Optics of soft x-ray beamline

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- **Outline**

✓ Beamline

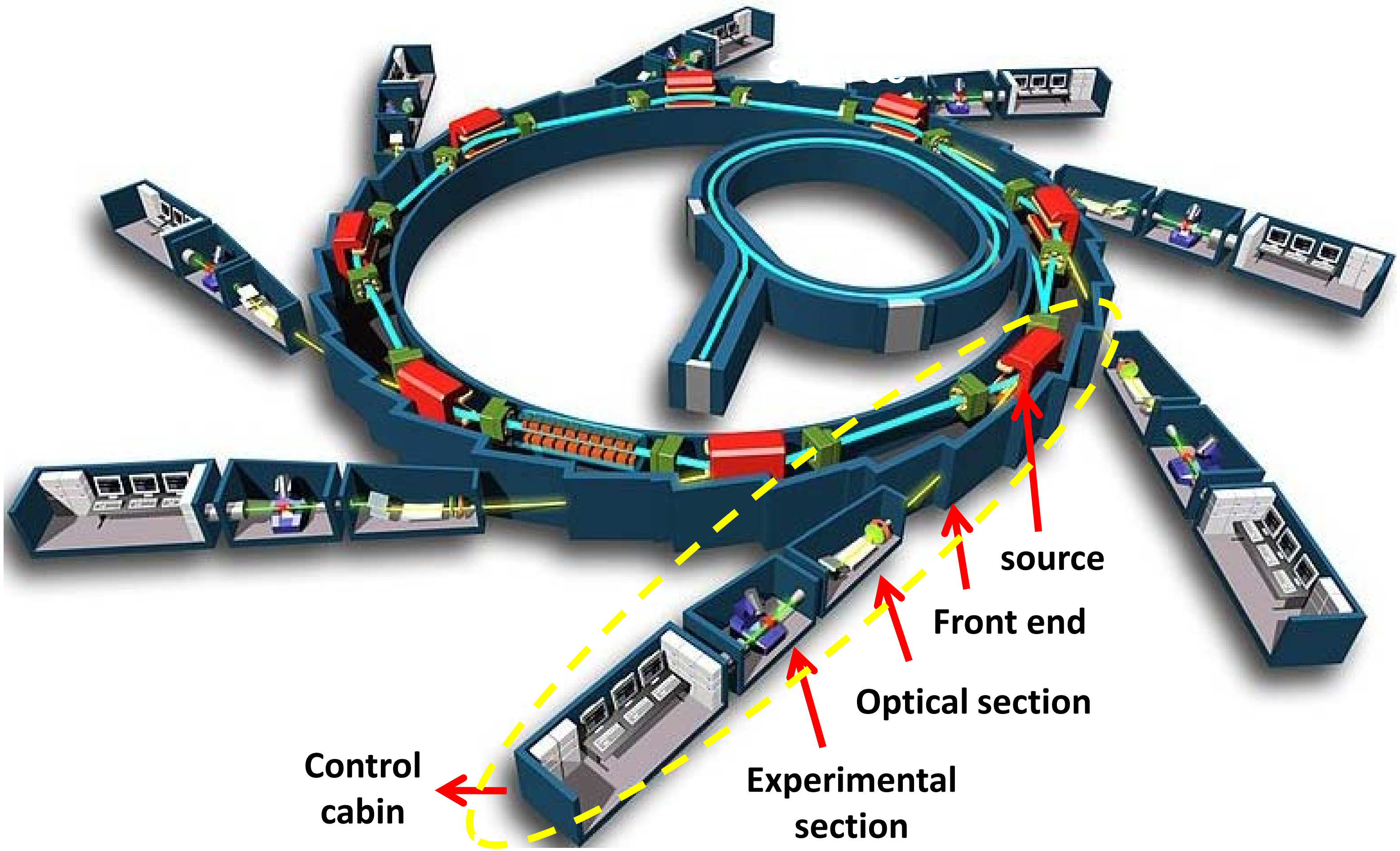
✓ soft x-ray beamline optics

  mirrors, Grating, monochromator, …

✓ Example of some soft X-ray beamlines

✓ Ray-tracing of a SpectroMicroscopy beamline of ILSF`

beamline



Schematic figure of synchrotron and different part of beamline

Optical section of Beamline

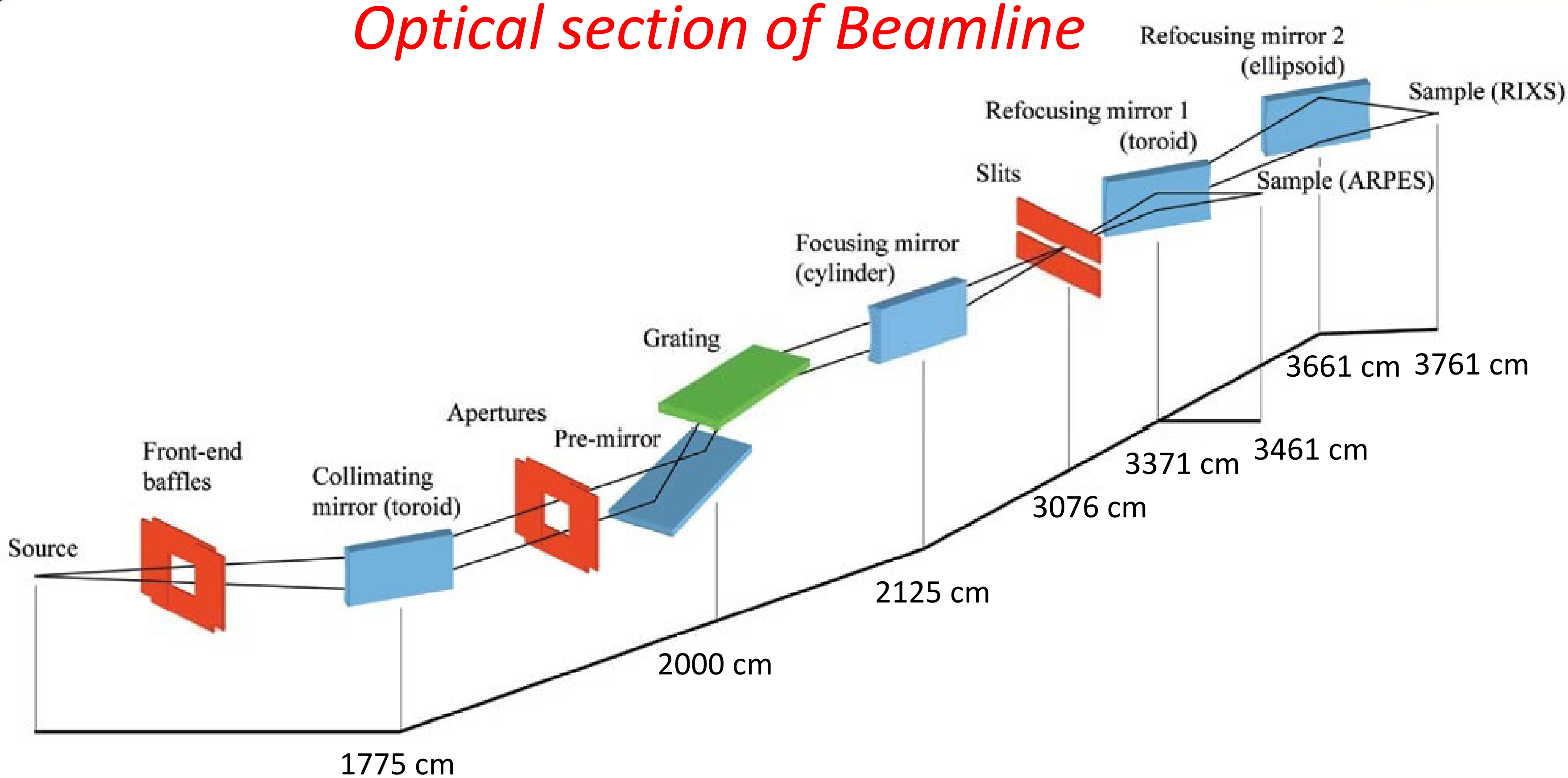
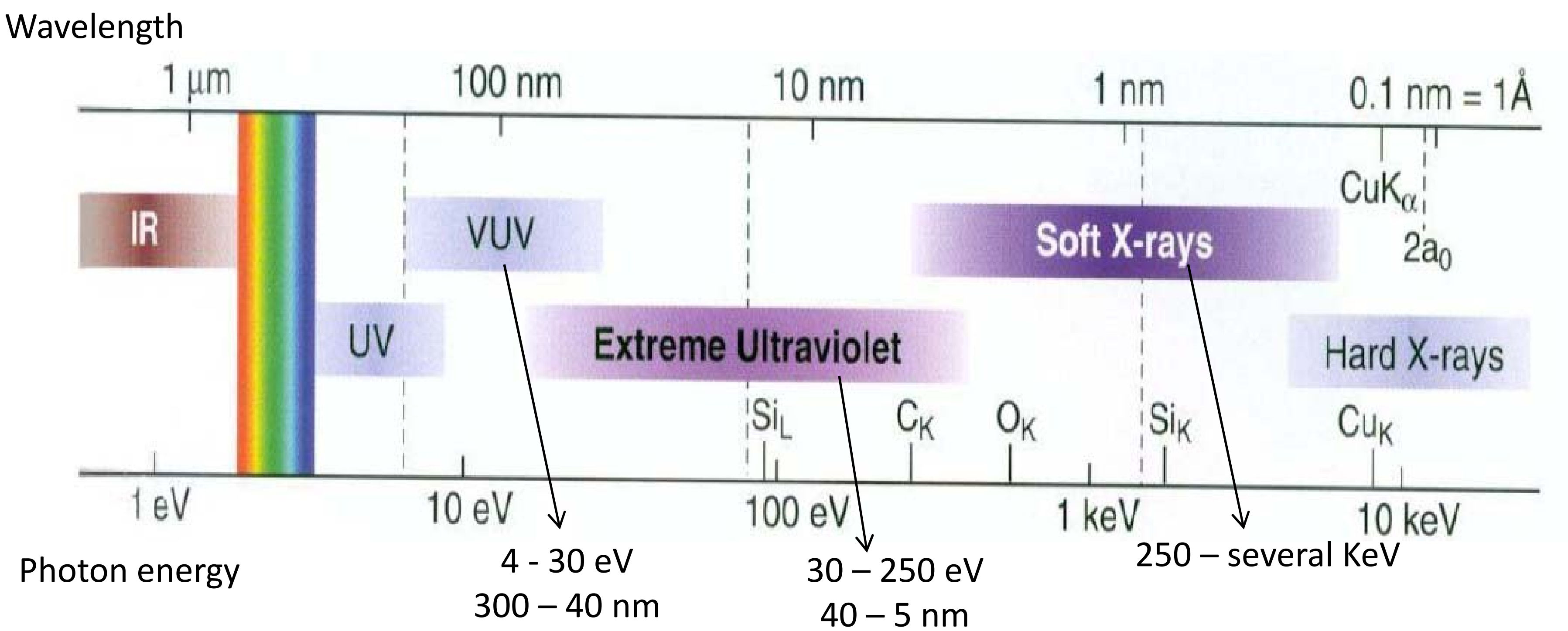


Fig: Sketch of the soft x-ray beamline

The beamline is the means of bringing the radiation from the source to the experiment transforming the phase volume in a controlled way, that is:
demagnifying and monochromatizing the source and refocusing it onto a sample.

VUV, EUV and soft x-rays



These regions are very interesting because are characterized by the presence of the absorption edges of most low and intermediate Z elements

mirrors

The mirrors which are included in a synchrotron radiation beamline perform different function:

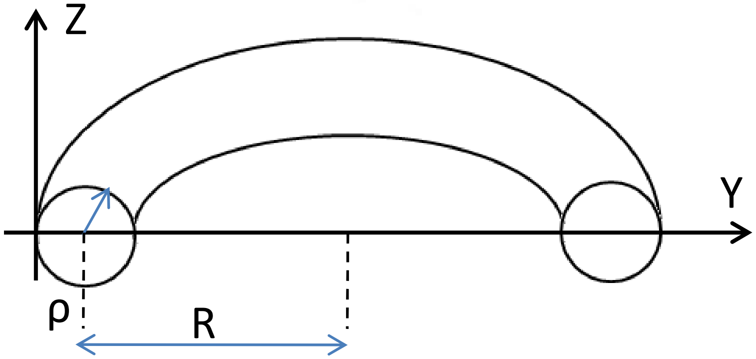
- ✓ Focusing the radiation
- ✓ To split the radiation and send it to two or more beamline
- ✓ To filter off the high photon radiation or eliminating the higher order output of the monochromator

Geometric shape of mirrors:

- ✓ Plane
- ✓ Spherical
- ✓ Aspherical (elliptical, paraboloidal, and troidal)
- ✓ Bent plane mirrors

Toroid

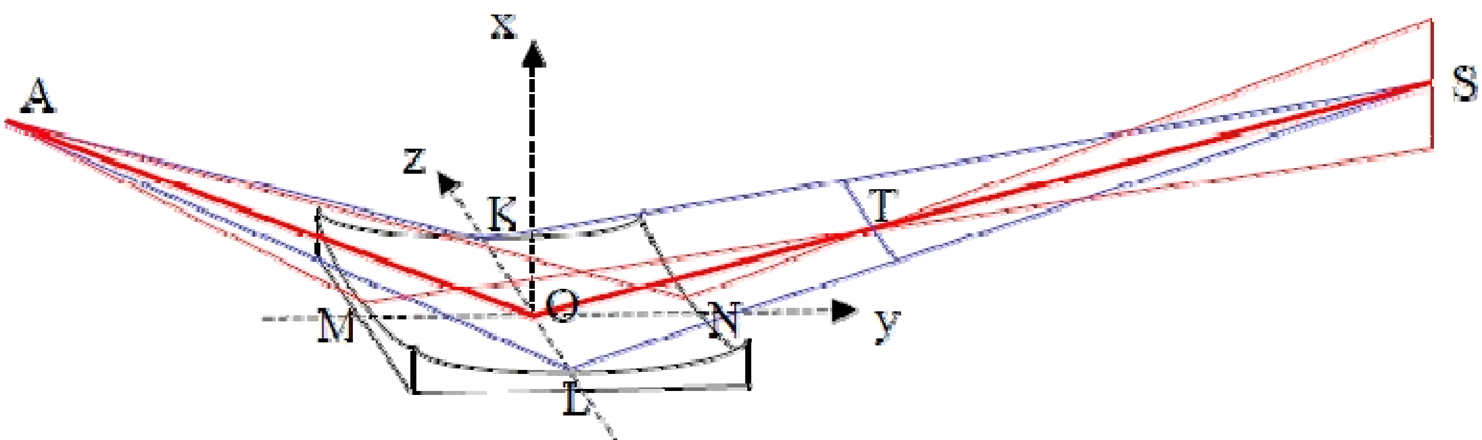
The toroid is generated by rotating a circle of radius ρ in an arc of radius R. In general, two non-coincident focii are produced: one in the meridional plane and one in the sagittal plane.



