S^{3}EPB

SLAC Summer Seminar on Electron and Photon Beams

Photon Beamlines

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August 6th, 2015

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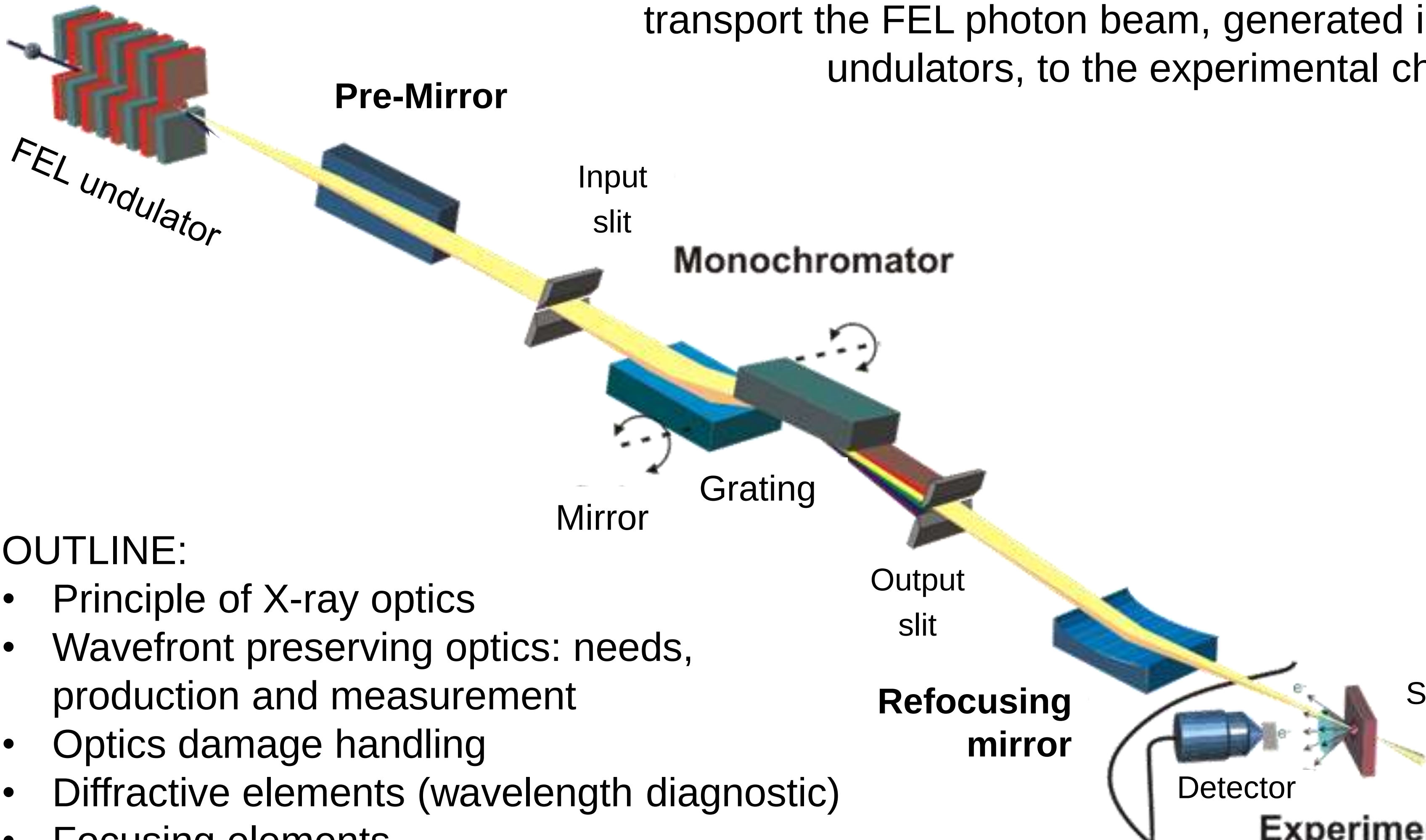
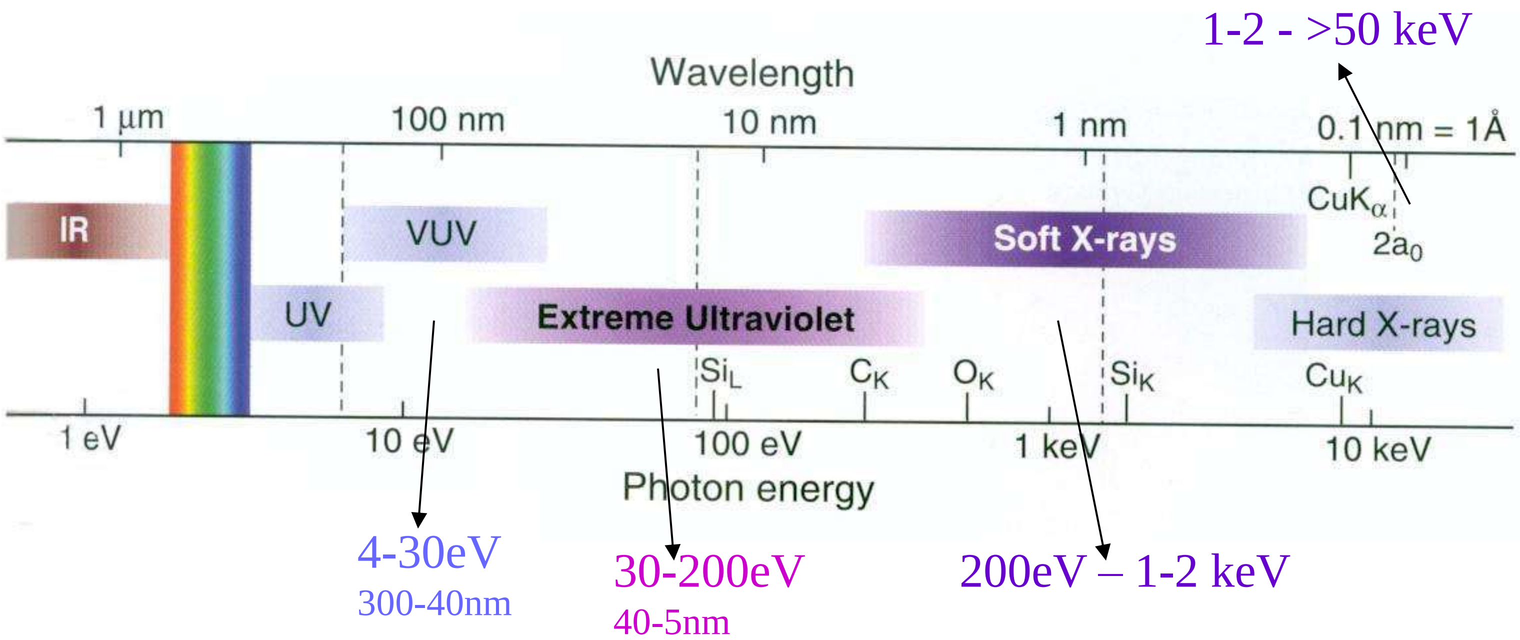
A *photon beamline* is everything necessary to transport the FEL photon beam, generated into the undulators, to the experimental chamber



OUTLINE:

- Principle of X-ray optics
- Wavefront preserving optics: needs, production and measurement
- Optics damage handling
- Diffractive elements (wavelength diagnostic)
- Focusing elements

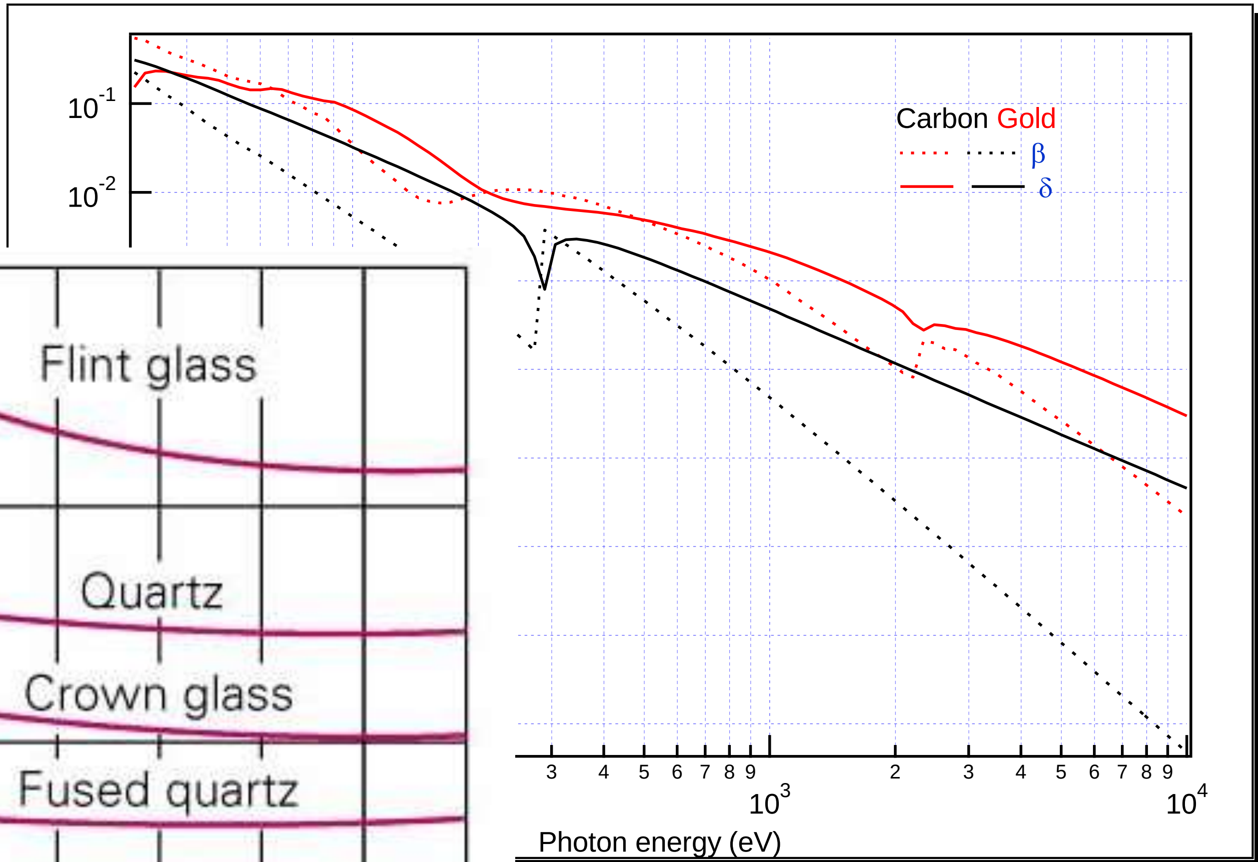
Photon energy regions

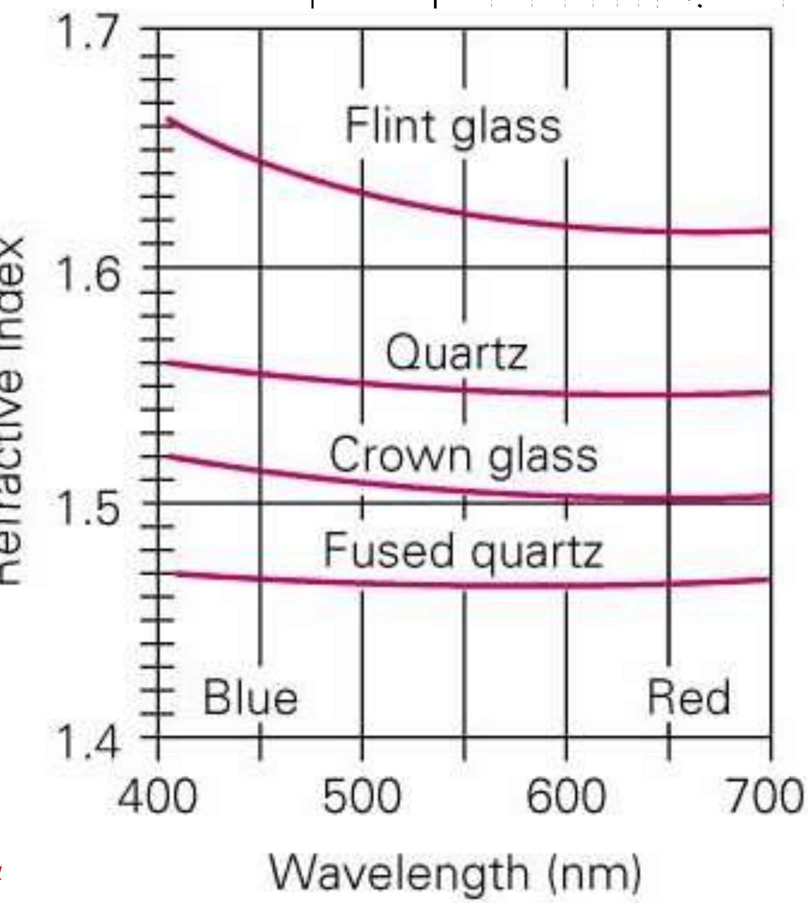


SXR: These regions are very interesting because are characterized by the presence of the absorption edges of most low and intermediate Z elements; photons with these energies are **a very sensitive tool** for elemental and chemical identification. PROBLEM: Absorption edges are bad things for photon transport

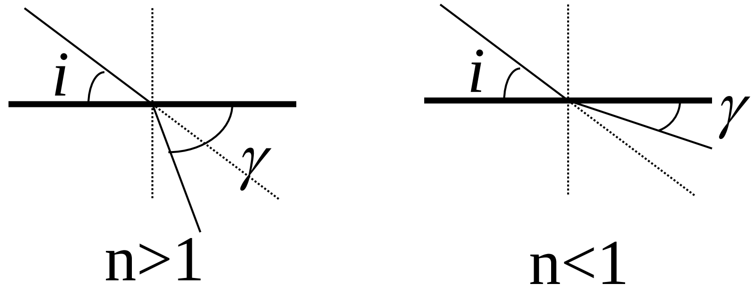
HXR: This region provide highly penetrating radiations, it is useful to study bulk rather than surface. The short wavelength make possible high spatial resolution microscopy or diffraction techniques. PROBLEM: penetration is not good for reflective optics.

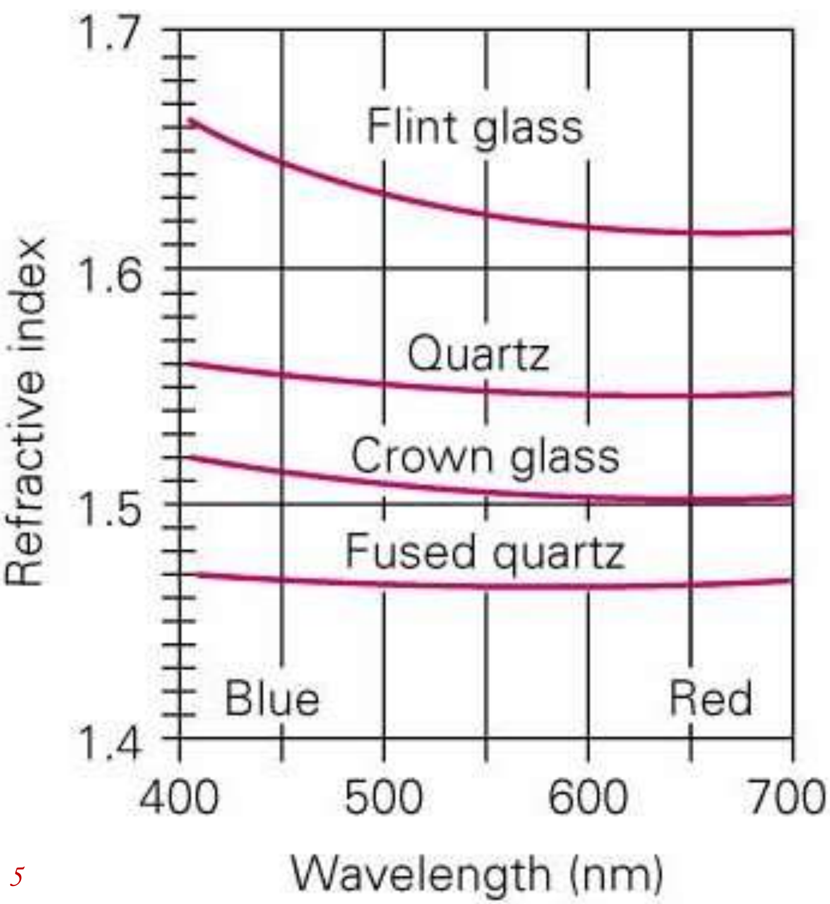
refractive index $\mu = 1 - \delta - i\beta$



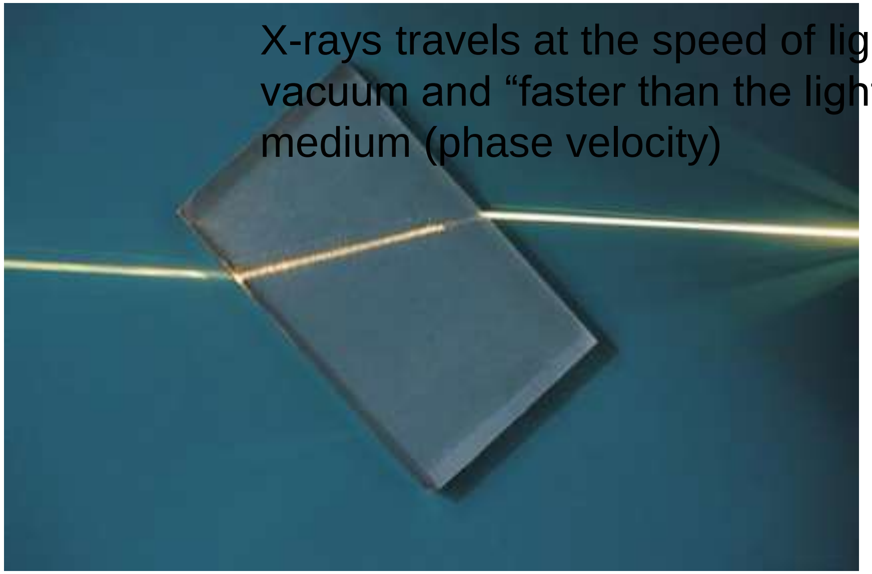


inear absorption coefficient



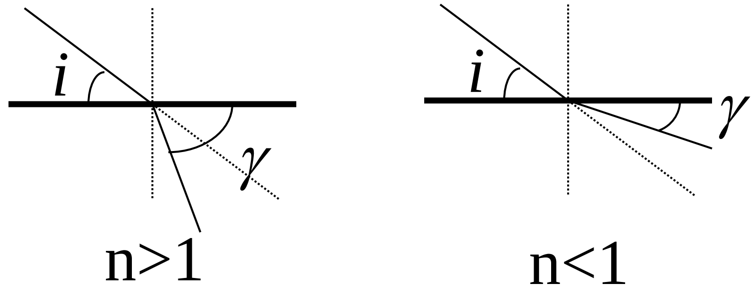


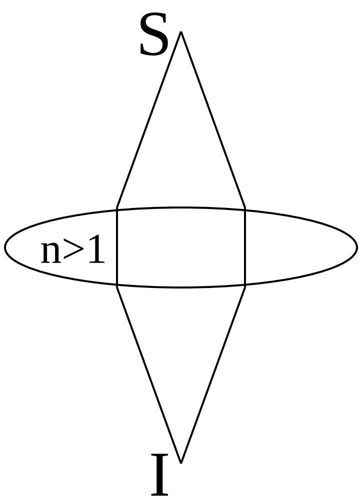
Snell's law: $n_1 \cos\gamma = n_2 \cos i$

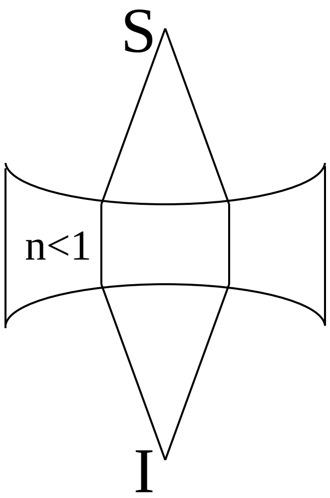


X-rays travels at the speed of light in vacuum and "faster than the light" in a medium (phase velocity)

Fermat's principle
The Light travels the path from A to B in the minimum possible time (valid for every wavelength)





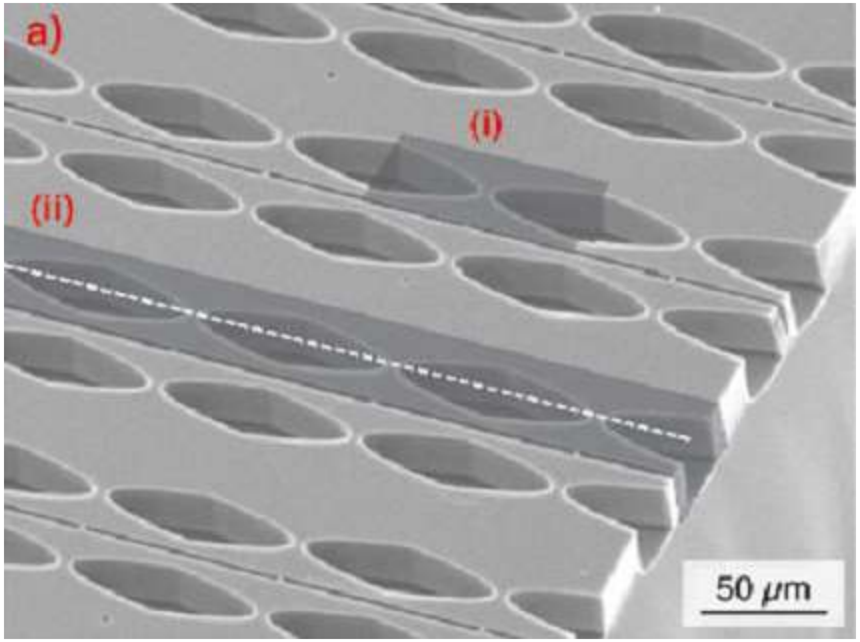


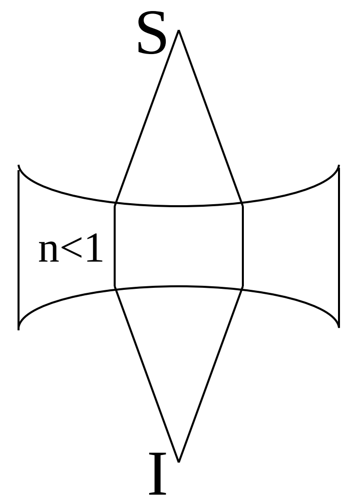
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \approx (1-\delta-1)\cdot\frac{2}{R} < 0$$

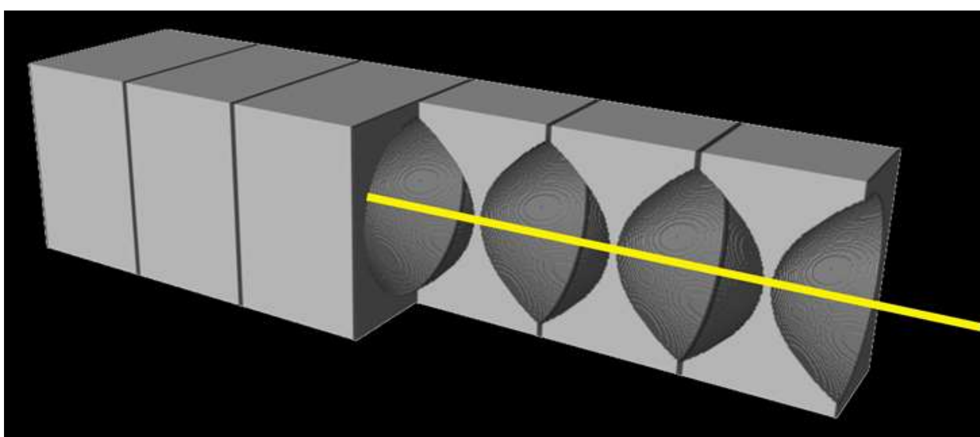
$$\delta = \frac{Ne^2\lambda^2}{2\pi mc^2} \approx 10^{-2} - 10^{-4}$$

$$\delta \approx 10^{-4} \quad HXR \Rightarrow f \approx 1m \quad if \quad R \approx 1mm$$

X-ray lens







$$if \quad R \approx 1mm$$

This could be, in principle, all you need

Total external reflection

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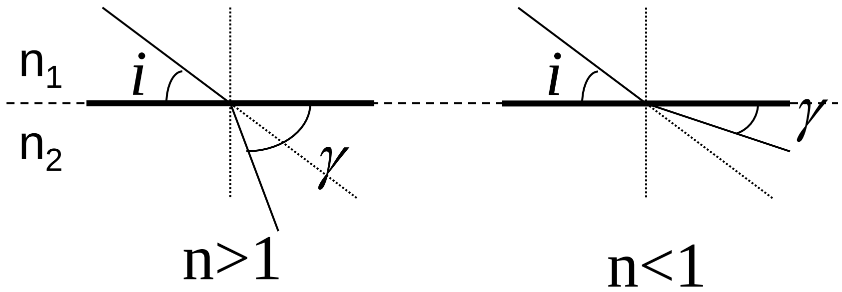
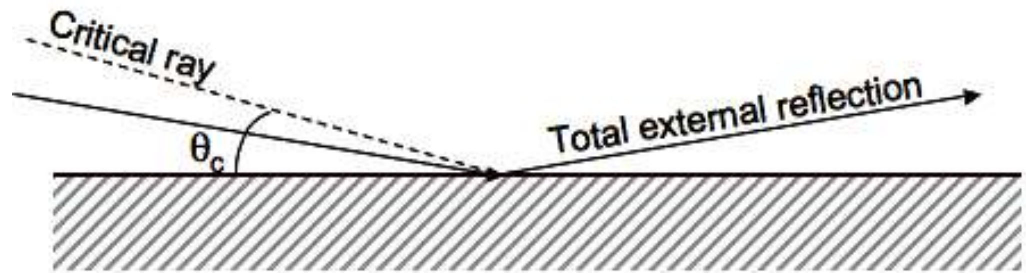




Snell's law: $n_1 \cos\gamma = n_2 \cos i$

Snell's law ($n_1=1$, vacuum):

$\cos\gamma = \cos i / n$

$\gamma = 0 \quad n = \cos i_c$

i_c critical angle: total external reflection

$$\sin i_c = \lambda (e^2 N / \pi m c^2)^{1/2}$$

$$\lambda_c(\mathrm{min}) = 3.333 \cdot 10^{-13}\, N^{-1/2} \sin i_c$$

Material	Density (g/cm^3)	N (electron/cm^3)	λ_{min} nm
Pentadecane (oil)	0.77	$7\text{x}10^{22}$	64.1sin$i$
Glass	2.6	$78\text{x}10^{22}$	37.9sin$i$
Aluminum oxide	3.9	$115\text{x}10^{22}$	31.2sin$i$
Gold	19.3	$466\text{x}10^{22}$	15.4sin$i$

$i=5^o$: λ_{min}glass=3.3nm=375 eV

λ_{min}gold=1.34nm=923eV

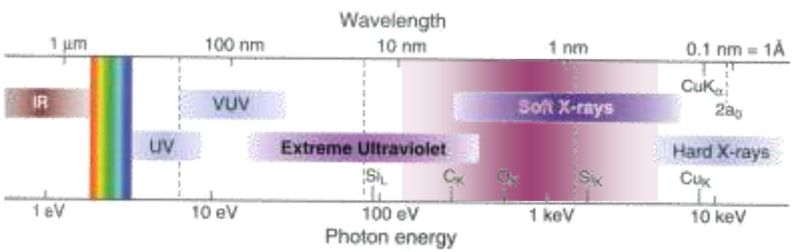
gold

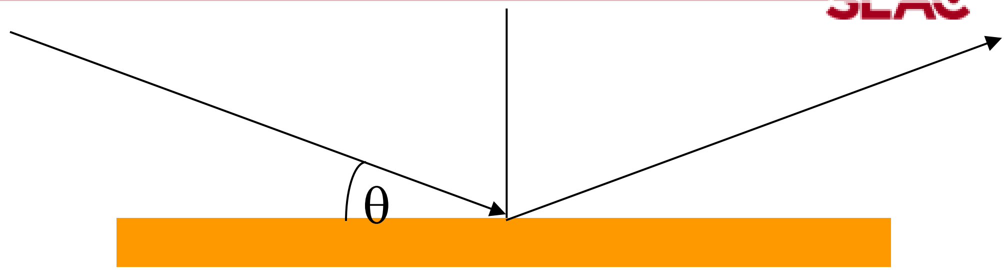
600 eV $\Rightarrow i_c \approx 7.4°$

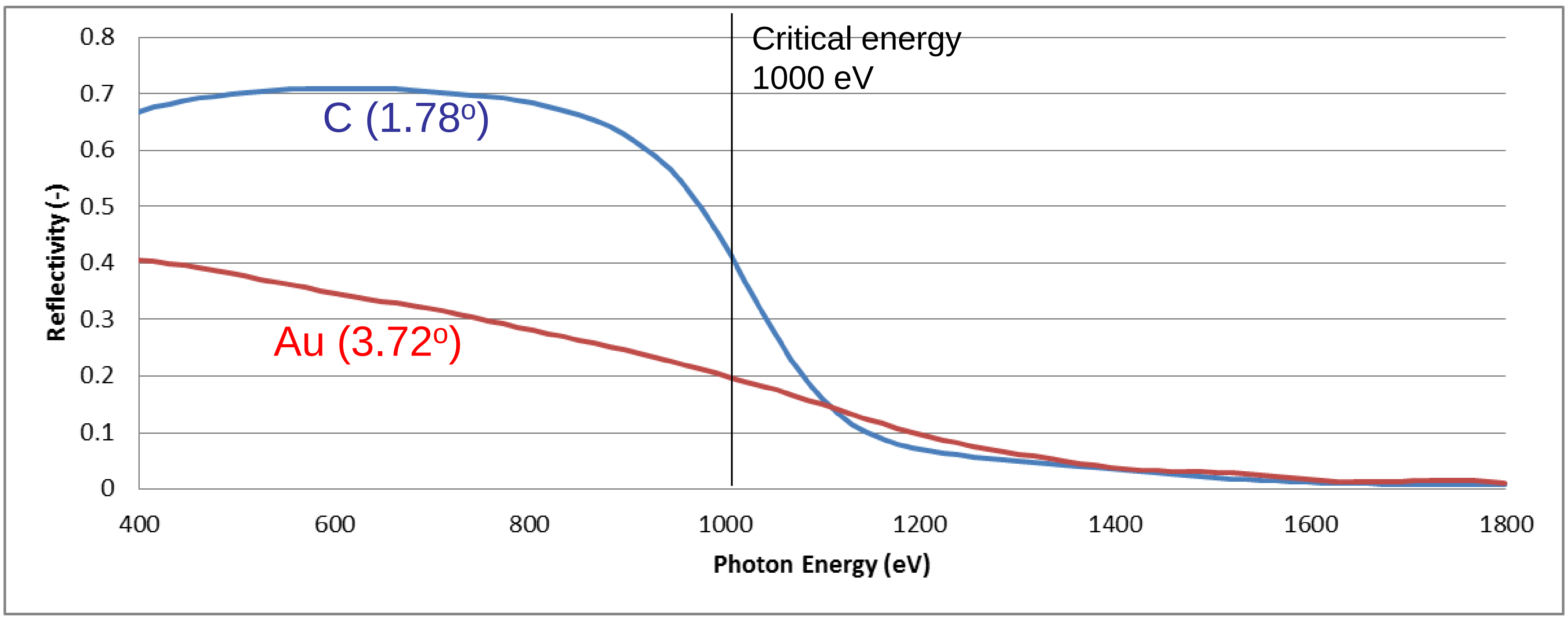
1200 eV $\Rightarrow i_c \approx 3.7°$

5 keV $\Rightarrow i_c \approx 0.9°$

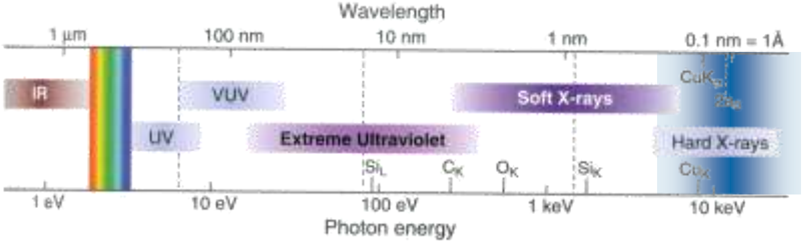
Mirror reflectivity and critical energy Soft X-ray

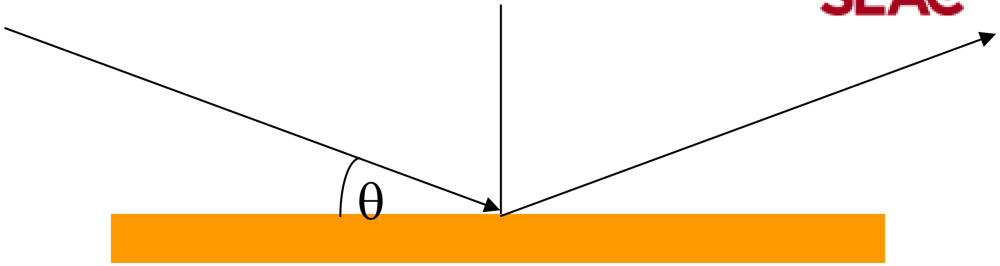


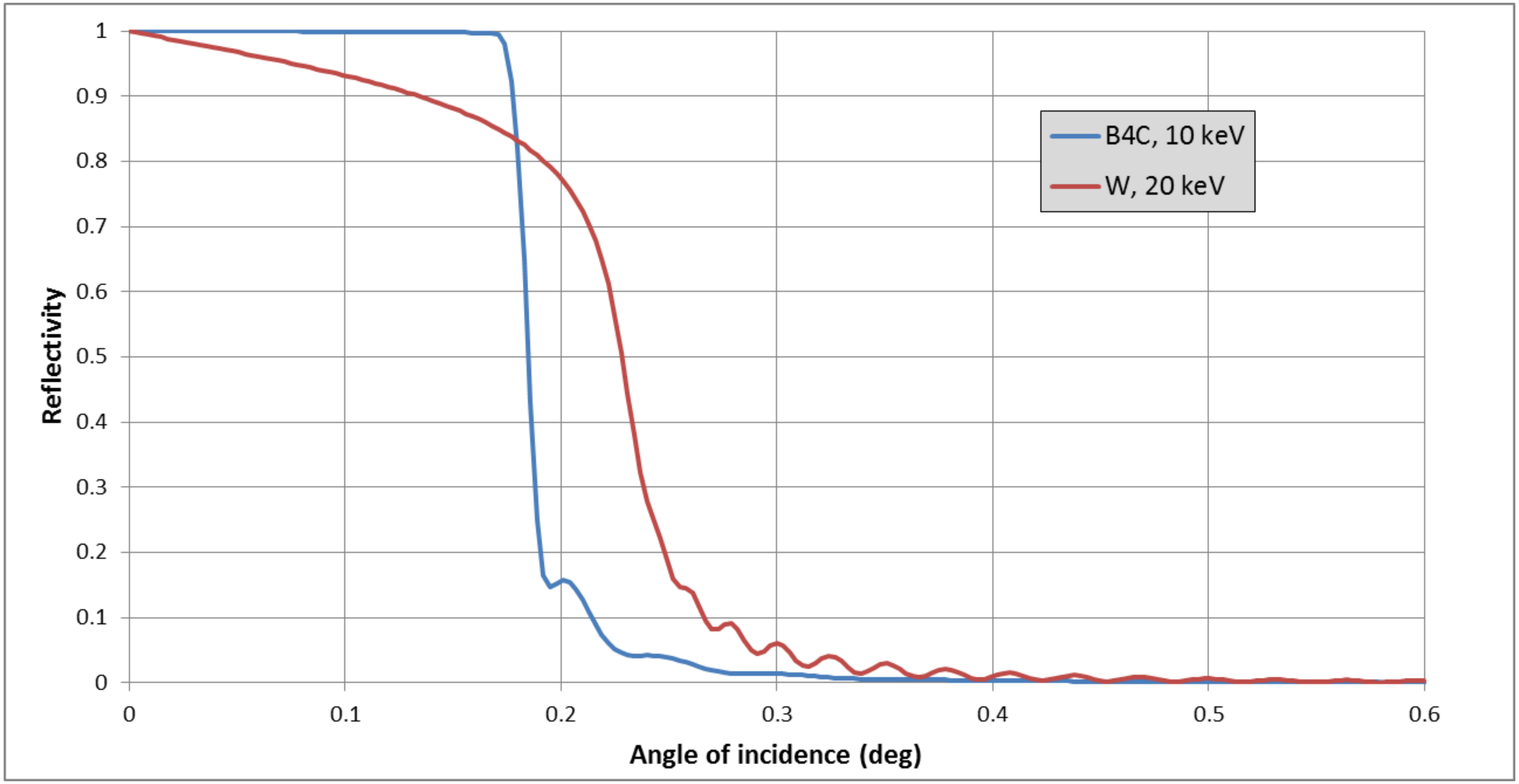




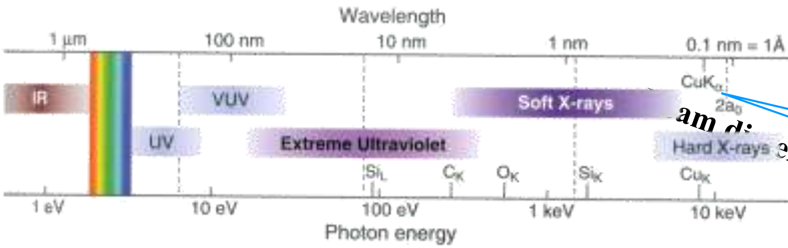
Mirror Reflectivity and critical angle (Hard X-ray)

