VUV & SX Optics

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Outline

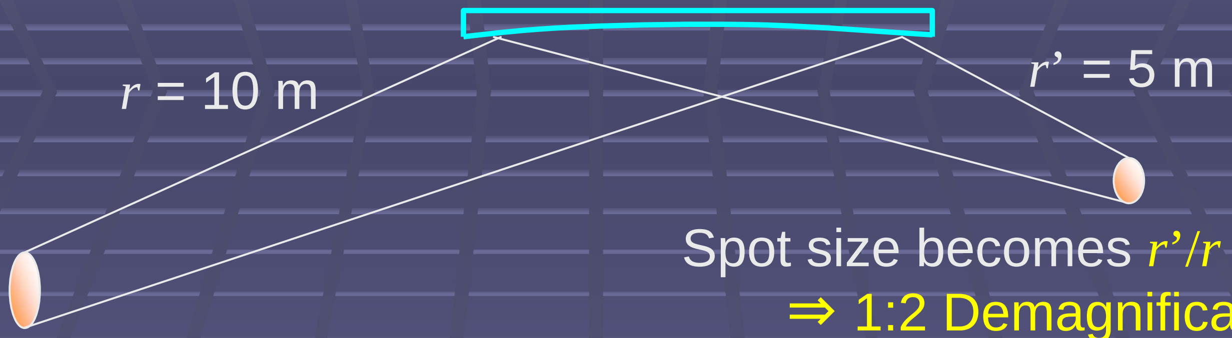
1. Mirrors
   - 1.1. focusing & collimation
   - 1.2. substrate materials
   - 1.3. coating & reflectivity

2. Diffraction Gratings
   - 2.1. principle - wavelength dispersion -
   - 2.2. energy resolution
     - - dispersion and focus -
   - 2.3. fabrication of gratings

1.1. focusing & collimation

Demagnification & Aberration

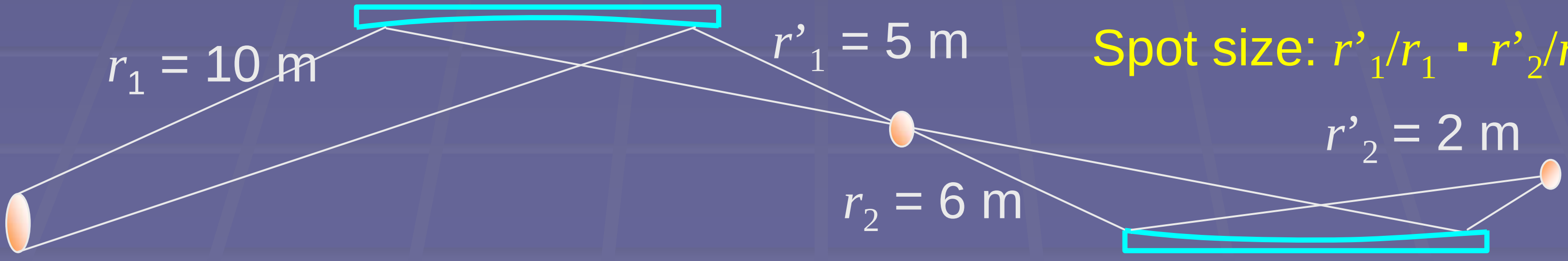
$$R = \frac{2}{(1/r + 1/r')\cos\theta}$$



Spot size becomes $r'/r = 1/2$
⇒ 1:2 Demagnification
* Divergence becomes 2 times larger

Elliptical mirror ⇒ perfect focus (determined by demagnification only)
Use of a cylindrical or spherical mirror ⇒ poor focus (aberration)
Larger divergence (larger illumination area) ⇒ larger aberration

Combination of focusing mirrors

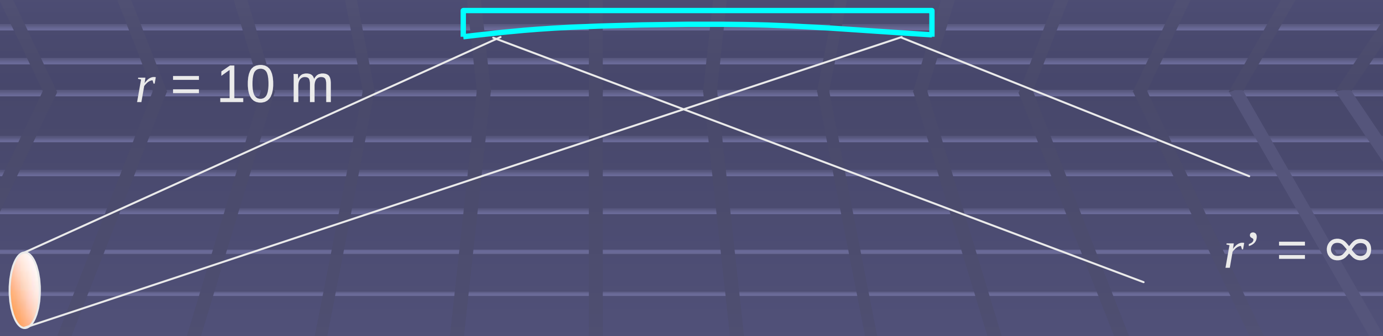


Spot size: $r'_1/r_1 \cdot r'_2/r_2 = 1/6$

Divergence: 6x

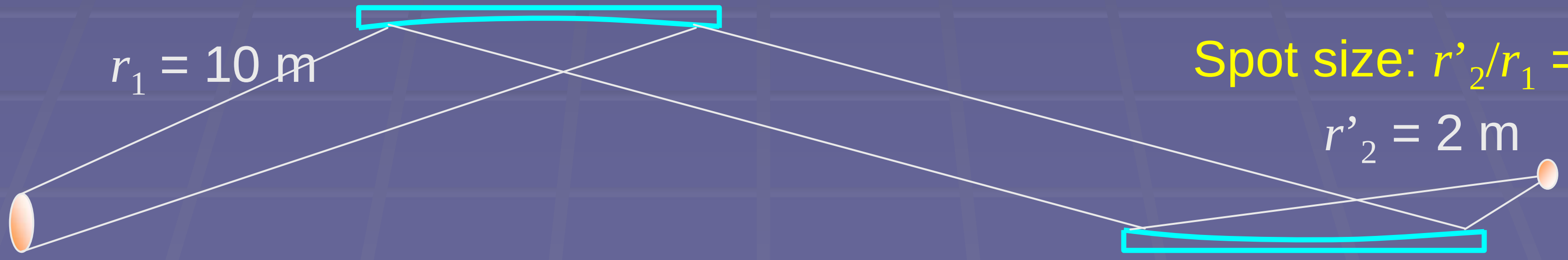
1.1. focusing & collimation

Collimation



Parabolic mirror ⇒ perfect collimation (spot-size limited)
Use of a cylindrical or spherical mirror ⇒ poor collimation (aberration)
Larger divergence (larger illumination area) ⇒ larger aberration

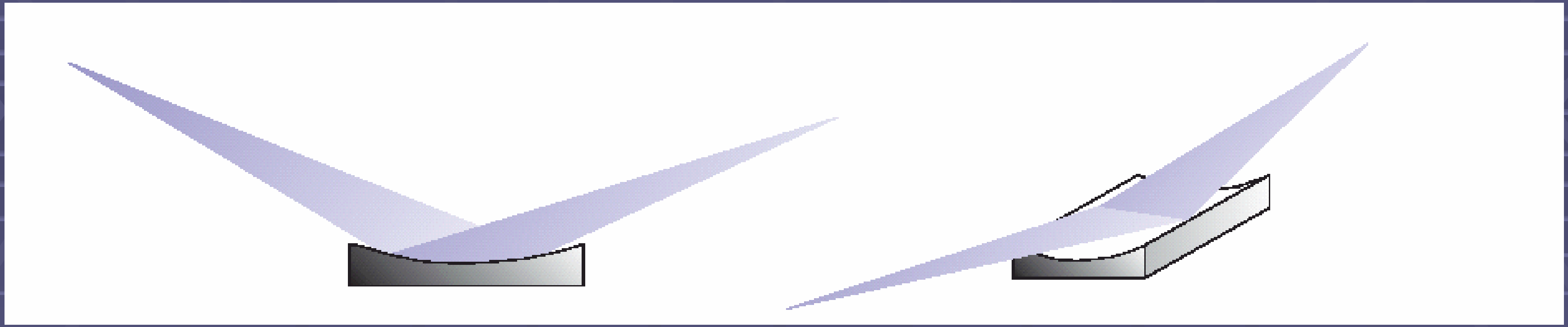
Combination of collimating mirrors



Spot size: r'_2/r_1 = 1/5

Divergence: 5x

1.1. focusing & collimation



Tangential focusing Sagittal focusing

Aberration: smaller in tangential focusing

* Sagittal focusing is often adopted undulator beamlines

Radius: smaller in sagittal focusing

$$R = \frac{2}{(1/r + 1/r')\cos\theta} \qquad \rho = \frac{2\cos\theta}{(1/r + 1/r')}$$

e.g. 88 deg, r = 10 m, r' = 5 m

⇒ R = 190 m (tangential focusing), ρ = 0.23 m (sagittal focusing)

Higher precision in sagittal focusing

e.g. R = 190 m ± 3%, ρ = 0.23 m ± < 0.5 %

Slope error effects: smaller in sagittal focusing

1.2. substrate materials

Needs:

