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

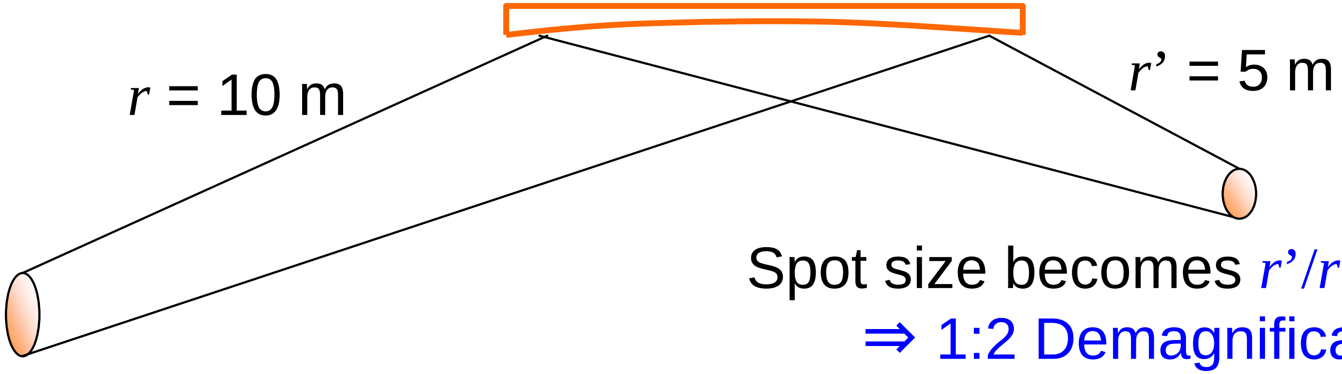
    - dispersion and focus -

    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

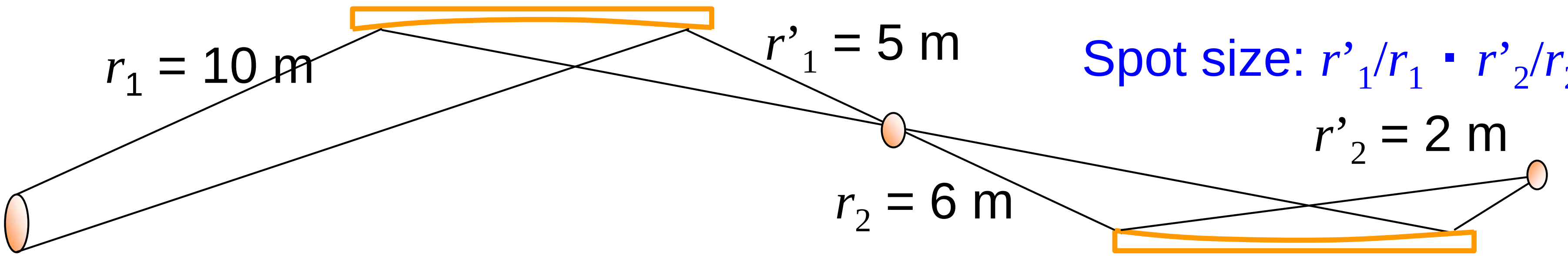
* Divergence becomes 2 times larger

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

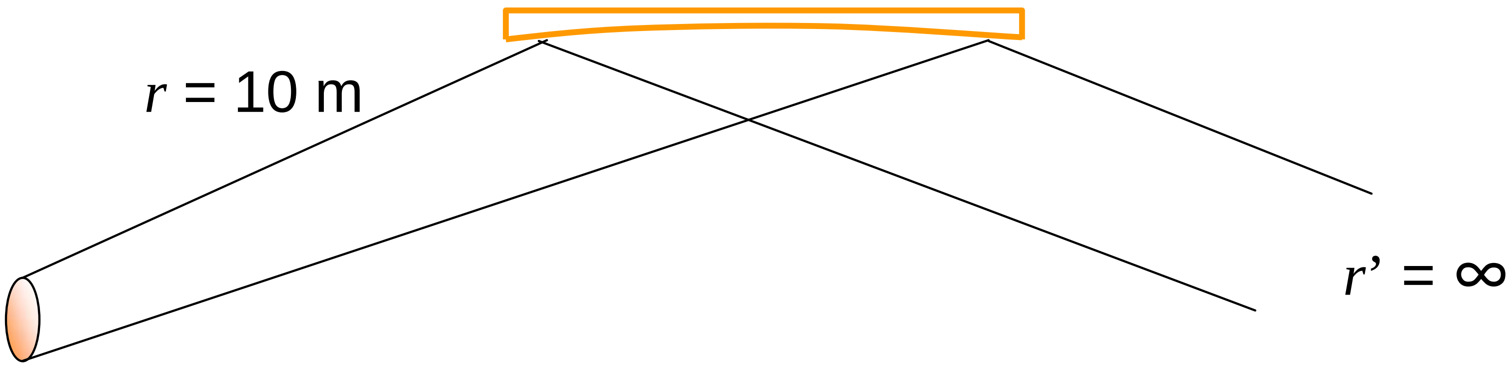


Spot size: $r'_1/r_1 \cdot r'_2/r_2$ = 1/6

Divergence: 6x

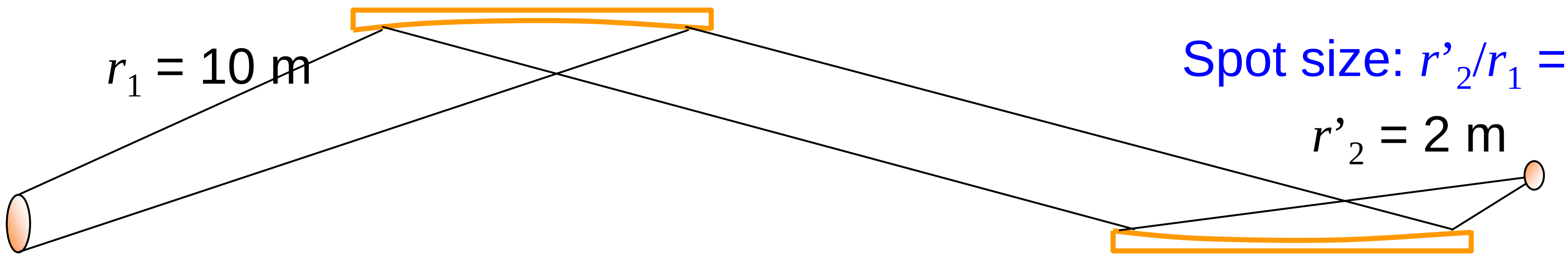
1.1. focusing & collimation

Collimation

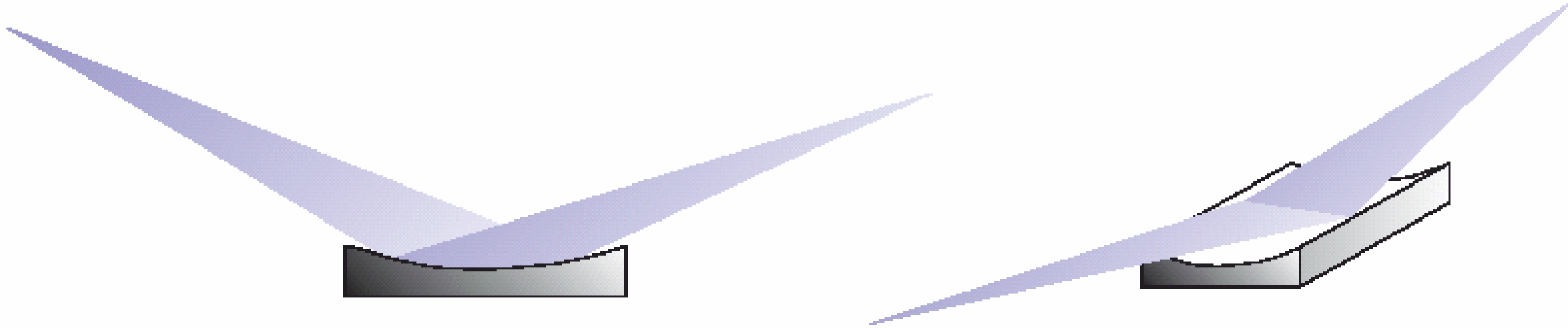


Parabolic mirror ⇒ perfect collimation (spot-size limited)
Use of a cylindrical or spherical mirror ⇒ poor collimation (aberration)
Larger divergence (larger illumination area) ⇒ larger aberration

Combination of collimating mirrors



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

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

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

e.g. 88 deg (from normal),
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

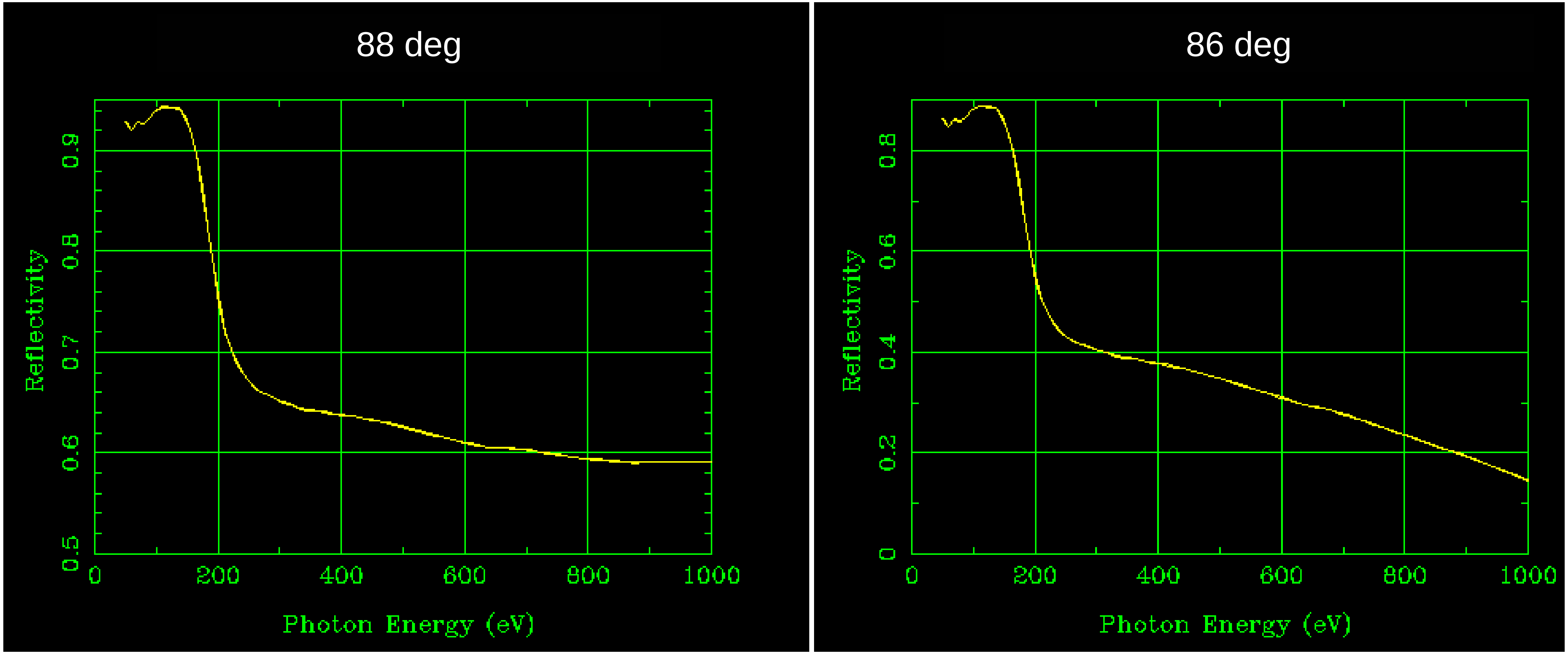
* SiO_2 is suitable for mirror current measurements

1.3. coating & reflectivity

Coating layer:

- High reflectivity by "total reflection"
- Protection against oxidation etc.