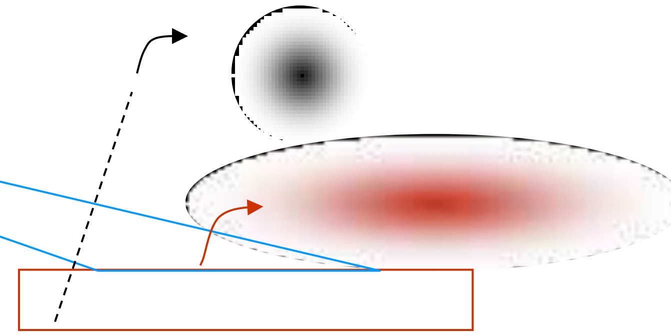


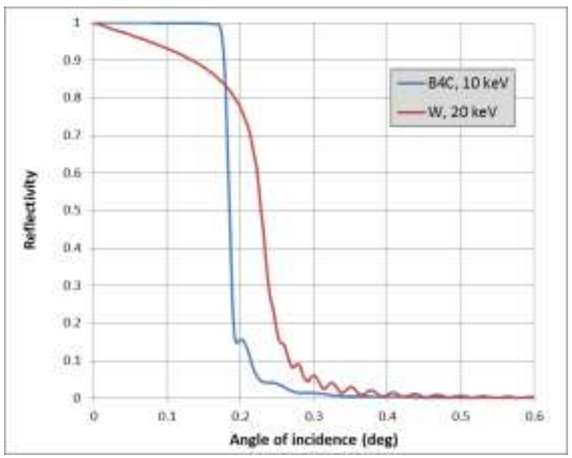




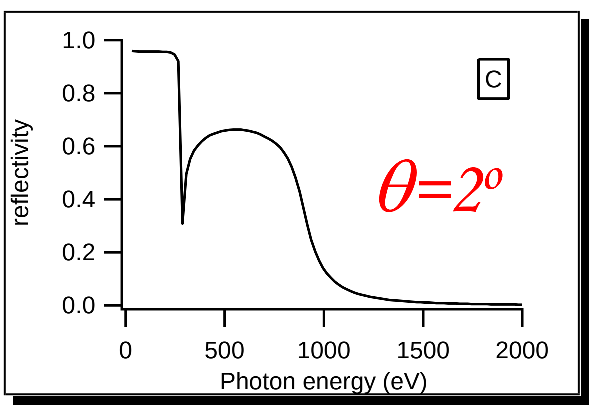
Mirror dimension



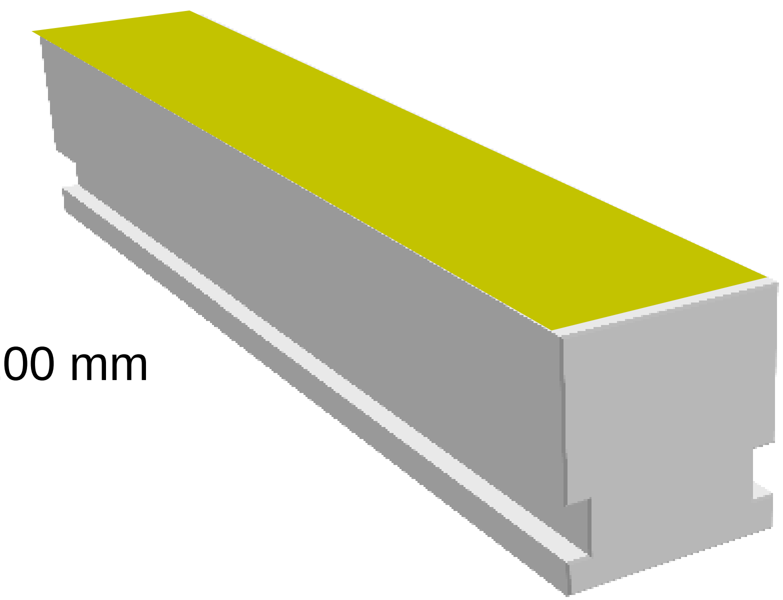




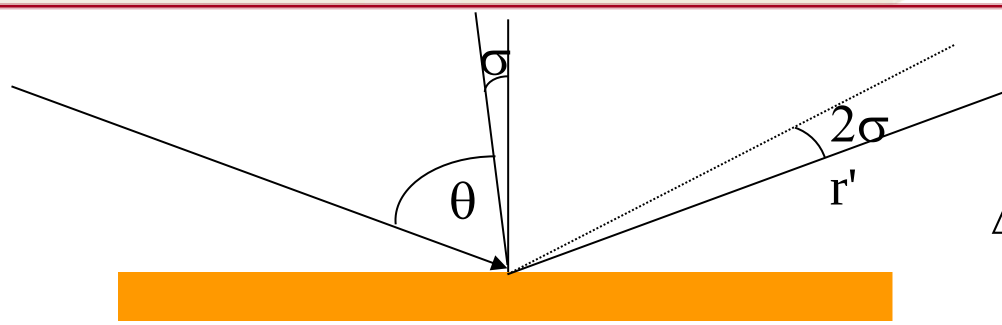
1 mm / sin(0.2º) > 1.5 m



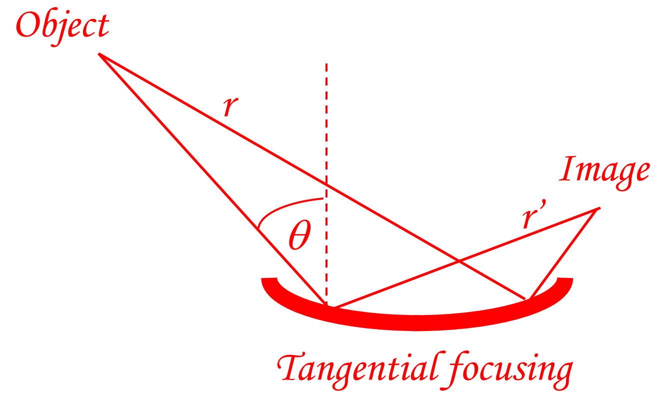
4-5 mm/sin(2º) < 200 mm

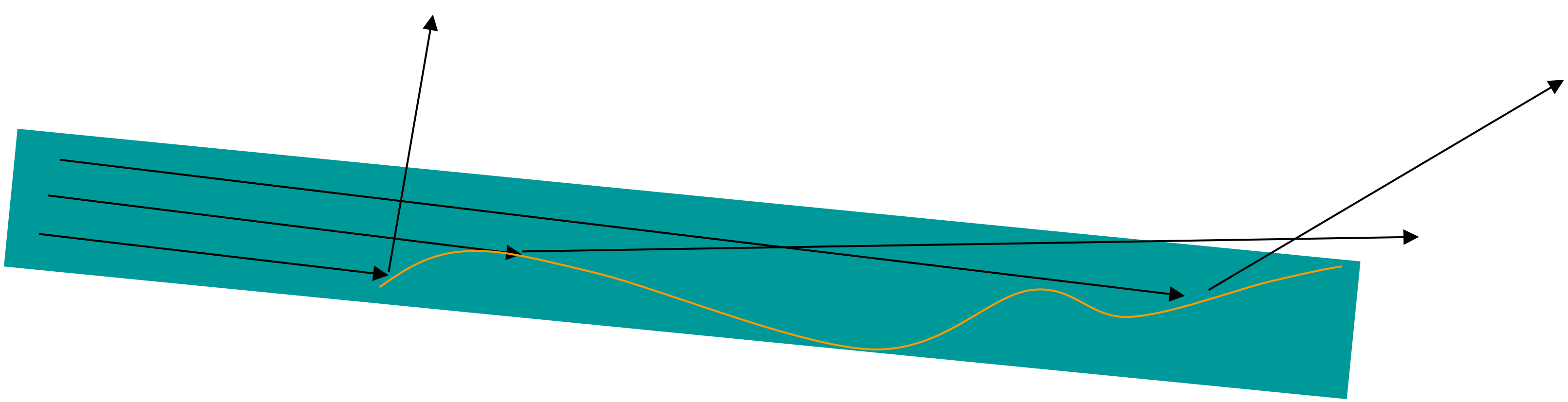


Defect effect

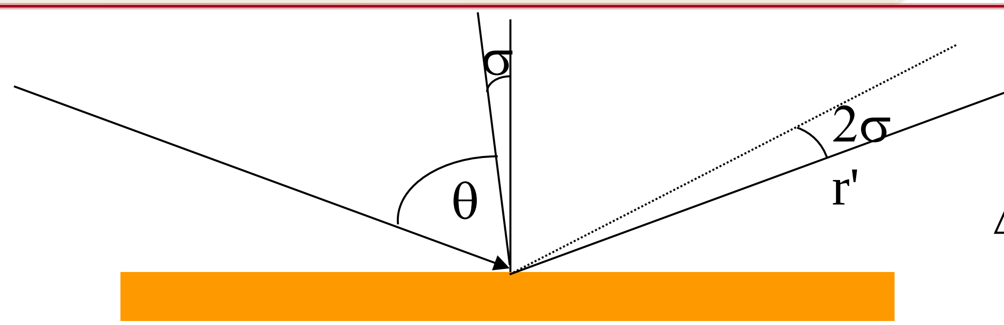


$\Delta s' = 2\, r' \sigma$

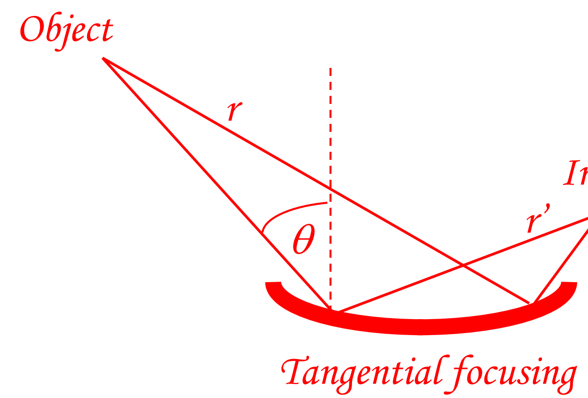




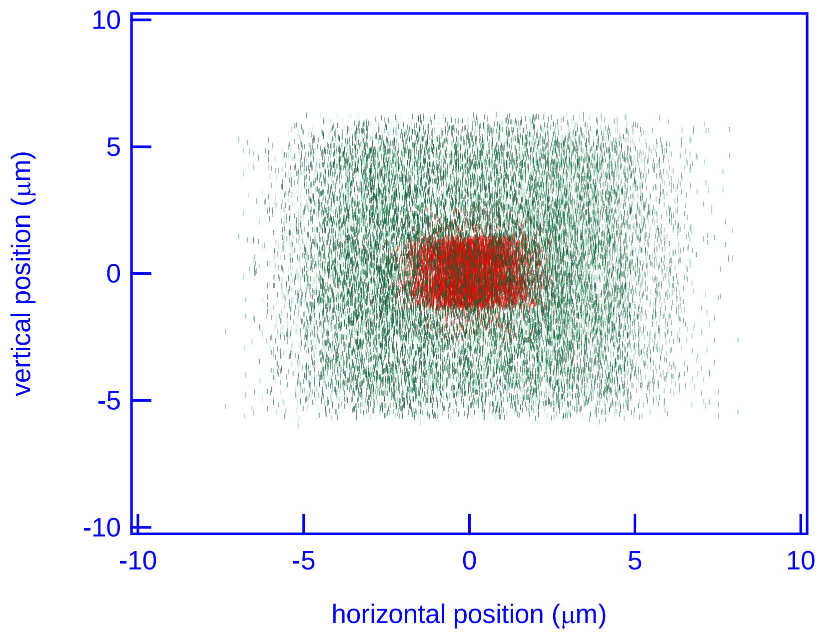
Defect effect



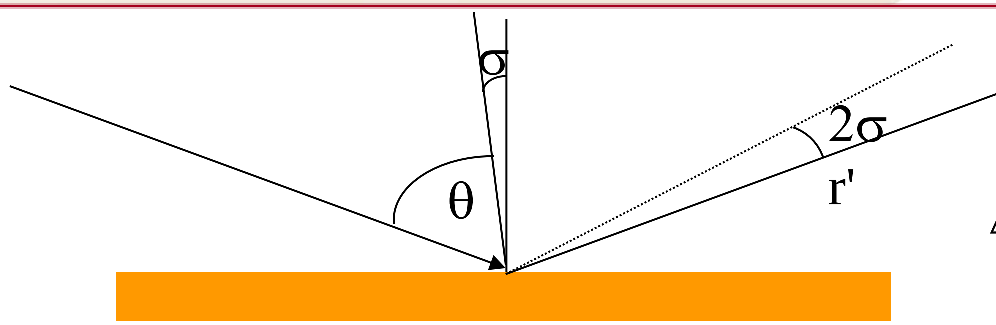
$\Delta s' = 2\, r'\sigma$



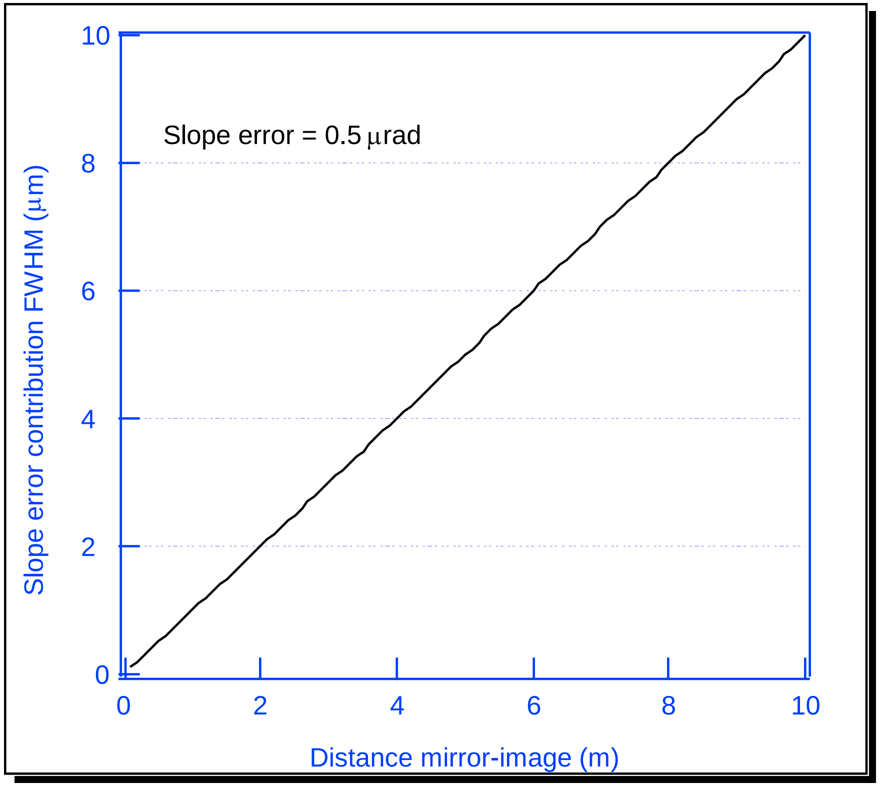
$s' = \overline{Ms + (2\, r'\sigma)^2}$

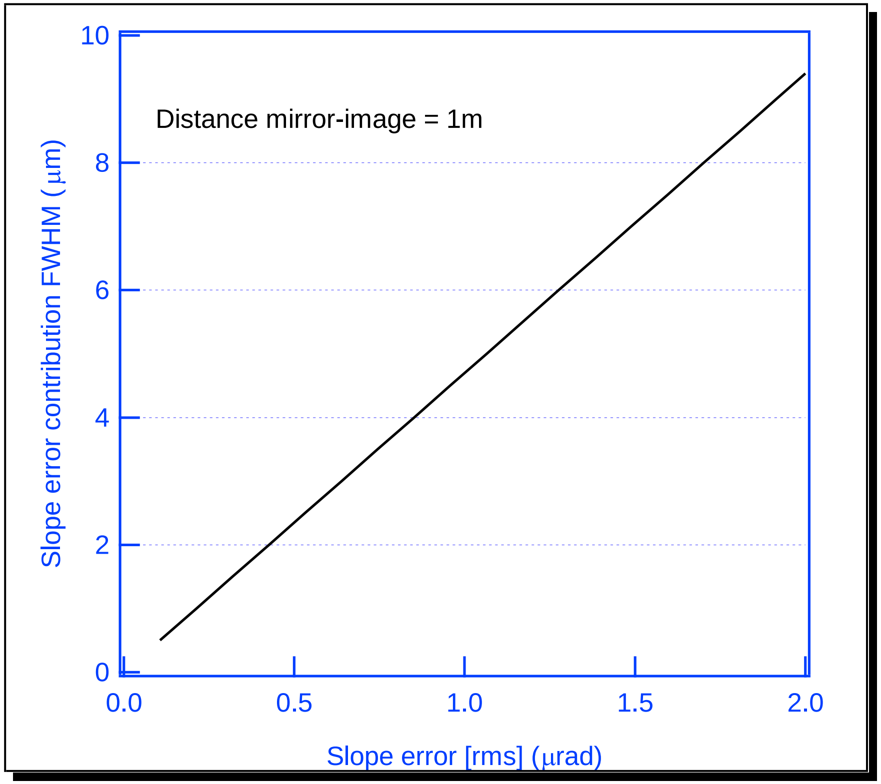


Defect effect (slide made on 2004)



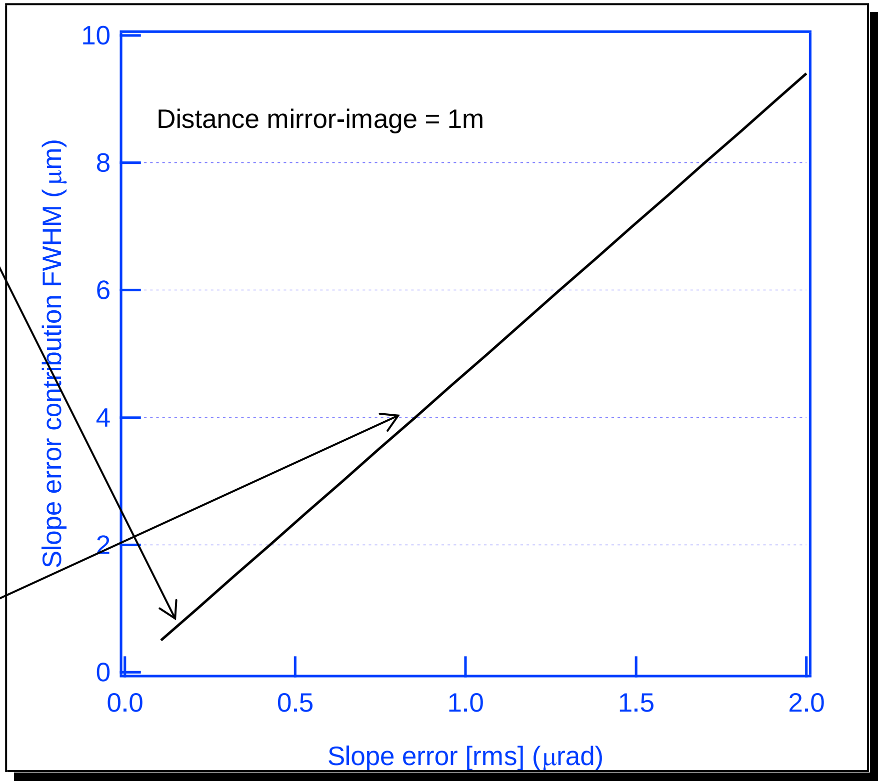
$\Delta s' = 2\, r'\sigma$



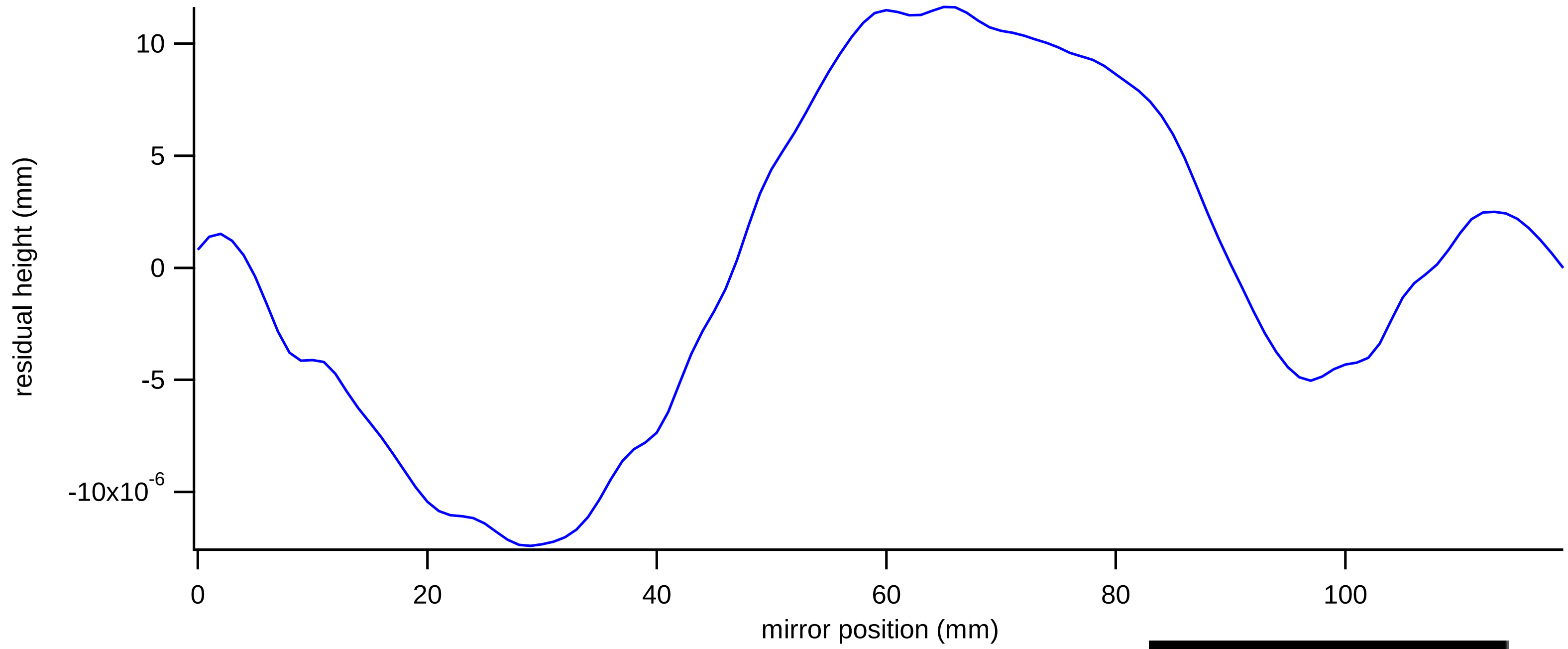


Typical manufacturer capabilities (SESO, ZEISS, Winlight, Insync)

Shape	Length	rms errors
Spherical/flat	Up to 500 mm	< 0.1 μrad
Spherical/flat	> 500 mm	< 0.5 μrad
Toroidal	Up to 500 mm	~ 1 μrad
Toroidal	> 500 mm	~ 2 μrad
Elliptical	Up to 500 mm	≥ 1-2 μrad
Elliptical	> 500 mm	> 2 μrad



State of the art SR manufacturer capabilities



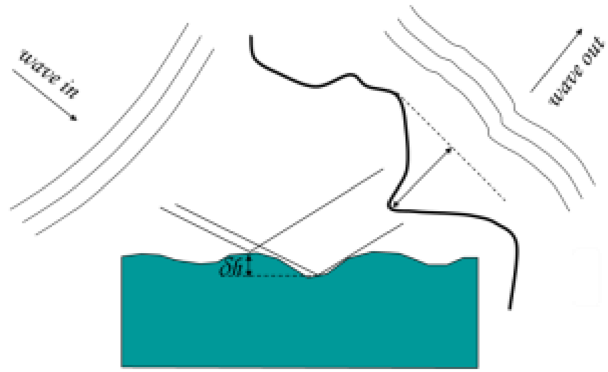
FEL mirrors (shape errors)

$$\text{Strehl Ratio} \approx e^{-(2\pi\varphi)^2} \approx 1-(2\pi\varphi)^2$$

The Strehl Ratio (SR) is defined as a ratio of the maximum intensity in the focus, with and without wave front distortions which are introduced by the optics

$$\varphi = \frac{2\delta h \sin\vartheta}{\lambda}$$

φ is the wave distortion (phase)



$$\delta h = \lambda \frac{\sqrt{1 - Strehl \quad Ratio}}{4\pi \sin\vartheta}$$

Maximum acceptable rms shape error for a given Strehl Ratio
SR ≥ 0.8 (according to the Marechal Criterion) is necessary to have “good” optical system

→ Angle of incidence dependent (larger angles need better shape errors)

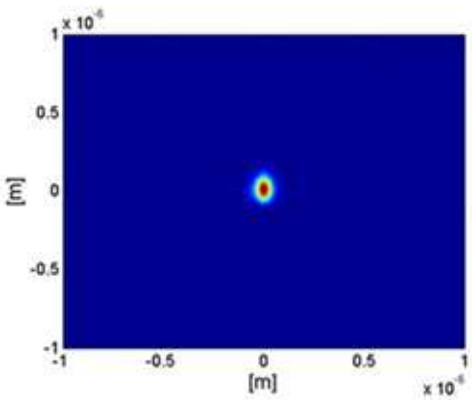
→ Wavelength depended (shorter wavelengths needs better shape errors)

→ This is the value we must “specify” for the mirrors

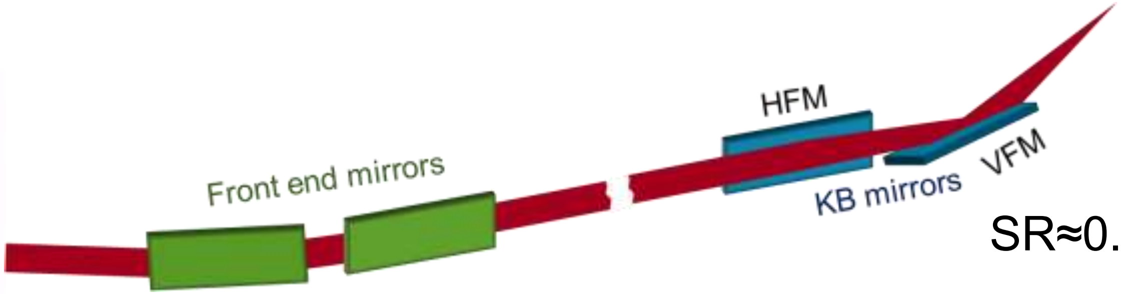
Angle of incidence (mrad/deg)	Photon Energy (KeV)	Shape error (nm)
3/0.17	5	2.1
	20	0.5
1.35/0.077	5	4.6
	20	1.1

The Marechal Criterion states that a good optical system has a SR ≥ 0.8; e.g.
In focus: the *Gaussian* spot intensity is ≥ 0.8 of the unperturbed *Gaussian* spot intensity

Simulations of 3 mirrors in one direction and 1 in the other for a global SR of 0.8



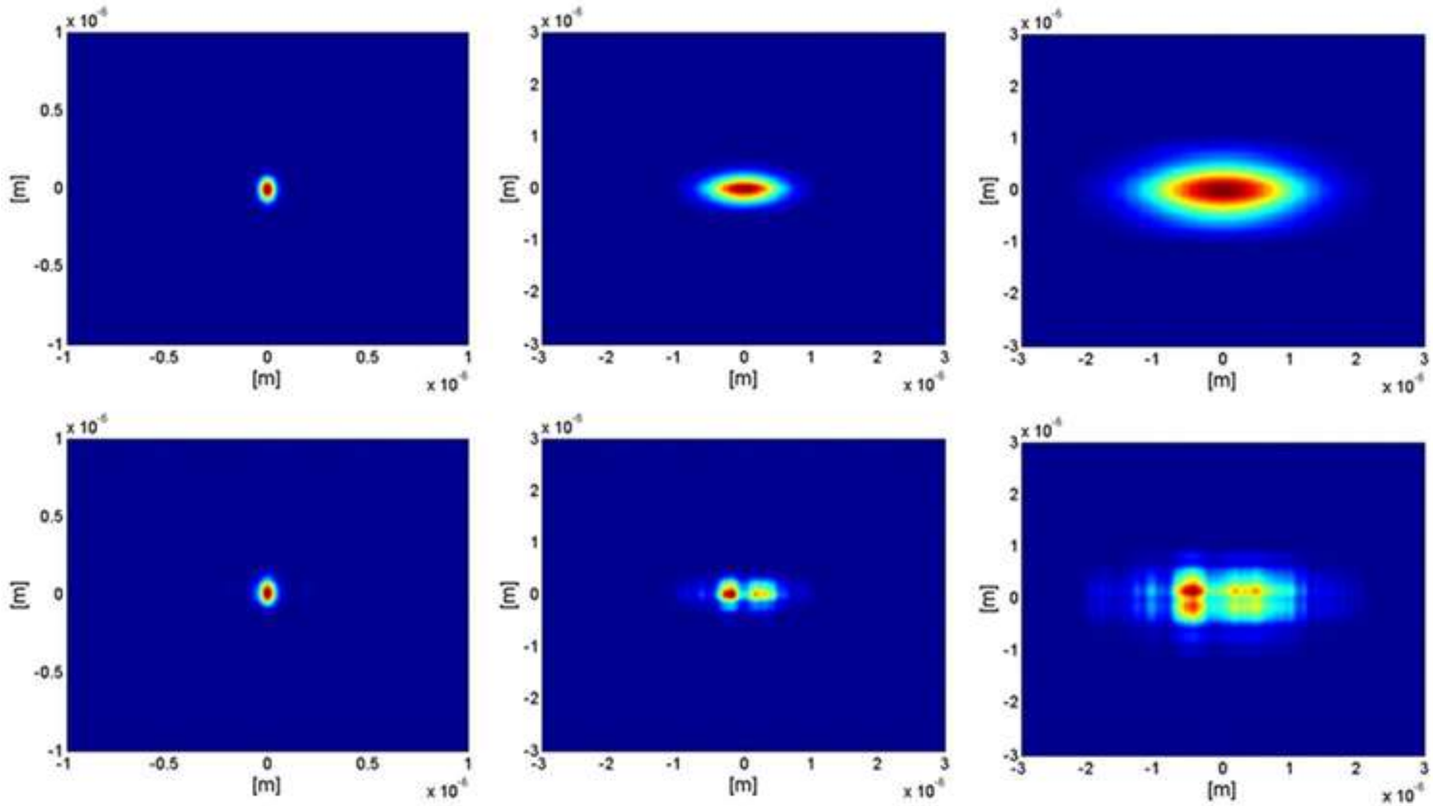
In focus



SR≈0.8

Simulations made by J. Krzywinski

We need better………..



SR≈0.97

SR≈0.8

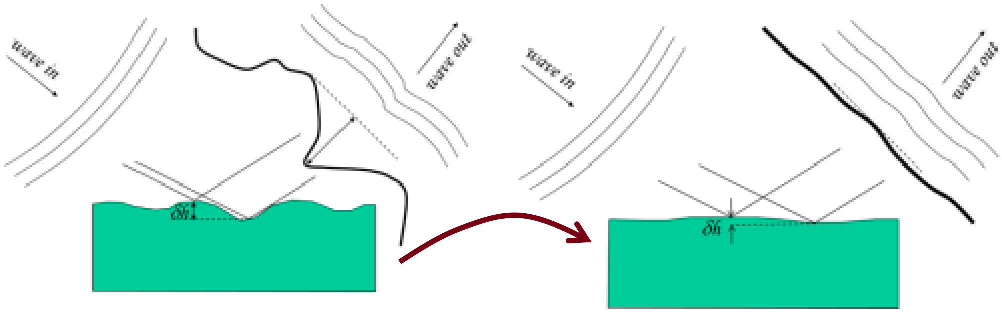
In focus

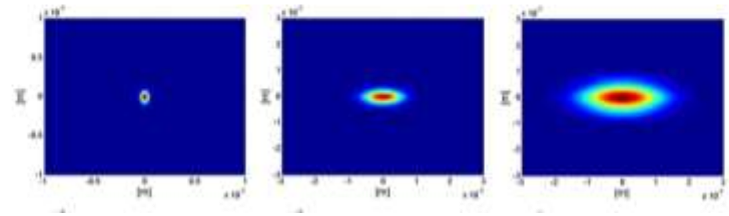
1 mm out of focus

2 mm out of focus

Simulations made by J. Krzywinski

How to compensate wavefront distortions

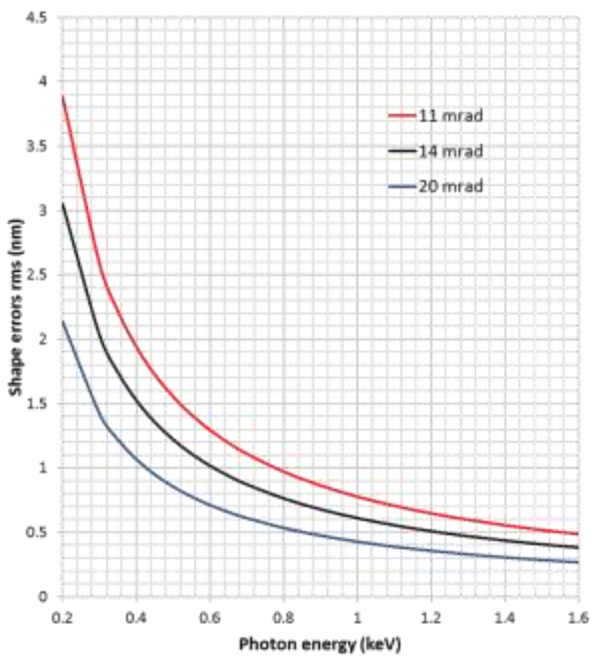


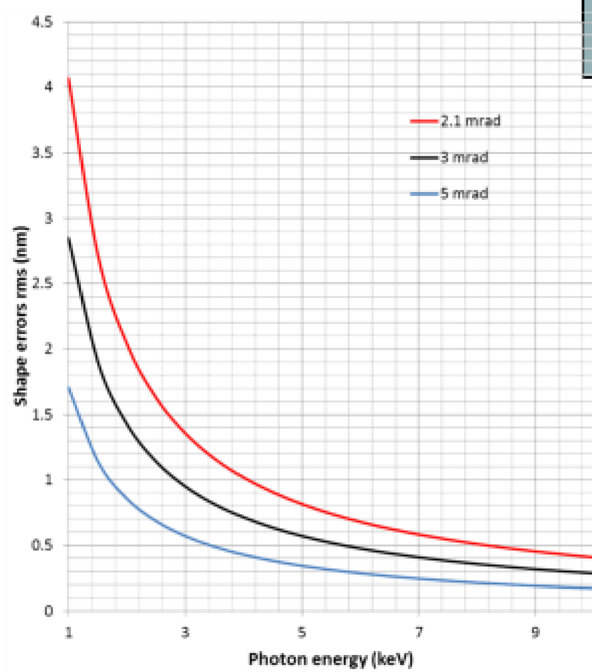


HXR; 1.35 mrad, 13 keV → **0.56 nm rms**

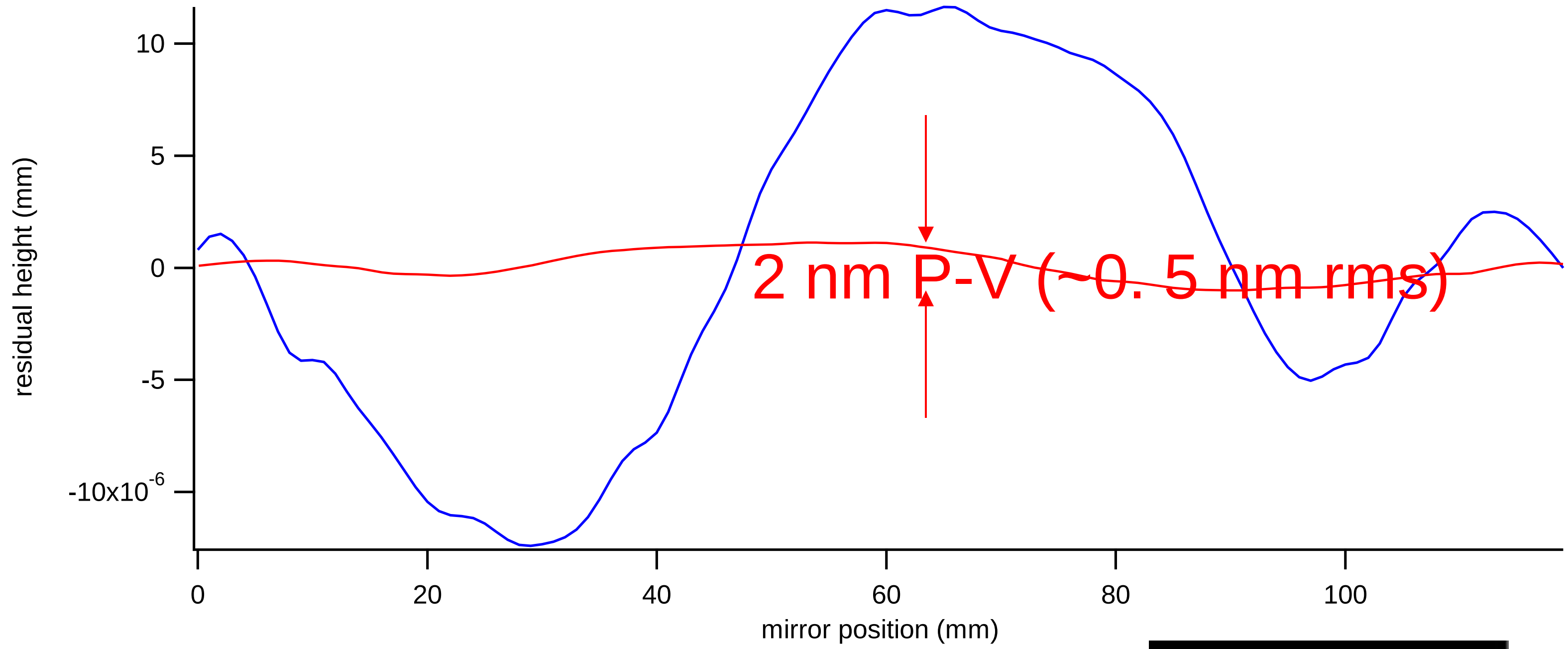
SXR; 12.0 mrad, 1.3 keV → **0.6 nm rms**