$$x^2 + y^2 + z^2 = 2Rx - 2R(R-\rho) + 2(R-\rho)\sqrt{(R-x)^2 + y}$$

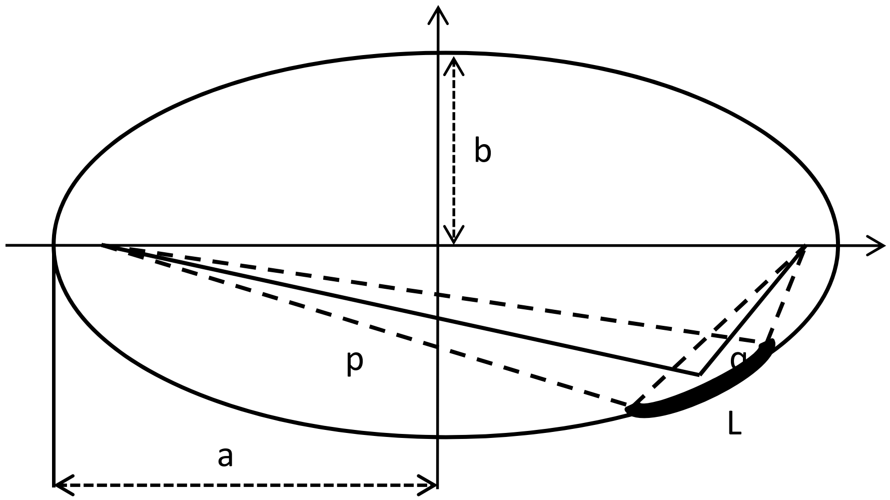
$$\left[\frac{1}{r} + \frac{1}{r_t'}\right]\frac{Cos\theta}{2} = \frac{1}{R}$$ Tangential focus

$$\left[\frac{1}{r} + \frac{1}{r_s'}\right]\frac{1}{2Cos\theta} = \frac{1}{\rho}$$ sagittal focus



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

ellipse



$$\frac{X^2}{a^2}+\frac{Y^2}{b^2}=1$$

$$a=\frac{p+q}{2}$$

$$b=a\sqrt{1-e^2}$$

$$e=\frac{1}{2}\sqrt{r^2+r'^2-2rr'\cos^2\theta}$$

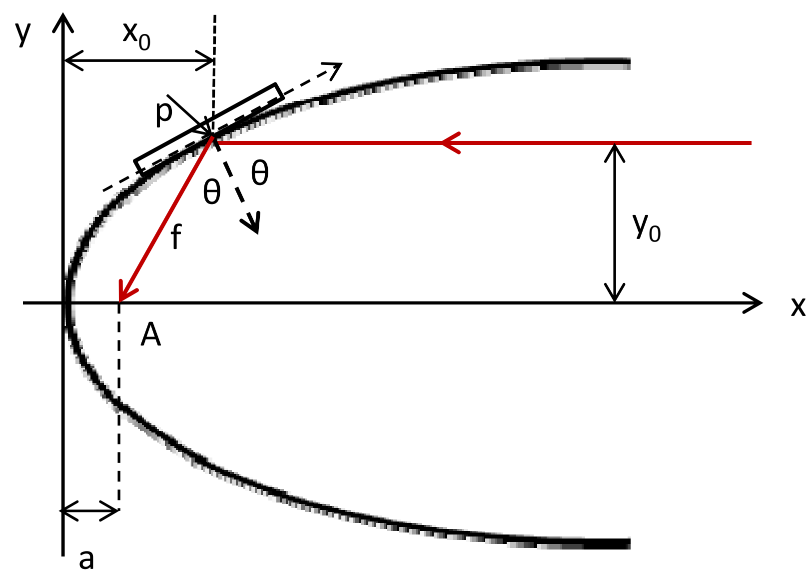
Parabola:

$$y^2=4ax$$

$$a=f\cos^2\theta$$

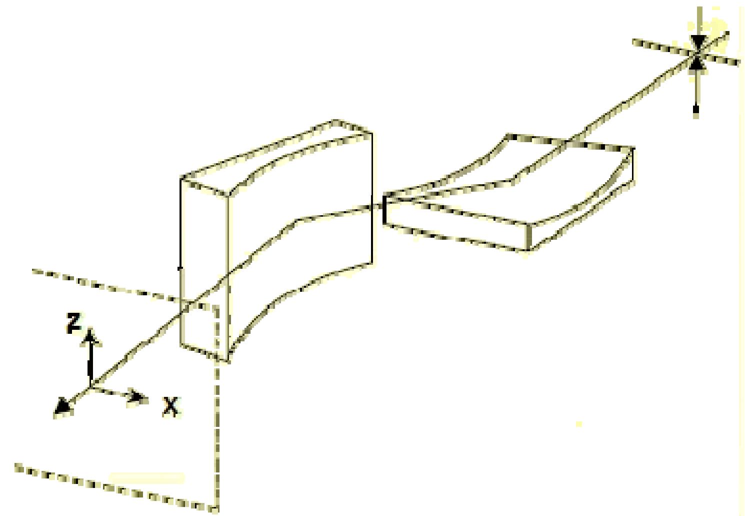
$$x_0=a\tan^2\theta$$

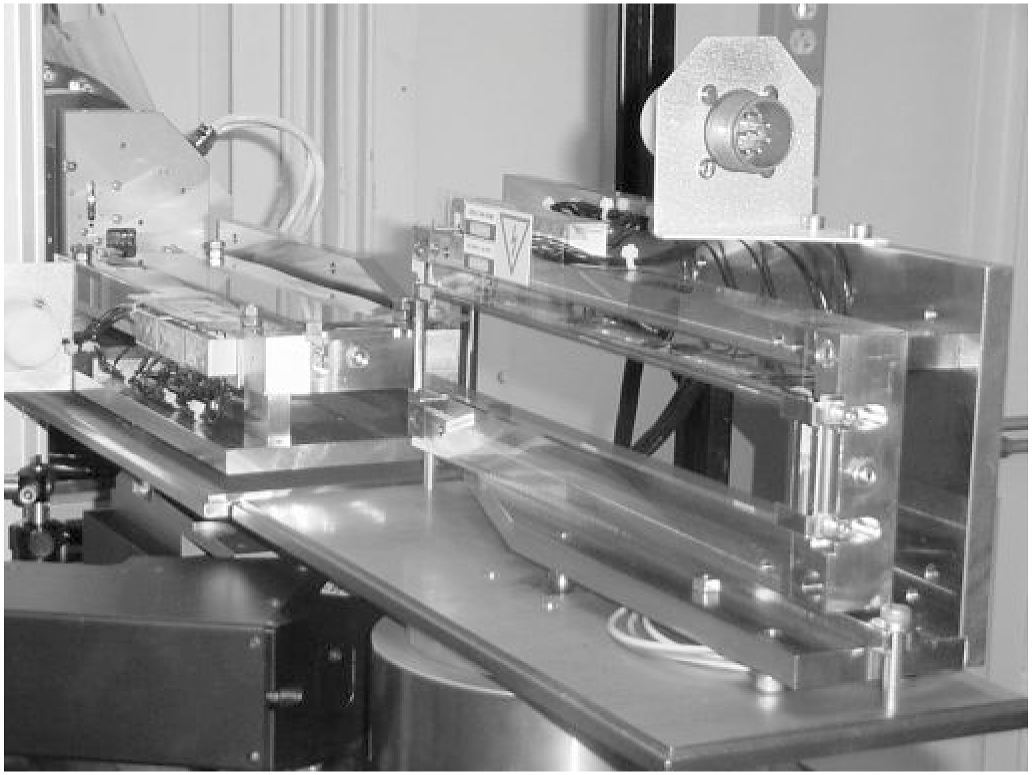
$$y_0=2a\tan\theta$$

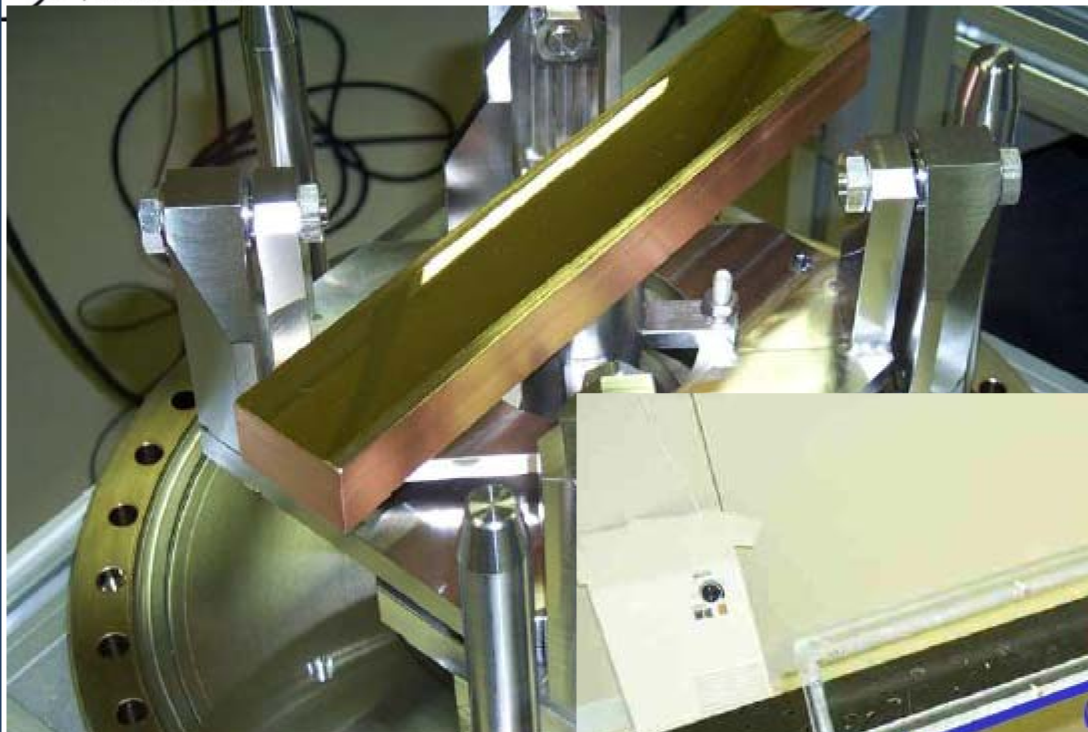


KB confoguration

The two mirror designed to separate to the functions of horizontal and vertical focussing








600 mm
110 mm

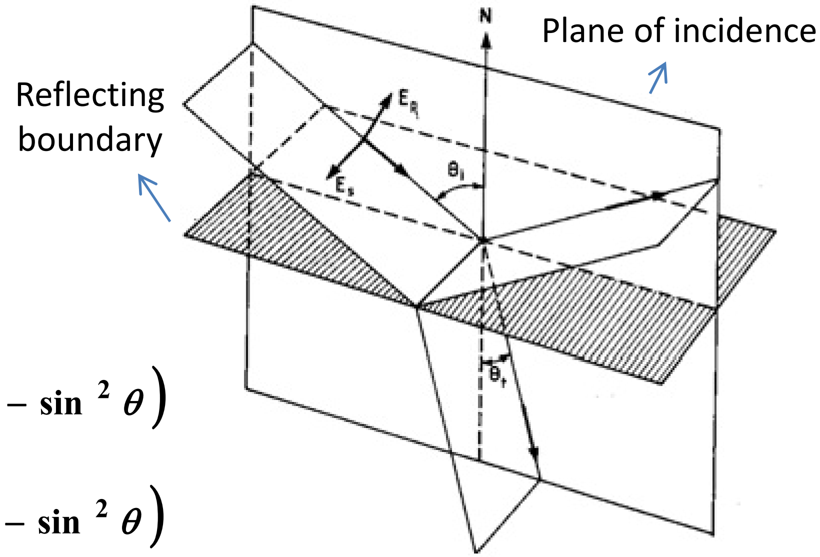
Reflectivity of mirrors

$$R_s = \frac{a^2 + b^2 - 2s\cos\theta + \cos^2\theta}{a^2 + b^2 + 2s\cos\theta + \cos^2\theta}$$

$$R_p = R_s\left(\frac{a^2 + b^2 - 2a\sin\theta\tan\theta + \sin^2\theta\tan^2\theta}{a^2 + b^2 + 2a\sin\theta\tan\theta + \sin^2\theta\tan^2\theta}\right)$$

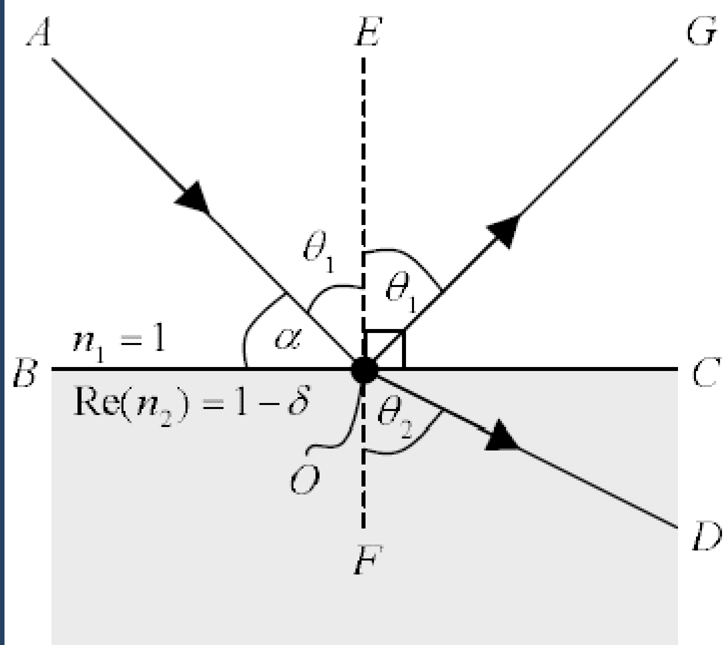
$$2a^2 = \left[\left(n^2 - k^2 - \sin^2\theta\right)^2 + 4n^2k^2\right]^{\frac{1}{2}} + \left(n^2 - k^2 - \sin^2\theta\right)$$

$$2b^2 = \left[\left(n^2 - k^2 - \sin^2\theta\right)^2 + 4n^2k^2\right]^{\frac{1}{2}} - \left(n^2 - k^2 - \sin^2\theta\right)$$