Typical coating material in VUV-SX: Au (50-100 nm)

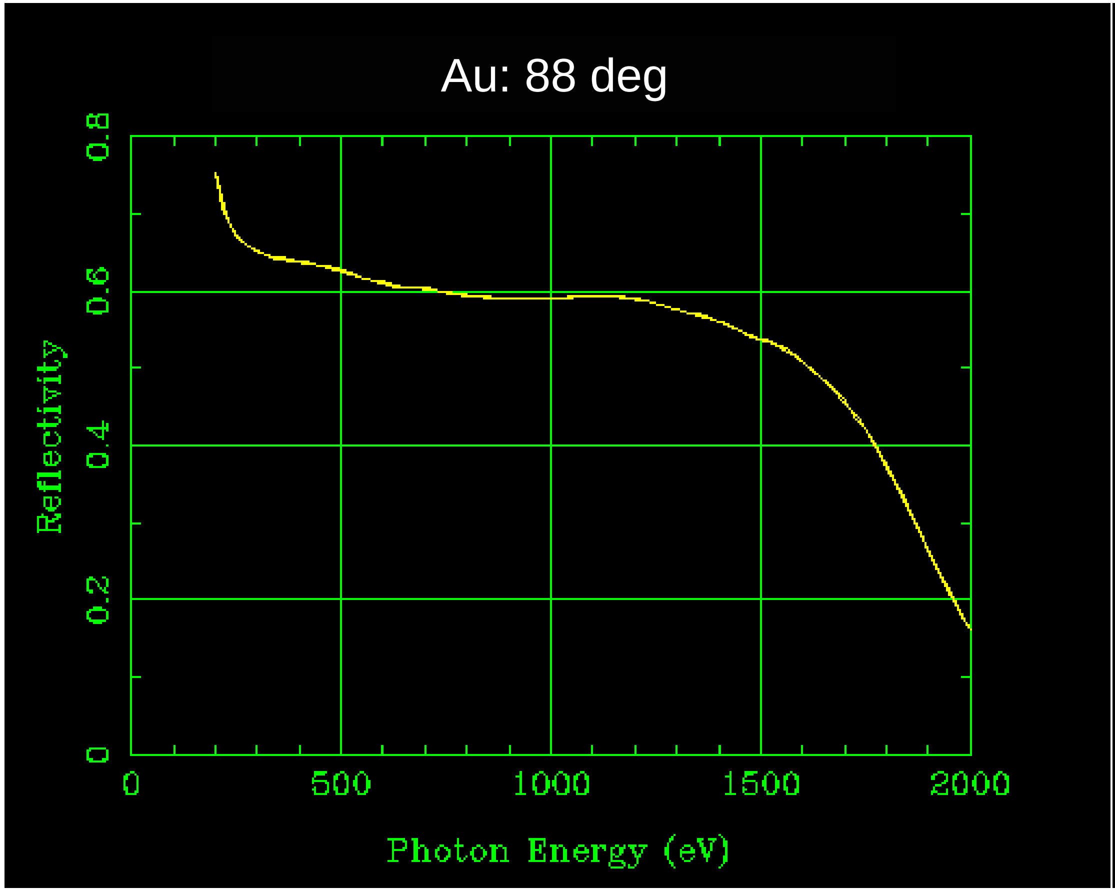


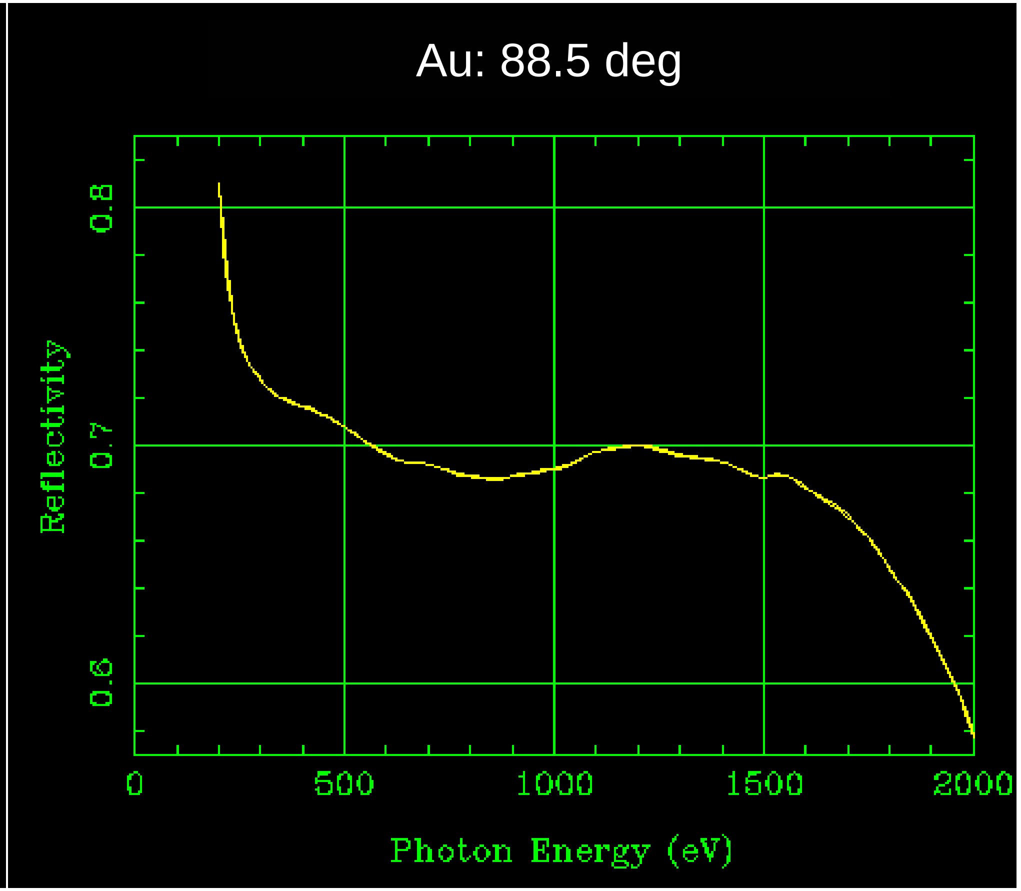
http://henke.lbl.gov/optical_constants/

1.3. coating & reflectivity

Higher energy region

Critical energy for total reflection depends on incidence angle





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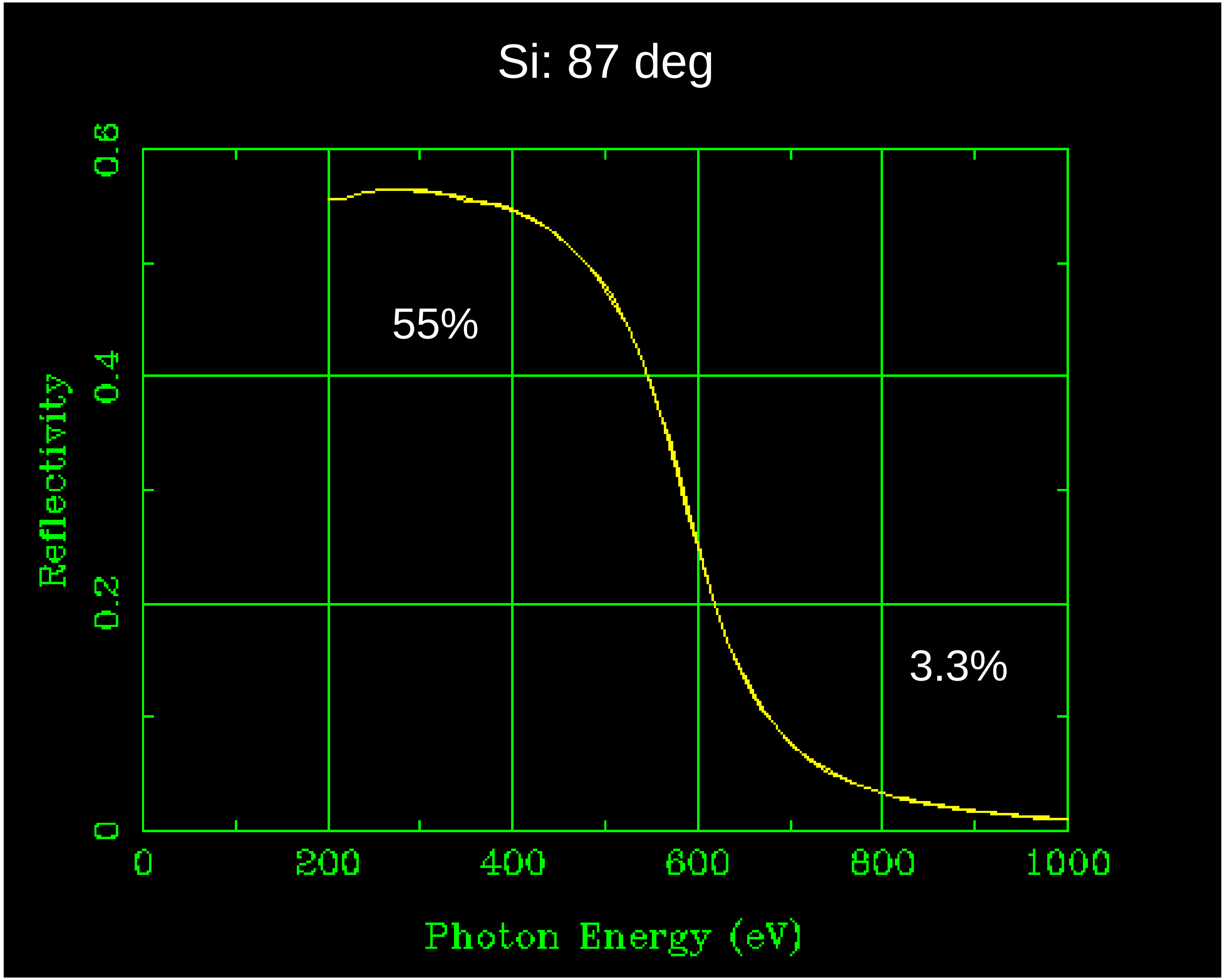
1.3. coating & reflectivity