Angle of incidence (mrad/deg)	Photon Energy (KeV)	Shape error (nm)
1.35/0.077	5	4.6
	20	1.1
	13	1.78





Mirror shape errors FEL



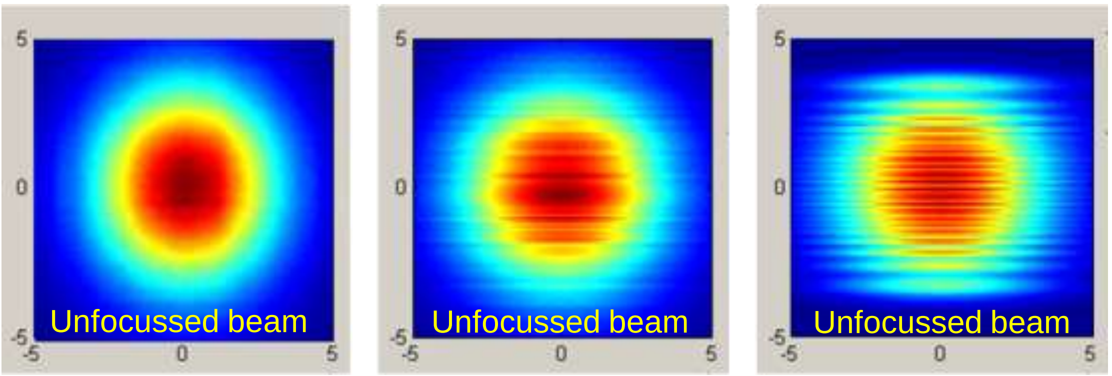
Typical SR mirrors

Required FEL mirrors

Wavefront Preservation – acceptance

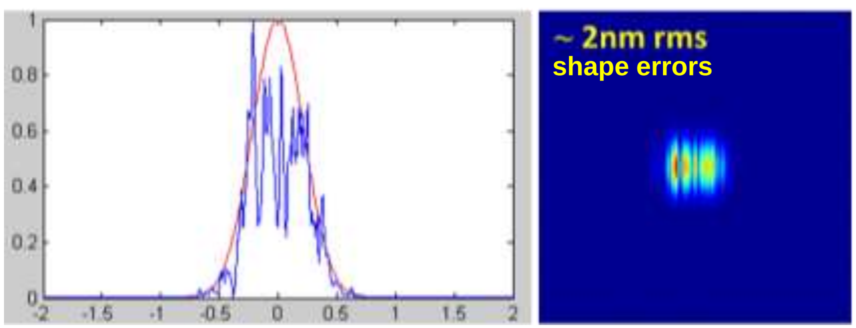
Affected by truncation (limited acceptance) and wavefront deformation (shape errors)

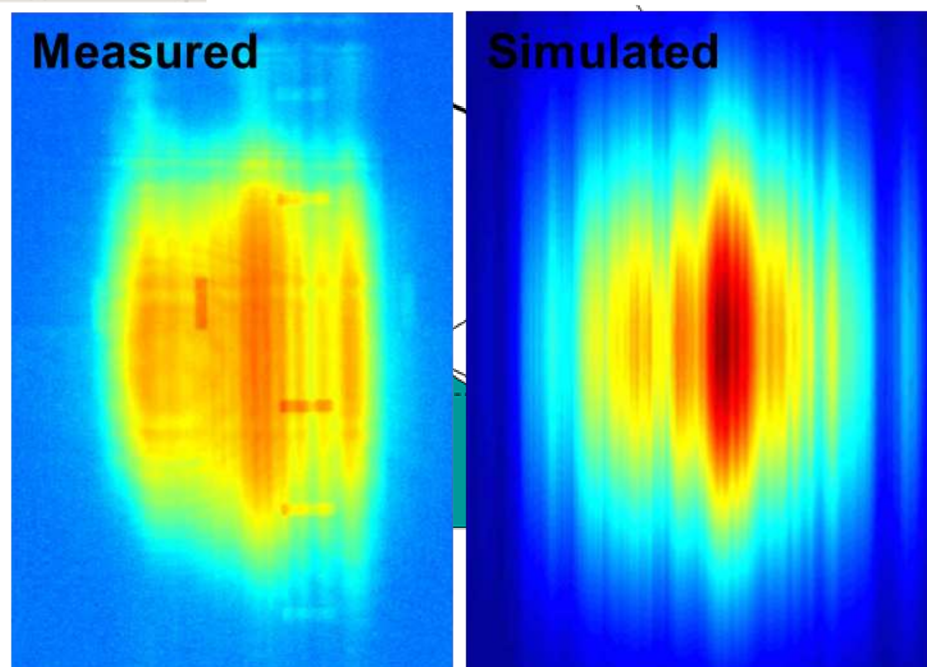
∞ acceptance | 2 FWHM accept. | 1 FWHM accept.



The LCLS mirrors were procured according to the state of the art availability e.g.
450 mm long mirrors with 2 nm rms shape error (compromise between shape and length)

Out of focus beam





LCLS is upgrading the mirrors with better figure and larger acceptance

State of the art evolution

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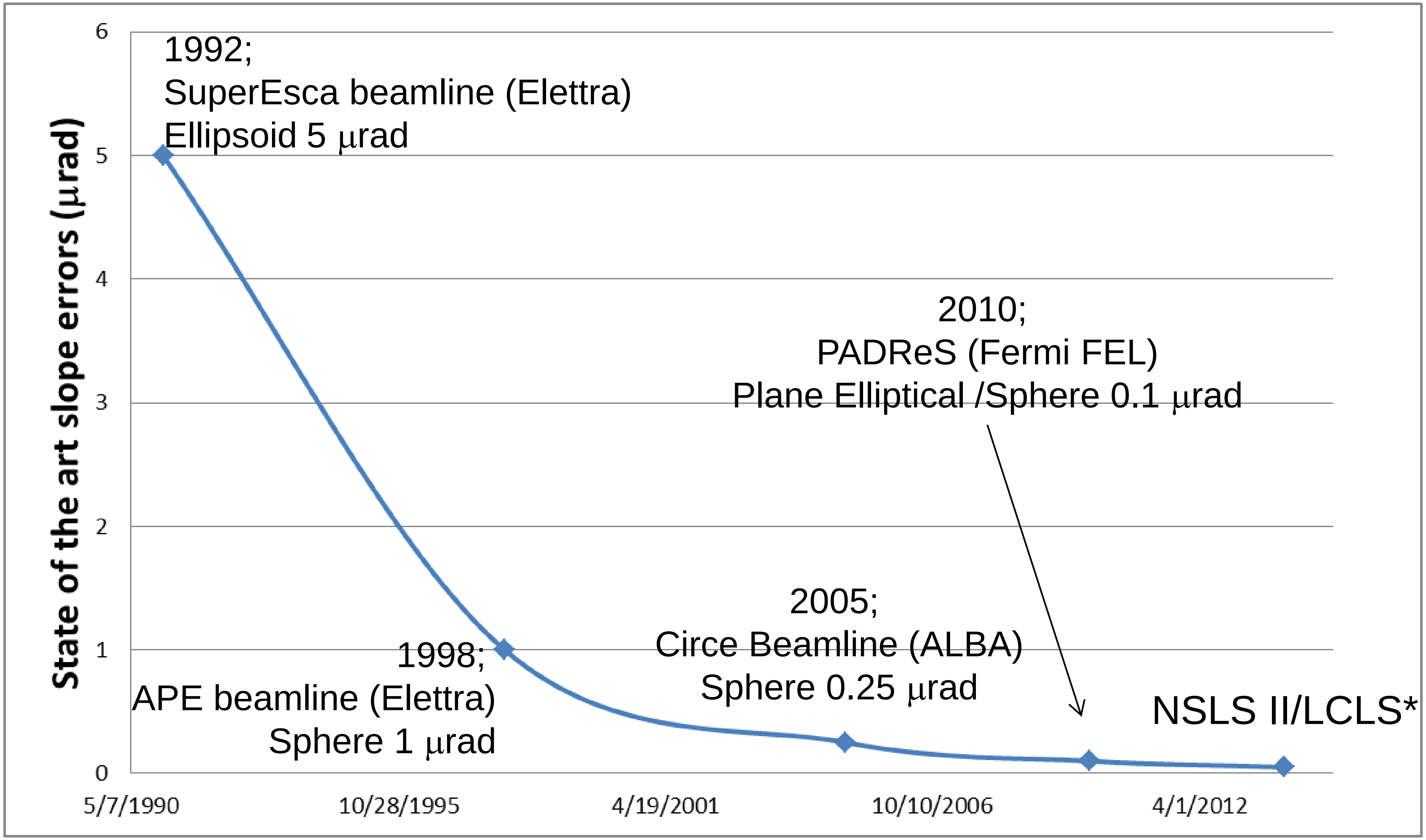
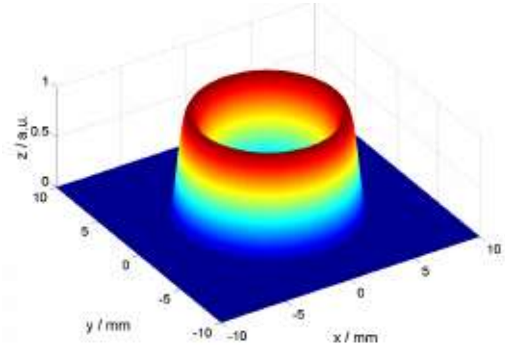
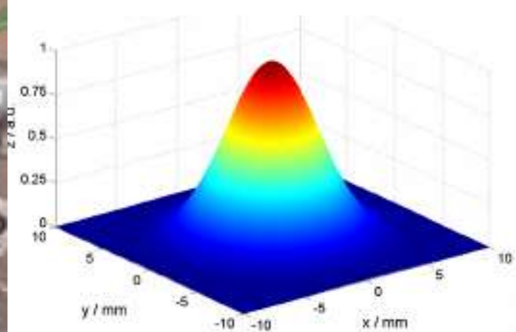


*LCLS mirrors are specified in height (nm rms).

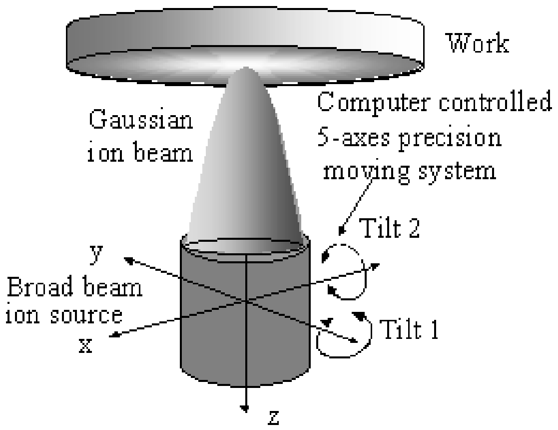
Polishing (CCP) effect

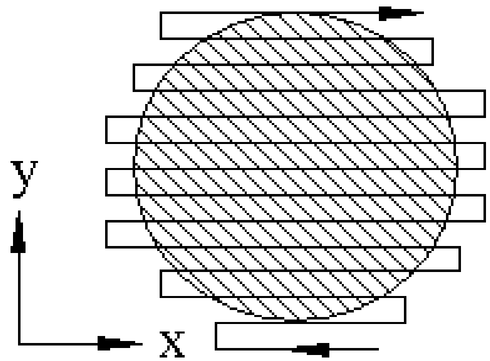


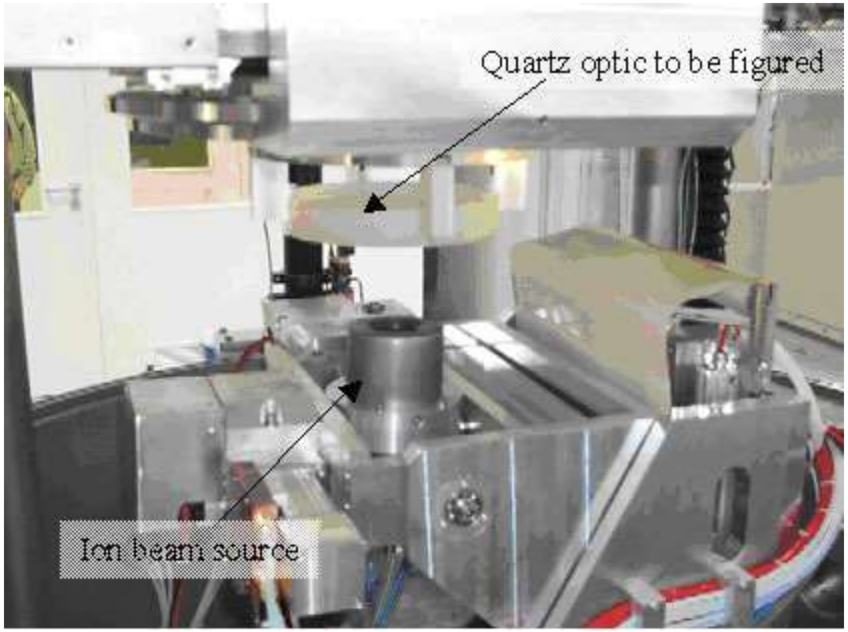


Estimated best quality:
2-3 nm rms; 0.5 μrad rms

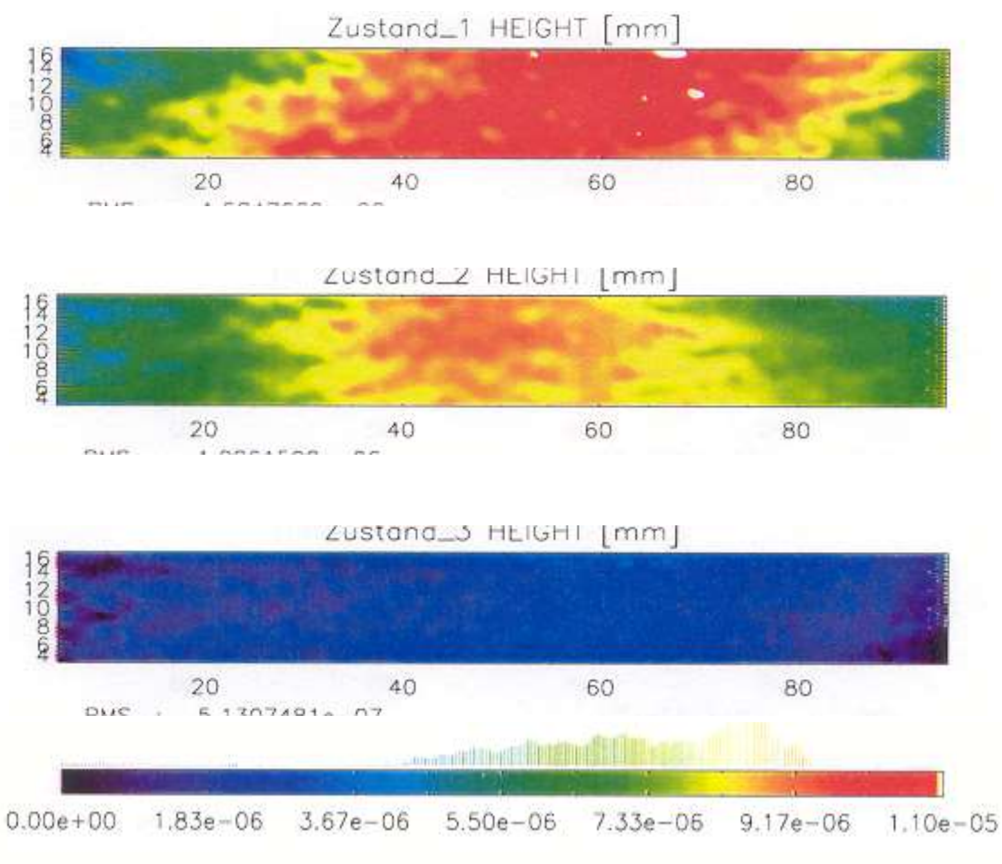
Ion beam finishing







Ion beam finishing



1. step

Height: 11.8 nm pv

2. step

Height: 5.1 nm pv

3. step

Height: 3.3 nm pv

Estimated best quality:
1 nm rms; 0.1 μrad rms

Preferential deposition technique

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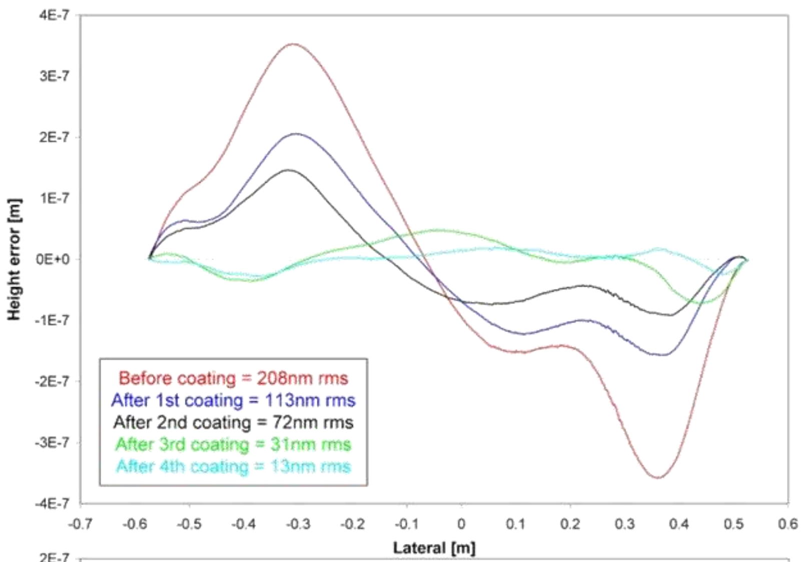
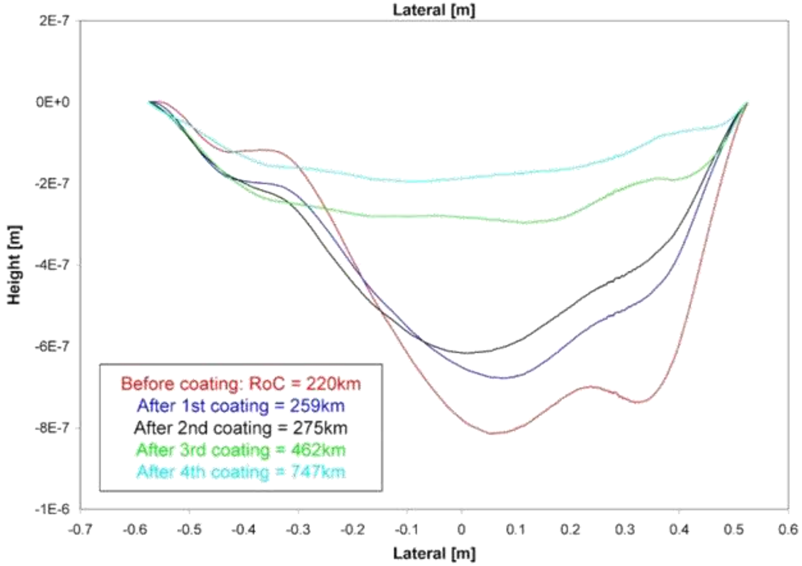
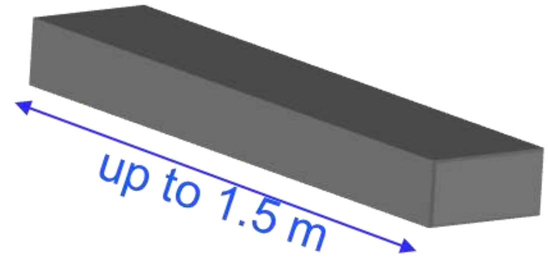






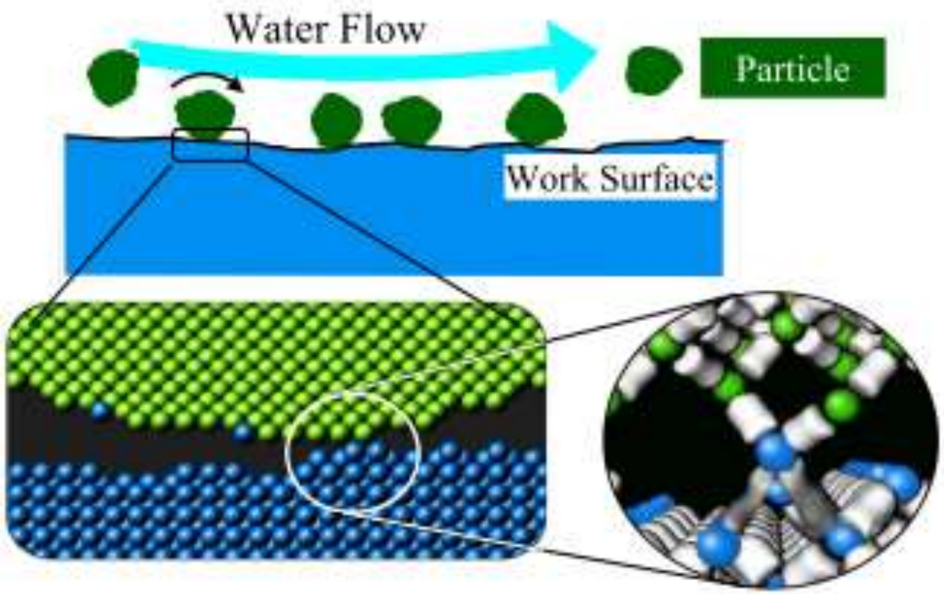
1) Classical polishing
2) High precision metrology
3) Error correction by Rh controlled deposition
4) Second itaration with metrology
5) Second differential coating deposition
6) Third.....
7) ......
8) ....
9)

nn) Final required slope/shape error reched (hopefully)

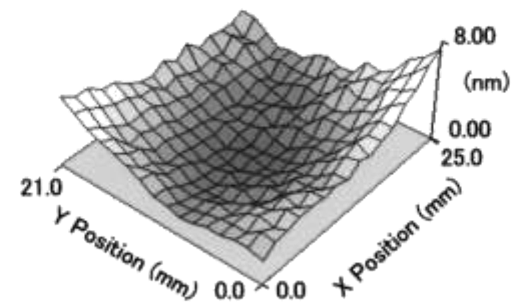
Estimated best quality:
2-3 nm rms; 0.1 μrad rms

Elastic Emission Machining - Jtec

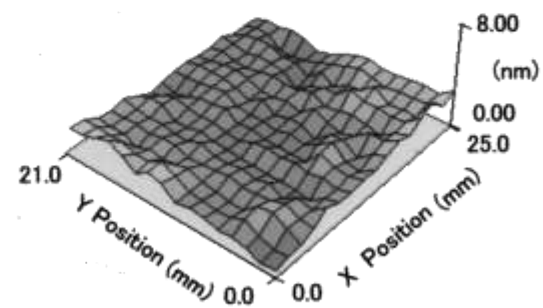
Processing technique to flat a surface in an atomic level



Pre-polishing (1.3 nm rms)



Measuring



Apply atomic level correction
(0.14 nm rms)

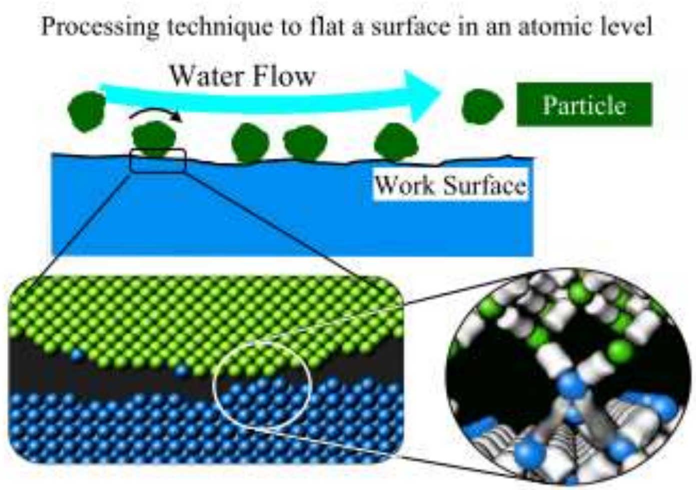
Strong Points :

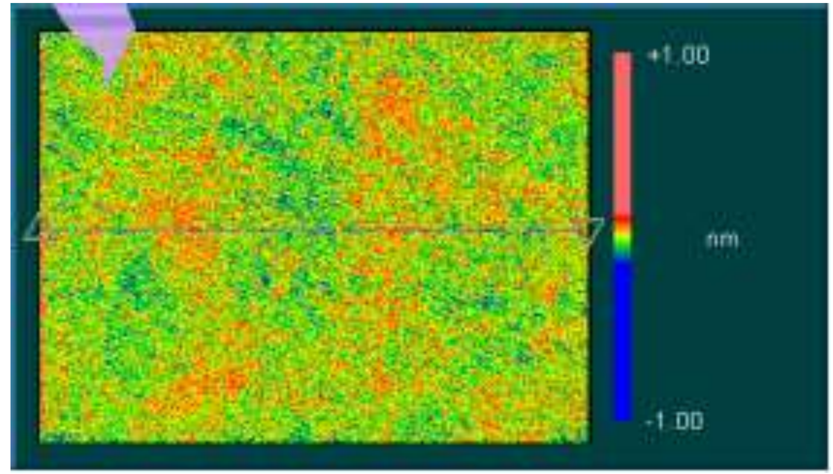
1. Owing to processing at an atom level, it is possible to be flatted at an atom level.

2. For chemical processing, no distortion on surface.

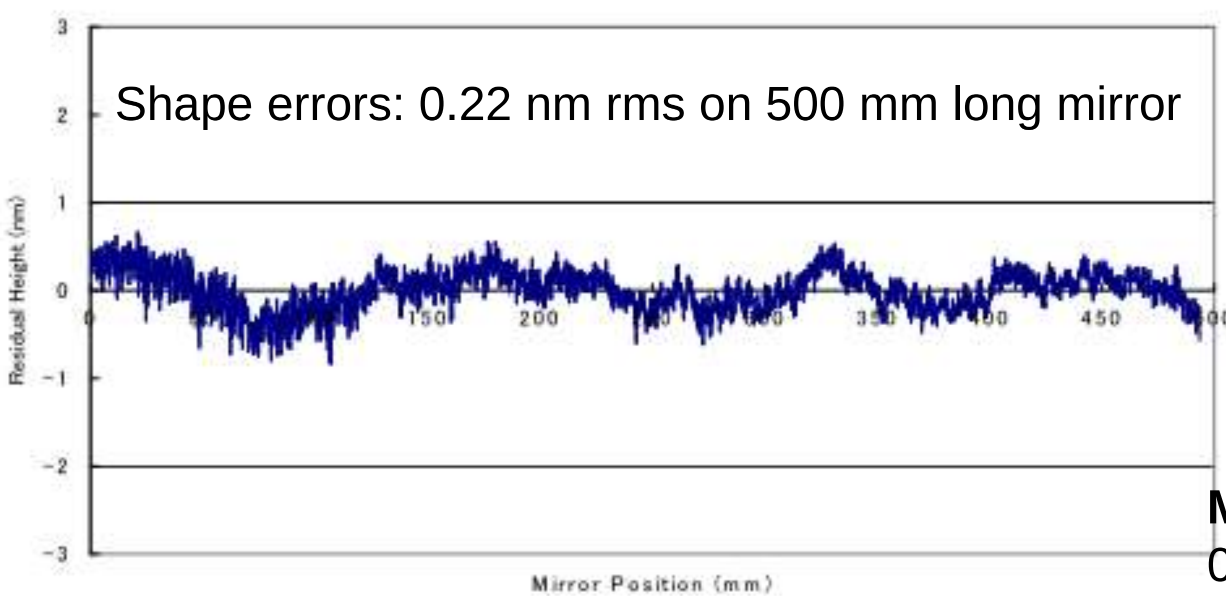
3. For regional processing by numerical control , it is possible to make various shape of mirrors.

Elastic Emission Machining – Jtec - Performance



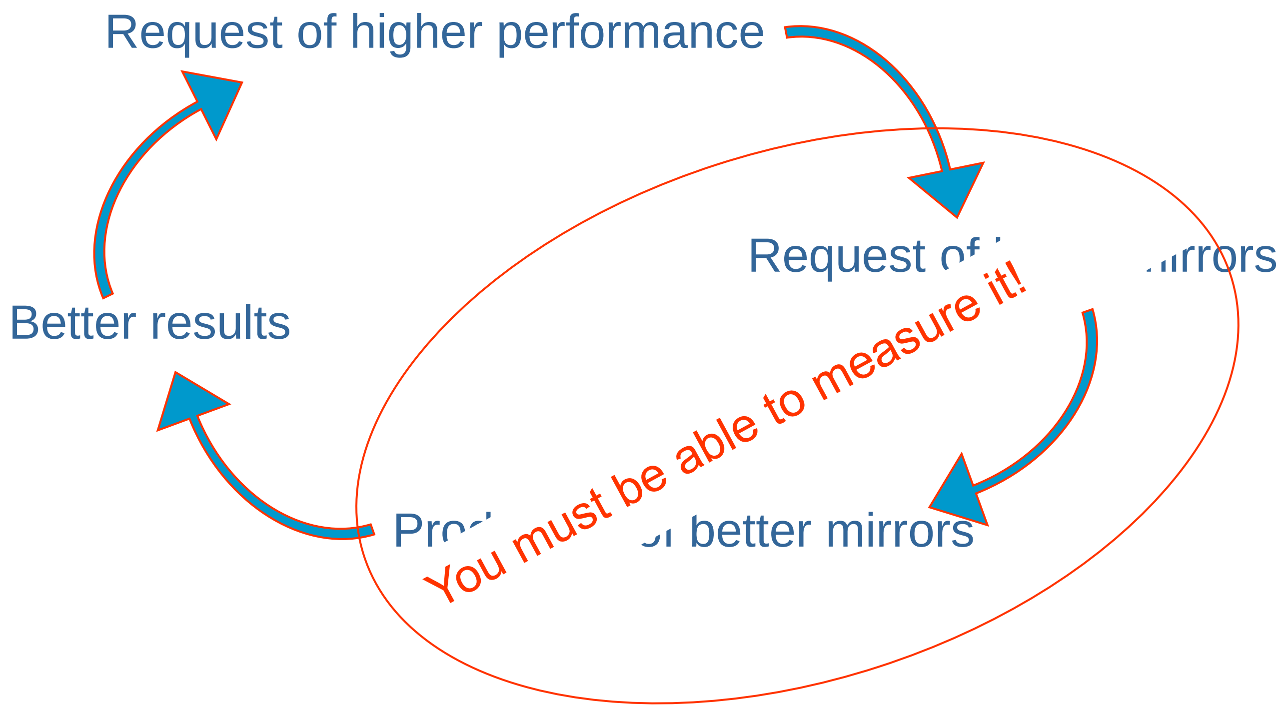


Roughness : 0.056 nm (0.6Å) rms



Measured best quality:
0.2 nm rms; 0.05 μrad rms

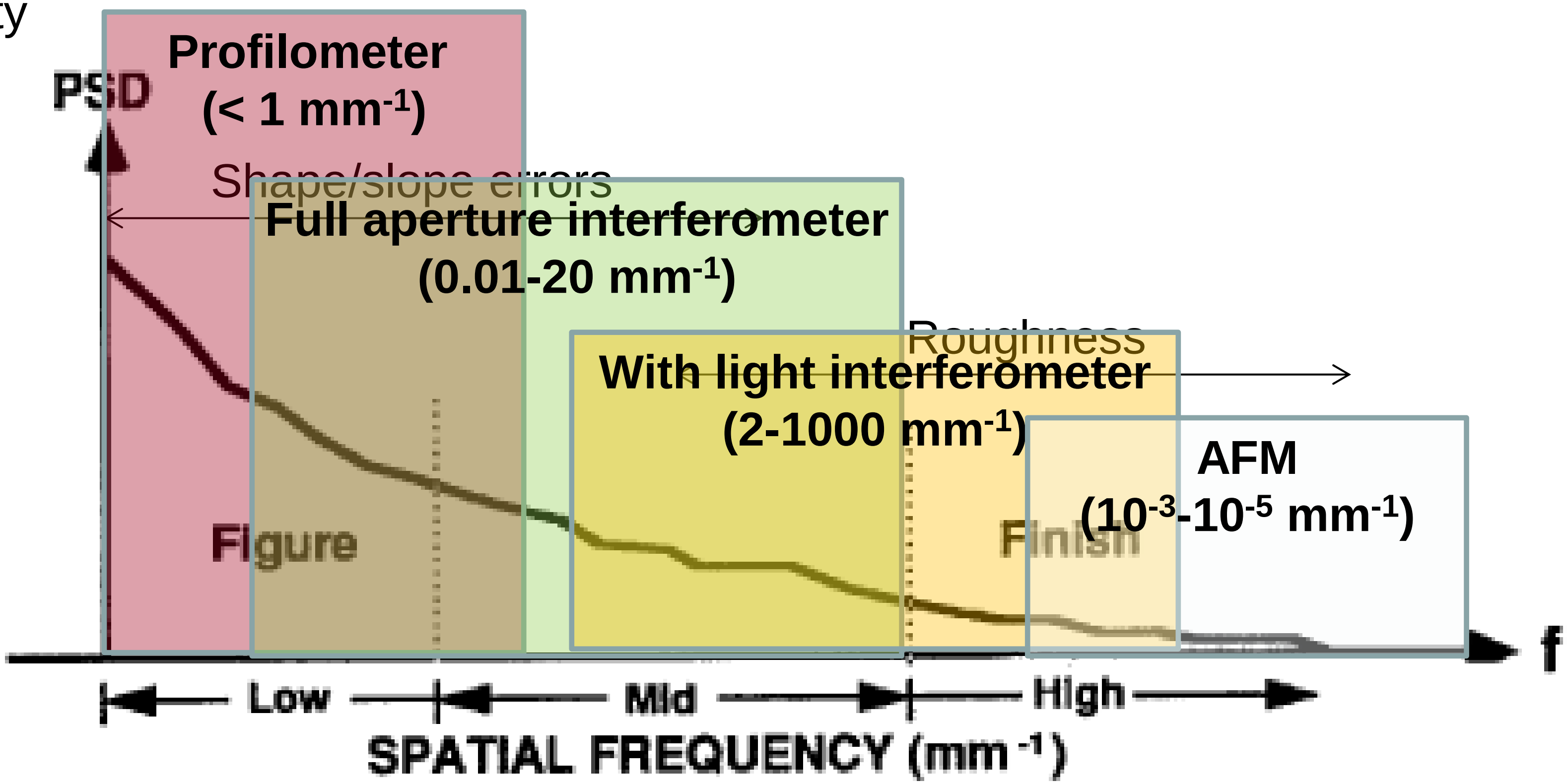
State of the art evolution

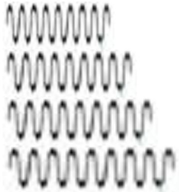


Metrology improvement drove the mirror manufacturing improvement and, ultimately, push the science forefront limits*

**….ok… it's a bit of a stretch…*

The rms deviation from the ideal surface at different periods is called the Power Spectral Density



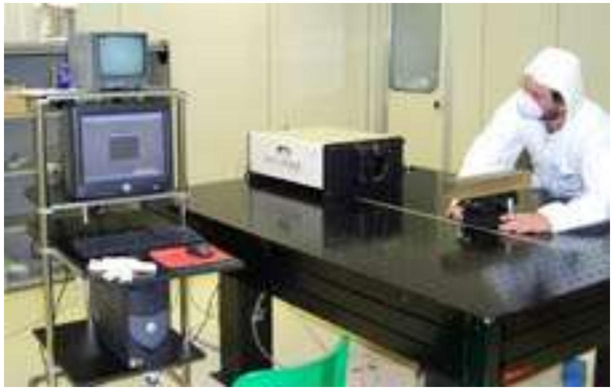


$$PSD(f) \propto \sum_{n=1}^{N} A_n e^{2\pi i f(nD)}$$

$$\sigma = \left(\int_{f_{min}}^{f_{max}} PSD(f)\,df \right)^{1/2}$$

A metrology lab

Clean Room class 10,000 minimum, 1,000 ideally.
Thermo stabilized within ±1° minimum (0.1° or better ideal)



