, Microroughness

→ the reflectivity decreases: $R = R_0 e^{-\left(\frac{4\pi\sigma\sin\vartheta}{\lambda}\right)^2}$



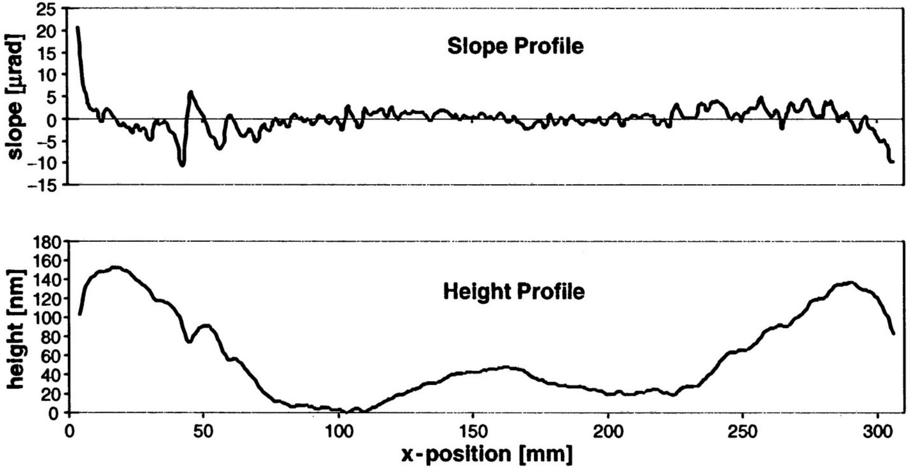
- R is the attenuated reflectivity, R_0 is the reflectivity of the ideal smooth surface





Beamline Components → Mirror defects, Slope

Slope errors: deviations from the the ideal profile of the mirror with **spatial period > 1 mm**
They are characterized by the rms value of the derivative of the error profile (**range 0.5-5 µrad**)



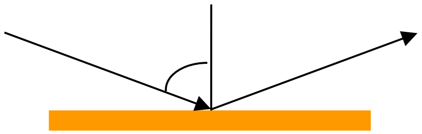
$$\delta(x) = \frac{dy}{dx}$$

$$y(x)$$

Beamline Components → Mirror defects, Slope

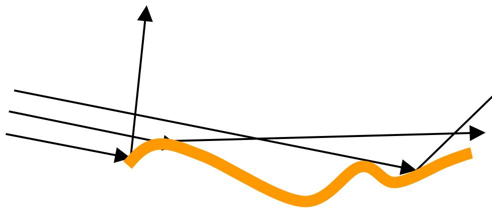
Slope errors enlarge the image formed by specular reflected beam

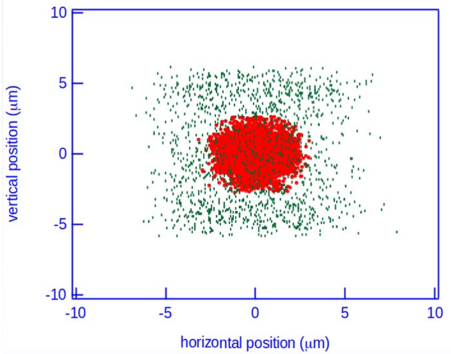
When a ray strikes the surface of a mirror at an incidence angle it is reflected at the same angle:

