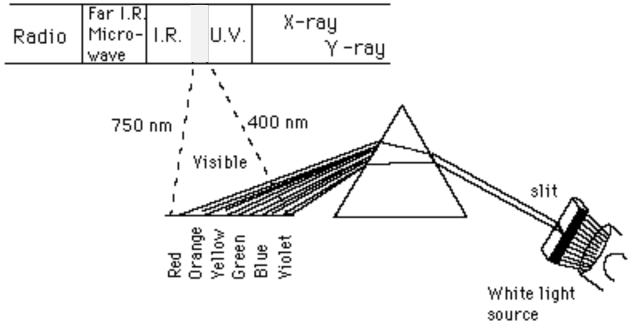
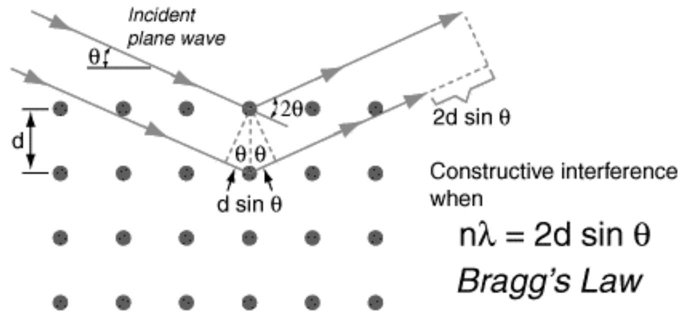
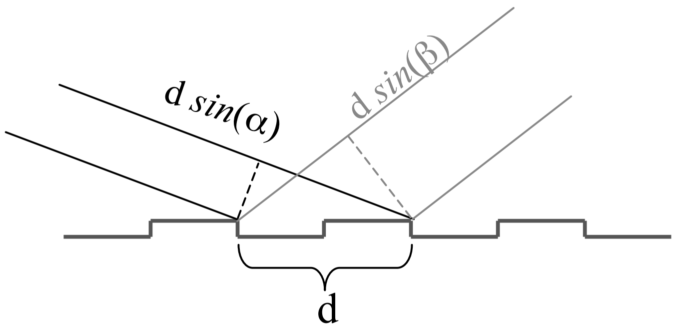
HXR monochromators

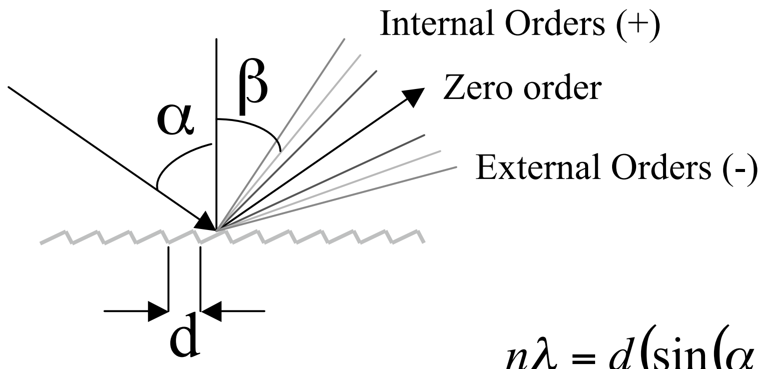


Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



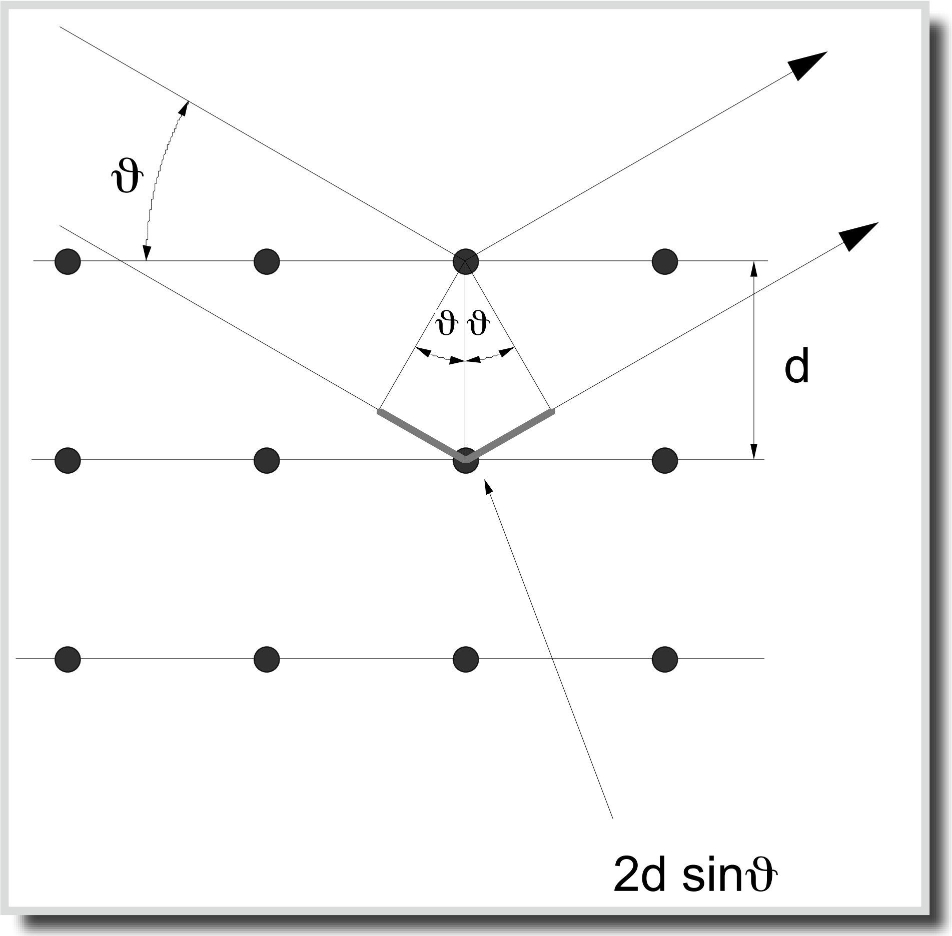
Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray





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

Bragg law



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:

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

$$\lambda_{max} = 2d \quad @\ \theta = 90°$$

EXAMPLES:

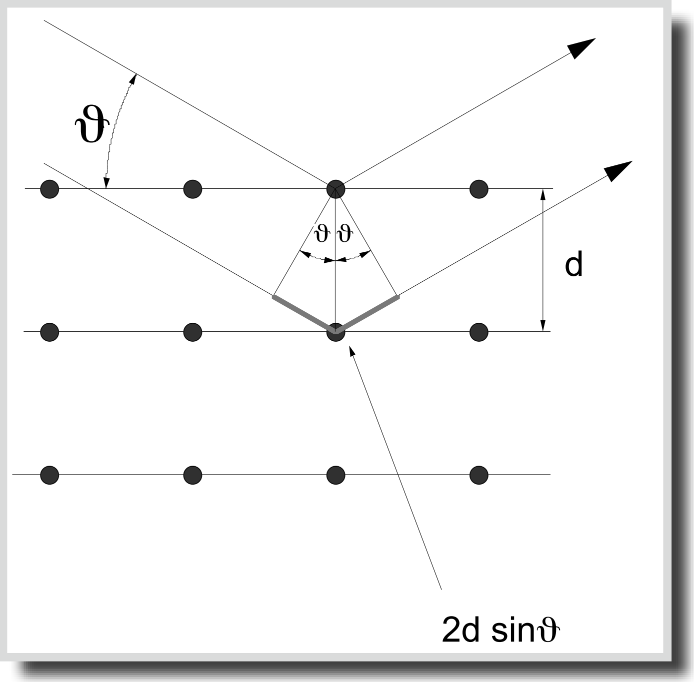
Si (111) d=3.13Å → Emin ≈ 2 keV

Si (311) d=1.64Å → Emin ≈ 3.8 keV

InSb (111) d=3.74Å → Emin ≈ 1.7 keV

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

Energy Resolution



$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta E}{E} = \Delta\vartheta \cot g(\vartheta)$$

$$\frac{\delta\lambda}{\delta\vartheta} = \frac{2d\cos\vartheta}{n} \rightarrow \frac{\delta\lambda}{\lambda} = \frac{2d\cos\vartheta}{n} * \frac{n}{2d\sin\vartheta} * \delta\vartheta$$

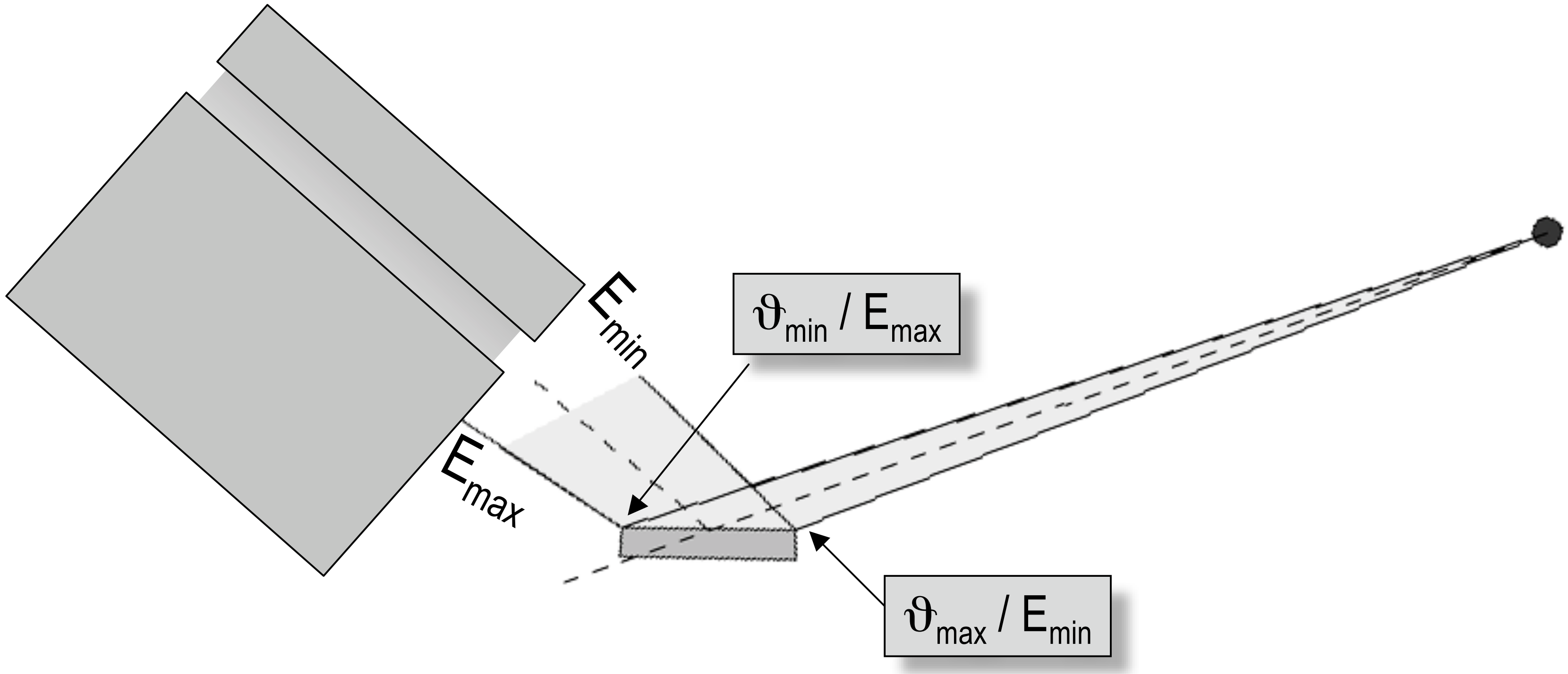
$\Delta\vartheta$ *has two contribution :*

$\Delta\vartheta_{beam}$ *beam angular divergence*

$\omega_{crystal}$ *intrinsic reflection width of the monochromator*

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

Beam divergence



$$2d \cdot \sin\vartheta_{\min} = n\lambda_0$$

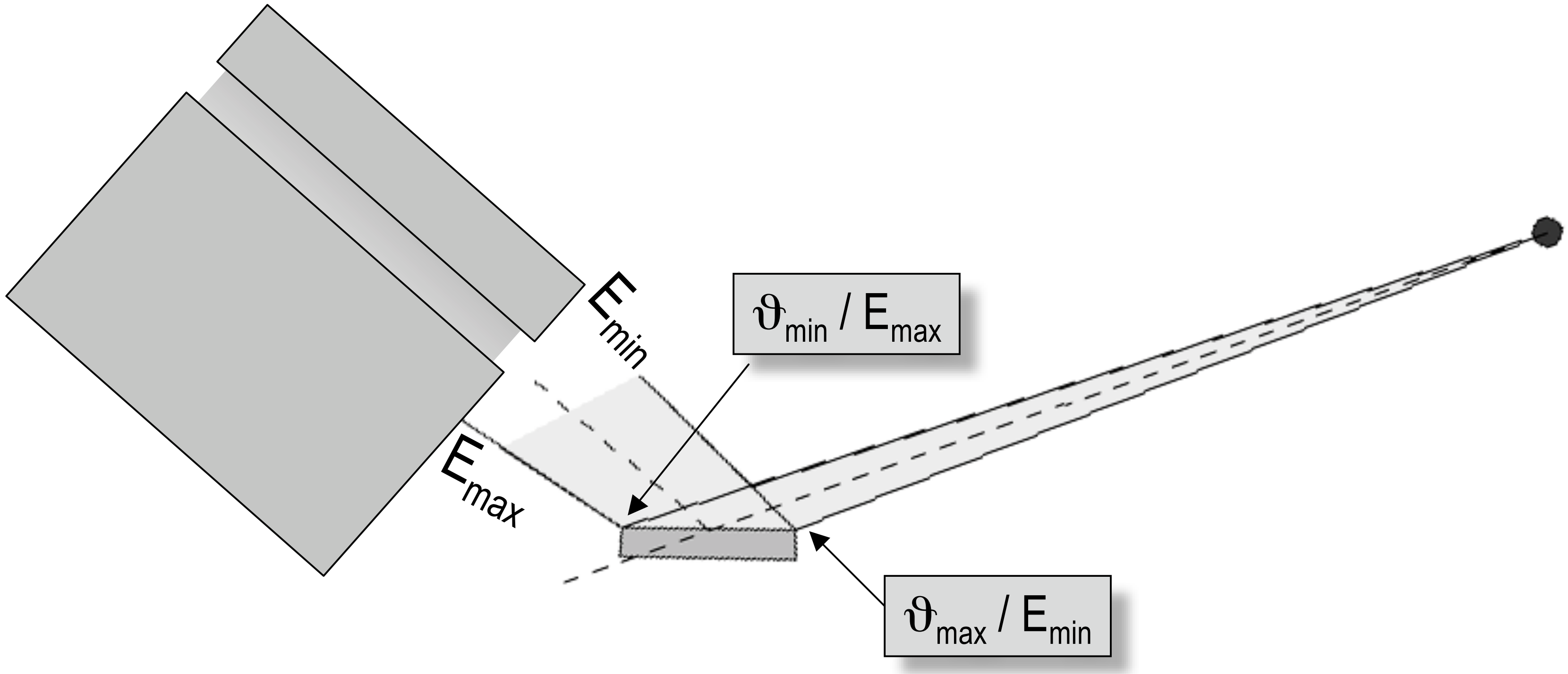
$$2d \cdot \sin\vartheta = n\lambda$$

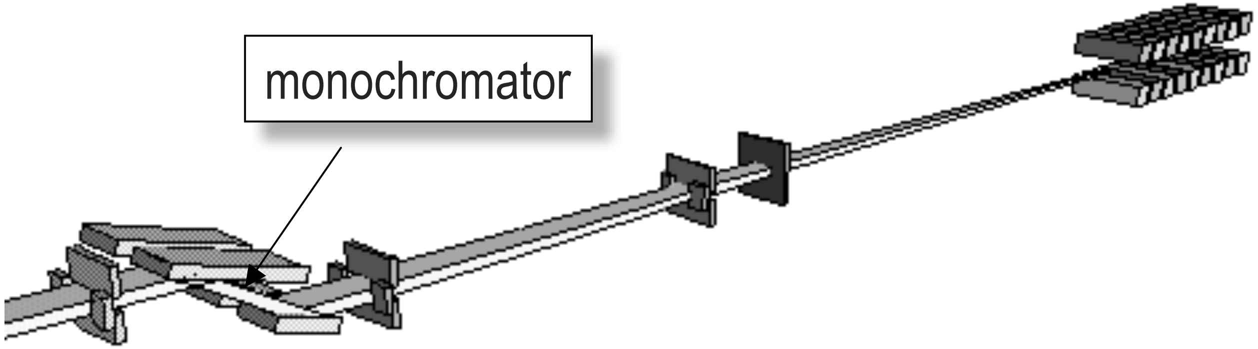
$$\Delta\vartheta = \vartheta_{\max} - \vartheta_{\min}$$

$$\Delta\lambda \propto \Delta\vartheta$$

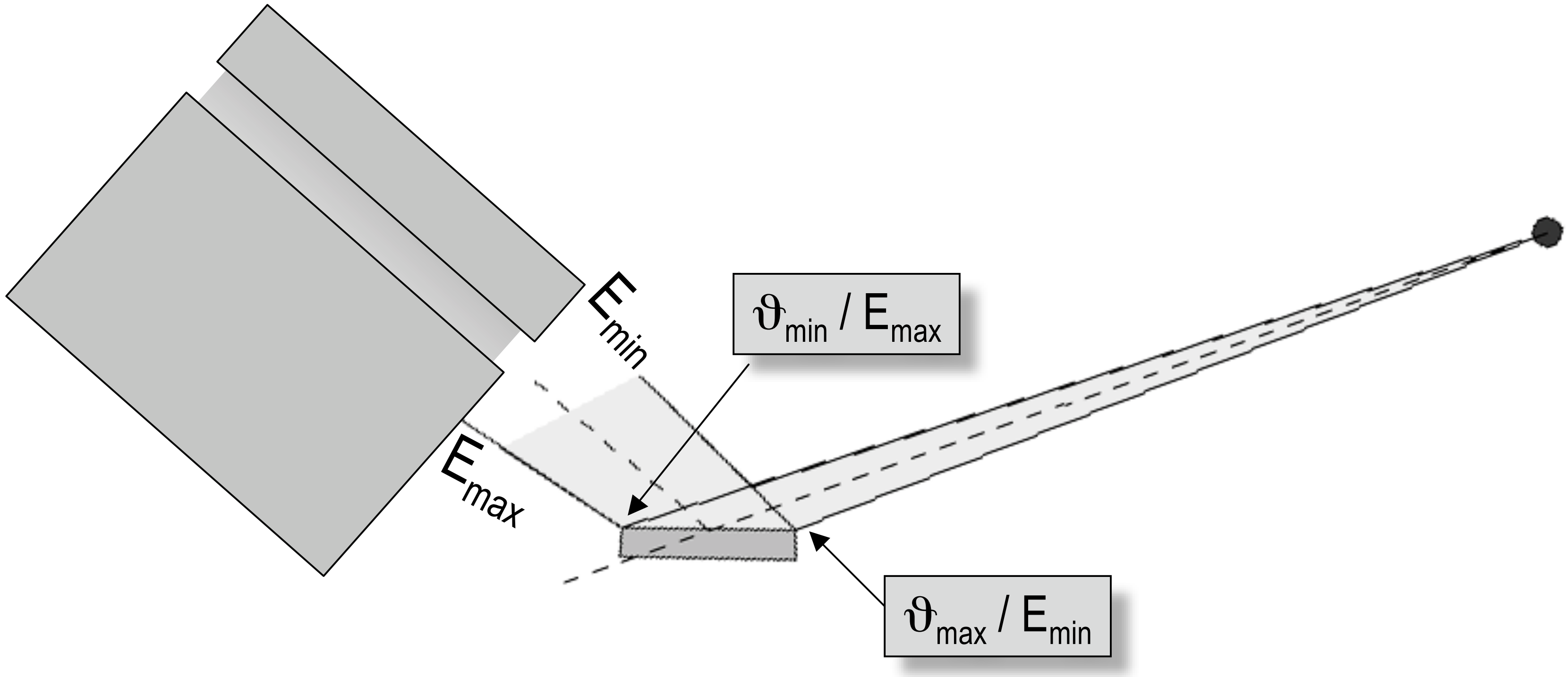
$$2d \cdot \sin\vartheta_{\max} = n\lambda_1$$