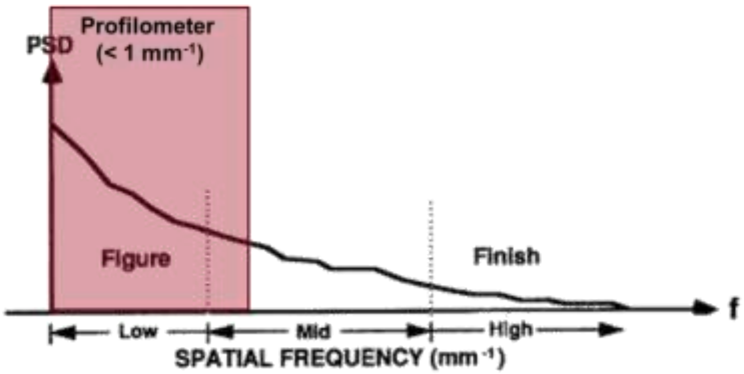
LTP / NOM
Direct slope measurement
50 nrad slope error accuracy (0.1 nm rms accuracy) after proper calibration and environmental control
Single trace measurement up to 1.2-1.5 m in length.
Minimum spatial period covered ~ 1 mm

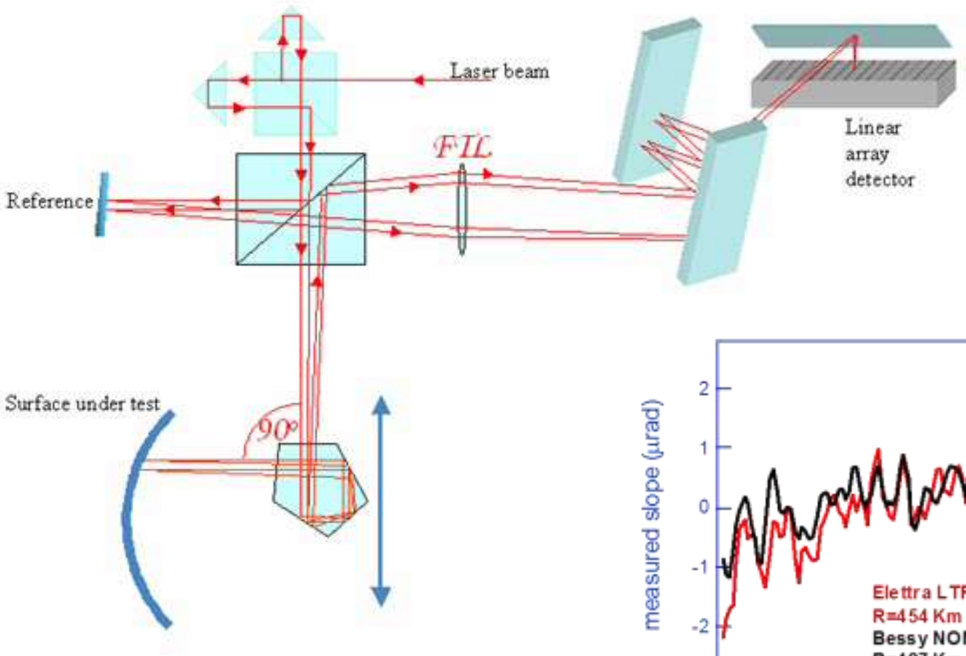
Interferometer
Direct height measurement
~ 0.5 nm rms after proper calibration and environmental control.
2D images up to 6' diameter
Possibility of stitching reducing the accuracy.
Minimum spatial period covered ~ 0.05 mm

White light micro interferometer
Direct heigth measurement
0.1 nm rms in proper environmental condition.
2D images up to ~0.5 mm^2
Minimum spatial period covered ~ 0.5 μm

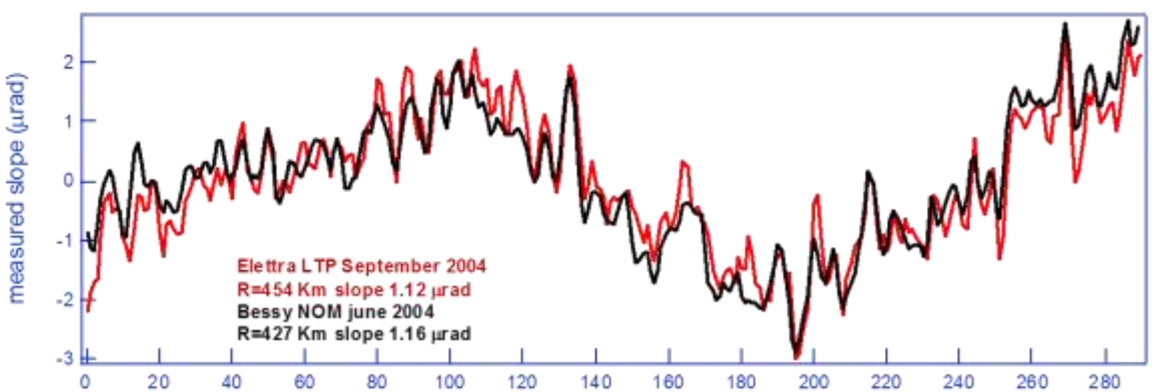
Long Trace Profilometer

We need something to measure accurately (0.1 nm rms) mirror with length up to 1 m minimum (1.5 m future prevision) and with arbitrary surface profile





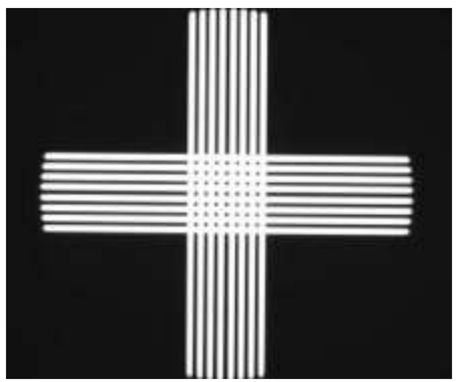
LTP
P. Takacs, S.N. Qian, S. Irick

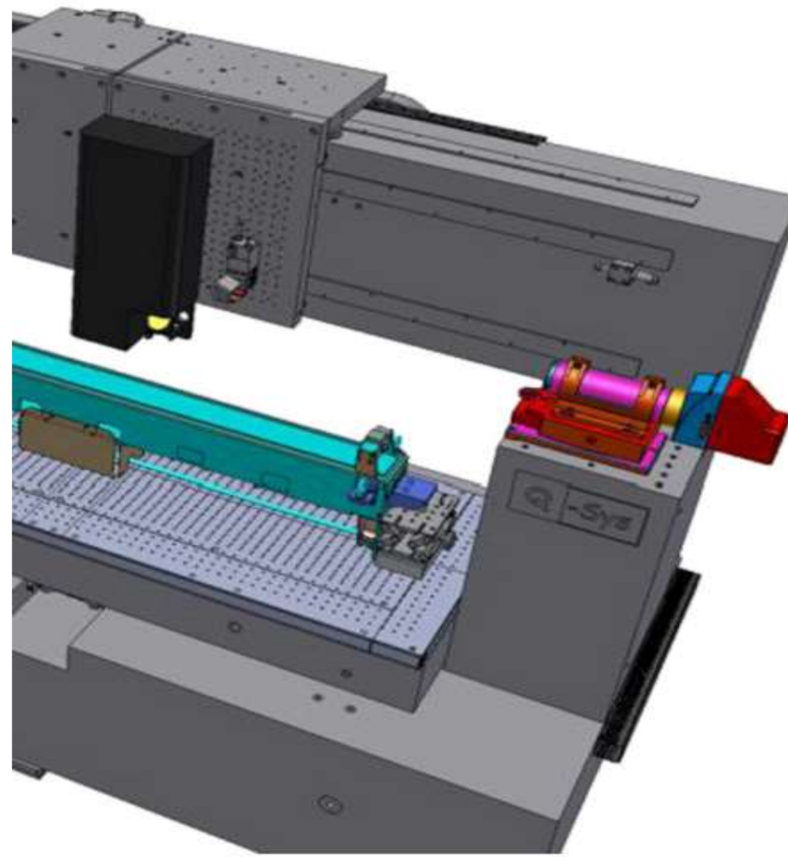


By using an autocollimator

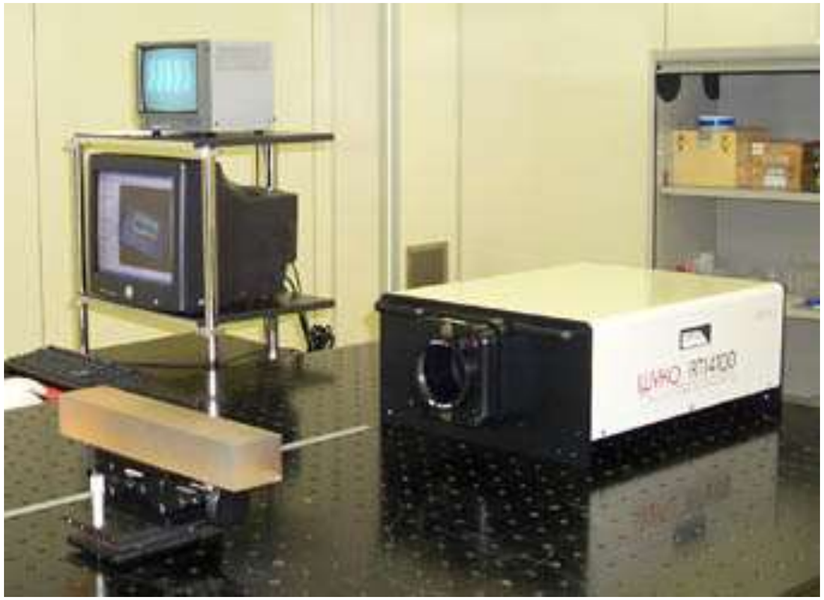
<u>THE</u> autocollimator to use is the Elcomat 3000/10 (by Möller-Wedel)

- Works in presence of multiple reflections
- Specifically developed for metrology application
- Simple repeatability 100 nrad (10 nrad averaging)
- Un-calibrated accuracy: 200 nrad over 100 μrad (fix distance).
- Accuracy worst than 1 μrad in the entire field of view.
- 10 mrad field of view





Precise but needs a lot of calibration



3D measurement of optical surfaces

Zygo specs: λ*/500 precision*

Tipical: λ*/2-3000 repeatability*

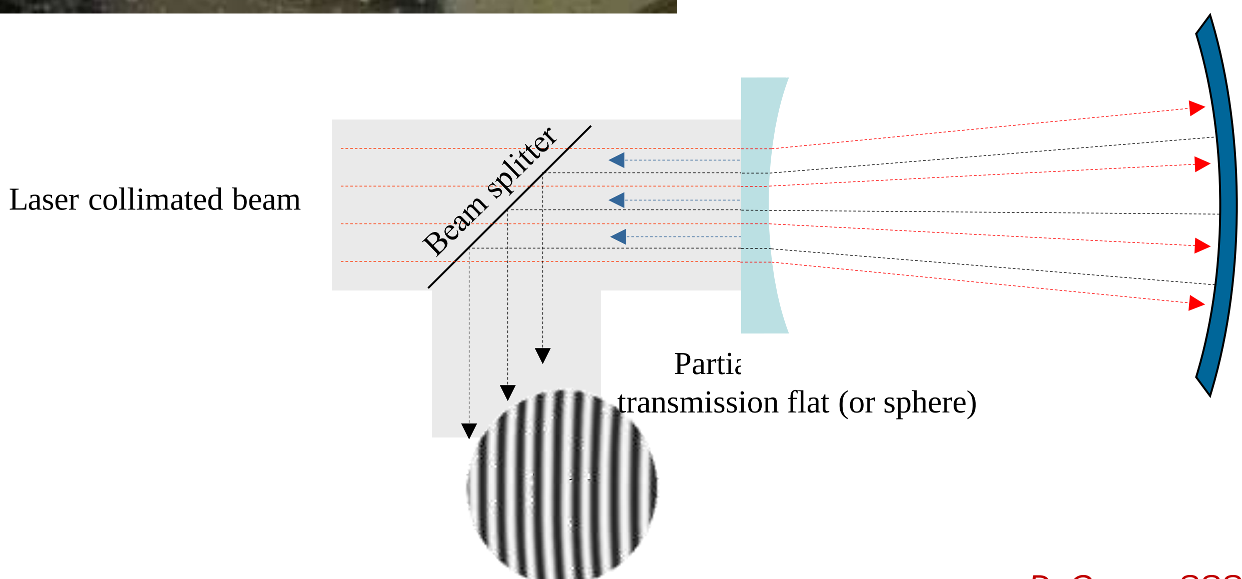
Direct measurement of radii down to 20-30 m

Optional Accessories

Transmission spheres

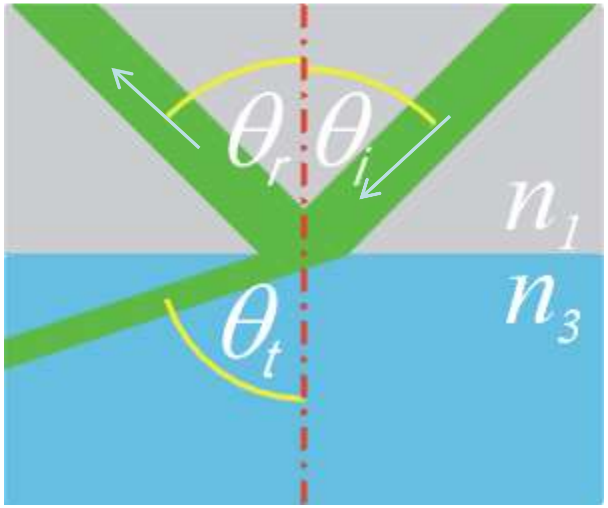
f /1.5-2 for sagittal radii and NI mirrors with R<1 m

f /15-30 diverger for NI mirrors with R>2 m

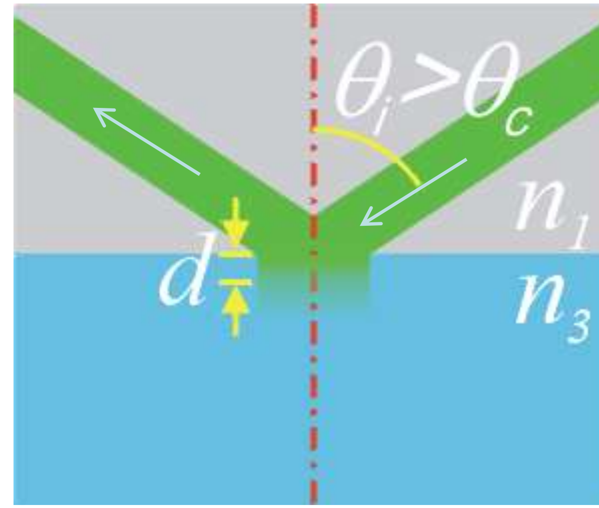


Optical surface damage

Above the grazing critical angle



Below the grazing critical angle



The non reflected energy is absorbed (1/e) in d ↘

$$d = \frac{\lambda\zeta}{4\pi\beta}$$

$$\zeta = \sqrt{\frac{\sin^2\theta - 2\delta + \sqrt{(\sin^2\theta - 2\delta)^2 + 4\beta^2}}{2}}$$

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

$$\delta = \frac{Ne^2\lambda^2}{2\pi mc^2}$$

R=reflectivity
P=pulse power
θ=angle of incidence
r=source distance
σ=source divergence
ρ=atomic density

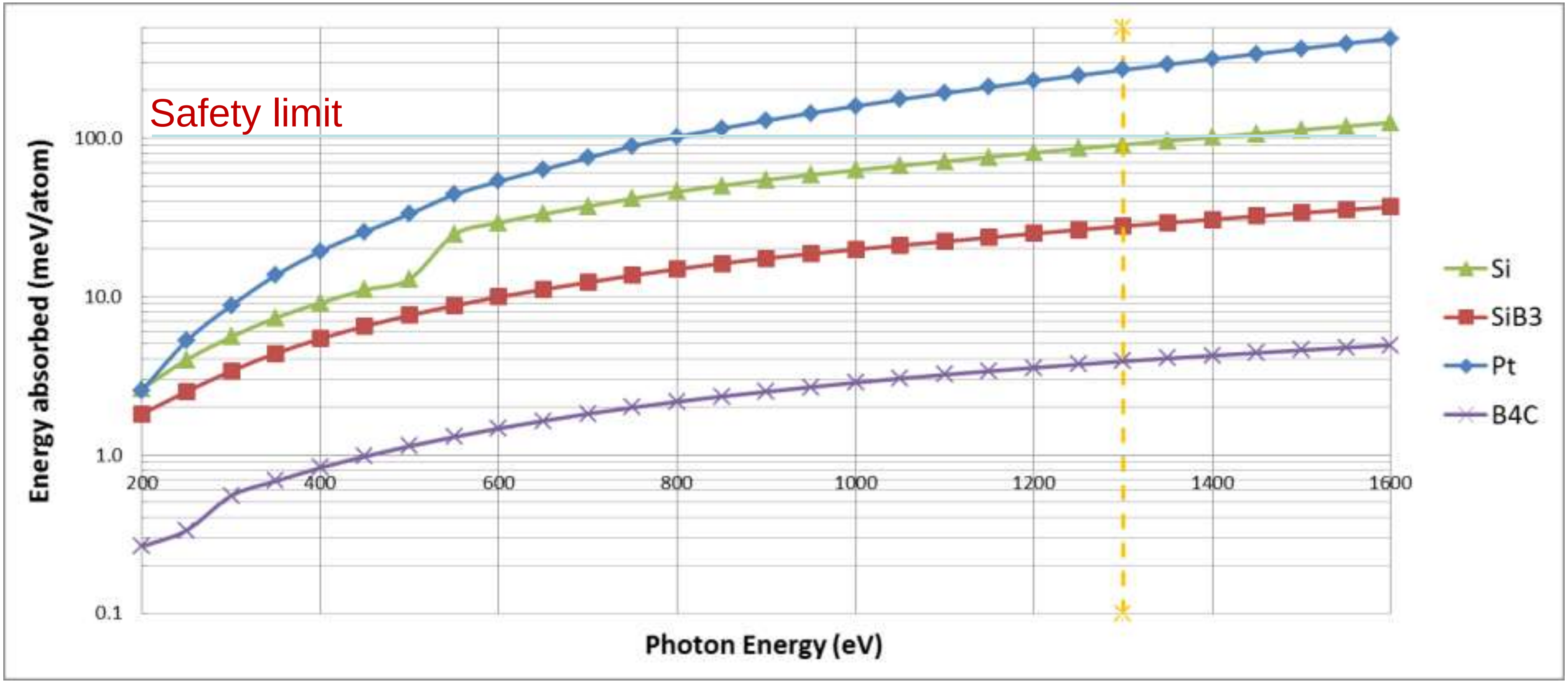
$$Aborbed \quad Energy_{ATOM} = \frac{(1-R)P\sin\vartheta}{r\sigma_x\sigma_y d\rho}$$

Ideal coating should have a large penetration depth (light materials) and good reflectivity (usually associated with heavy materials)

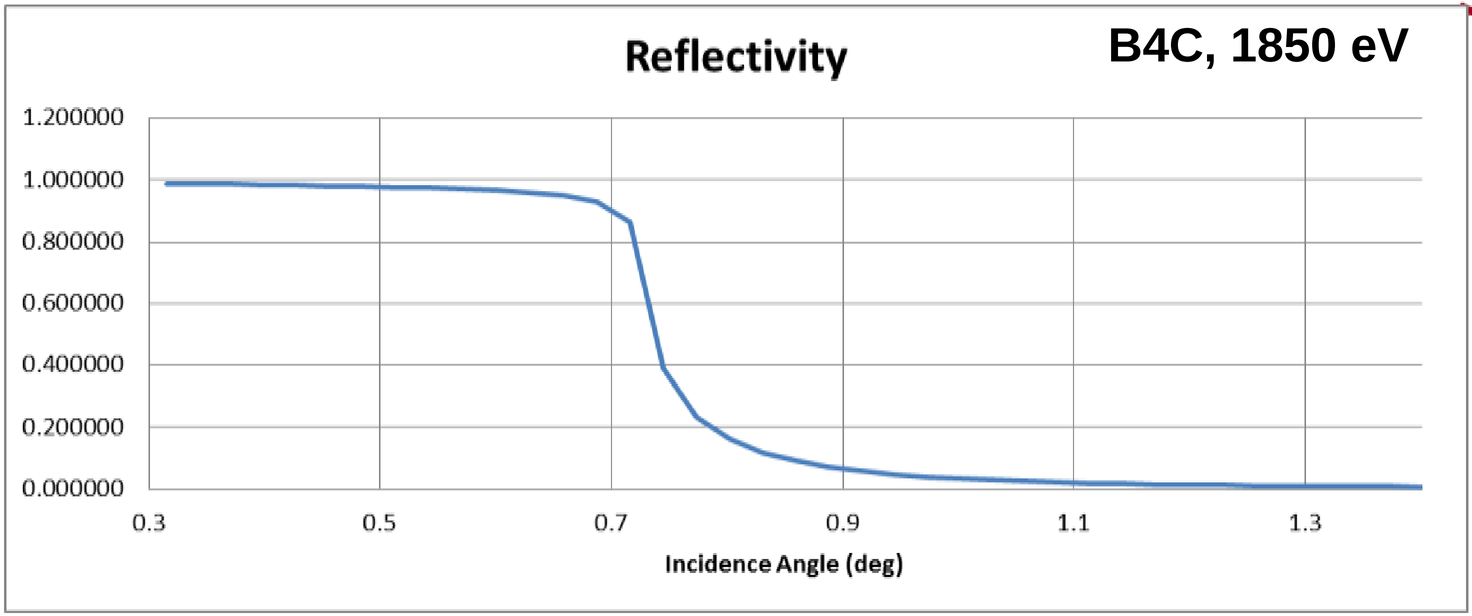
Optical surface damage

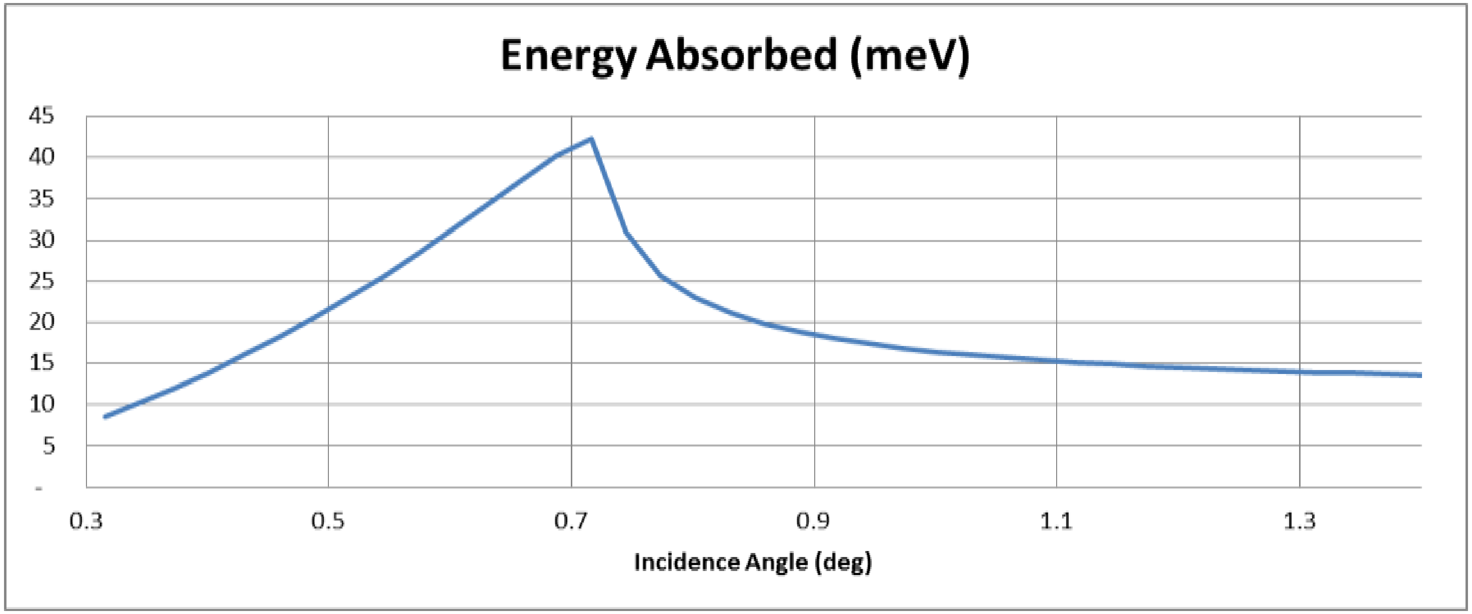
LCLS II case: 200 to 1300 eV with 2 mJ incident pulse energy

Try to work at the lowest possible angle of incidence spread the power over a large surface

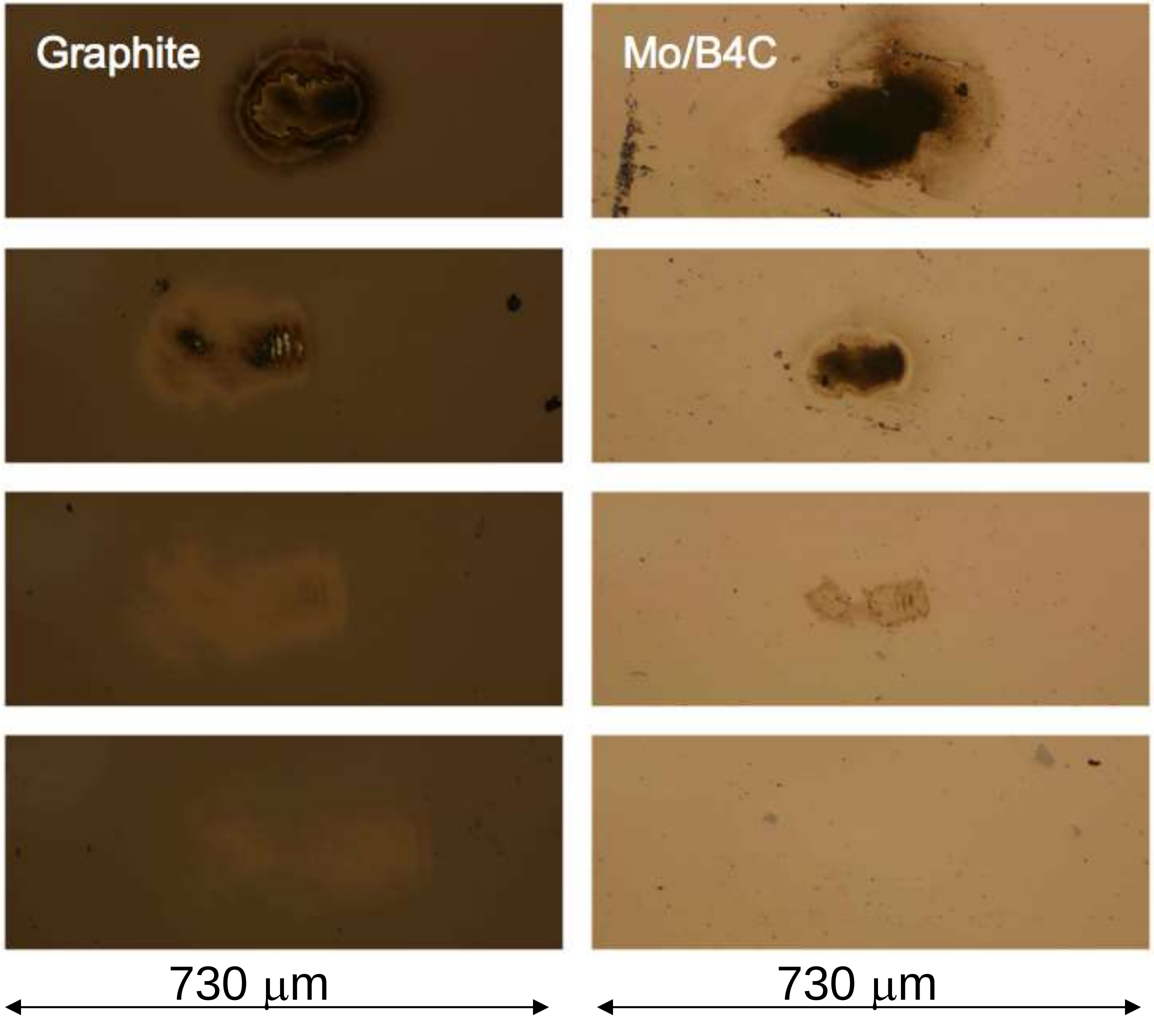


Energy absorbed vs critical angle





Example of damage for UV sources (Fermi@Elettra)



In focus
Fluence: 180 mJ/cm2

1 mm out of focus
Fluence: 60 mJ/cm2

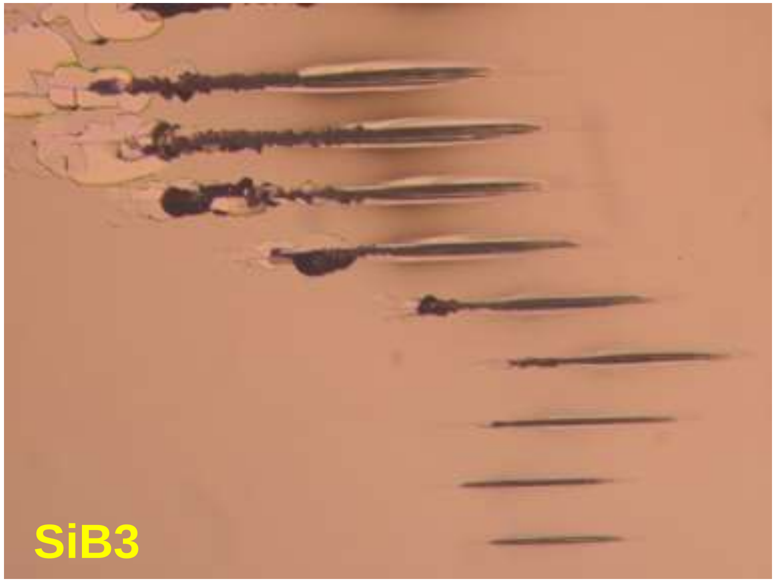
2 mm out of focus
Fluence: 25 mJ/cm2

3 mm out of focus
Fluence: 12 mJ/cm2

α-C	60 mJ/cm^2
B4C	200 mJ/cm^2

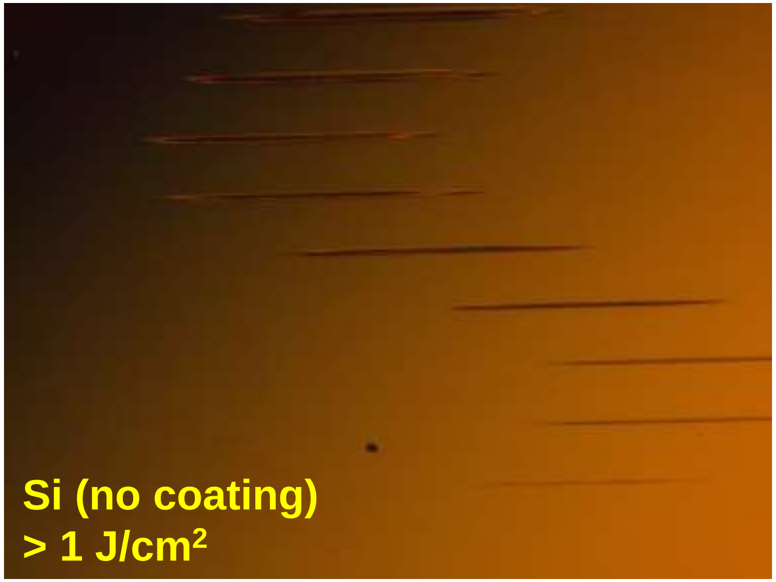
Measured at 400 nm at the EIS laser lab

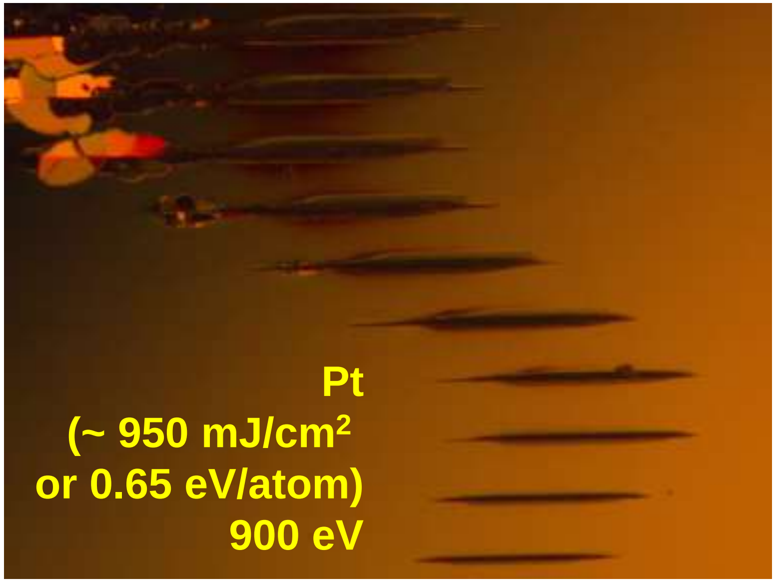
Test on LCLS mirror samples



Calculation and prediction helps… measuring the actual damage is better

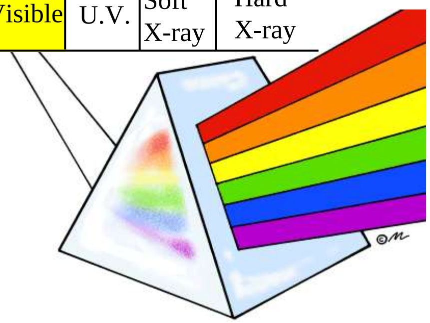
By varying the fluence (power) arriving on the sample and measuring the area of the damaged surface, it is possible to estimate the damage threshed for different material and different energies.