Easy to fabricate: precise control of the mirror shape

Low defects, pores

Hardness: small distortion

High thermal conductivity: cooling efficiency

Low thermal expansion: against a heat load

Typical materials

Si: for high heat load, with cooling

SiO_2: without cooling

* SiO_2 is suitable for mirror current measurements

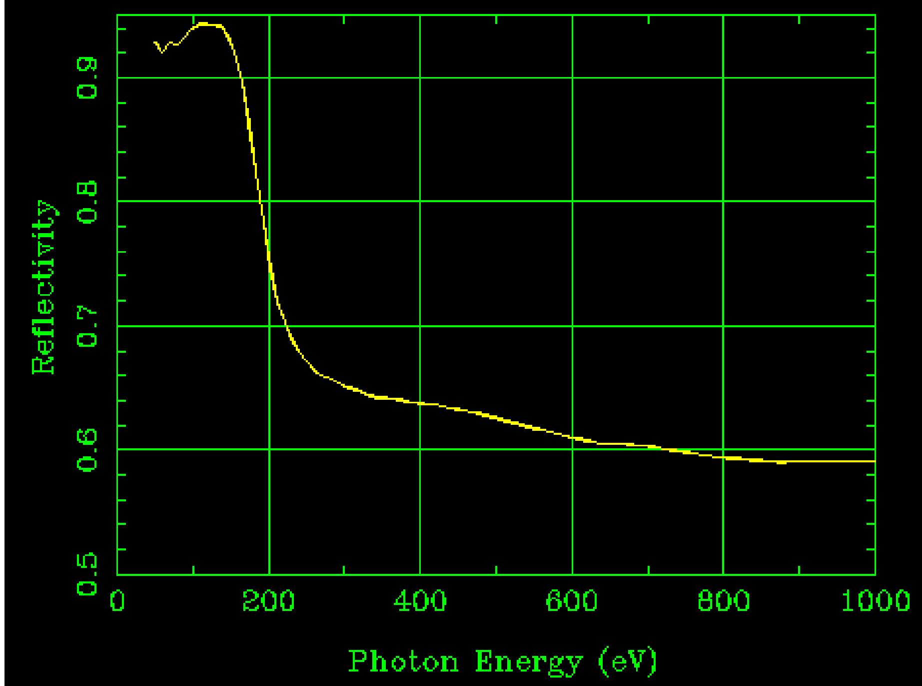
1.3. coating & reflectivity

Coating layer:

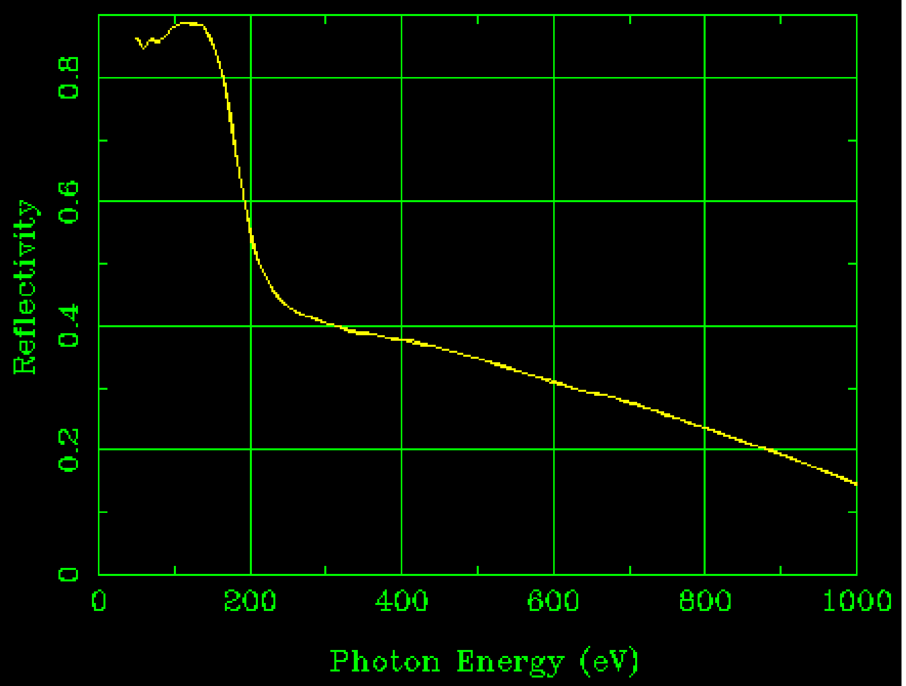
High reflectivity

Protection against oxidation etc.