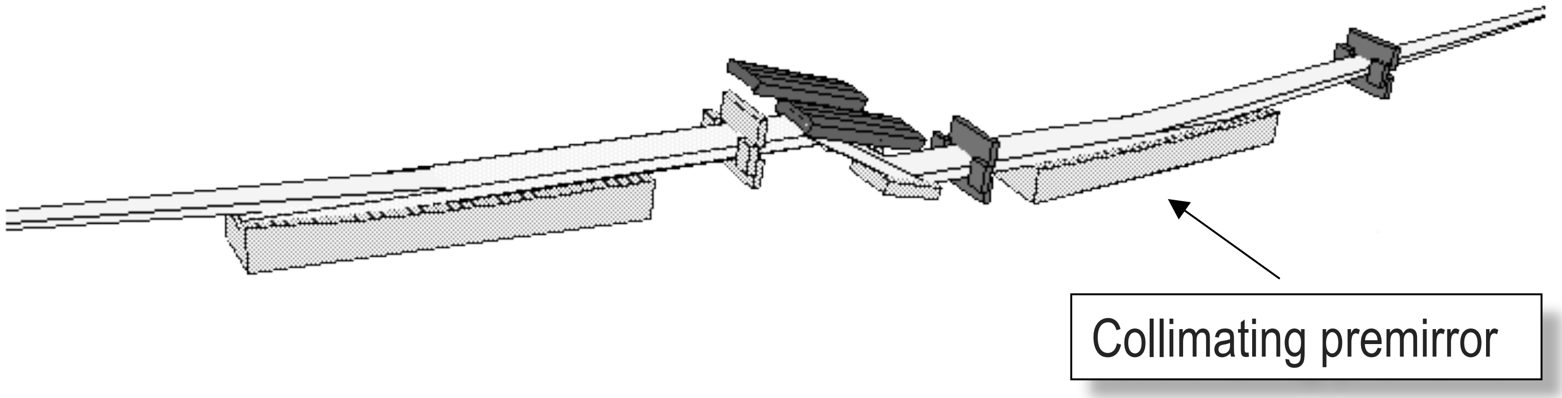
Beam divergence



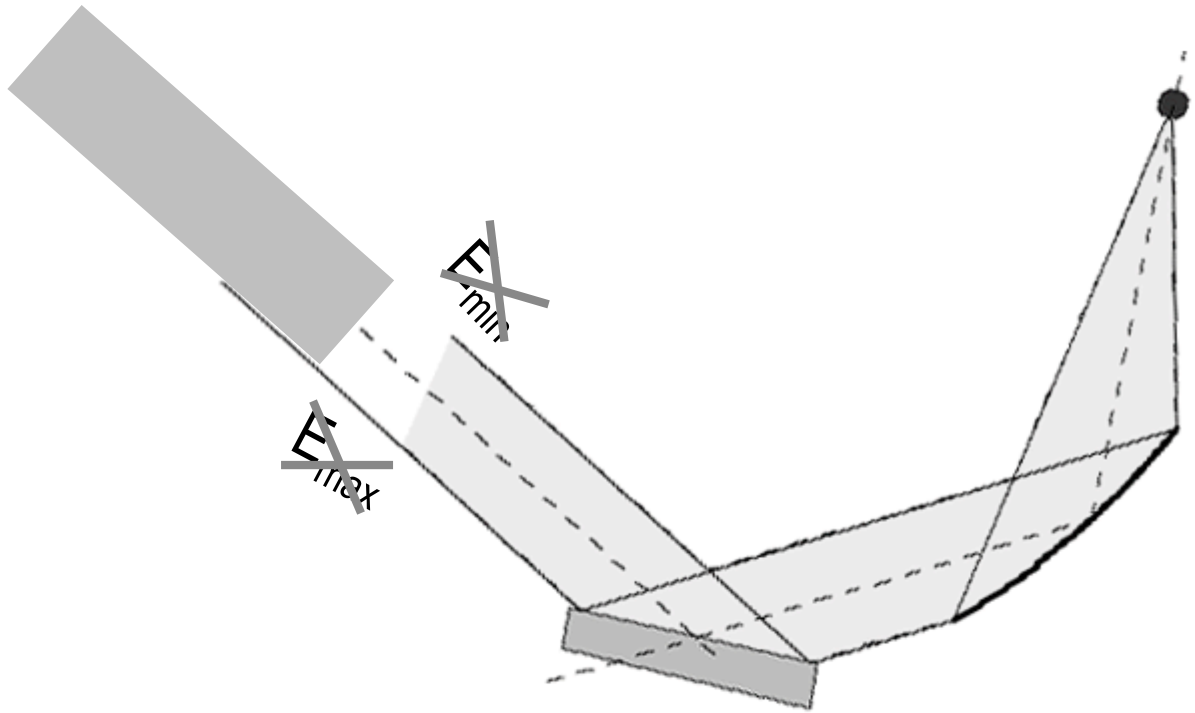


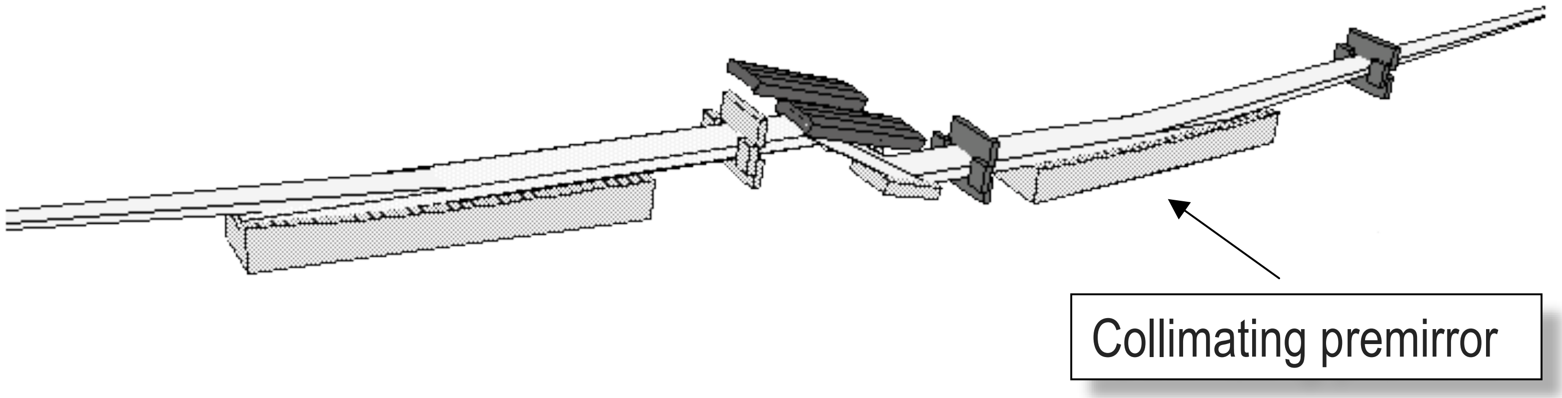
Collimating mirror



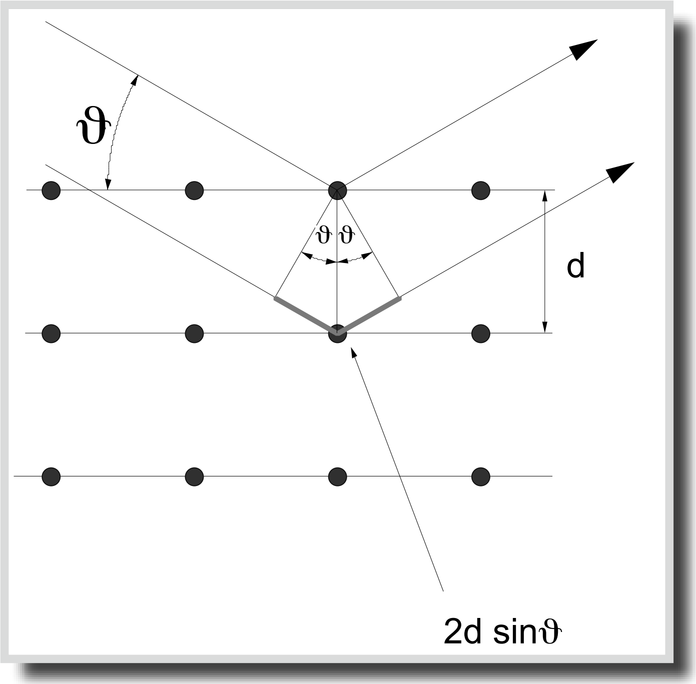


Collimating mirror





The Darwin curve



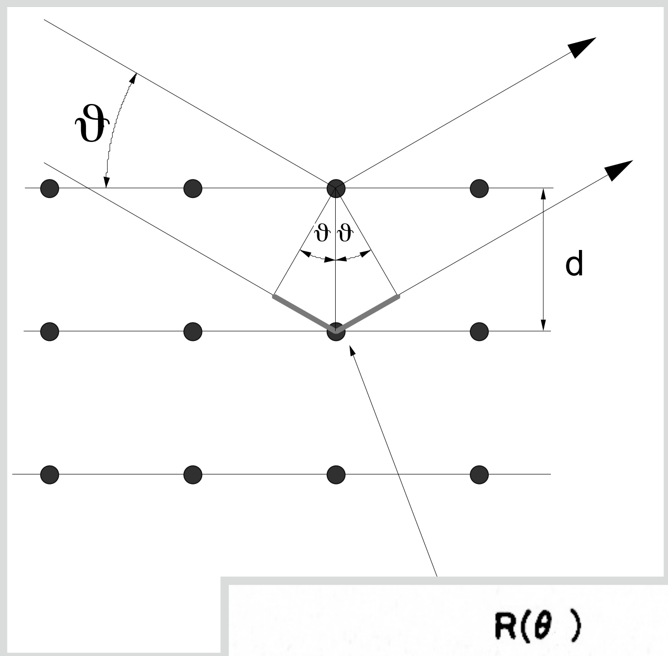
$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta E}{E} = \Delta\vartheta \cot g(\vartheta)$$

$\Delta\vartheta$ *has two contribution :*

$\Delta\vartheta_{beam}$ *beam angular divergence*

$\omega_{crystal}$ *intrinsic reflection width of the monochromator*

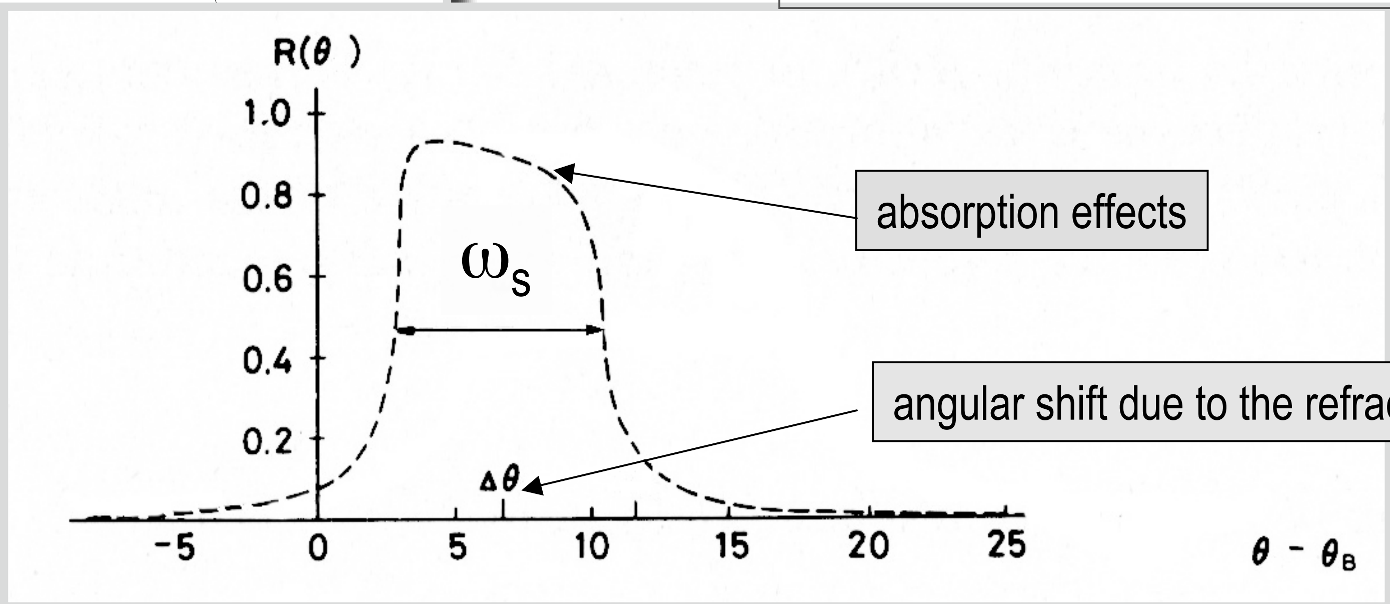
The Darwin curve



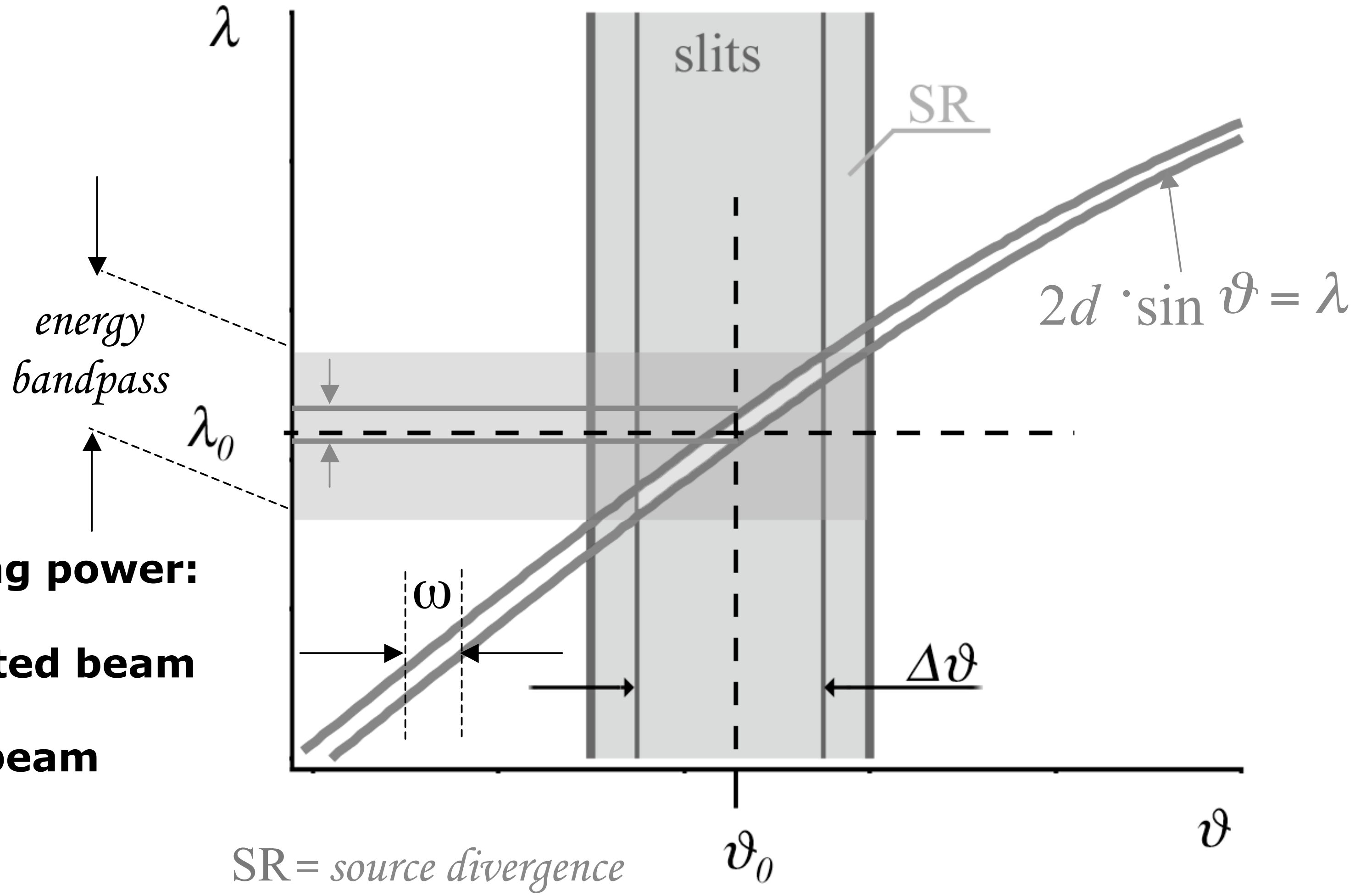
$$\omega_s = \frac{2}{\sin 2\vartheta_B}\frac{r_e\lambda^2}{\pi V}C\left|F_{hr}\right|e^{-M}$$

n	order of the reflection
λ_1	wavelength of the fundamental
$e^{-M(n)}$	temperature factor
V	volume of the unit cell
ϑ_B	Bragg angle
R_e	radius of the electron e^2/mc^2

F_{hr} real part of the structure factor related to the diffracted direction **h**(h,k,l)