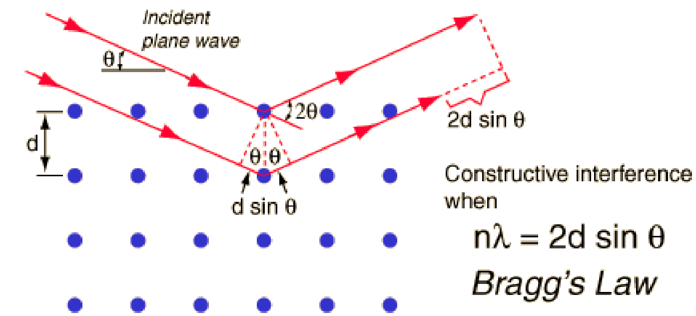


Dispersive elements

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

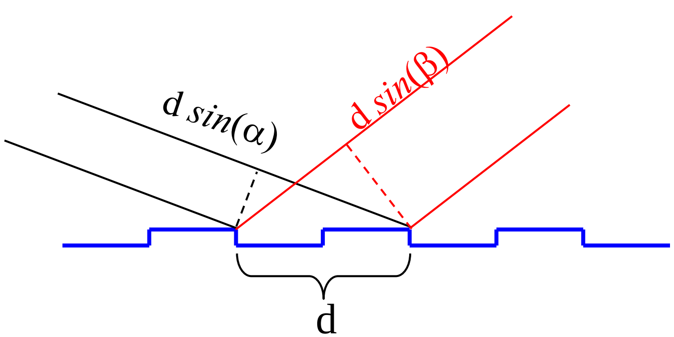


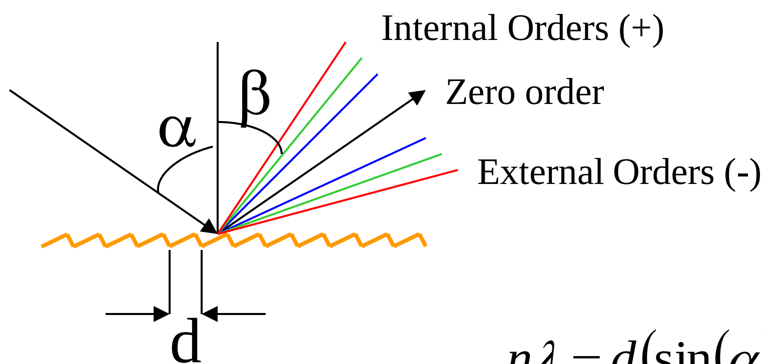
Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



limit ~ 1-2 keV (1 nm)

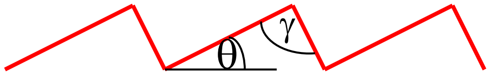
Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



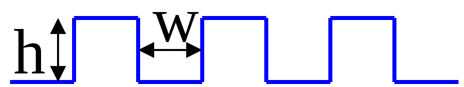


$$n\lambda = d(\sin(\alpha) - \sin(\beta))$$

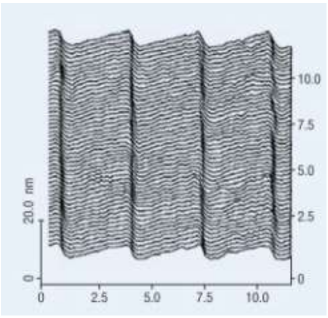
Grating profiles

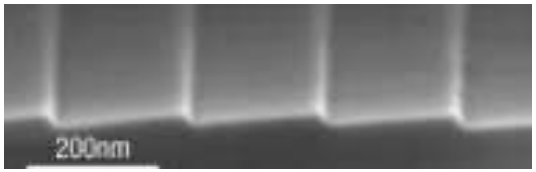


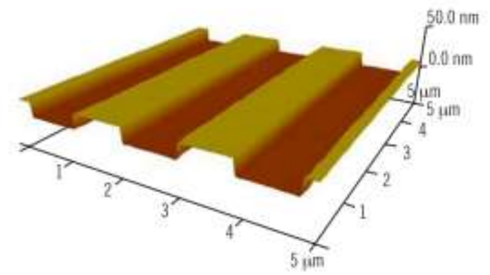
Blaze profile



Laminar profile

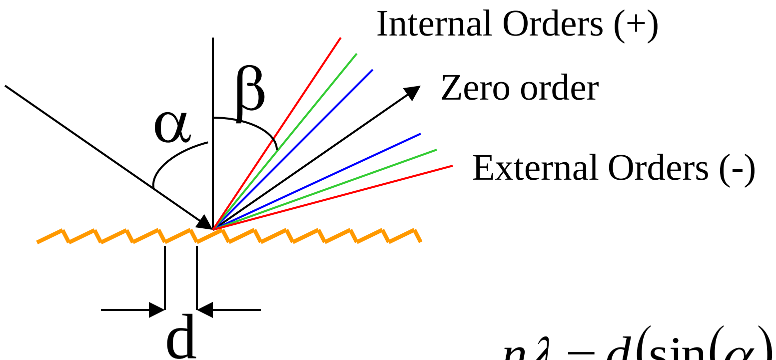






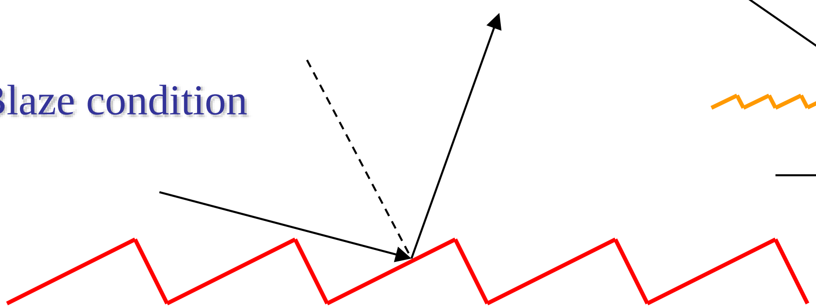
Higher efficiency

Higher spectral purity
Higher resolving power



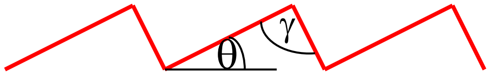
$$n\lambda = d(\sin(\alpha) - \sin(\beta))$$

Blaze condition

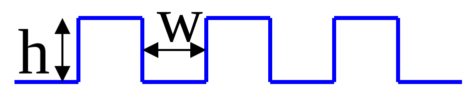


Blaze angle=(α+β)/2

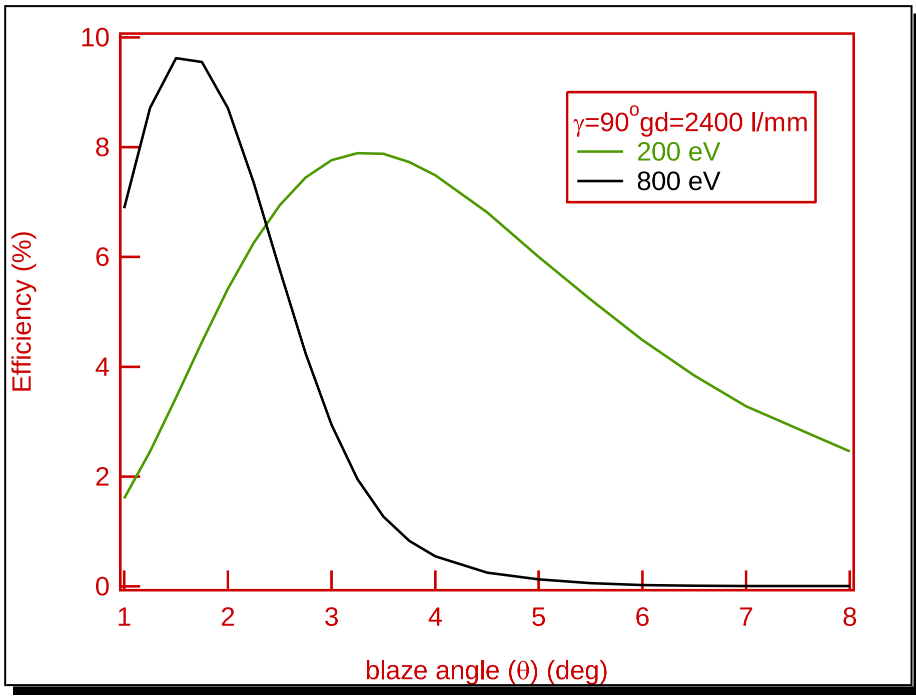
Grating Efficiency

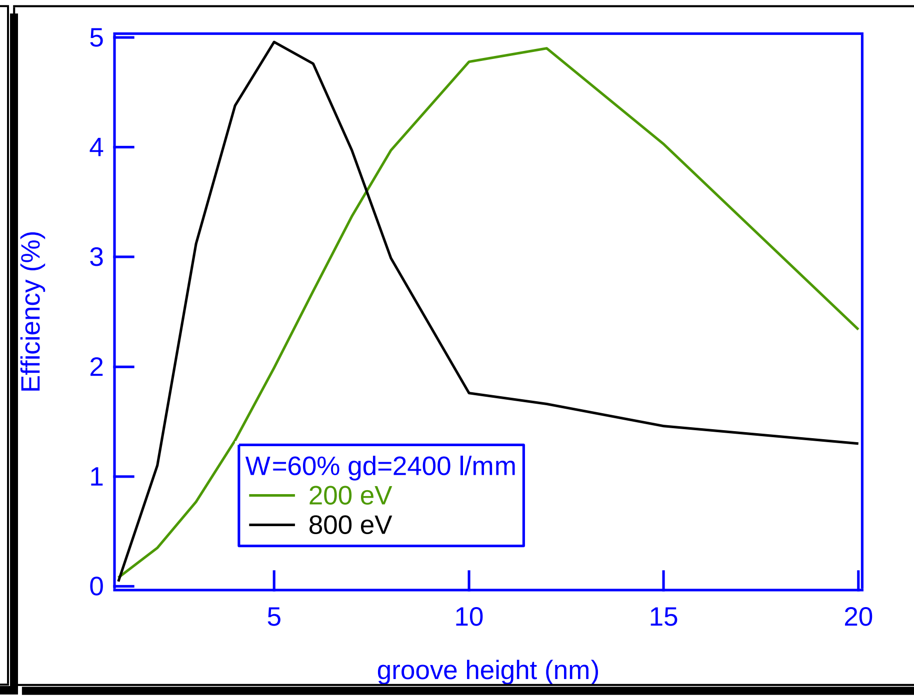


Blaze profile



Laminar profile

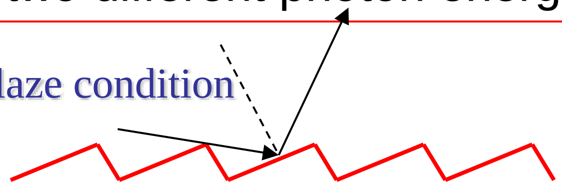




Efficiency as a function of the blaze angle for two different photon energies

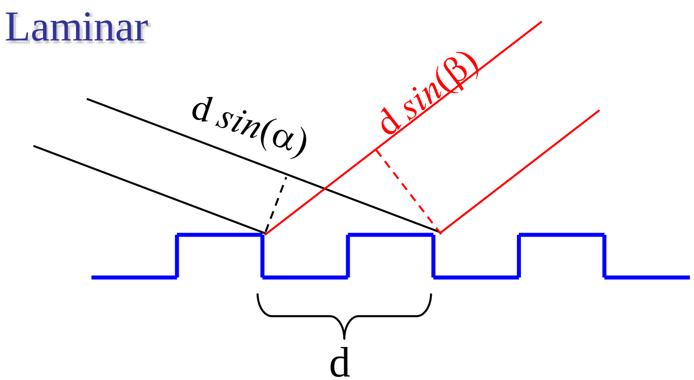
Efficiency as a function of the groove depth for two different photon energies

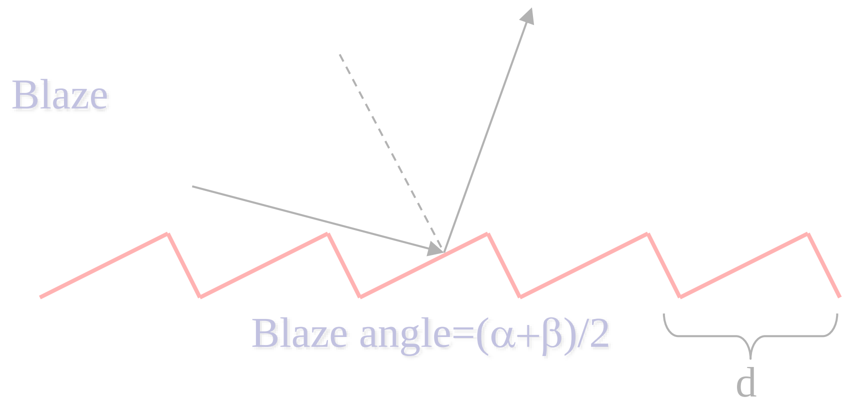
Blaze condition



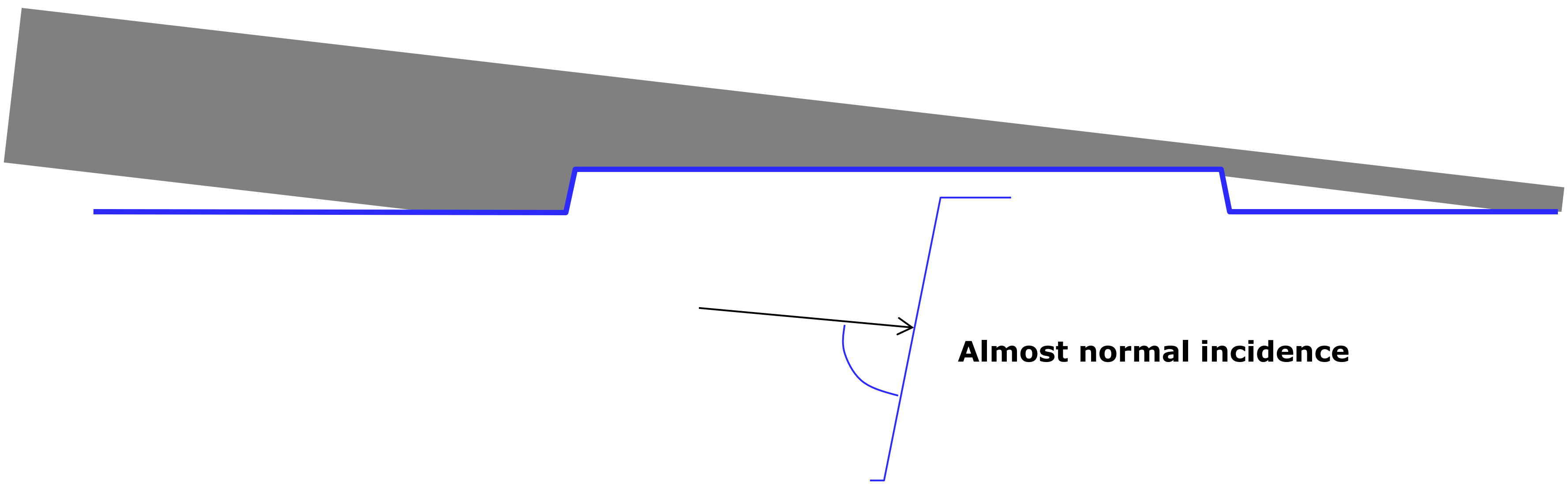
Blaze angle=(α+β)/2

Grating Damage (laminar)

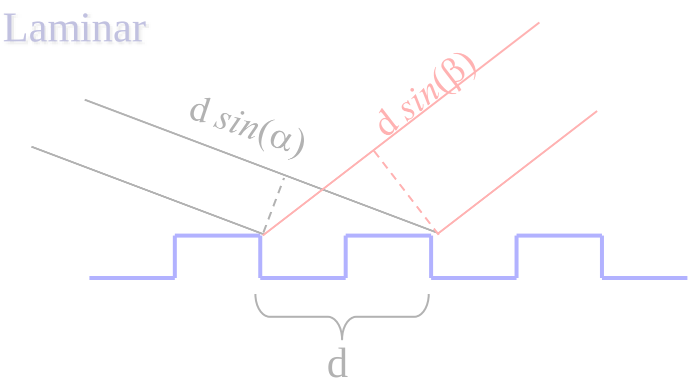




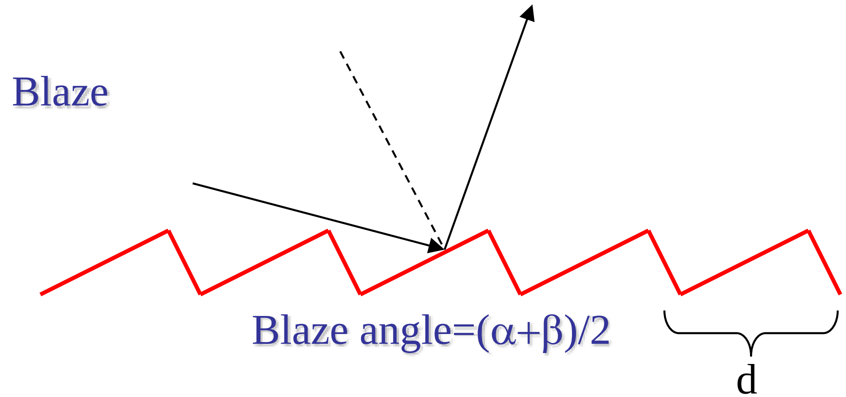
A lot of energy deposited on the grating facet



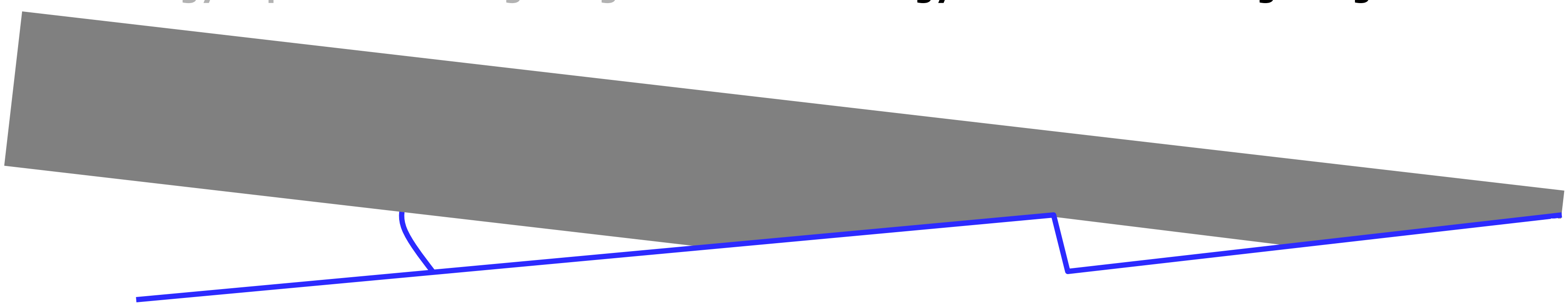
Grating Damage (blaze)



A lot of energy deposited on the grating facet



Energy distributed on the grating facet



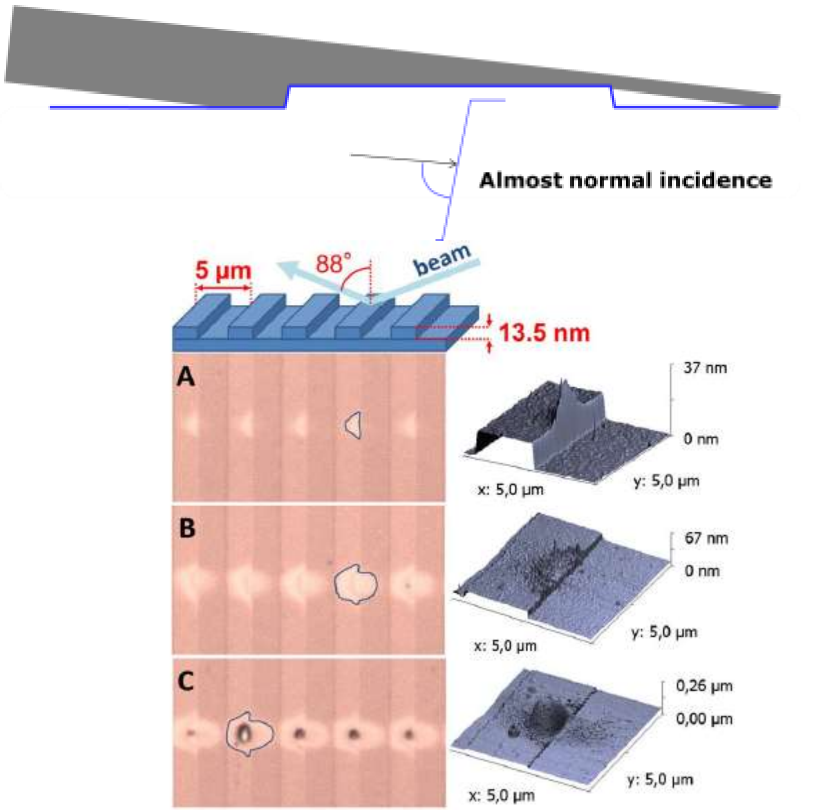


Fig. 1. (Color online) Top: schematic of the interaction of the experiment. Below: DIC microscopy (left) and AFM (right) measurements for three different fluences 356 (A), 806 (B), and 1115 mJ/cm^2 (C).

The reported damage threshold (0.5 eV/atm) is **3** times lower the observed on a flat mirror. 1.5eV/atom)

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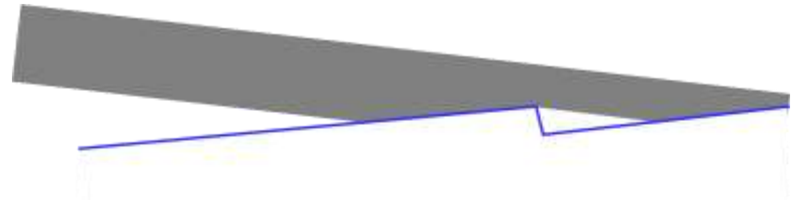
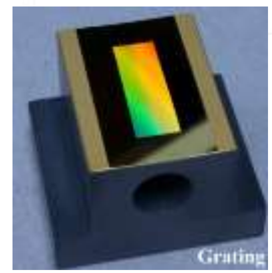
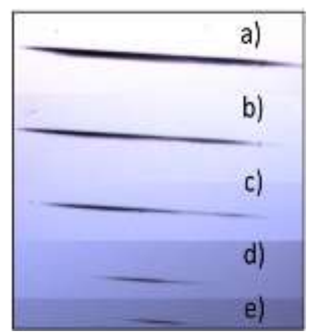




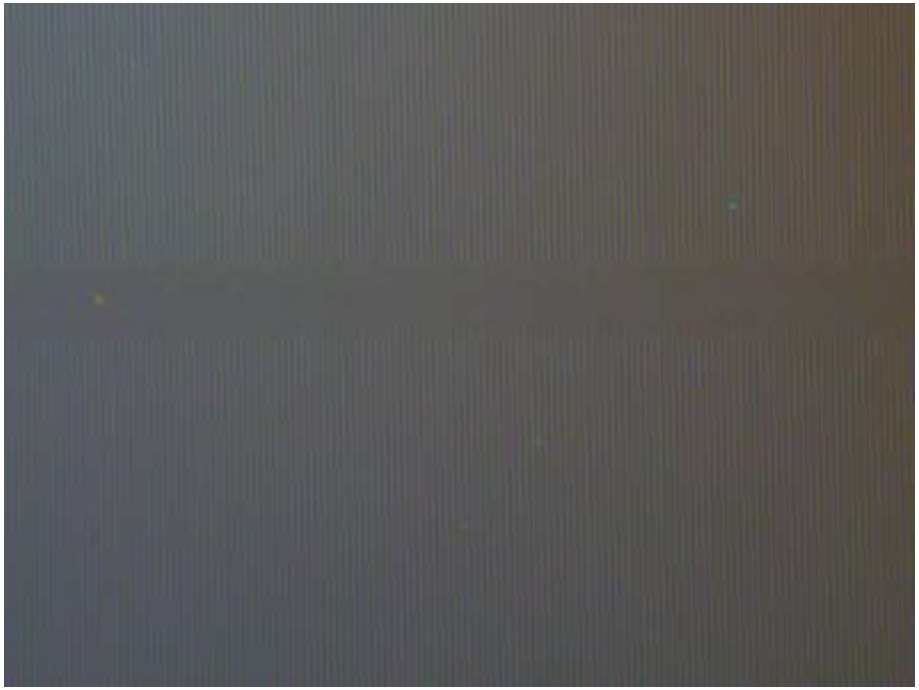


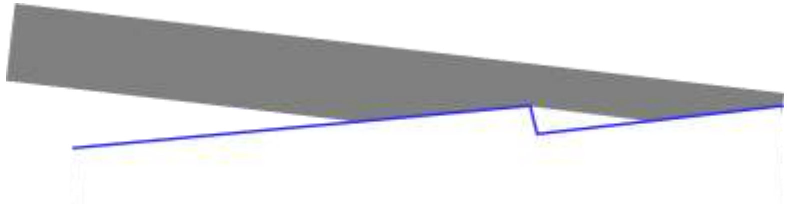
Single Shot damage ~ 8-10 eV/atom

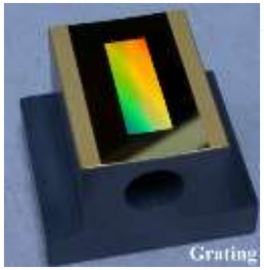
Multi shot damage ~ 720 meV/atom

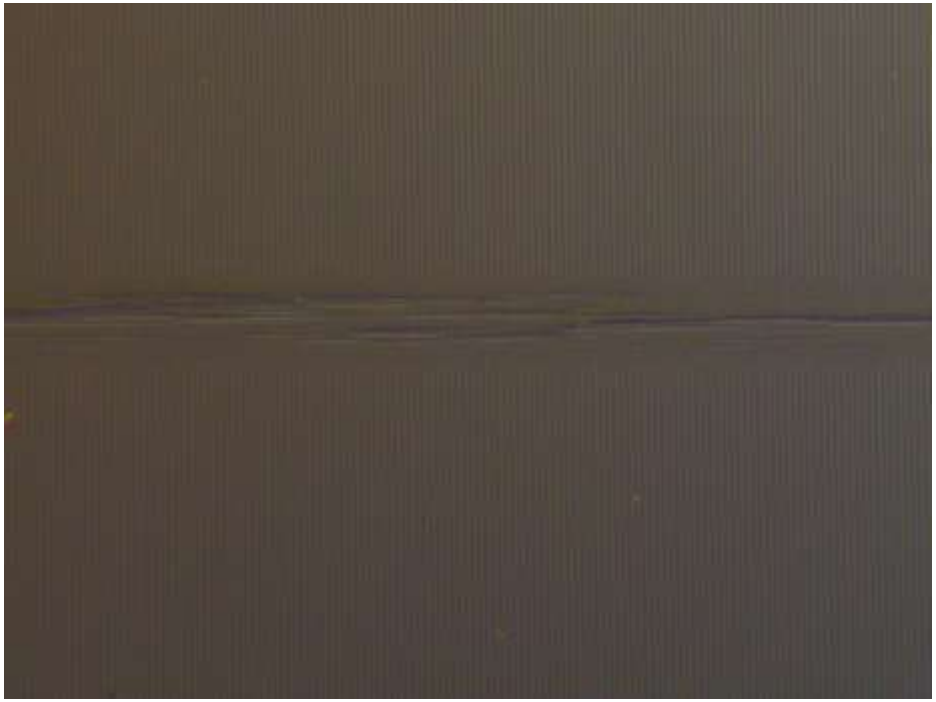
Defined the maximum working energy for the Pt grating according to these tests

Damage tests on gratings

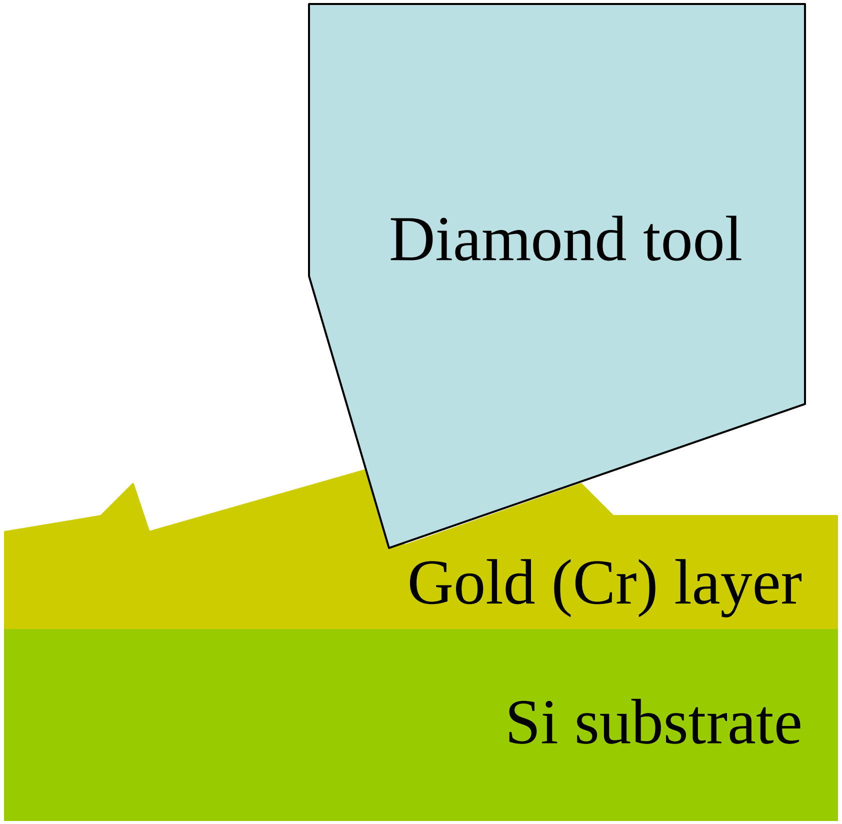






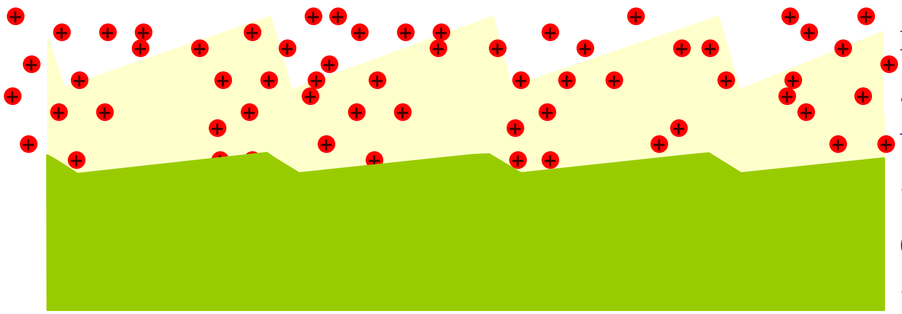


Result still under investigation but, it looks like that the grating has the same damage threshold of a mirror with an angle of incidence identical to the angle of the grating facet with respect the radiation. It means, the blaze angle shall be really small!



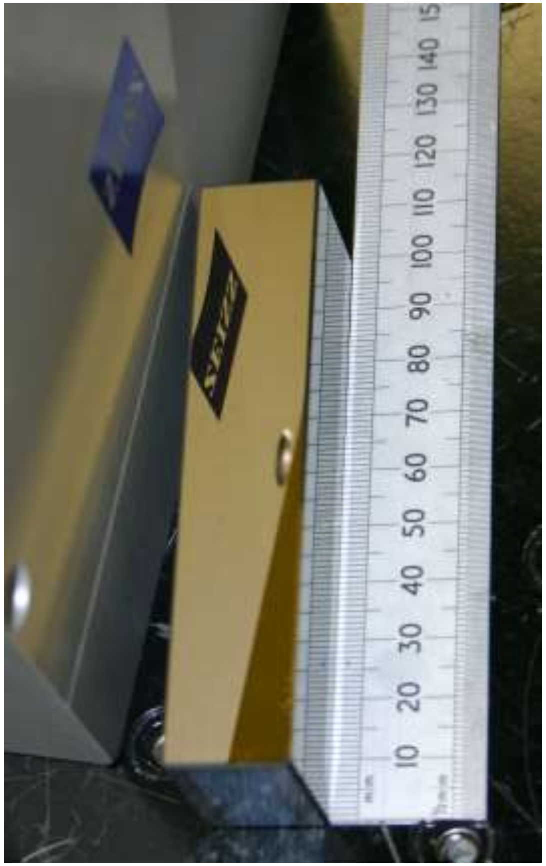
- Thermal evaporation of Gold on the Si substrate (plus Cr binding layer)
- Grooves formed by plastic deformation of the ruling layer

Mechanically ruled grating – toward very shallow blaze angle

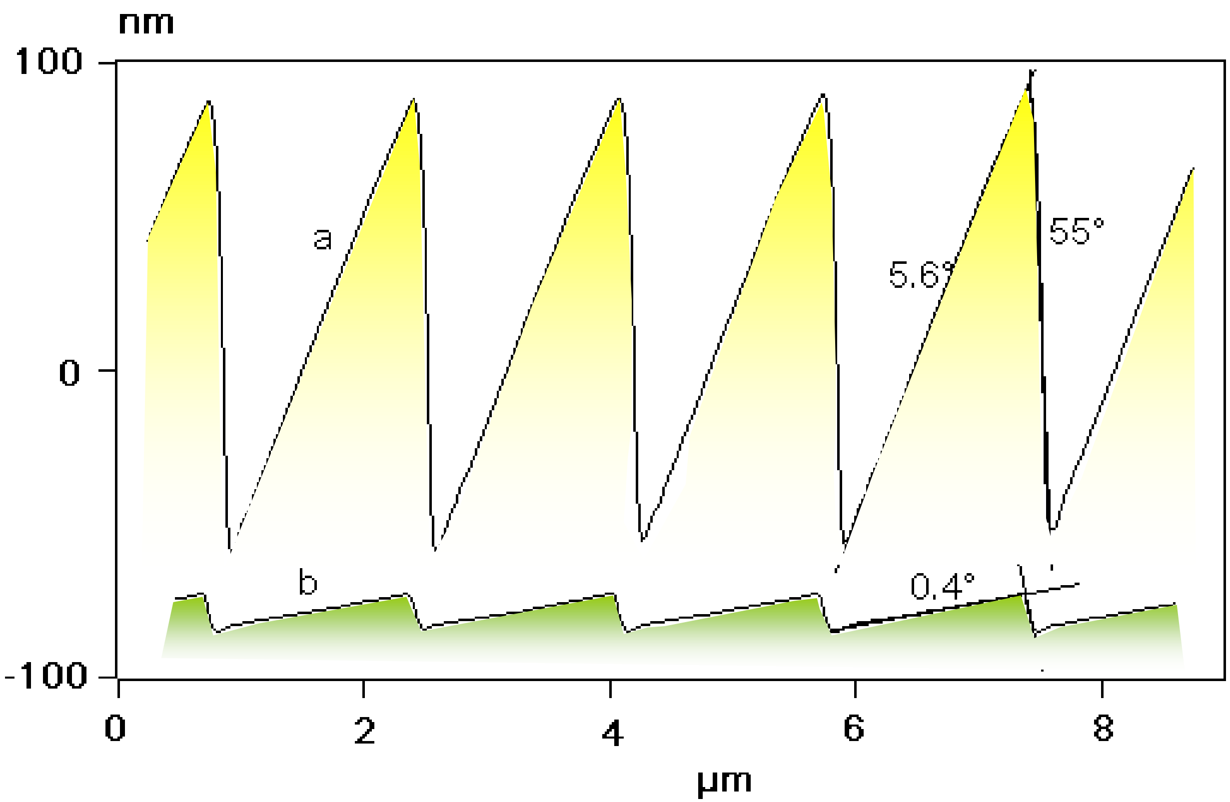


- Thermal evaporation of Gold on the Si substrate (plus Cr binding layer)
- Grooves formed by plastic deformation of the ruling layer
- Realization of low micro-roughness blaze grating with 20<gd<5000 l/mm and down to 1.5^{o} of blaze angle
- Ar^+ ion etching (200 mm diameter collimated beam)
- Ar^+ ion etching rate on gold much larger then on Silicon
- An angle reduction of a factor 3 (even higher if Ar^+ + O^+ is used) can be achieved by this technique
- Roughness and anti blaze angle are also reduced.