R_s= Reflectivity of the component whose E vector is perpendicular to the plane of incidence
R_p= Reflectivity of the component whose E vector is parallel to the plane of incidence
Complex refractive index:
$\tilde{N}(E) = n(E) - ik(E)$
n(E) is the real part and the usual index of refraction
k(E) is the imagainary part and extinction coefficient

Grazing angles



$$\mathrm{Re}(n_1)Sin\theta_1 = \mathrm{Re}(n_2)Sin\theta_2$$

$$Sin\theta_1 = (1-\delta)Sin\theta_2 \Rightarrow \theta_2 > \theta_1$$

$$\theta_1^{Crit} \rightarrow \theta_2 = \pi/2$$

$$\alpha^{Crit} = \pi/2 - \theta_1^{Crit}$$

$$Sin\theta_1^{Crit} = Sin(\pi/2-\alpha) = Cos\alpha^{Crit} = 1-\delta$$

$$Cos\alpha^{Crit} = 1 - 1/2(\alpha^{Crit})^2 = 1-\delta$$

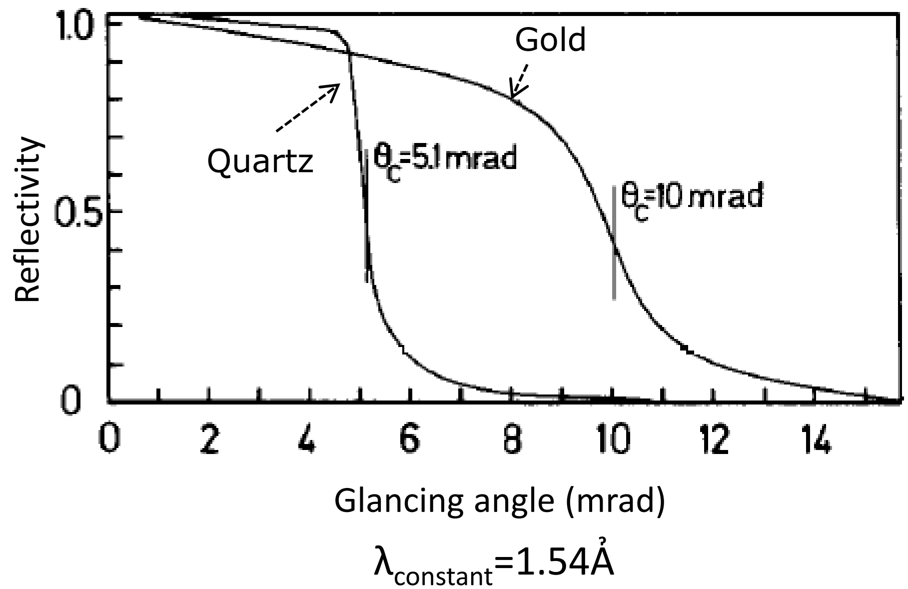
$$\Rightarrow \quad \alpha^{Crit} = \sqrt{2\delta}$$

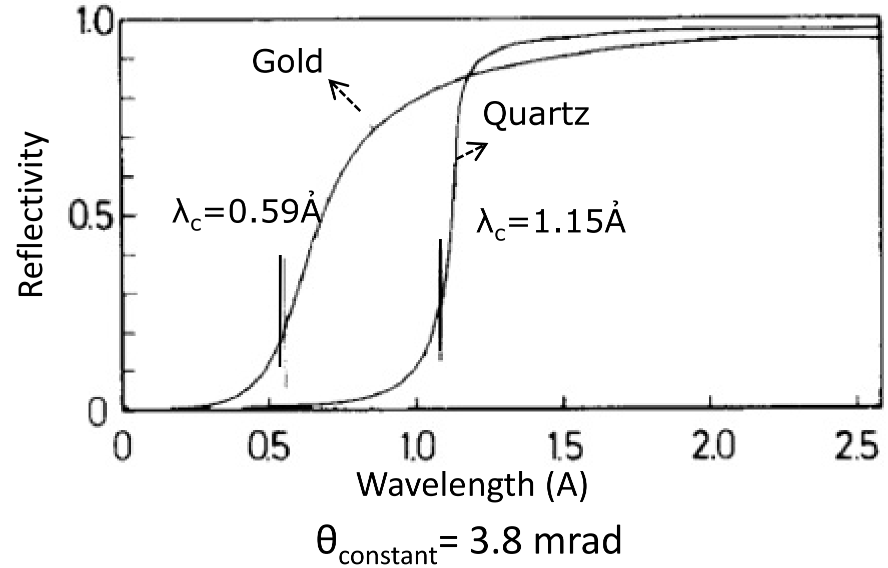
$$\delta = \frac{e^2\rho}{2\varepsilon_0 m_e C^2 k^2}$$

$$\alpha^{Crit} = \frac{\lambda e}{2\pi C}\sqrt{\frac{\rho}{\varepsilon_0 m_e}}$$

ρ: the number of electrons per unit volume
ε_0: the electrical permittivity of free space
m_e: the rest mass of the electron
c: the speed of light in vacuum
k: the wave-number of the X-ray radiation

Grazing angles



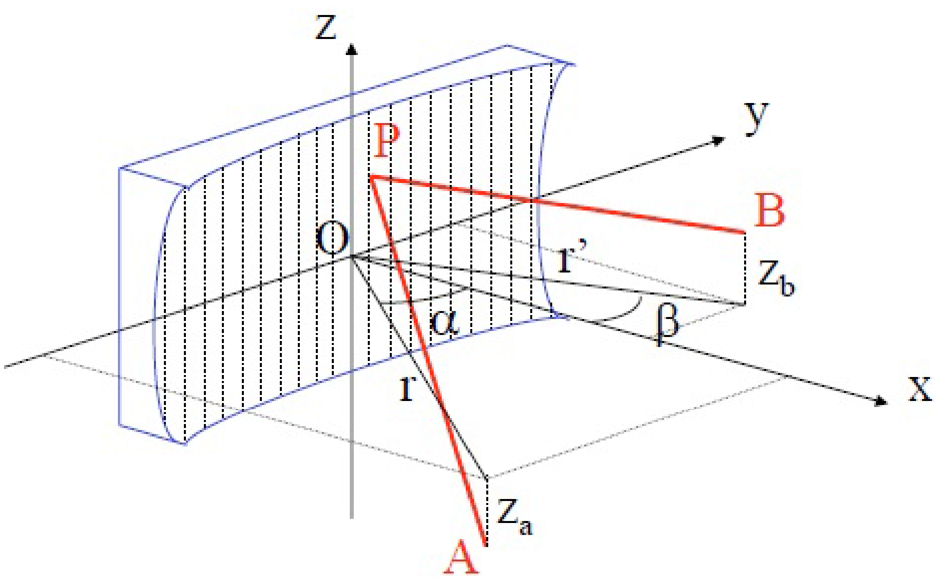


material	Crown glass	SiO_2	Ni	Au	Pt
θ_c(mrad)	4.1	5.1	7.42	10	10.5

Critical angles of total reflection at λ=1.54Å calculated for some mirror material

Optical Path function

Fermat's principle: ligth rays choose their paths to minimize the optical length.



F = AP + PB + Nkλy

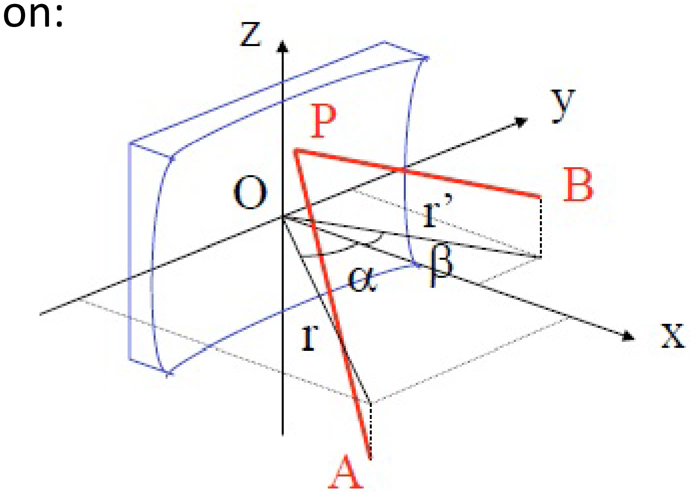
N: line density
K: diffraction order,(± 1, ± 2 …)
λ: wavelength of the light being diffracted

Perfect focus condition:

F = AP + PB + Nkλy

$$\frac{\partial F}{\partial z} = \frac{\partial F}{\partial y} = 0$$

In general form of the surface is expressed by the equation:



$$x = \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} a_{ij} y^i z^j$$

$$a_{00} = a_{10} = 0; \; j = even$$

If x-y plane is a symmetry plane

a_{ij} coefficient:

Toroid

$$a_{02} = \frac{1}{2\rho}; \quad a_{20} = \frac{1}{2R}; \quad a_{22} = \frac{1}{4R^2\rho}; \quad a_{40} = \frac{1}{8R^3};$$

$$a_{04} = \frac{1}{8\rho^3}; \quad a_{12} = 0; \quad a_{30} = 0$$

Sphere, cylinder and plane are apecial case of toroid:

R=ρ → sphere
R=∞ → cylinder
R=ρ=∞ → plane

a_{ij} coefficient

paraboloid:

$$a_{02} = \frac{1}{4f\cos\vartheta}\;; \quad a_{20} = \frac{\cos\vartheta}{4f}; \quad a_{22} = \frac{3\sin^2\vartheta}{32f^3\cos\vartheta}\;;$$

$$a_{12} = -\frac{\tan\vartheta}{8f^2}; \quad a_{30} = -\frac{\sin\vartheta\cos\vartheta}{8f^2}$$

$$a_{40} = \frac{5\sin^2\vartheta\cos\vartheta}{64f^3}; \quad a_{04} = \frac{\sin^2\vartheta}{64f^3\cos^3\vartheta}$$

Ellipsoid:

$$a_{02} = \frac{1}{4f\cos\vartheta}; \quad a_{20} = \frac{\cos\vartheta}{4f}; \quad a_{04} = \frac{b^2}{64f^3\cos^3\vartheta}\left[\frac{\sin^2\vartheta}{b^2} + \frac{1}{a^2}\right];$$

$$a_{12} = \frac{\tan\vartheta}{8f^2\cos\vartheta}\sqrt{e^2-\sin^2\vartheta}; \quad a_{30} = \frac{\sin\vartheta}{8f^2}\sqrt{e^2-\sin^2\vartheta}\;;$$

$$a_{40} = \frac{b^2}{64f^3\cos^3\vartheta}\left[\frac{5\sin^2\vartheta\;\cos^2\vartheta}{b^2} - \frac{5\sin^2\vartheta}{a^2} + \frac{1}{a^2}\right];$$

$$a_{22} = \frac{\sin^2\vartheta}{16f^3\cos^3\vartheta}\left[\frac{3}{2}\cos^2\vartheta - \frac{b^2}{a^2}\left(1 - \frac{\cos^2\vartheta}{2}\right)\right]$$

$$where \quad f = \left[\frac{1}{r} + \frac{1}{r'}\right]^{-1}$$

Optical path function

$$F = \sum_{ijk} F_{ijk} y^i z^j$$
$$= F_{000} + yF_{100} + zF_{011} + \frac{1}{2}y^2F_{200} + \frac{1}{2}z^2F_{020} + \frac{1}{2}y^3$$
$$+ \frac{1}{2}yz^2F_{120} + \frac{1}{8}y^4F_{400} + \frac{1}{4}y^2z^2F_{220} + \frac{1}{8}z^4F_{040}$$
$$+ yzF_{111} + \frac{1}{2}yF_{102} + \frac{1}{4}y^2F_{202} + \frac{1}{2}y^2zF_{211} + \dots$$

Perfect focus condition:

$$\frac{\partial F}{\partial z} = \frac{\partial F}{\partial y} = 0 \xrightarrow{F = \sum_{ijk} F_{ijk} y^i z^j} F_{ijk} = 0 \text{ for all } ijk \neq (000)$$

Most important imaging errors

$$F_{100}=0\Rightarrow \sin\alpha+\sin\beta=Nk\lambda$$ Grating equation

$$F_{200}=0\Rightarrow\left(\frac{\cos^2\alpha}{r}+\frac{\cos^2\beta}{r'}\right)-2a_{20}(\cos\alpha+\cos\beta)=0$$ Tangential focus

$$F_{020}=0\Rightarrow\frac{1}{r}+\frac{1}{r'}-2a_{02}(\cos\alpha+\cos\beta)=0$$ Sagittal focus

Example: Toroidal mirror $\left(\frac{1}{r}+\frac{1}{r'}\right)\frac{\cos\theta}{2}=\frac{1}{R}$ $\left(\frac{1}{r}+\frac{1}{r'}\right)\frac{1}{2\cos\theta}=\frac{1}{\rho}$