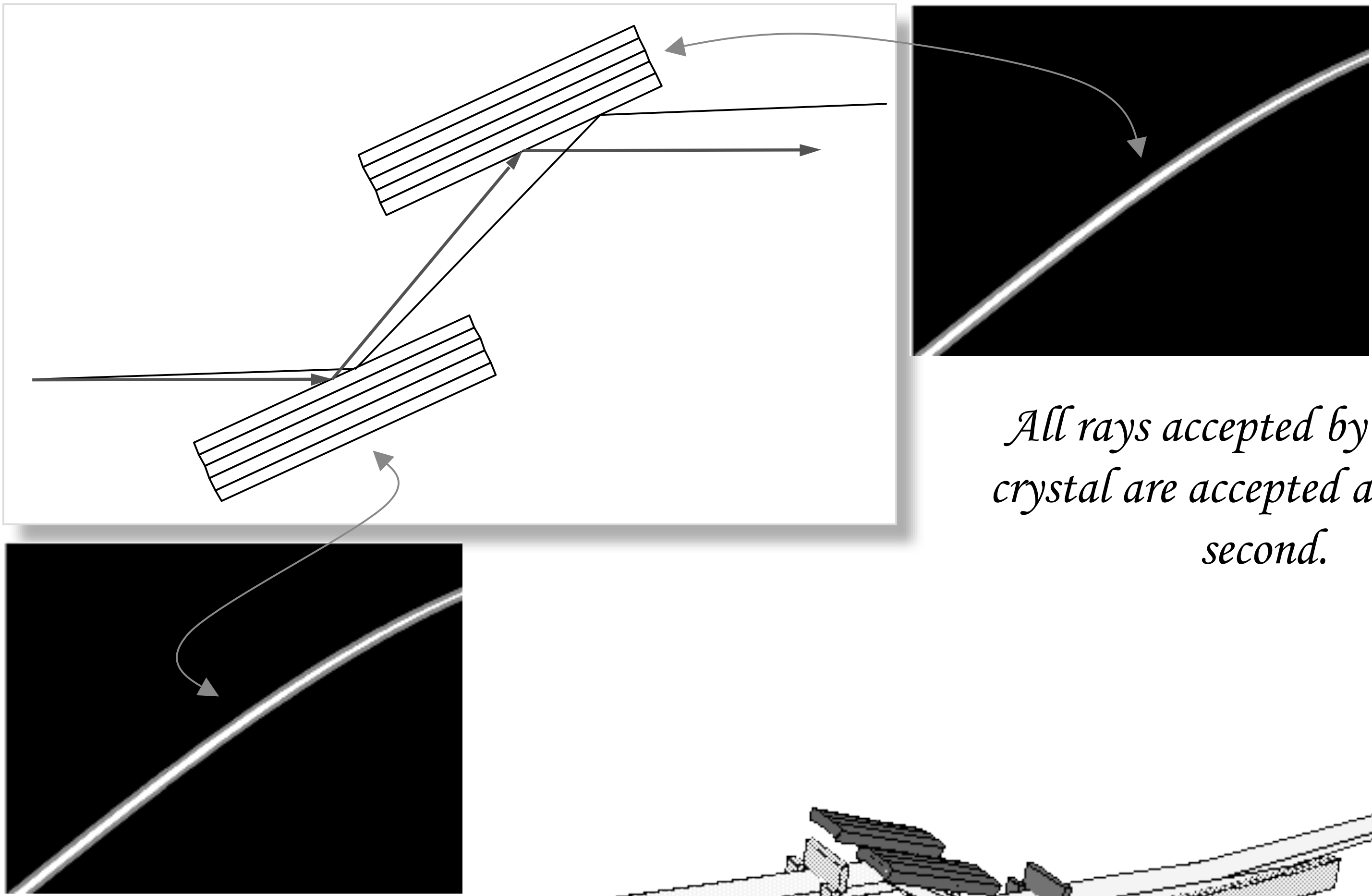
DuMond Diagram



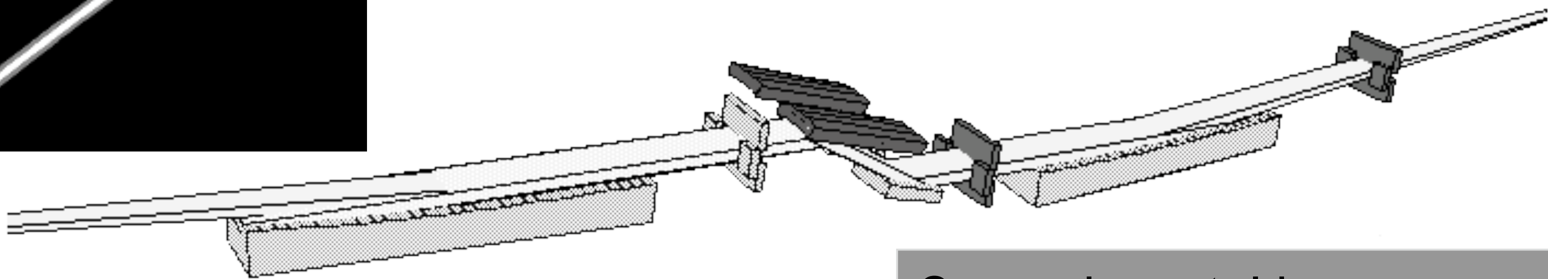
Typical resolving power:
E/ΔE ≈ 10^3-10^4
for non collimated beam
E/ΔE ≈ 10^4-10^5
for collimated beam

SR= *source divergence*
slit= *angular acceptance of the slit*

Crystal Monochromator

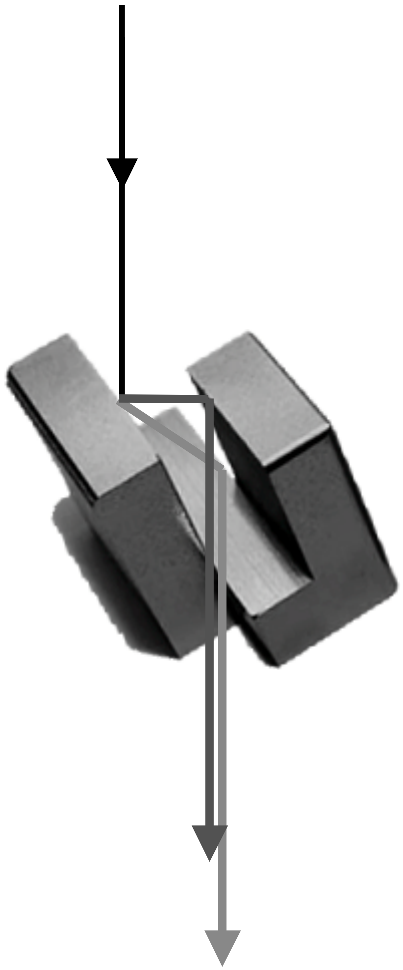


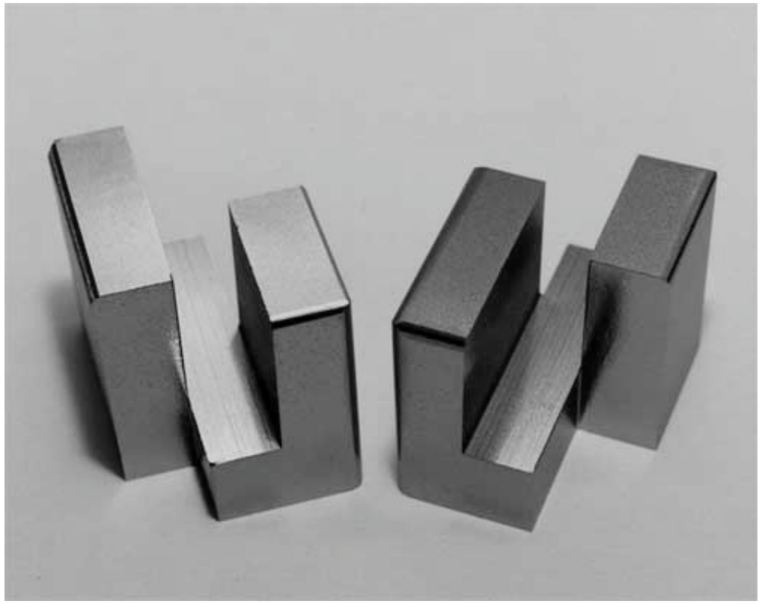
All rays accepted by the first crystal are accepted also at the second.



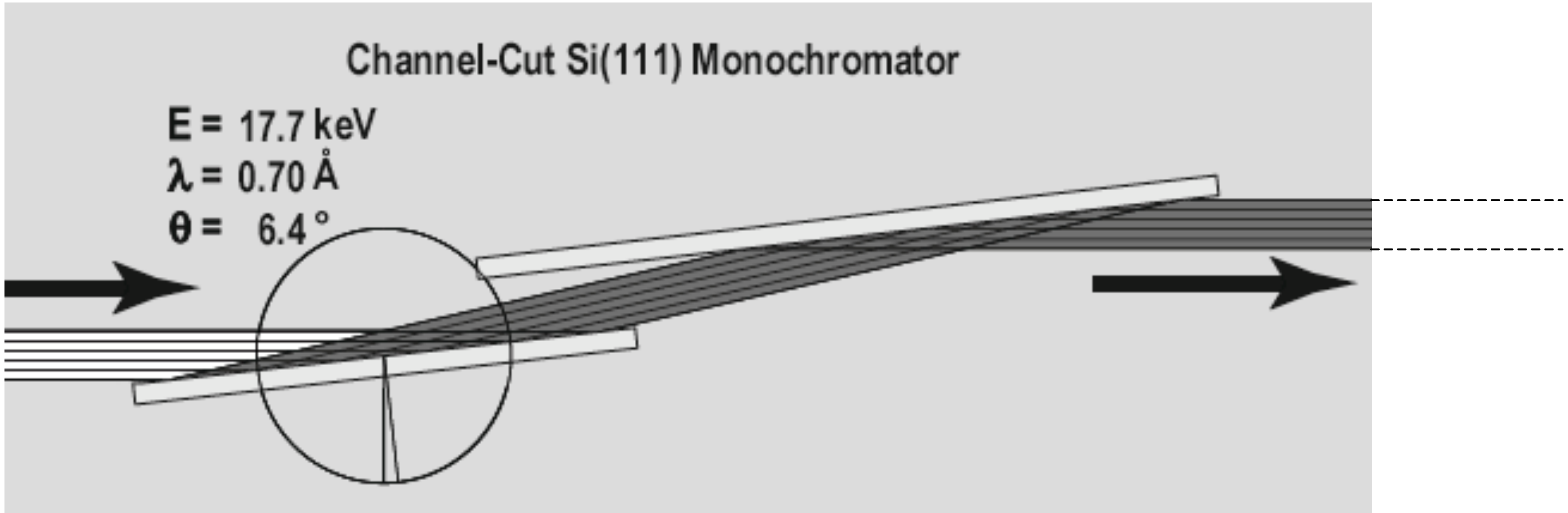
Second crystal in
non dispersive configuration

Channel cut



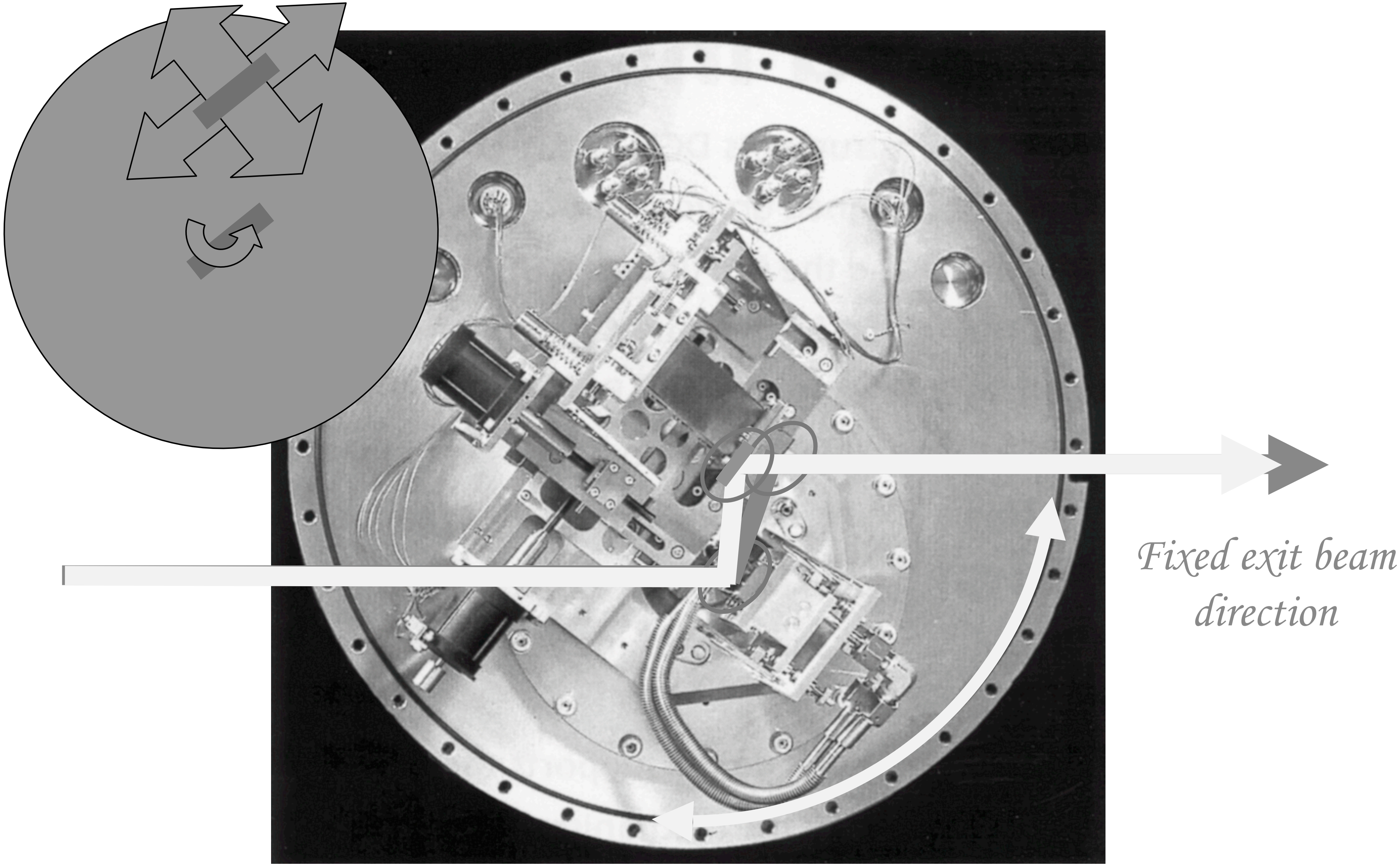


Channel cut

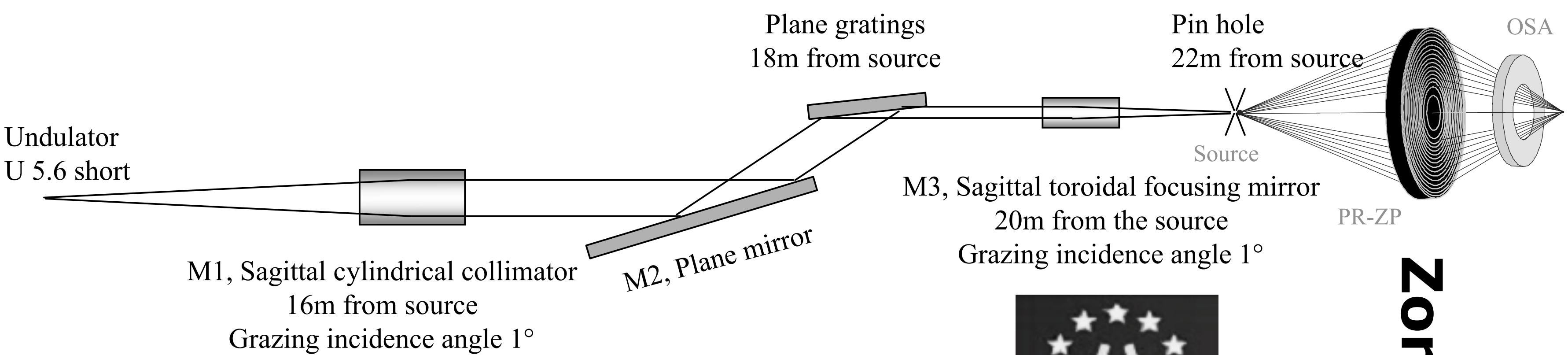


Much easier to allign!
Exit beam displacement!
Impossible to detune (No more true)

Double Crystal monochromator



Twin Mic beamline

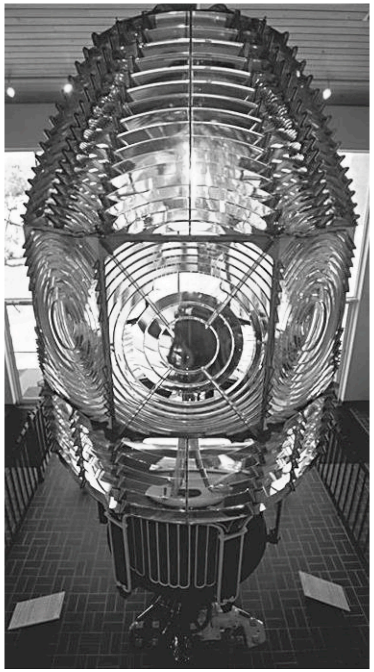


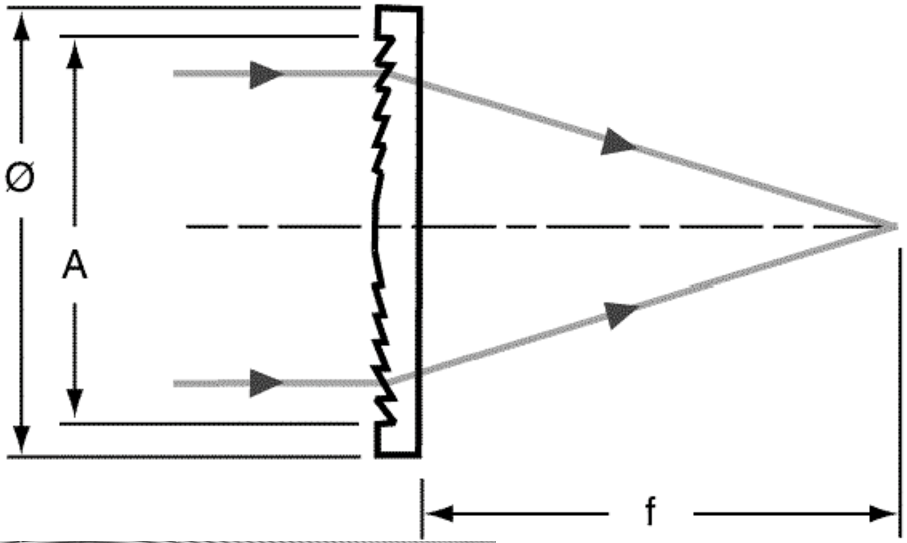
Zone plate

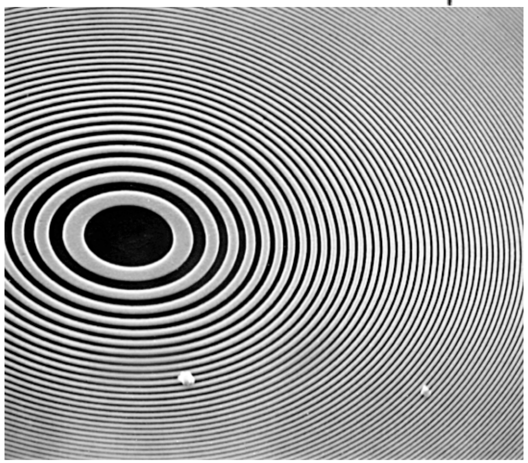
0.2-2keV (0.2-4keV desired) photon energy range
Moderate resolving power, high flux.
Fulfil the requirement of full field imaging and scanning mode