Typical coating material in VUV-SX: Au



88 deg

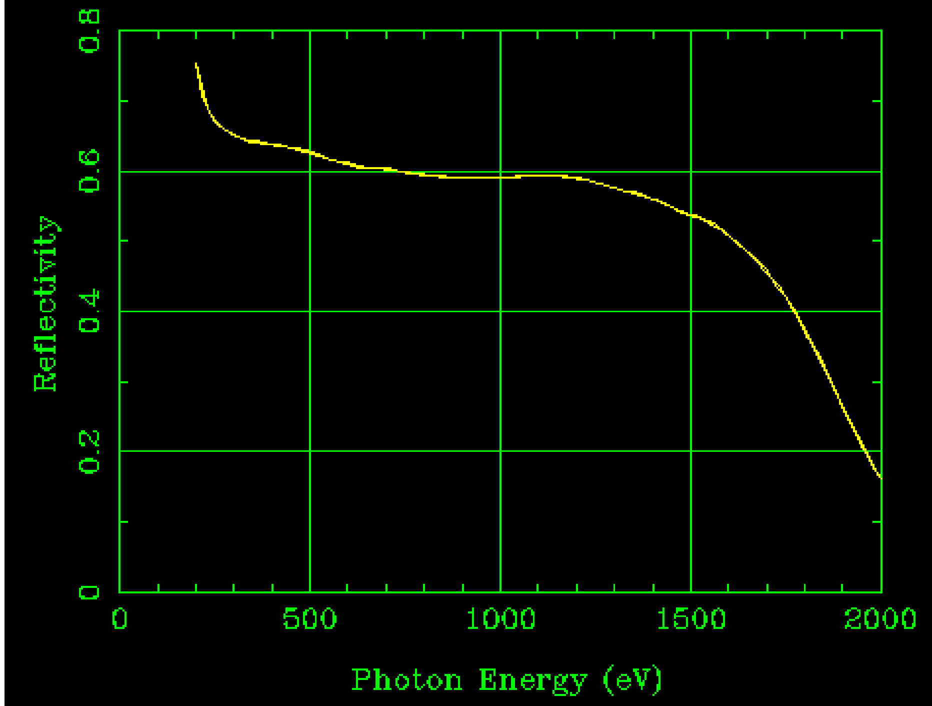


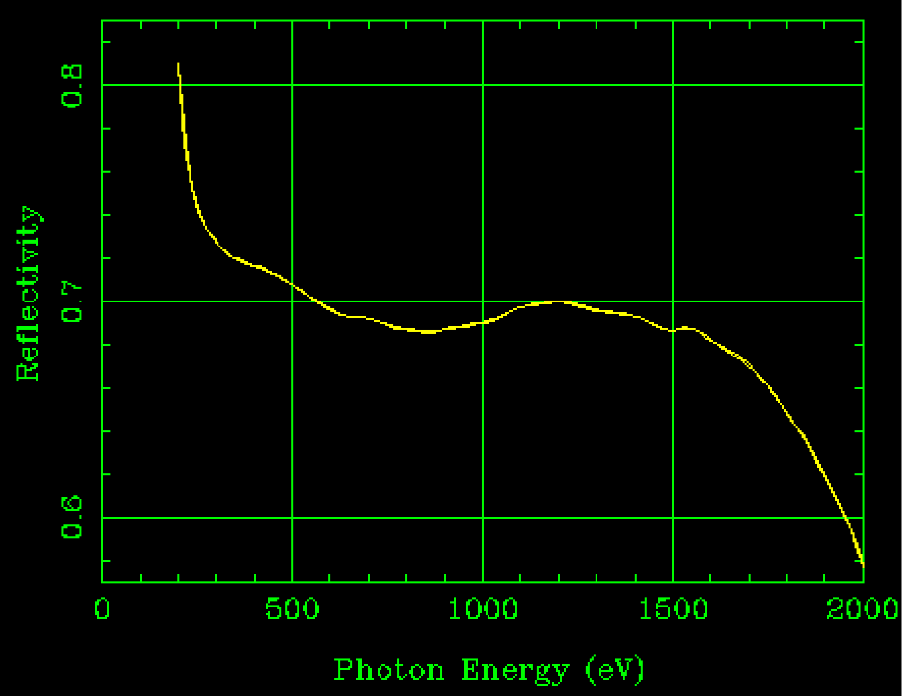
86 deg

http://henke.lbl.gov/optical_constants/

1.3. coating & reflectivity

Higher energy region


Au: 88 deg


Au: 88.5 deg

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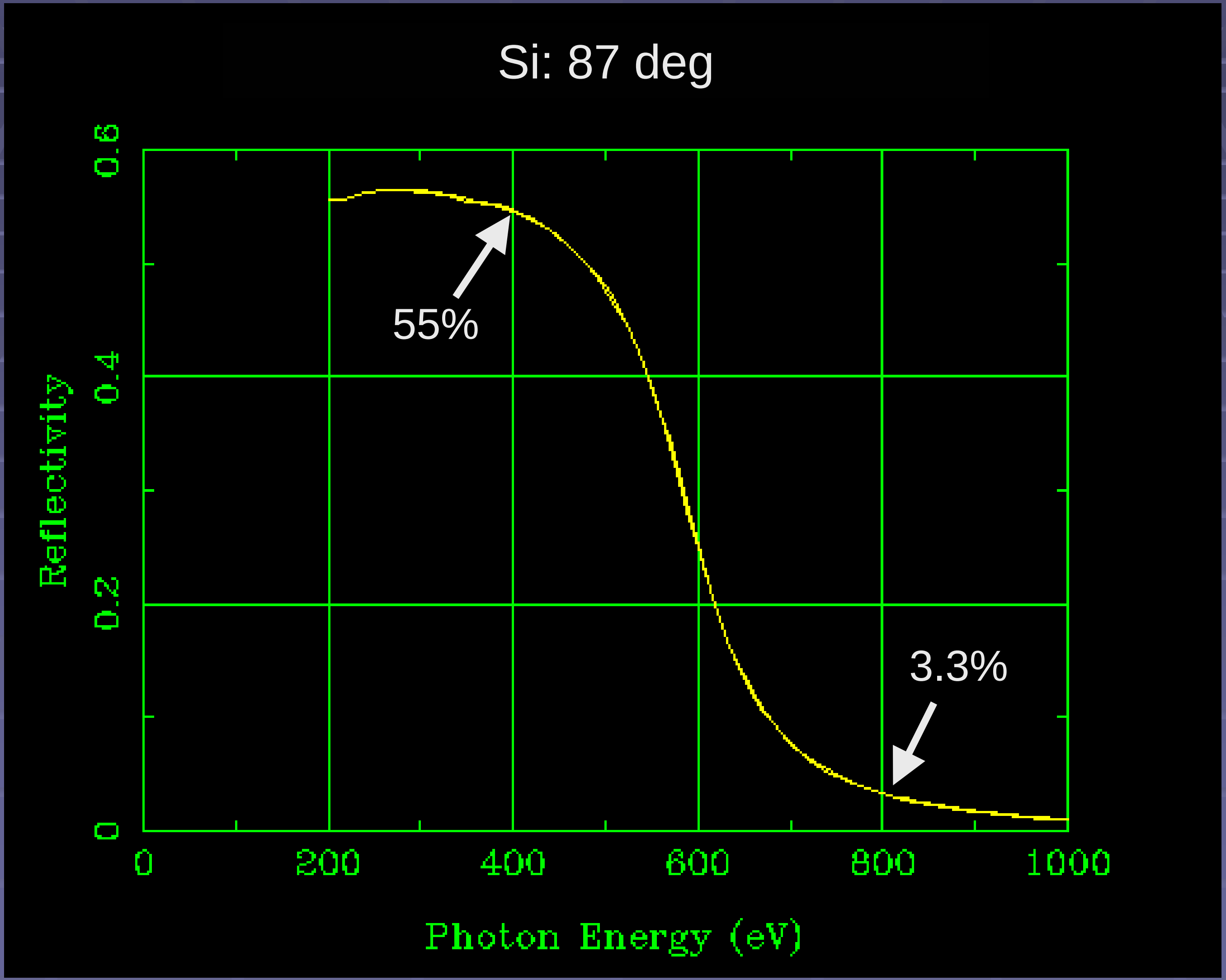
1.3. coating & reflectivity

Higher order suppression



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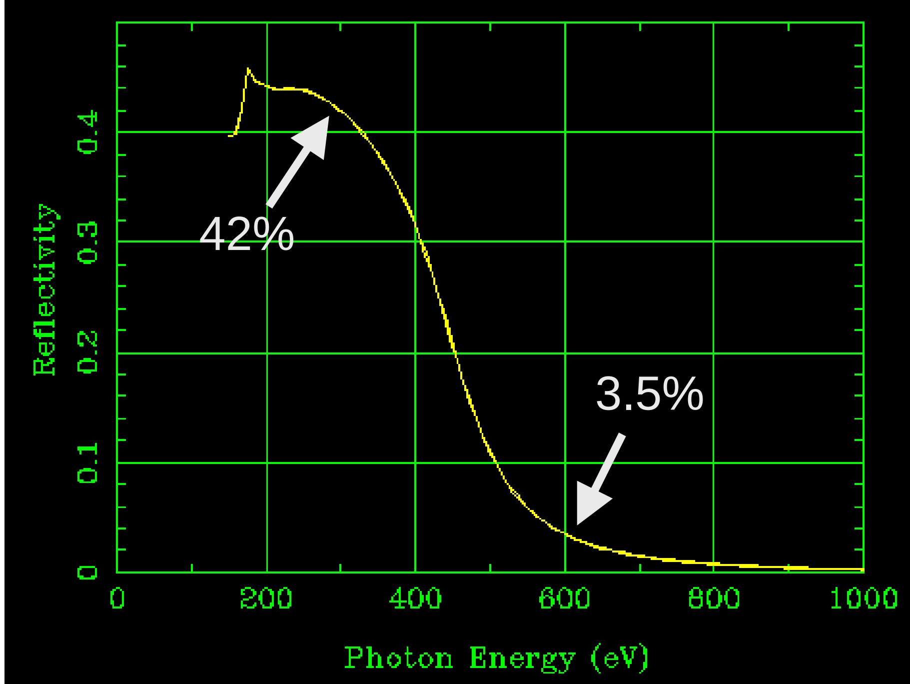
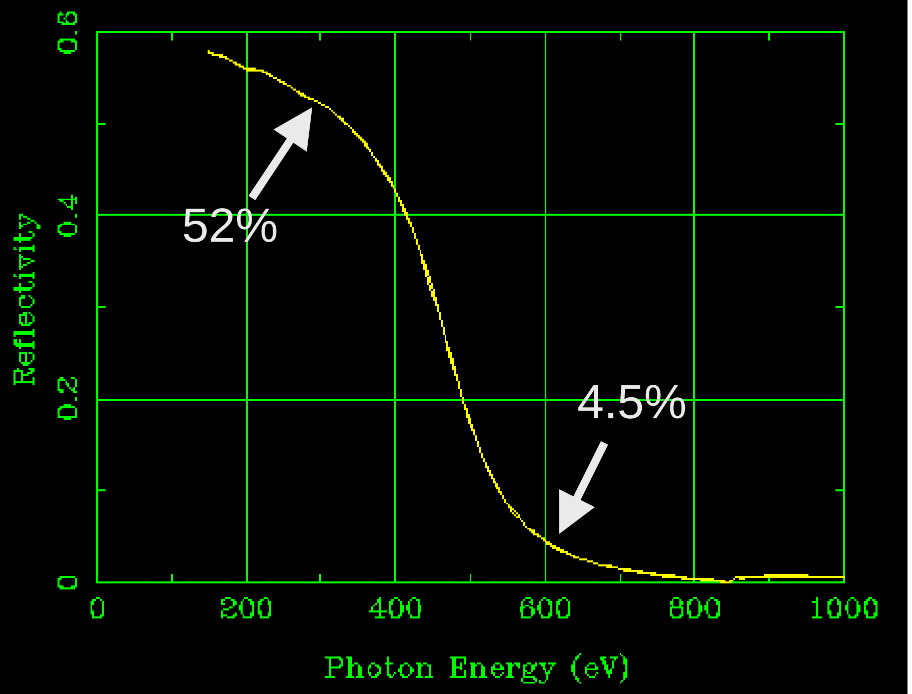
1.3. coating & reflectivity

