Elettra
Sincrotrone
Trieste

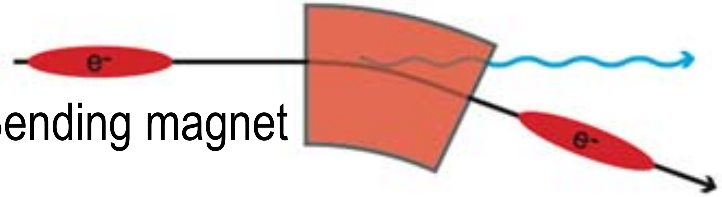
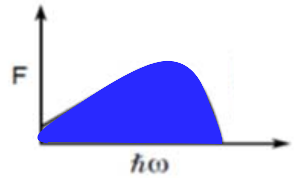
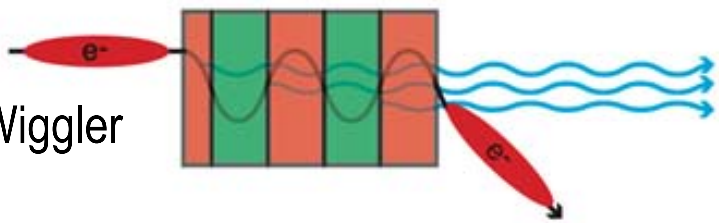
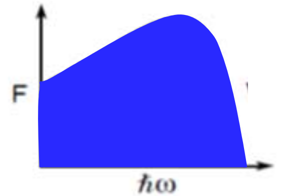
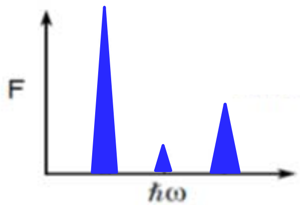
Instrumentation at Synchrotron Radiation Beamlines

M. Altissimo, L. Raimondi

Elettra Sincrotrone Trieste SCpA
S.S. 14, km163.5, Basovizza (TS)

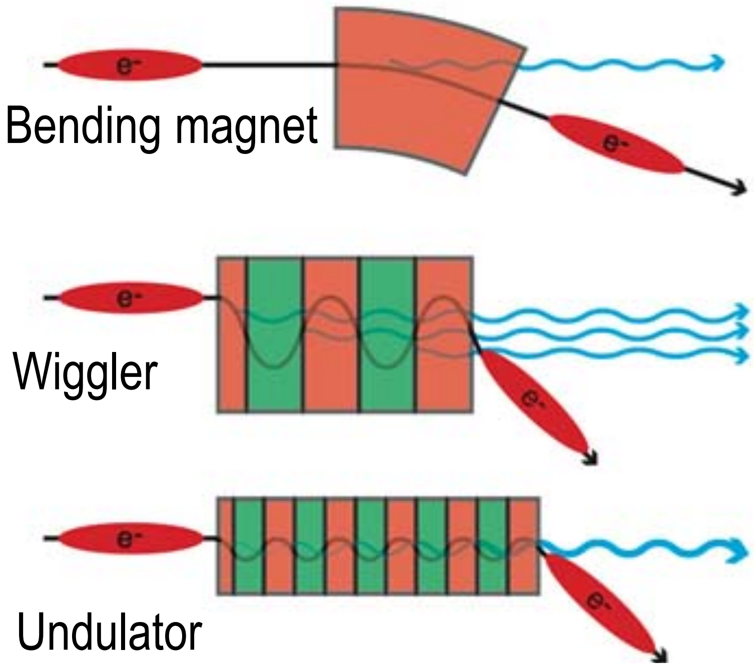
Synchrotron beam emitted by source

$$\gamma = 1957\ E_e[\mathrm{GeV}]$$

Source	Spectrum	Divergence σ	Typically
Bending magnet 		$\sim \frac{1}{\gamma}$	~ mrad
Wiggler 		$\sim \frac{1}{\gamma}$	~ mrad
Undulator 		$\sim \frac{1}{\gamma\sqrt{N}}$	~ 100's µrad

What does it mean in terms of beamsize?

Source	Beam size @ 20 m
Bending magnet	~ 1 - 10’s mm
Wiggler	~ 1 - 10’s mm
Undulator	~ mm

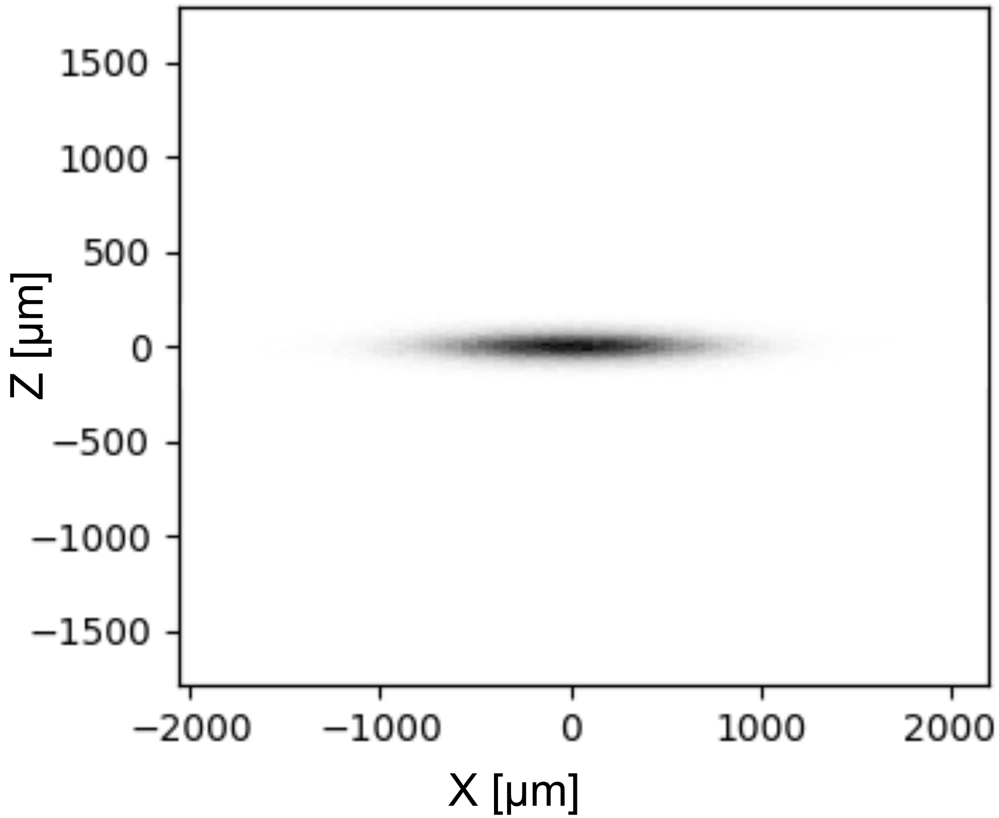


For a typical experiment: required beam size ~ 0.1 to 10’s of μm or more

A couple of undulator simulations (3rd generation storage ring)

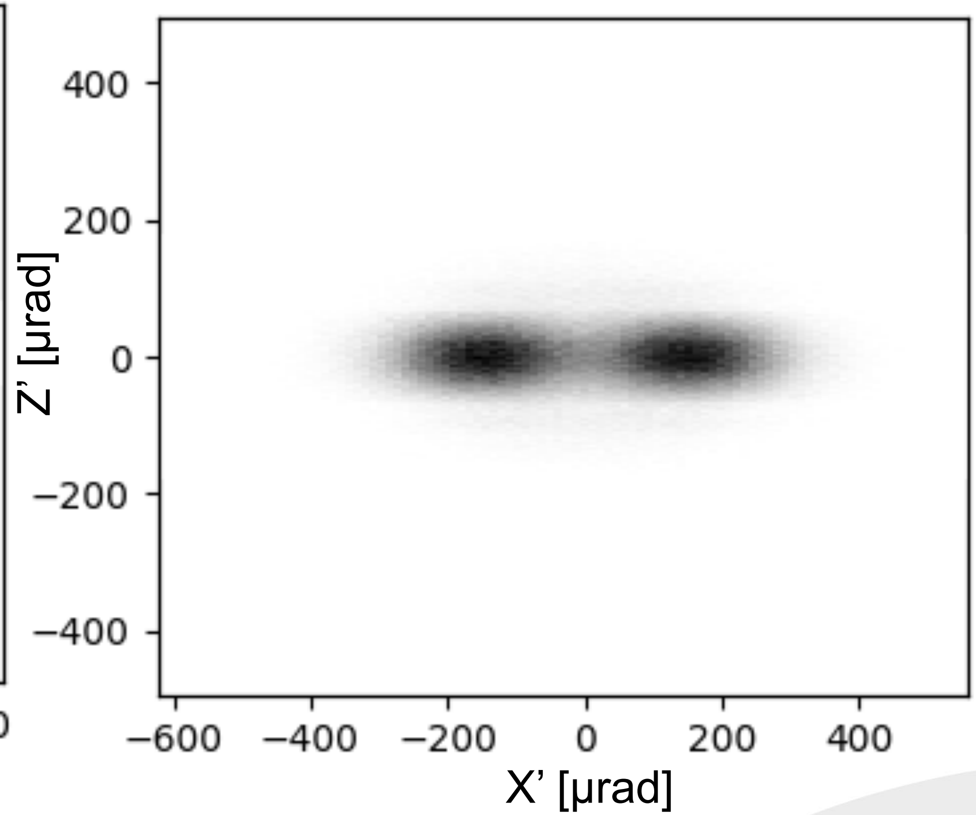
E_e=2.4GeV, N = 17, period = 56mm, first harmonic only

Source Size



FWHM: 1000 x 100 µm²

Divergence

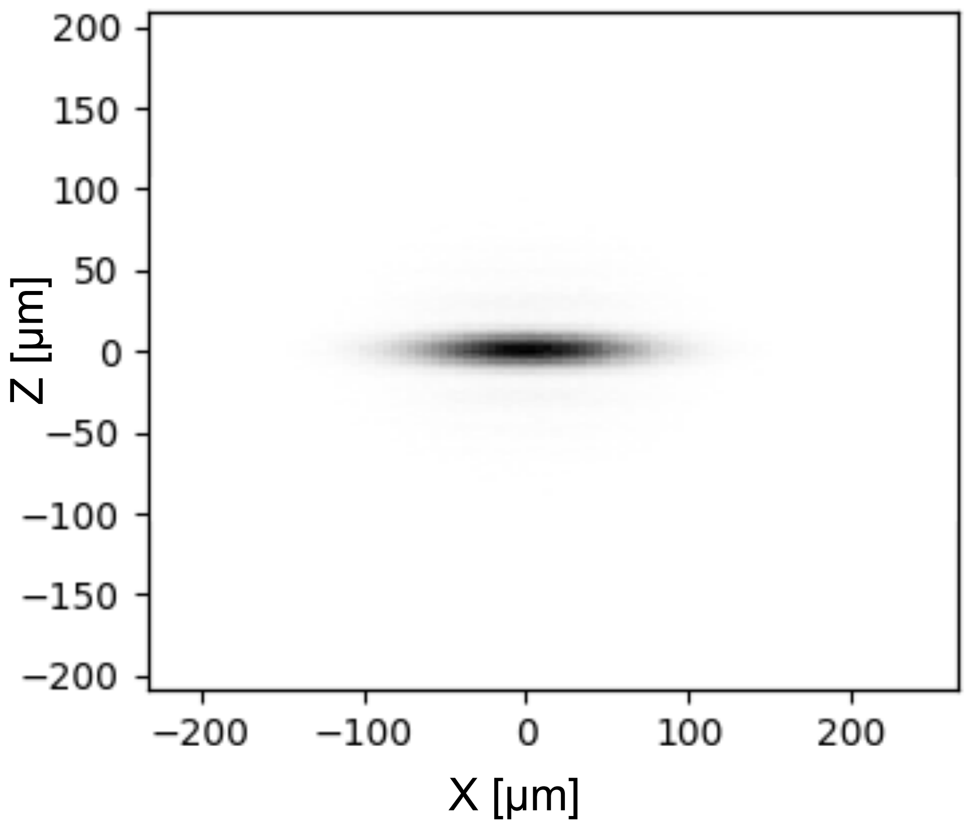


FWHM: 485 x 80 µrad²

A couple of undulator simulations (next generation storage ring)

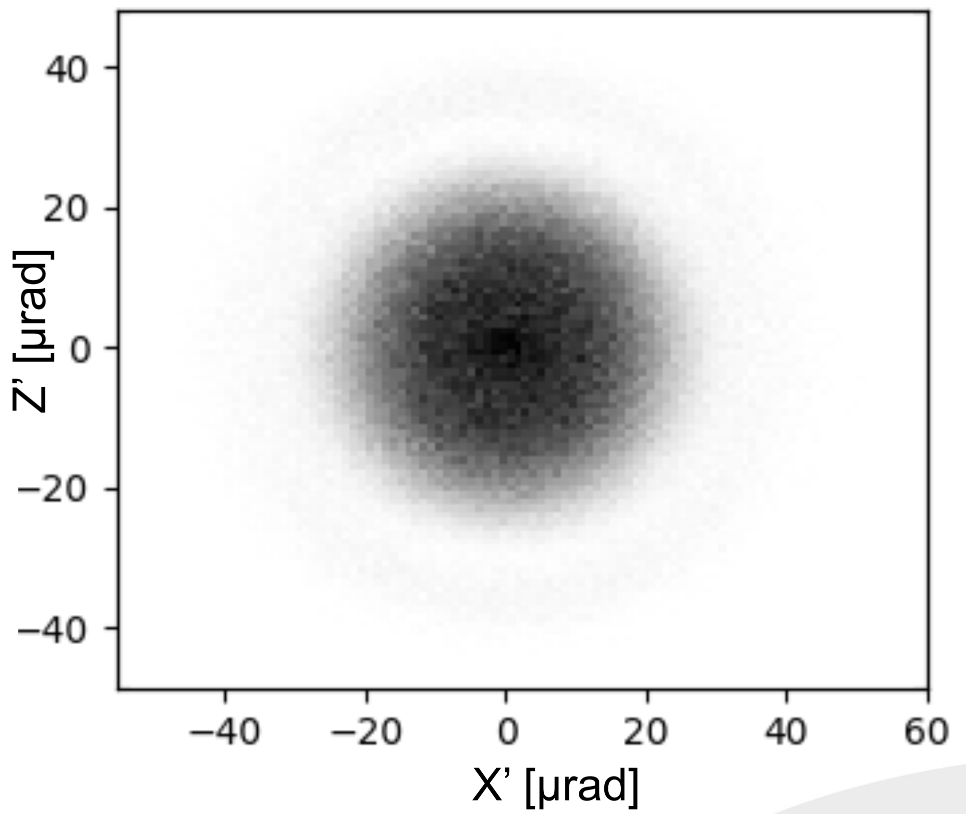
E_e=2.4GeV, N = 17, period = 56mm, first harmonic only

Source Size



FWHM: 100 x 13 µm²

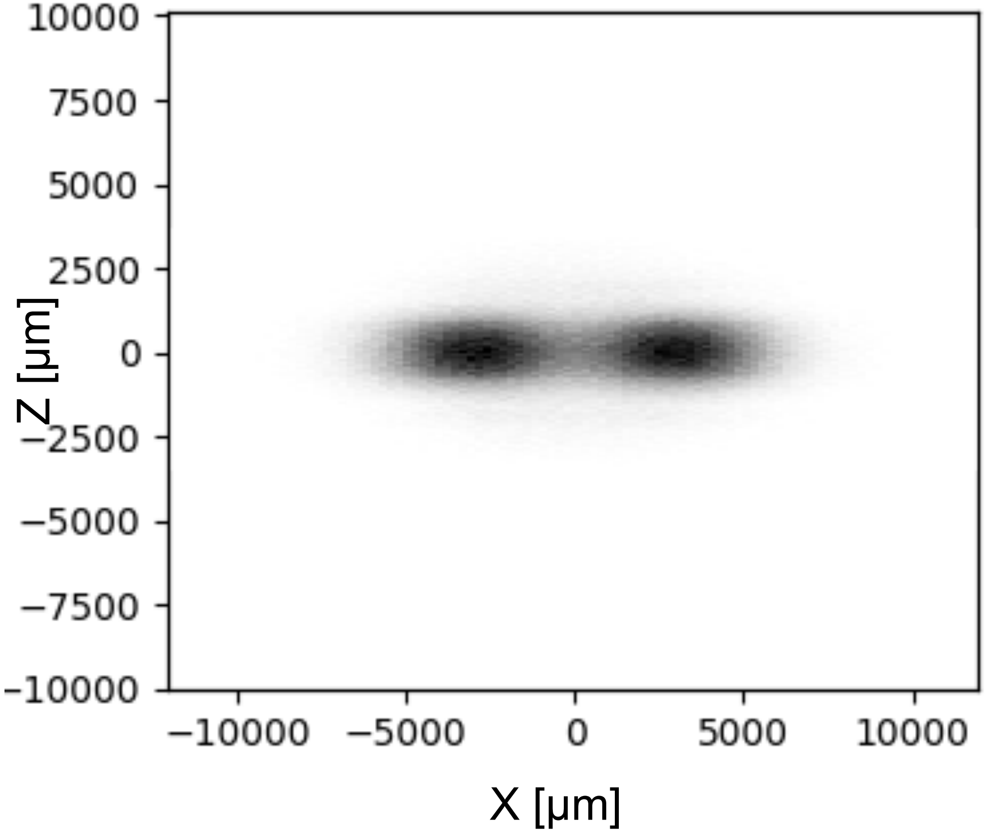
Divergence



FWHM: 33 x 33 µrad²

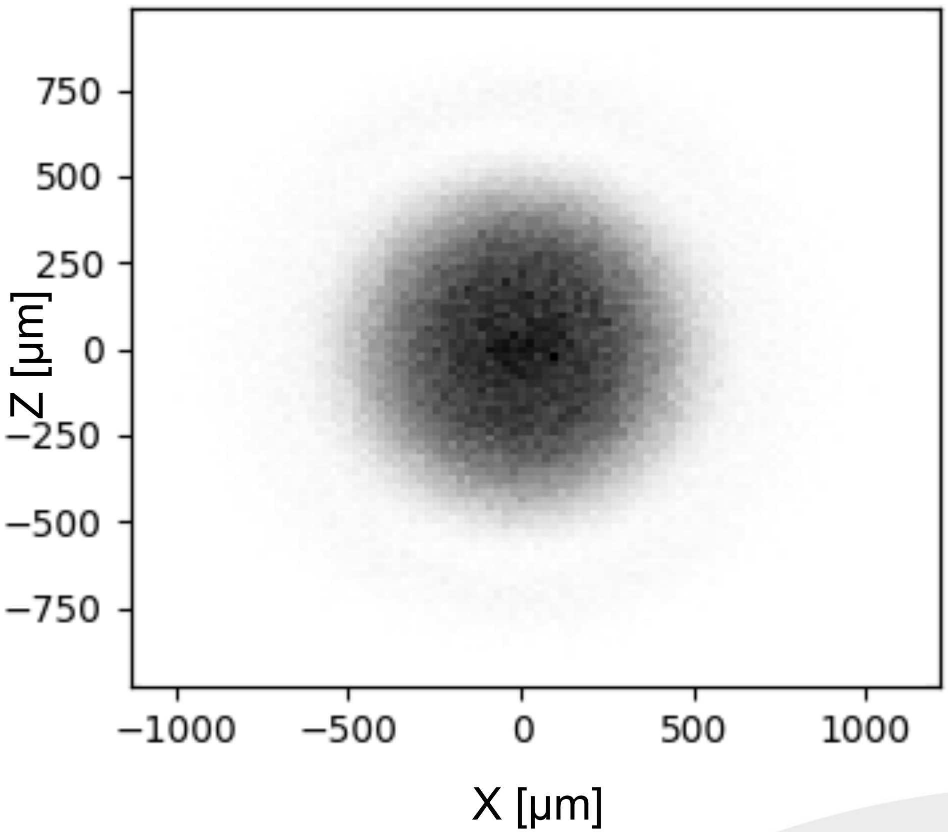
… and if we propagate those 20 m downstream

3rd generation storage ring



FWHM: 9600 x 1570 μm²

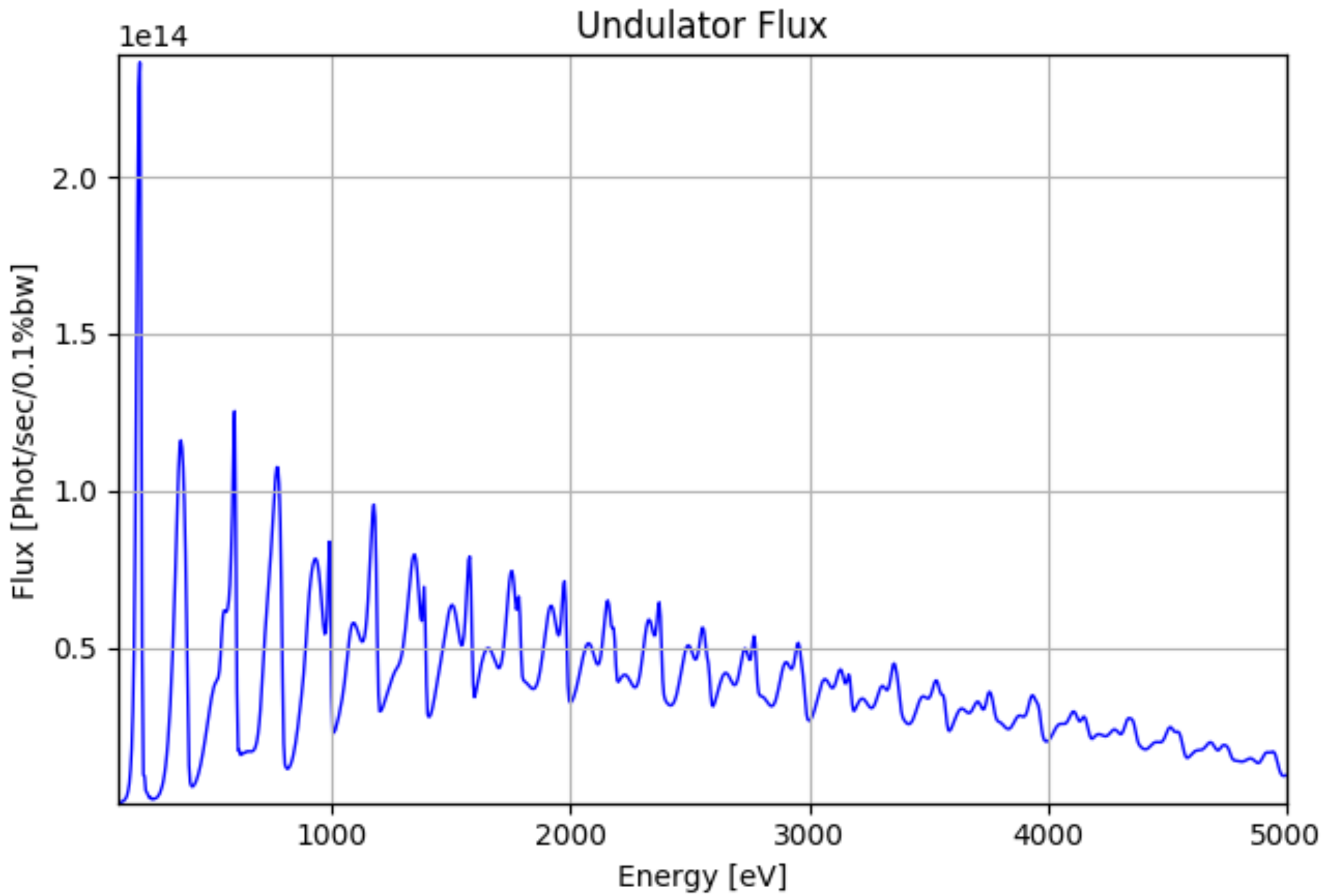
Next generation storage ring



FWHM: 680 x 670 μm²

It's even more complicated…

E_e=2.4GeV, N = 17, period = 56mm



Total flux ~ 10^{19} ph/s

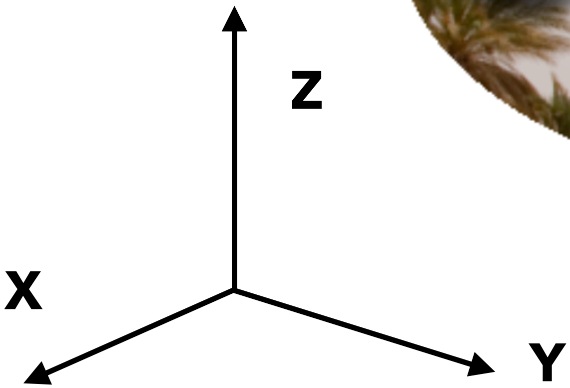
What do we mean by “Instrumentation at Synchrotron Radiation beamlines”?