Zone Plate

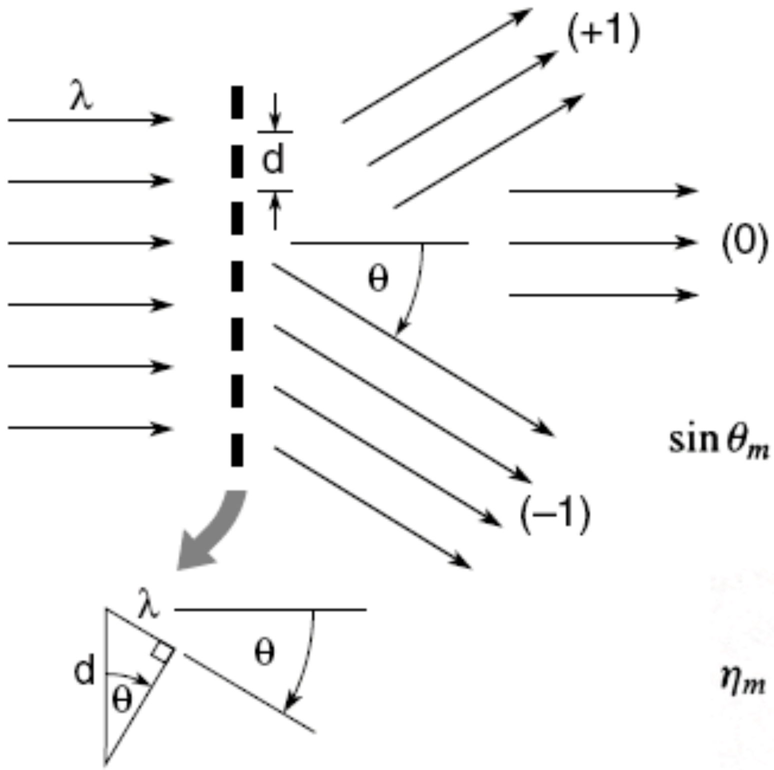
Fresnel lens







Zone Plate



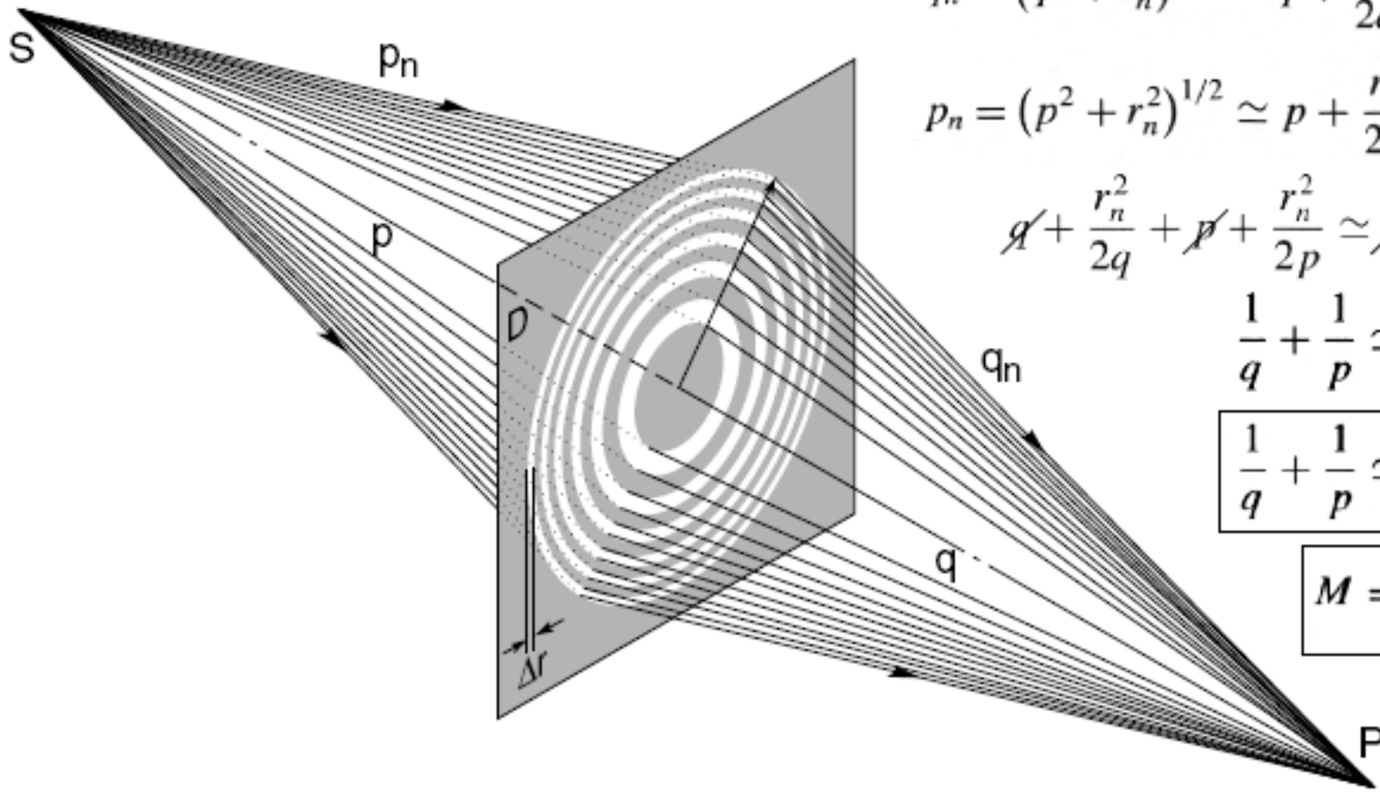
$$\sin\theta_m = \frac{m\lambda}{d} \ ; \quad m = 0,\ \pm 1,\ \pm 2,\ \pm 3,$$

$$\eta_m = \begin{cases} \frac{1}{4} & m = 0 \\ 1/m^2\pi^2 & m \text{ odd} \\ 0 & m \text{ even} \end{cases}$$

(50% absorbed)

Zone Plate

$$r_n^2 = fn\lambda$$



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

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

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

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

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

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

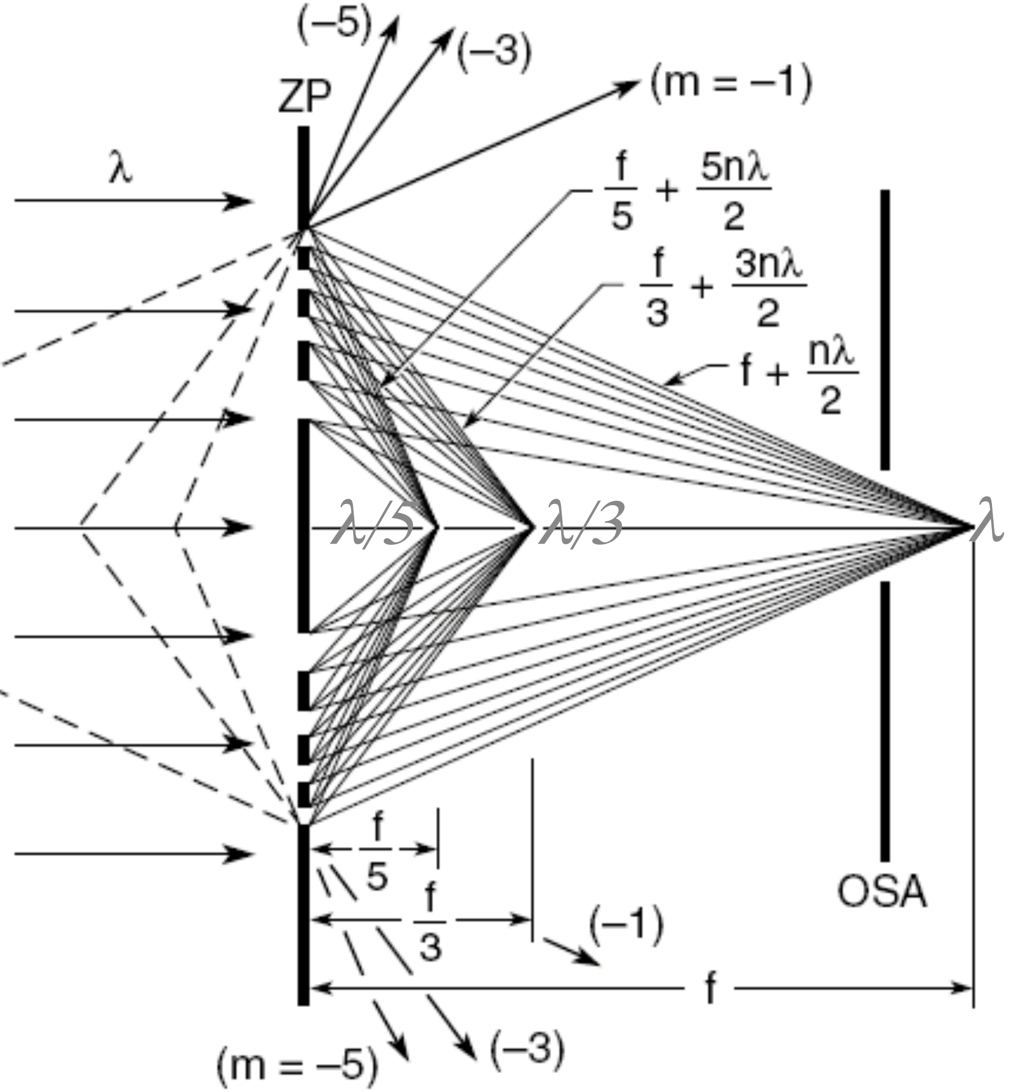
$$\boxed{M = \frac{p}{q}}$$

Zone Plate

$$r_n^2 = fn\lambda$$

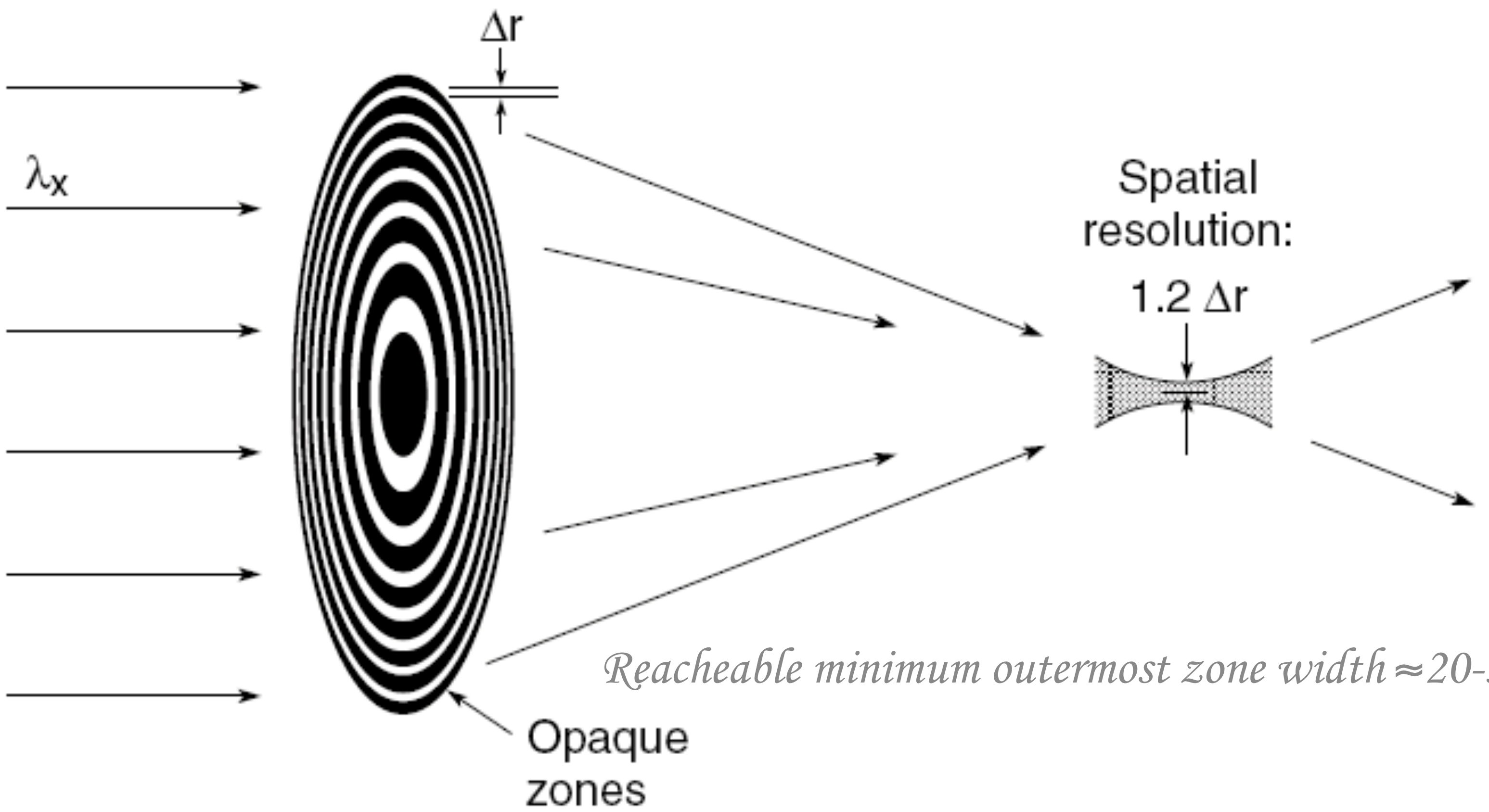
$$f = \frac{r_n^2}{n\lambda} = \frac{f_0}{n} \quad n\ odd$$

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



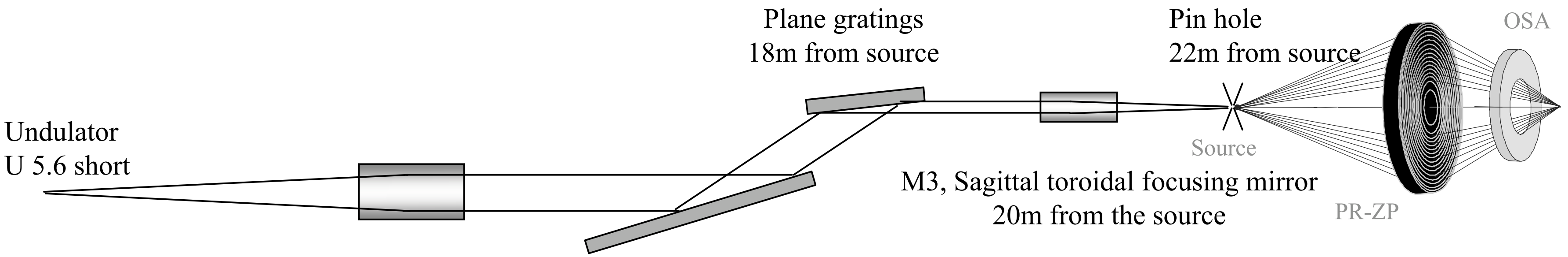
Higer order focused at different longitudinal positions

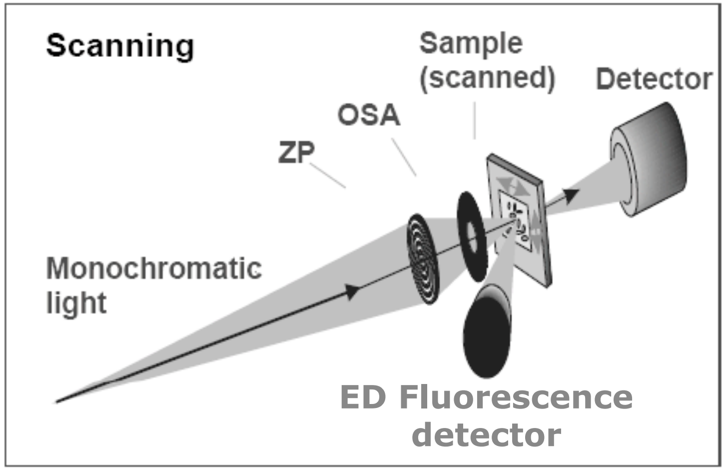
Zone Plate

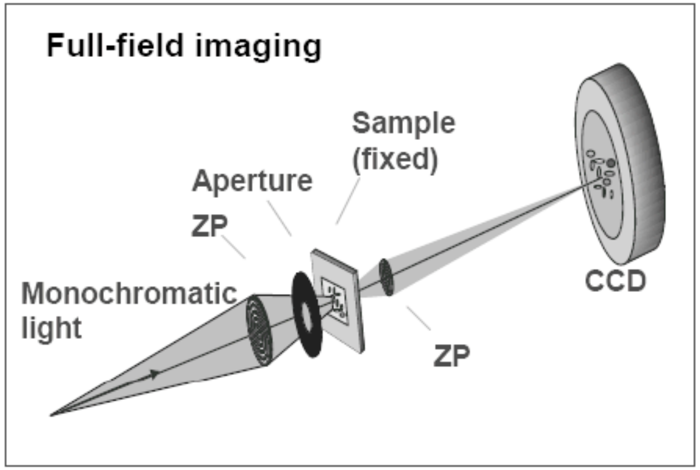


Reacheable minimum outermost zone width ≈ 20-30 nm

Microscopes







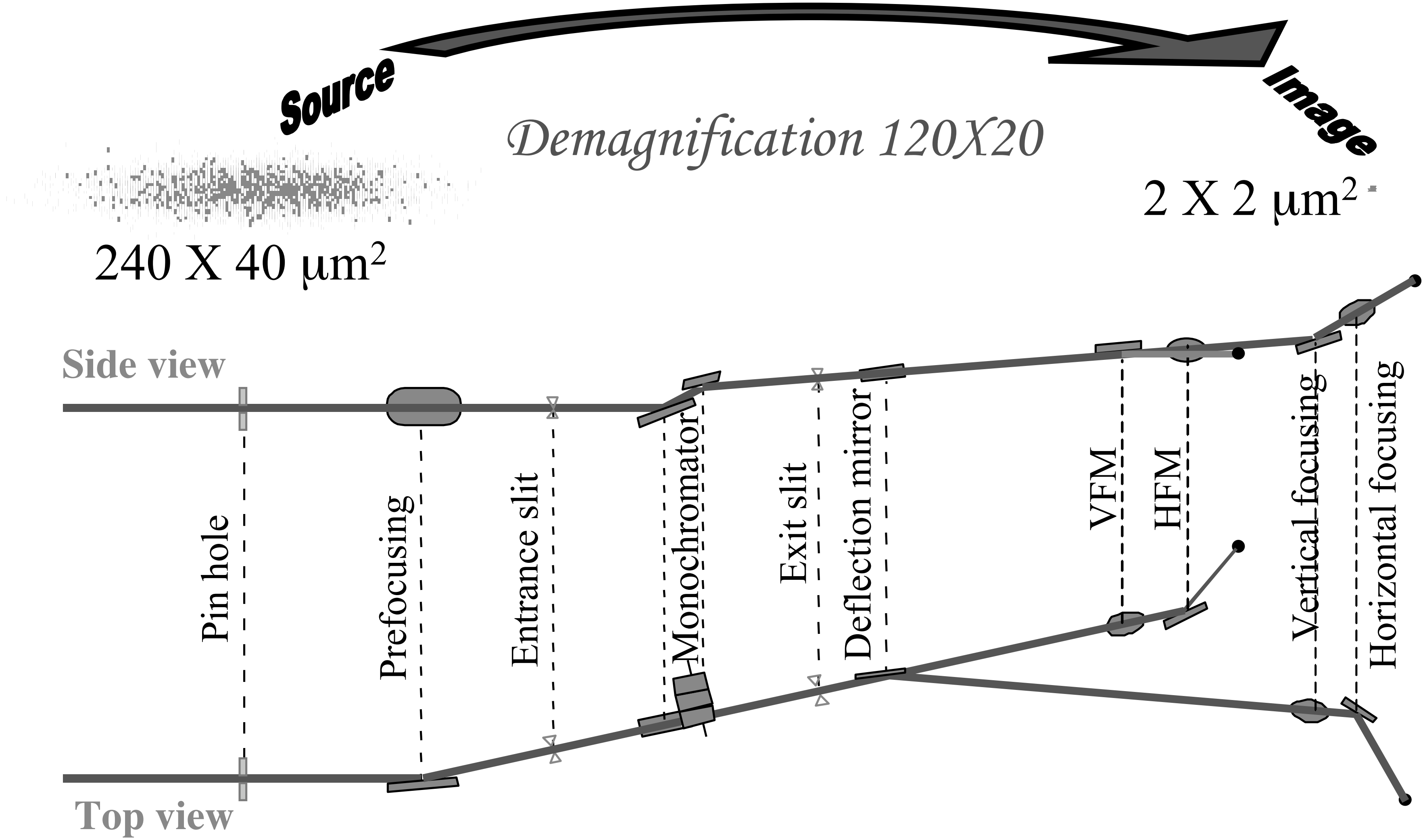
+ versatile detectors can run simultaneously;
+ easier optics set-up;
- long exposure time;
- complex electronics.