Shallow Blaze Angle grating



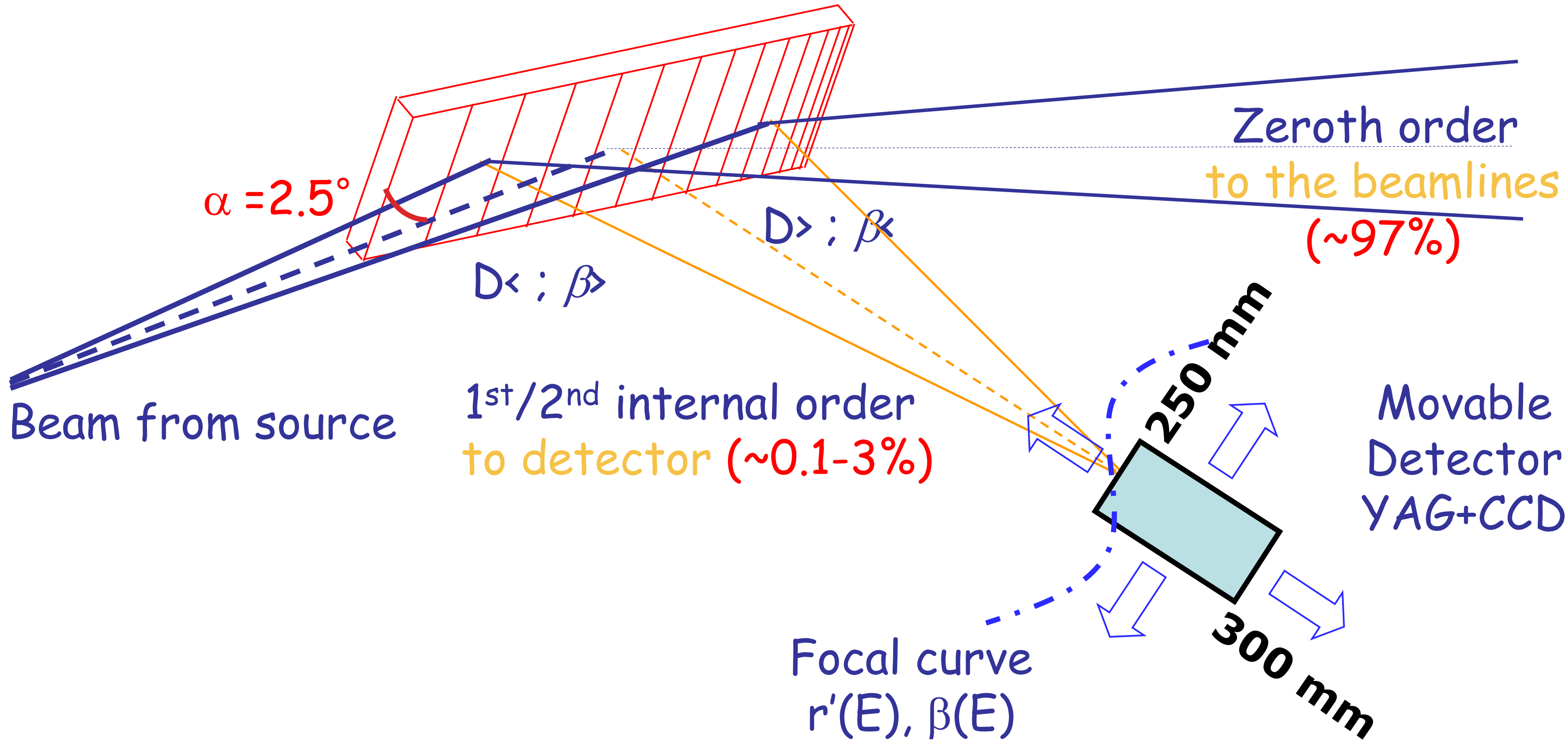
Plane substrate 600 l/mm gold coated
80X5 mm useful area, blaze angle 0.4º



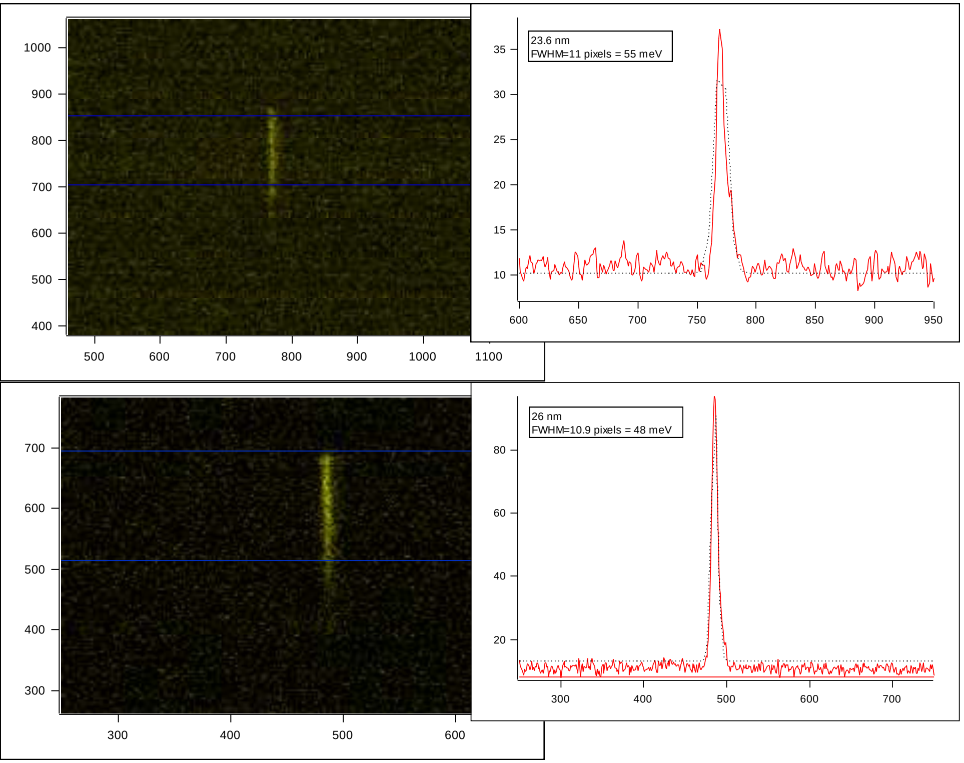
SLAC

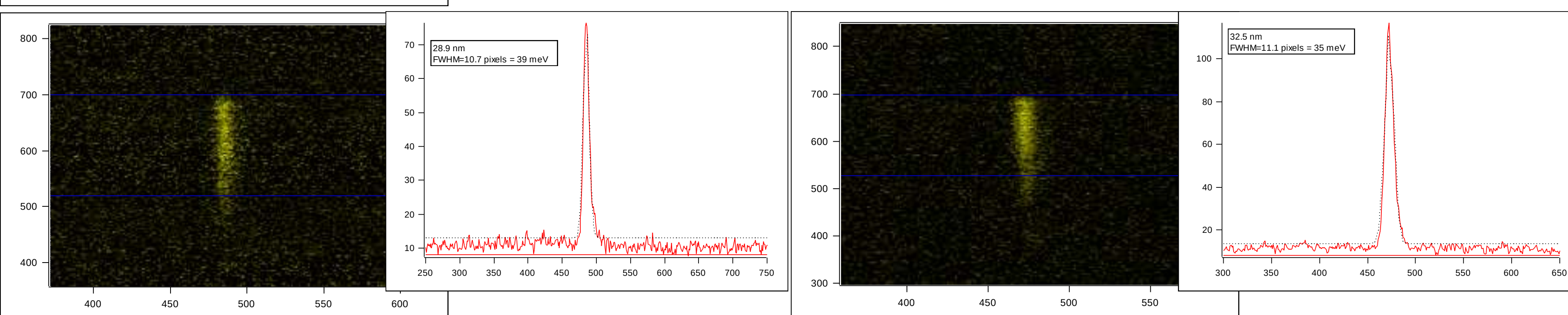
Groove density expanded in Taylor series

$D(y) = D_0 + D_1 y + D_2 y^2 + \ldots$



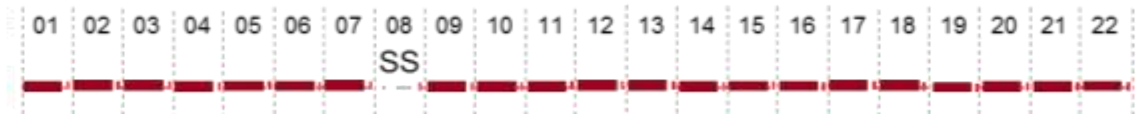
Measured HGHG Seeded FEL beam

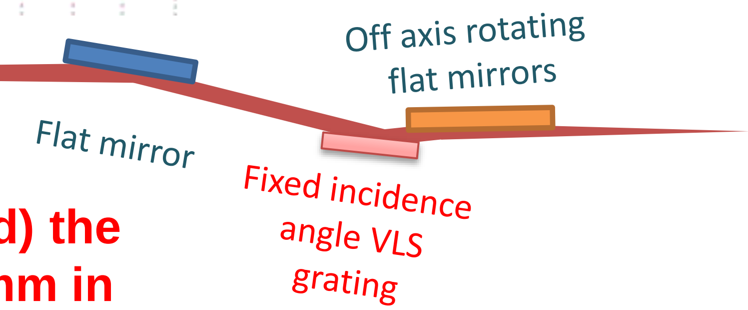




Curtesy of Fermi@Elettra - PADReS

FEL Monochromator

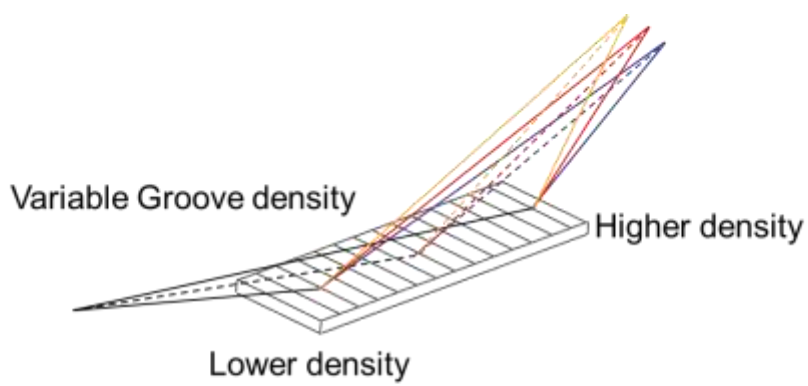




To survive and handle the variable focal distance (without adaptive optics involved) the grating must be a VLS of more than 500 mm in length

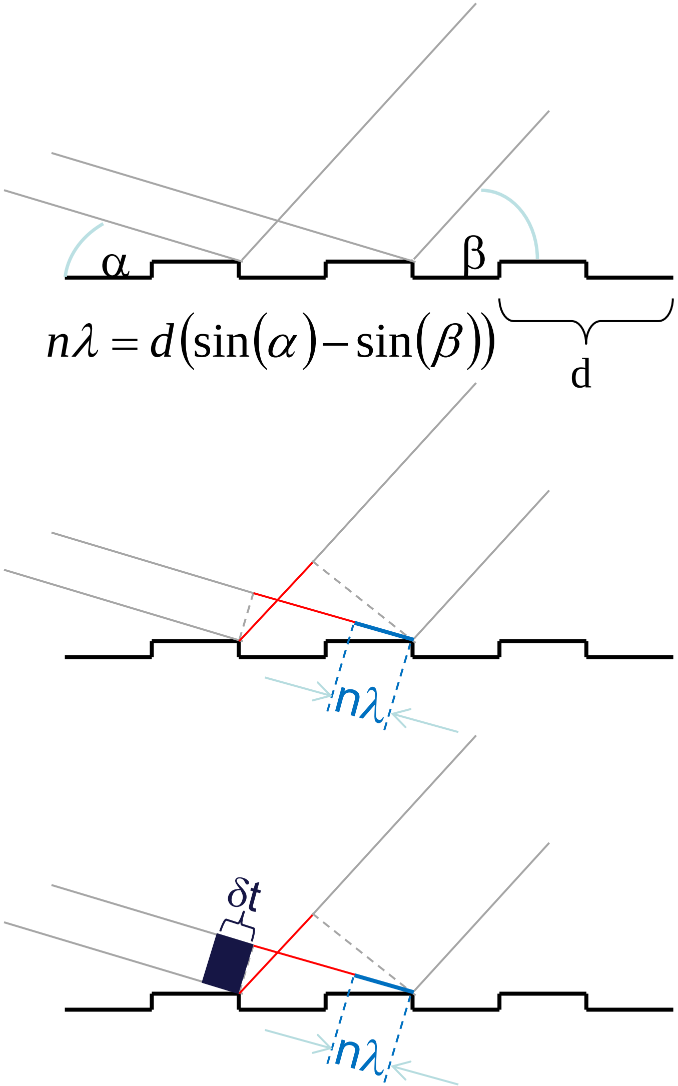
Variable source distance

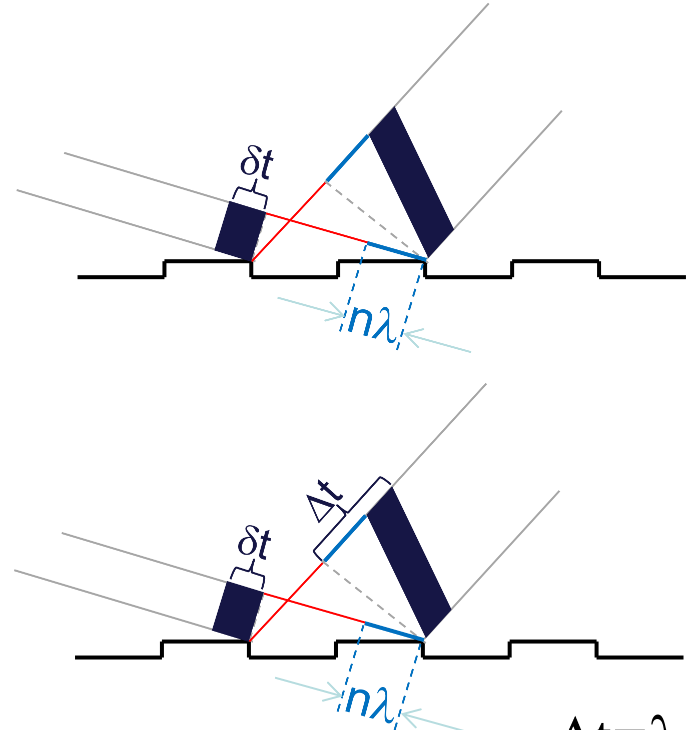
Fixed focal distance and direction



Source position calculated by J. Krzywinski

Pulse Length preservation





$$\Delta t = \lambda / c$$

$$\Delta t = \sqrt{\left(\frac{N\lambda}{c}\right)^2 + \delta t^2}$$

Pulse Length preservation

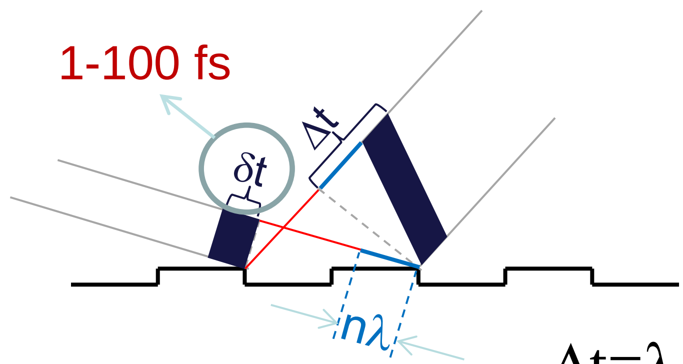
Need of long substrates to distribute the power:

1200 l/mm grating, 500 mm, 500 eV

~5,000 fsec

10 l/mm grating, 500 mm, 500 eV

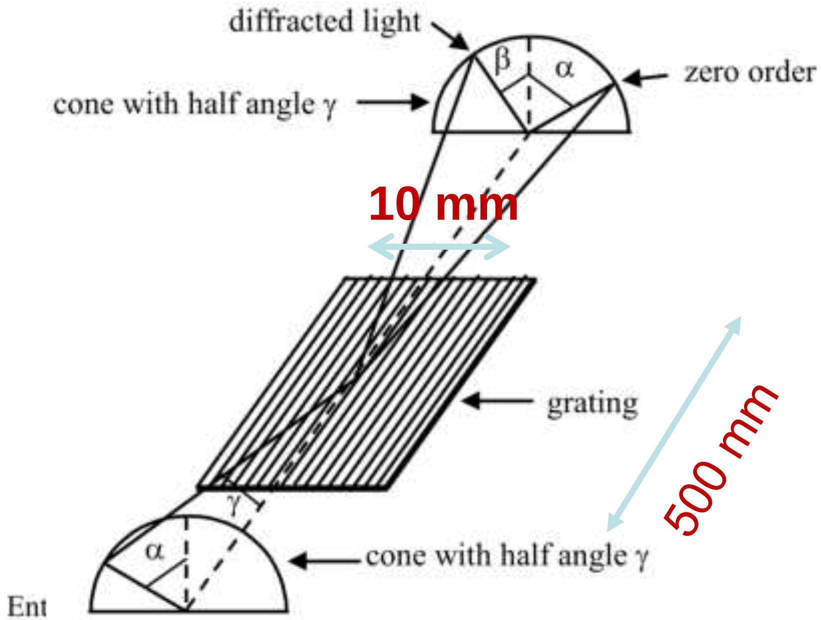
~40 fsec

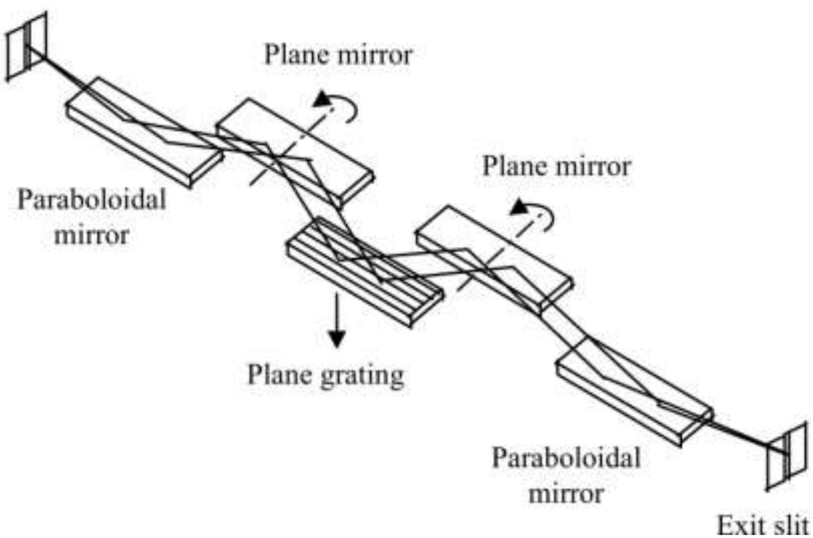


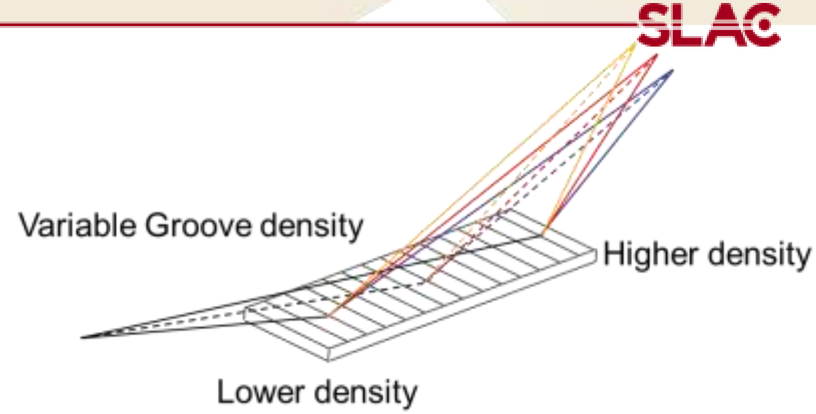
$$\Delta t = \lambda / c$$

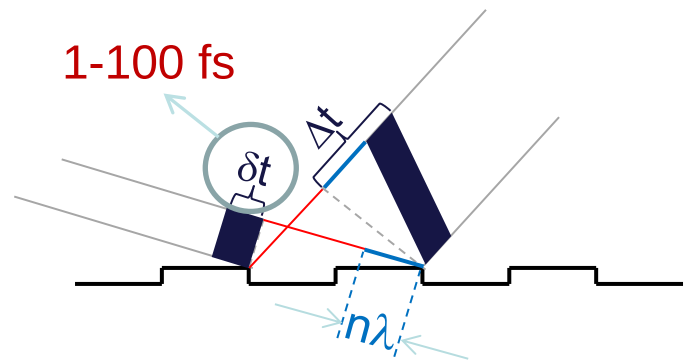
$$\Delta t = \sqrt{\left(\frac{N\lambda}{c}\right)^2 + \delta t^2}$$

Conical Diffraction

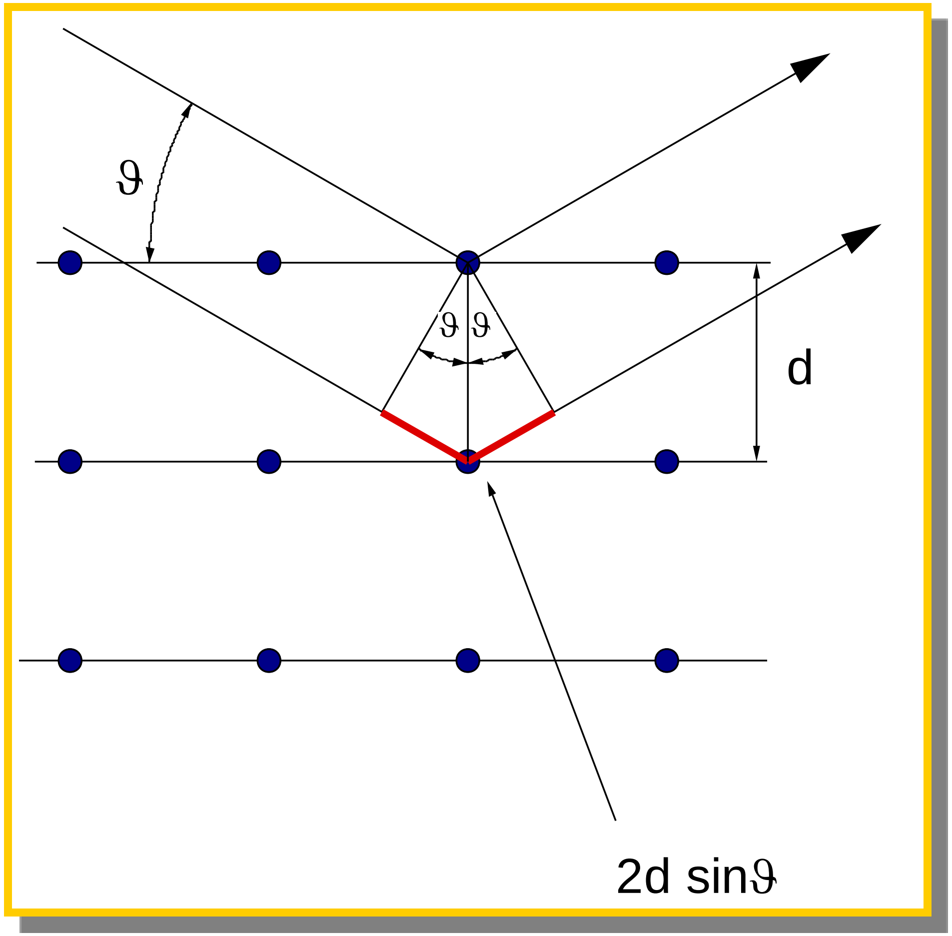








$$\Delta t = \sqrt{\left(\frac{N\lambda}{c}\right)^2 + \delta t^2}$$



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

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

Limits:

$$\sin\vartheta = 1 \Rightarrow \lambda_{max}$$

$$\lambda_{max} = 2d$$ *@ θ=90°*

EXAMPLES:

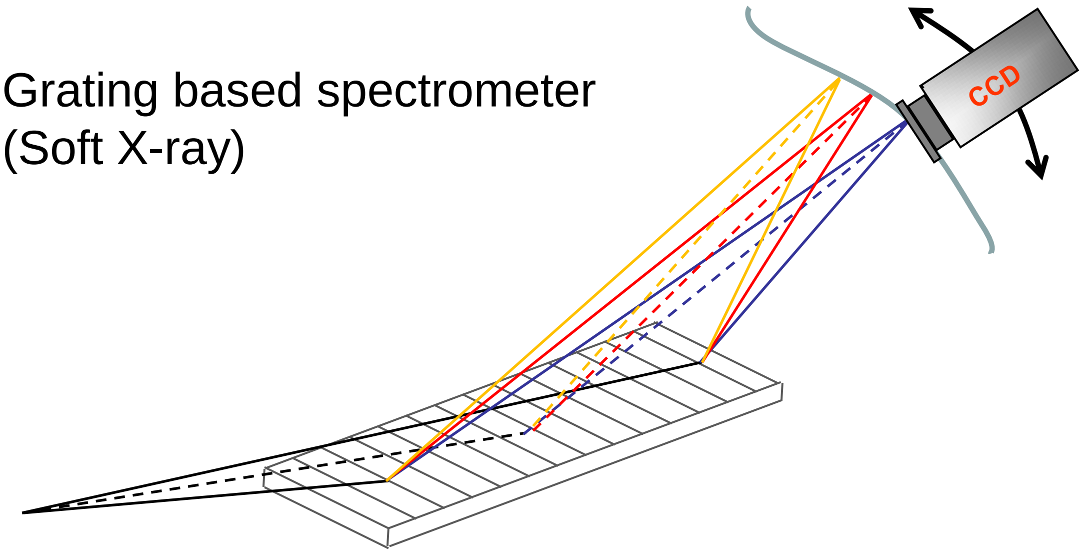
Si (111) d=3.13Å → Emin ≈ 2 keV

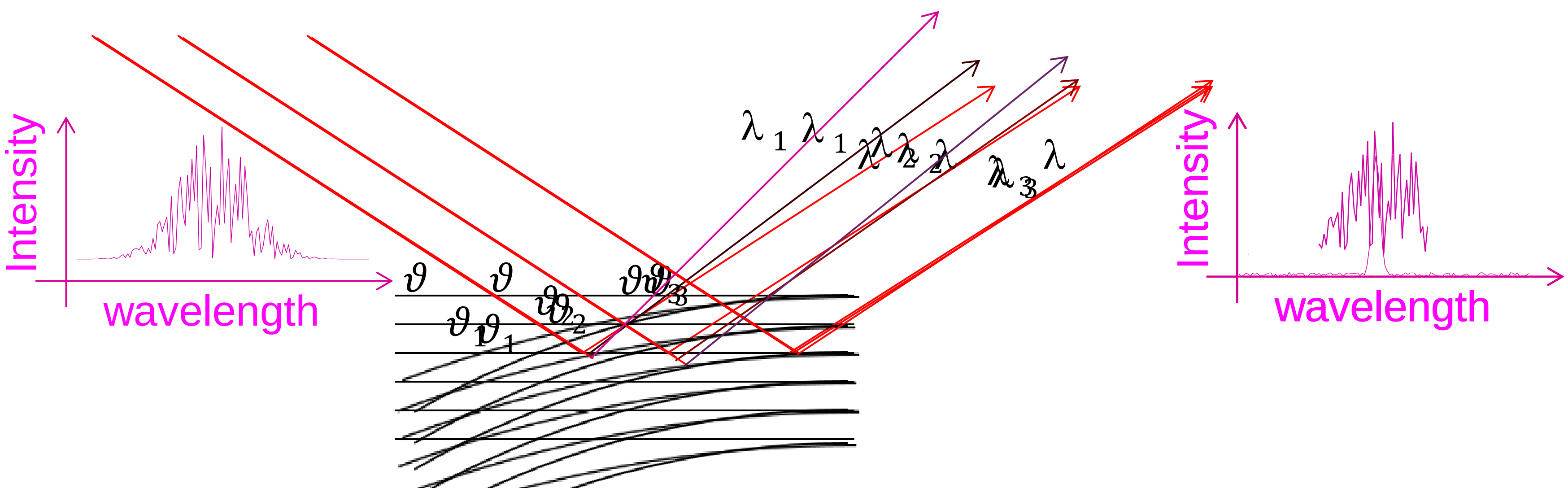
Si (311) d=1.64Å → Emin ≈ 3.8 keV

InSb (111) d=3.74Å → Emin ≈ 1.7 keV

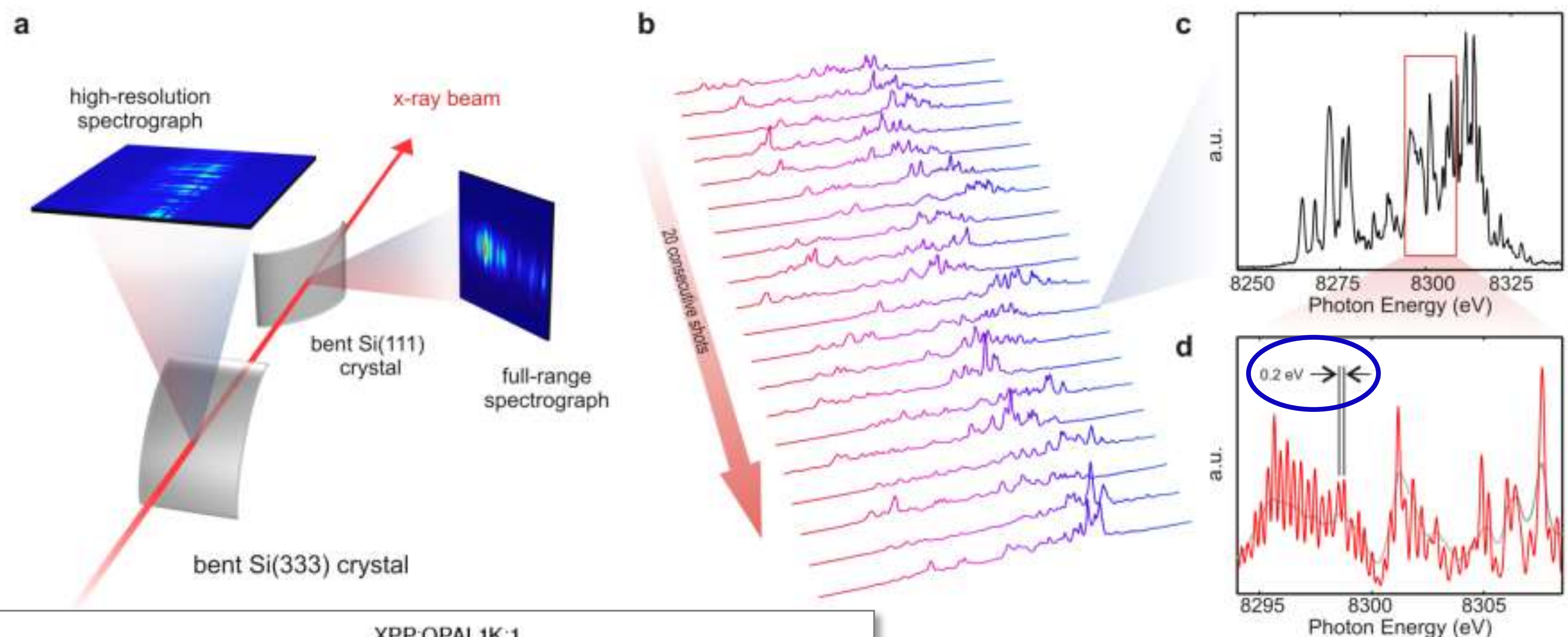
Beryl (10$\bar{1}$0) d=7.98Å → Emin ≈ 0.8 keV

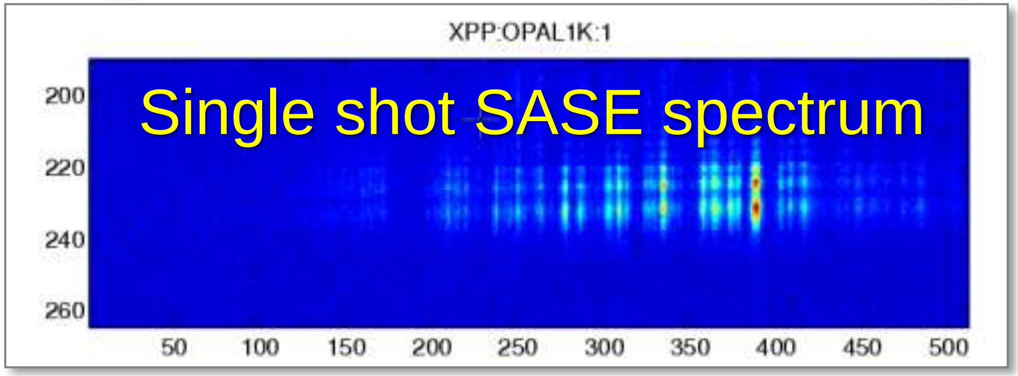
Grating based spectrometer
(Soft X-ray)





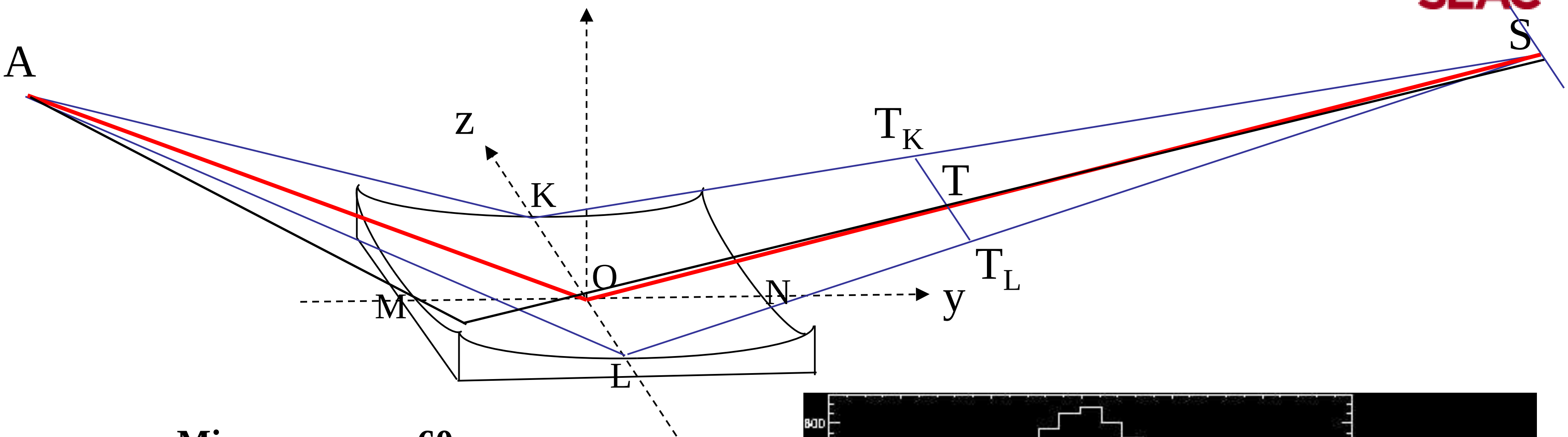
$$2d\sin\vartheta = n\lambda$$



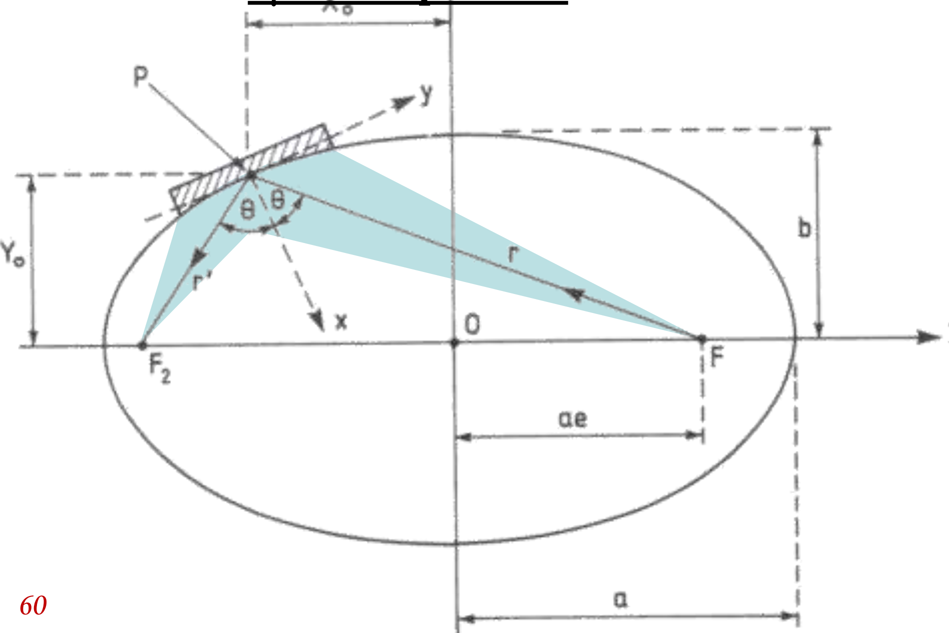


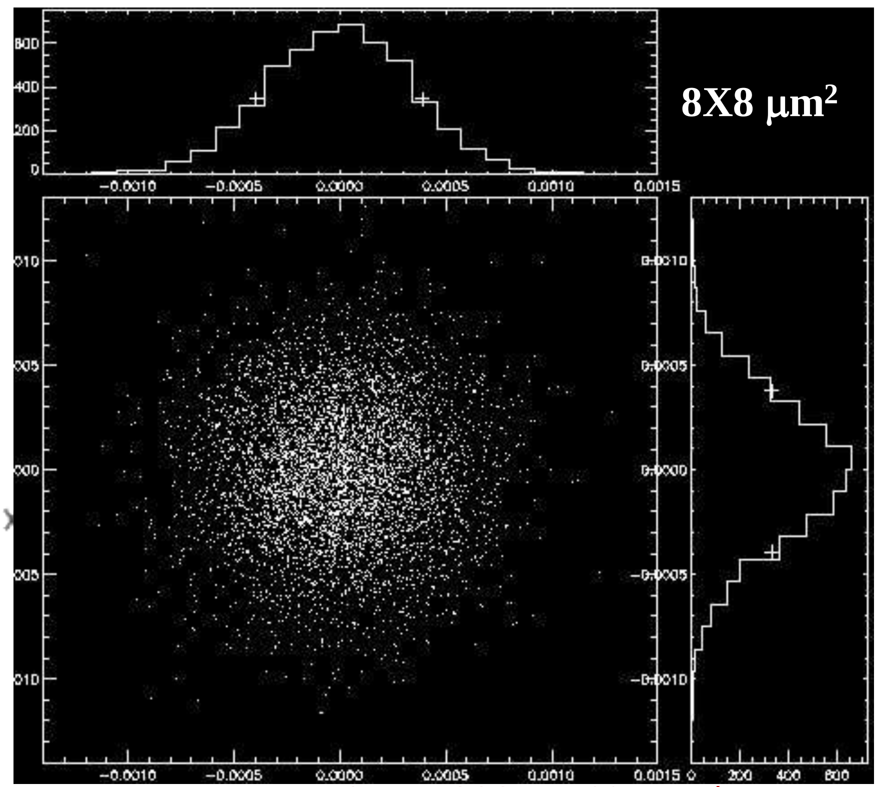
SASE Spike width ≈ 0.2 eV at 8.3 keV (0.002%)