It’s a set of interconnected devices designed and operated in order to:

- Deliver the beam produced in the storage ring to the sample
- Shape the beam size and divergence
- Select the photon energy appropriate for the experiment

Photon transport systems

Quick word about simulations



By SHADOW convention,
Y is the BEAM PROPAGATION DIRECTION

C. Welnak, P. Anderson, M. Khan, S. Singh, and F. Cerrina, “Recent developments in SHADOW,” *Review of Scientific Instruments*, vol. 63, p. 865, 1992.

O. Chubar, P. E. P. O. T. E. Conference, 1998, “Accurate and efficient computation of synchrotron radiation in the near field region,” *accelconf.web.cern.ch*

L. Rebuffi, M. Sanchez del Rio, "OASYS (OrAnge SYnchrotron Suite): an open-source graphical environment for x-ray virtual xperiments”, Proc. SPIE 10388, 103880S (2017) . DOI: 10.1117/12.2274263

L. Rebuffi, M. Sanchez del Rio, "ShadowOui: A new visual environment for X-ray optics and synchrotron beamline simulations”, J. Synchrotron Rad. 23 (2016). DOI:10.1107/S1600577516013837

Spoiler alert!

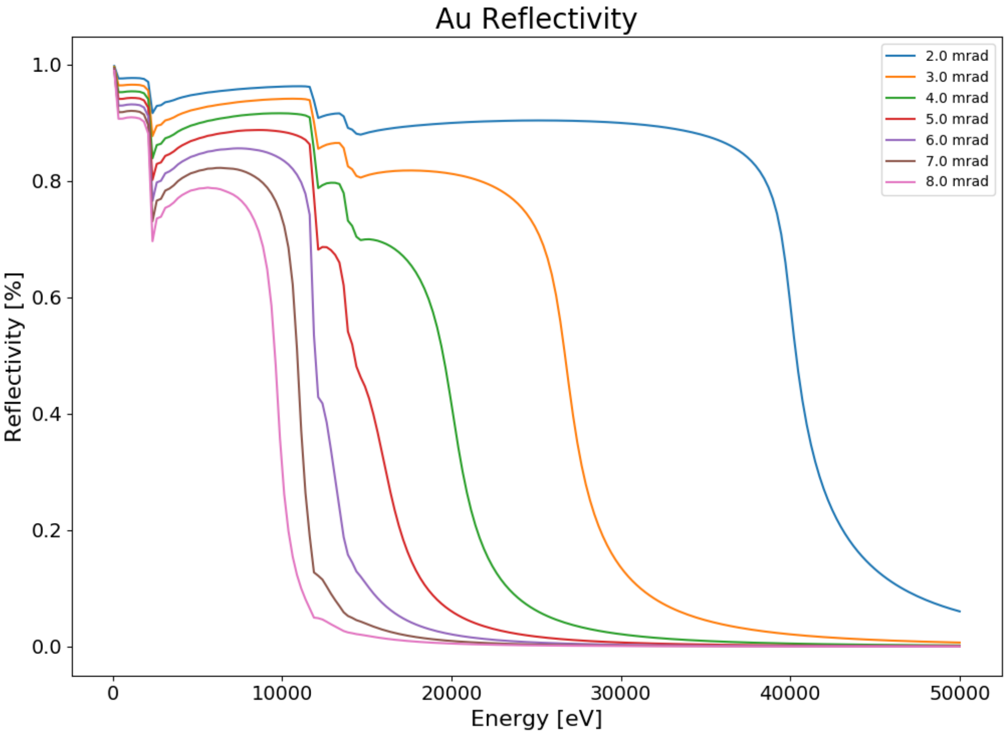
Introducing some optics relations

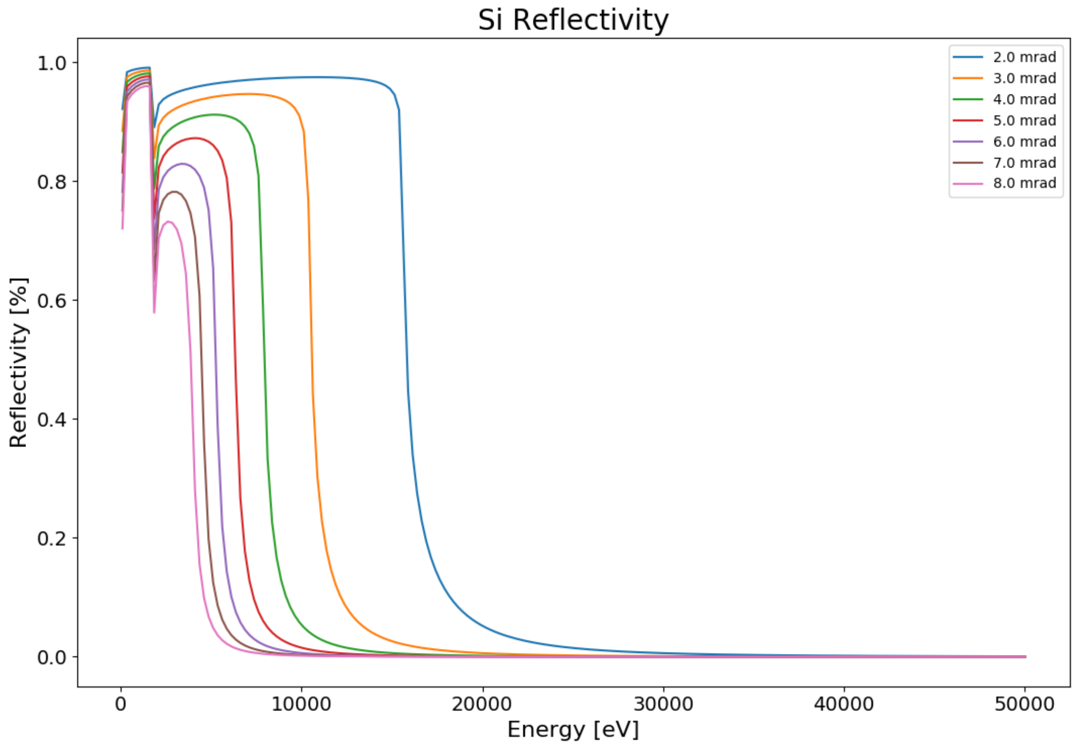
Handles available for "manipulating" photons

			Usage
Refraction	$n = 1 - \delta + i\beta$	$\delta = 10^{-1} \div 10^{-6}$ $\beta = 10^{-1} \div 10^{-8}$	Focussing
Reflection	$\sin\phi' = \frac{\sin\phi}{n} \cong \frac{\sin\phi}{1-\delta}$	$\theta_C \approx \sqrt{2\delta} \quad (rad)$ $\theta_C \approx 81\sqrt{\delta} \quad (degrees)$	Transport Divergence corrections Focussing
Diffraction	$2d \cdot \sin\theta = m\lambda$	$d \cong \lambda$	Monochromatization Focussing

A quick look at reflectivities

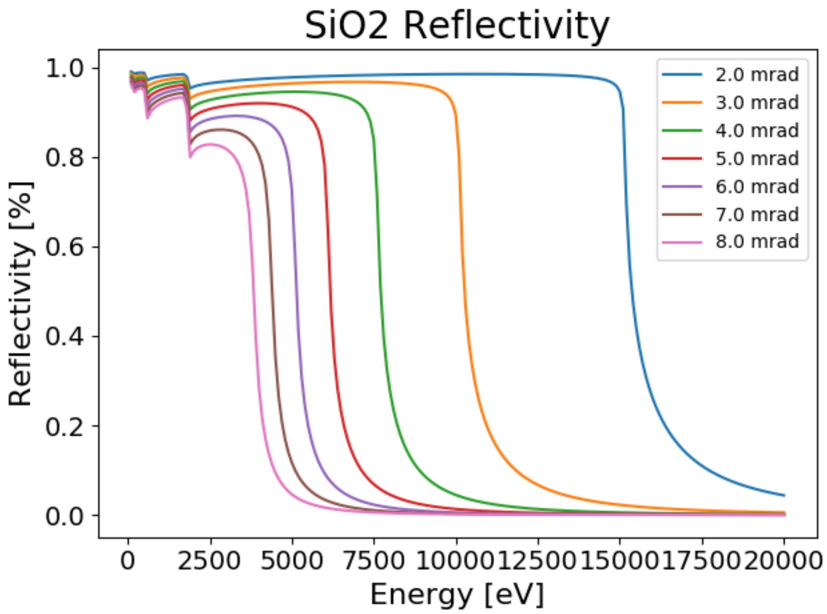
$$\theta_c = \sqrt{2\delta} \propto \lambda\sqrt{Z}$$

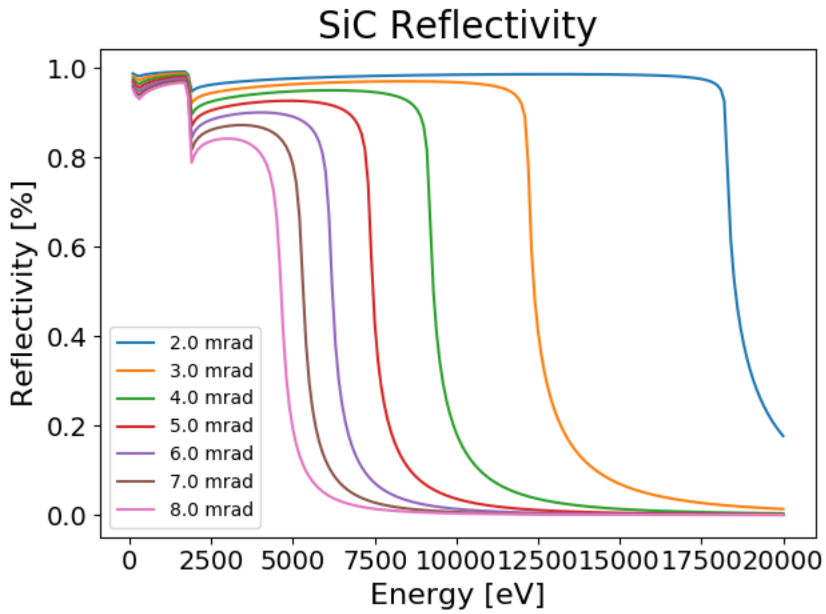


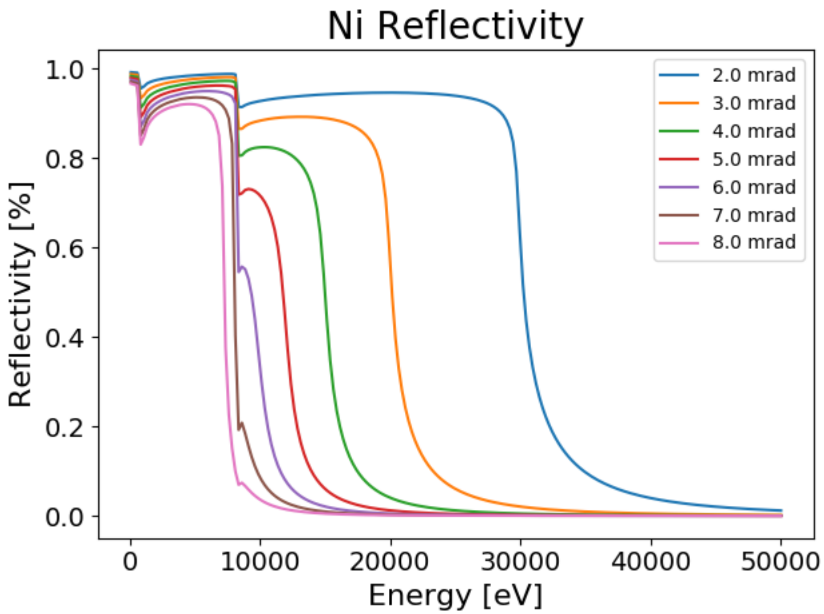


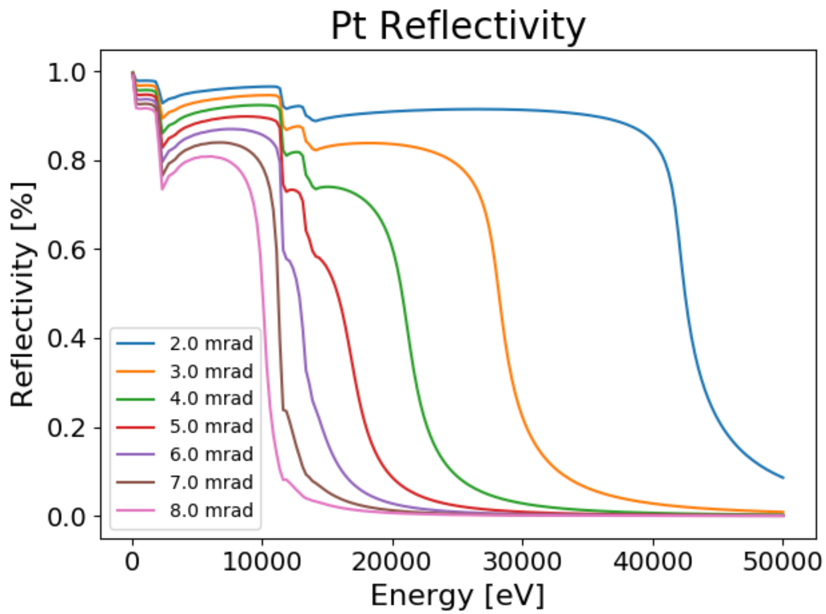
The higher the energy, the more grazing the incidence angle

A quick look at reflectivities



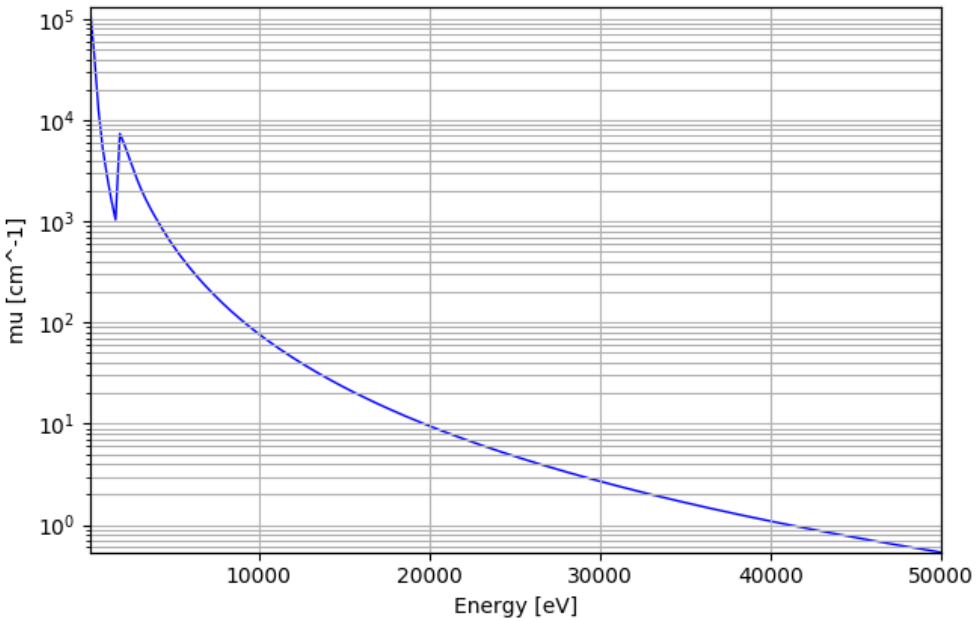


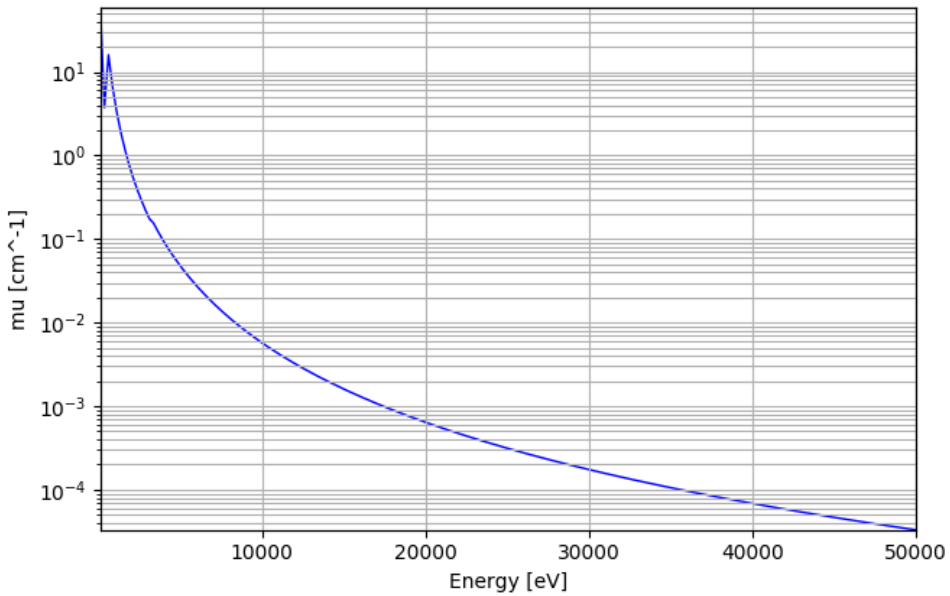




A quick look at attenuation coefficients

$$l_{att} \propto \beta$$





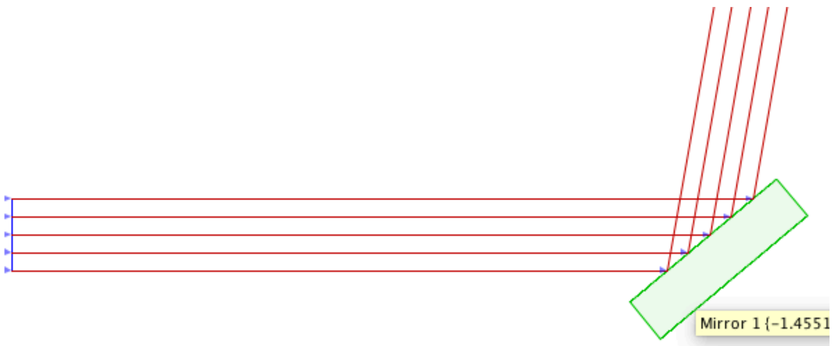
All beamlines must be in vacuum!