Higher order suppression

Si: 86 deg



Ni: 84 deg



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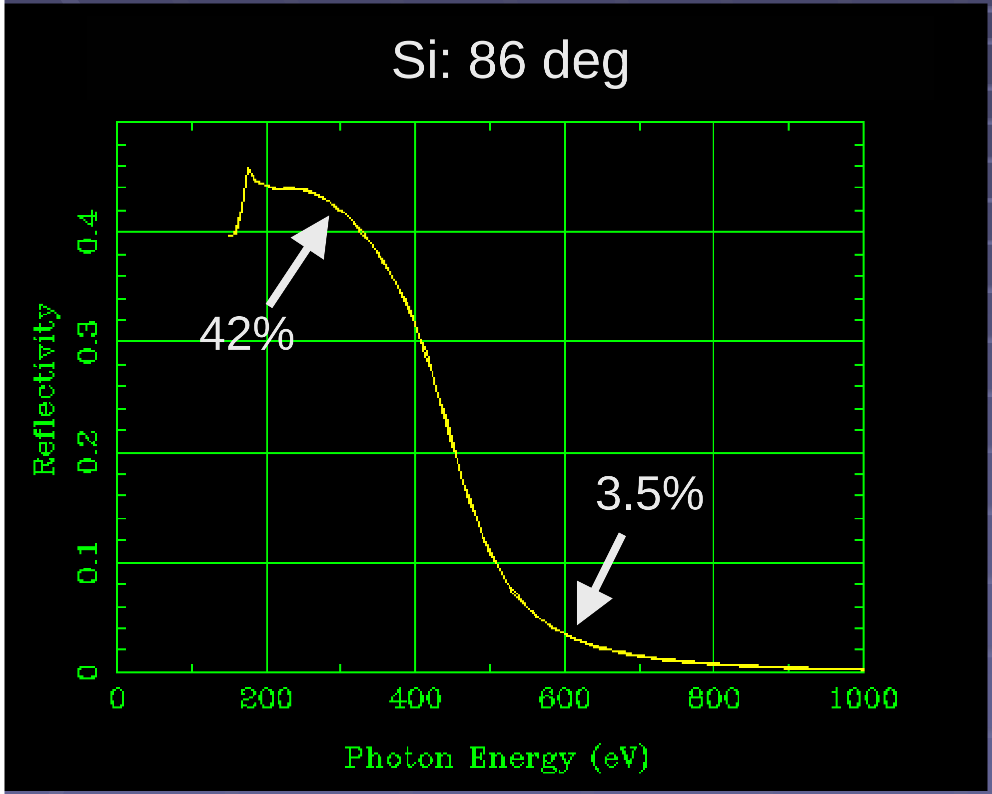
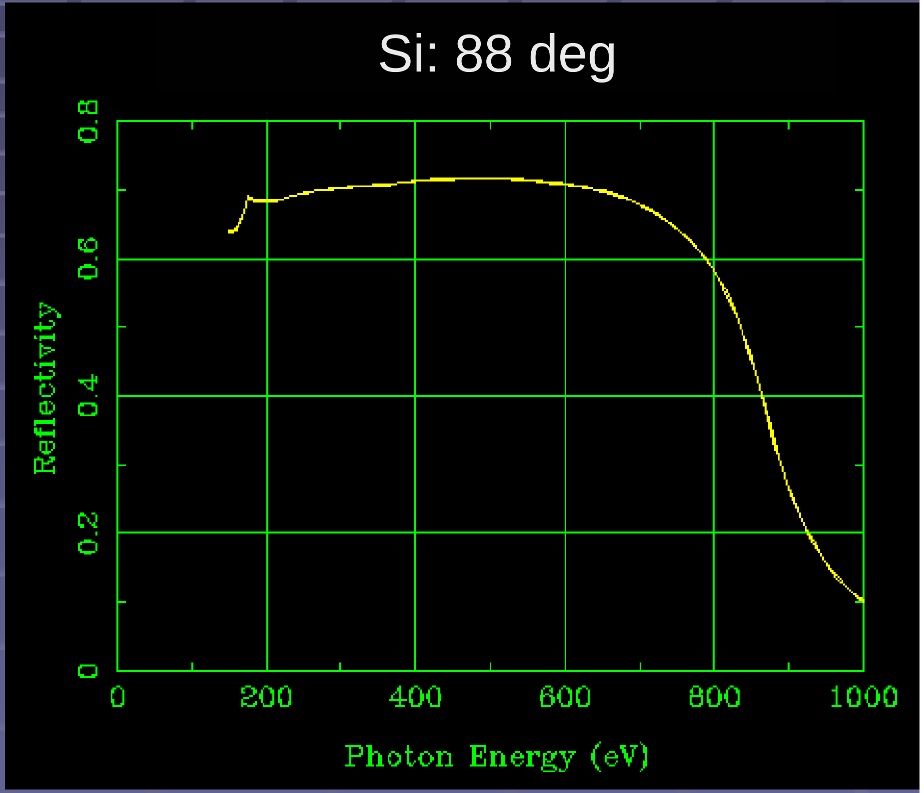
1.3. coating & reflectivity

Higher order suppression: incidence angle dependence


Si: 86 deg

42%

3.5%

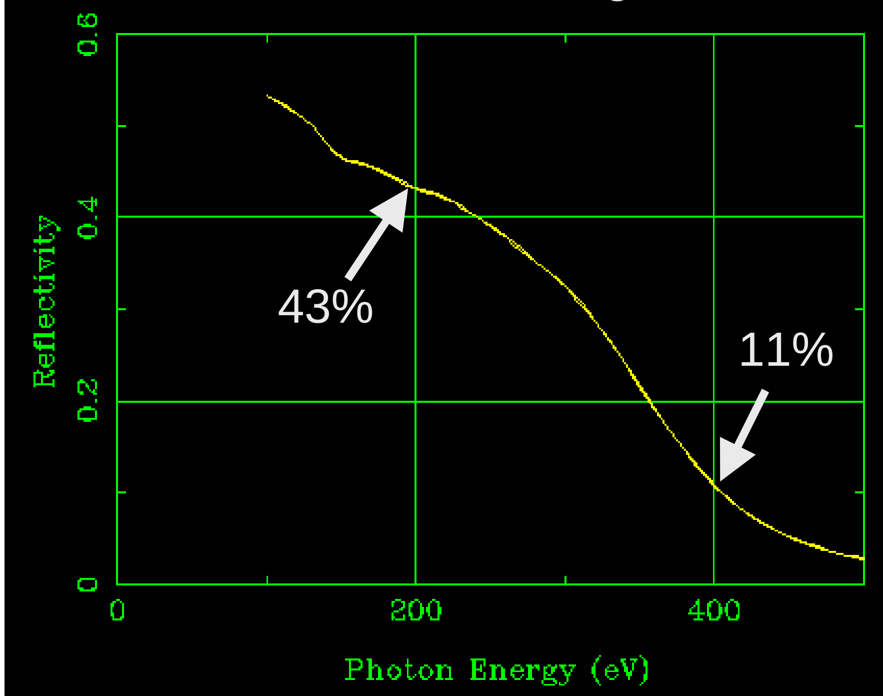

Si: 88 deg

http://henke.lbl.gov/optical_constants/

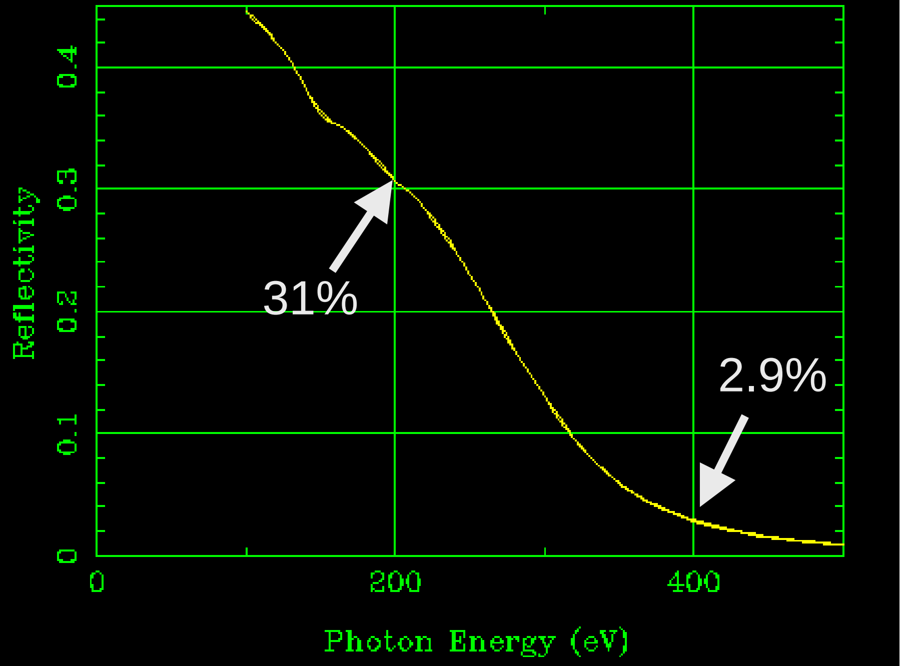
Simultaneous rotation with energy scan is necessary
No precise control is required

1.3. coating & reflectivity

Higher order suppression in low energy region



Ni: 82 deg



Ni: 80 deg

http://henke.lbl.gov/optical_constants/

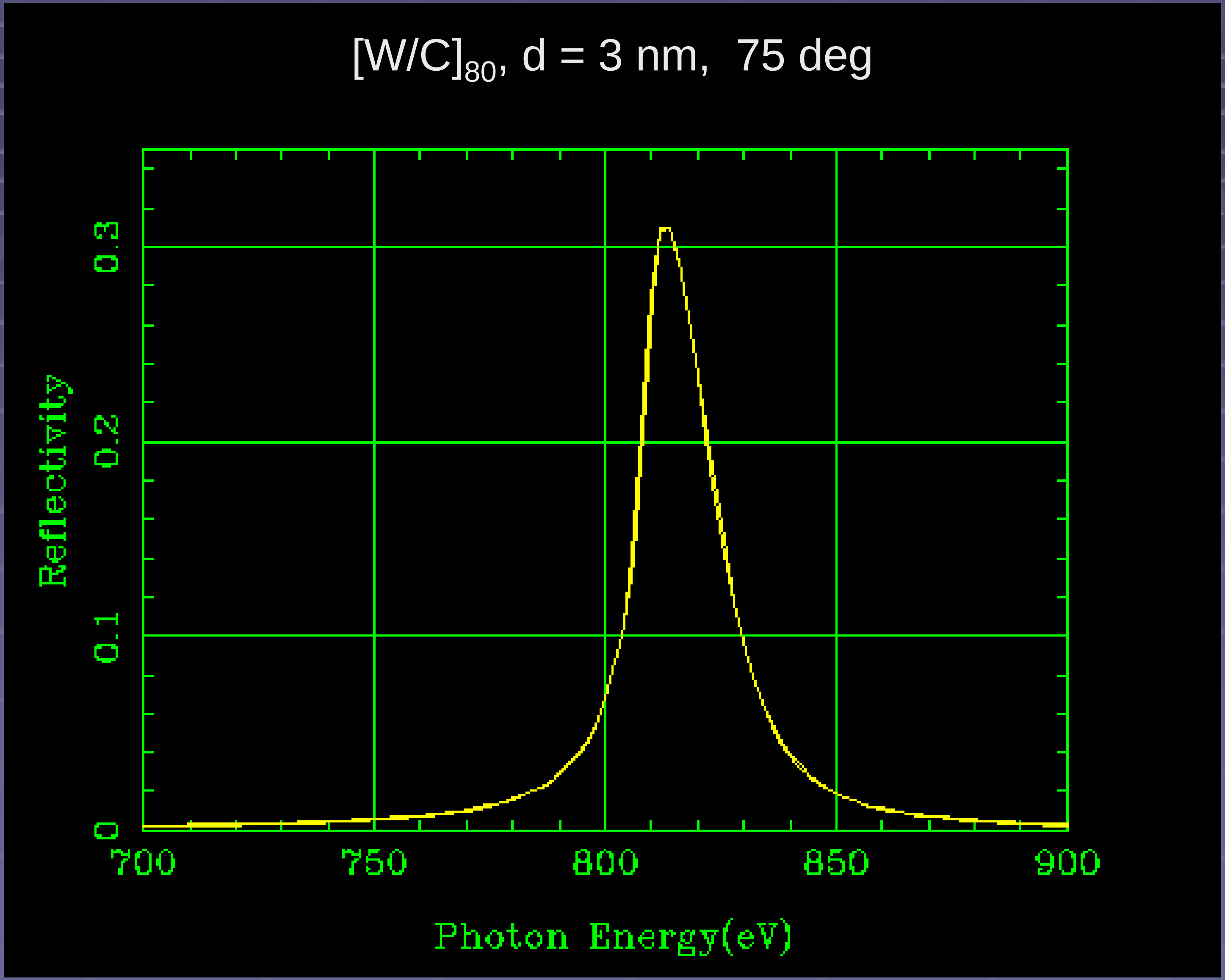
It is difficult to achieve high reduction ratio
keeping high reflectivity for fundamental light