Ideal for spectromicroscopy

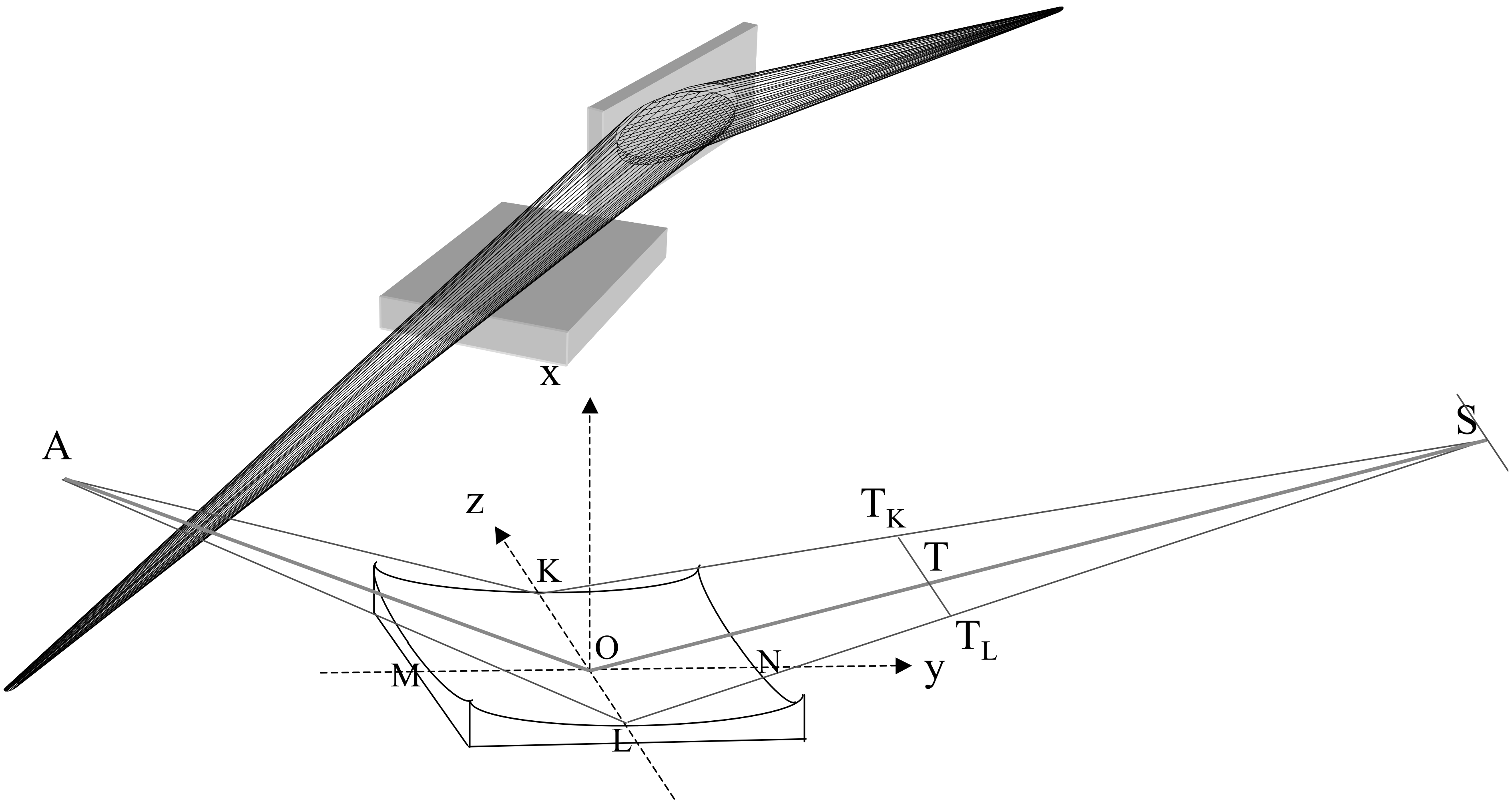
+ short exposure time;
+ higher resolution - static system;
- complex optical alignment.

Ideal for dynamic studies and tomography

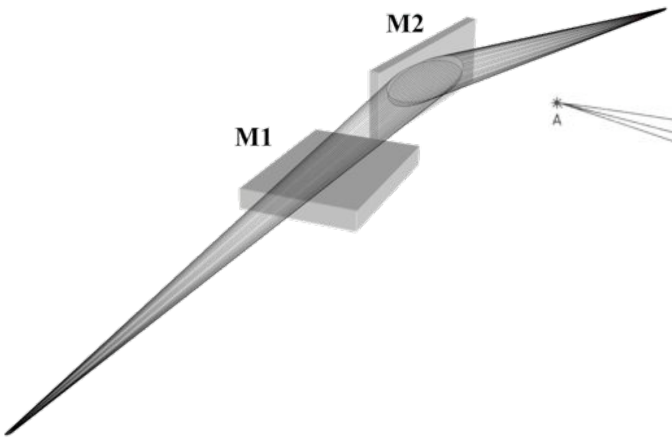
Small spots - Large acceptance

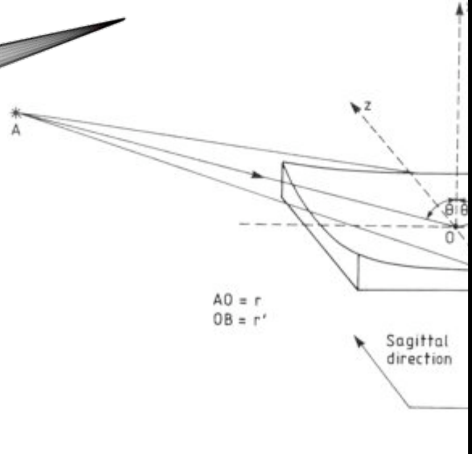


KB mirrors

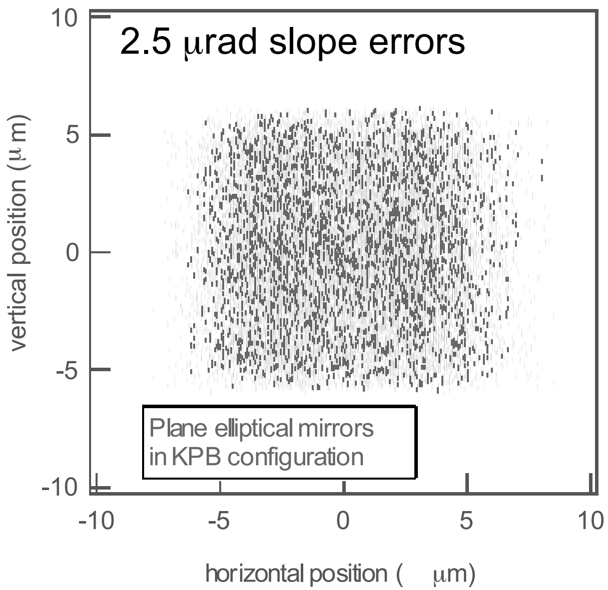


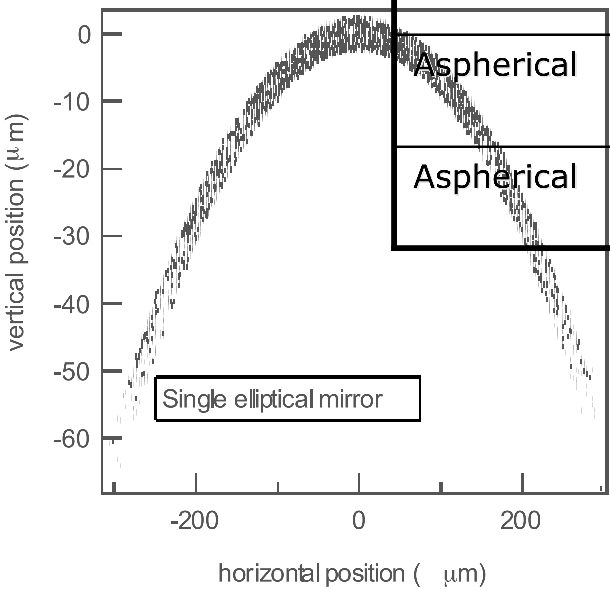
Small spot with KB

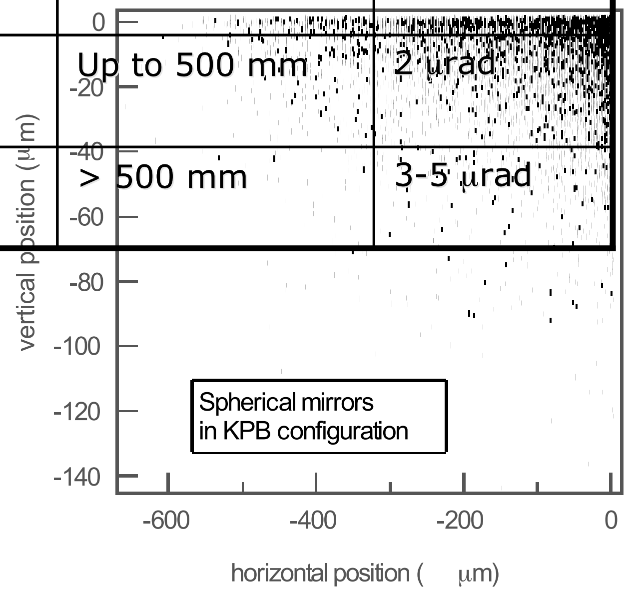




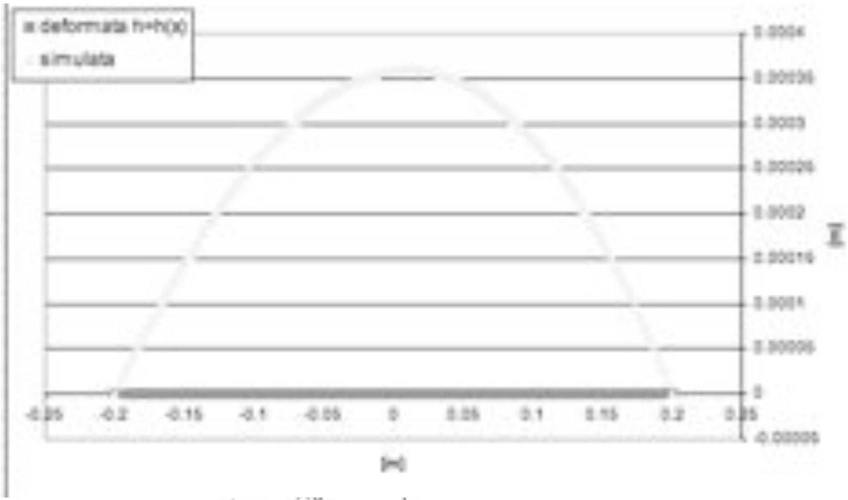
Shape	Length	rms errors
Spherical/flat	Up to 500 mm	< 0.5 μrad
Spherical/flat	> 500 mm	1-2 μrad
Toroidal	Up to 500 mm	< 1 μrad
Toroidal	> 500 mm	> 1 μrad
Aspherical	Up to 500 mm	2 μrad
Aspherical	> 500 mm	3-5 μrad