Higher order suppression



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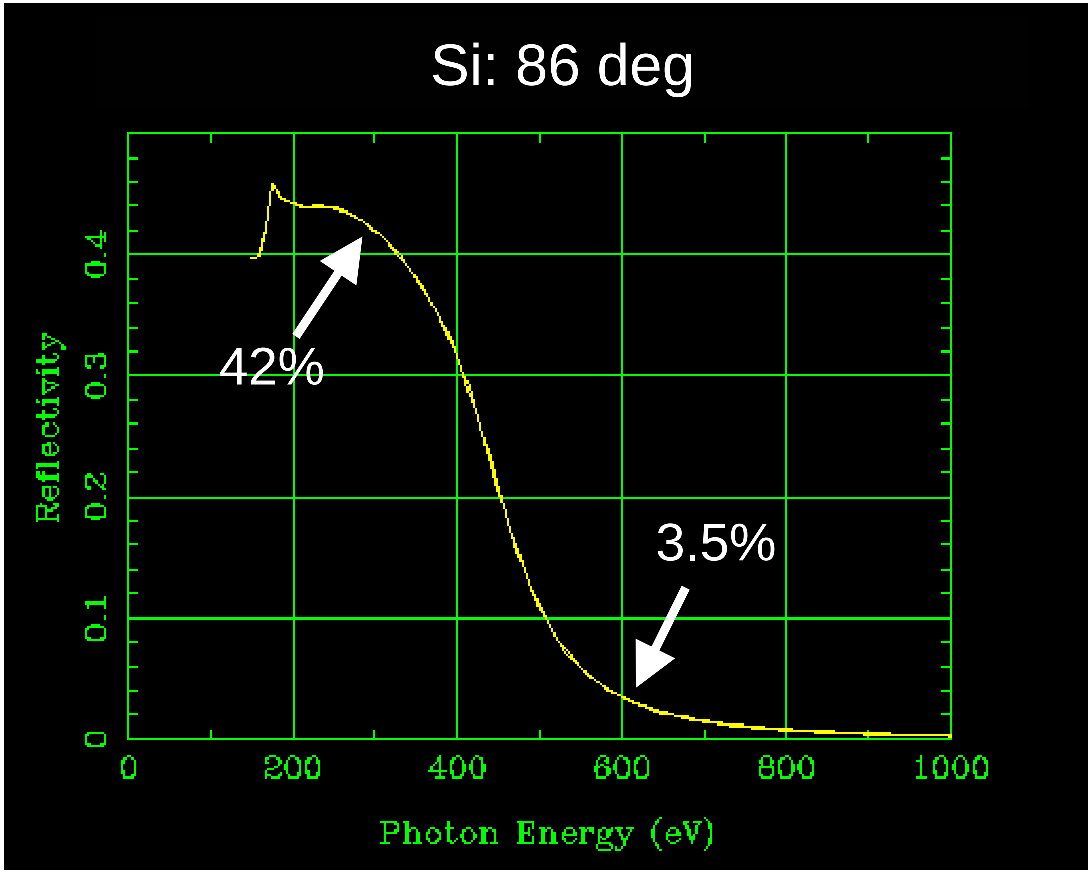
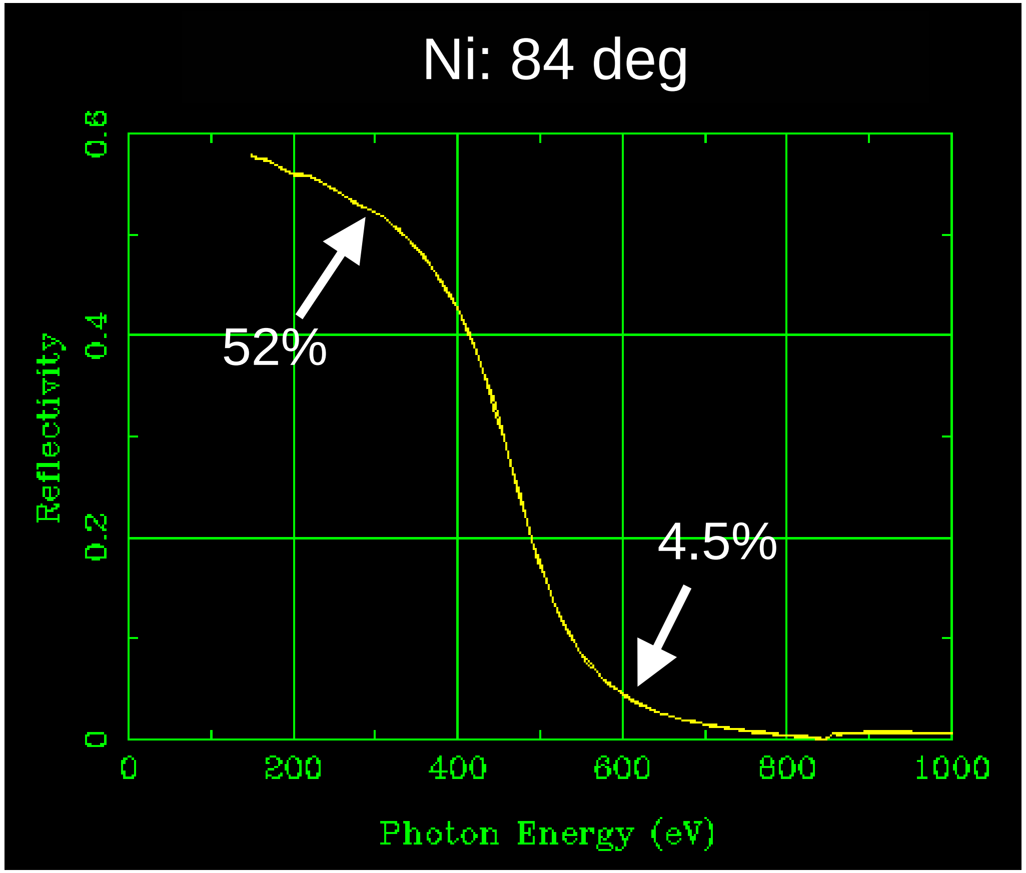
1.3. coating & reflectivity

Higher order suppression: coating material dependence





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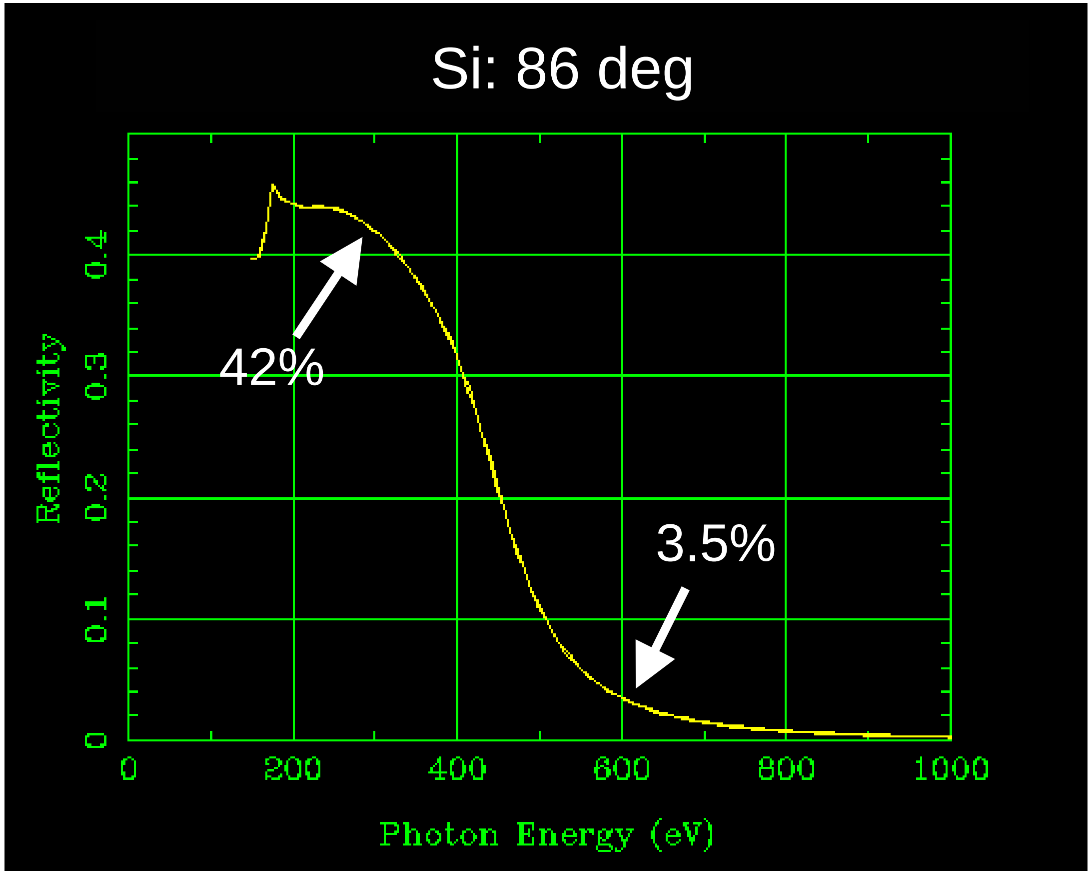
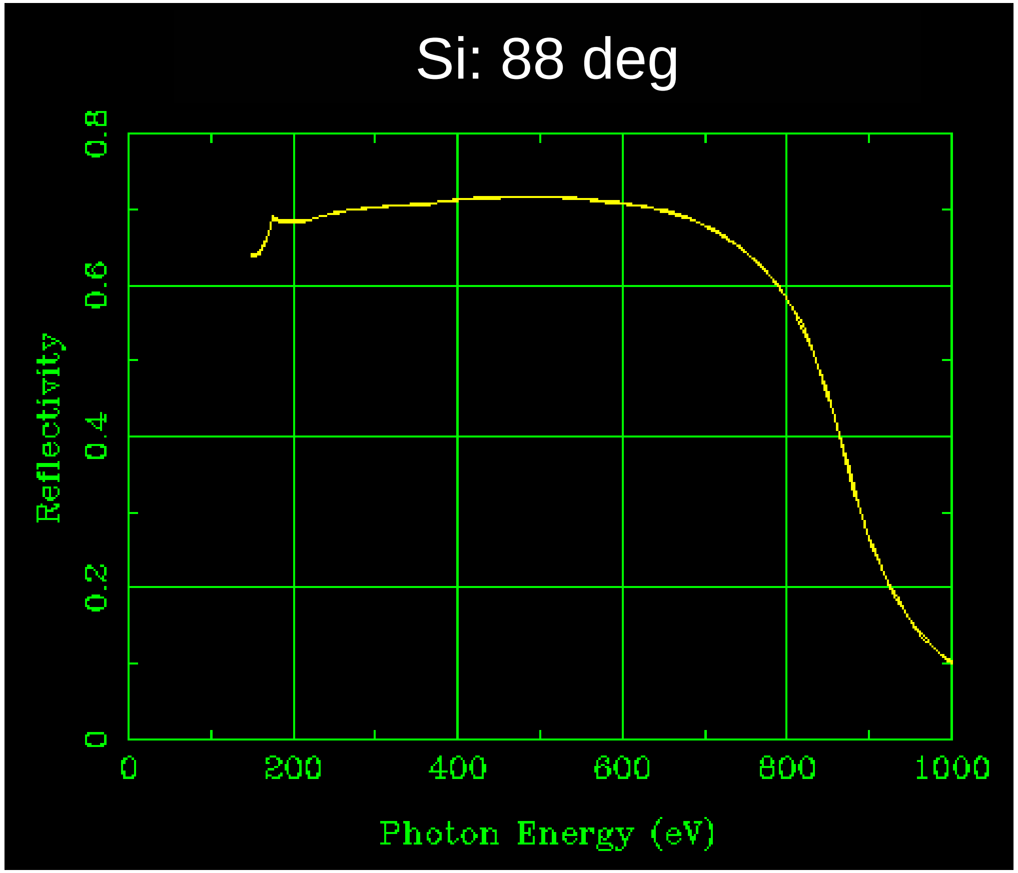
1.3. coating & reflectivity