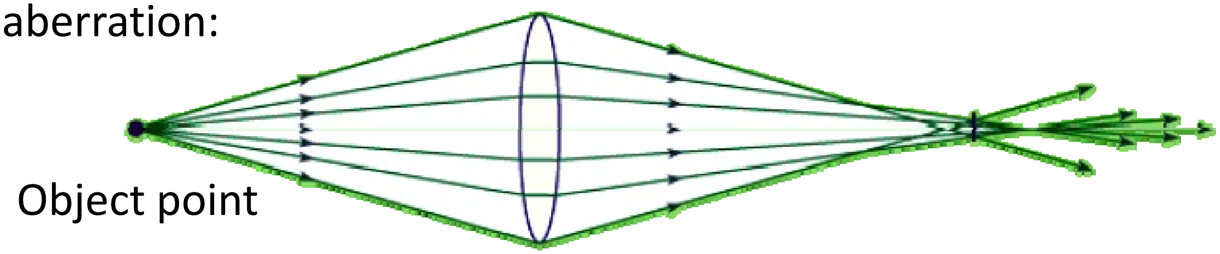
The dispersive contribution to resolution,Δλ, caused by aberrations:

$$\Delta\lambda=\frac{1}{Nk}\left[yF_{200}+\frac{3}{2}y_2F_{300}+\frac{1}{2}z^2F_{120}+\frac{1}{2}y^3F_{400}+\frac{1}{2}yz^2F_{220}+zF_{111}+\frac{1}{2}F_{102}+\frac{1}{2}yF_{202}+yzF_{211}\dots\right]$$

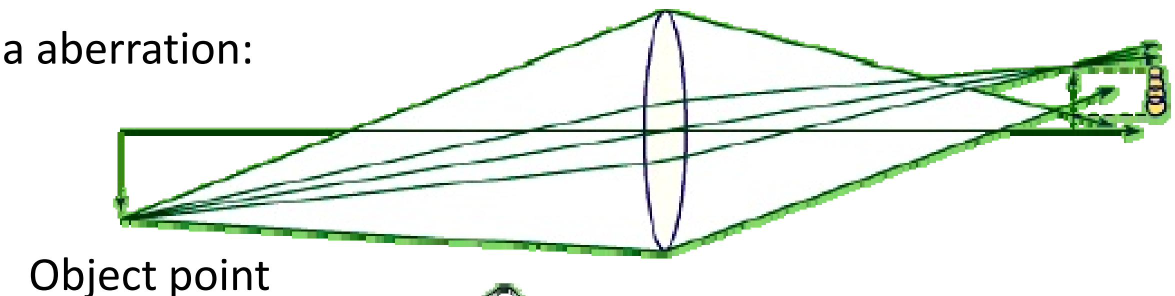
F_{200}	defocus
F_{020}	astigmatism
F_{300}	primary coma
F_{120}	astigmatic coma
F_{400} F_{220} F_{040}	spherical aberration

Aberration

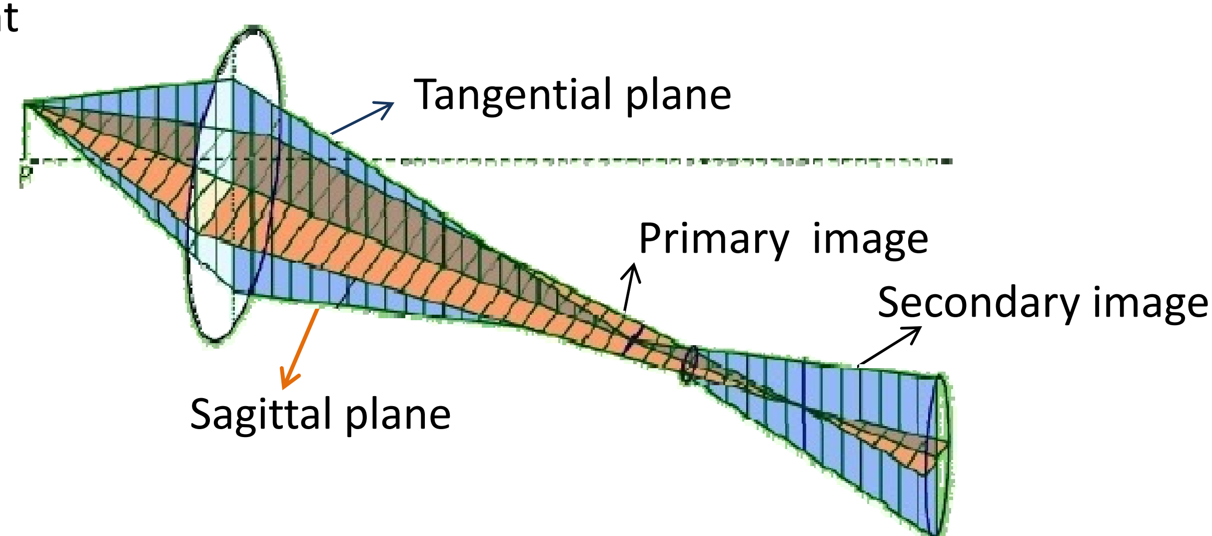
Spherical aberration:



Coma aberration:



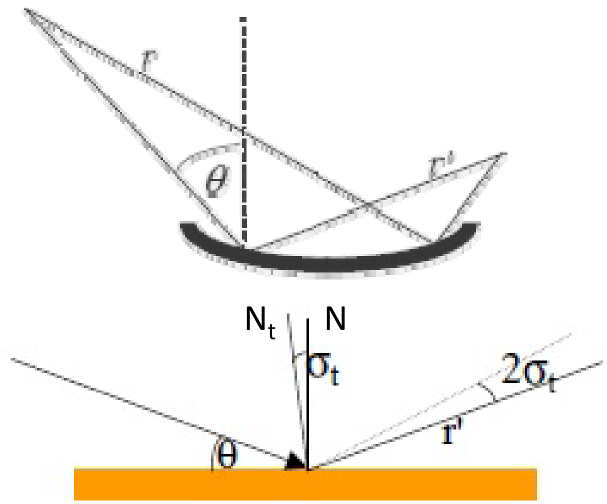
Astigmatism:



Slope errors

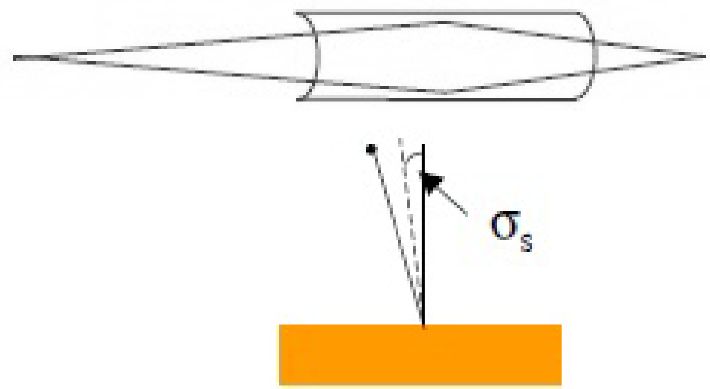
Slope errors = every deviation from the ideal surface with period larger then ~ 1, 2 mm (measured by the long trace profilometer (LTP))

There is a significant difference in the effectiveness of tangential errors and sagittal errors.



Side view

$\Delta s'_{tan} = 2r'\sigma_t$



End-on view

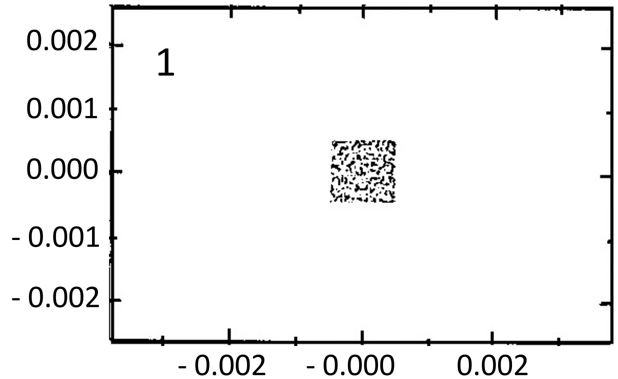
$\Delta s'_{sag} = 2r'\sin\theta.\sigma_s$
$\approx 2r'\theta.\ \sigma_s$

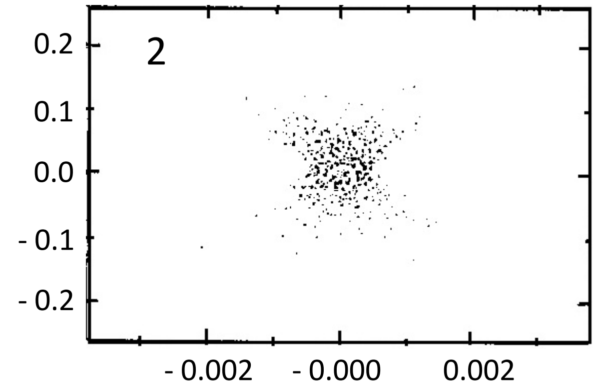
$$\frac{\Delta s'_{tan}}{\Delta s'_{sag}} \equiv 1 \approx \frac{2r'\Delta_{tan}}{2r'\theta_g \Delta_{sag}} \rightarrow \theta_g = \frac{\Delta_{tan}}{\Delta_{sag}}$$

$\theta_g = 2^{\circ} = 3.5 \times 10^{-2}$ rad; $\Delta_{sag} = 29\ \Delta_{tan}$

The effect of Tangent Errors on Line Width

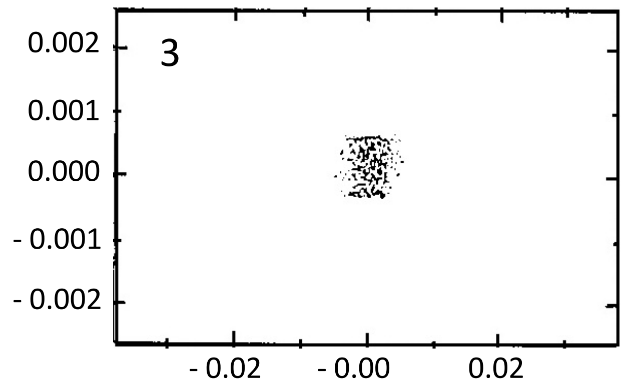
σ_{sag} (sec)=0
σ_{mer}(sec)=0

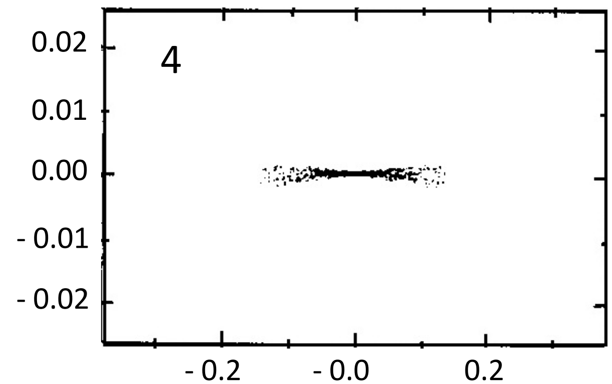




σ_{sag} (sec)=0
σ_{mer}(sec)=1

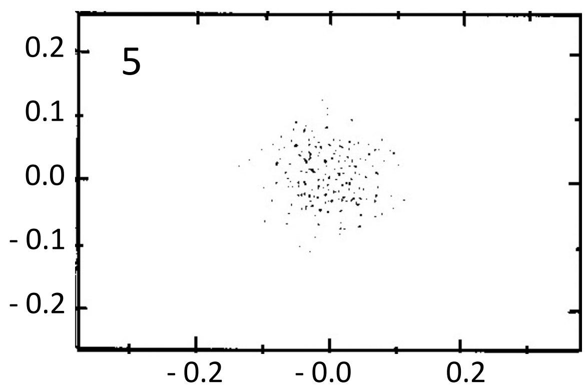
σ_{sag} (sec)=1
σ_{mer}(sec)=0

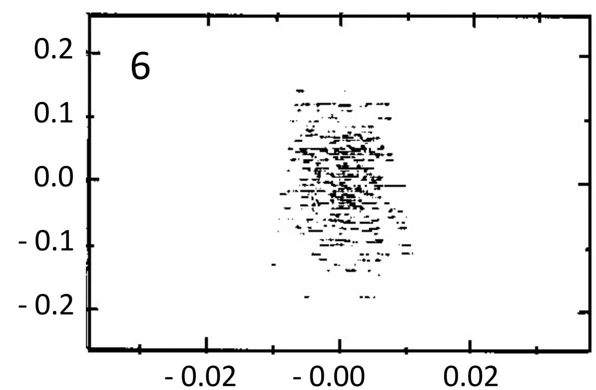




σ_{sag} (sec)=30
σ_{mer}(sec)=0

σ_{sag} (sec)=30
σ_{mer}(sec)=1





σ_{sag} (sec)=2
σ_{mer}(sec)=0.9

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The effect of Tangent Errors on Line Width

Angle of incidence $\theta g=2^{\circ}= 3.5\times10^{-2}$ radian
Arm length $r=r'=6000$ mm

Source: 0.001mm² x,y
1mrad FWHM divergence in the x and y planes

$\Delta s'_{mer}=2r'\Delta_{mer}$
$2\times6000\times1.14\times10^{-5}$rad=0.14 mm

$\Delta s'_{sag}=2r'\theta g\Delta_{sag}$
$2\times6000\times3.5\times10^{-2}$rad $\times1.14\times10^{-5}$rad$=4.8\times10^{-3}$ mm

$\Delta s'_{sag}=2r'\theta g\Delta_{sag}$
$2\times6000\times3.5\times10^{-2}$rad $\times1.14\times10^{-5}$rad$=4.8\times10^{-3}$ mm

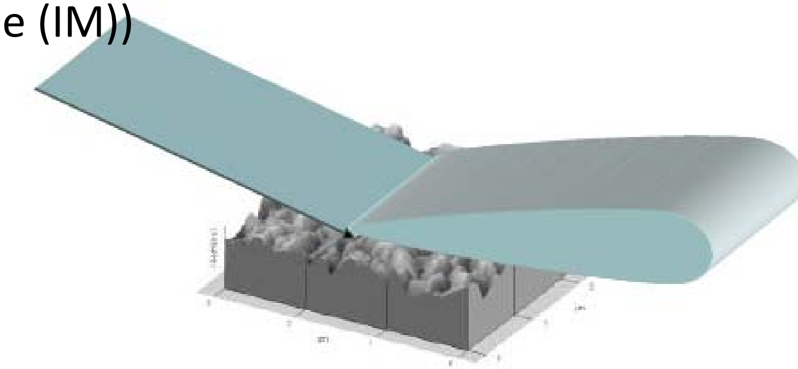
$\Delta_{mer}= 1$ sec
$\theta_g\Delta_{sag}=(1/29)\times30 \sim 1$