Not effective below ~100 eV

1.3. coating & reflectivity

Multilayer mirror

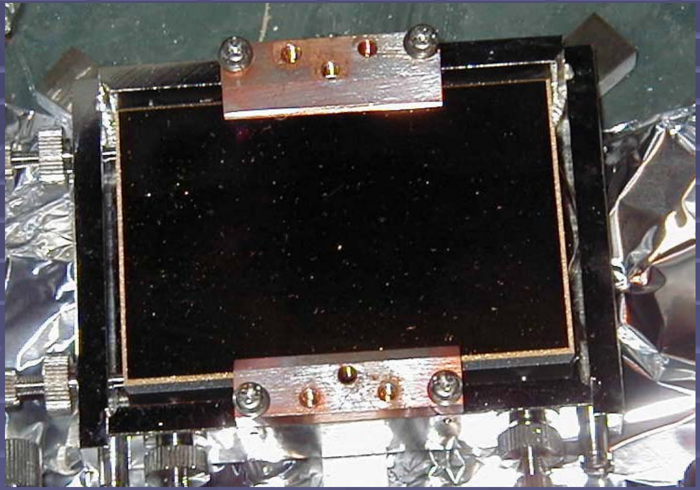
$[W/C]_{80}$, d = 3 nm, 75 deg

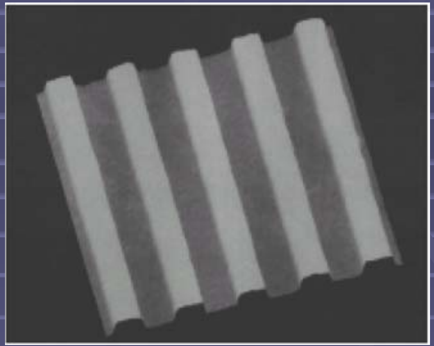


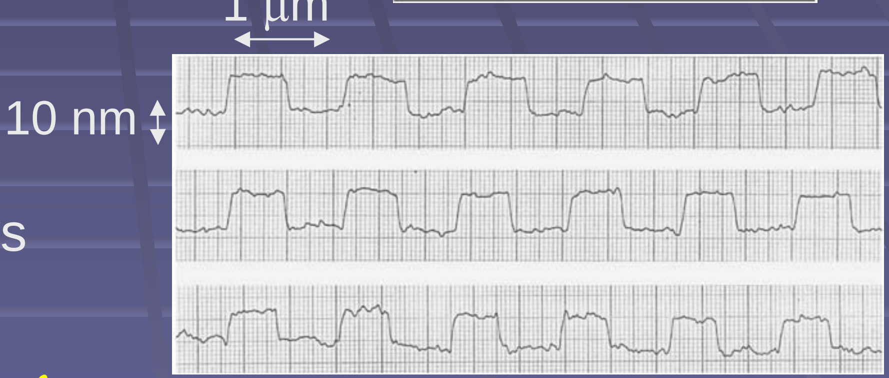
http://henke.lbl.gov/optical_constants/

2.1. principle - wavelength dispersion -

Diffraction grating: Periodic grooves on a substrate

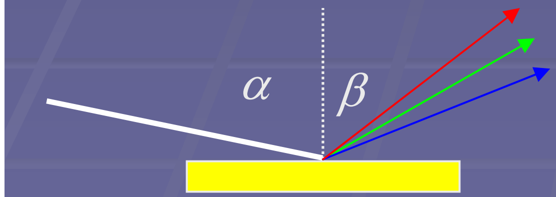






Principle: Interference between the rays reflected at different grooves

Enhanced when light path difference = $m\lambda$



* $\alpha > 0$

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

* $\alpha \neq |\beta|$

(if $\alpha = |\beta|$, any λ satisfies the above condition at $m = 0$)

⇒ zero-th order light

n: groove density

m: diffraction order

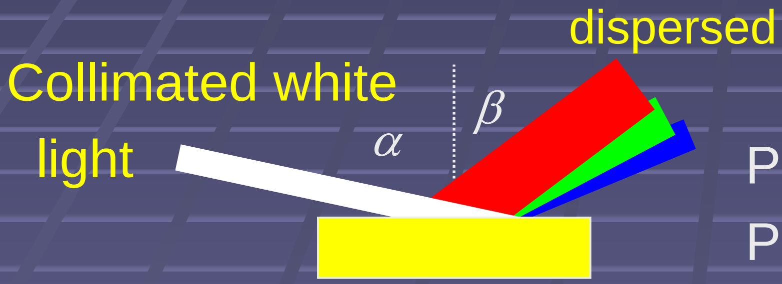
β depends on λ ⇒ Wavelength dispersion

(conversion of wavelength to angle)

2.2. energy resolution - dispersion and focus -

How can we monochromatize by using a diffraction grating?

Most basic mode: collimated-light illumination



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

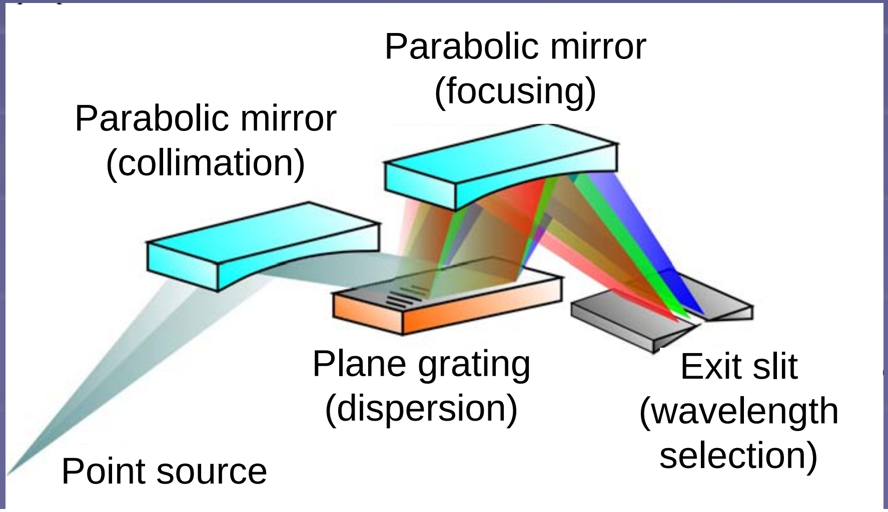
Problem 1: SR is not a collimated light !

Problem 2: Superposition of diffracted lights

⇒ difficult to be resolved

Solution 1: Collimation of diverging light with a parabolic mirror

Solution 2: Focusing of diffracted lights with another parabolic mirror

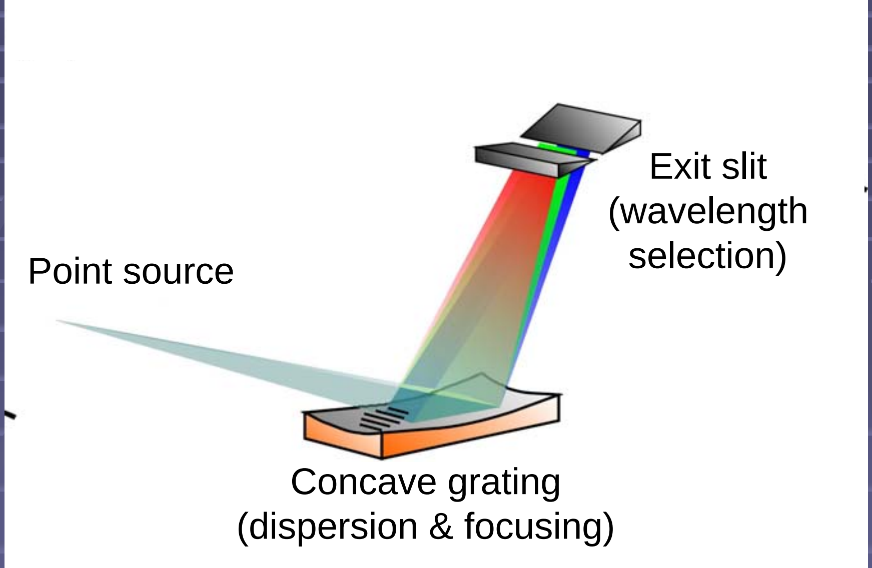


Focused diffracted lights are well resolved in wavelength at the exit slit !