Higher order suppression: incidence-angle dependence





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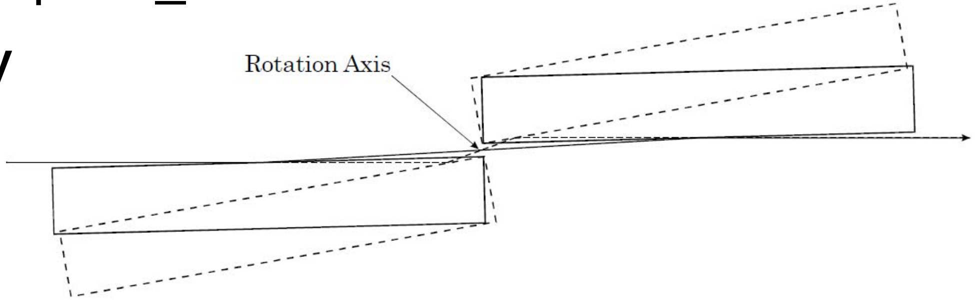
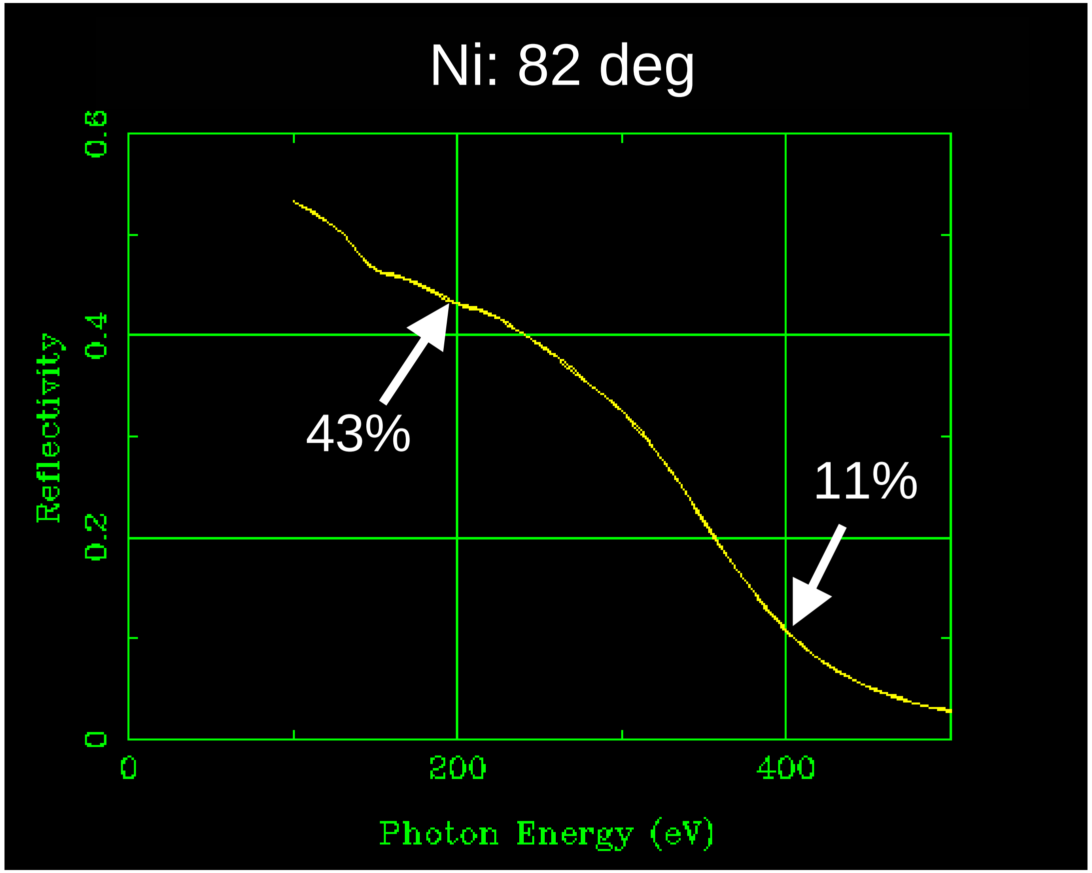
Simultaneous rotation with energy scan is necessary