$\Delta s'_{mer}= 0.11=2\times6000\times\Delta_{mer}$
$\Delta_{mer}=0.81$ sec
$\Delta s'_{sag}=9.5\times10^{-3}=2\times6000\times3.5\times10^{-2}\Delta_{sag}$
$\Delta_{sag}=2.0$ sec

	Δ_{sag} (sec)	Δ_{mer} (sec)	$FWHM_{sag}$(mm)	$FWHM_{mer}$(mm)
1	0	0	1.0×10^{-3}	1.0×10^{-3}
2	0	1	1.1×10^{-3}	0.134
3	1	0	4.9×10^{-3}	1.0×10^{-3}
4	30	0	0.14	1.1×10^{-3}
5	30	1	0.14	0.14
6	2	0.9	$8\text{-}11\times10^{-3}$	0.11

Surface roughness

Roughness: Every deviation from the ideal surface with period smaller then ~ 0.5 – 1 mm (determind by an interferometric microscope (IM))



$$R=R_0 \exp[-(4\pi\ \sigma \sin\theta_g/\lambda)^2]$$

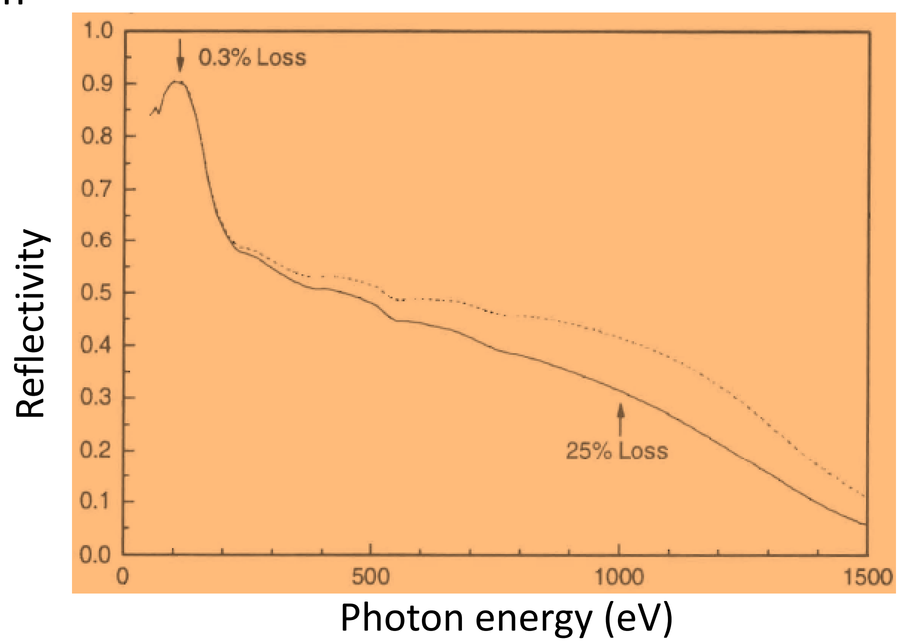
R_0: smooth surface reflectivity

R: attenuated reflectivity

σ : micro surface roughness in rms <0.5 nm

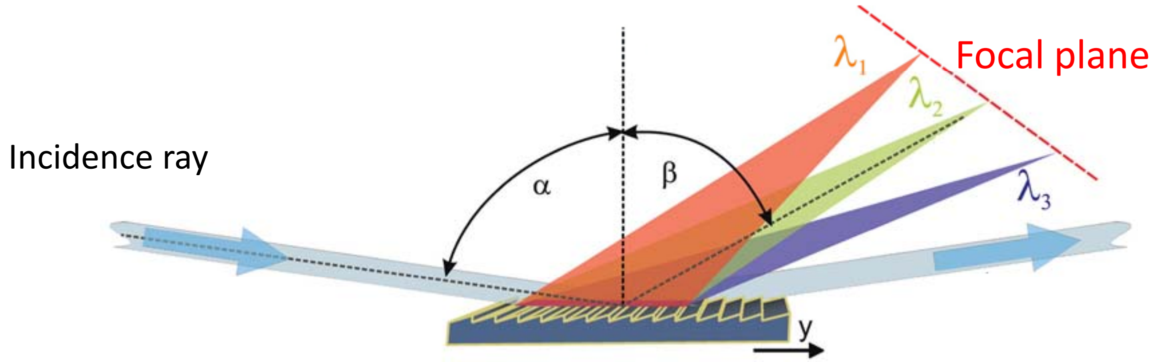
θ_g : glancing angle of incidence

The effect of surface roughness on a platinum coated mirror for energies 50-1500 eV is shown.
The loss of reflection at 100 eV is only 0.3% whereas at 1000 eV the loss is 25%.



Gratings

The core of a vacuum ultraviolet/soft x-ray monochromator is the diffraction grating.
A reflection diffraction grating consist of a reflecting surface with a periodic array of lines.



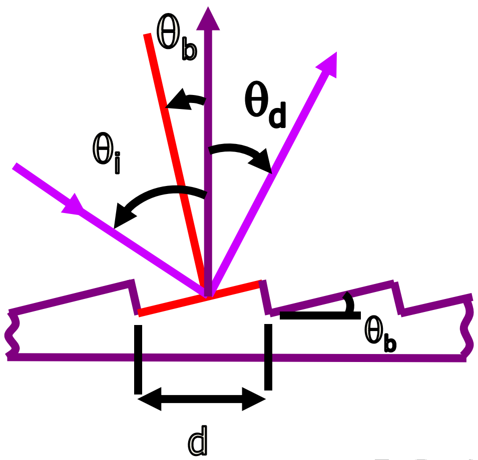
Variable line spacing grating

$$Sin\,\alpha + Sin\,\beta = Nm\,\lambda$$
$$m = 0,\ \pm1,\ \pm2, ...$$

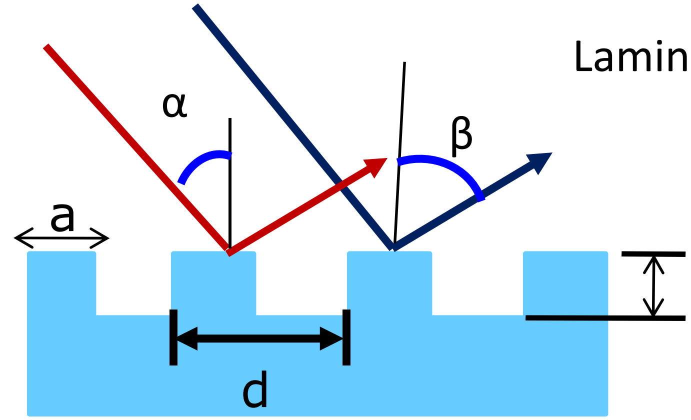
α and β: incidence and diffraction angels
m: order of the diffraction
N: line density

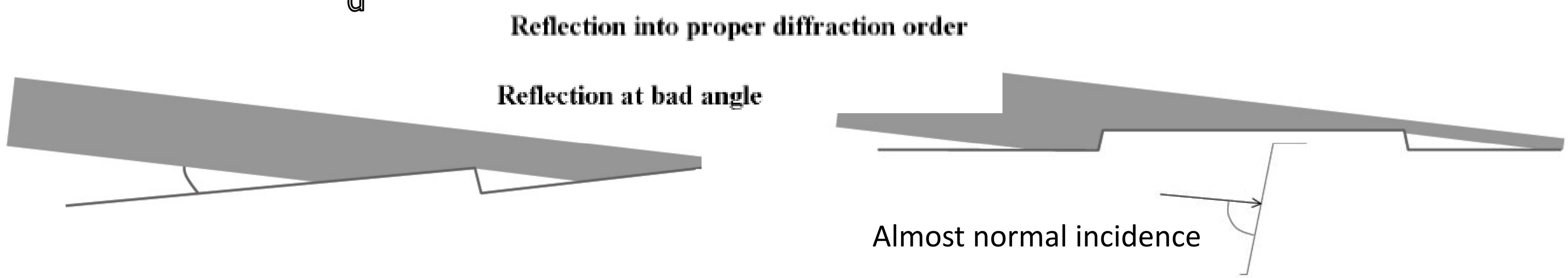
Grating profiles

Blaze

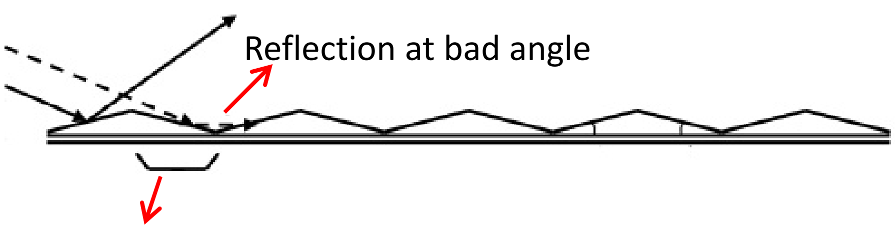


Laminar





Reflection into proper diffraction order



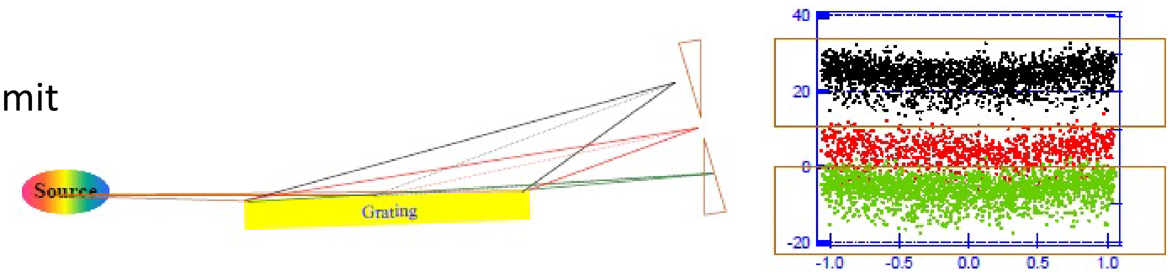
Blaze gratings:	Higher efficiency
Laminar gratings:	Higher spectral purity Higher resolution

The resolving power of a monochromator is a measure of how finely it is able to distinguish between photons of different energies.

The resolution, ΔE, is a measure of smallest amount by which two energies can differ and still be distinguished (or resolved)

$$\frac{\lambda}{\Delta\lambda} = Nml$$

Diffraction limit



ΔE Energy resolution
(E/ΔE) Resolving power
l grating length

Entrance slit contribution

$$Sin\,\alpha + Sin\,\beta = Nm\,\lambda$$

$$\left(\frac{d\lambda}{d\alpha}\right) = \frac{\cos(\alpha)}{Nk} \qquad \Delta\alpha = \frac{s}{r} \qquad \Delta\lambda_{entrance} = \frac{1}{Nk}\frac{s}{r}\cos(\alpha)$$

$$\left(\frac{d\lambda}{d\beta}\right) = \frac{\cos(\beta)}{Nk} \qquad \Delta\beta = \frac{s'}{r'} \qquad \Delta\lambda_{exit} = \frac{1}{Nk}\frac{s'}{r'}\cos(\beta)$$

Exit slit contribution

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Contribution of the Grating Tangent Errors, σ_{te}, to resulution

$$\Delta\lambda_{exit} = \frac{1}{Nk}\frac{\Delta s'}{r'}\cos\beta \xrightarrow{\Delta s' = 2\times 2.35 r'\sigma_{te}} \Delta\lambda_{te} = \frac{2\times 2.35\sigma_{te}\cos\beta}{kN}$$

The resolution, ΔE, being the Gassian sum of different terms such as the entrance and exit slit dimensions, the slope errors, and the residual aberrations.

dispersion

The angular dispersion is the rate at which the diffraction angle changes with energy.
The spatial dispersion is the physical spacing on the focal plane of two lines of different energies.

$$Sin\,\alpha + Sin\,\beta = Nm\,\lambda \qquad \frac{d\beta}{d\lambda} = \frac{Nm}{Cos\beta}$$

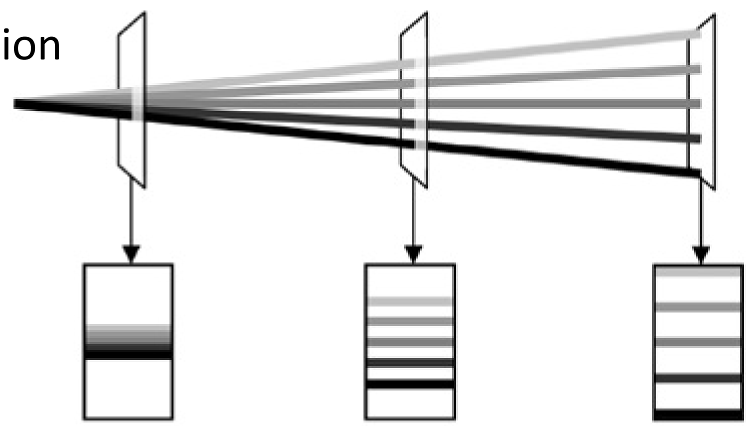
angular dispersion

The angle between the principle maximum of diffraction (m=1) and its first Rayleigh minimum is given by:

$$d\beta = \frac{\lambda N}{ml\cos\beta}$$

$$f\frac{d\beta}{d\lambda} = \frac{dx}{d\lambda} = \frac{Nmf}{\cos\beta}$$

Spatial dispersion is determined by dβ/dλ and focal plane (f)



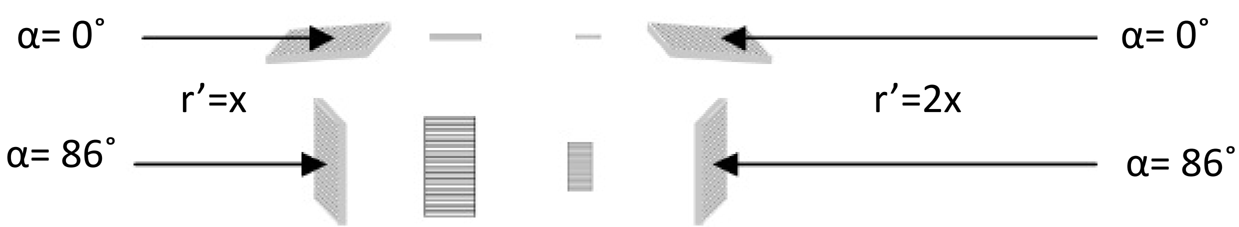
Grating efficiency

The efficiency of a grating, or the fraction of incident photons that it successfully focuses onto the exit slit depend on …

Geometric efficiency is the fraction of available photons that are successfully transmitted through the system as a result of the sizes of the optical elements.