Dispersion and Focus

2.2. energy resolution - dispersion and focus -

The simplest monochromator



Both the "dispersion" and "focus" are achieved by a diffraction grating only.

Is that really possible?

It is impossible to obtain a perfect focus at all wavelength

But, "perfect focus" is not necessary !

Small number of optical elements

2.2. energy resolution - dispersion and focus -

What determines the energy resolution?

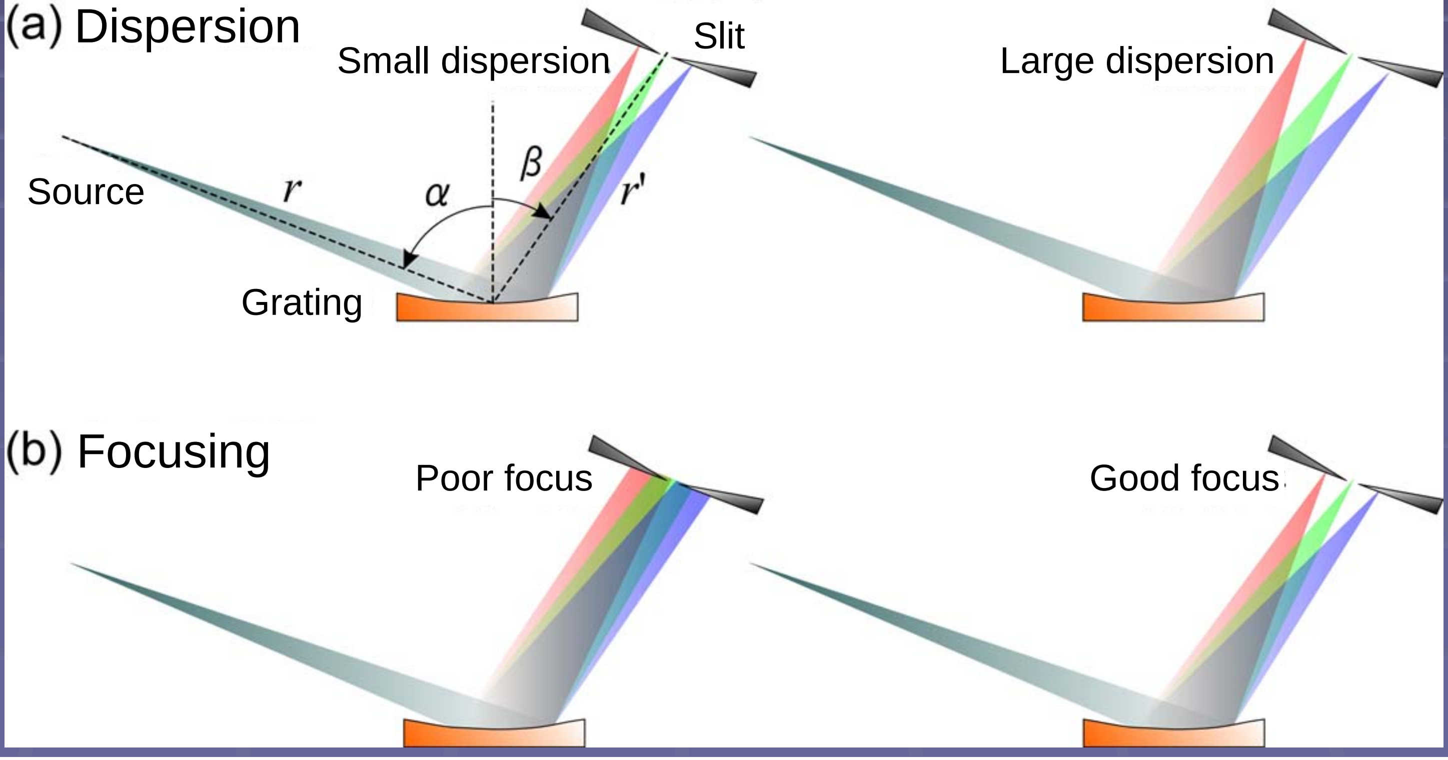
"Dispersion": separation of lights with different wavelengths ⇒ $dz/d\lambda$

sin α + sin $\beta = nm\lambda$ ⇒

$$\cos\beta d\beta = nmd\lambda, \quad dz/d\lambda = r'd\beta/d\lambda = r'nm/\cos\beta$$

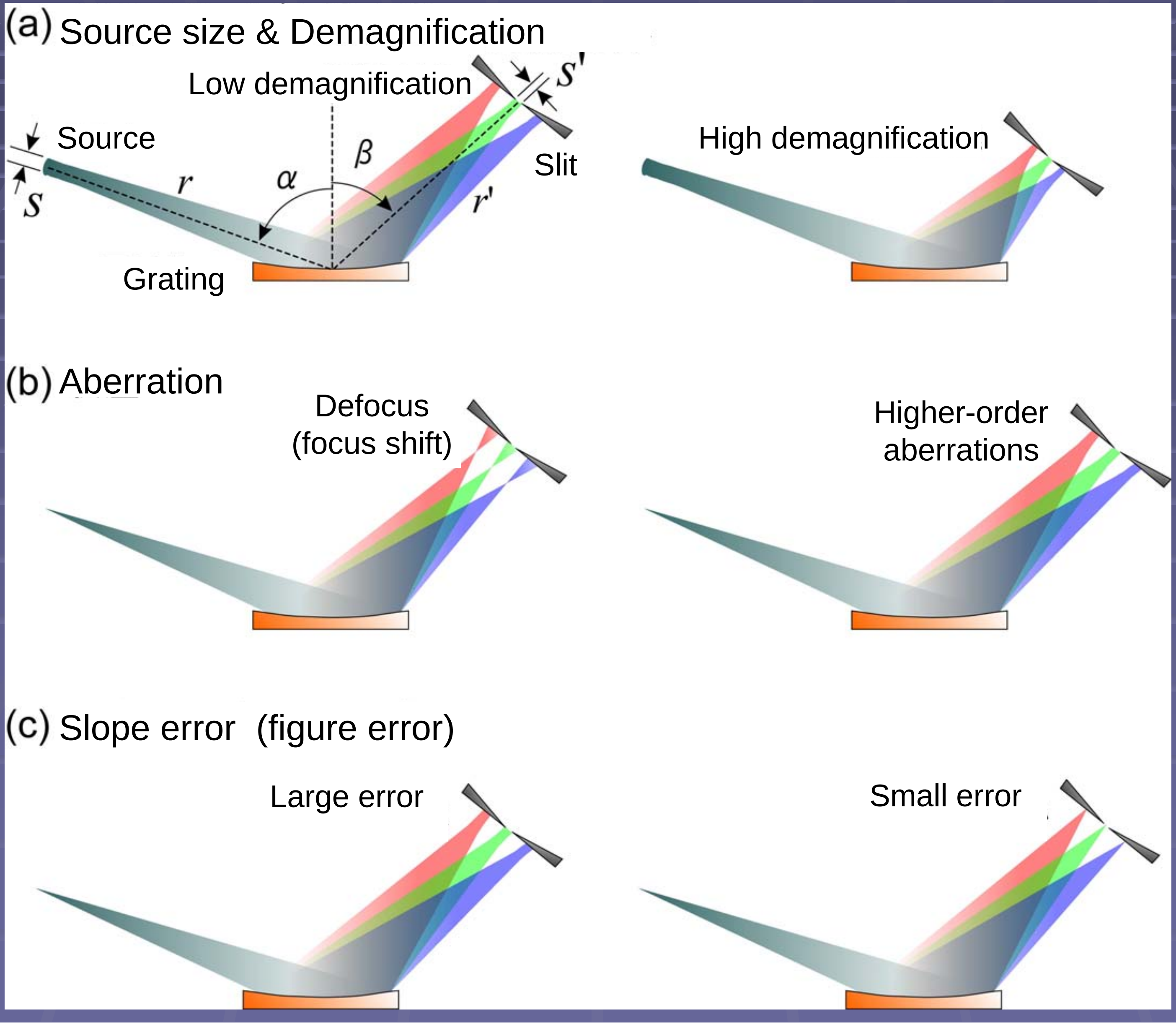
Ratio between "dispersion" and "light size" determines resolution.

i.e. large dispersion & small focus ⇒ high energy resolution



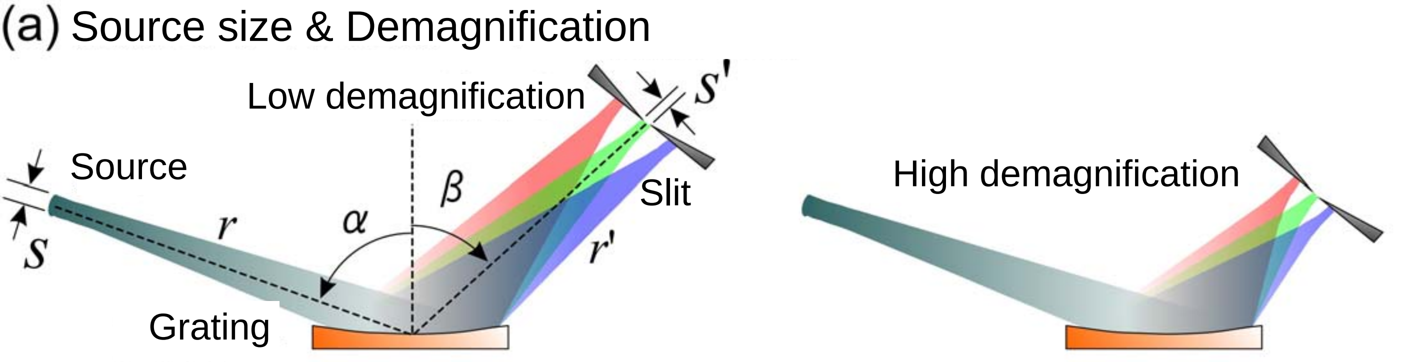
2.2. energy resolution - dispersion and focus -

What determines the focus size?