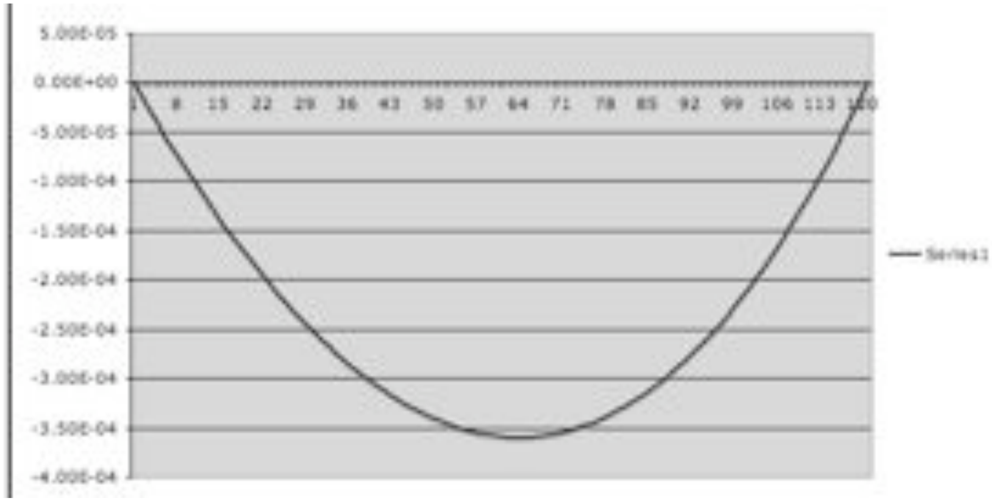


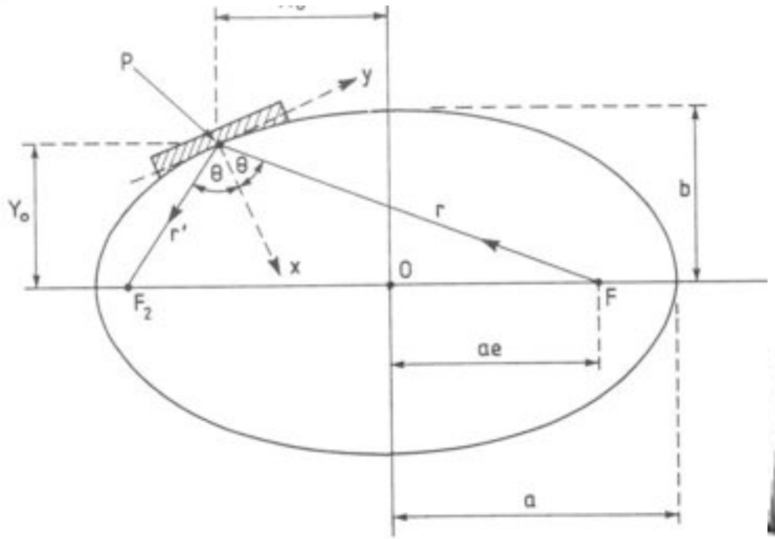


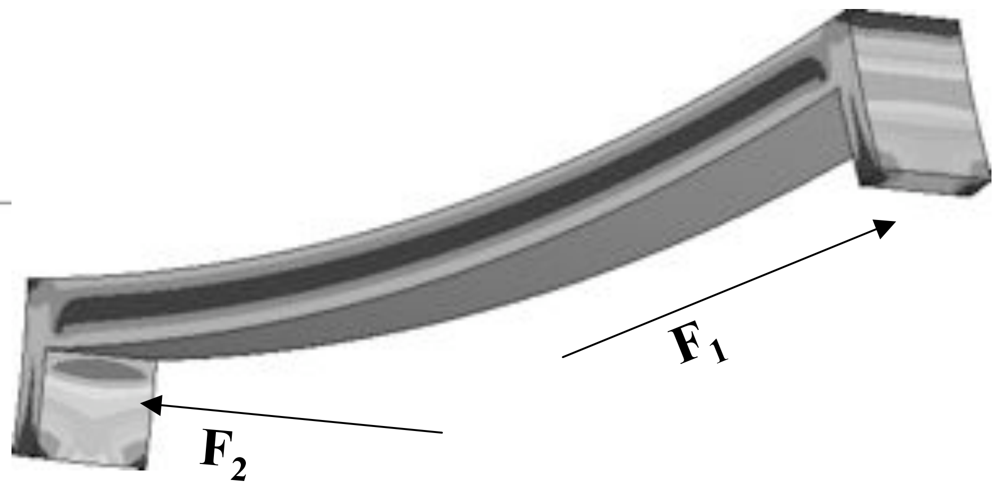


Approach best ellipse



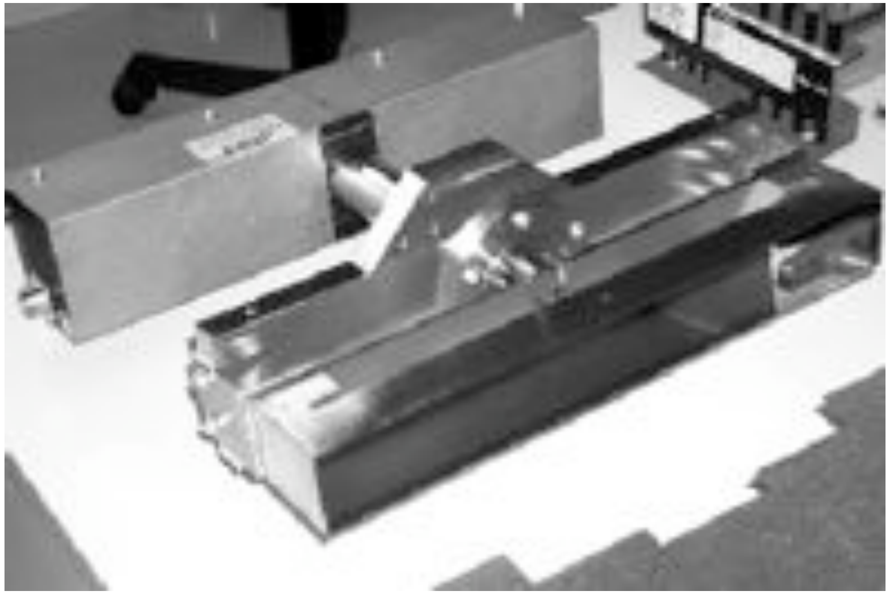


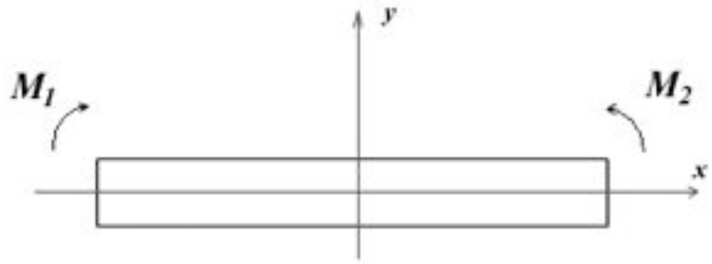


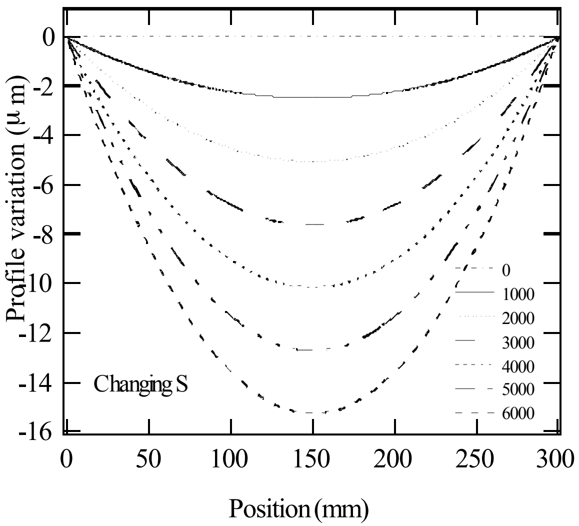


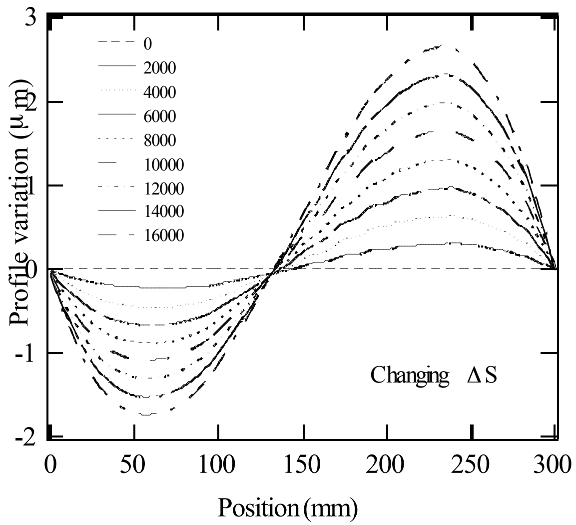
Two unequal moment applied at the edges

Correction by polishing

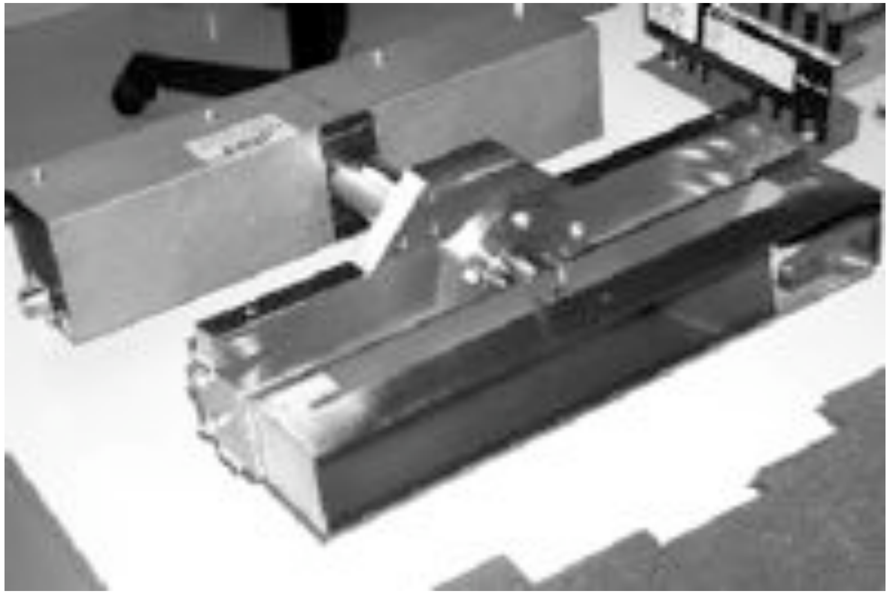


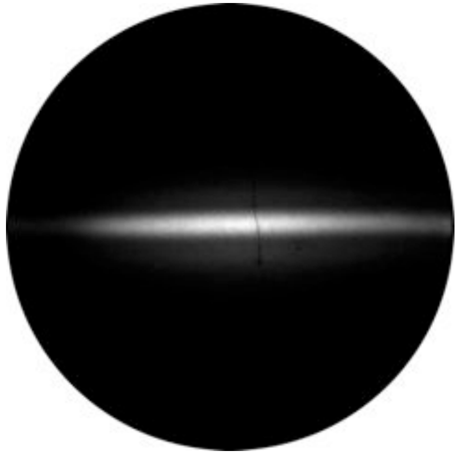






Correction by polishing

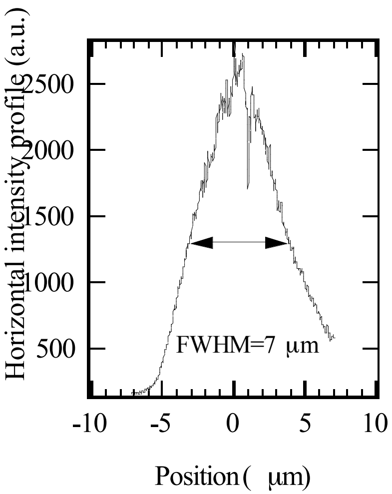


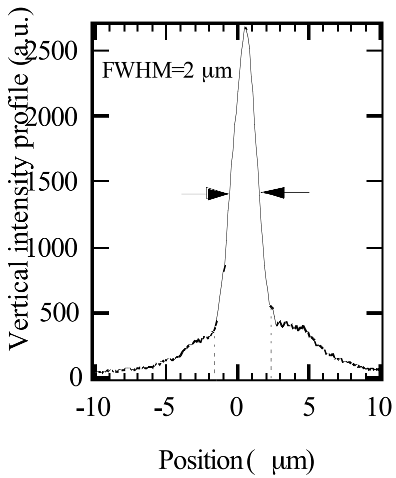


Sample tilted by 76°

2X7 μm²

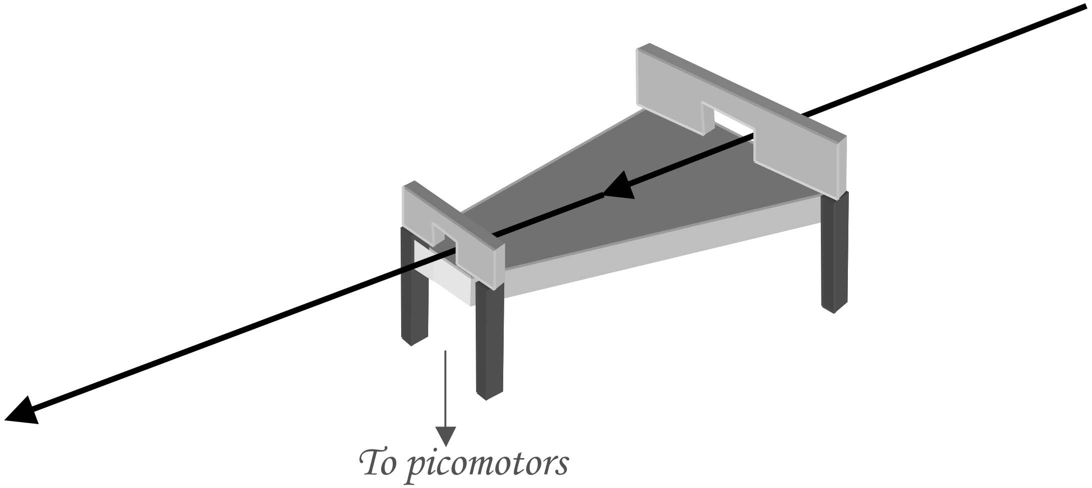
Flux 1x10¹³ ph/sec





Corrected by variable width

micro-fluorescence & micro-diffraction (HXR)



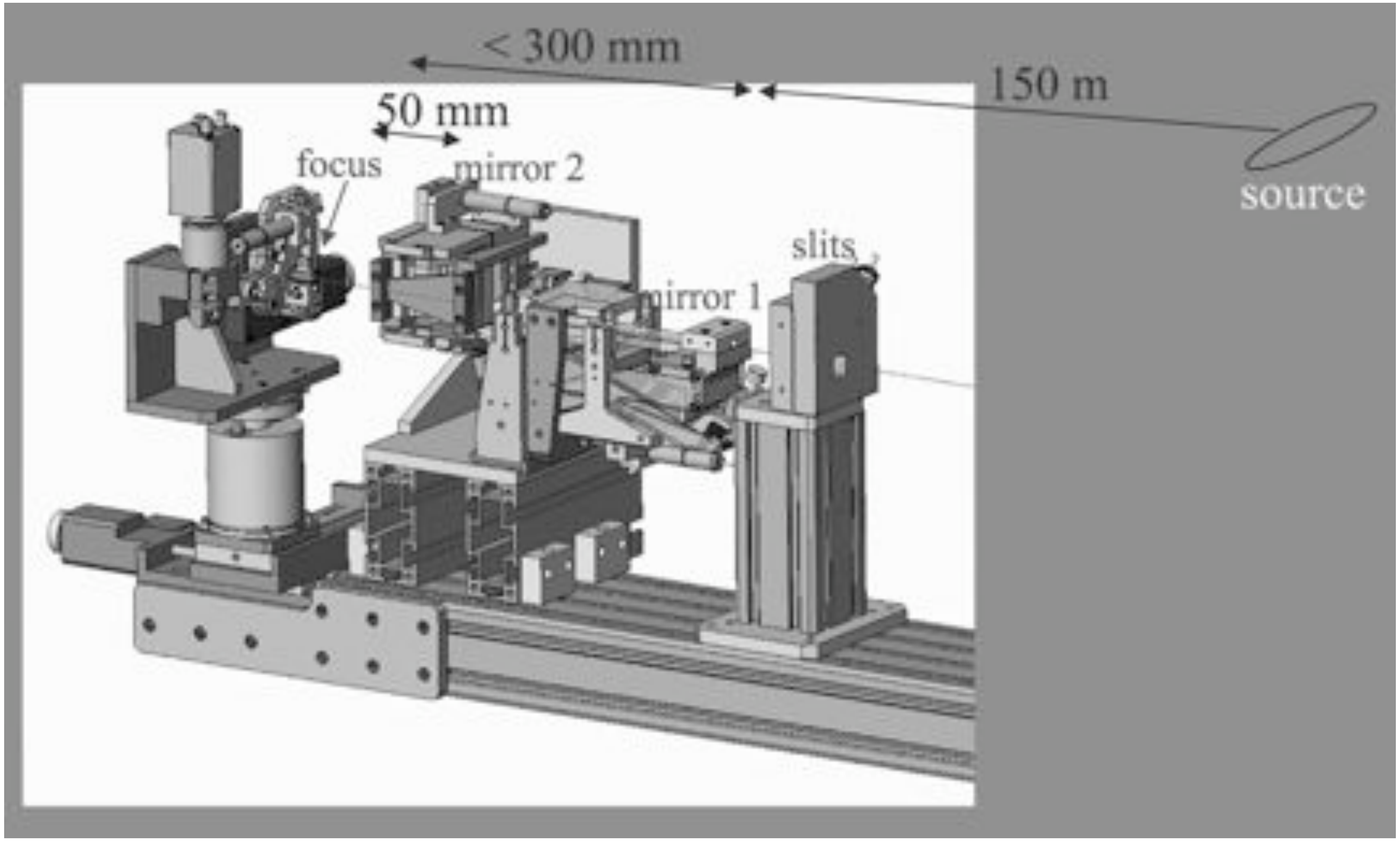
Bending system

The mirror must be shaped according to the required working distance and angle of incidence constant thickness but linear width variation.

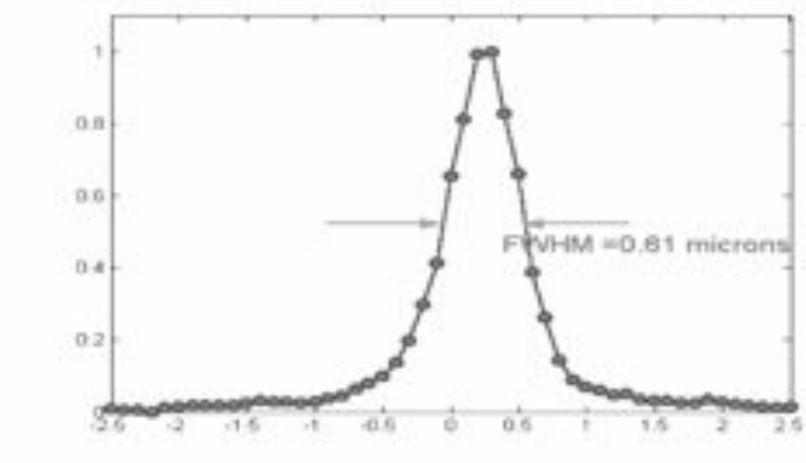
Open clamping system to let the beam pass trough

Picomotors for the bending driving system (2 for each mirror)
Two different moments are applied at the end of the flat polished substrate

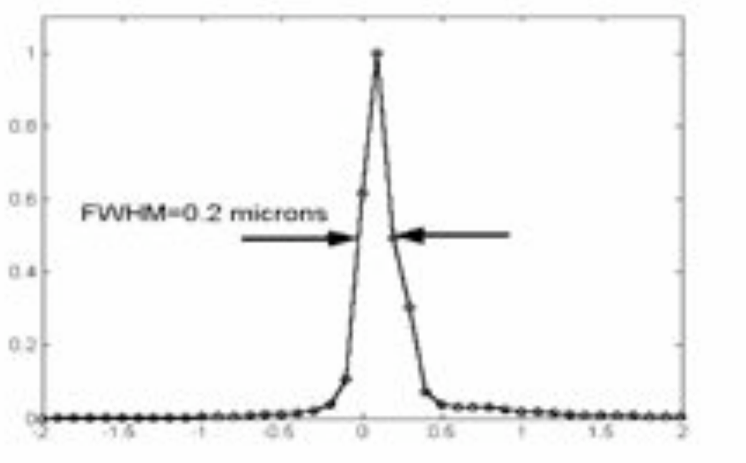
Corrected by variable width



Corrected by variable width



Vertical scan



Horizontal scan

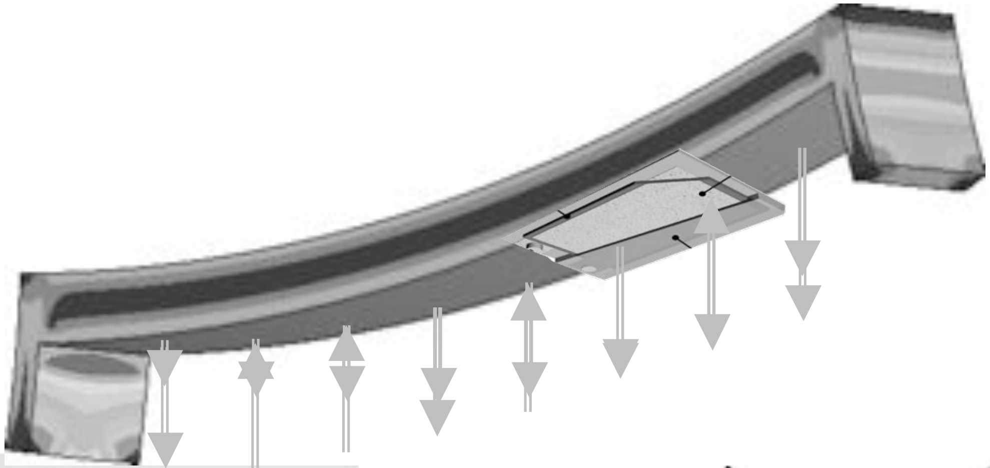
2001 **Beamline: ID 19**
Energy 19 KeV
Gain 3.5 10^5

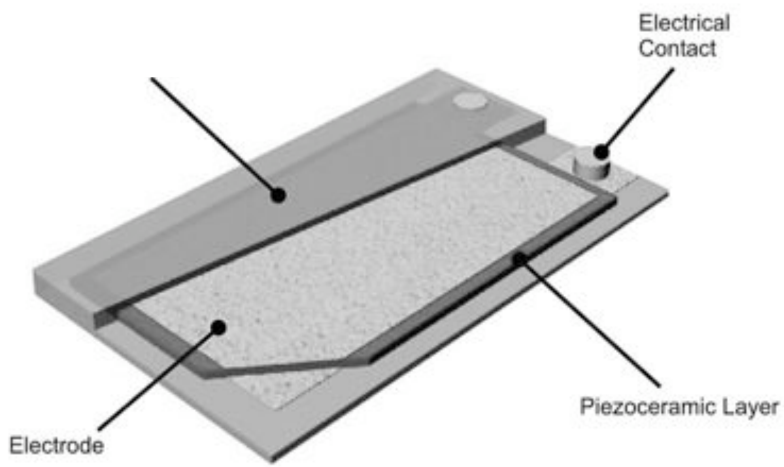
Hybrid systems

Higher order corrected by:

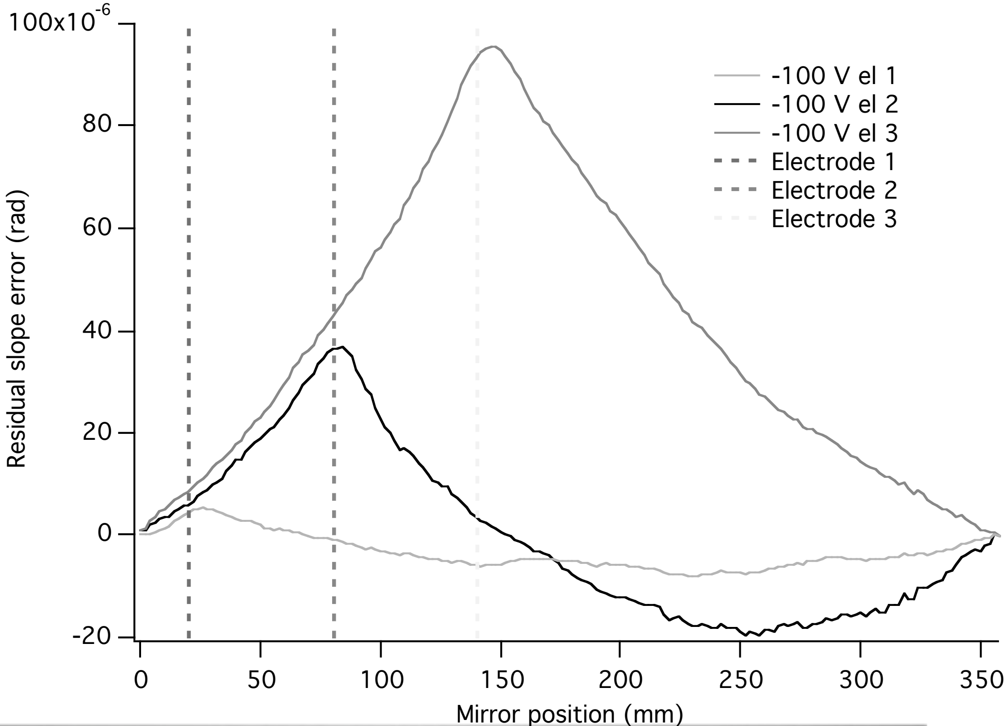
Dynamic variation of the moment of Inertia