Effective area of the grating →

- Size of the grating
- Incidence angle
- Source – grating distance



Diffraction efficiency is the fraction of the photons incident on a grating that are diffracted into the desired diffraction order (m).

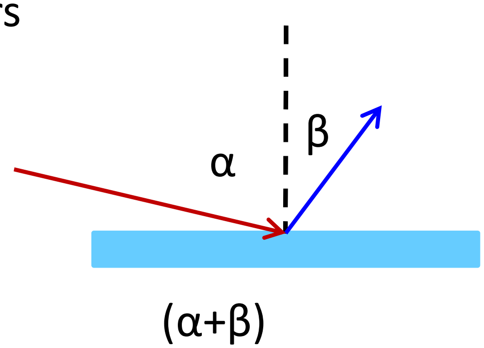
1) Line density (N), 2) Incidence angle (α), 3) Energy or wavelength of photons (E,λ), 4) Groove profile, 5) Grating material (coating)

Energy range

1. High-energy region (> ~ 150 eV)
   Grazing incidence (> ~ 85 deg) monochoromator is inevitable
   Except for multilayer grating

2. Low-energy region (< ~ 50 eV)
   Near normal incidence monochromator is also available

3. Wide-energy beamline (e.g. 30 eV – 1500 eV)
   Combination of grazing and normal incidence monochromators
   Variable included angle monochromator
   Interchangeable gratings



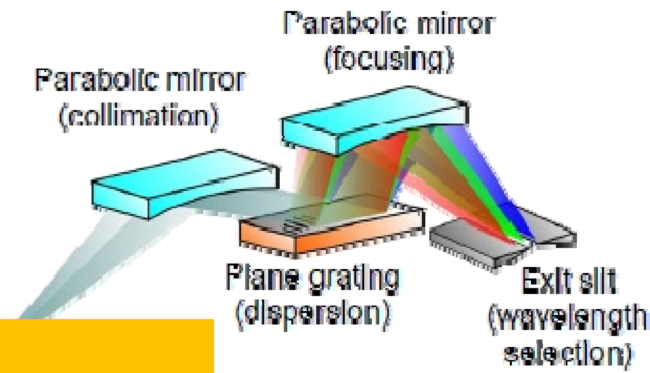
Resolution and intensity

1. Energy resolution depends on…

Dispertion & Focus

Focus size depends on …

Source size, demagnification, aberration, slope error, …



Perfect monochromator, in principle,

Exce

Slop

We must compromise !!

Intensity, resolution, energy range, …

– free monochromator

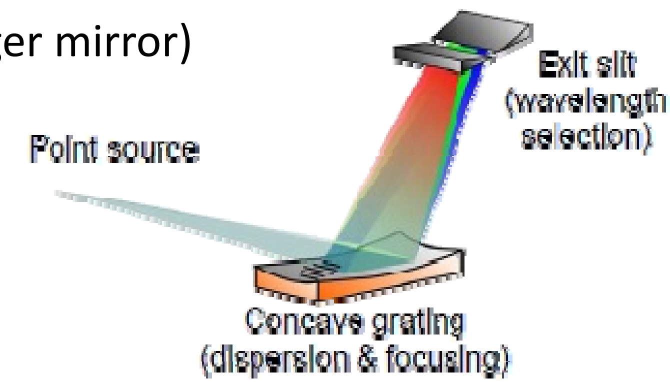
2. Intensity depend on …

Number of optical elements

Incidence angle & acceptance (larger incidence needs larger mirror)

Diffraction efficiency of the grating

High groove density large dispersion but low efficiency



Minimum intensity loss (no mirror)

Focal condition depends on wavelength

Aberration might be serious

The simplest monochromator

Some hints for the choice

1. Grating shape (plane, spherical, …)

Spherical: dispersion & focus ⟶ small number of optical elements
be careful for aberrations

2. Groove density (uniform or varied)

3. Included angle (constant or varied)

Variable: higher degree of freedom ⟶ resolution & intensity in wide energy range
Scanning mechanism is more complicated

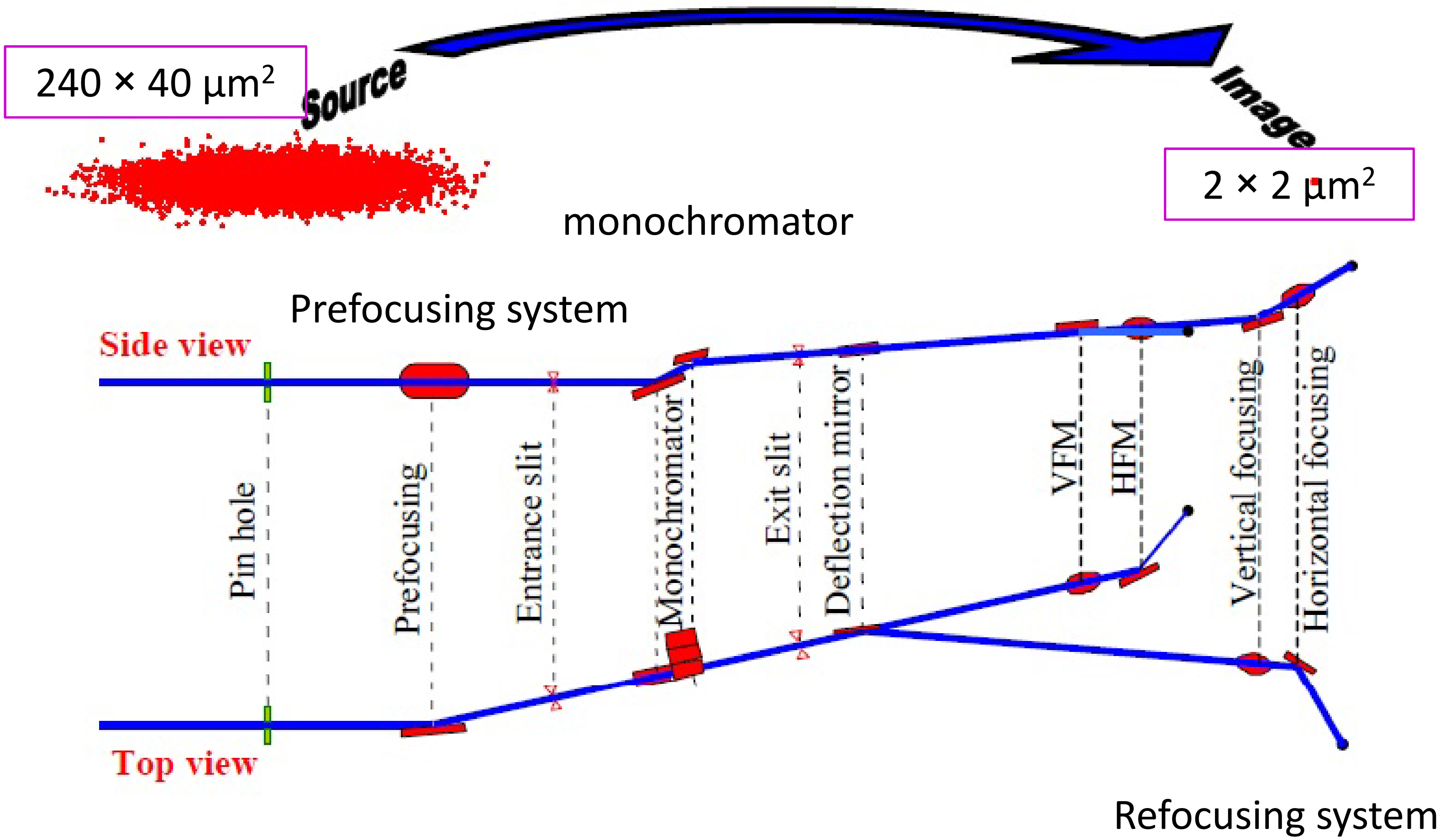
4. Entrance slit

Without slit: source size of SR itself directly affects
With slit: higher resolution can be achieved at the sacrifice of the resolution intensity
Pre-focusing optics is necessary

Elettra's soft x-ray beamlines:

- *TwinMic*
- *Nanospectroscopy*
- *Esca Microscopy*
- *SpectroMicroscopy*
- *VUV photoemission*
- *CiPo*
- *GasPhase*
- *BACH*
- *APE*
- *IUVS*
- *SISSI*

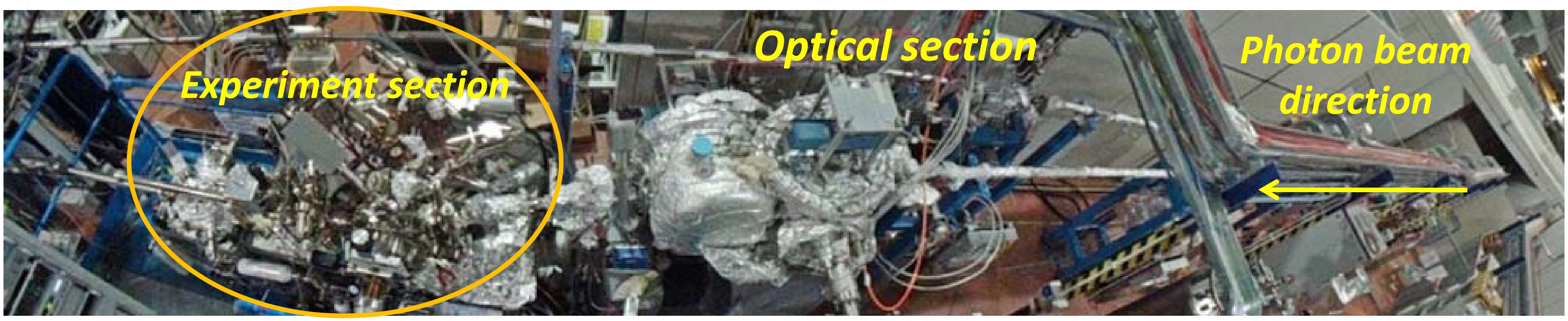
Nanospectroscopy beamline



Horizontal demagnification = 1/M= 240/2=**120**
vertical demagnification = 1/M= 40/2=20

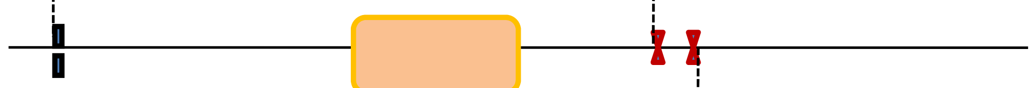
Nanospectroscopy beamline

source:	2 undulators, with phase modulation electromagnet
Period (mm)	100
polarisation	linear horizontal, linear vertical, elliptical
energy range	5-1000 eV
Effective size of the source (FWHM)	240 µm × 40 µm
Flux density (Ph/sec/µm^2)	14
beam defining aperture size (10 m behind the source)	1 × 2 mm^2
Acceptance angle of beamline	0.1 mrad × 0.2 mrad



Pinhole
Source distance= 10 m

Horizontal focus of mirror M1, 18 m from the source, this is the source for the following mirrors in the horizontal plane



Side view

Troidal mirror (M1)
Source distance= 16 m

Vertical focus of mirror (M1) (entrance slit), 19 m from the source, this is virtual source for the monochromator

Troidal mirror:

Source to mirror distance (m)	p=16
Radius of curvature	R= 116.429 m, ρ= 15.43 cm
Tangential focal point Sagittal focal point	q_t= 2m q_s= 3m
Grazing angle	1.75˚
Horizontal demagnification	8
Mirror dimention	10 × 1 cm
Substrate	Glidcop
Tang. Slope error rms	3 – 4 µrad

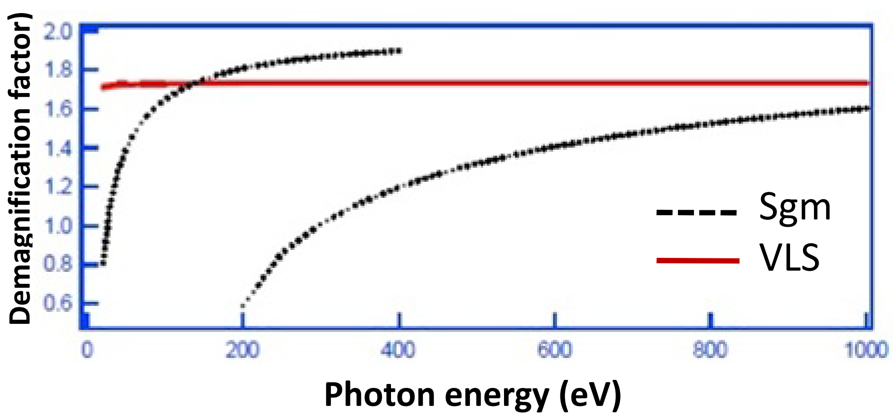
Nanospectroscopy beamline

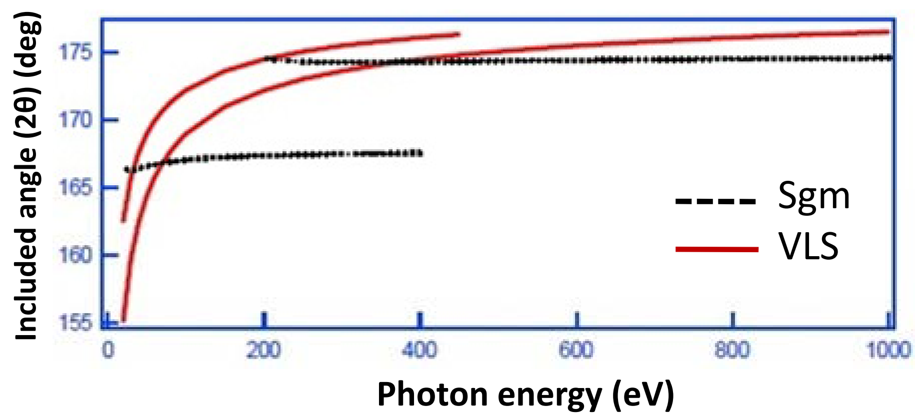
- Variable included Angle Spherical Grating Monochromator:

It can provide very high resolving power
To obtain very high resolving power, several gratings are required
The included angle working curve is flat

- A plane variable line spacing grating:

No high resolving power
It can cover a large energy rang with a relatively small change in the resolving power





Nanospectroscopy beamline

A second horizontally focusing mirror has a demagnification factor greater then 10, so it must be chosen carefully.