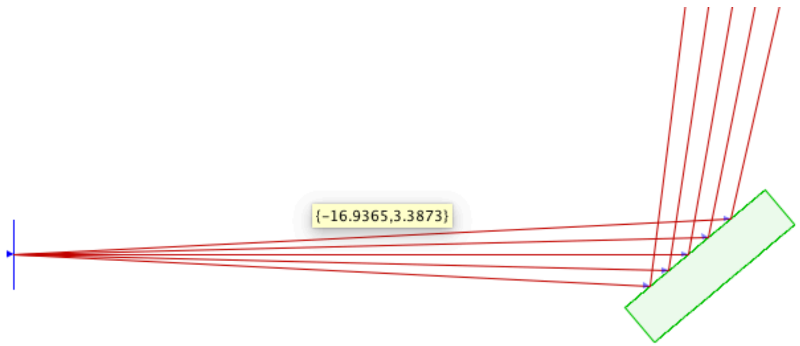
Reflecting elements

Reflection optics

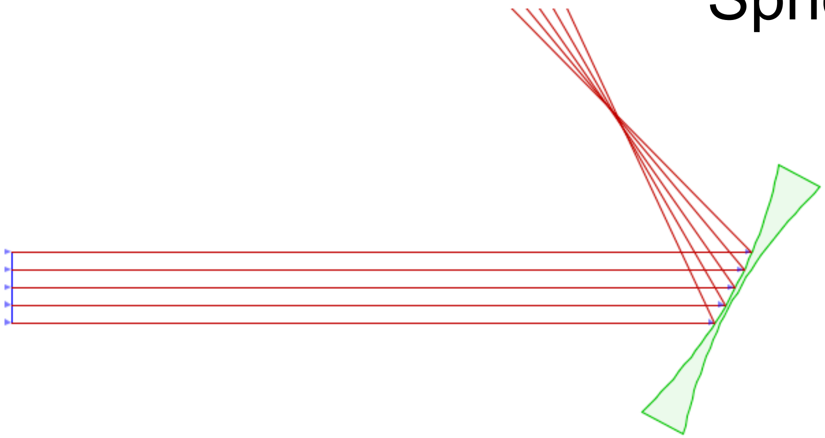
$$\theta_{inc} = \theta_{refl}$$

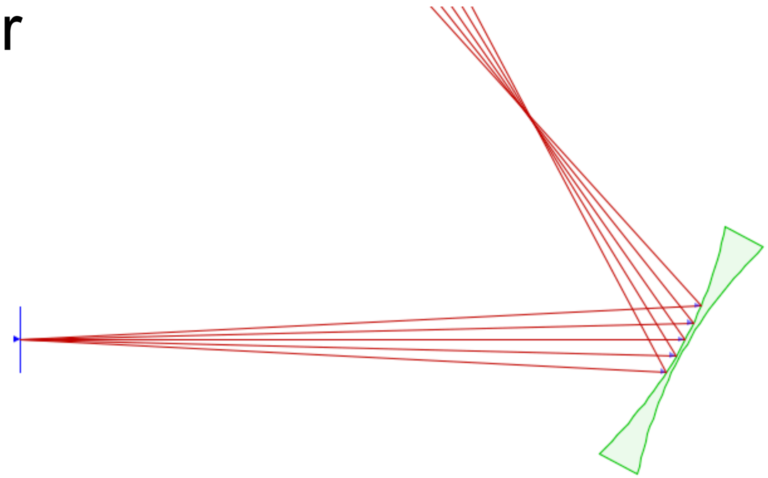
Plane mirror



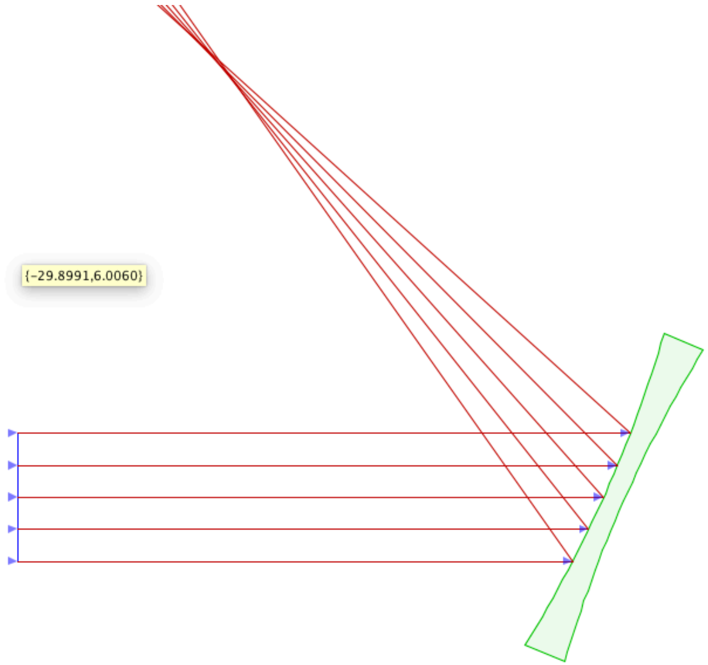


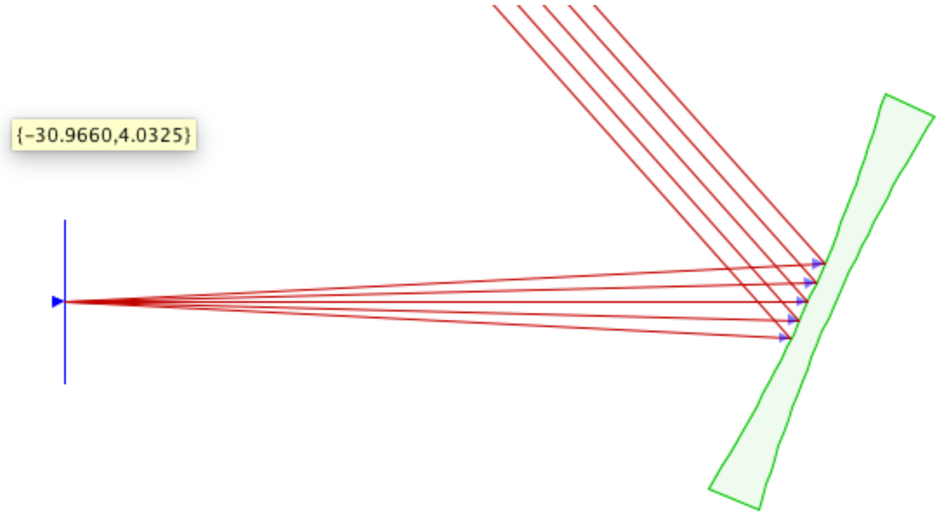
Spherical mirror





Parabolic mirror





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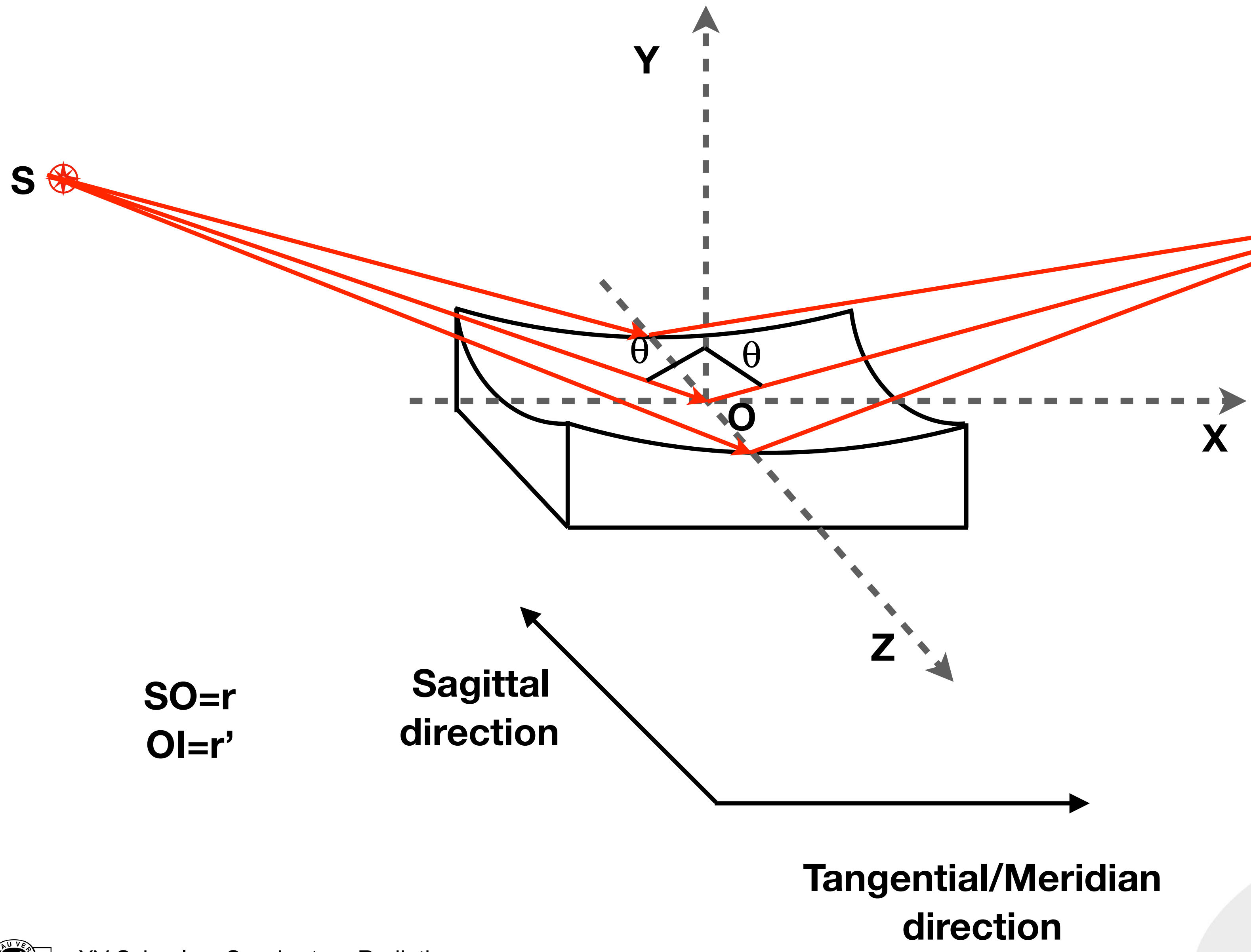
Some nomenclature



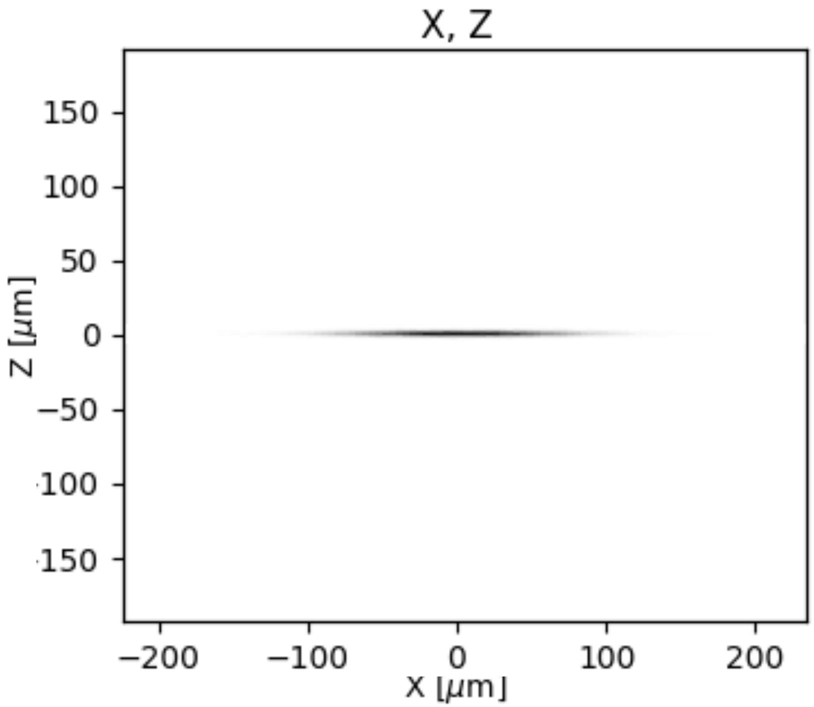
SO=r
OI=r'

Source for examples

Spatial Dimensions:

$$\sigma_x = 48\mu m \qquad \sigma_z = 1.3\mu m$$

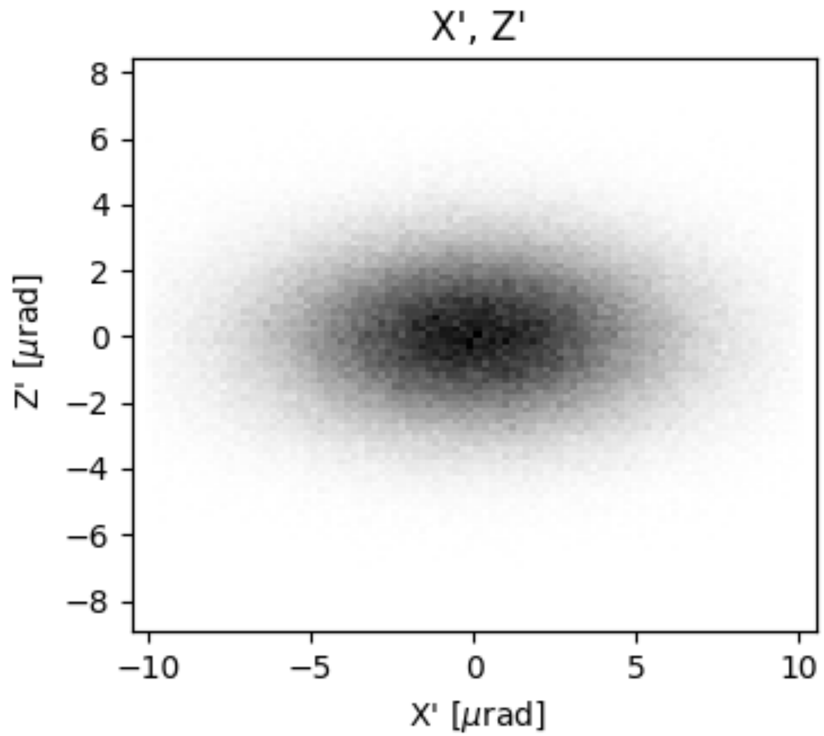
FWHM (X)=105 μm FWHM(Z)=3 μm



Angular dimensions:

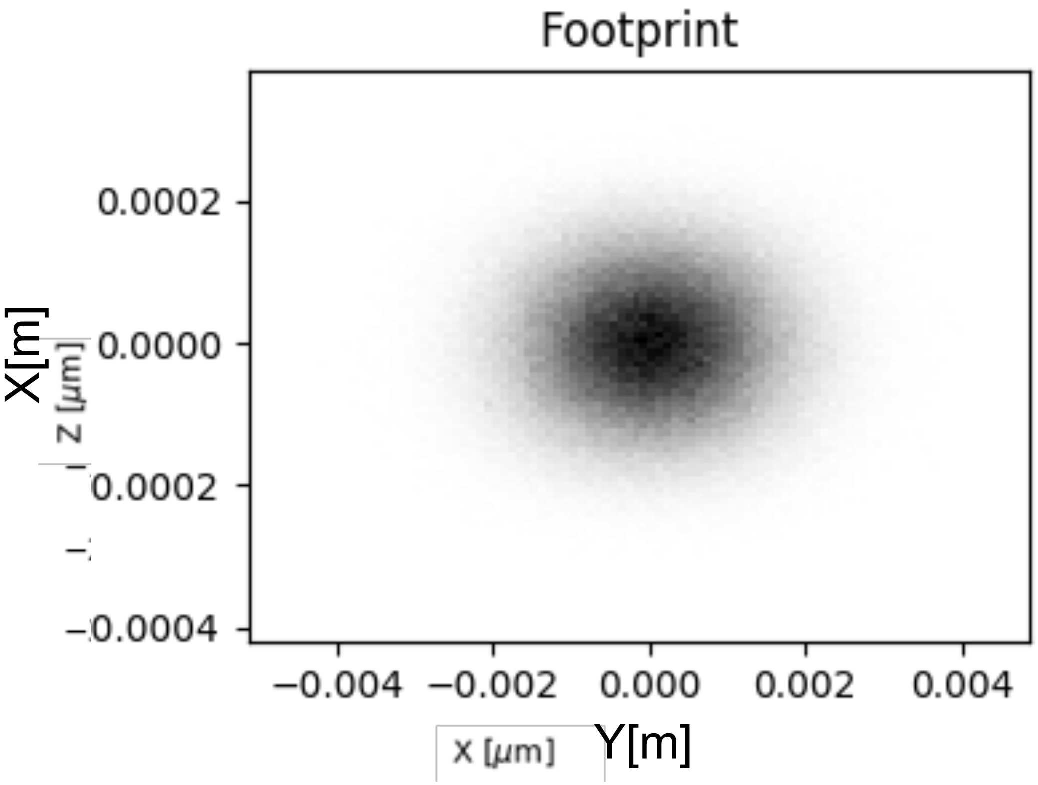
$$\sigma_x^{'} = 3.8\mu rad \qquad \sigma_z^{'} = 1.82\mu rad$$

FWHM (X')=8.6 μrad FWHM(Z')=4.2 μrad

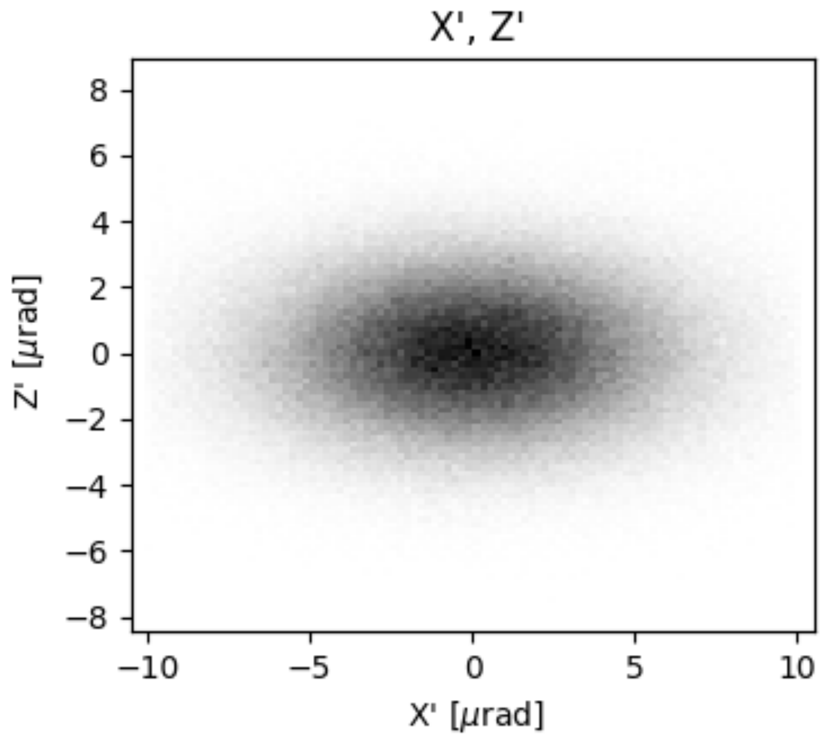


Plane mirror, r = 20 m, r' =20 m, $\theta = 88°$

Spatial Dimensions:



Angular dimensions:



FWHM (Y)=3.0 mm FWHM(X)=150 µm

FWHM (X)=253 µm FWHM(Z)=204 µm

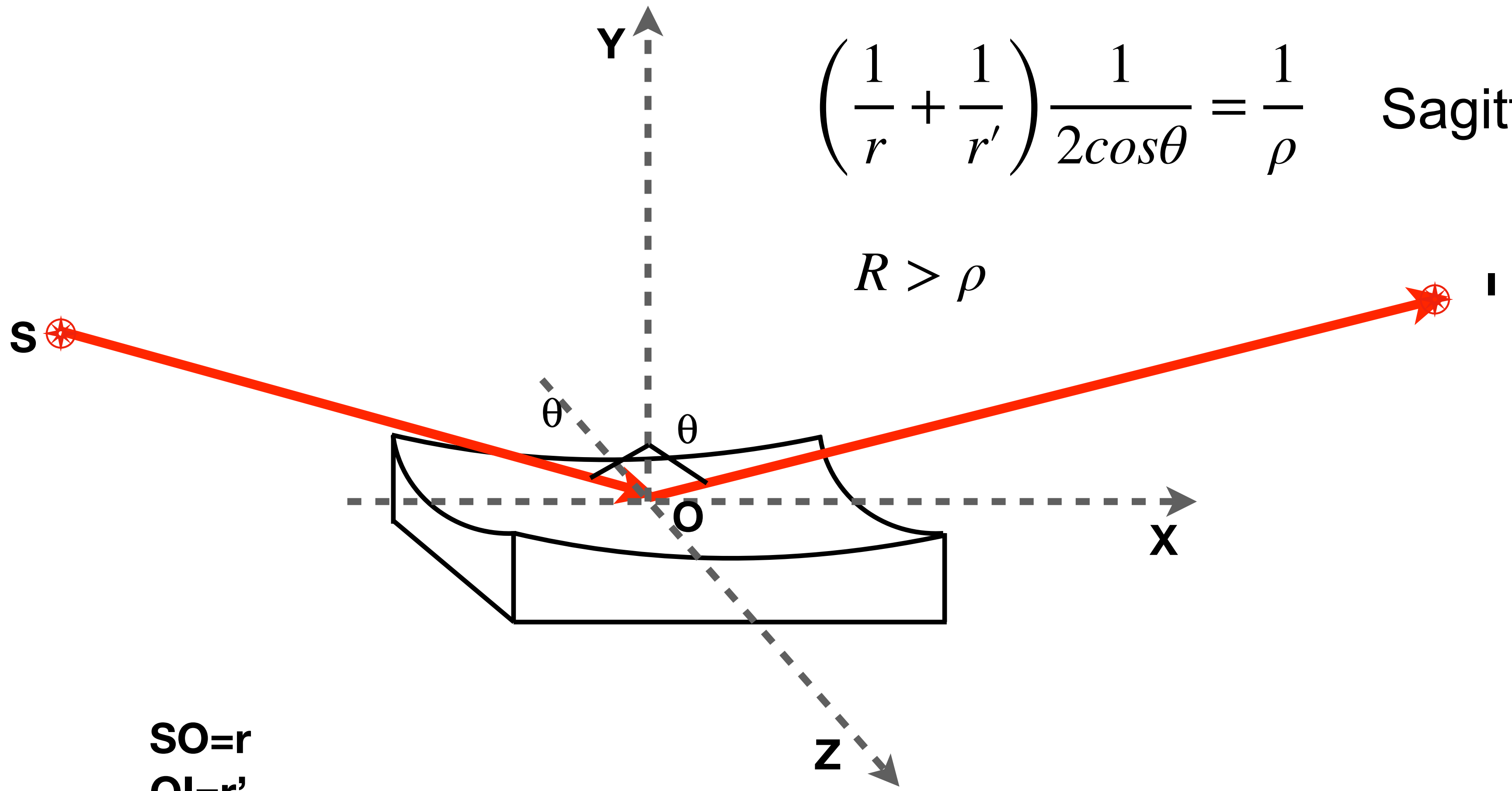
FWHM (X')=8.6 µrad FWHM(Z')=4.2 µrad

Toroidal mirror

$$\left(\frac{1}{r}+\frac{1}{r'}\right)\frac{cos\theta}{2}=\frac{1}{R}$$ Tangential focus

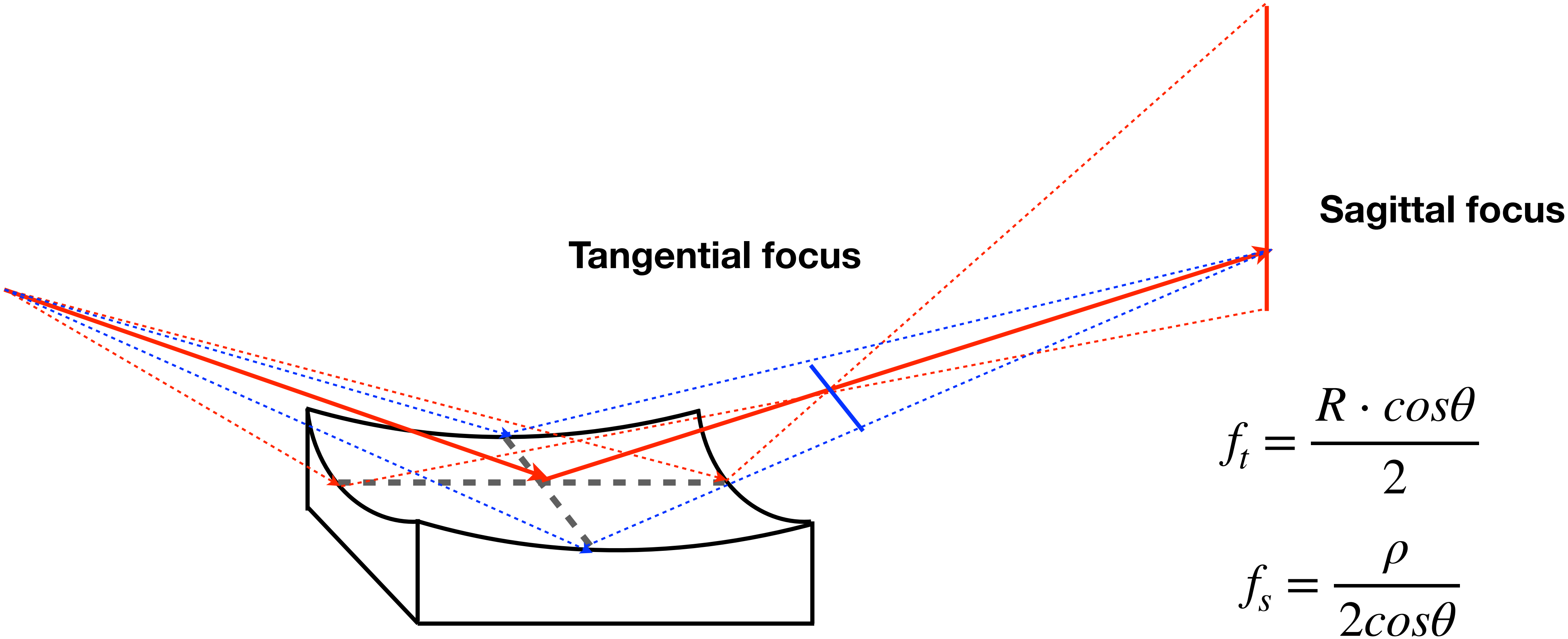
$$\left(\frac{1}{r}+\frac{1}{r'}\right)\frac{1}{2cos\theta}=\frac{1}{\rho}$$ Sagittal focus

$$R>\rho$$



SO=r
OI=r'

Toroidal mirror: focussing properties



$$f_t = \frac{R \cdot cos\theta}{2}$$

$$f_s = \frac{\rho}{2cos\theta}$$

Condition for a stigmatic image of a point source:

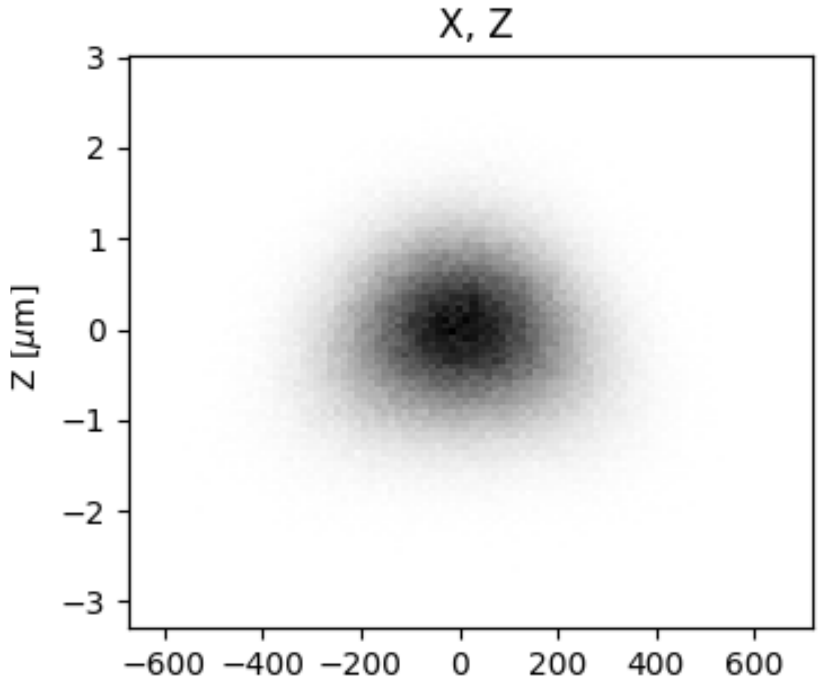
$$\frac{\rho}{R} = cos^2\theta$$

Toroidal mirror, r = 20 m, r' =10 m, $\theta = 88°$

$$R = \left(\left(\frac{1}{r} + \frac{1}{r'} \right) \frac{cos\theta}{2} \right)^{-1} = 382 \text{ m} \quad \rho = \left(\left(\frac{1}{r} + \frac{1}{r'} \right) \frac{1}{2cos\theta} \right)^{-1} = 0.23 \text{ m}$$

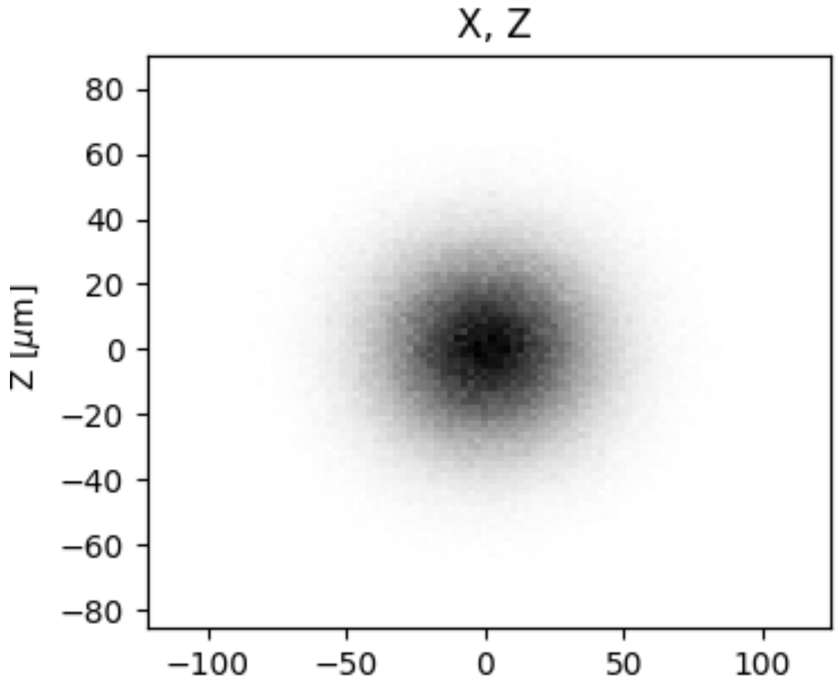
$$f_t = \frac{R \cdot cos\theta}{2} = 6.6 \text{ m} \quad f_s = \frac{\rho}{2cos\theta} = 3.3 \text{ m}$$