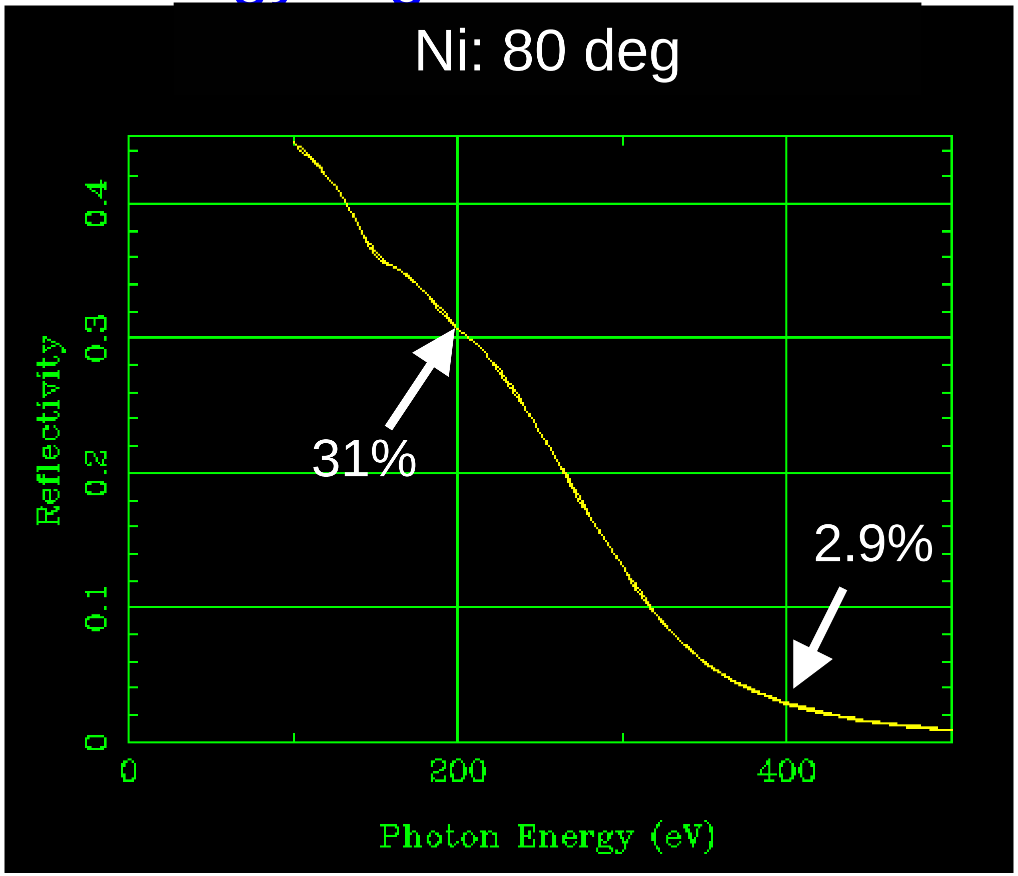
No precise control is required



1.3. coating & reflectivity

Higher order suppression in low energy region





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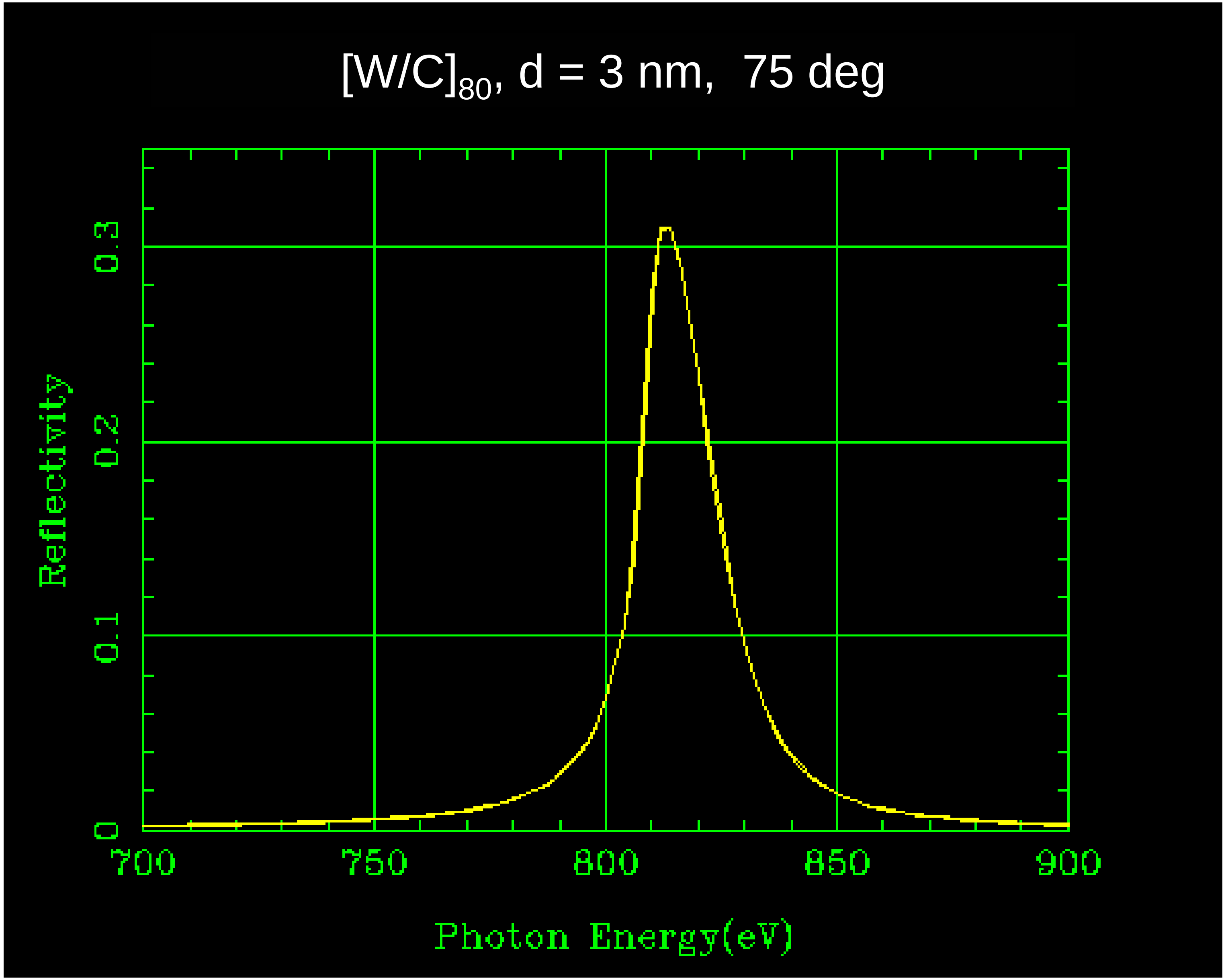
It is difficult to achieve high reduction ratio keeping high reflectivity for fundamental light

Not effective below ~100 eV

1.3. coating & reflectivity

Multilayer mirror



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1. Mirrors

   1.1. focusing & collimation

   1.2. substrate materials

   1.3. coating & reflectivity

2. Diffraction Gratings

   2.1. principle - wavelength dispersion -

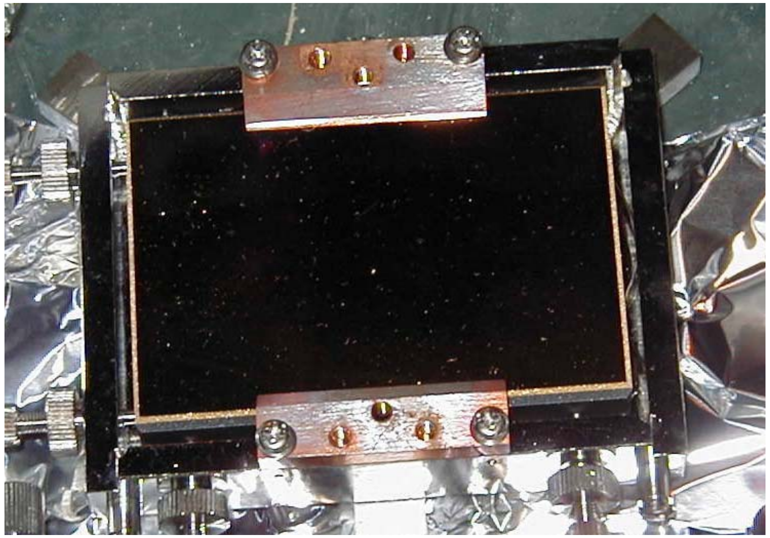
   2.2. energy resolution

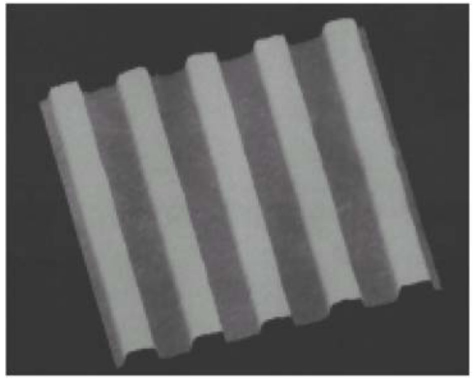
   - dispersion and focus -

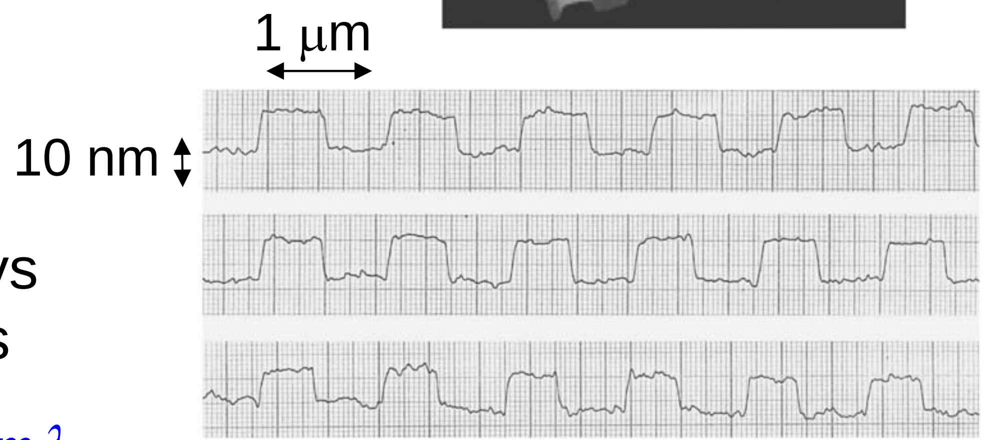
   2.3. fabrication of gratings

2.1. principle - wavelength dispersion -

Diffraction grating： Periodic grooves on a substrate

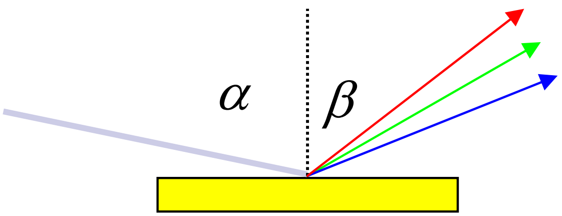






Principle： Interference between the rays reflected at different grooves

Enhanced when light path difference = $m\lambda$



* $\alpha > 0$

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

n: groove density

m: diffraction order

β depends on λ ⇒ Wavelength dispersion (conversion of wavelength to angle)

* $\alpha \neq |\beta|$

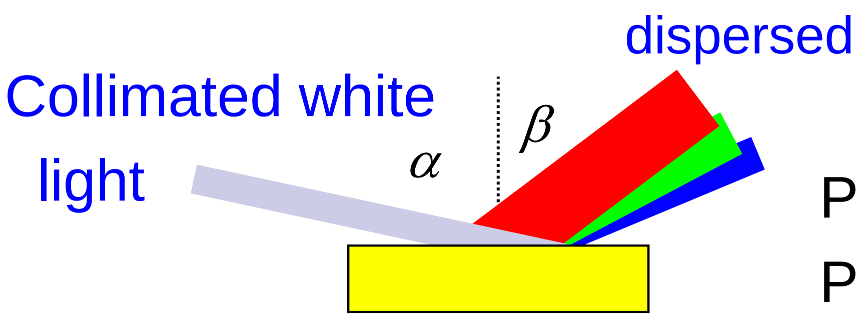
(if $\alpha = |\beta|$, any λ satisfies the above condition at m = 0)

⇒ zero-th order light

2.2. energy resolution - dispersion and focus -

How can we monochromatize by using a diffraction grating?

Most basic mode: collimated-light illumination



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

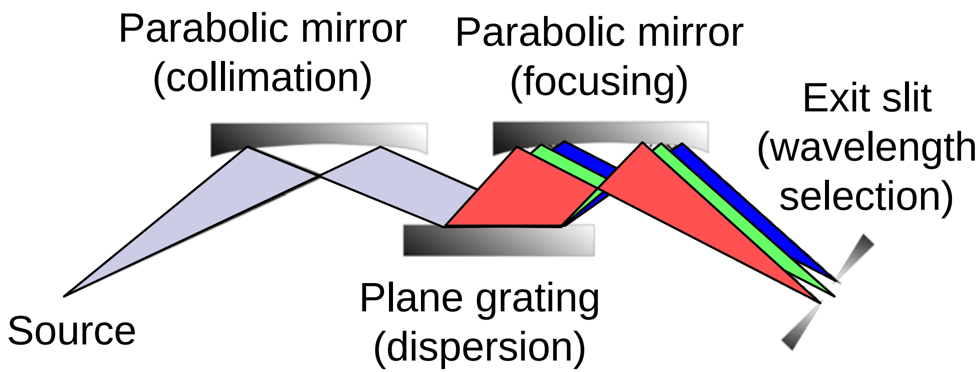
Problem 1 : SR is not a collimated light !

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

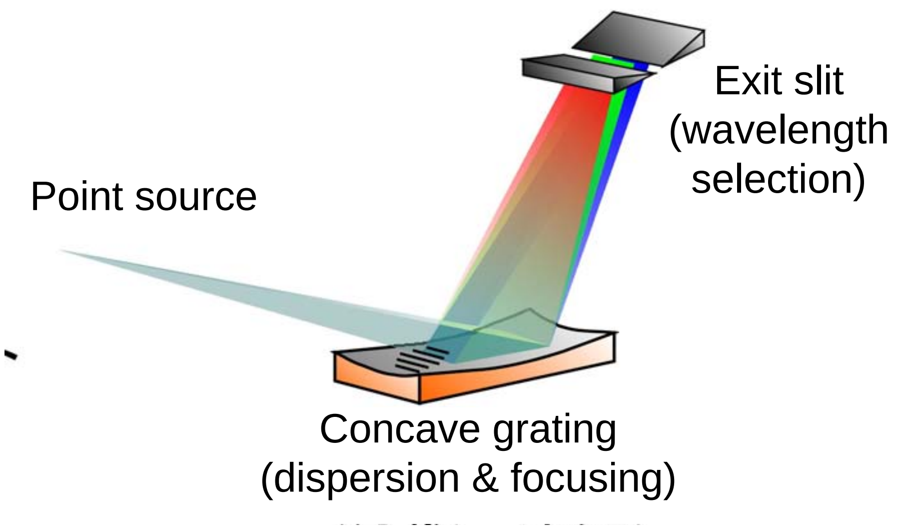


Focused diffracted lights are well resolved in wavelength at the exit slit !