To produce a spot smaller then 5 μm, 1 μrad slope error is the minimum requirement.

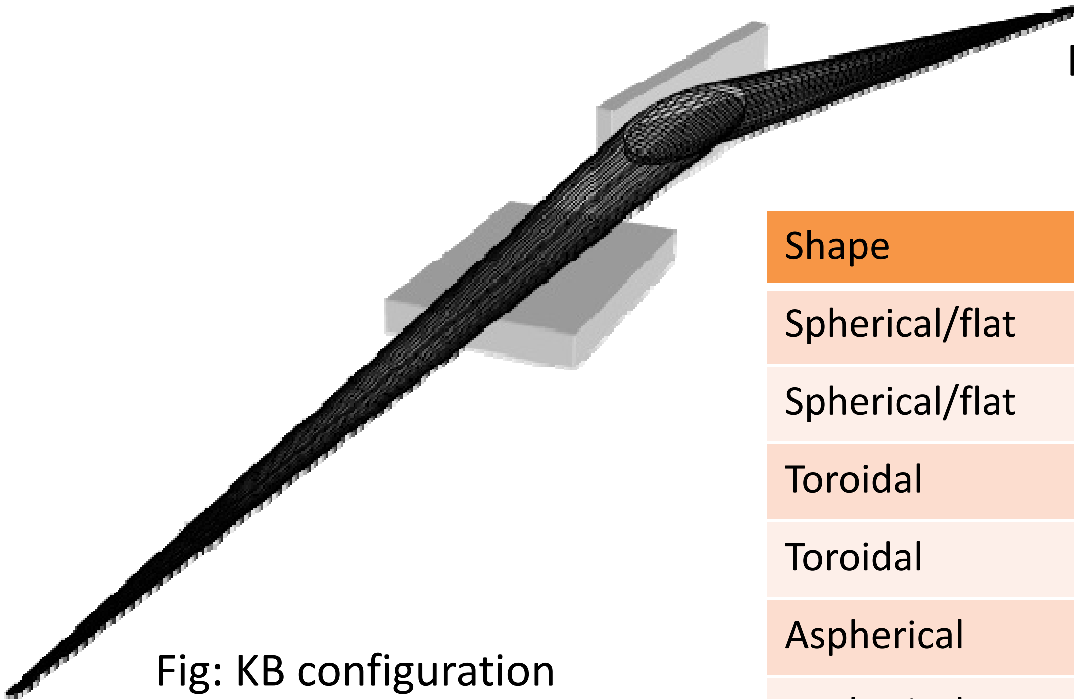
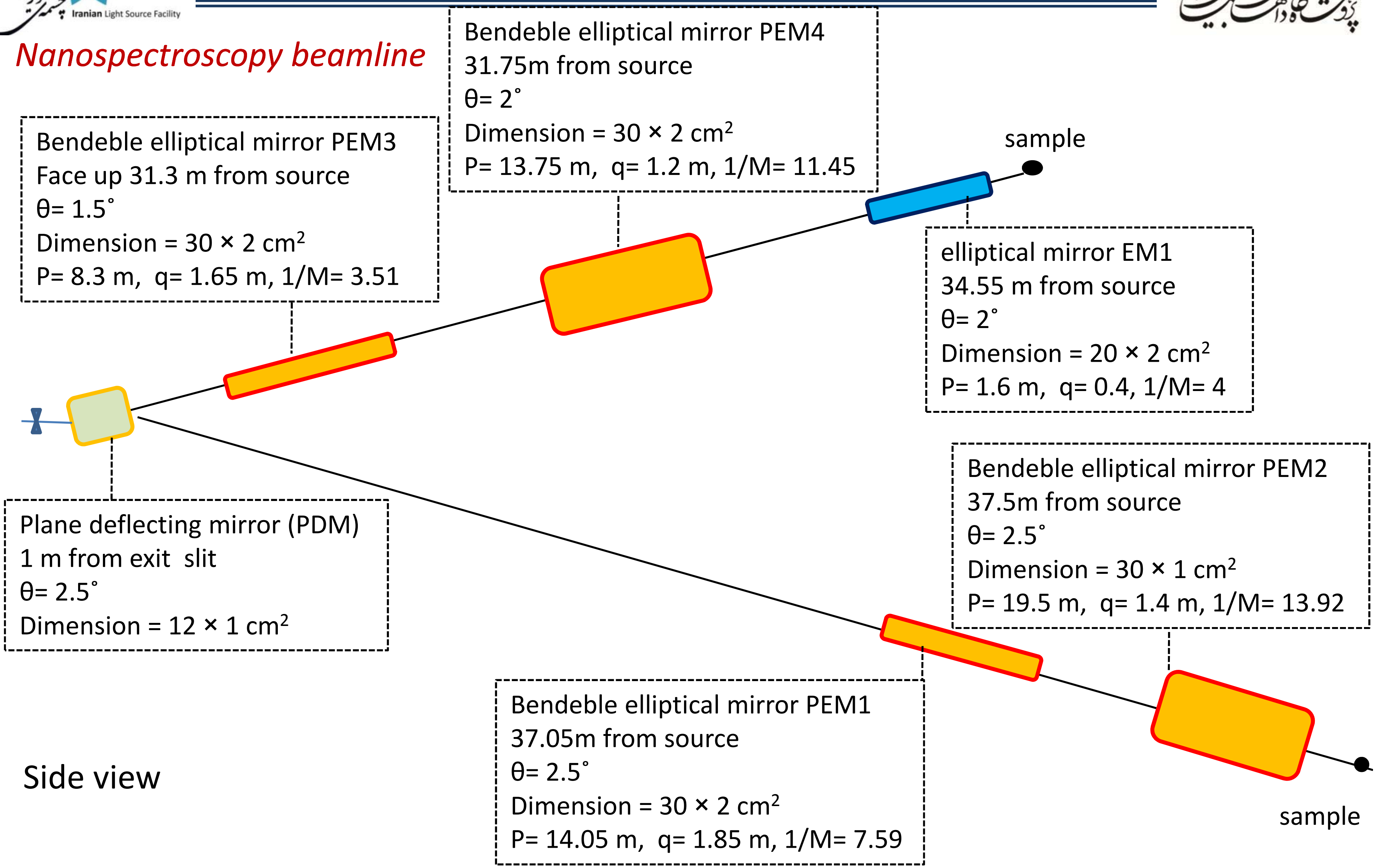


Fig: KB configuration

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

The only way to have a real micro-focus is to start from a flat or spherical surface and bent it to a ellipse.

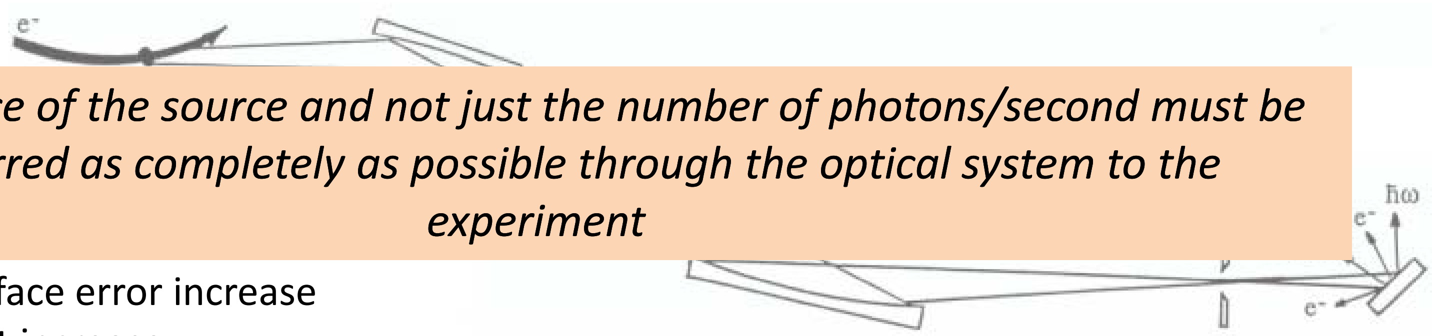
Nanospectroscopy beamline



brilliance

$$Brilliance = \frac{Photon\ Flux}{I} \frac{1}{\sigma_x \sigma_z \sigma'_x \sigma'_z\ BW}$$

Photon flux = photons/sec
I = electron current in the storage ring
$\sigma_x \sigma_y$ = the transverse area from which SR is emitted
$\sigma'_x \sigma'_z$ = the solid angle into which SR is emitted
BW= spectral bandwidth, usually ΔE/E= 0.1%



The

The brilliance of the source and not just the number of photons/second must be transferred as completely as possible through the optical system to the experiment

- The surface error increase
- The cost increase

The source must be demagnified:

- The vertical aperture remains small
- The optical aberration decrease
- The surface error decrease
- The cost decreases

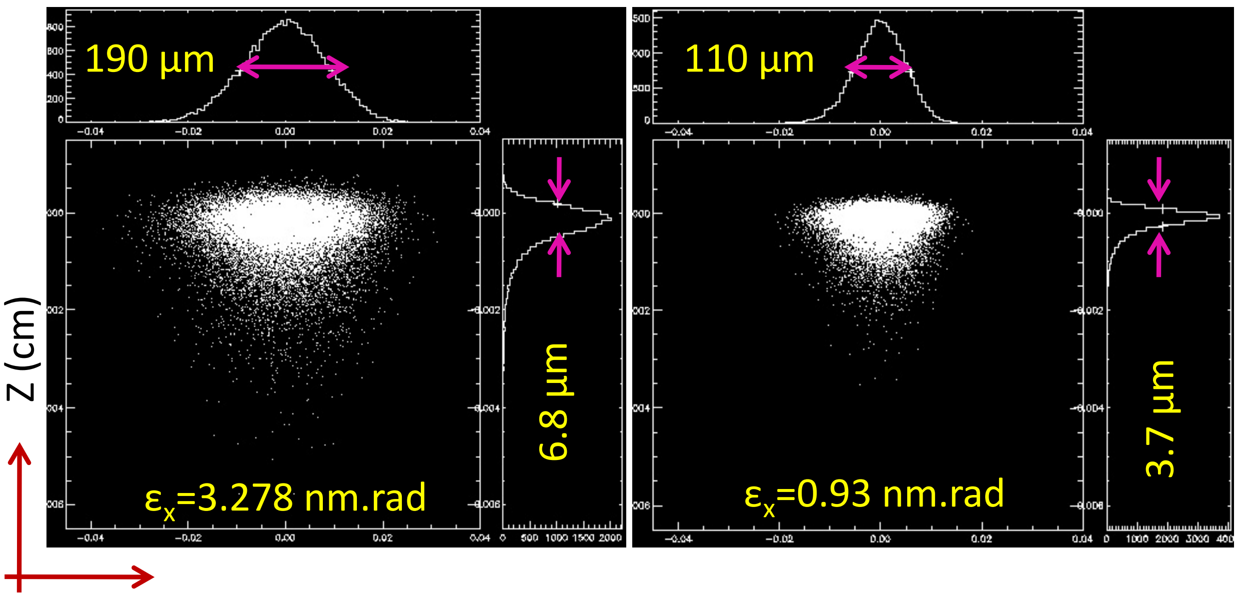
✓ Small focus volume
✓ Higher flux density

Spot size and divergence of the photon beam for two different undulators length (L=2.127 m and 6 m) at two energy values (1 KeV and 10 KeV).

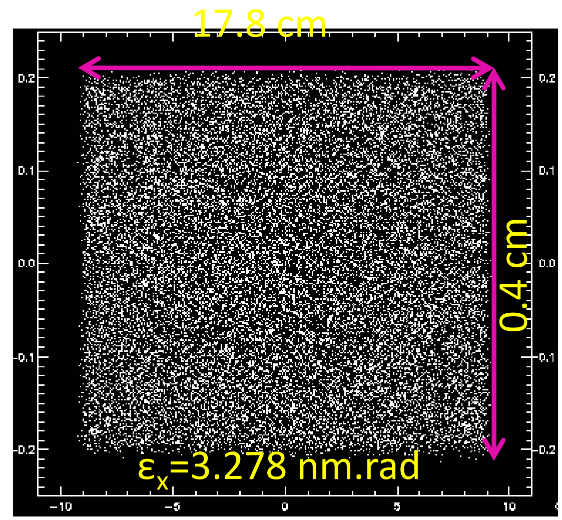
E (KeV)		1			10		
ε_x (nm.rad)		0.93		3.278	0.93		3.278
		Medium	Long	Medium	Medium	Long	Medium
L= 2.127 m	$\sigma_{t,x}$(μm)	58.1	153.4	156.4	57.0	153.4	156.2
	$\sigma_{t,y}$(μm)	5.2	8.3	10.3	3.5	7.32	7.3
	$\sigma'_{t,x}$(μrad)	37.3	24.2	48.3	29.5	7.7	38.4
	$\sigma'_{t,y}$(μrad)	24.3	24.2	31.4	8.2	7.7	11
L= 6 m	$\sigma_{t,x}$(μm)	57.4	153.5	156.7	57.0	153.4	156.2
	$\sigma_{t,y}$(μm)	7.6	9.96	14.7	3.9	7.5	7.9
	$\sigma'_{t,x}$(μrad)	31.9	14.4	41.7	28.8	4.6	37.6
	$\sigma'_{t,y}$(μrad)	14.7	14.4	19.6	5.4	4.6	7.7

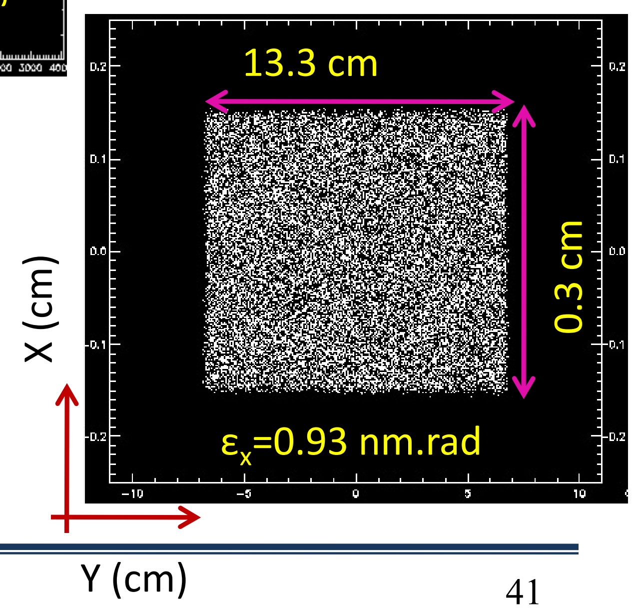
Table shows the results, as it can be seen the spot size has been reduced by a factor of **2.7×2** in the medium straight section of low emittance case relative to high emittance, and so it is greatly appreciated. It should be noted that the decreasing of spot size is mostly due to using low value of β_y .