2D focusing – 1 mirror option - Ellipsoid

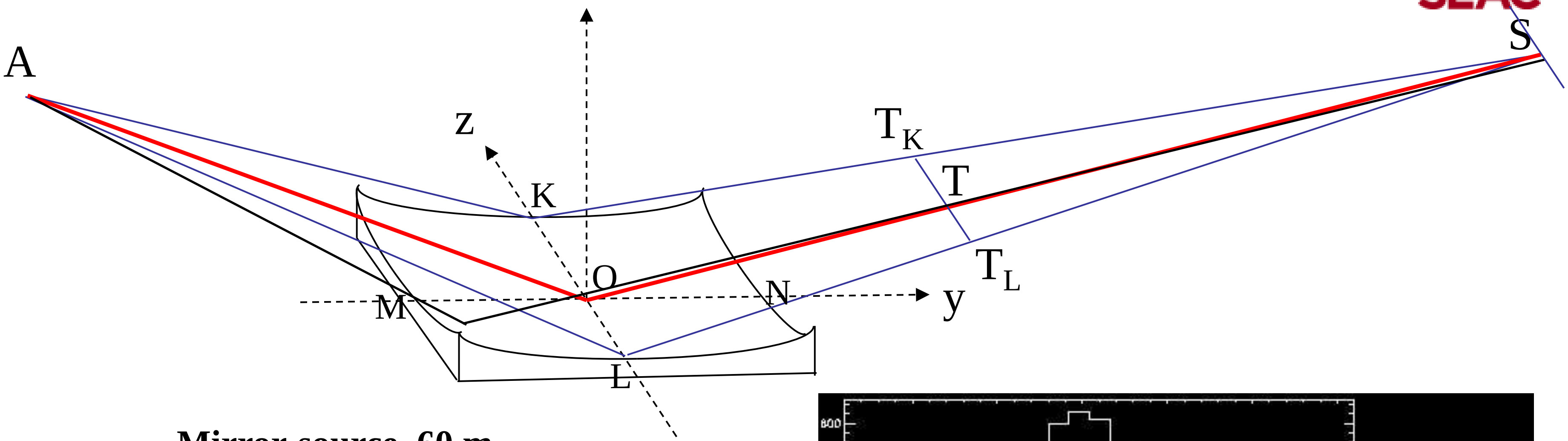


Mirror-source 60 m
Mirror-image 1 m
<u>0μrad slope error</u>

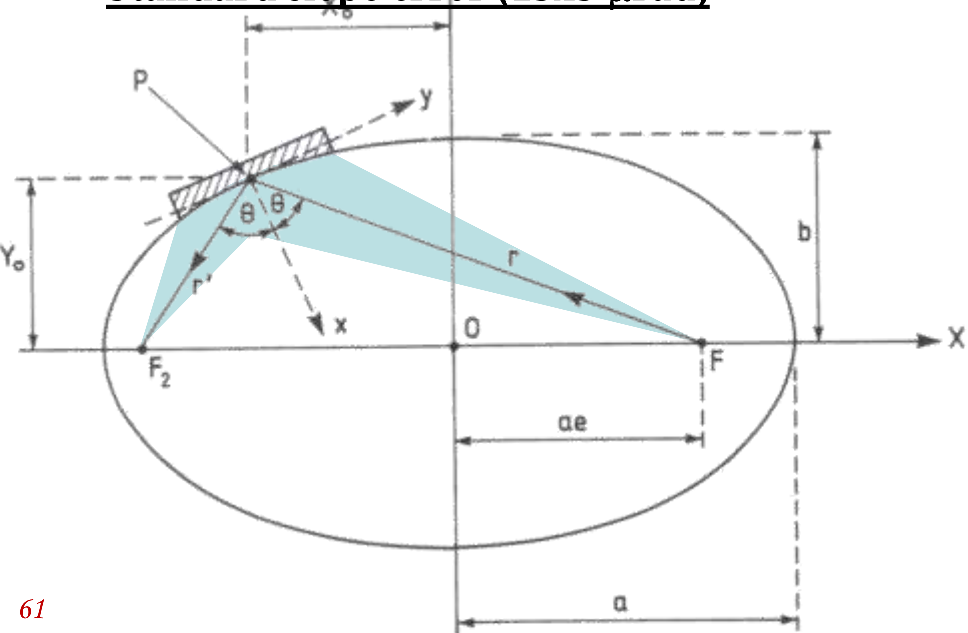


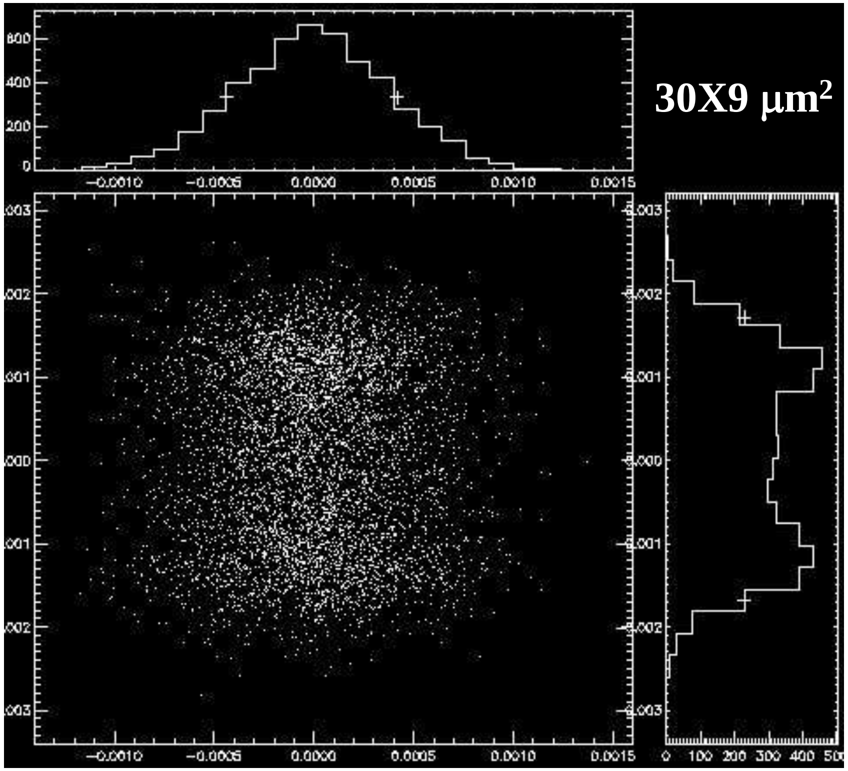


2D focusing – 1 mirror option - Ellipsoid

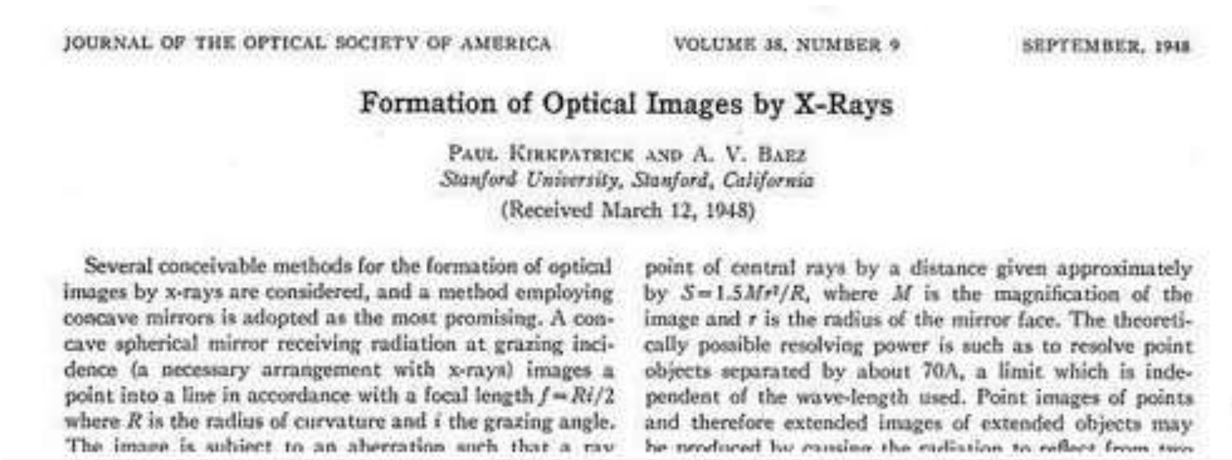


Mirror-source 60 m
Mirror-image 1 m
<u>Standard slope error (15x5 µrad)</u>





2D focusing – 2 mirrors option

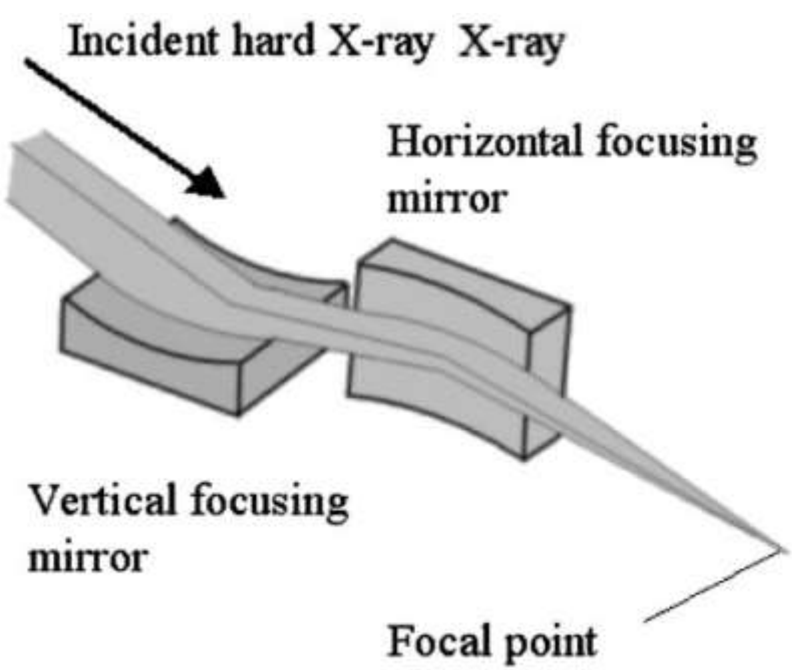

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 9 SEPTEMBER, 1948

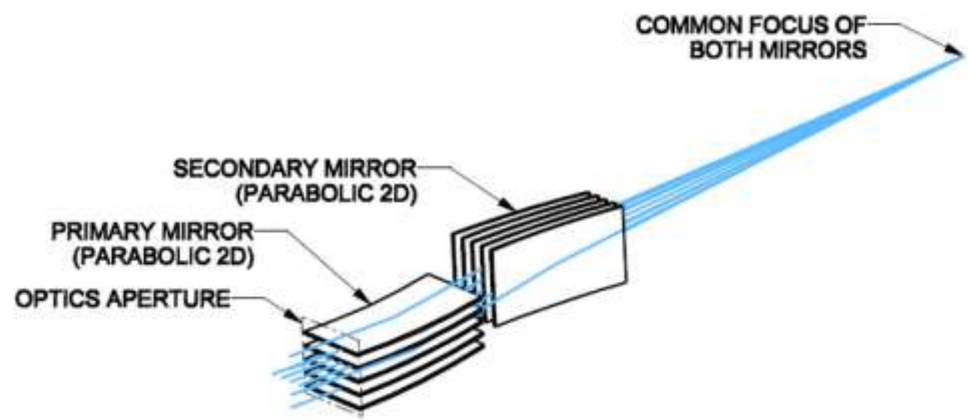
Formation of Optical Images by X-Rays

PAUL KIRKPATRICK AND A. V. BAEZ
Stanford University, Stanford, California
(Received March 12, 1948)

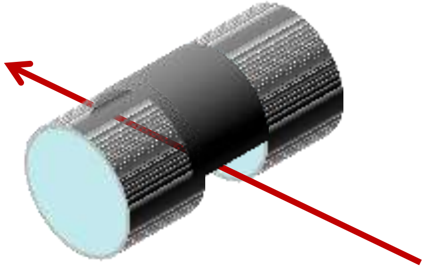
Several conceivable methods for the formation of optical images by x-rays are considered, and a method employing concave mirrors is adopted as the most promising. A concave spherical mirror receiving radiation at grazing incidence (a necessary arrangement with x-rays) images a point into a line in accordance with a focal length $f = Ri/2$ where R is the radius of curvature and i the grazing angle. The image is subject to an aberration such that a ray point of central rays by a distance given approximately by $S = 1.5Mr^2/R$, where M is the magnification of the image and r is the radius of the mirror face. The theoretically possible resolving power is such as to resolve point objects separated by about 70A, a limit which is independent of the wave-length used. Point images of points and therefore extended images of extended objects may be produced by causing the radiation to reflect from two

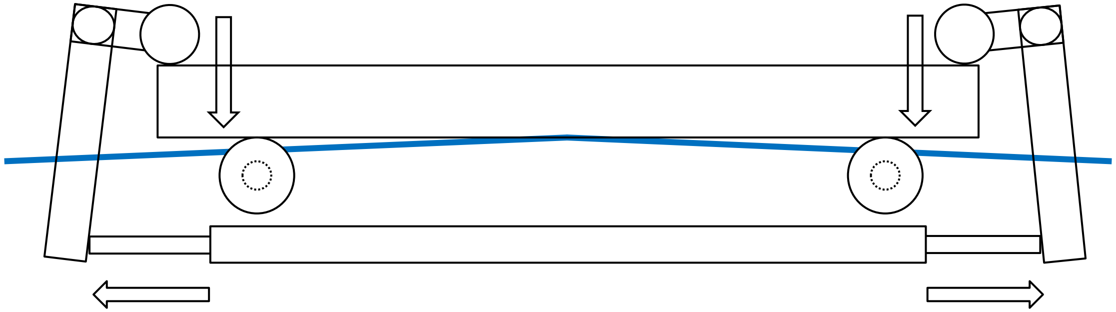
This optical configuration is generally known as KB optics.
Could be made by 2 spherical mirrors, two elliptical mirror or other shapes, static or adaptive.



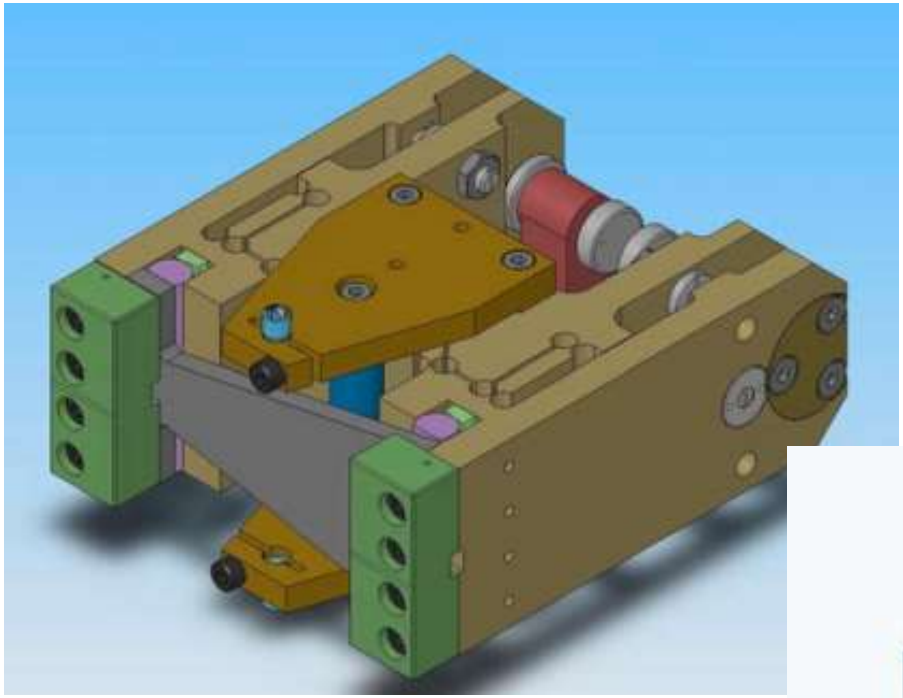


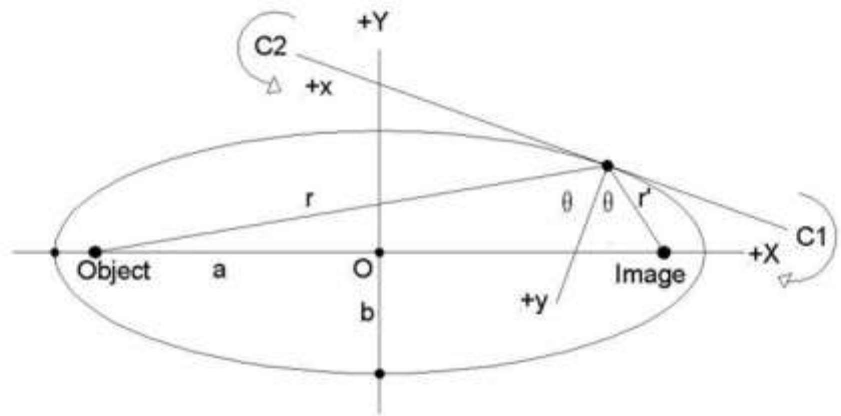
4 cylinders bender (SESO)

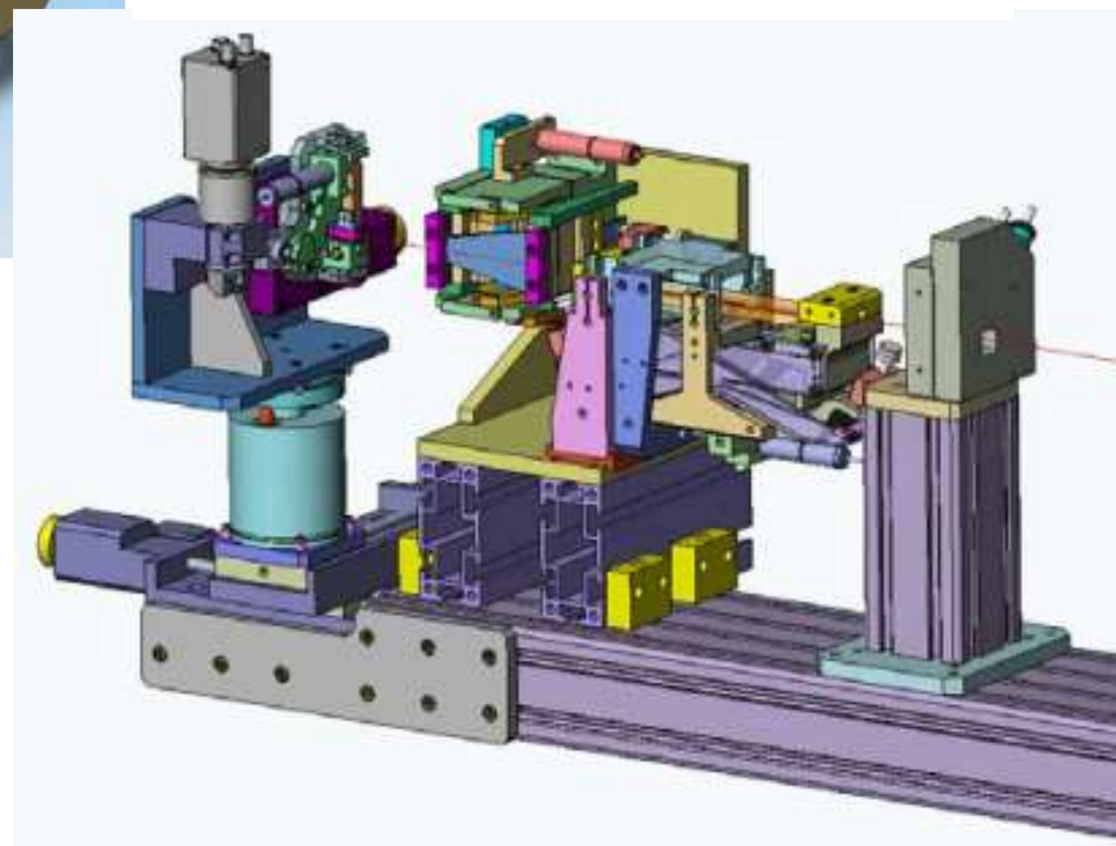




ESRF Trapezoidal Bender

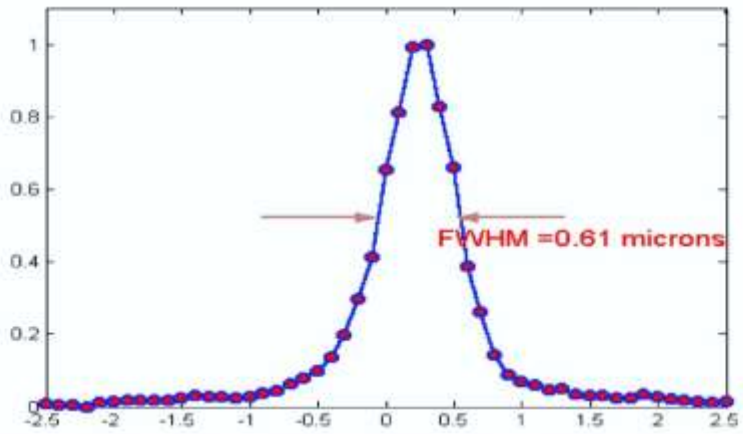




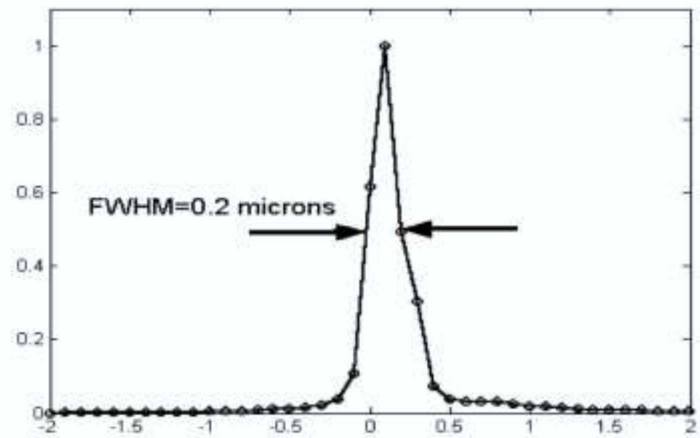


Need to control at least 3 parameter to approximate an ellipse starting from a flat

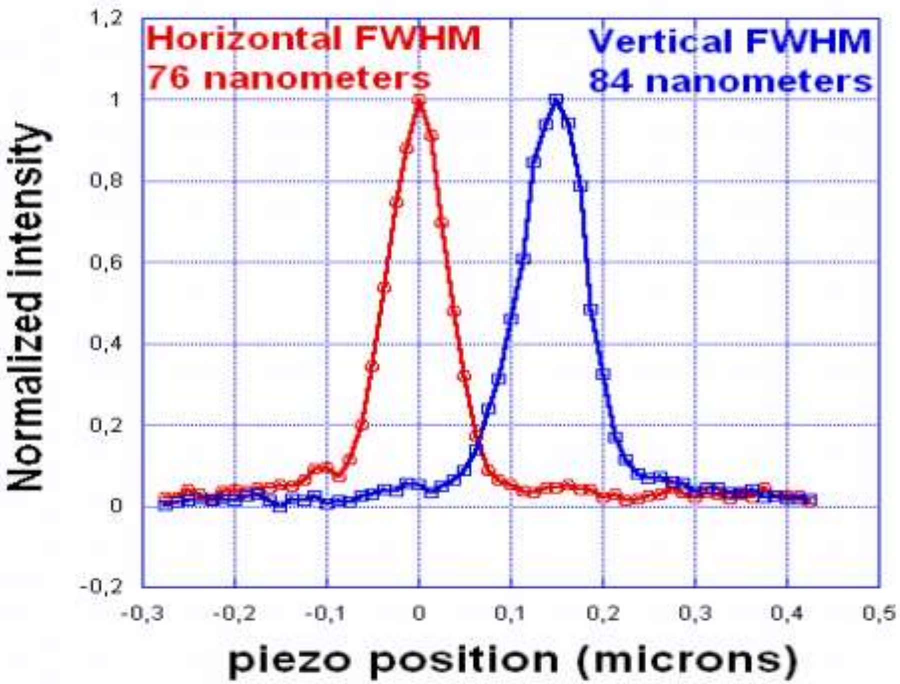
SLAC



ID 22 Spot size measurement



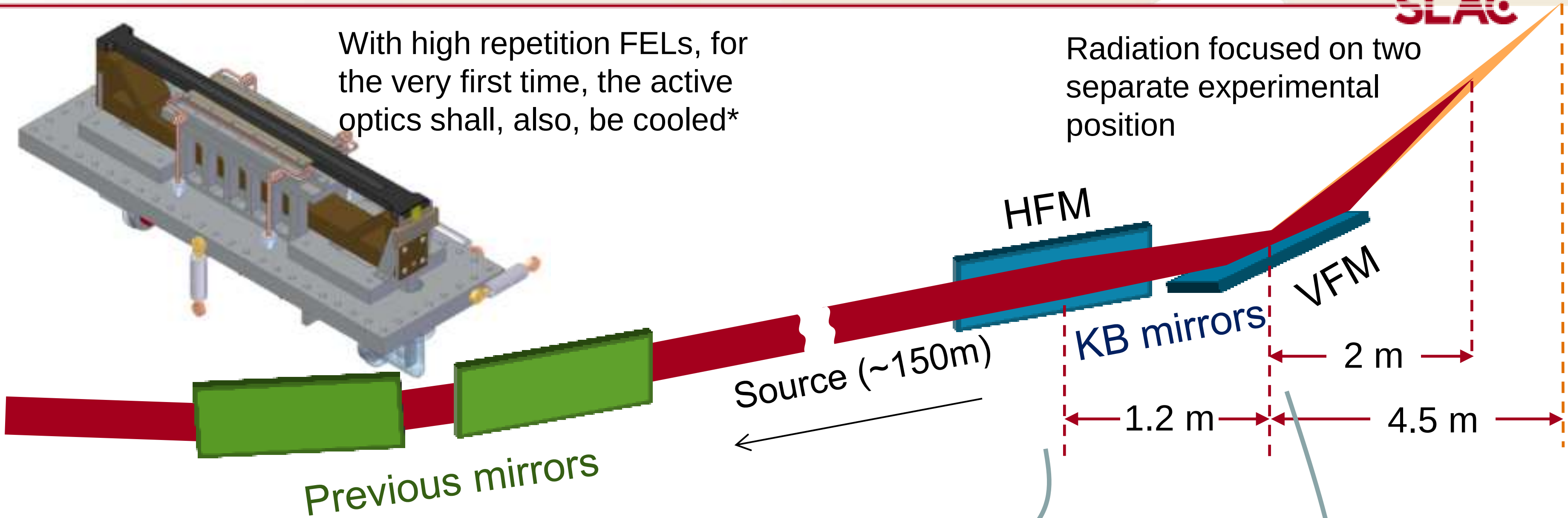
Horizontal scan

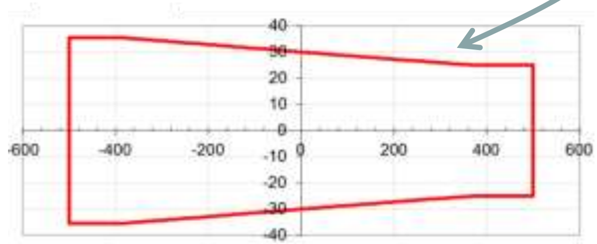


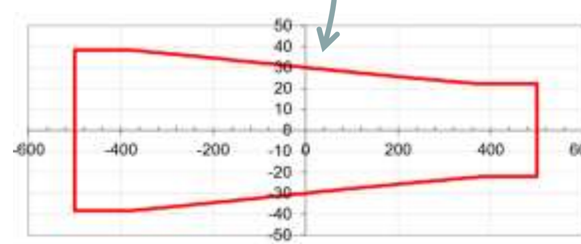
KB system for high power FELs

With high repetition FELs, for the very first time, the active optics shall, also, be cooled*

Radiation focused on two separate experimental position



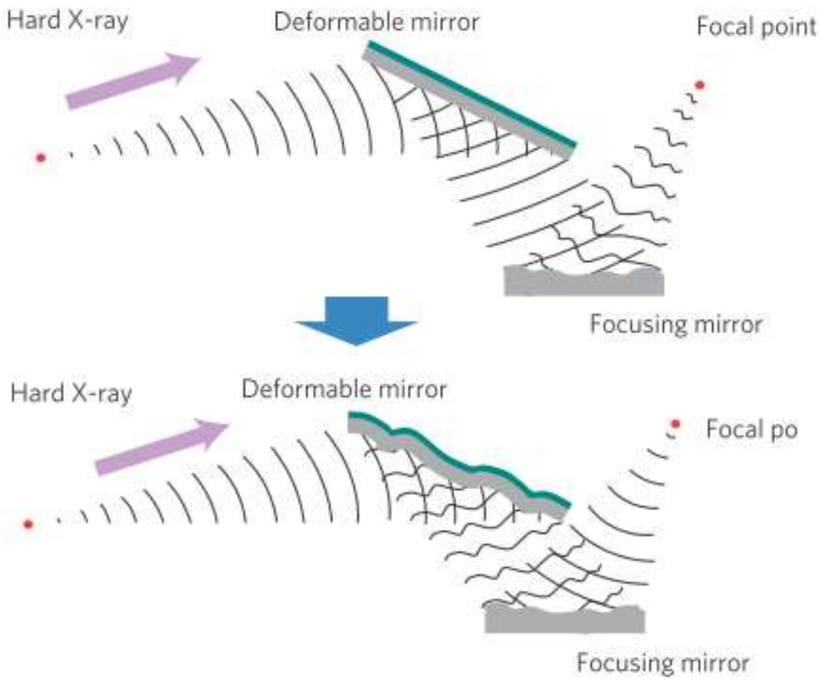


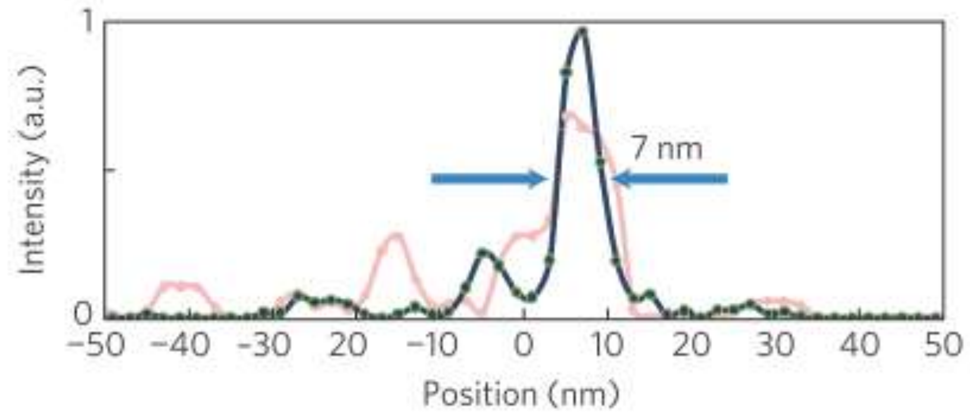


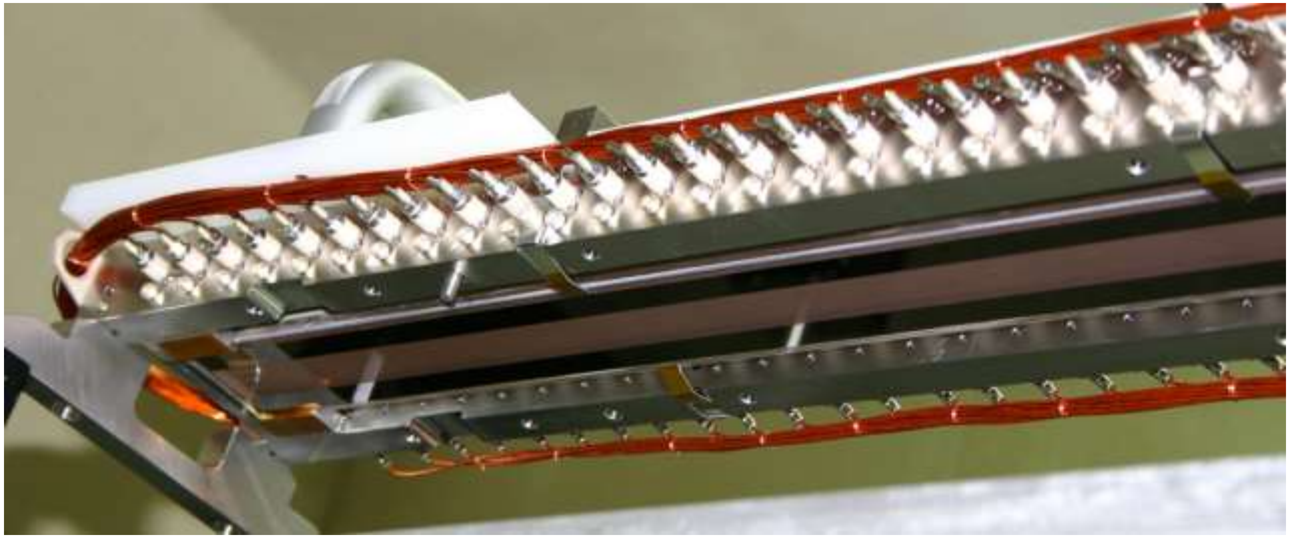
Virtually no residual rms slope errors when focusing in the 1st chamber → **~0.9X1.2 μm² spot 1st chamber**

Residual rms slope errors when focusing in the second chamber → HFM: 0.13 μrad, VFM: 0.42 μrad → **~3X5μm² spot 2nd chamber**

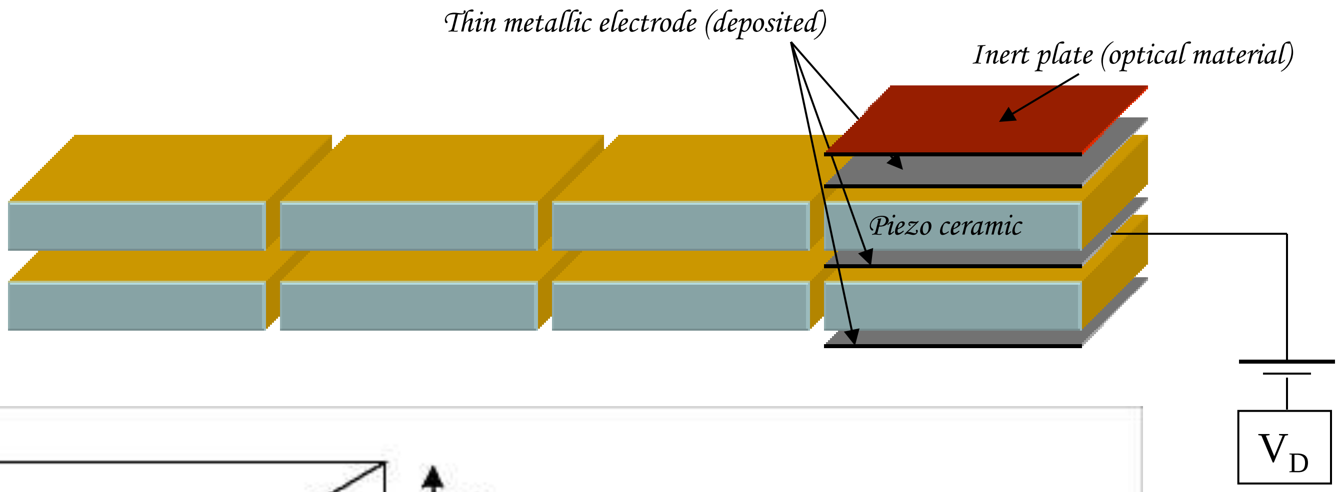
*KB system design by D. Morton, L. Zhang

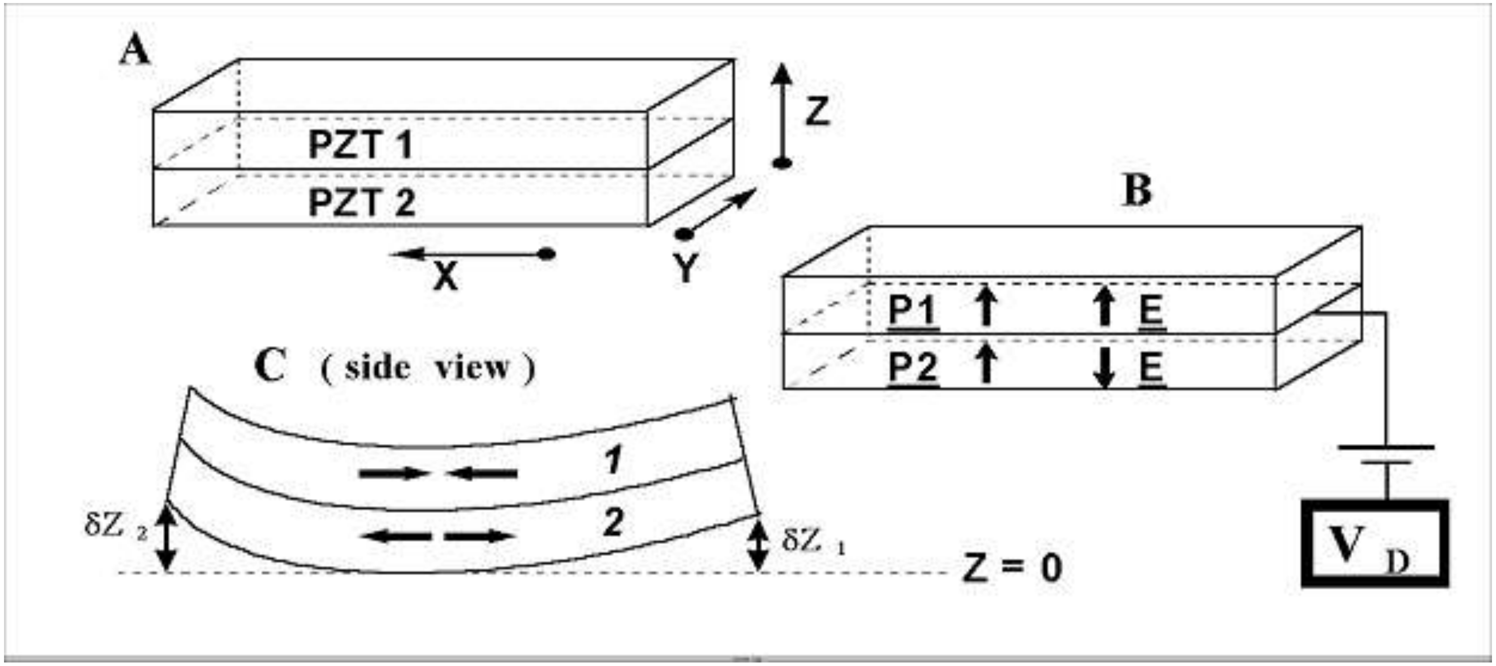

Hard X-ray
Deformable mirror
Focal point
Focusing mirror
Hard X-ray
Deformable mirror
Focal po
Focusing mirror


Intensity (a.u.)
1
0
7 nm
−50 −40 -30 20 −10 0 10 20 30 40 50
Position (nm)