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?

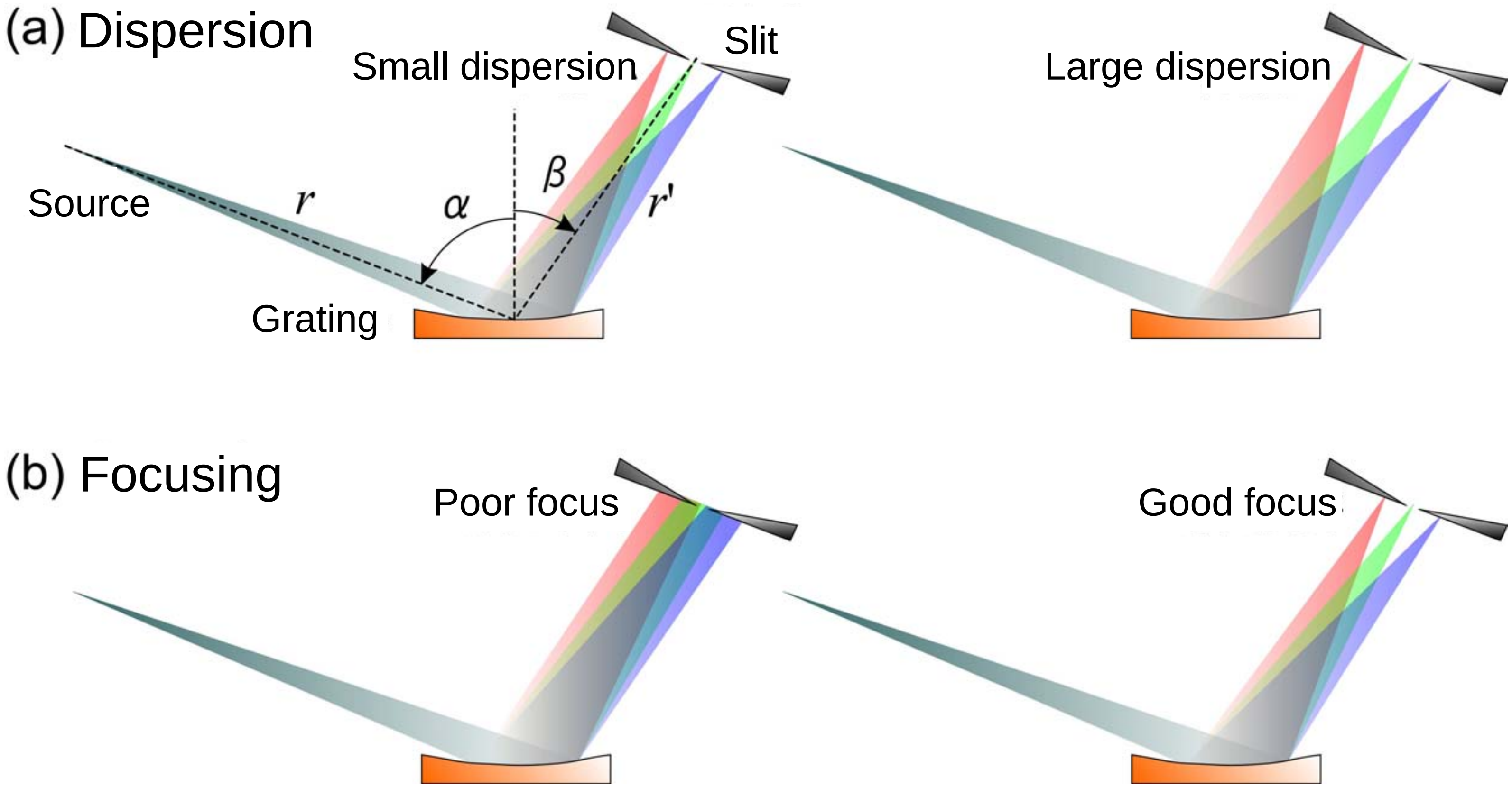
"Dispersion": separation of lights with different wavelengths ⇒ $dz/d\lambda$

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

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

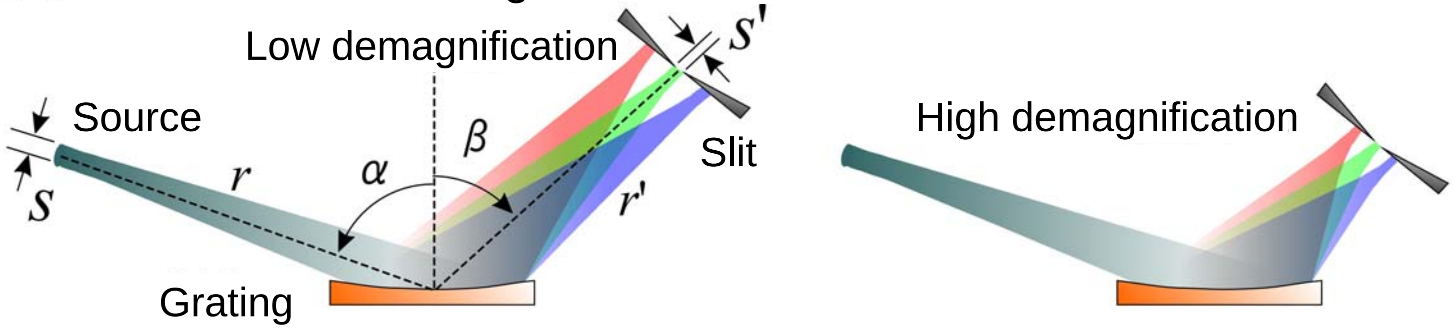
Ratio between "dispersion" and "light size" determines resolution.

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

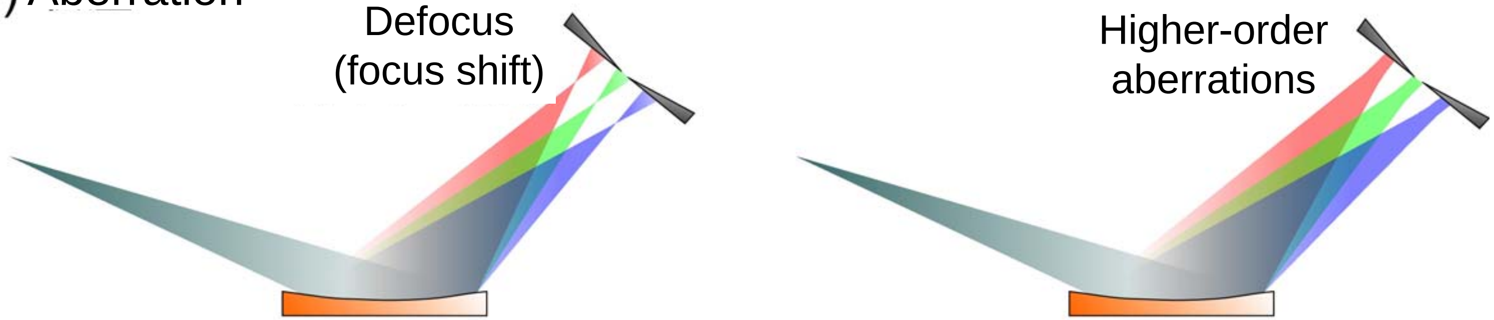


2.2. energy resolution - dispersion and focus - What determines the focus size?

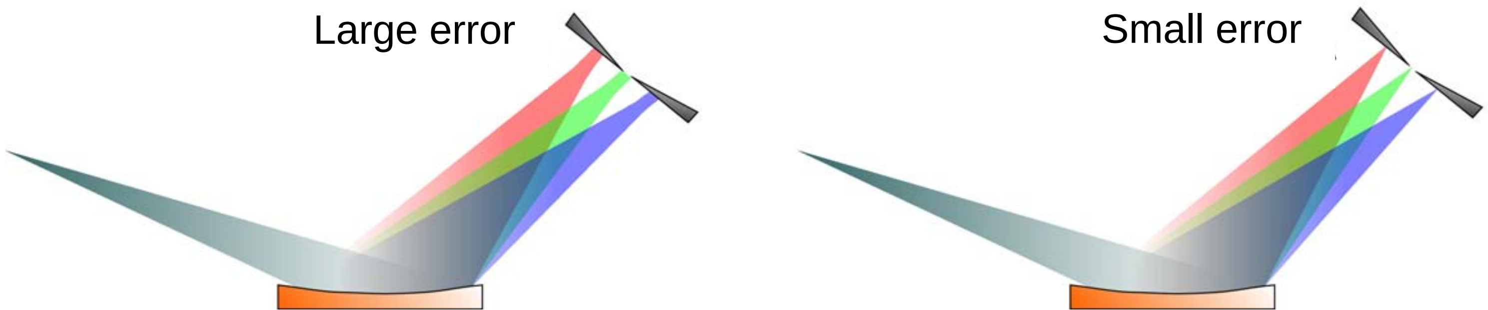
(a) Source size & Demagnification



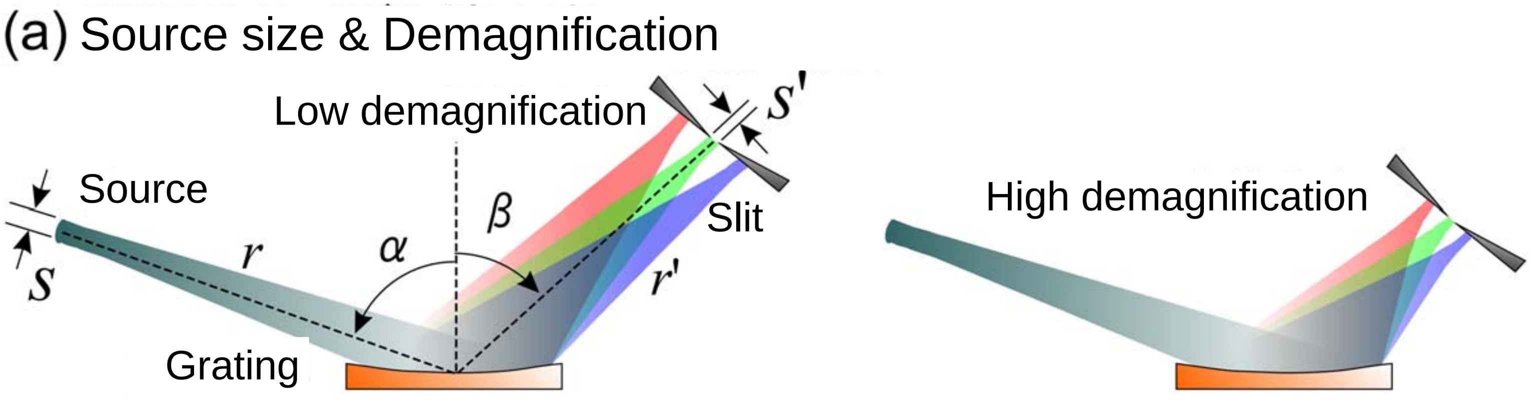
(b) Aberration



(c) Slope error (figure error)