Spot size of the photon beam at the focal plane of KB mirrors (spherical mirrors) with undulator source in two values of emittance: 3.278 & 0.93 nm.rad.



Foot print of photon beam on the mirror with BM source





- Increasing of Resolving Power
- Reduction of the photon beam aberration
- Reduction of foot prints on the optical elements (technically and budget)
- Simpler beamline design by using higher quality and simpler optical element or lower number of optical elements, etc.

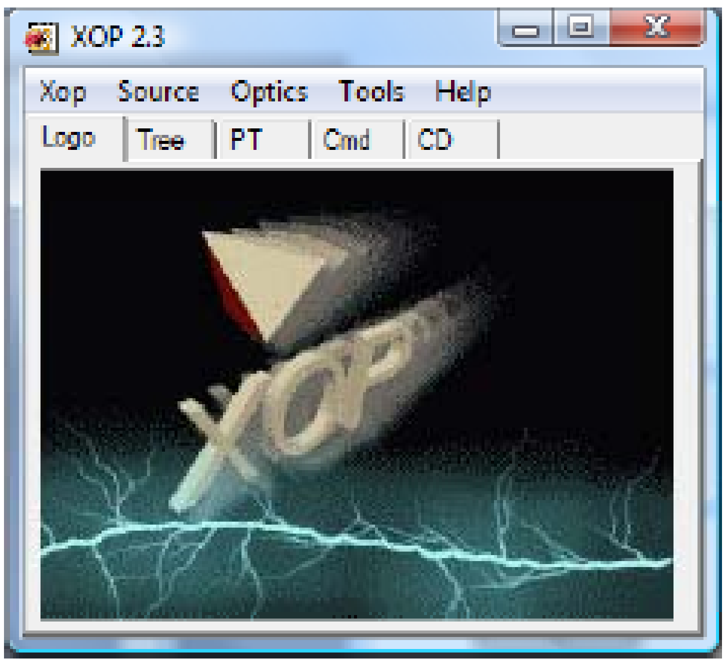
Ray tracing:

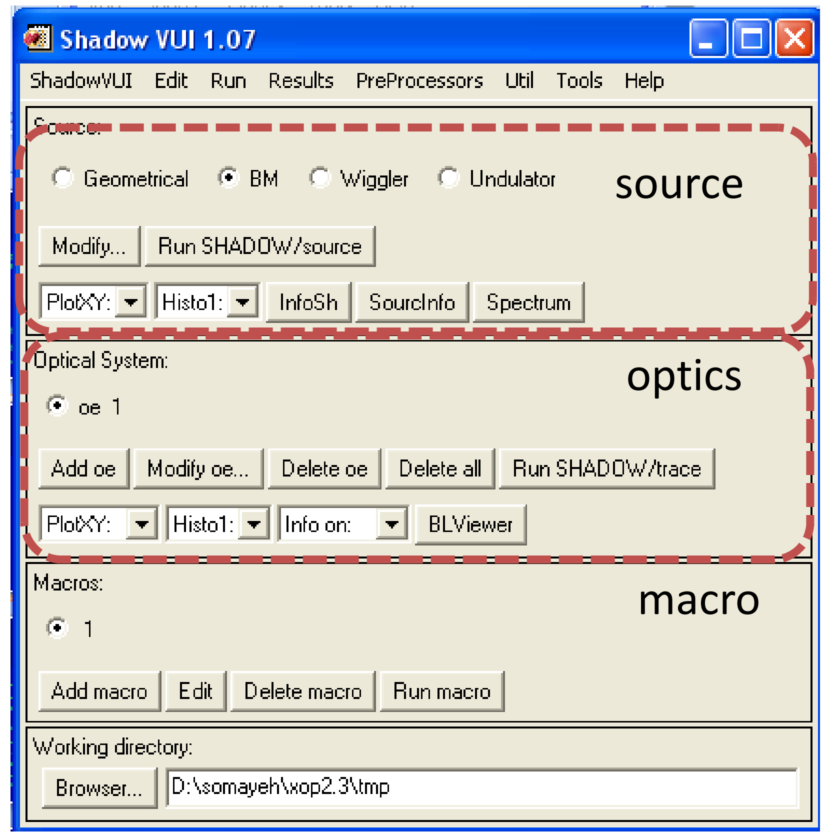
In the vacuum ultraviolet and soft x-ray portion of the spectrum only three optical principle are required for basic ray trace program:

a) The optical path between physical elements of the optical system is a straight

b) The angle of reflection is equal to the angle of incidence

c) Diffraction phenomena are governed by Bragg's law





Power density calculations

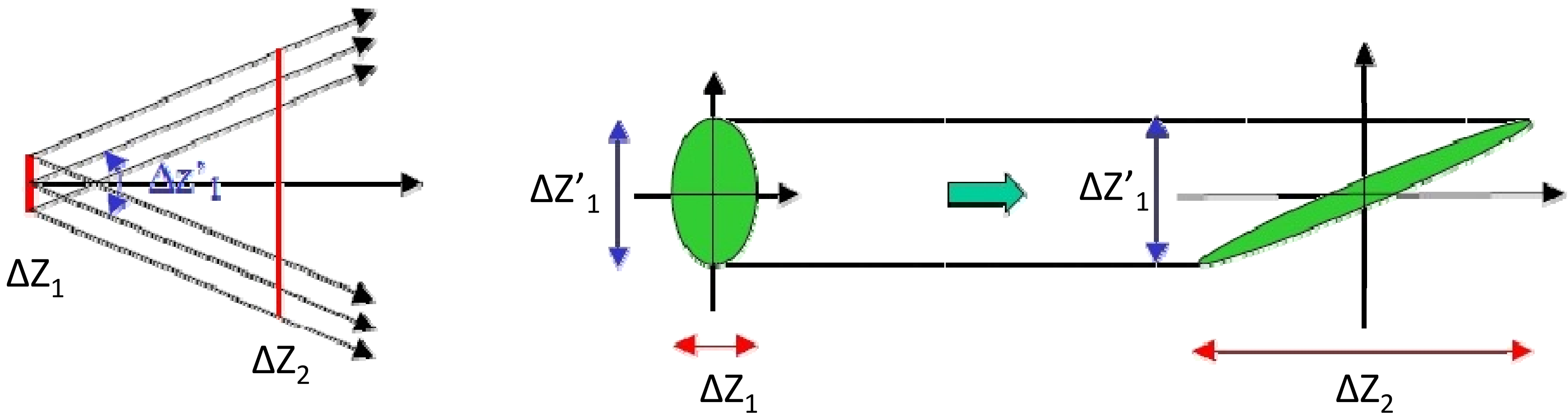
$$p(\theta,\psi)=10.84E^4B_0ING\left[1-\left(\lambda\frac{\theta\times0.001}{K}\right)^2\right]^{0.5}\left[\frac{1}{\left[1+(\gamma\psi\times0.001)^2\right]^{\frac{5}{2}}}+\frac{5(\gamma\psi\times0.001)^2}{7\left[1+(\gamma\psi\times0.001)^2\right]^{\frac{7}{2}}}\right]$$

$$G=K\times\frac{\left[K^6+\left(\frac{24}{7}K^4\right)+(4K)^2+\frac{16}{7}\right]}{(1+K^2)^{\frac{7}{2}}}$$

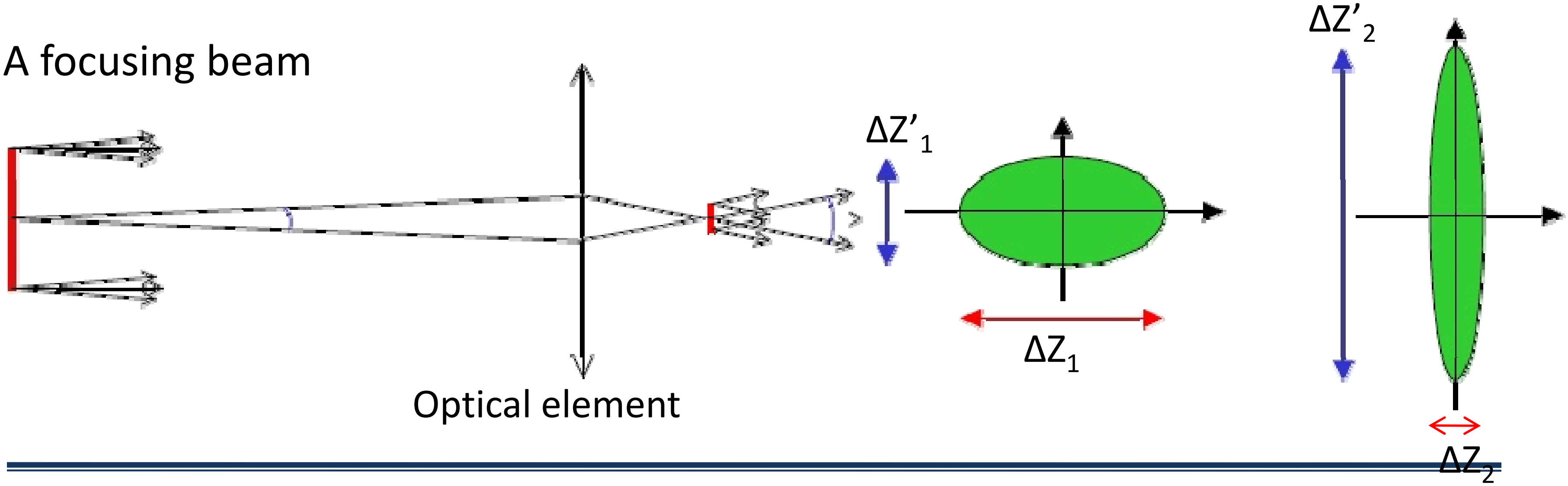
θ: horizontal angular displacement
Ψ: Vertical angular displacement in mrad
K: deflection parameter
G: normalizing factor

P(ψ) is the angular power density function in W/mrad² in the vertical only (θ=0). Ψ= 0, 0.02, … , 126.1 mrad
P(ψ) is the angular power density function in W/mrad² in the vertical only (θ=0). θ = 0, 0.02, … , 126.1 mrad)

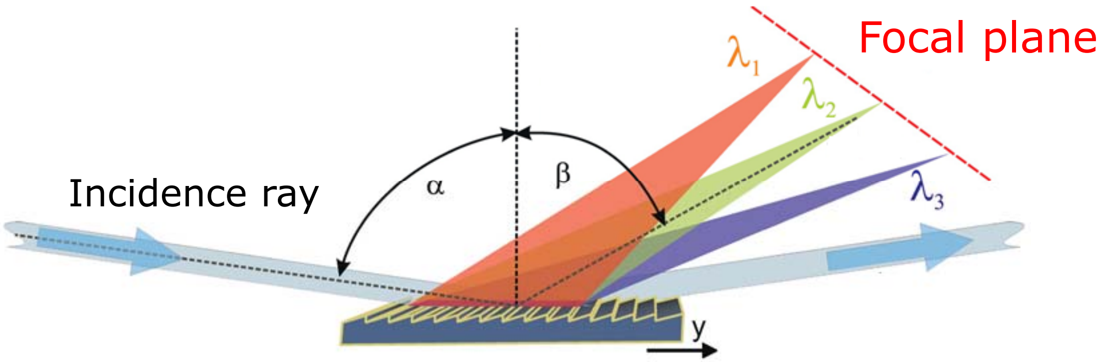
A diverging beam



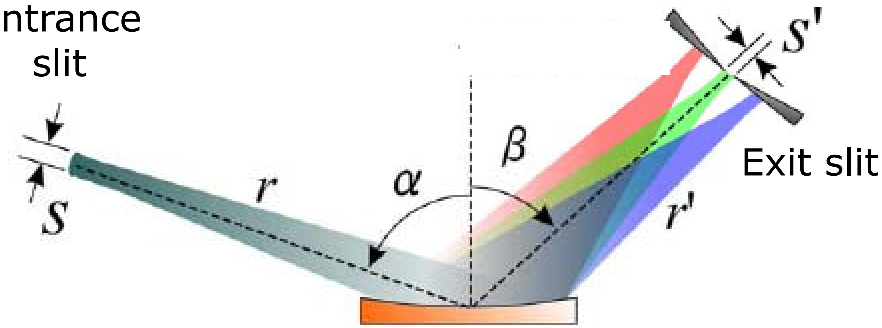
A focusing beam



Grating



Variable line spacing grating



$$Sin\,\alpha + Sin\,\beta = Nm\,\lambda$$

$$m = 0,\ \pm 1,\ \pm 2, ...$$

$$\frac{E}{\Delta E} = Nml$$

ΔE Energy resolution
(E/ΔE) Resolving power
l grating length

$$\Delta\lambda_{Entrance} = \frac{s.Cos\,\alpha}{Nmr}$$

$$\Delta\lambda_{Exit} = \frac{s'.Cos\beta}{Nmr'}$$

$$\frac{d\beta}{d\lambda} = \frac{Nm}{Cos\beta}$$ angular dispertion

$$\frac{\Delta x}{\Delta\lambda} = \frac{Cos\beta}{Nmf}$$ Spatial dispertion