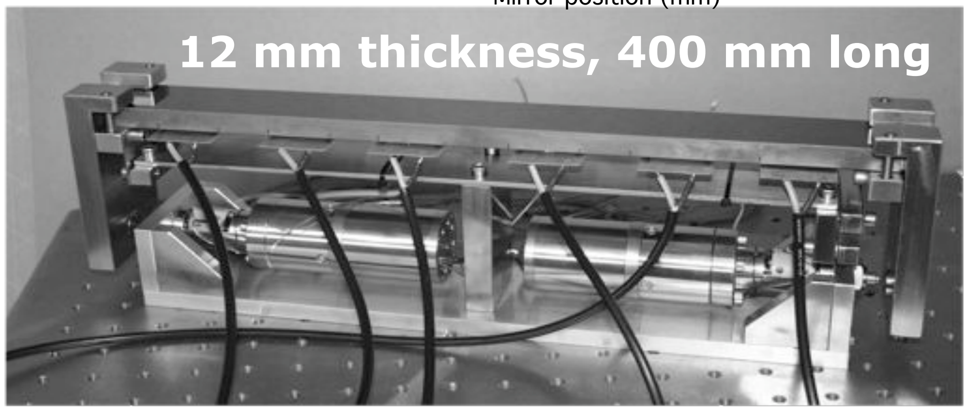
Correction of low frequency shape errors

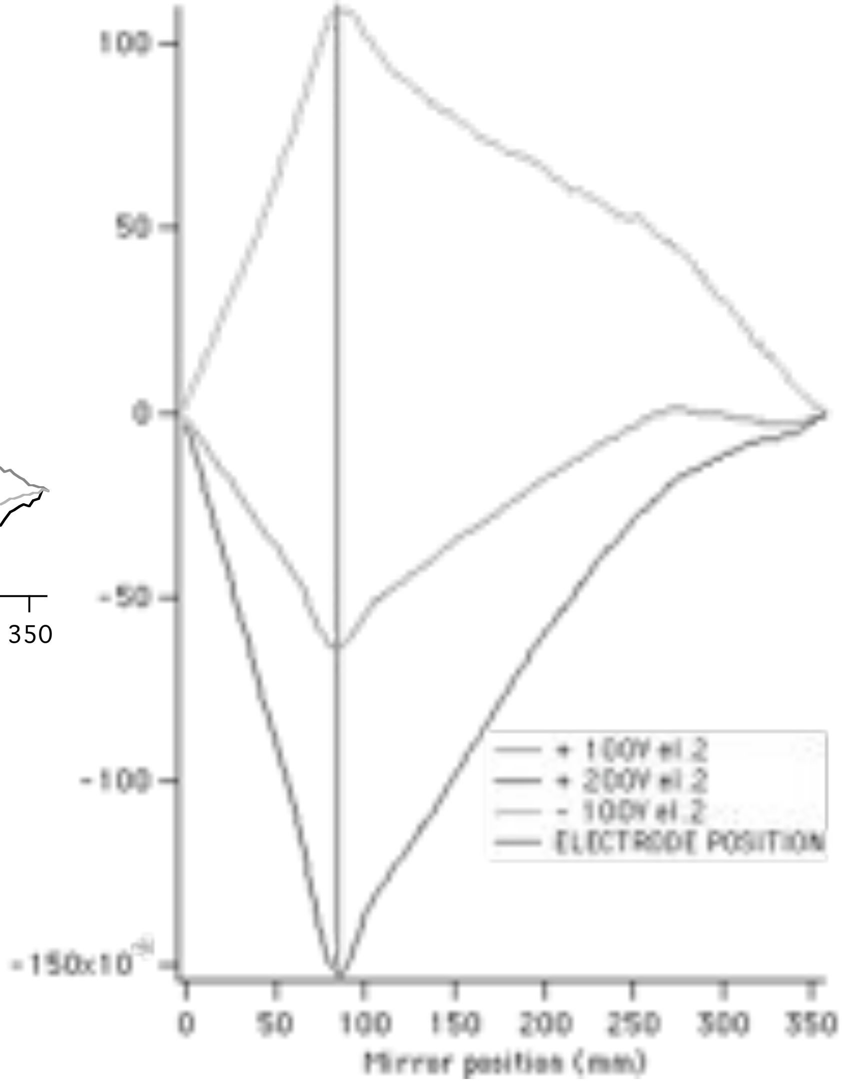




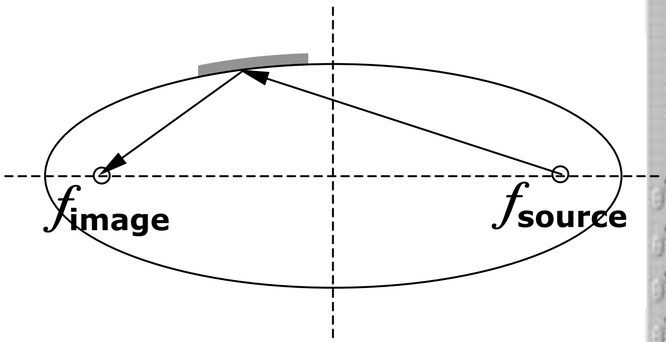
Hybrid Systems



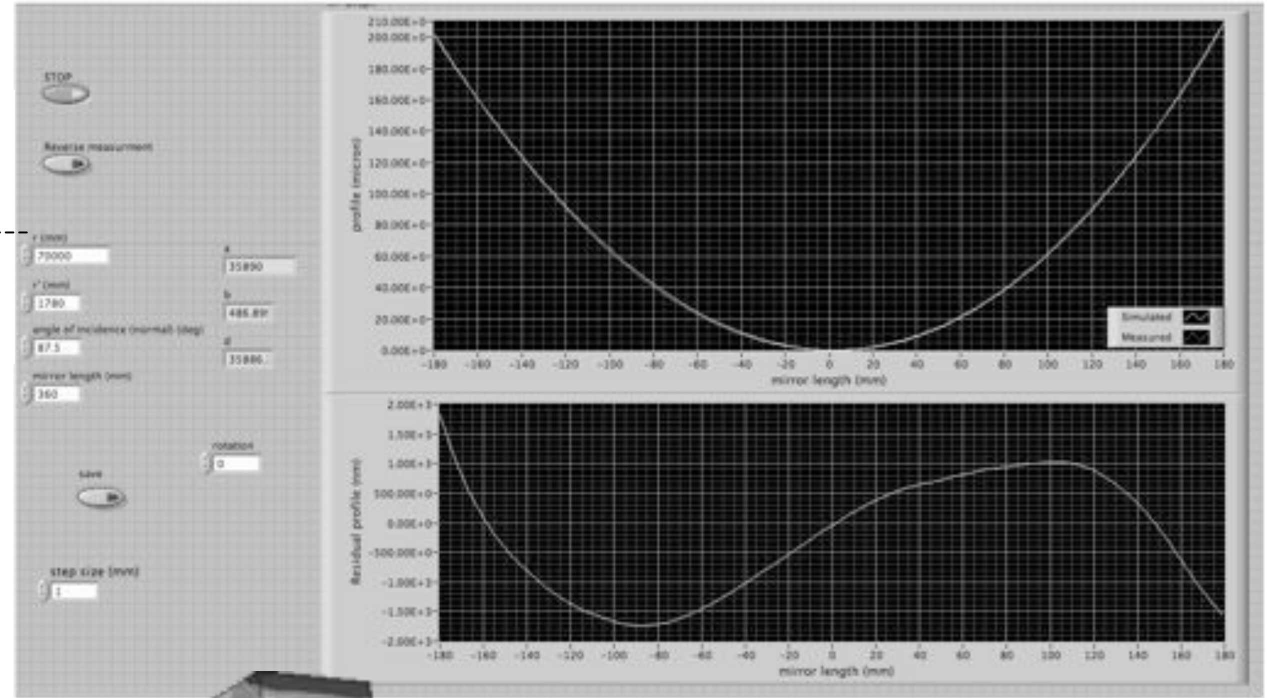


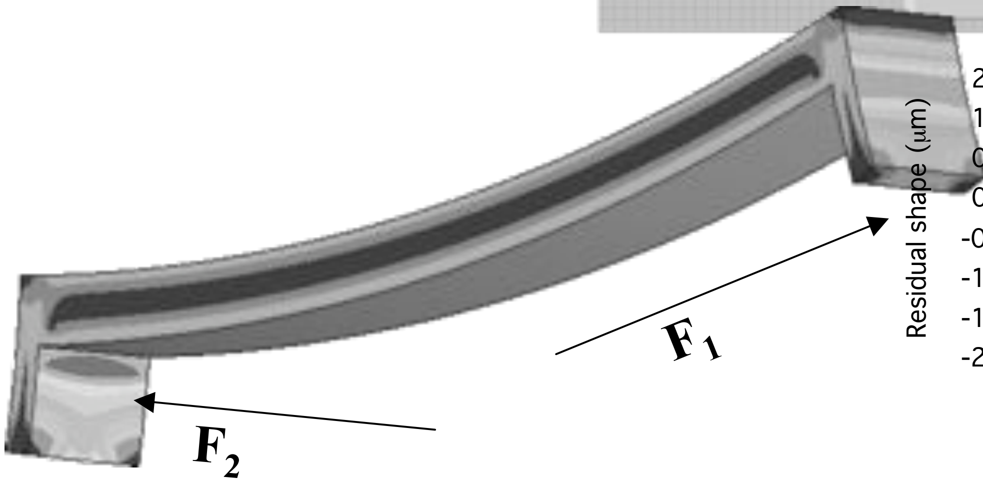


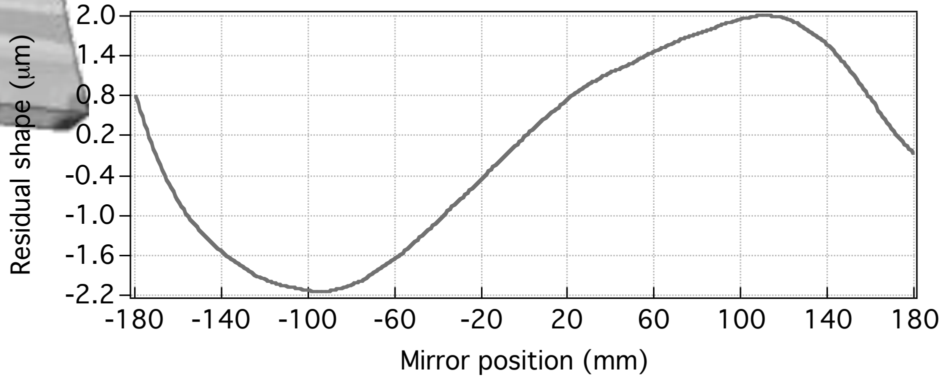
Larger dynamical range



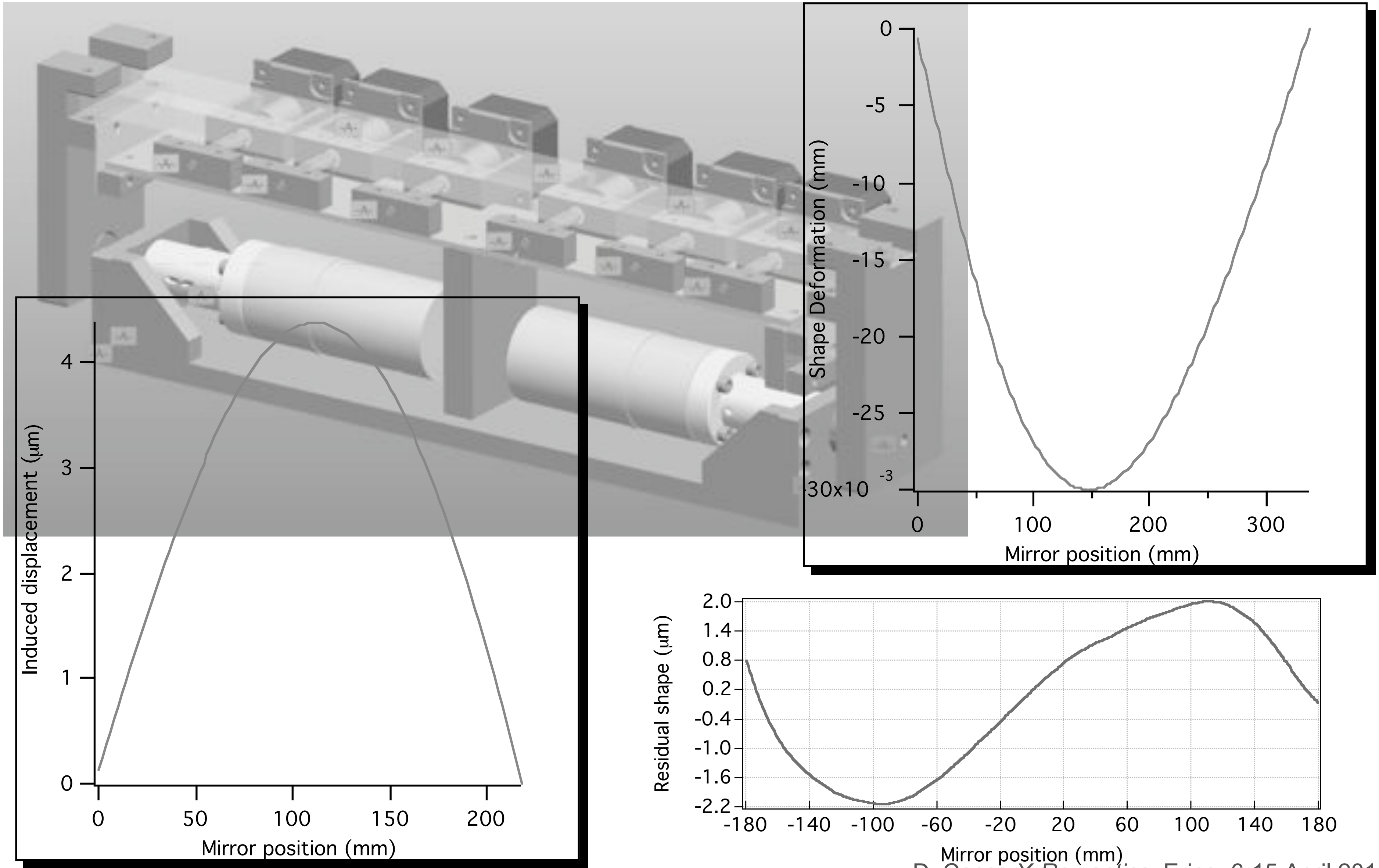
From flat to less than 1 m
image distance
Angle of incidence above 2°



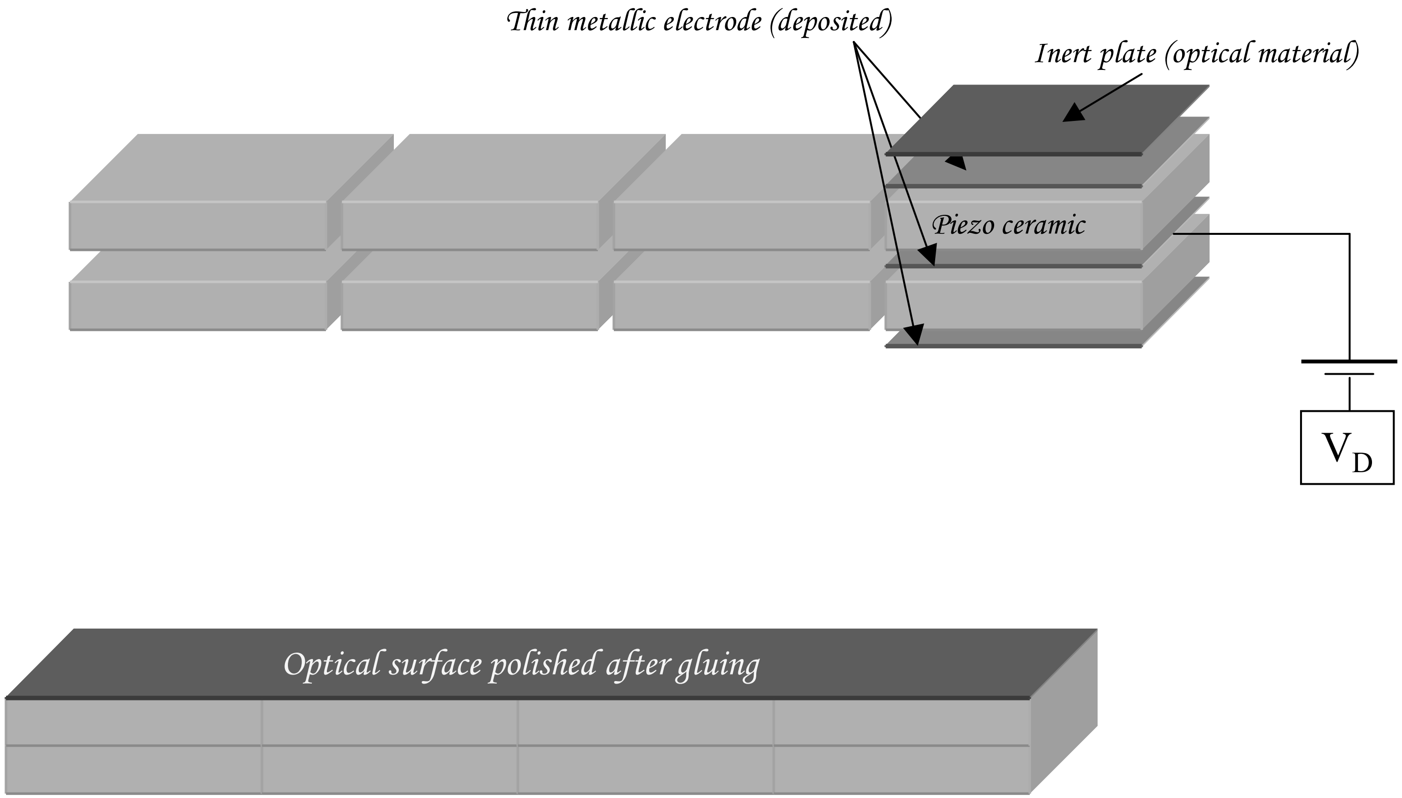




Other systems (larger dynamical range)