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':

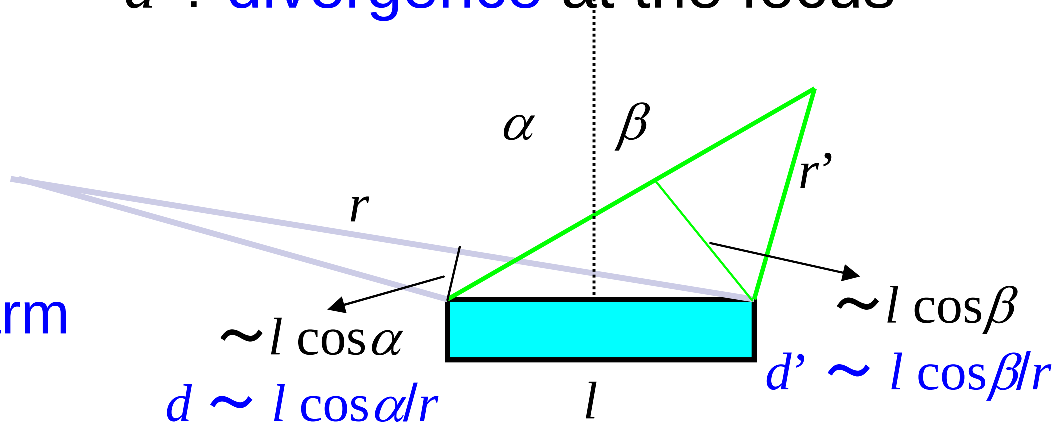
1. reduce r' compared to r

   long entrance arm & short exit arm

2. decrease $|\beta|$ compared to α

   make the incidence angle more grazing

   (keeping the diffraction condition satisfied)



⇒ High groove density

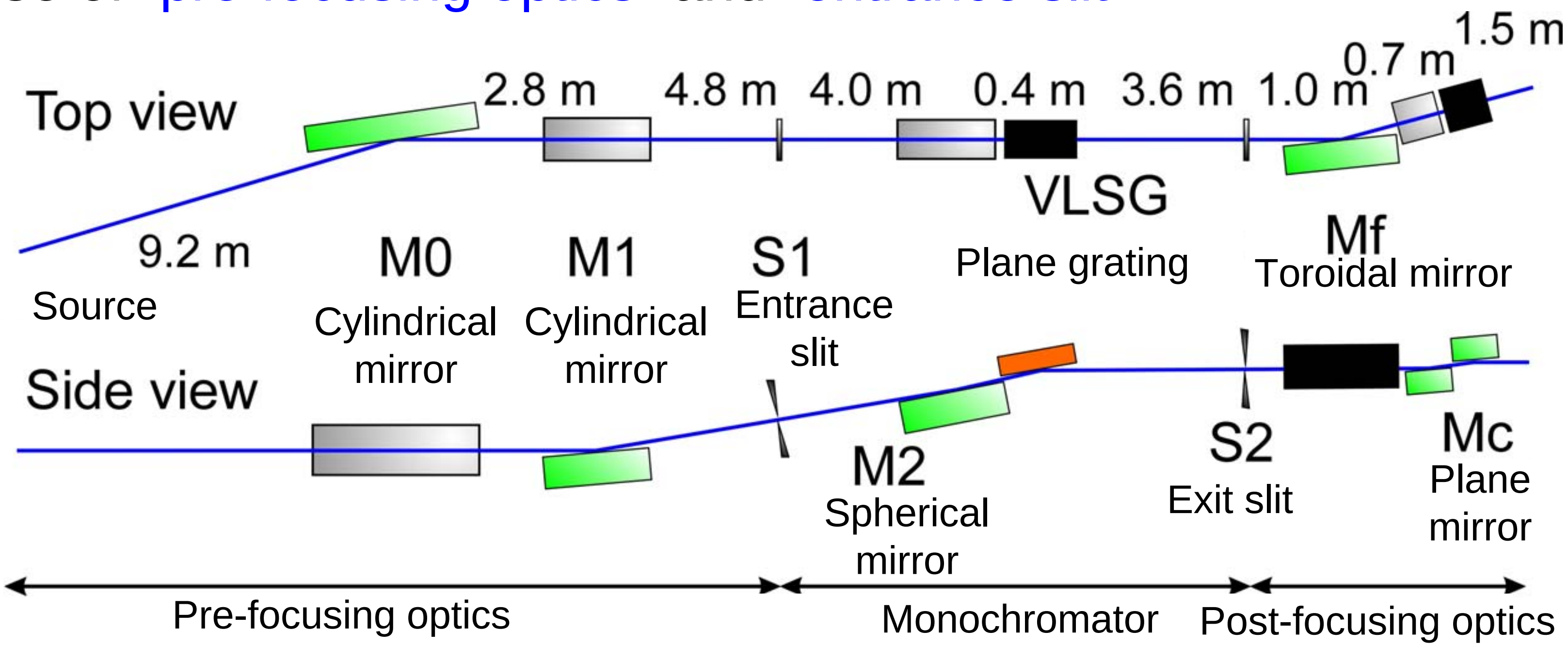
large included angle ($\alpha-\beta$)

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

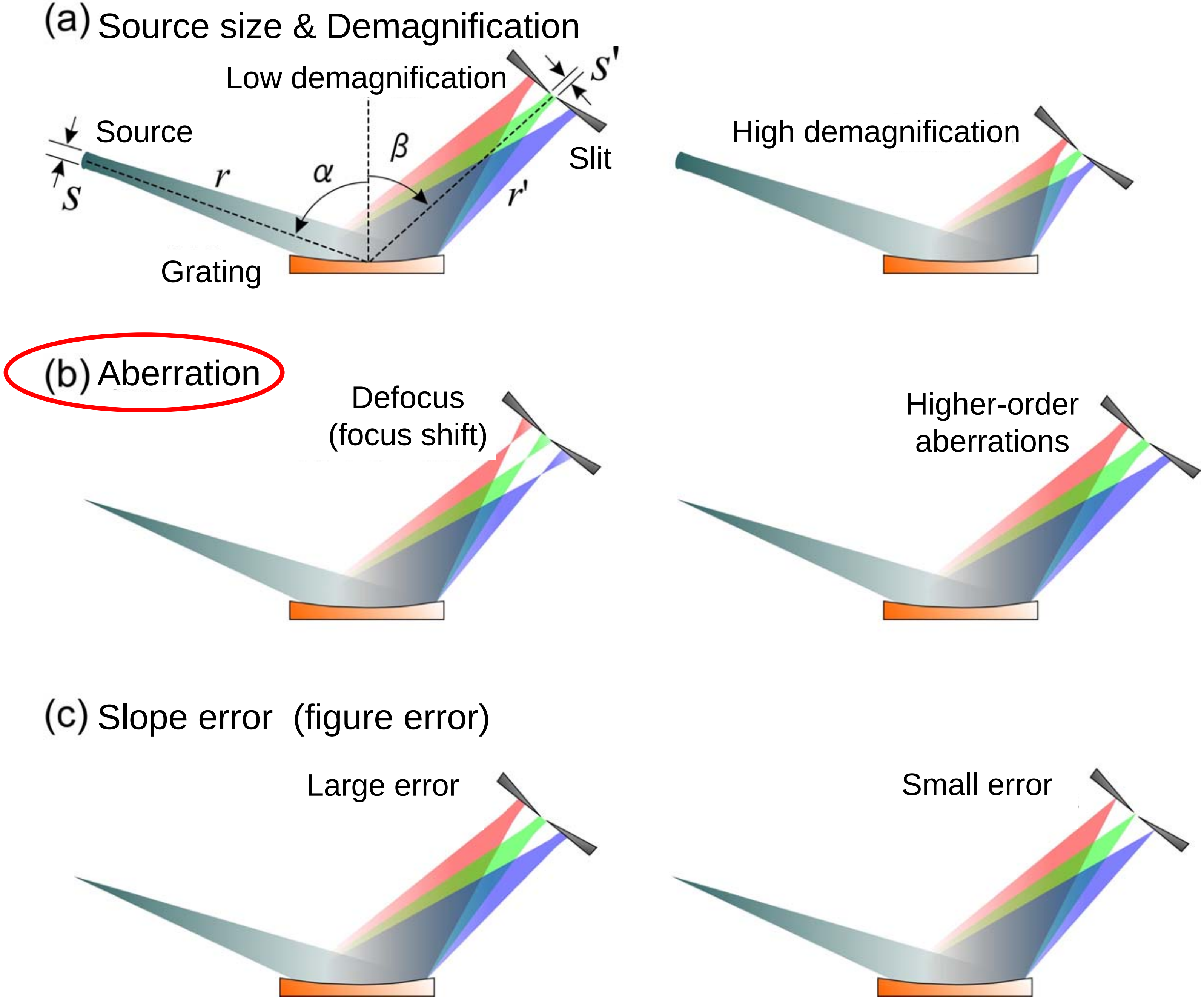
Source size can be controlled by entrance-slit opening

(at the sacrifice of intensity)

Demagnification in the pre-focusing optics is effective

(* divergence increases)

2.2. energy resolution - dispersion and focus - What determines the focus size?