2.2. energy resolution - dispersion and focus -

(a) Source size & Demagnification



s' (lower limit) $= s\, d/d'$

d : divergence at the source

d' : divergence at the focus

How to reduce s':

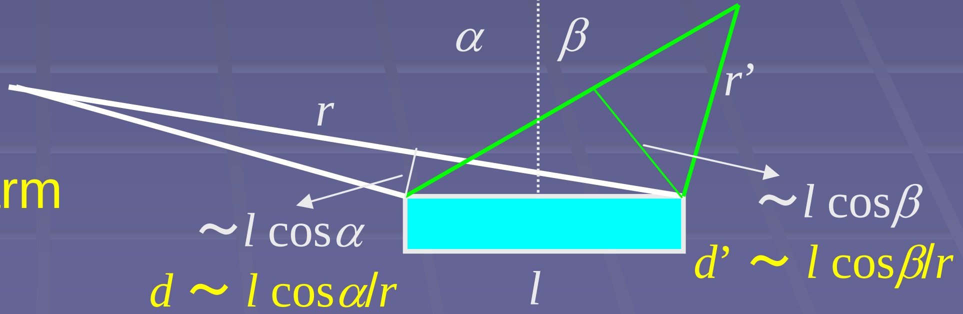
1. reduce r' compared to r

   long entrance arm & short exit arm

2. decrease $|\beta|$ compared to α

   make the incidence angle more grazing ⇒ High groove density

   (keeping the diffraction condition satisfied) large included angle $(\alpha - \beta)$

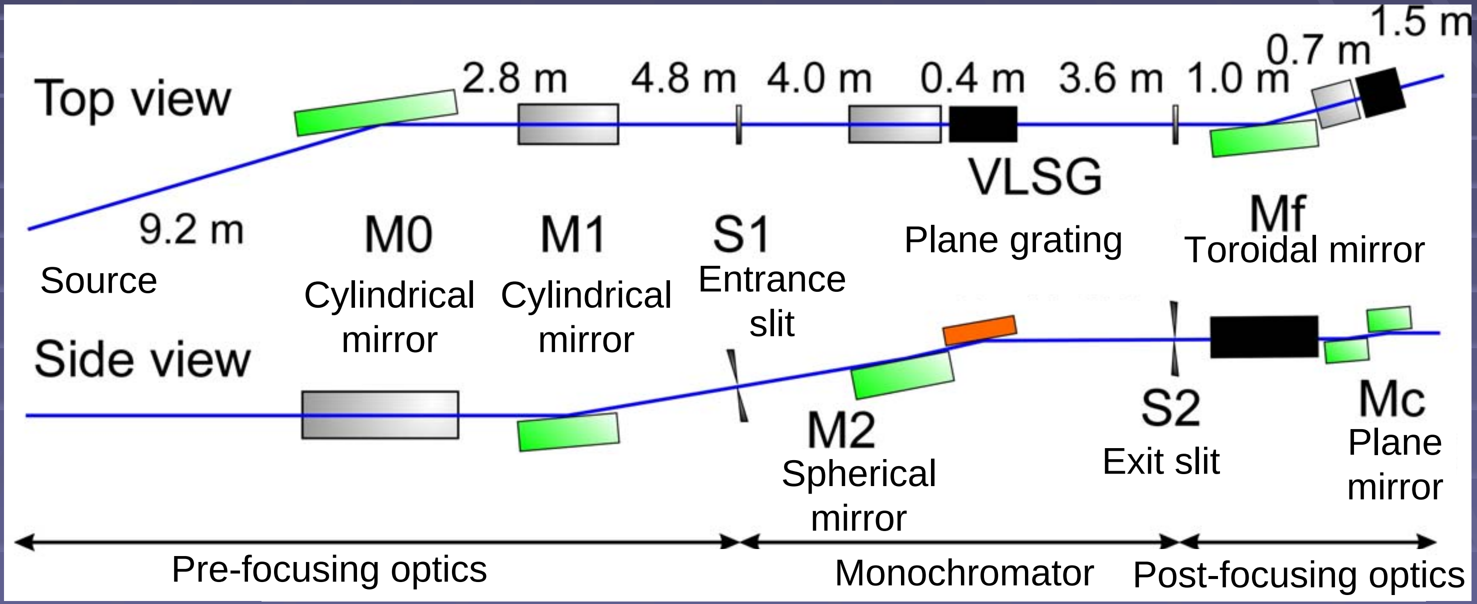


2.2. energy resolution - dispersion and focus -

3. reduce the source size (s)

Must we reduce the size of the SR source itself?

Use of "pre-focusing optics" and "entrance slit"



"entrance slit" can be regarded as a virtual source

Source size can be controlled by entrance-slit opening

(at the sacrifice of intensity)

Demagnification in the pre-focusing optics is effective

(* divergence increases)

2.2. energy resolution - dispersion and focus -

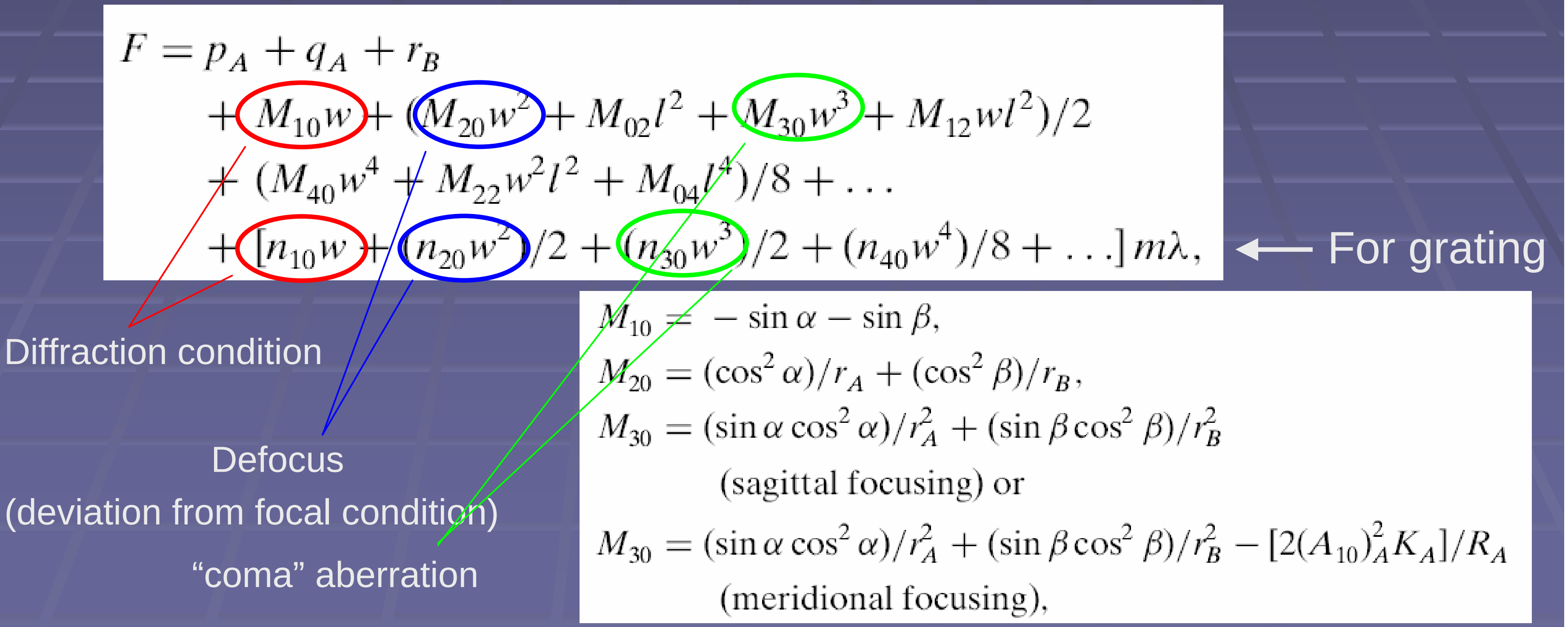
(b) Aberration

Caused by a deviation from the elliptical (or parabolic) shape

e.g. Use of a spherical mirror instead of elliptical one

Diffraction effects should be taken into account for a diffraction grating

Aberration is usually expanded in a power series of the position on the optical element, (*w*, *l*), using the light path function, *F*



$$\begin{aligned} F = {} & p_A + q_A + r_B \\ & + M_{10} w + (M_{20} w^2 + M_{02} l^2 + M_{30} w^3 + M_{12} w l^2)/2 \\ & + (M_{40} w^4 + M_{22} w^2 l^2 + M_{04} l^4)/8 + \ldots \\ & + [n_{10} w + (n_{20} w^2)/2 + (n_{30} w^3)/2 + (n_{40} w^4)/8 + \ldots] m\lambda, \end{aligned}$$