Tangential focus



FWHM (X)=333 µm FWHM(Z)=1.5µm

Sagittal focus



FWHM (X)=56 µm FWHM(Z)=42µm

Spherical mirrors

Same as toroidal mirrors with:

$$R = \rho$$

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

$$f_t = \frac{R \cdot cos\theta}{2}$$

$$f_s = \frac{R}{2cos\theta}$$

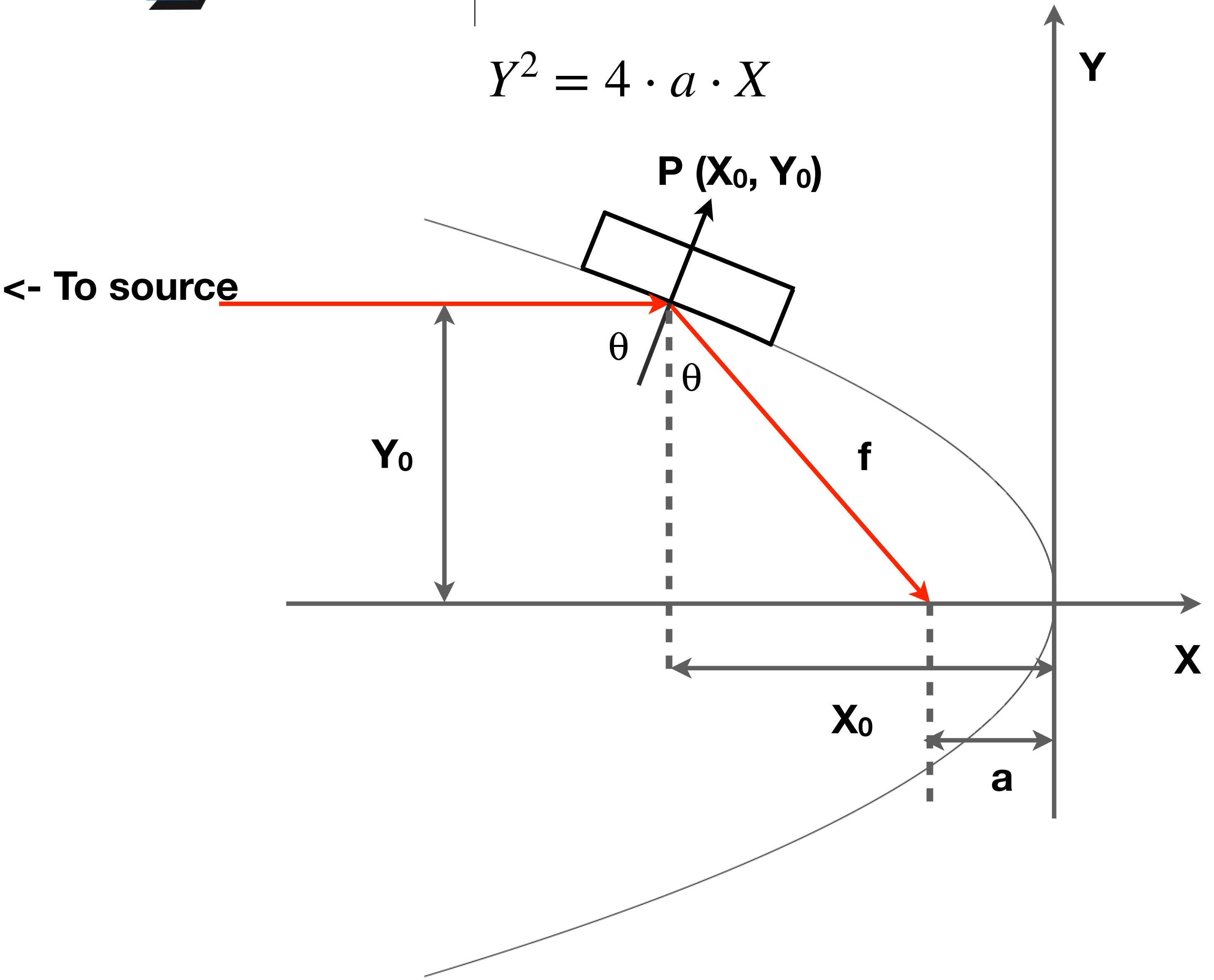
A stigmatic image is only possible if:

$$\frac{\rho}{R} = cos^2\theta = 1$$

i.e. this is possible only for normal incidence!

Paraboloidal mirror

$$Y^2 = 4 \cdot a \cdot X$$



P (X_0, Y_0):

$$X_0 = a \cdot tan^2\theta$$

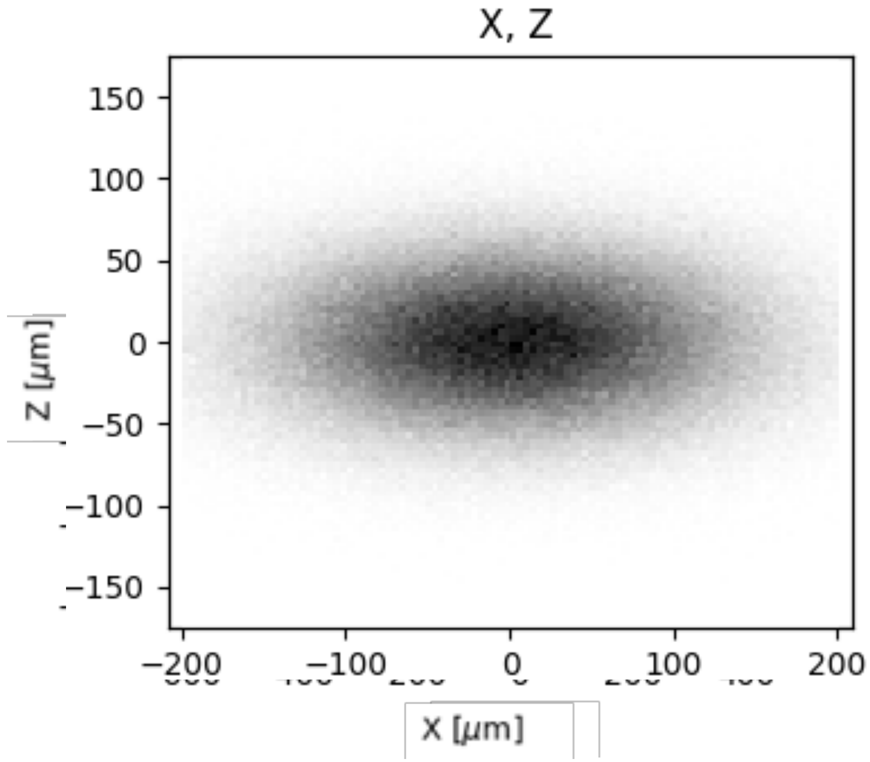
$$Y_0 = 2a \cdot tan\theta$$

$$f = \frac{a}{cos^2\theta}$$

Paraboloidal mirror, r = 20 m, r' =20 m, $\theta = 88°$

Parabola parameter $a = fcos^2\theta = 0.02435$m

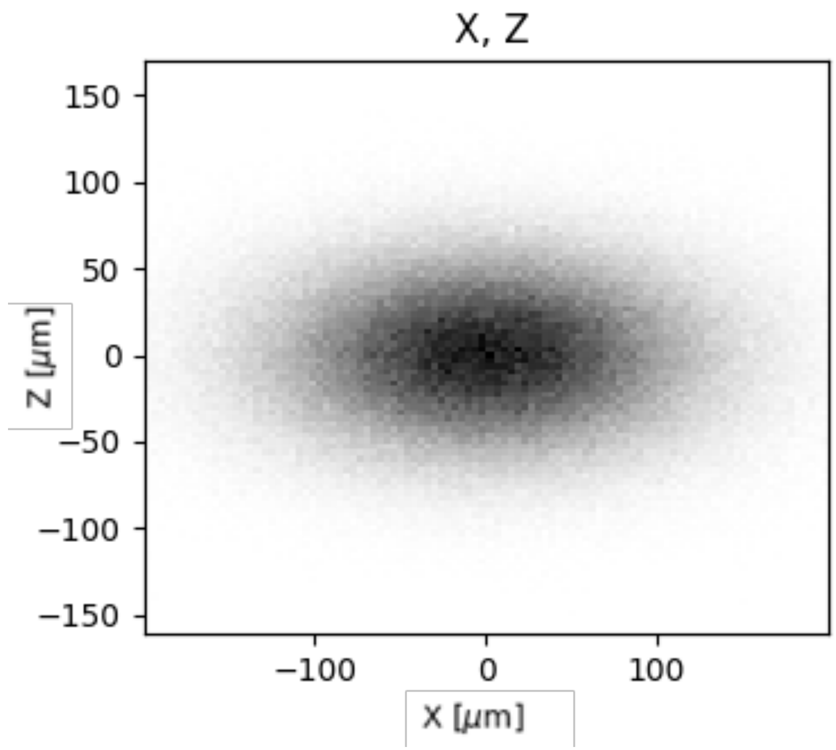
Source image @ 20 mt



FWHM (X)=250 μm FWHM(Z)=86 μm

FWHM (X')=8.6 μrad FWHM(Z')=4.2 μrad

Paraboloidal Mirror image



FWHM (X)=172 μm FWHM(Z)=83 μm

FWHM (X')=5.2μrad FWHM(Z')=0.1μrad

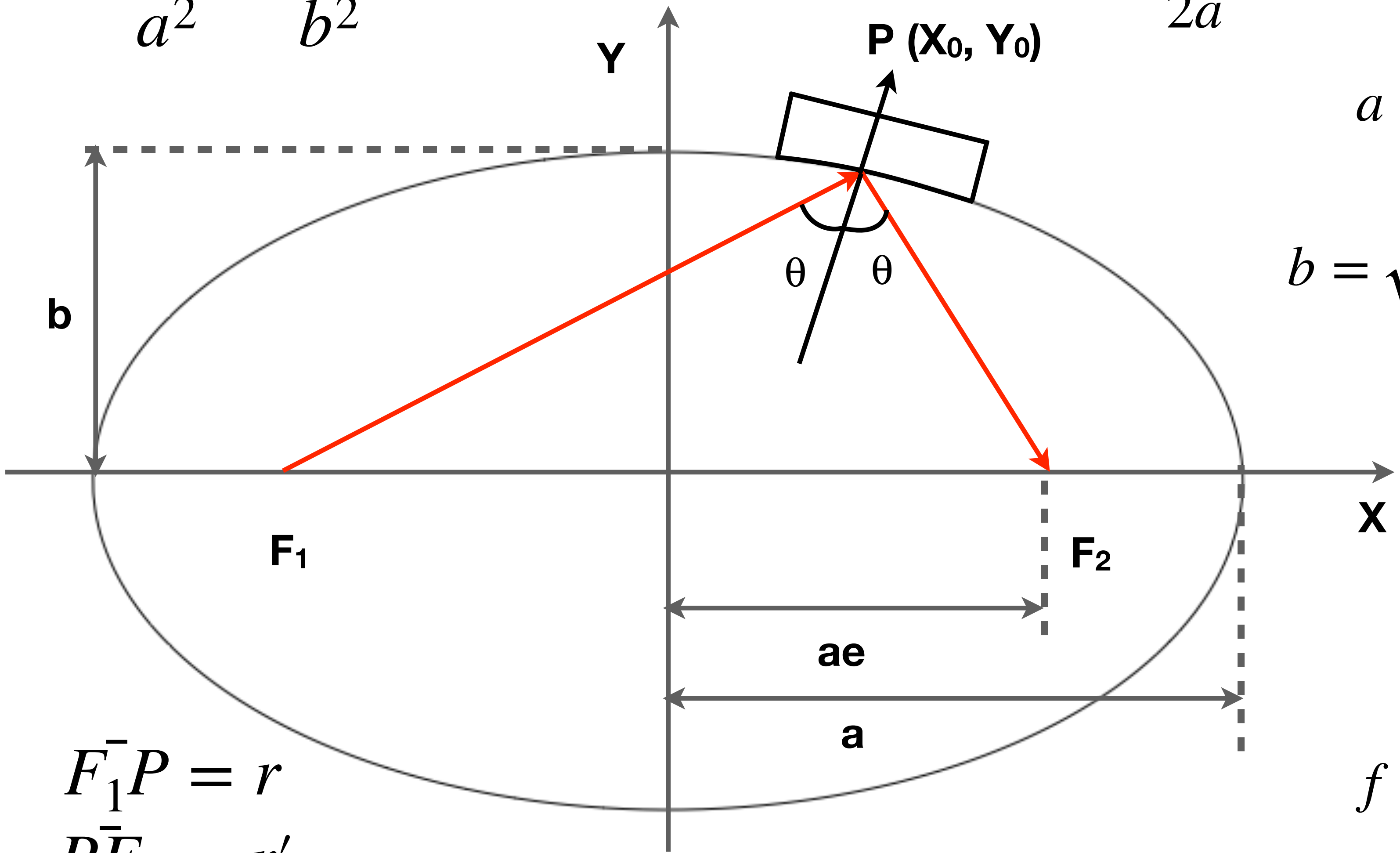
Ellipsoidal mirror

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

$$e = \frac{1}{2a}\sqrt{r^2 + r'^2 - 2rr'cos2\theta}$$

$$a = \frac{(r + r')}{2}$$

$$b = \sqrt{a^2\left(1 - e^2\right)}$$



$$\overline{F_1P} = r$$
$$\overline{PF_2} = r'$$

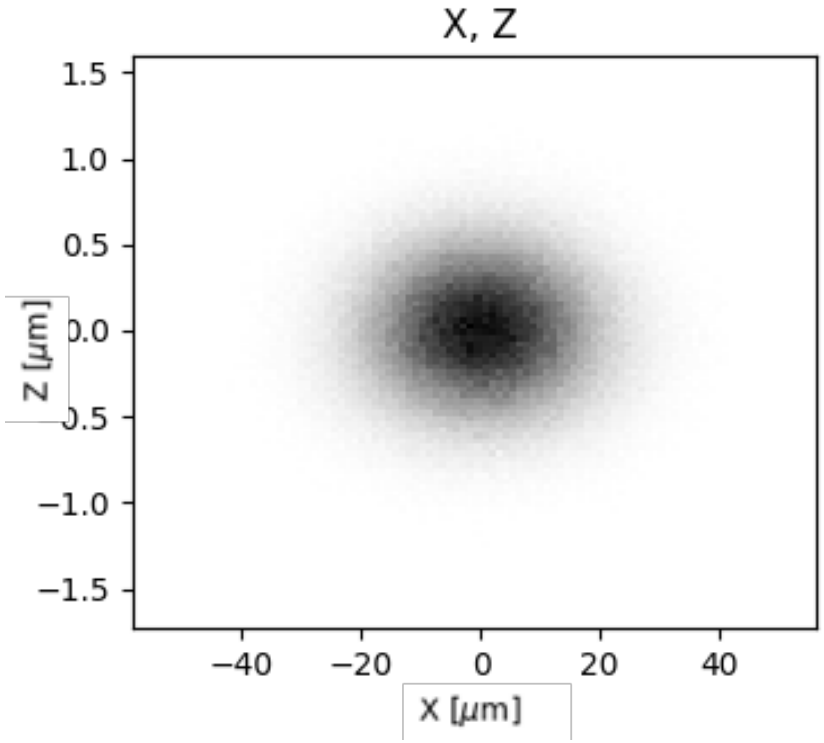
$$f = \left(\frac{1}{r} + \frac{1}{r'}\right)^{-1}$$

Ellipsoidal mirror, r = 20 m, r' =5 m, $\theta = 88°$

a = 12.5 m, b = 0.349 m, e=0.999610

Our source dimensions are: FWHM (X)=105 μm FWHM(Z)=3 μm

$M = \frac{r'}{r} = 0.25$ i.e. we expect a focus of ~ 26 x 0.75 μm (FWHM)



FWHM (X)=26 μm FWHM(Z)=0.7 μm

WARNING!

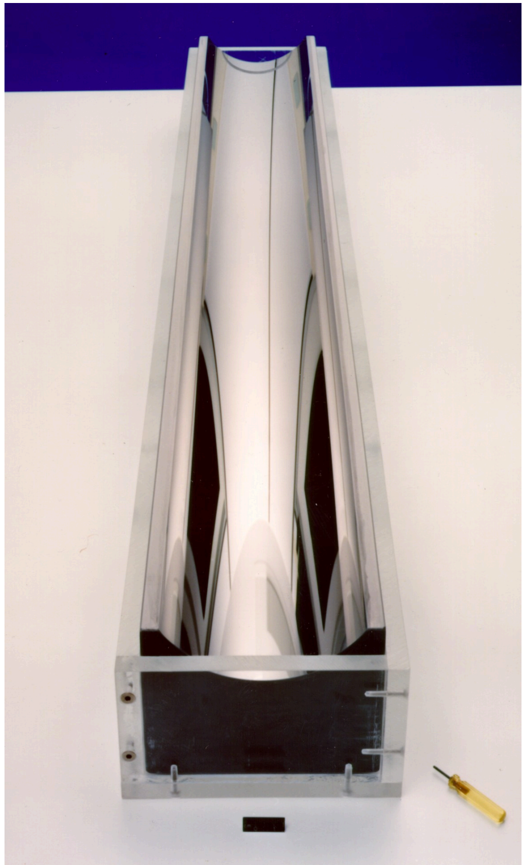
All the simulations above are for educational purposes!

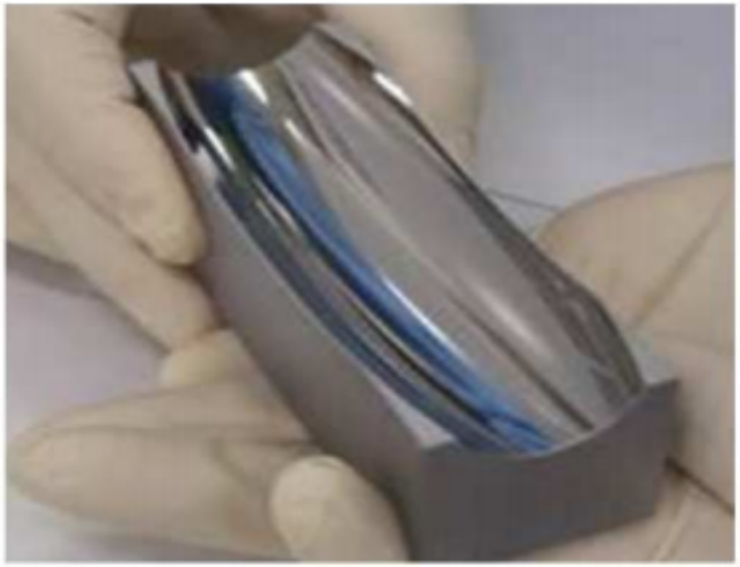
- Reflectivity set to 1, and independent of energy
- Ideal source
- No mirror errors (roughness, figure errors, etc)

Mirror figures used in synchrotron beamlines

		Some numbers
Plane	Re-direction	R>100km
Cylindrical	1D focusing	R~ 100's m
Spherical	2D focusing	R~ 100's m
Paraboloid	Infinity to point (or viceversa)	a ~ cm, f ~ m
Elliptical	Point to point focusing	r>>r`
Toroidal	Astigmatic focusing	R ~ 100m, ρ ~ 10's cm

All this with an rms roughness ~ nm or less





http://www.esrf.eu/home/UsersAndScience/Experiments/CBS/ID09/OpticsHutch/mirror.html

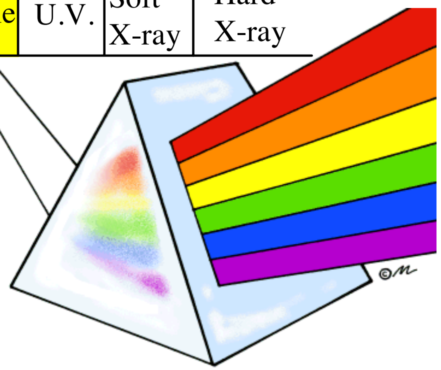
http://www.crystal-scientific.com/mirror_plano.html

R. Radhakirshnan et al,
DOI 10.1149/07711.1255ecst

Diffracting elements

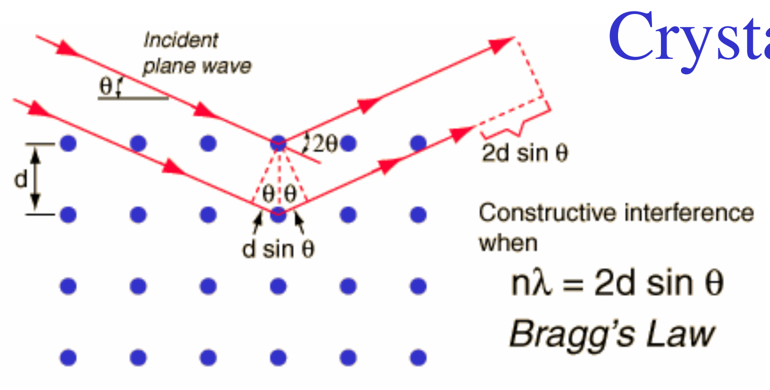
Usage:
Overwhelmingly for monochromatization

Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



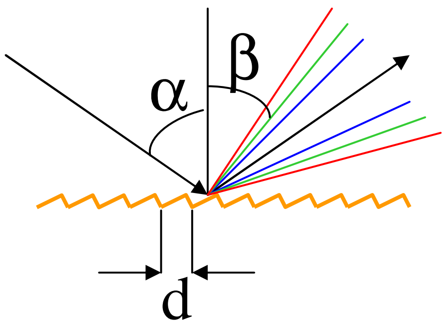
Prism

Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



Crystal

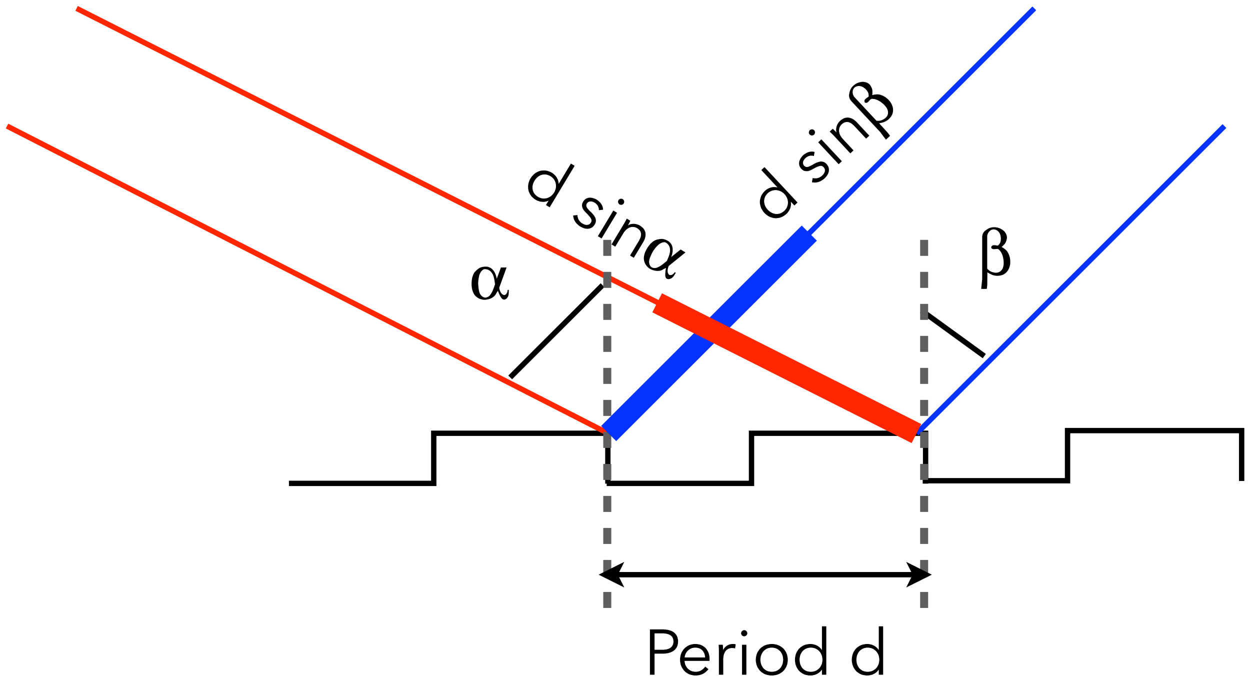
Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



Grating

Diffraction gratings

Artificial periodic structure, with a precisely defined period d.