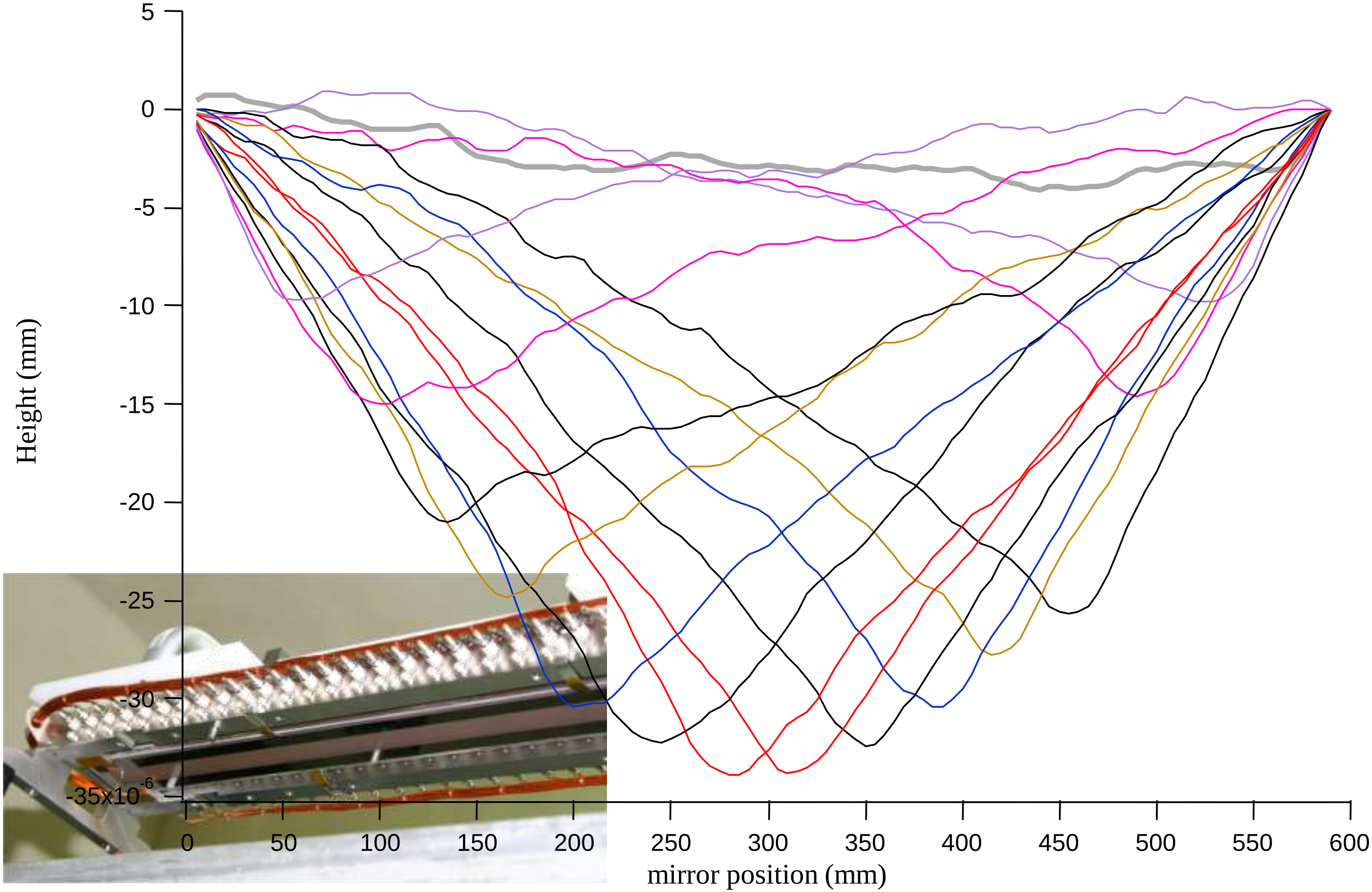


Bimorph Mirrors



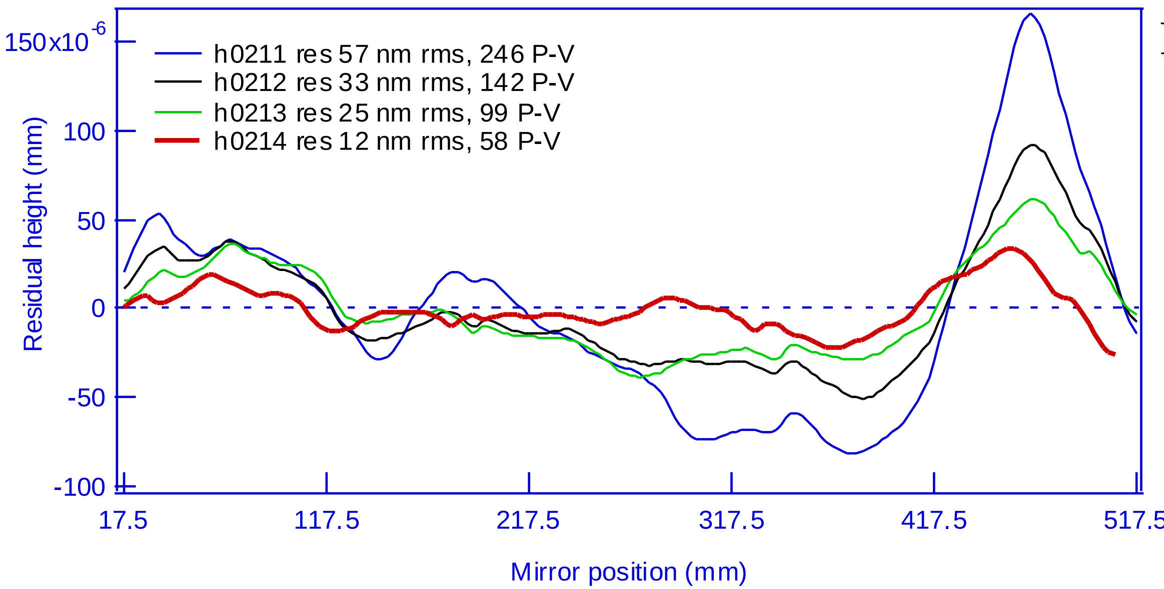


Correction Matrix

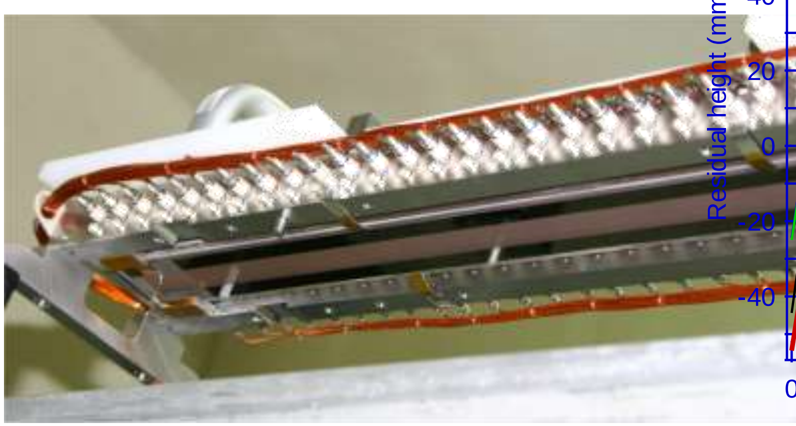


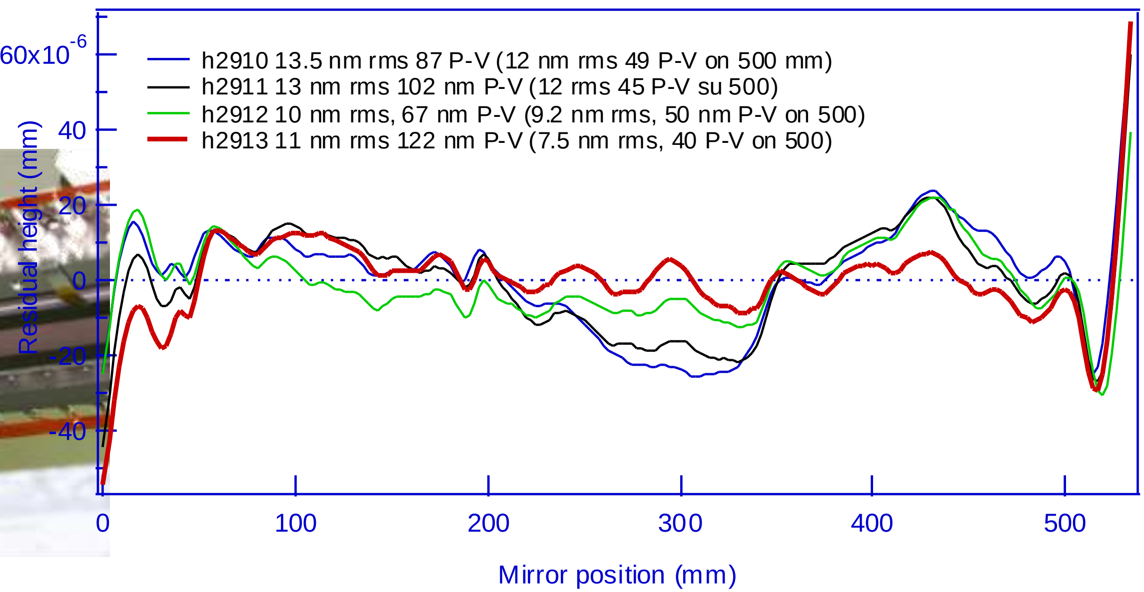
Shape Correction

R=2 Km



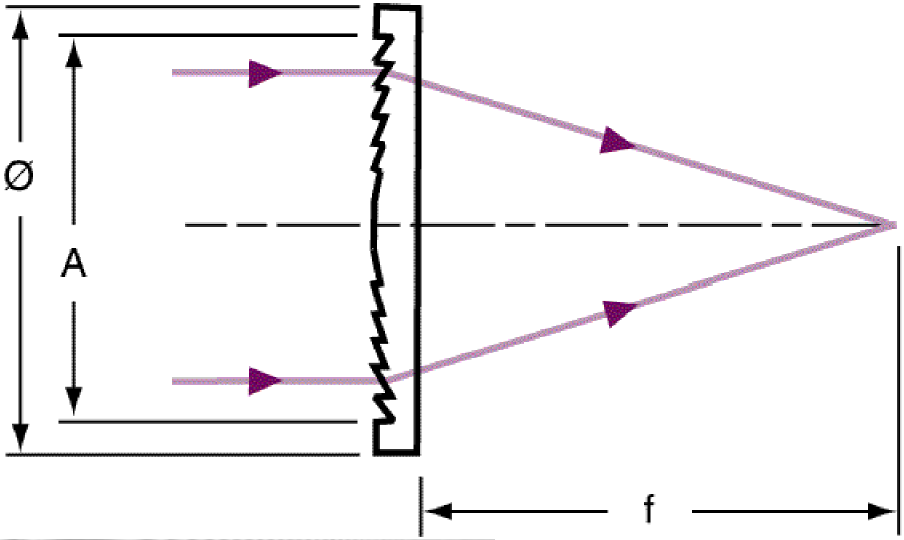
R=4.5 Km

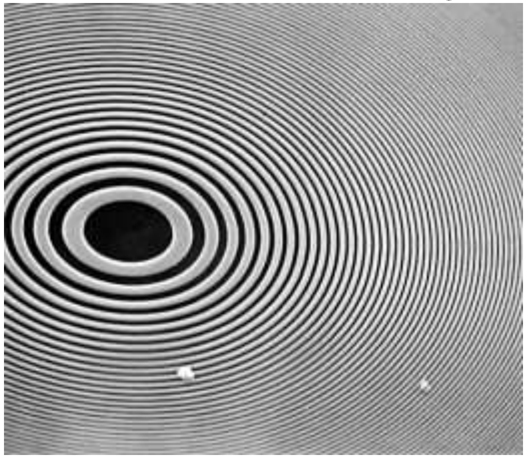




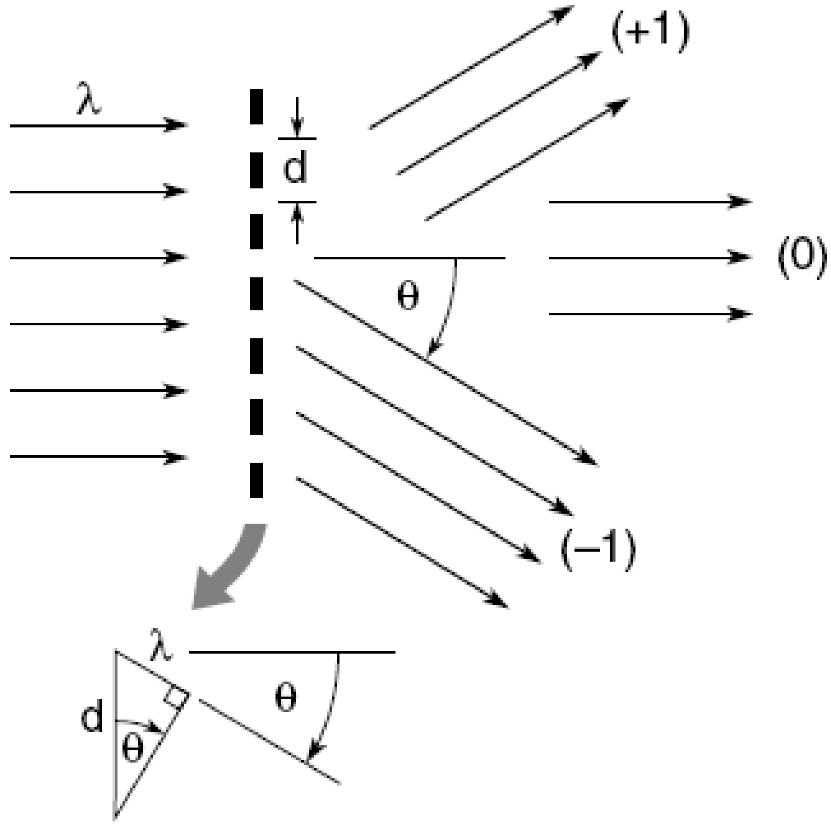
Zone Plate

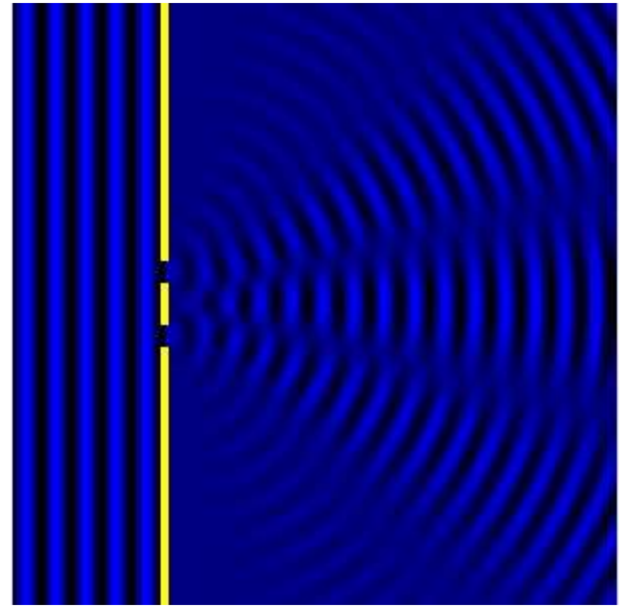
Fresnel lens

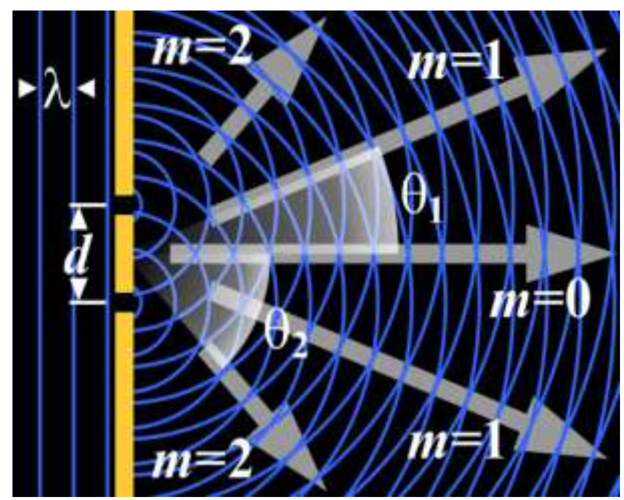




$$\sin\theta_m = \frac{m\lambda}{d}\ ; \quad m = 0,\ \pm1,\ \pm2,\ \pm3,$$

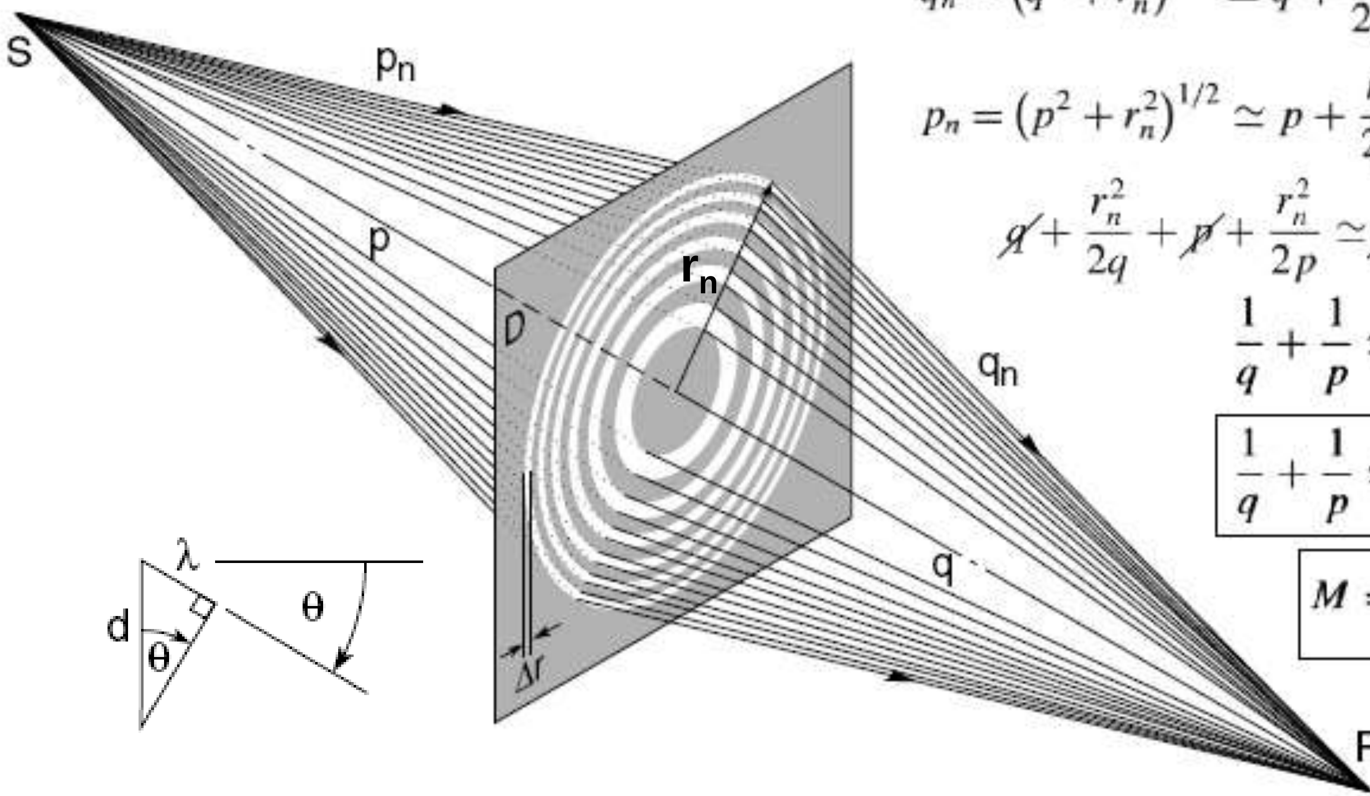






Zone Plate

$$r_n^2 = fn\lambda$$



$$q_n + p_n = q + p + \frac{n\lambda}{2}$$

$$q_n = (q^2 + r_n^2)^{1/2} \simeq q + \frac{r_n^2}{2q}$$

$$p_n = (p^2 + r_n^2)^{1/2} \simeq p + \frac{r_n^2}{2p}$$

$$\not{q} + \frac{r_n^2}{2q} + \not{p} + \frac{r_n^2}{2p} \simeq \not{q} + \not{p} + \frac{n\lambda}{2}$$

$$\frac{1}{q} + \frac{1}{p} \simeq \frac{n\lambda}{r_n^2}$$

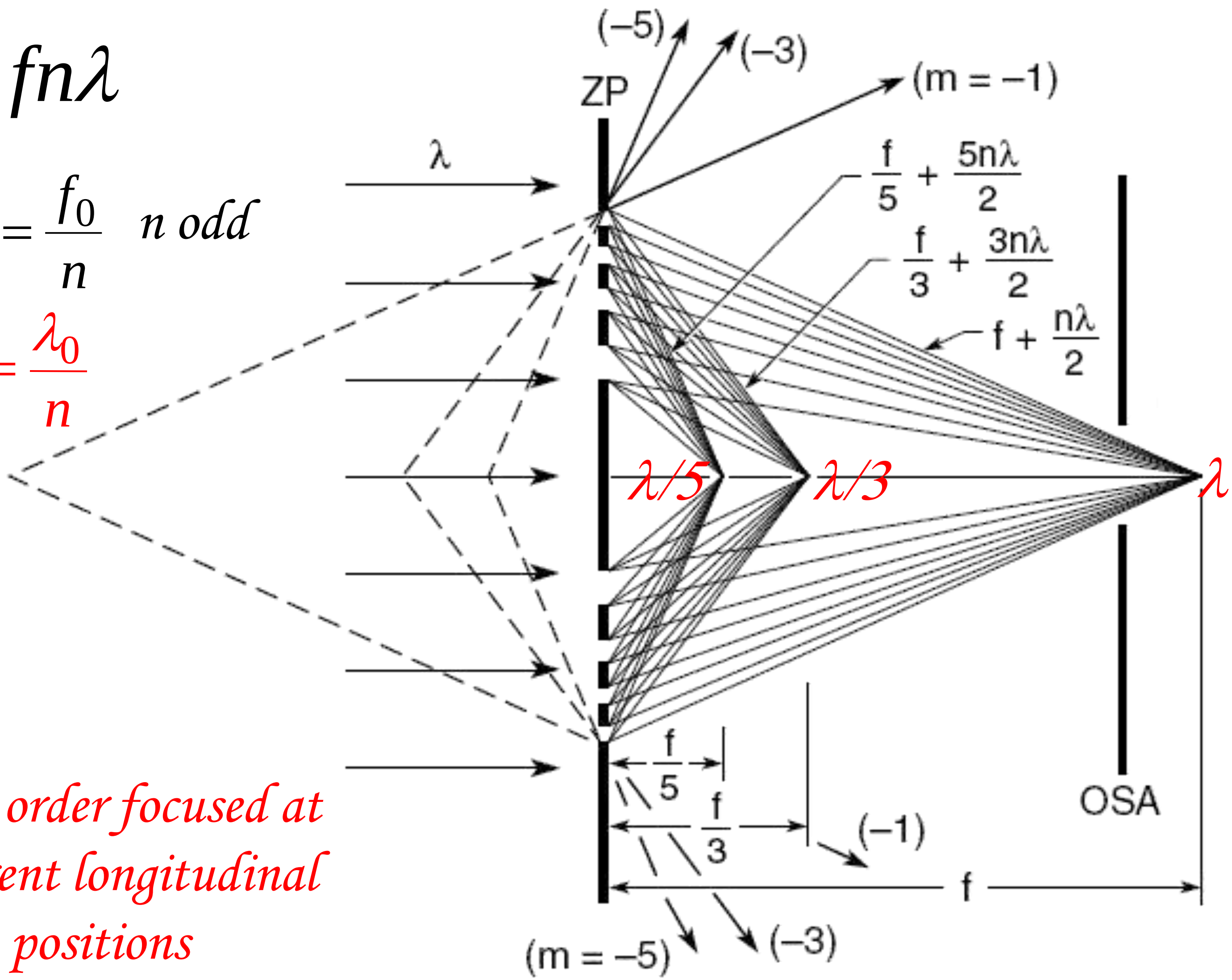
$$\boxed{\frac{1}{q} + \frac{1}{p} \simeq \frac{1}{f}}$$

$$\boxed{M = \frac{p}{q}}$$

$$r_n^2 = fn\lambda$$

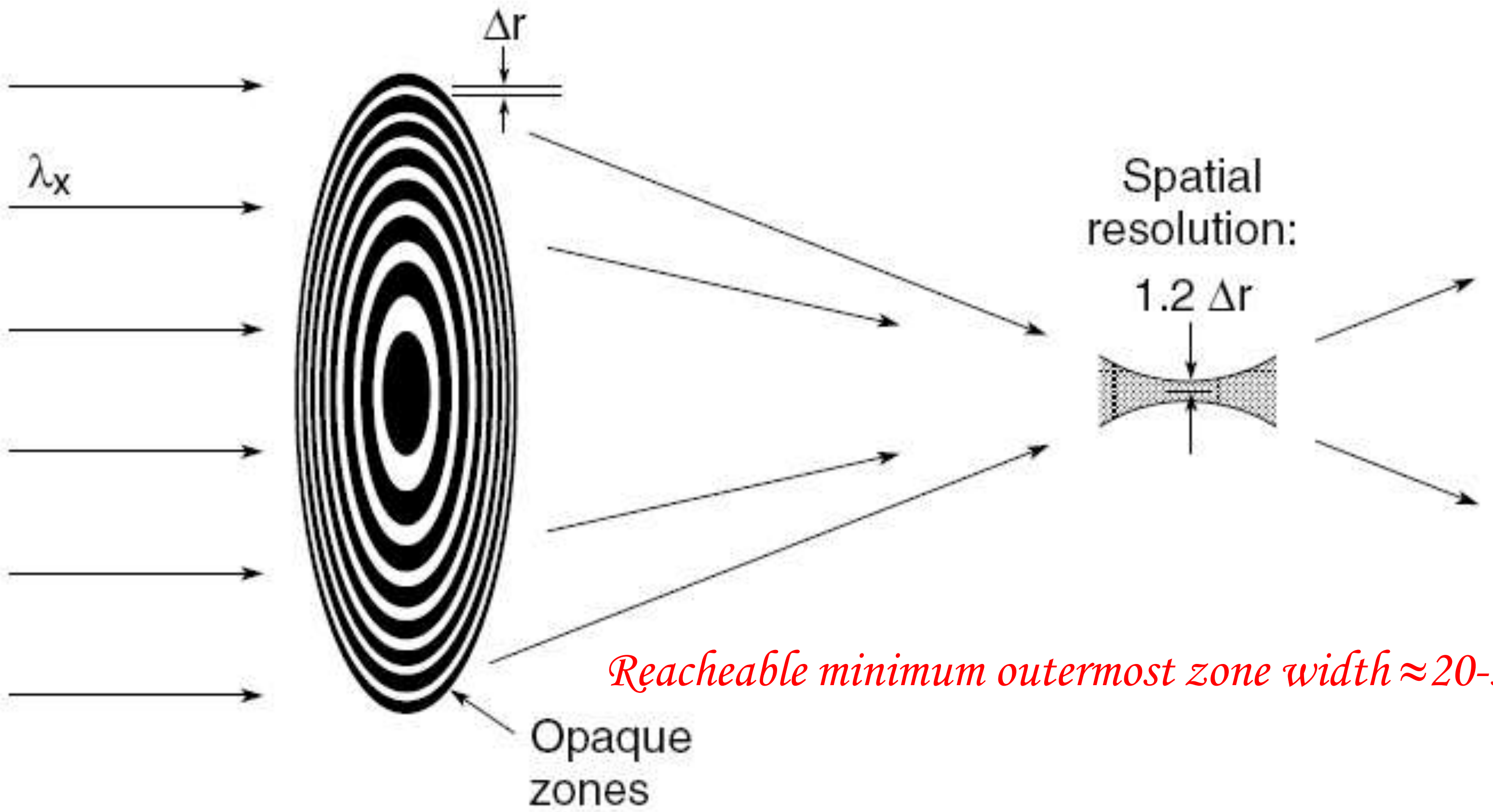
$$f = \frac{r_n^2}{n\lambda} = \frac{f_0}{n} \quad n \text{ odd}$$

$$\lambda = \frac{r_n^2}{nf} = \frac{\lambda_0}{n}$$



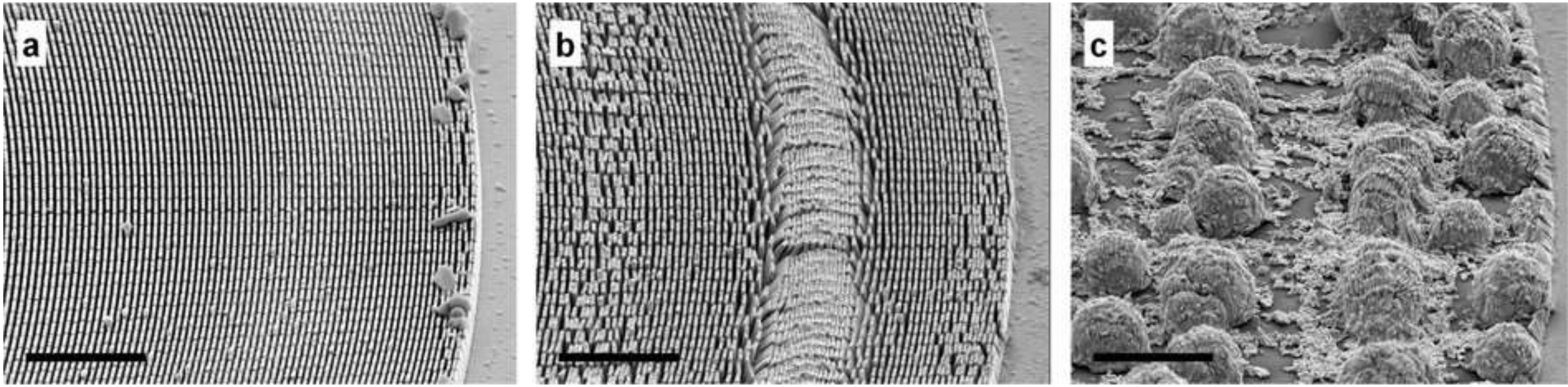
Higer order focused at different longitudinal positions

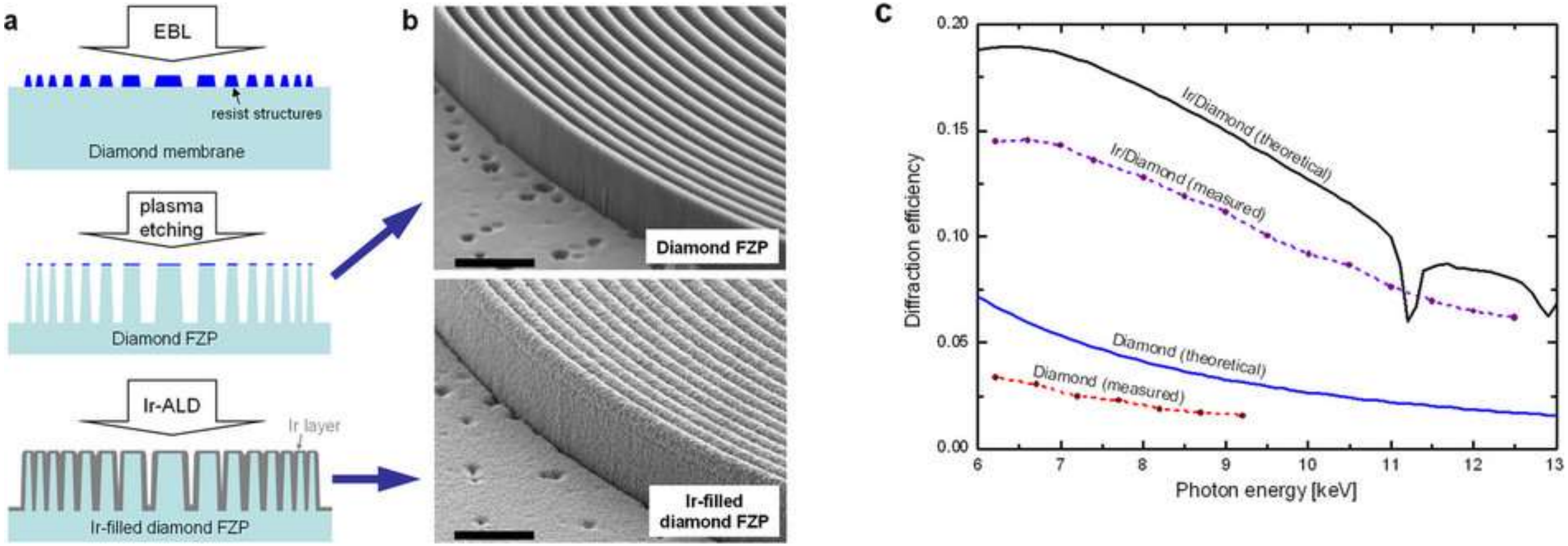
Zone Plate



Reacheable minimum outermost zone width ≈ 20-30 nm

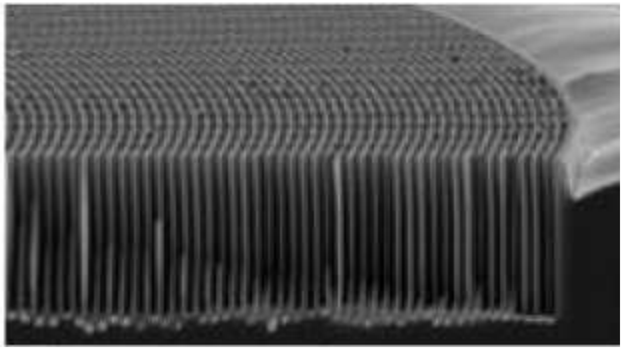
Zone Plates under FEL beam

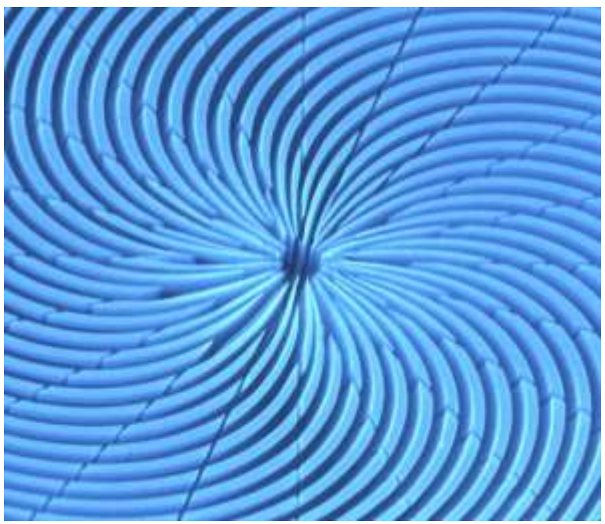


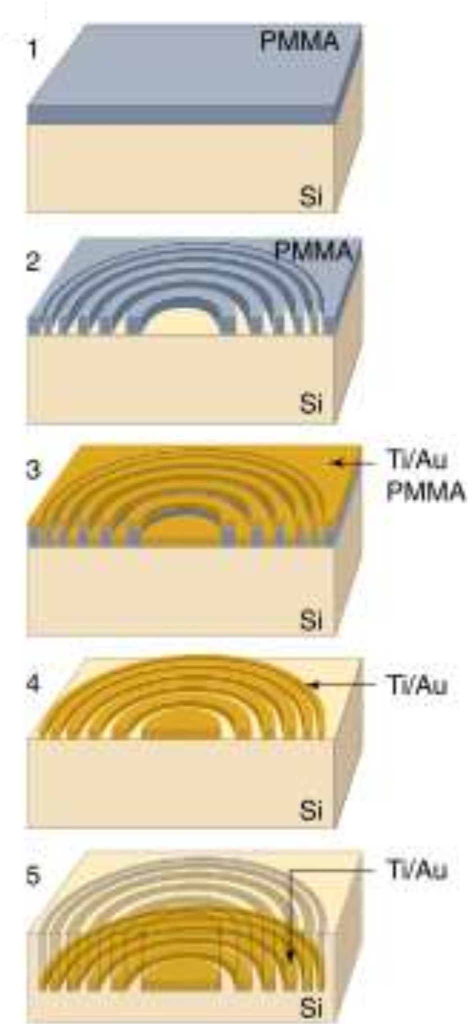


Courtesy by C. David

High Aspect Ration Zone Plate







Scanning electron microscope (SEM) images of **zone plates** pattern produced with the V-MACE technique.
(Ref. Chieh Chang, Anne Sakdinawat)

Very good efficiency on the HXR but… does it survive the FEL radiation?

1 µm

Literature

Books/tutorials

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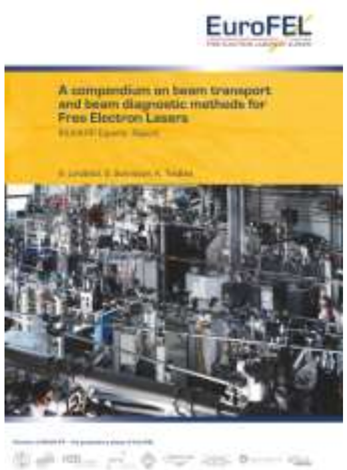

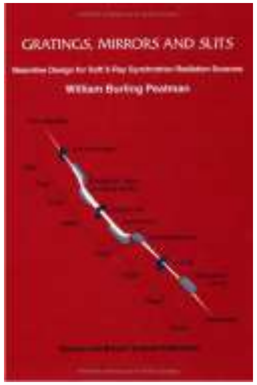

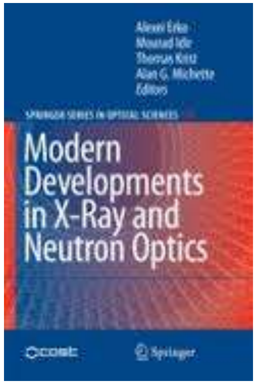

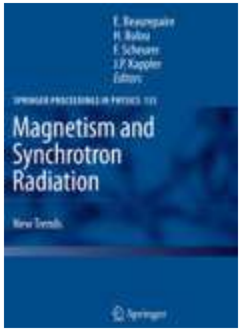

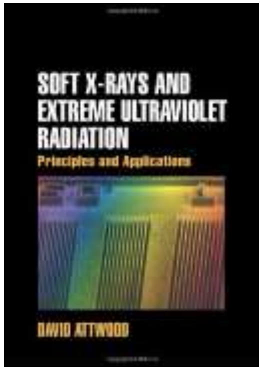

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