⟵ For grating

$$\begin{aligned} M_{10} &= -\sin\alpha - \sin\beta, \\ M_{20} &= (\cos^2\alpha)/r_A + (\cos^2\beta)/r_B, \\ M_{30} &= (\sin\alpha\cos^2\alpha)/r_A^2 + (\sin\beta\cos^2\beta)/r_B^2 \\ & \qquad \text{(sagittal focusing) or} \\ M_{30} &= (\sin\alpha\cos^2\alpha)/r_A^2 + (\sin\beta\cos^2\beta)/r_B^2 - [2(A_{10})_A^2 K_A]/R_A \\ & \qquad \text{(meridional focusing),} \end{aligned}$$

Diffraction condition

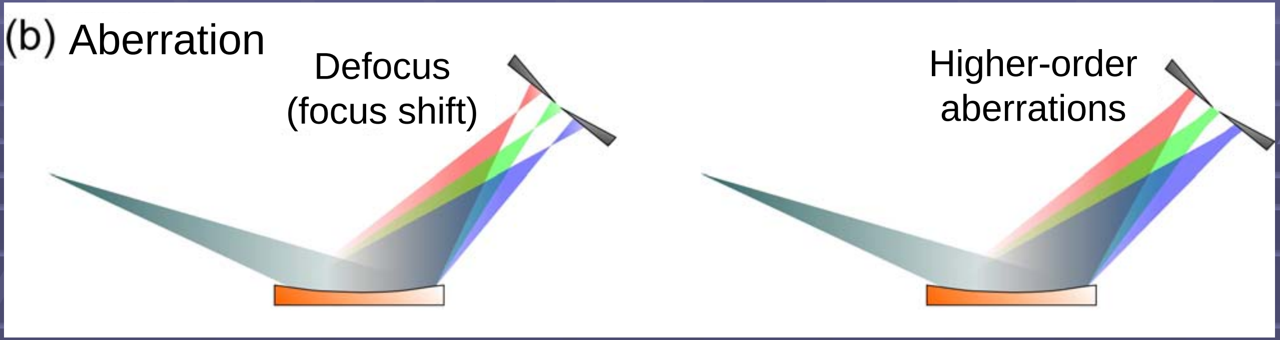
Defocus

(deviation from focal condition)

“coma” aberration

Larger illumination area (larger w and l) ⇒ larger effects of aberration

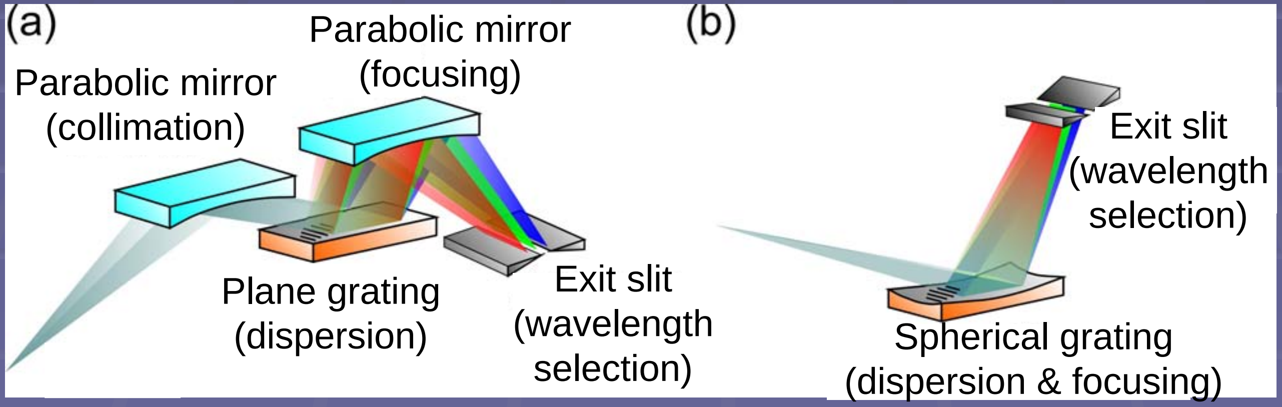
2.2. energy resolution - dispersion and focus -



How to reduce the aberration:

- Defocus can be compensated by adjusting the exit-slit position
- Higher-order aberrations can be canceled by a combination of mirrors (not easy)
- Reduce the illumination area ⇒ small divergence (acceptance)

Examples for aberration-free or low-aberration optics



No aberration

"Rowland condition"

$r = R \cos \alpha, r' = R \sin \beta$

2.2. energy resolution - dispersion and focus -

(c) Slope errors

Errors in fabrication of optical elements (e.g. undulation of a plane mirror)

Not systematic ⇒ compensation is impossible

⇒ One have to fabricate optical elements with small slope error

or design optics to reduce the effects of the slope errors

Demagnification is also effective to reduce the slope-error effects

(d) Number of illuminated grooves

Intrinsic problem of diffraction

Resolving power $(\lambda/\Delta\lambda) \sim N$

* Small divergence

⇒ small effects of aberration but small number of grooves

2.3. fabrication of gratings

1. **Substrate** (Plane, Cylindrical, Spherical, Toroidal,…)

   Same as mirror fabrication

2. **Fabrication of grooves** (uniform or varied line spacing)

   $N = N_0 (1 + a_1 w + a_2\, w^2 + a_3\, w^3)$ (groove density)

$$
\begin{aligned}
F = {} & p_A + q_A + r_B \\
& + M_{10}w + (M_{20}w^2 + M_{02}l^2 + M_{30}w^3 + M_{12}wl^2)/2 \\
& + (M_{40}w^4 + M_{22}w^2l^2 + M_{04}l^4)/8 + \dots \\
& + [\boxed{n_{10}w} + \underbrace{(n_{20}w^2)/2 + (n_{30}w^3)/2 + (n_{40}w^4)/8 + \dots}_{= 0 \text{ for uniform line spacing}}]\, m\lambda,
\end{aligned}
$$

(a) **Mechanical ruling**

All groove parameters (a_1, a_2,…) can be **controlled** !

Relatively **rough surface** ⇒ causes **stray light**

Suitable for “**Brazed**” gratings

2.3. fabrication of gratings

(b) Holographic recording

Interference patterns of Laser lights

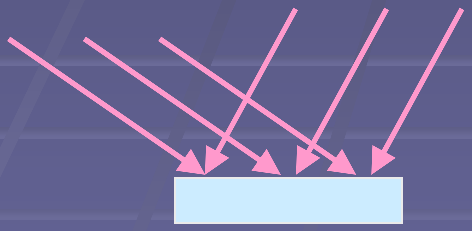
Some groove parameters might not be controlled

* aspheric wavefront recording is available

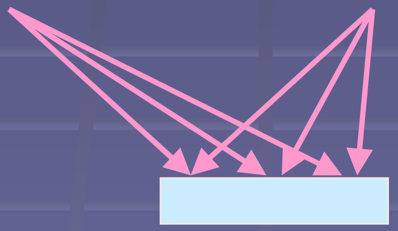
Relatively smooth surface ⇒ high reflectivity & low stray light

Both the “Laminar” and “Brazed” gratings can be fabricated

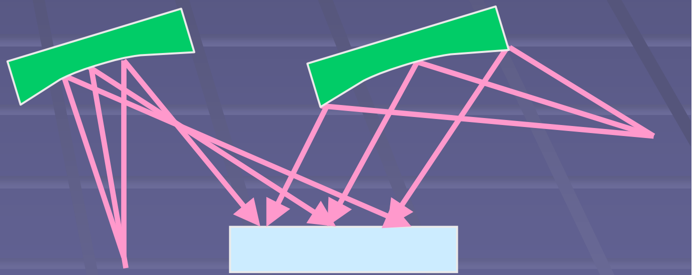
* some manufacturer strongly prefers the Laminar type



Collimated lights
⇒ uniform line spacing



Spherical wavefronts
⇒ varied line spacing
(poor control)



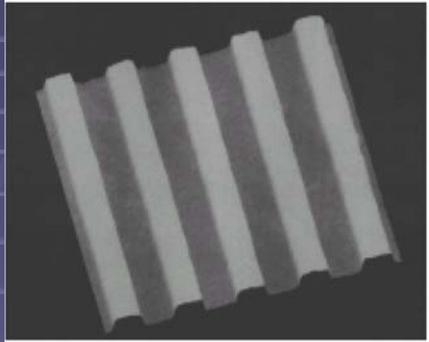
Aspheric wavefronts
⇒ varied line spacing
(fine control)

T.Namikoka and M.Koike
Appl. Opt. 34 (1995) 2180

2.3. fabrication of gratings

3. Groove shape (Laminar & Brazed)

(a) Laminar type

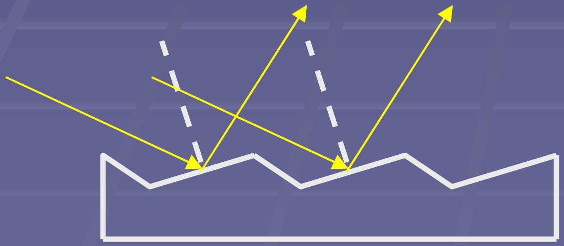


Medium diffraction efficiency

Higher order suppression

interference between top and bottom parts

(b) Brazed type



High diffraction efficiency when “on Braze”

Strong higher orders