Grating equation

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

m is the diffraction order

Line density

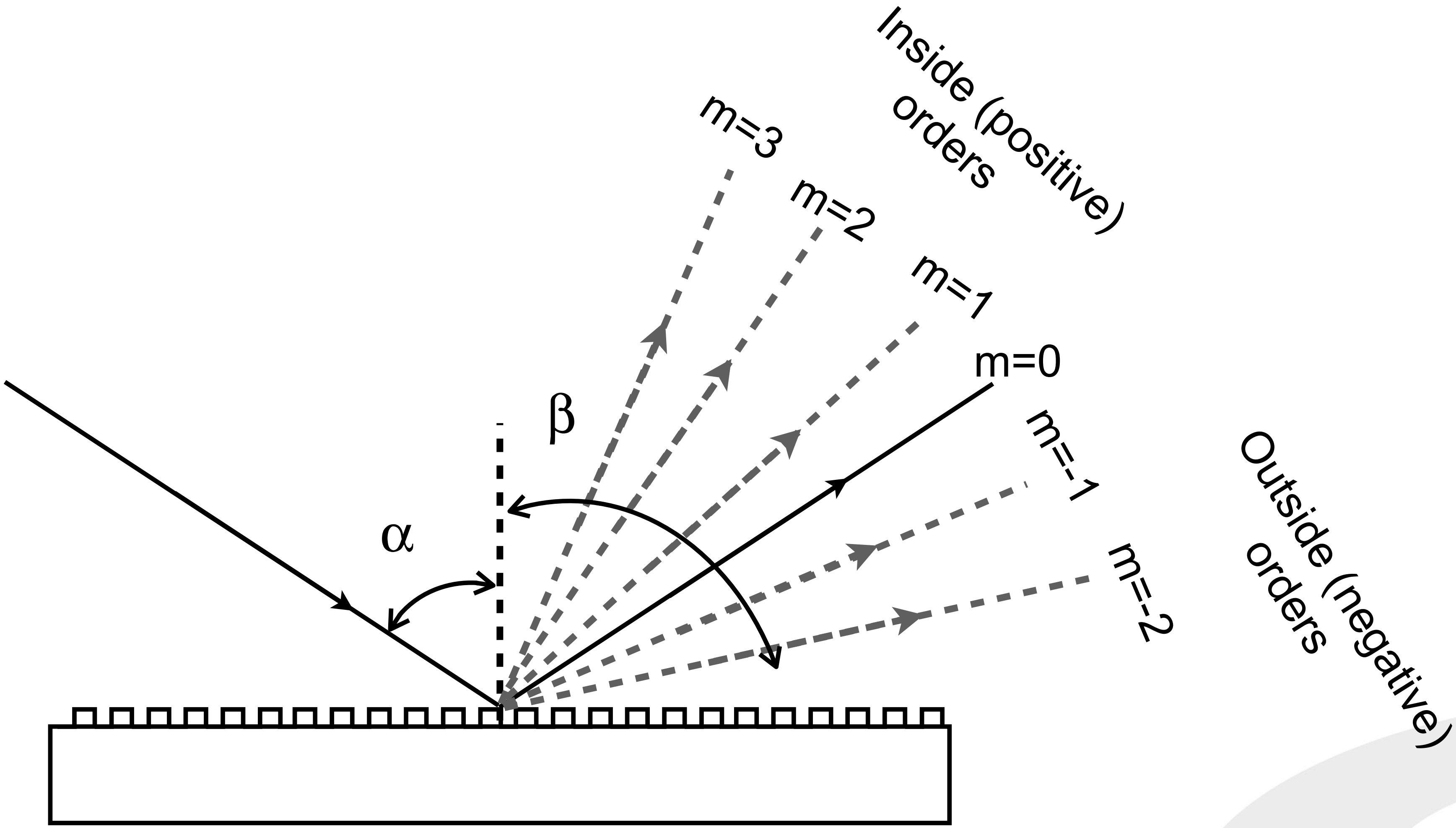
$$L = \frac{1}{d}$$

α and β have opposite signs if on opposite side of the surface normal

Diffraction gratings

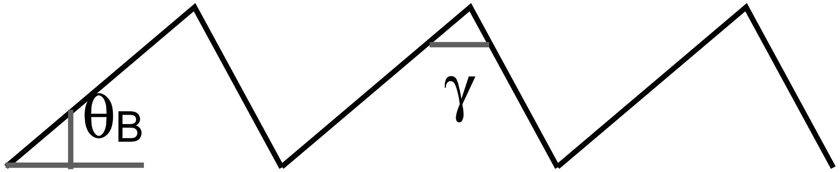
Grating equation

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

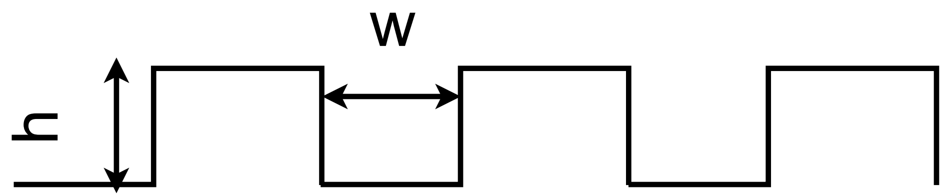


Grating profiles

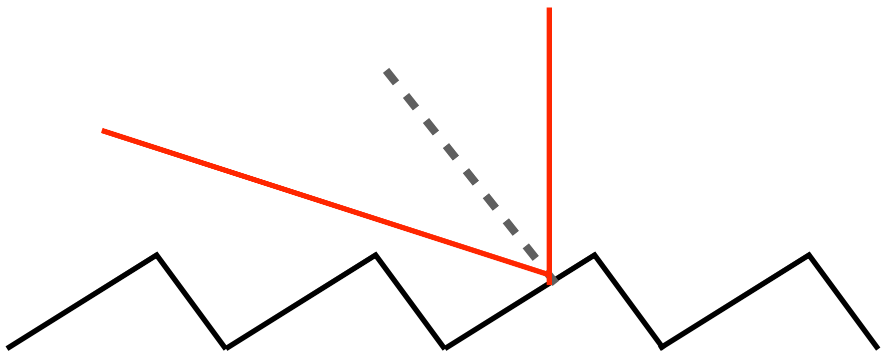
Blazed profile



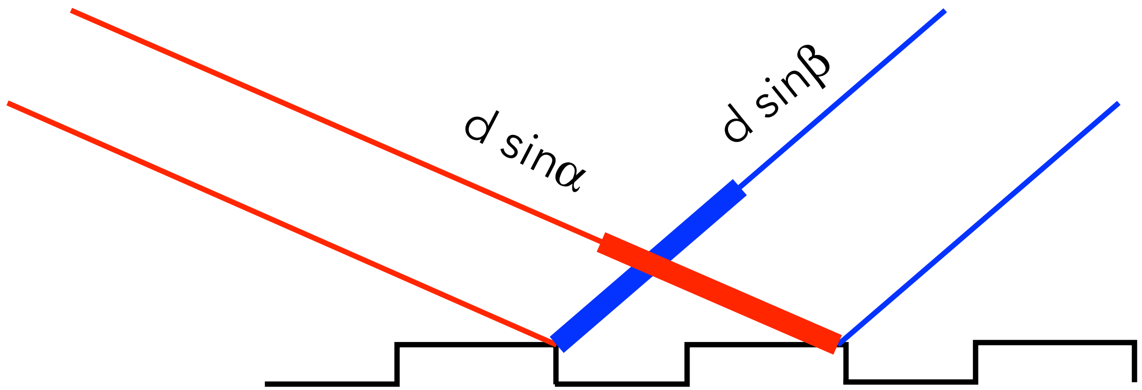
Laminar profile



Blaze condition:



$$\theta_B = \frac{\alpha + \beta}{2}$$

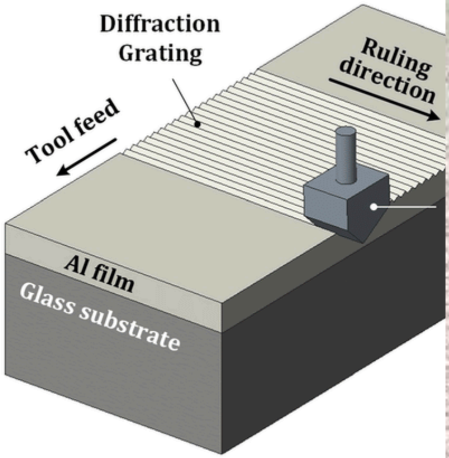


Higher efficiency

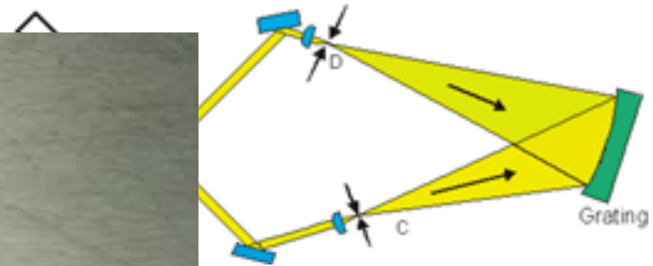
Higher spectral purity

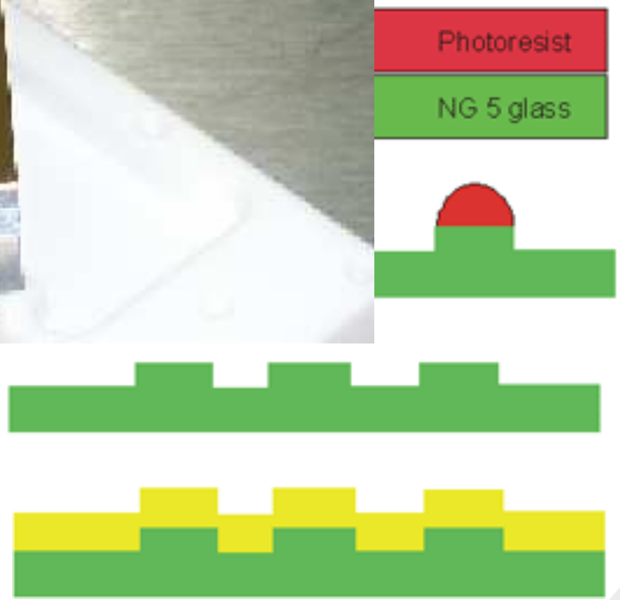
Making of a grating

Mechanical ruling



Holographic ruling





Substrate

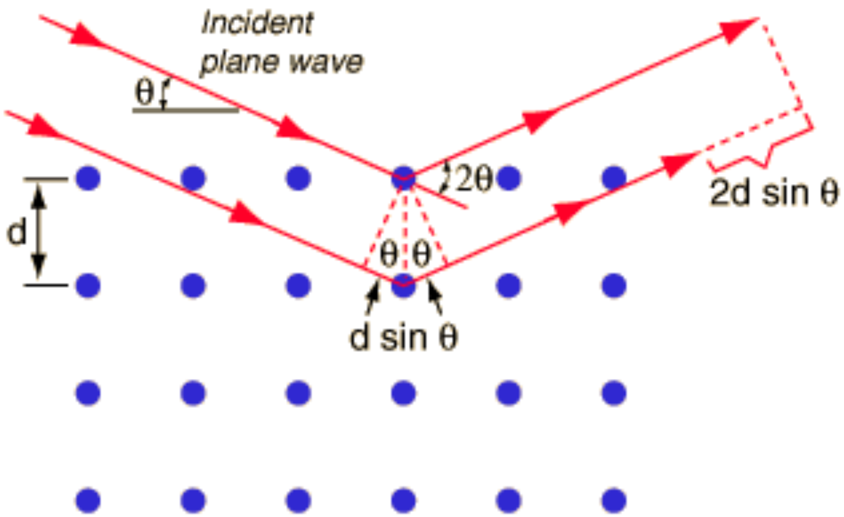
After development and etching

Resist removed

Final coating

Crystals

Based on Bragg's law: $2dsin\theta = m\lambda$

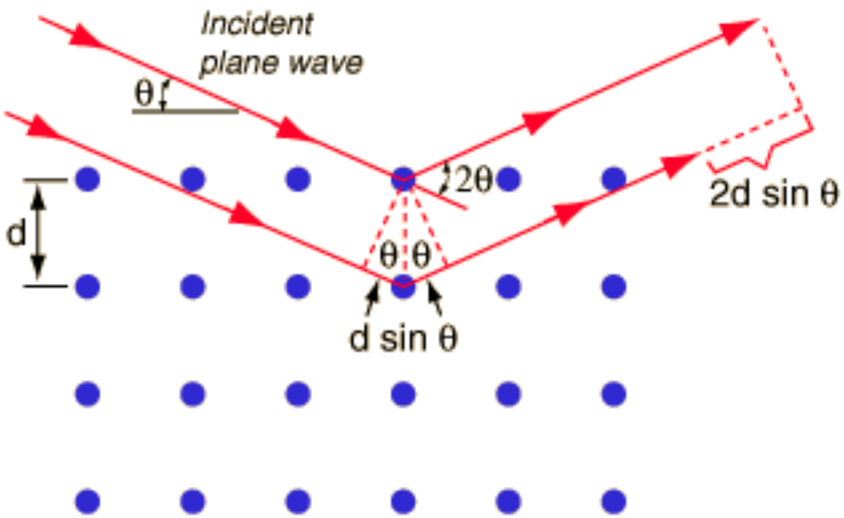


Since $sin\theta \leq 1$, $\lambda \leq \lambda_{MAX}$ $(E \geq E_{MIN})$ =2d

Si(111): d=3.13 Å (E_{MIN}~2keV) Si(311): d=1.64 Å (E_{MIN}~3.8keV)

InSb(111): d=3.74 Å (E_{MIN}~1.7keV)

Crystals' resolving power



$$\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \Delta\theta \frac{cos\theta}{sin\theta}$$

Angular spread of the beam

Where does $\Delta\theta$ come from?

$\Delta\theta_{beam}$ Angular divergence of the incoming beam *

$\omega_{crystal}$ Intrinsinc width of Bragg reflection, the Darwin curve

* more on this later…

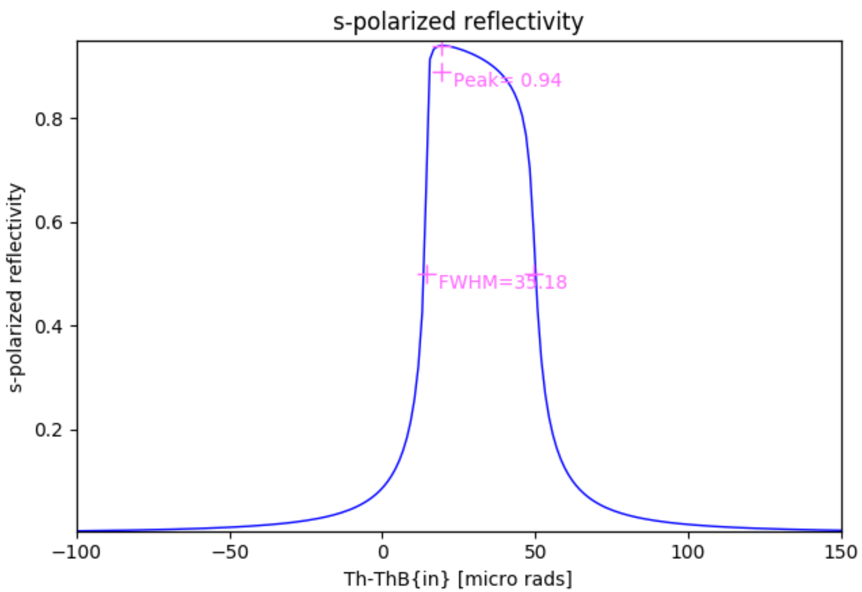
A quick word on the Darwin curve (ω_s)

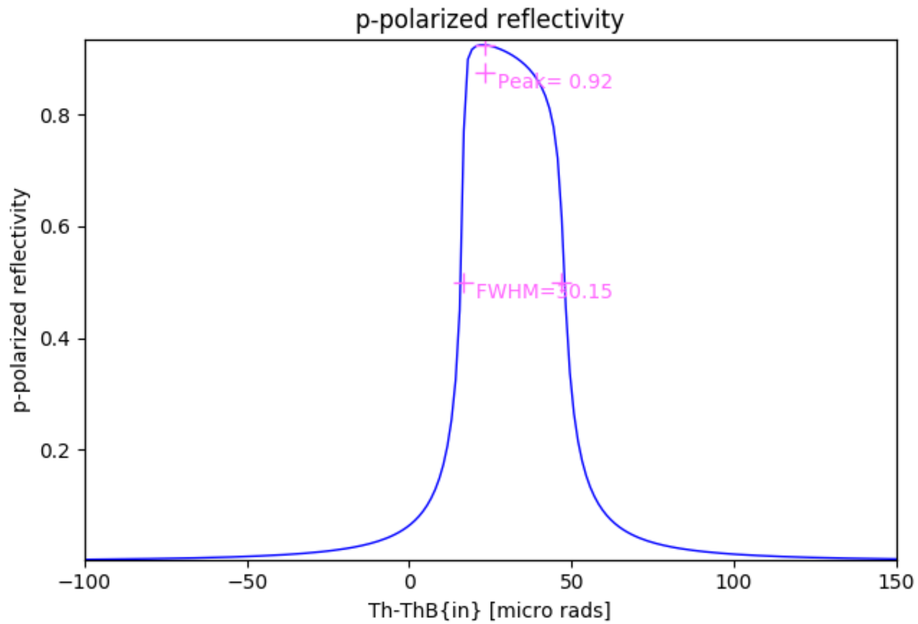
Obtained by measuring the crystal reflectivity R with:

1) Strictly monochromatic beam which is
2) Perfectly collimated

And as a function of $\Delta\theta = \theta - \theta_{Bragg}$

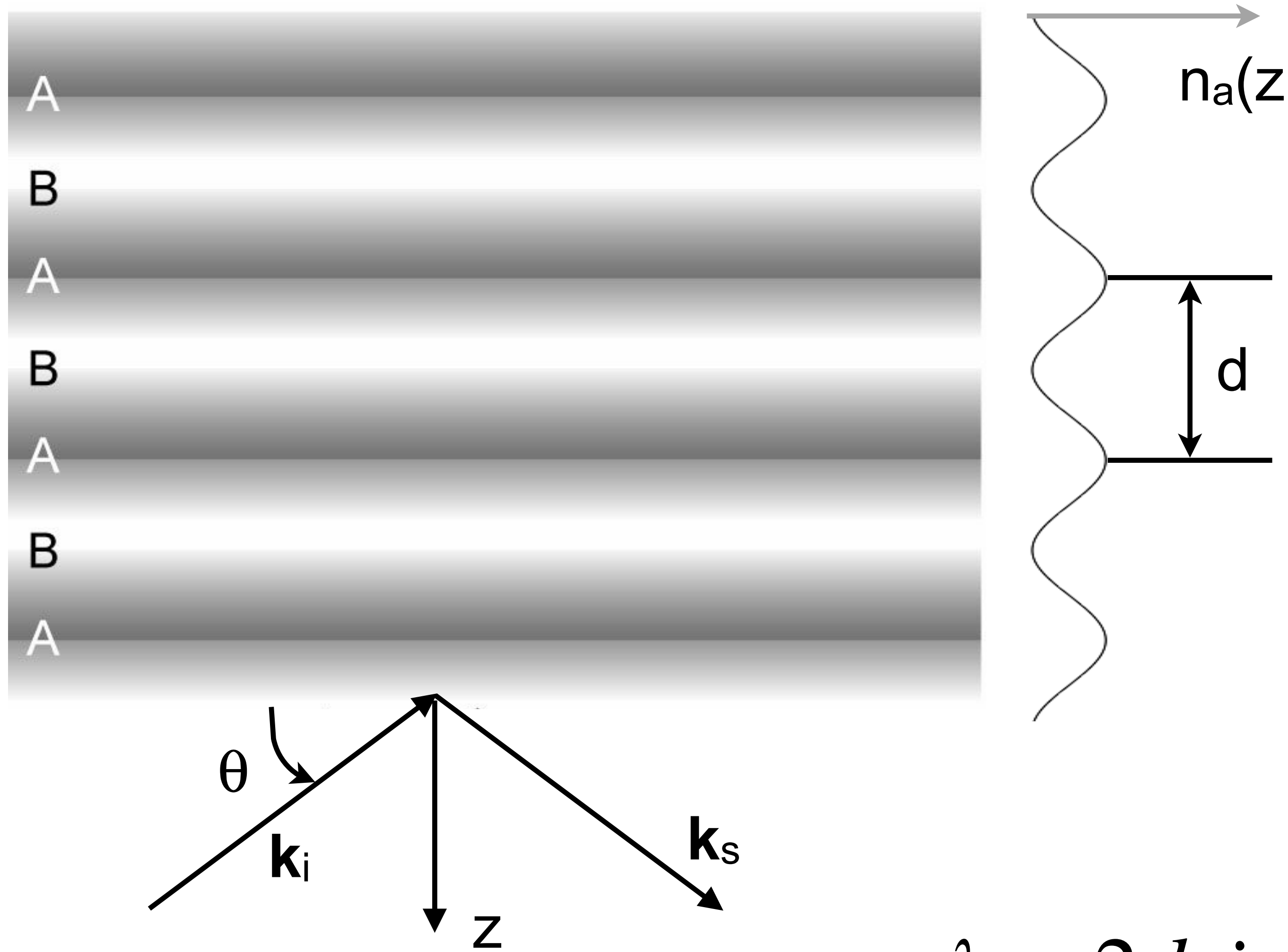
Its expression is derived by dynamic diffraction theory, which includes scattering, and is polarisation-dependent

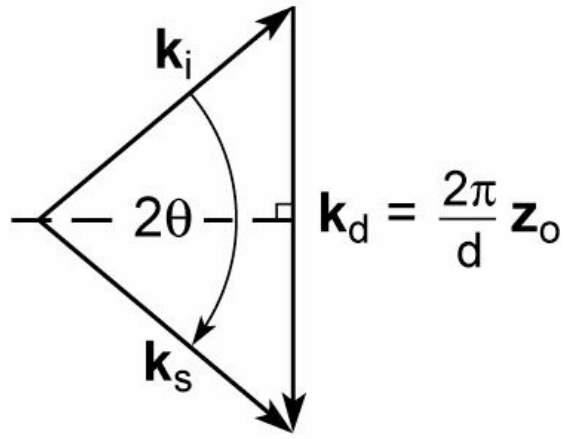




Simulations for Si (111) at 8keV

Multi-layer mirrors





$$\omega_s = \omega_i + \omega_d$$

$$\mathbf{k}_s = \mathbf{k}_i + \mathbf{k}_d$$

But $\omega_d = 0$, therefore:

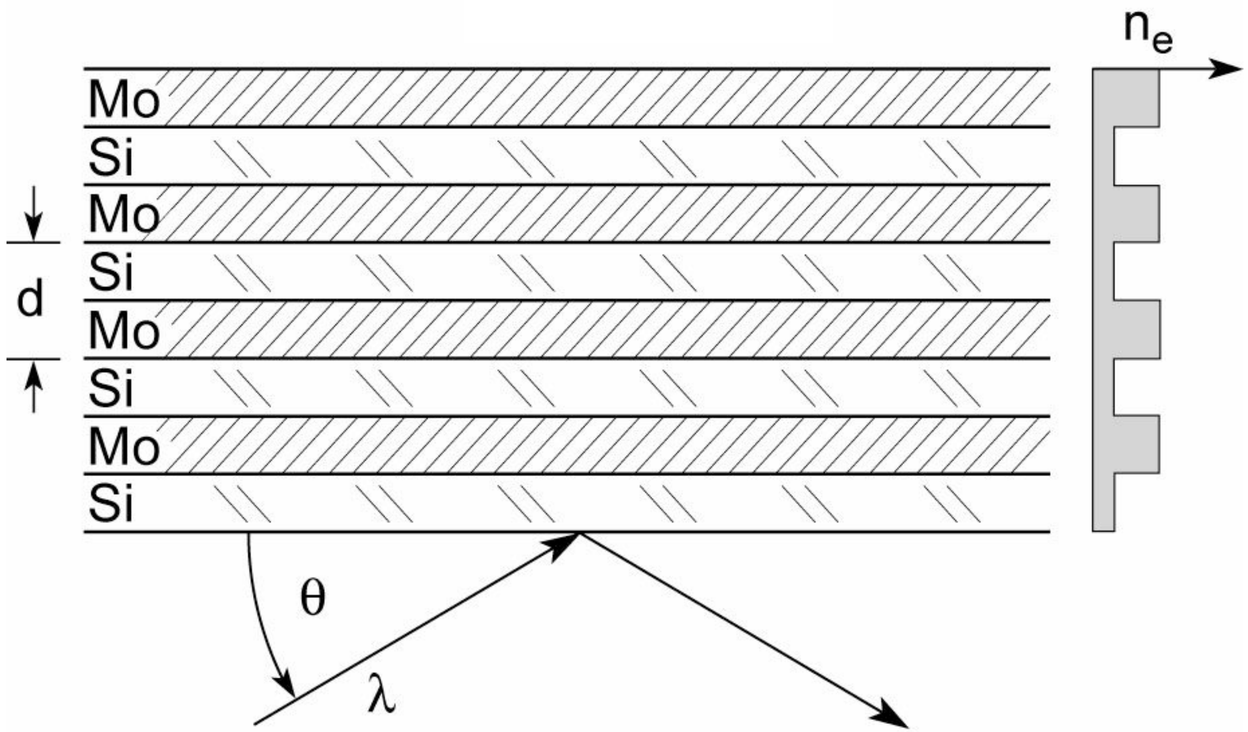
$$|\mathbf{k}_s| = |\mathbf{k}_i| = 2\pi/\lambda$$

$$sin\theta = \frac{k_d/2}{k_i}$$

$$\lambda = 2dsin\theta$$

Multi-layer mirrors

What if $n_a(z)$ is still periodic, but not a simple sinusoid?