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*

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

← For grating

Diffraction condition

Defocus
(deviation from focal condition)

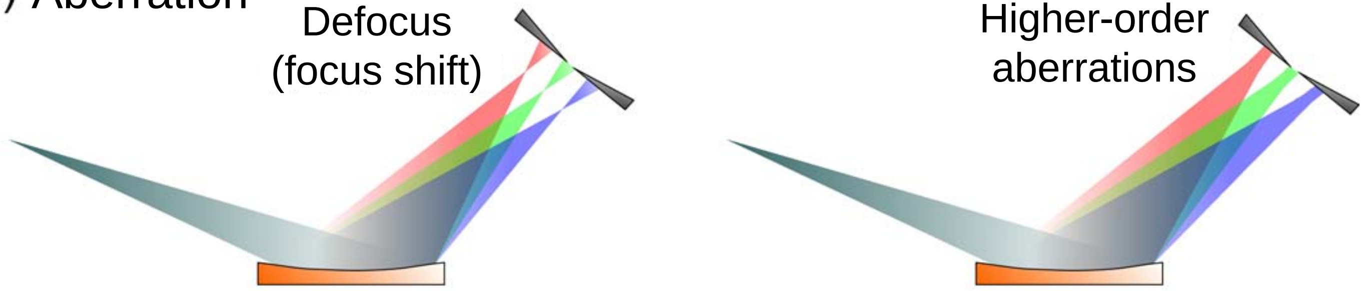
“coma” aberration

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

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

2.2. energy resolution - dispersion and focus -

(b) Aberration

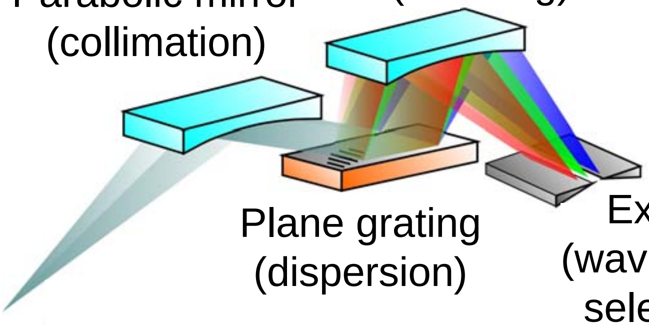


How to reduce the aberration:

- 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)

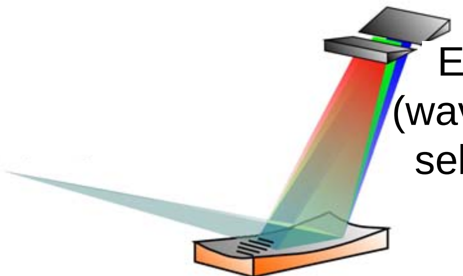
Examples for aberration-free or small-aberration optics

(a)



No aberration

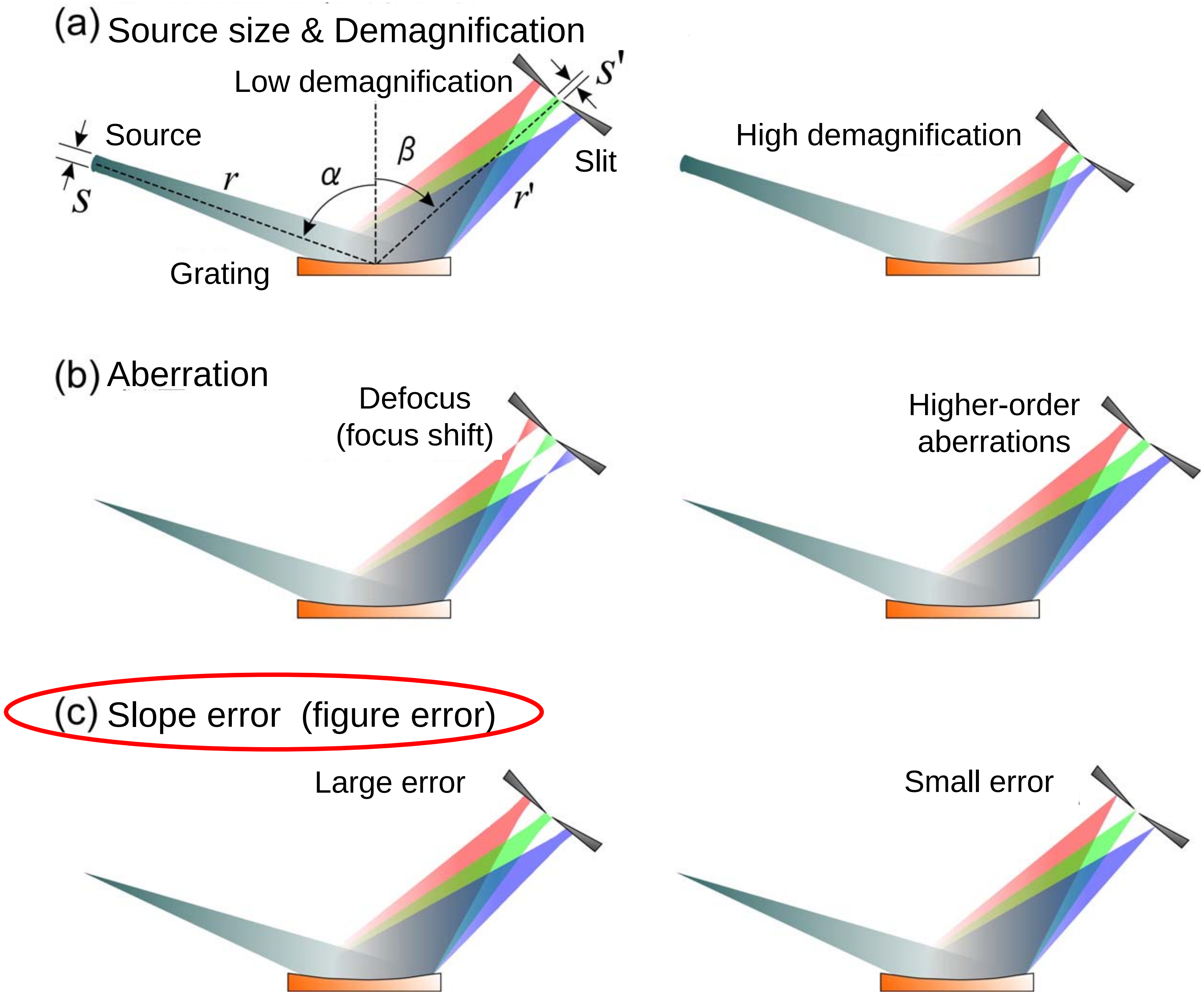
(b)



"Rowland condition"

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

2.2. energy resolution - dispersion and focus - What determines the focus size?



2.2. energy resolution - dispersion and focus -

(c) Slope errors

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

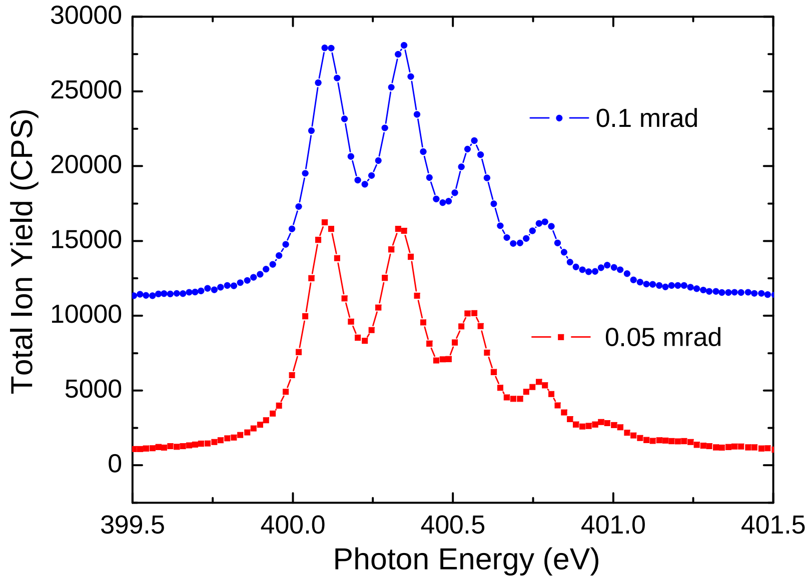
Not systematic ⇒ compensation is impossible

⇒ 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)

$$N = N_0 (1 + a_1 w + a_2 w^2 + a_3 w^3) \quad \text{(groove density)}$$

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

$= N_0$ = 0 for uniform line spacing

(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

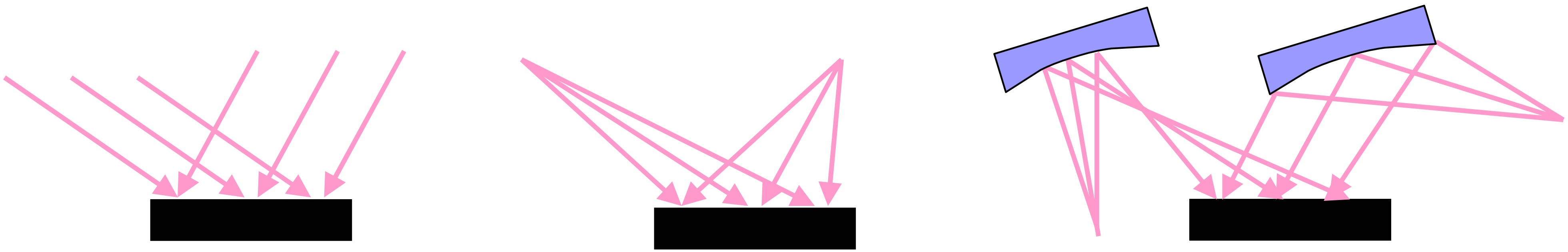
Some groove parameters might not be controlled

* 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)

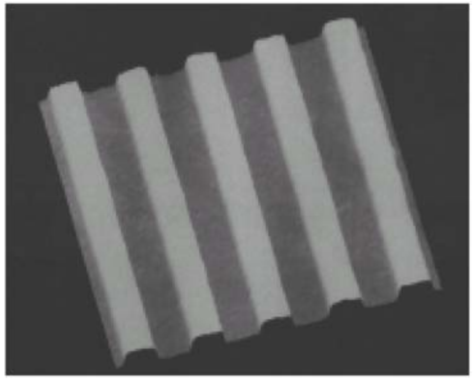
Aspheric wavefronts ⇒ varied line spacing (fine control)

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

2.3. fabrication of gratings

3. Groove shape (Laminar & Brazed)

(a) Laminar type

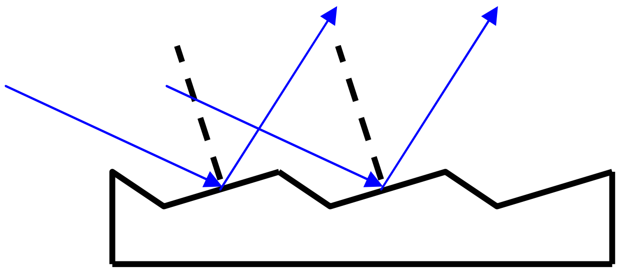


Medium diffraction efficiency (typically 20-30%)

Higher order suppression

interference between top and bottom parts

(b) Brazed type



High diffraction efficiency when “on Braze”

Strong higher orders

Thank you for your attention !