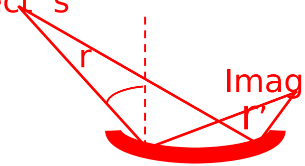


- Slope errors locally rotate the direction of the normal to the optical surface

→ rotate the direction of the reflected beam







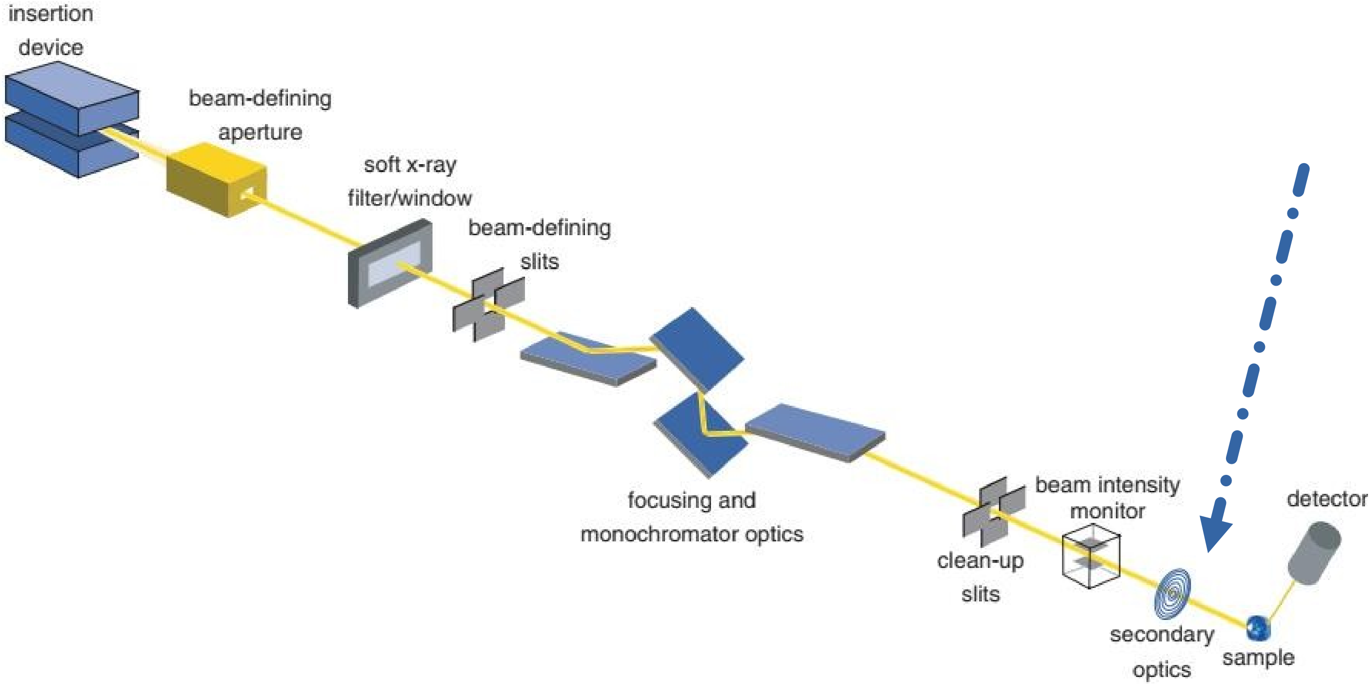
Beamline Components → Mirror Manufacture

Shape	Spherical/ Flat	Toroidal/ aspherical
Roughness (Å) on glass based materials	3Å standard 1Å best	5Å standard 3Å best (1-2 some times happen)
Roughness (Å) on metallic materials	5Å standard 3Å best	5Å standard 3Å best

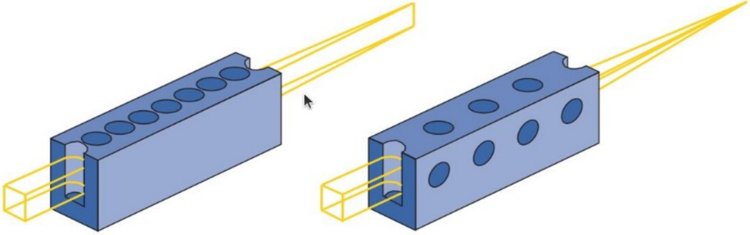
Typical values (SESO, ZEISS, Winlight, Jobin Yvon)

Shape	Length	rms slope errors
Spherical/ flat	Up to 500 mm	< 0.5 µrad
Spherical/ flat	> 500 mm	1-2 µrad
Toroidal	Up to 500 mm	1 µρad
Toroidal	> 500 mm	2 µrad
Aspherical	Up to 500 mm	2 µrad
Aspherical	> 500 mm	3-5 µrad

Beamline Definition → Other optics



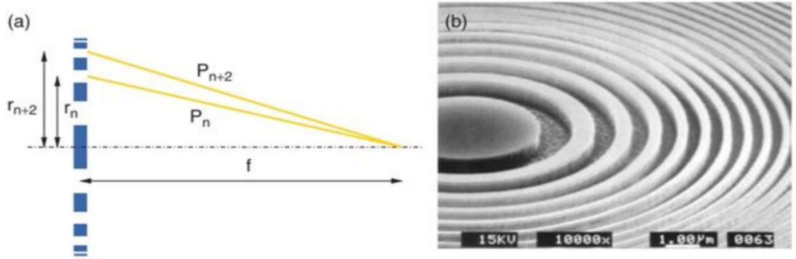
Beamline Definition



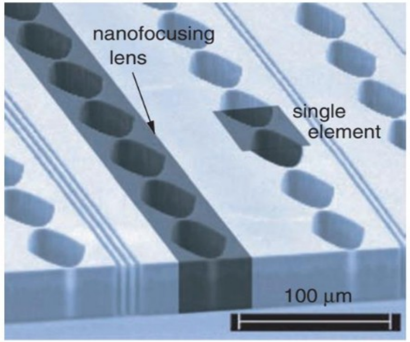
compound refractive lenses (CRLs)

Be lenses

Refractive x-ray lenses on a holder



Fresnel zone plates. (a) The path difference between adjacent transparent rings, $P_{n+2} - P_n$, in a zone plate should be equal to the wavelength of the x-rays being focused. (b) An electron microscopy image of a zone plate manufactured using electron-beam microlithography.



nanofocusing lens array fabricated by lithographic and ion-etching techniques

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Beamline Definition