$$m\lambda = 2d sin\theta$$

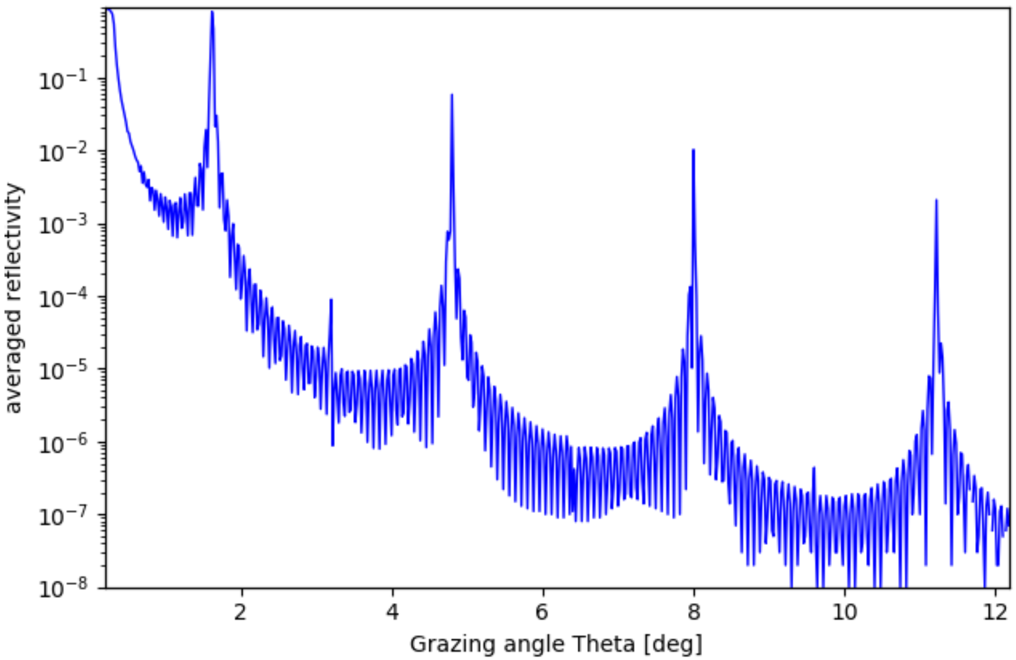
If $\theta = \pi/2$, and m=1:

$$\lambda = 2d$$

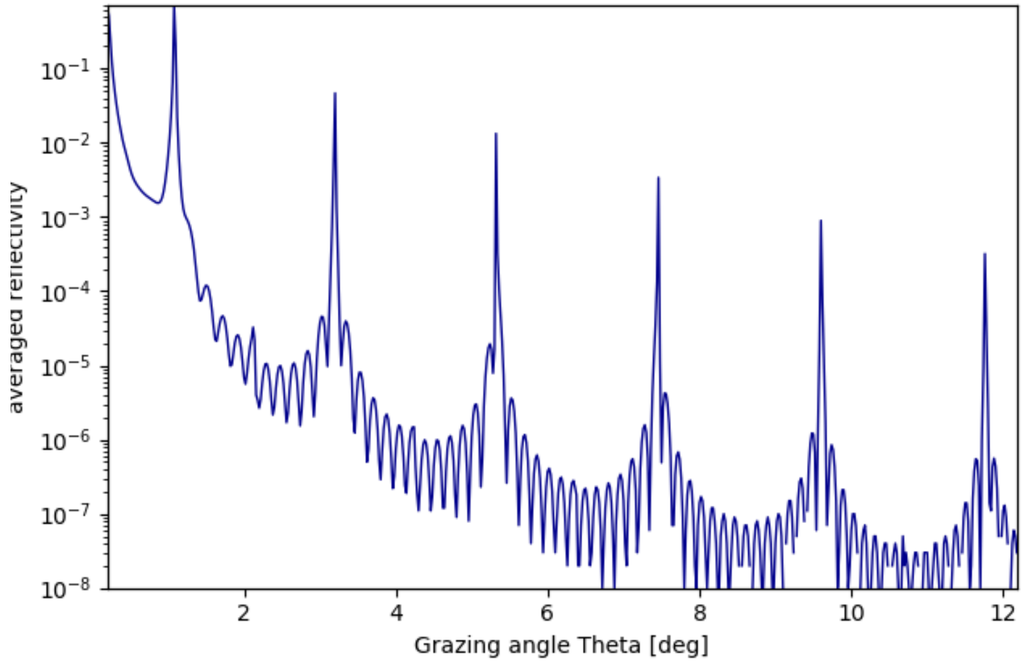
Multi-layer mirrors

W/C, d=22.3 Å, Γ=0.5, N= 100

E=10keV



E=15keV



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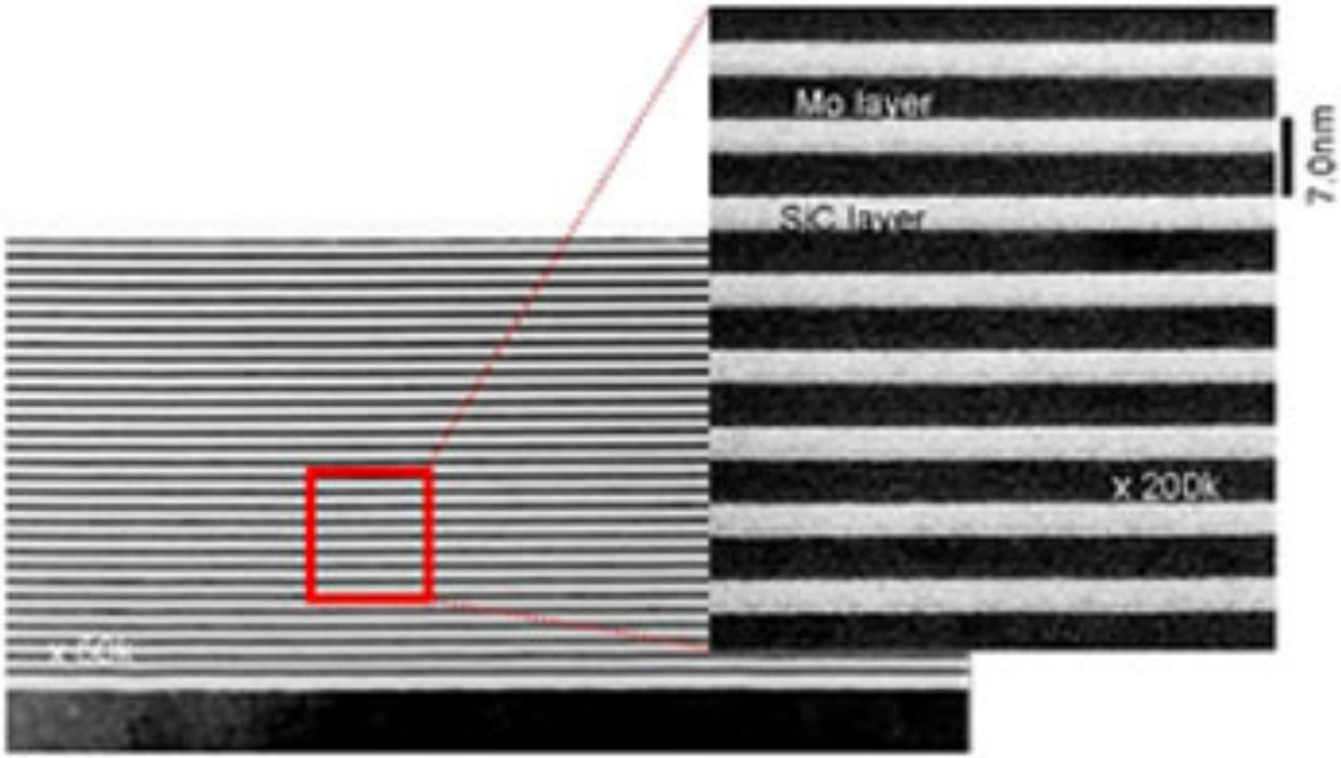
Making of Multi-layer mirrors

Typically by Magnetr

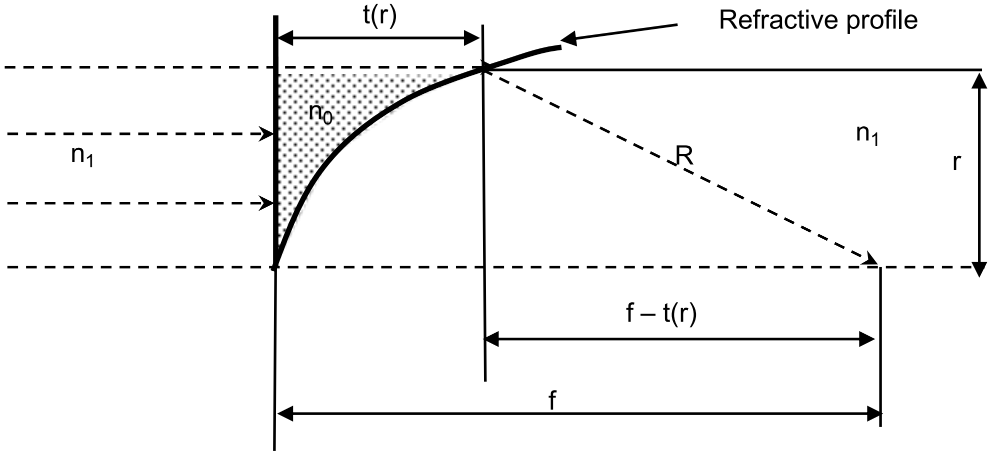
- Coating uniformity
- High refractive inde
- Minimal absorption
- Chemically stable i
- Minimal interdiffusi
- Minimal interfacial r
- Thermal stability
- Chemical stability i



From NTT-AT website

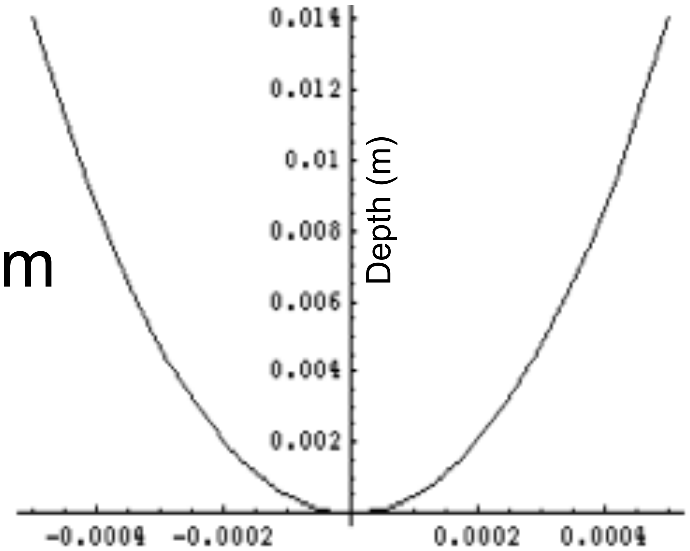
Zone plates

$$n = 1 - \delta + i\beta$$

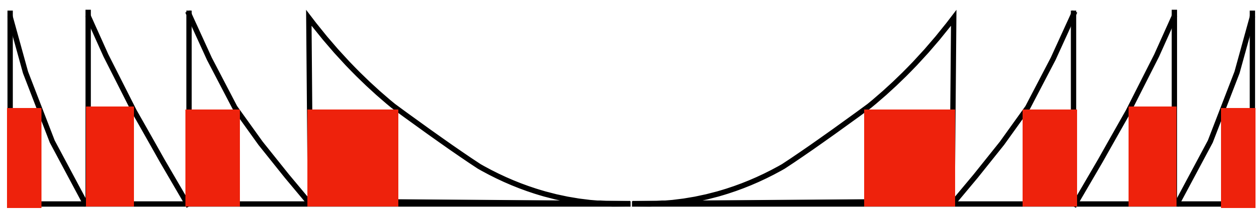


f = 10 cm

$\delta = 10^{-4}$



$$\Delta\phi = \delta\left(\frac{2\pi}{\lambda}\right) t = 2\pi$$



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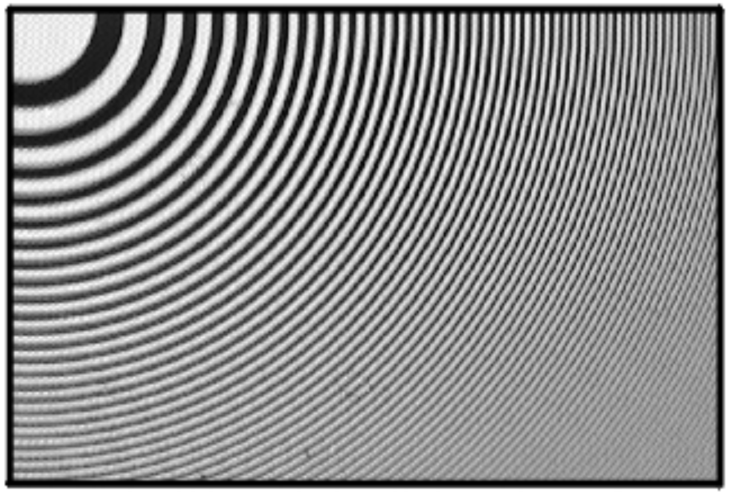
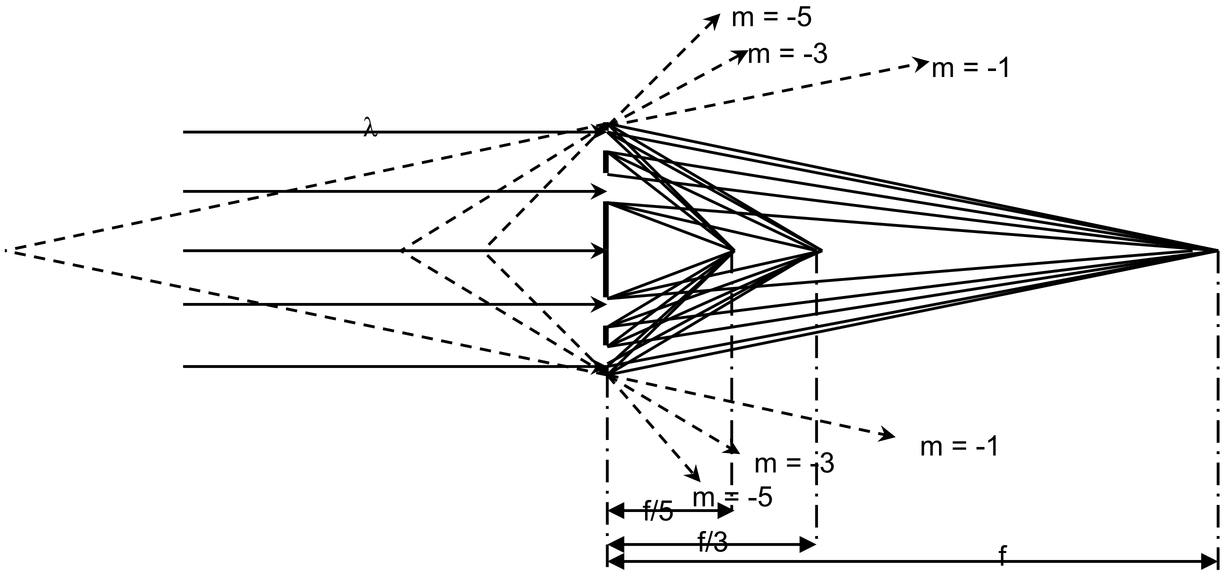
A couple of points on Zone Plates



A ZP is a circularly simmetric diffraction grating, with constant groove area, i.e. is periodic in r^2

If N > 100, then: $\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$



$f_m = D\,\delta r_N / m\,\lambda$

$$\delta_m = 1.22\,\delta r_N / m$$

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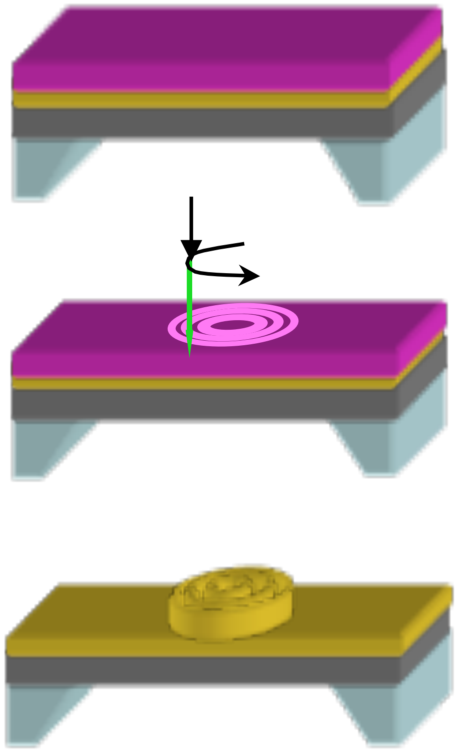
Making of Zone Plates

Electron beam lithography



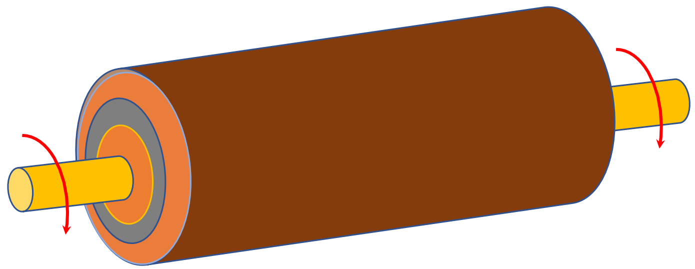
D ~ 0.1 to 1 mm, δr_N=6 nm and up

t ~ 0.05 to 1.5 μm

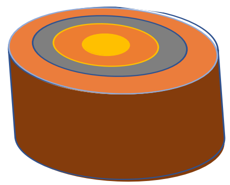
Sputtering and slicing

Cu/Al sputtering

Au wire



Slicing and polishing

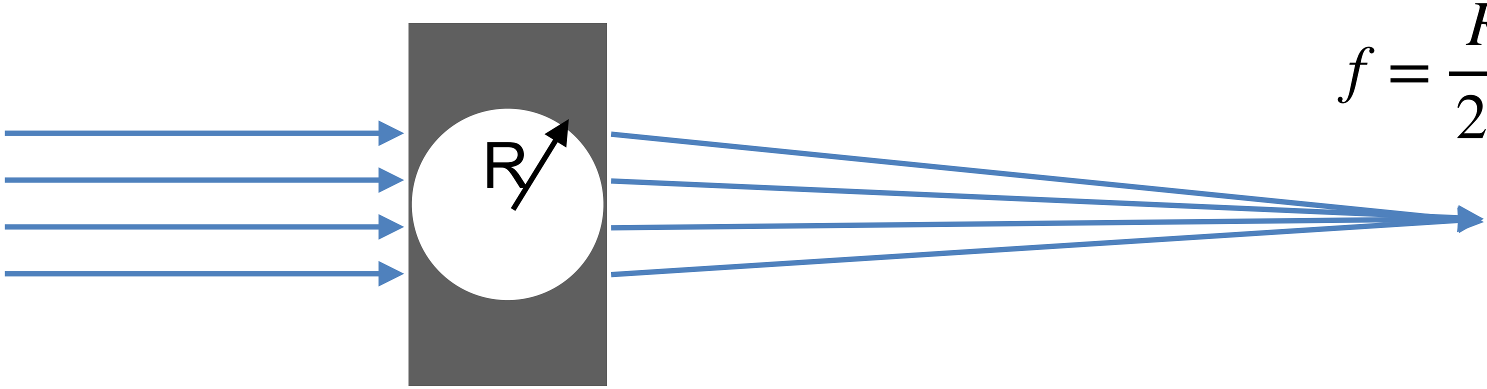


t ~ 20 -50 μm

D ~ 80 -100 μm

Refracting elements

Compound refracting lenses

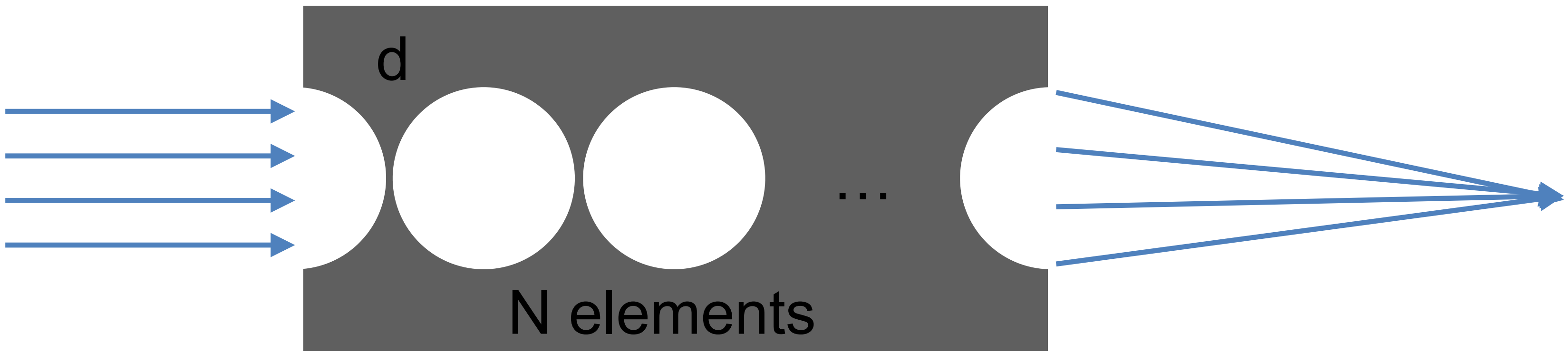


$$f = \frac{R}{2\delta}$$

R~ 100 μm

$\delta \sim 10^{-5}$

f~ 0.5 m

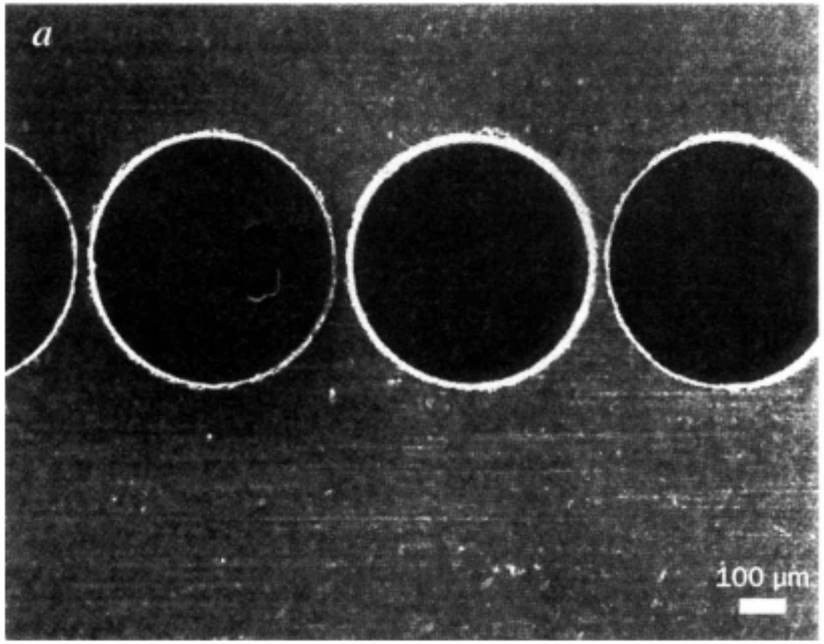


$$f = \frac{R}{2N\delta}$$

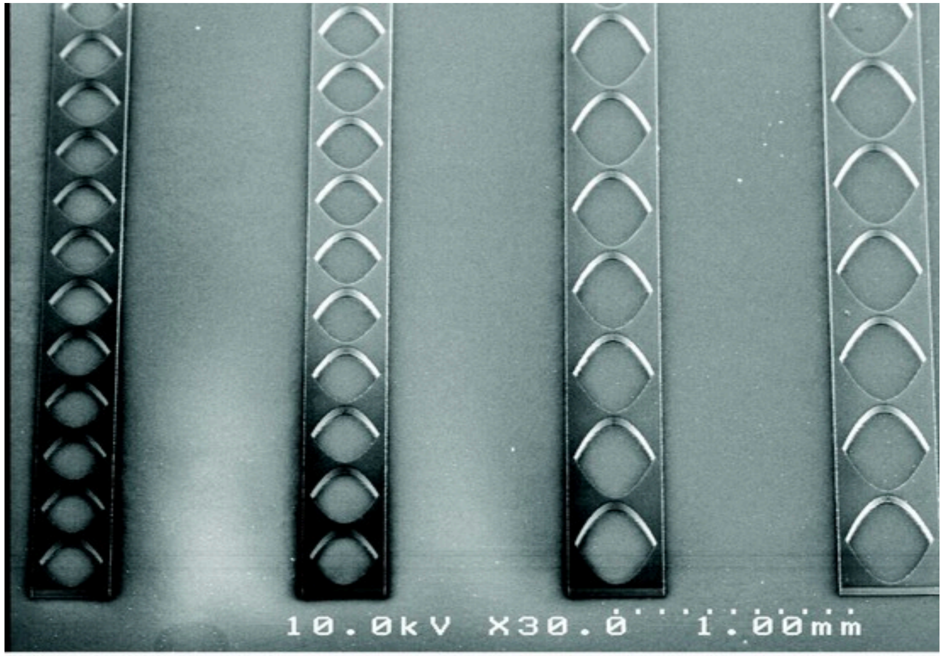
$$\sigma_{dl} \propto \frac{f\lambda}{A} \qquad A = 2R\sqrt{\left(\frac{\lambda}{2\pi\beta RN}\right)}$$

Compound refracting lenses

Characteristics:
- Must be made of low Z materials (Al, C, Be…)
- Focus only in 1D
- Paraboloid as ideal profile



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



Alianelli, L., et al, Journal of Applied Physics. 108, 123107 (2010)

Monochromator

- Need for collimated illumination
- Crystal monochromators
- Plane grating monochromators

The need for collimated illumination

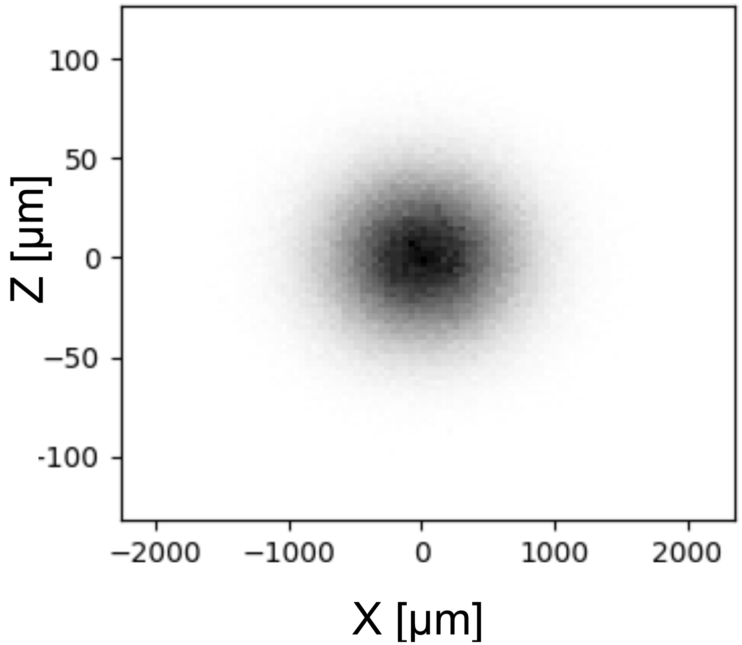
Crystals Energy resolution:

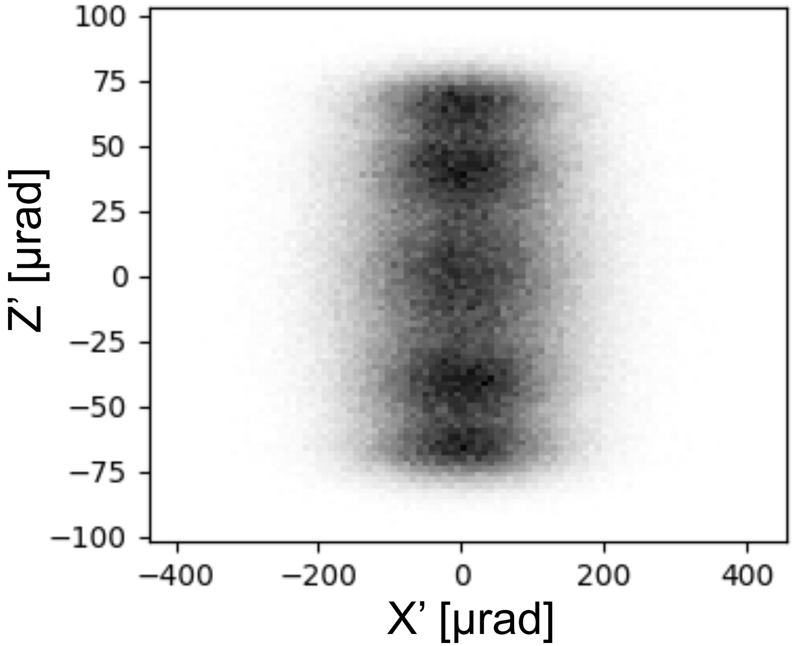
$$\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \boxed{\Delta\theta}\frac{cos\theta}{sin\theta}$$

Same for multilayers

Gratings

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





Undulator

5th Harmonic (~1 keV)
ΔE=500eV

The need for collimated illumination

Collimating mirror before monochromator

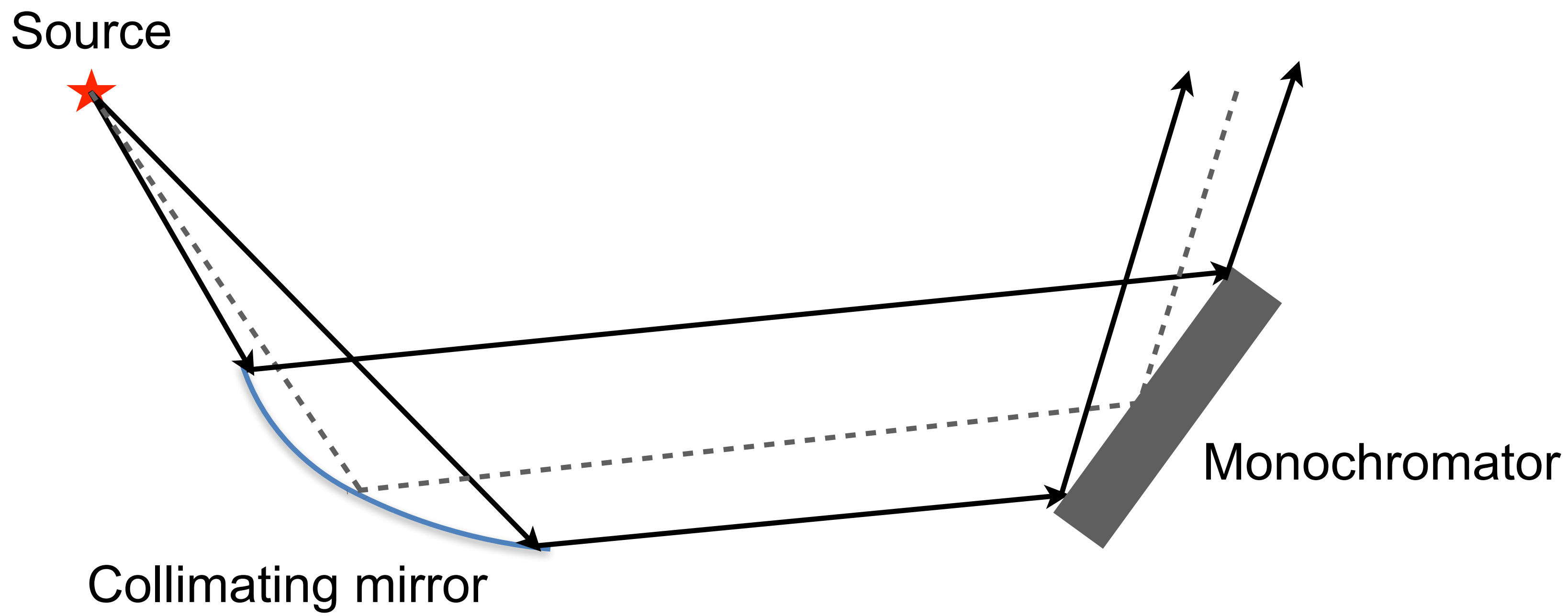


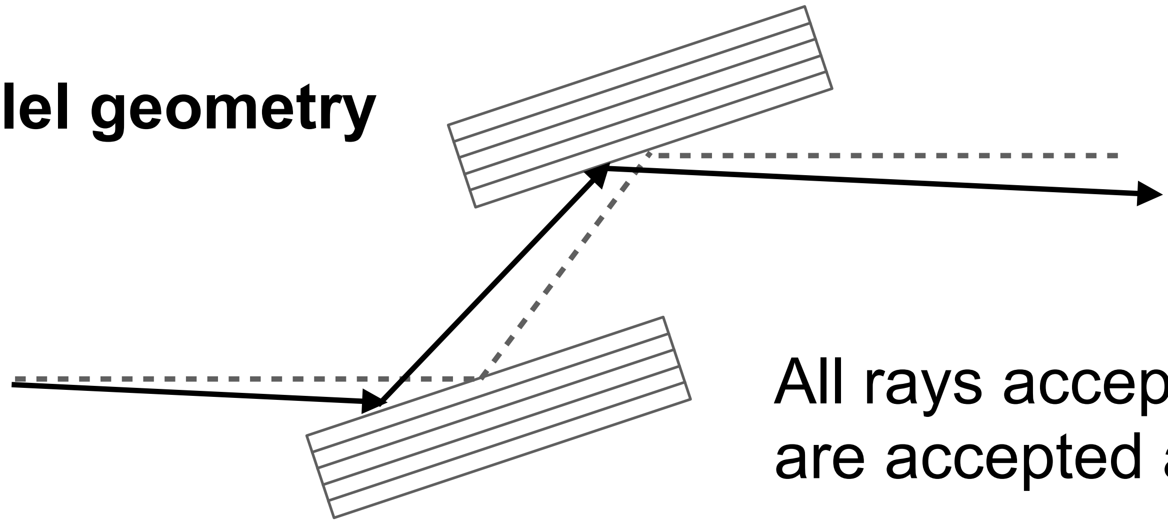
Figure calculated setting r' negative and very far (~100s m)

Double Crystal monochromator

$$2d\sin\theta = m\lambda$$

$$\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \Delta\theta\frac{\cos\theta}{\sin\theta}$$

Parallel geometry



All rays accepted by first crystal are accepted also by the second

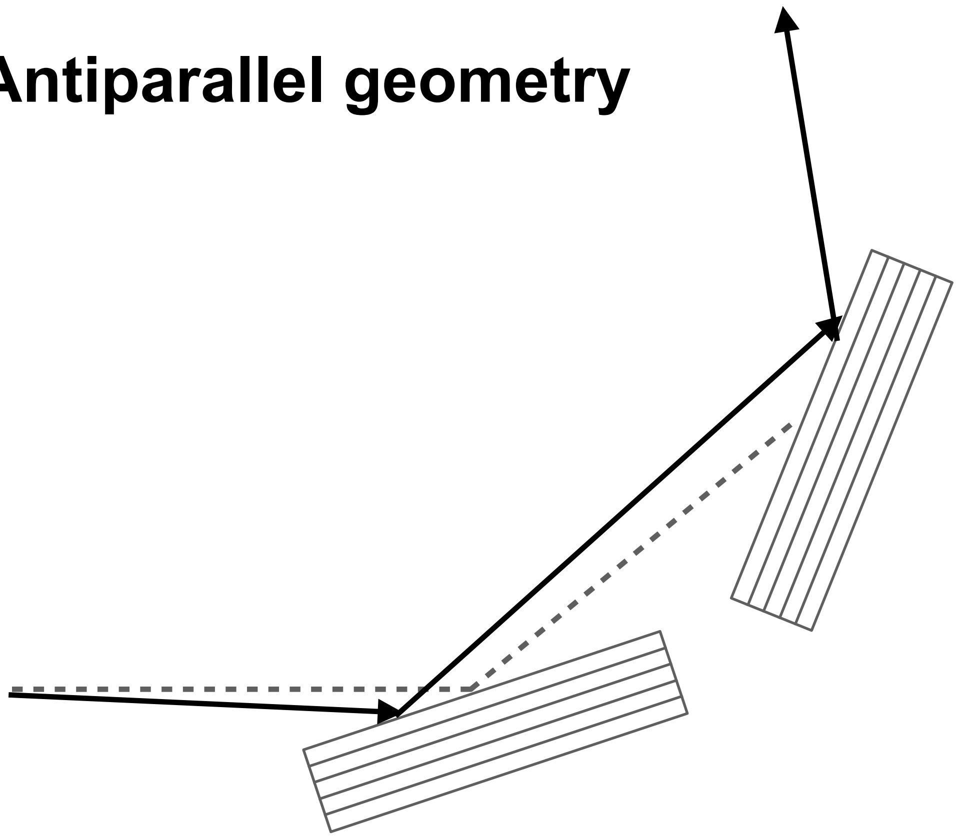
Second crystal acts merely as a mirror

Double Crystal monochromator

$$2d\sin\theta = m\lambda$$

$$\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \Delta\theta\frac{\cos\theta}{\sin\theta}$$

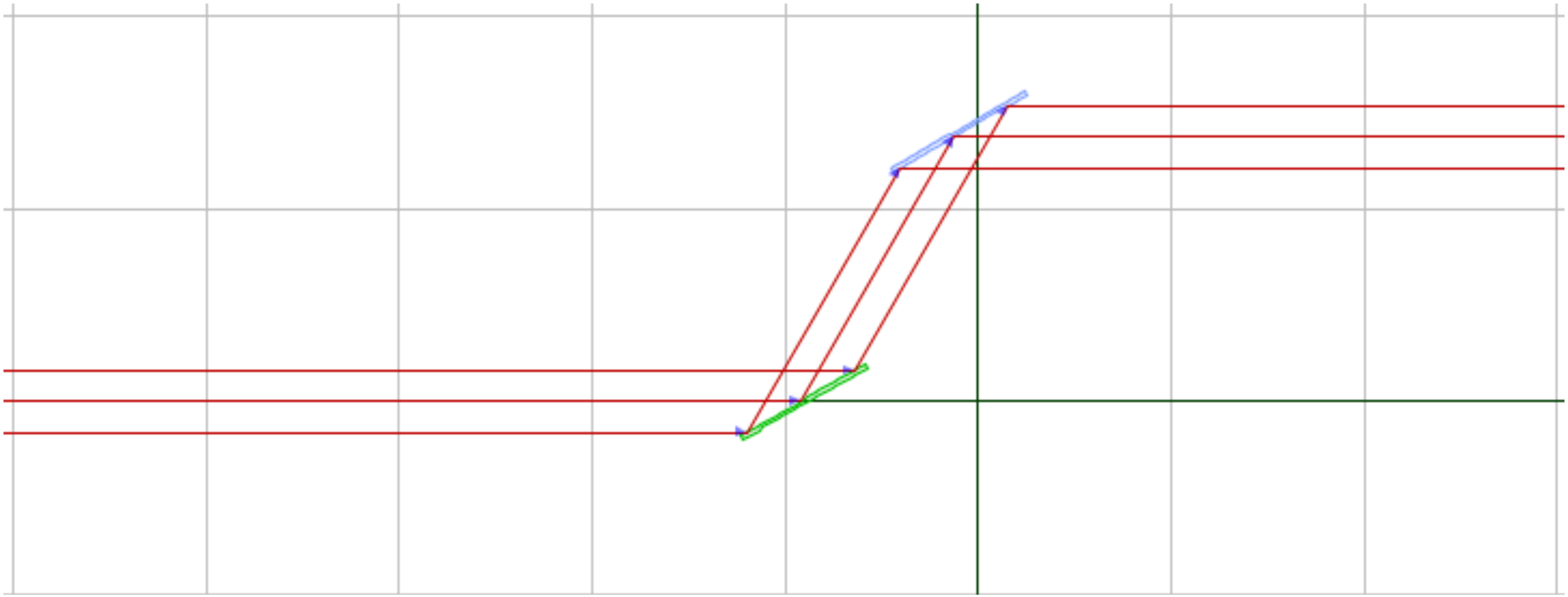
Antiparallel geometry



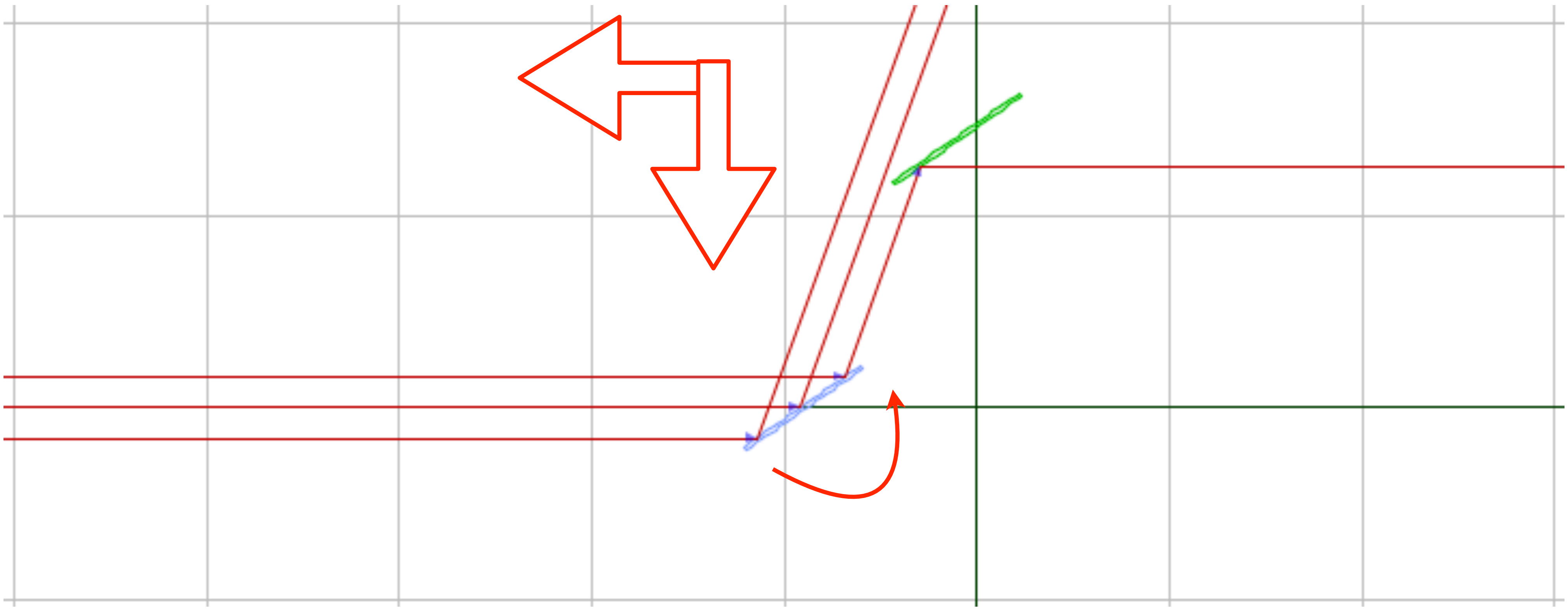
Second crystal is dispersive

Higher $\Delta E/E$
Lower flux

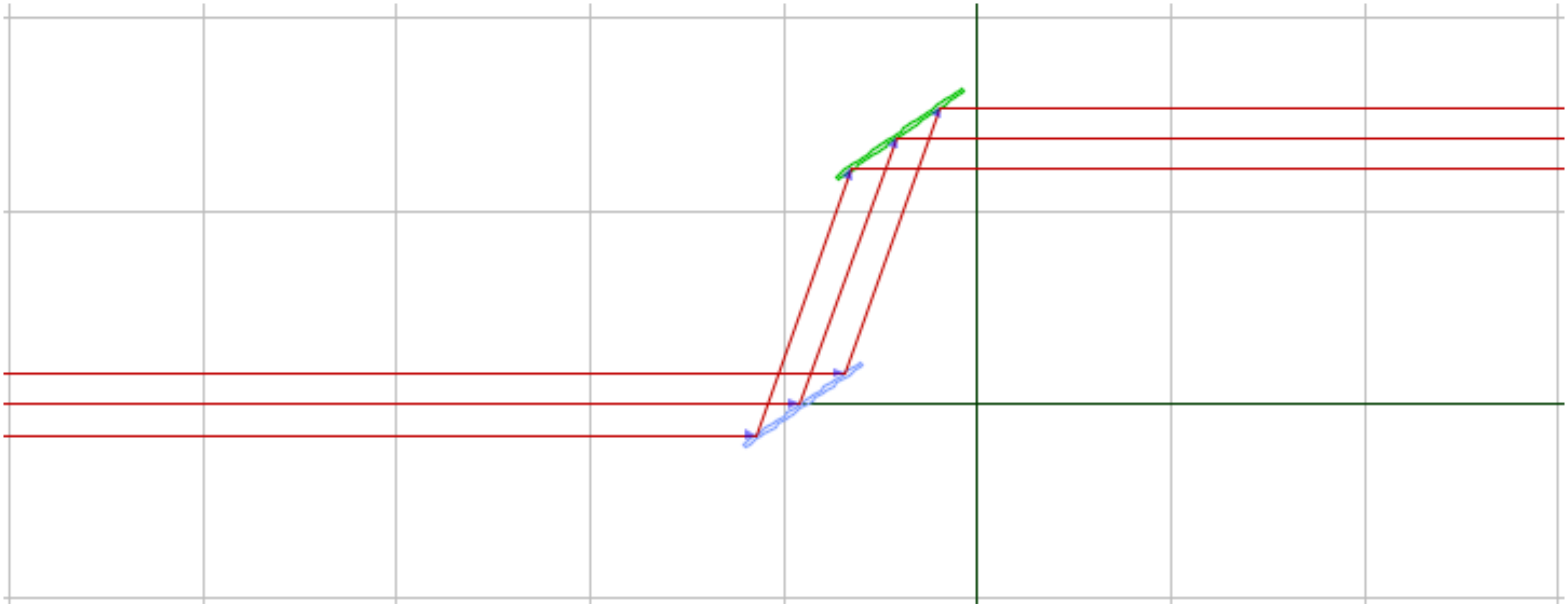
DCM in parallel configuration



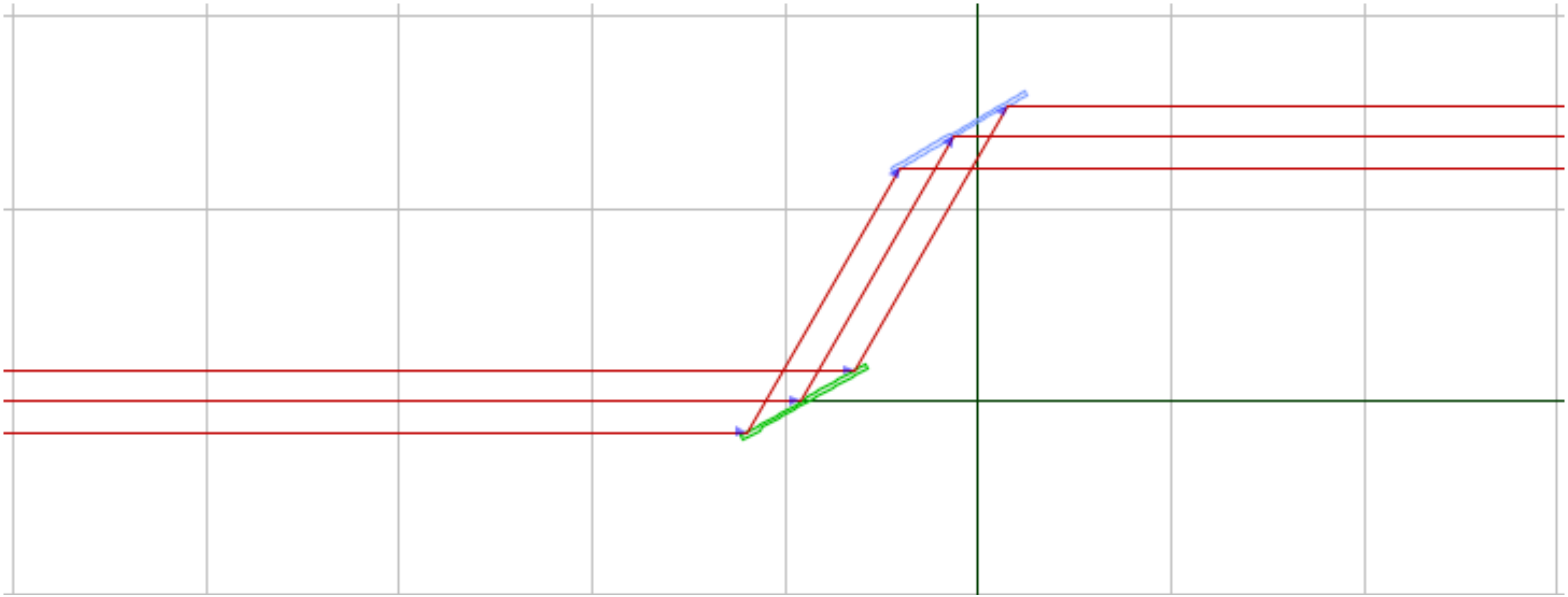
DCM in parallel configuration



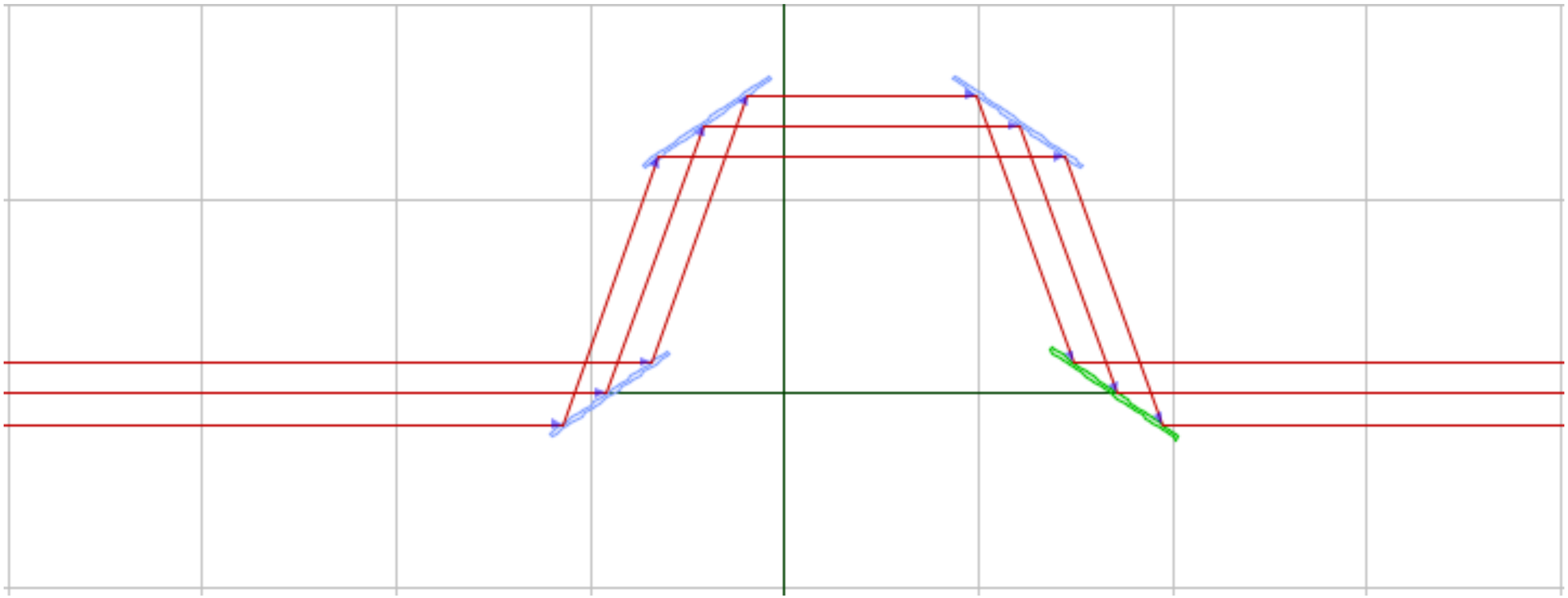
DCM in parallel configuration



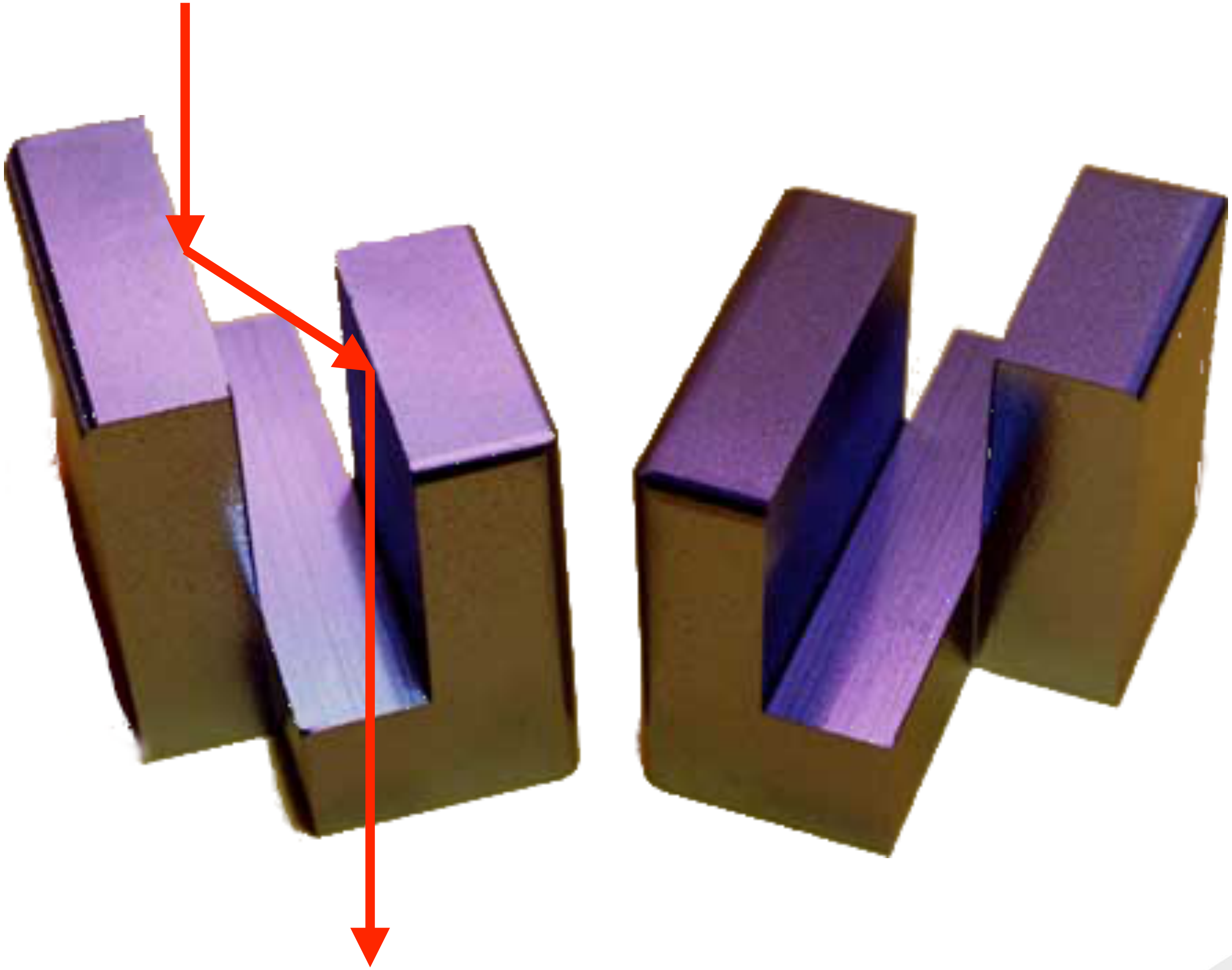
DCM in parallel configuration



2 X DCM in parallel configuration



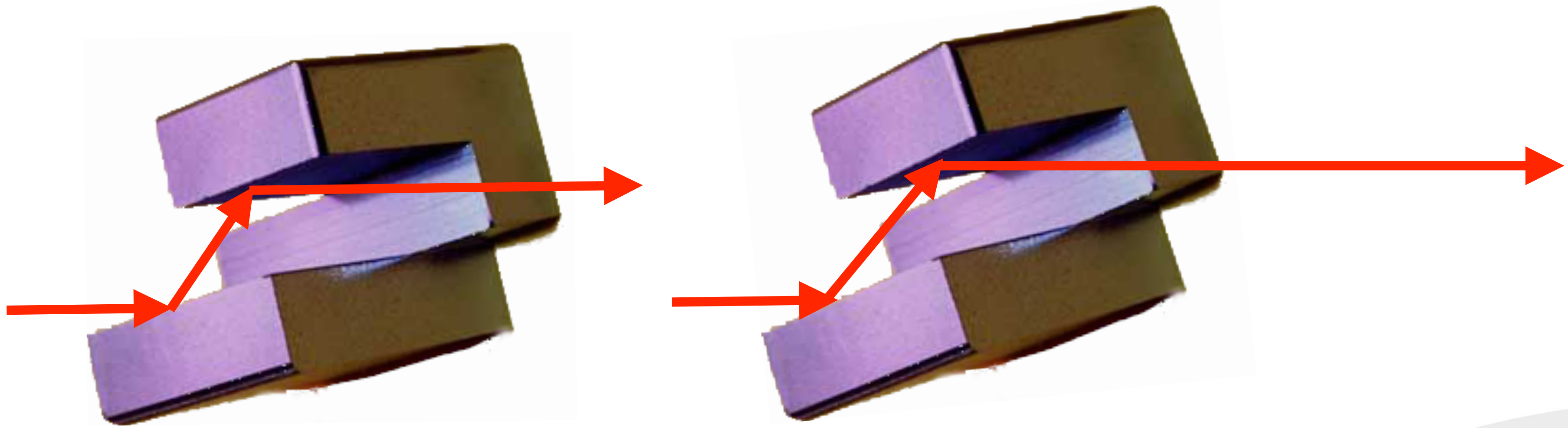
Channel cut Si monochromator



Channel cut Si monochromator

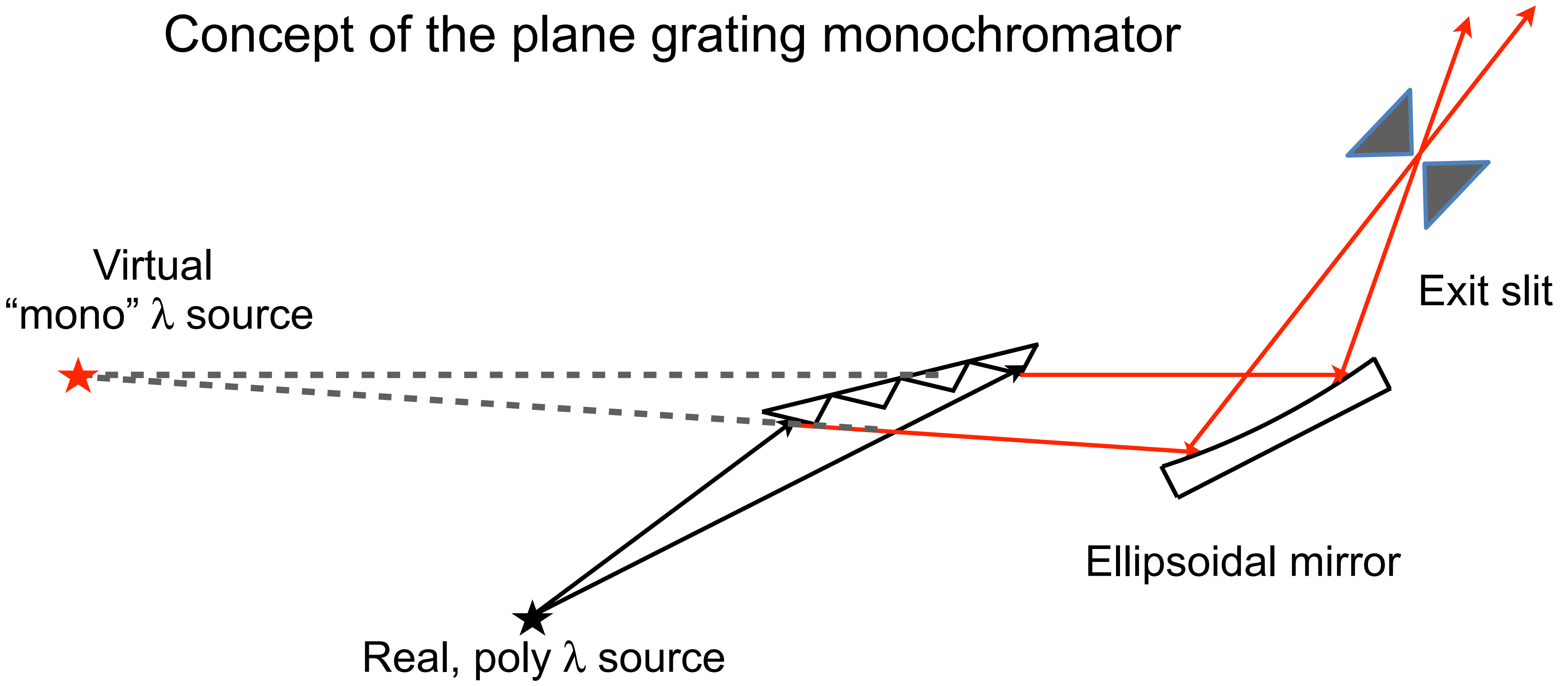
Easy to fabricate
Easy to align

Beam position not maintained if θ changes
Limited angular range



Plane grating monochromator

Concept of the plane grating monochromator



H. Petersen. O. Communication, vol. 40, no. 6. 1982, pp. 402–406.

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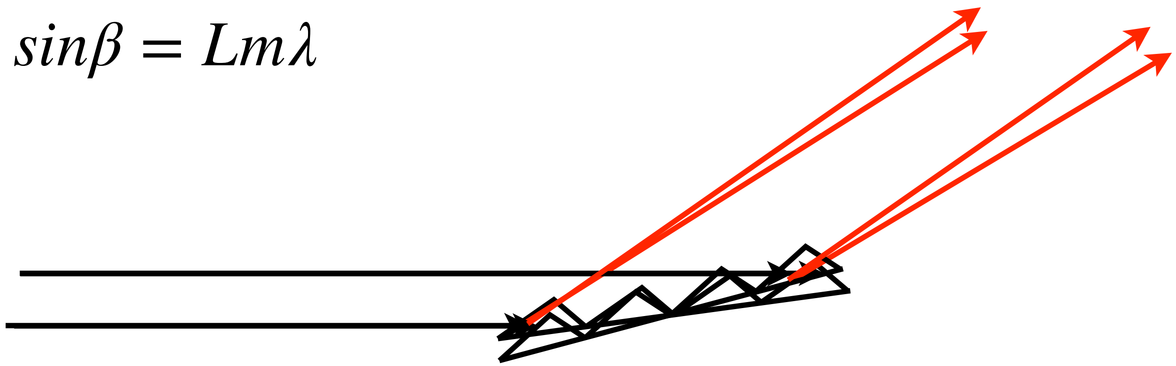
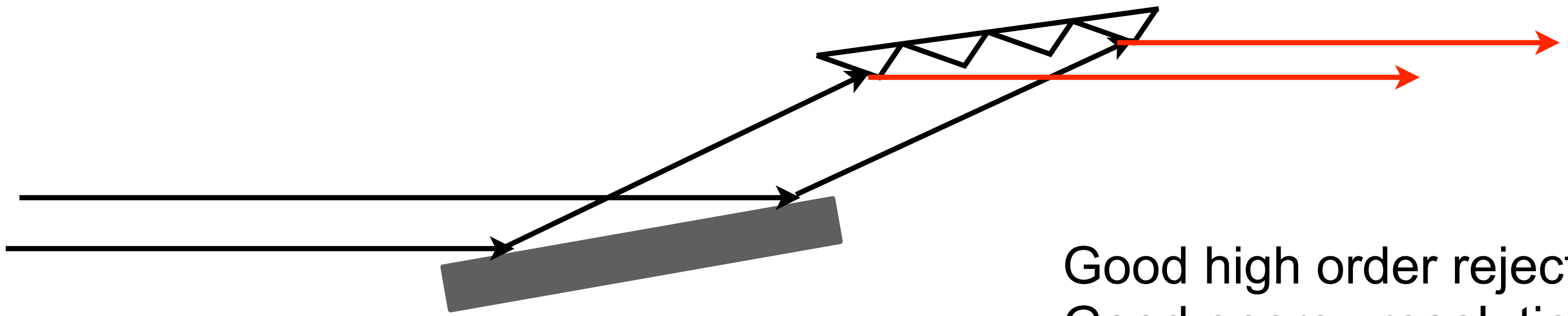
Plane grating monochromator

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





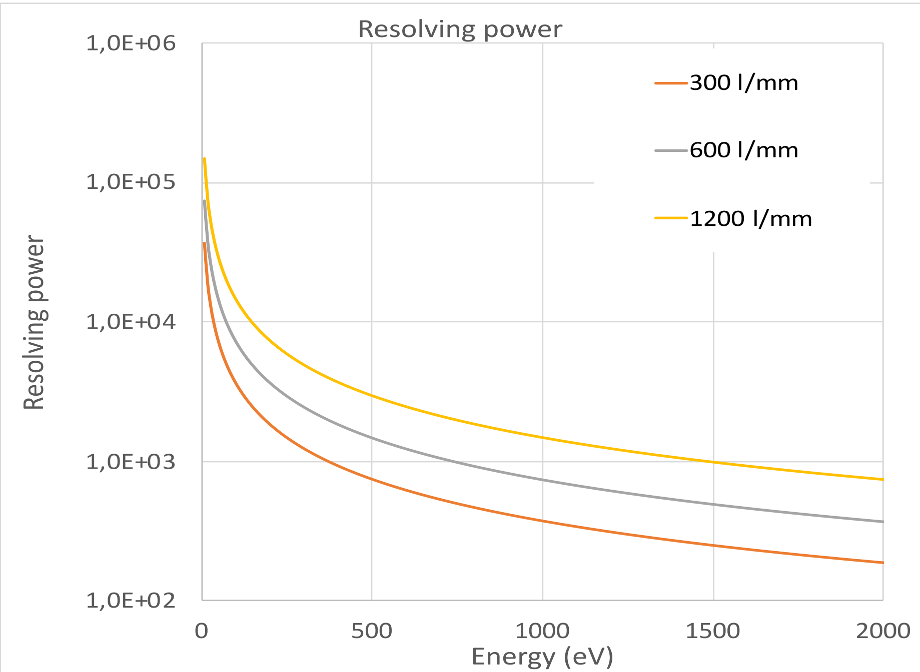
Plane pre-mirror

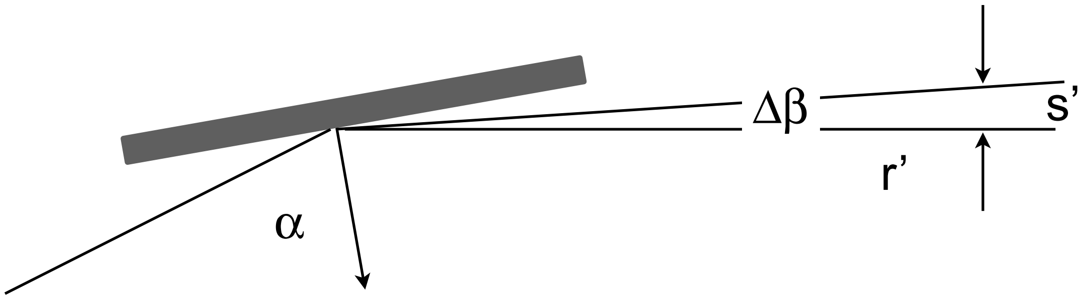
Good high order rejection
Good energy resolution
Fixed exit slit

Grating resolving power

Angular dispersion of a grating with line density L: $\Delta\lambda = \dfrac{\cos\beta}{Lm}\Delta\beta$

Resolving power R: $R = \dfrac{E}{\Delta E} = \dfrac{\lambda}{\Delta\lambda} = \dfrac{\lambda L m r'}{s'\cos\beta}$





If R=1000, @ 100eV:

$\Delta E = 100meV$

… finally a couple of examples

TwinMic Beamline @ Elettra

Elettra Sincrotrone Trieste

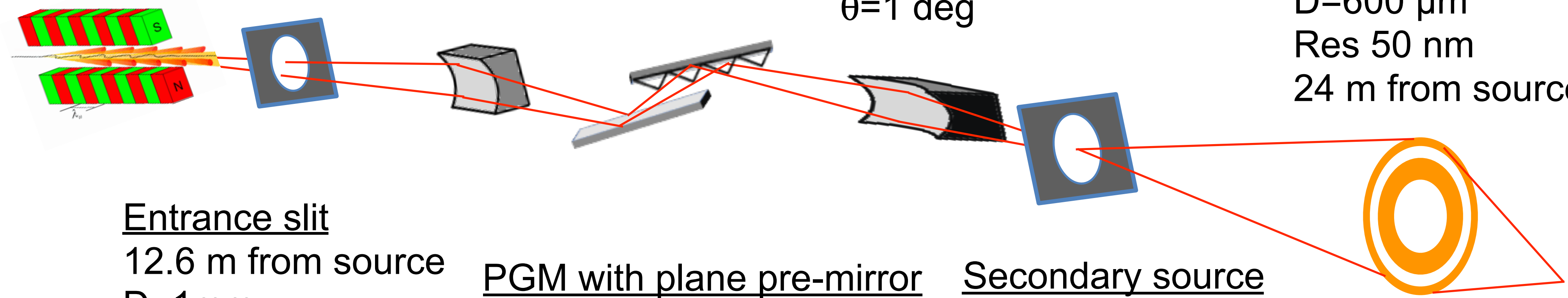
Photon energy: 400eV to 2 keV
X-ray microscopy and microFluorescence

Undulator source
N=17
Period=56mm
Min gap: 25 mm

Cylindrical mirror
16 m from source
Au coated
ρ=0.56m
θ=1 deg

Toroidal mirror
20 m from source
Au Coated
R=211m
ρ=0.07m
θ=1 deg

Zone Plate
D=600 μm
Res 50 nm
24 m from source



Entrance slit
12.6 m from source
D=1mm

PGM with plane pre-mirror
18 m from source
Blazed grating, θ_b=1.1 deg
Au coated
L= 600 l/mm

Secondary source
22 m from source
5-100μm diameter

Experiment
~ 24.5 m from source
Focal spot dia:
100 nm to 1.5 μm

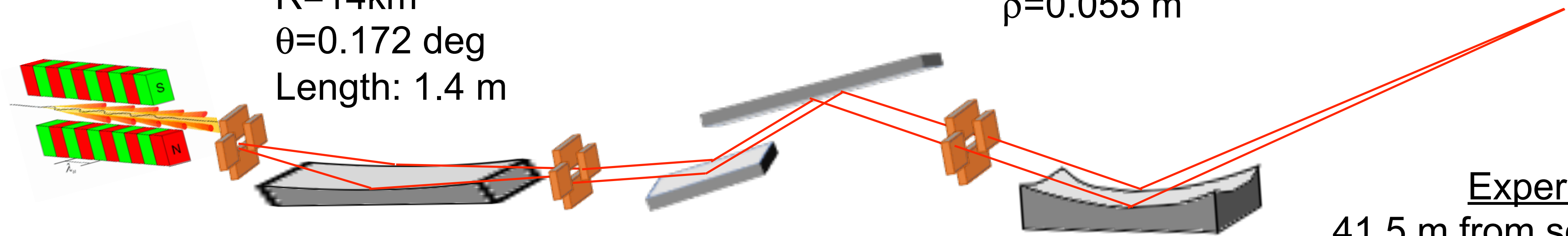
Diffraction Beamline @ Elettra

Elettra Sincrotrone Trieste

Photon energy: 4 to 21 keV

Cylindrical mirror for vertical collimation
22 m from source
Pt Coated
R=14km
θ=0.172 deg
Length: 1.4 m

Toroidal focussing mirror
28 m from source
Sagittally cylindrical, bendable
R=9km (5km to ∞)
ρ=0.055 m



Multi-pole wiggler
N=54, 1.5T mag field
Period=140mm
Critical Energy: 5.8keV @ 2.4GeV
5kW total power @ 140 mA

Double crystal mono
24 m from source
Si(111), ω_s=25 μrad @ 8keV

Experiment
41.5 m from source
Focal spot:
0.7 x 0.2 mm^2
$\Delta E/E$~4000

Thank you!