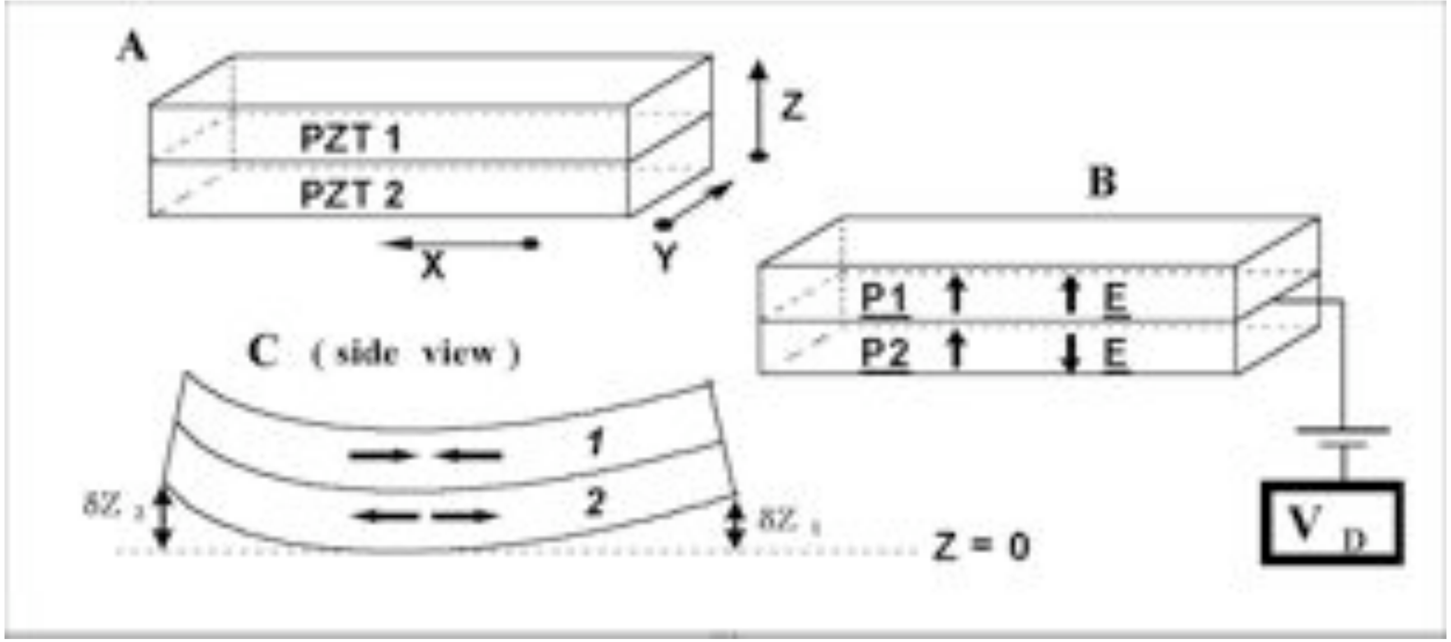


Bimorph mirrors



Bimorph mirrors

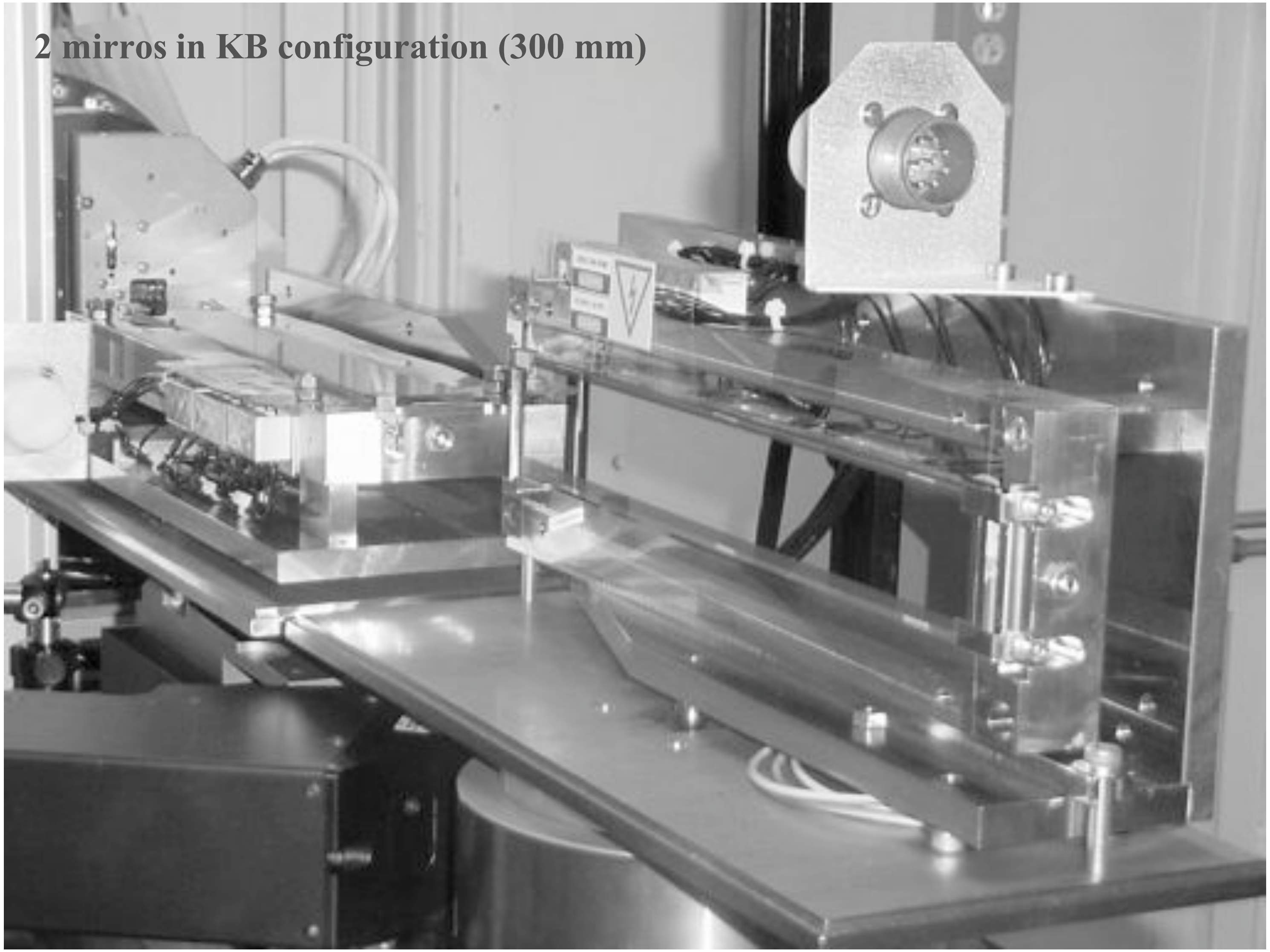
Dimension: from 150 mm (single element) to 1400 mm.



Radius variation: 370 m (+1500V) to 2300 m (-1500V)

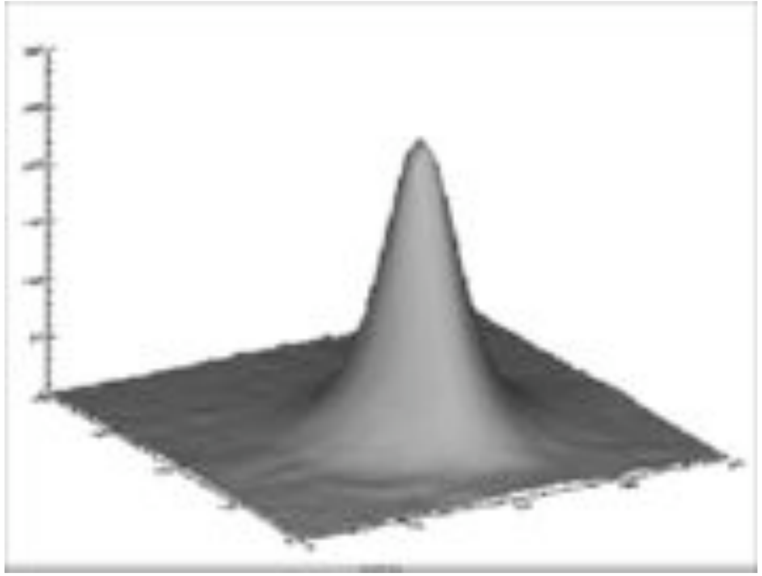
Stability: $\Delta R/R \cong 0.8\%$ on 1 day scale
$\Delta R/R \cong 2.0\%$ on 10 day scale

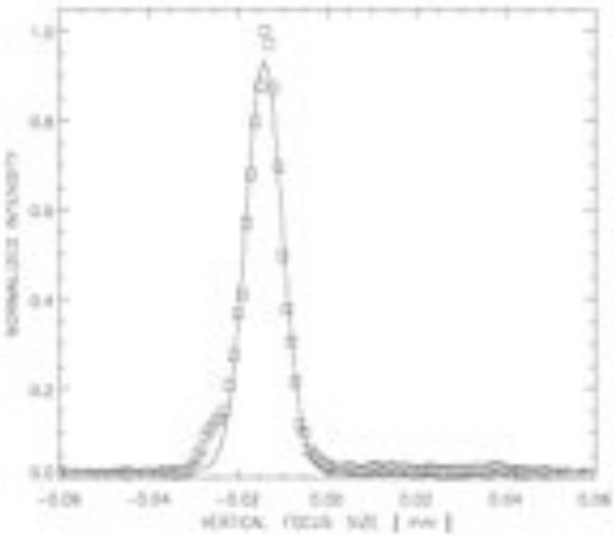
Bimorph mirrors

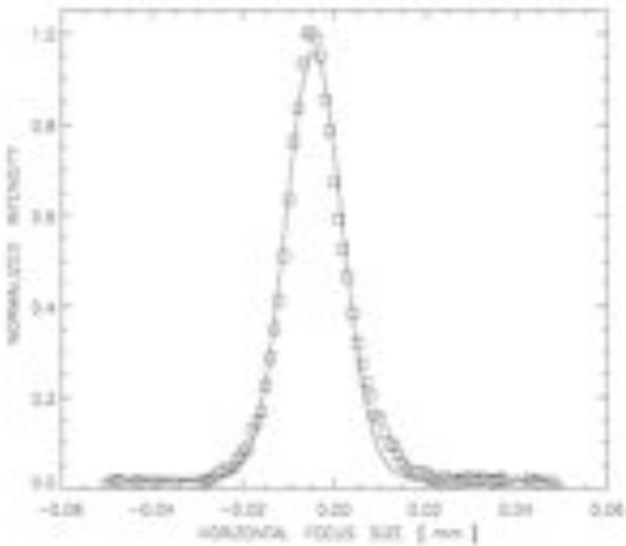


Bimorph mirrors

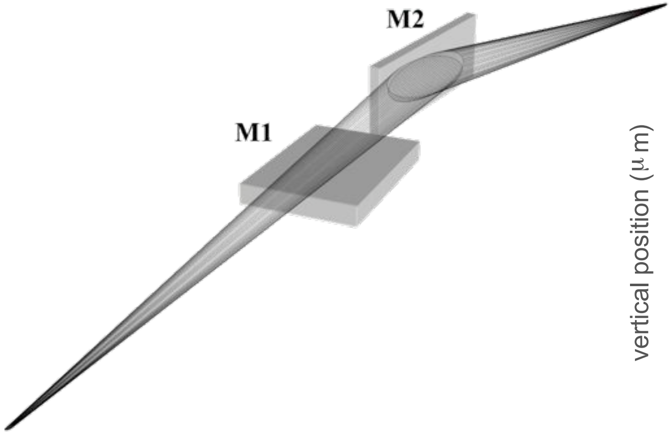
Photon Energy	33.167 KeV
Grazing angle	2 mrad
Coating	Pt
Source size	510 X 30 μm^2
Footprint	260 mm
VFM Demag	40
HFM Demag	62
Spot dimension	8.5 X 6.0 μm^2

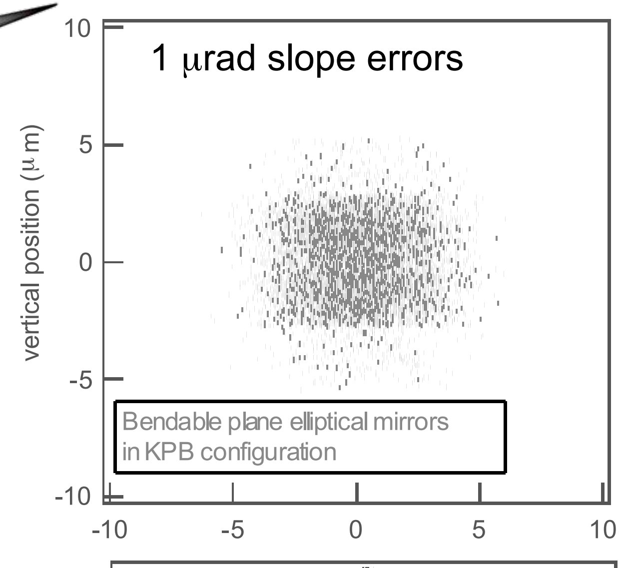




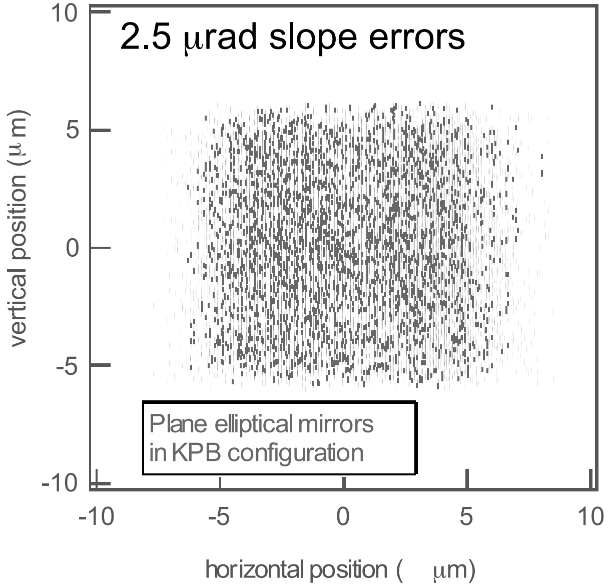


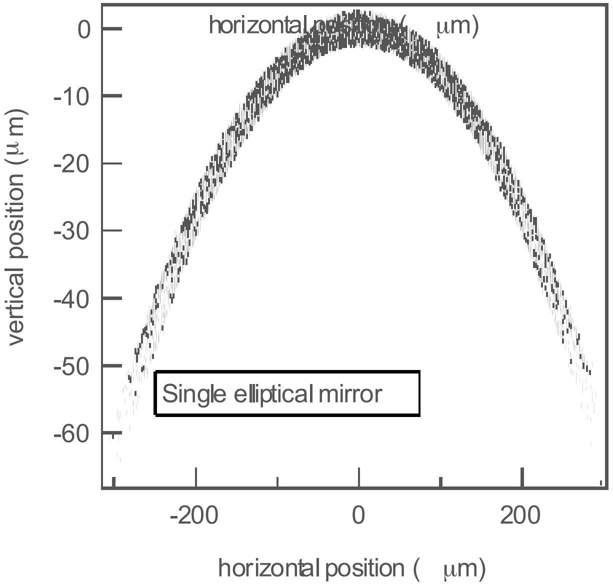
Small spot comparison

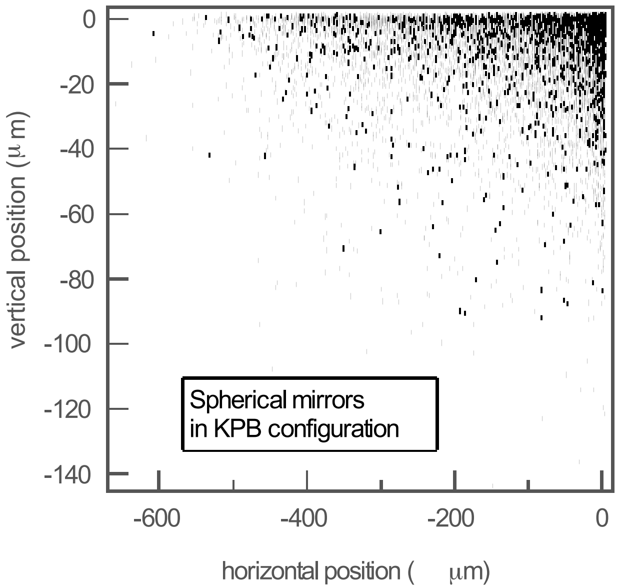




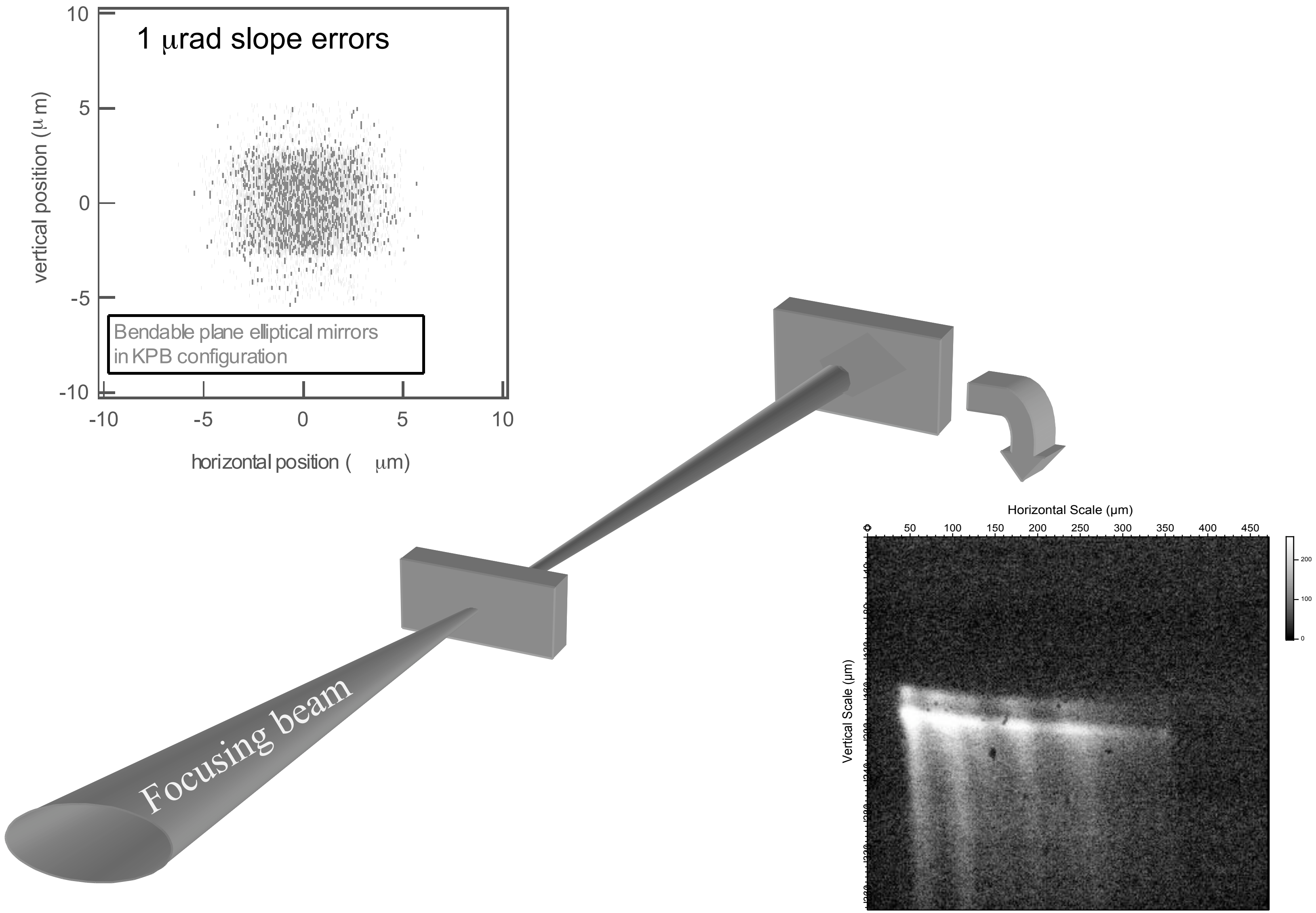
The only way to have a real micro-focus is to start from a flat or spherical surface and bent it to an mono dimensional ellipse



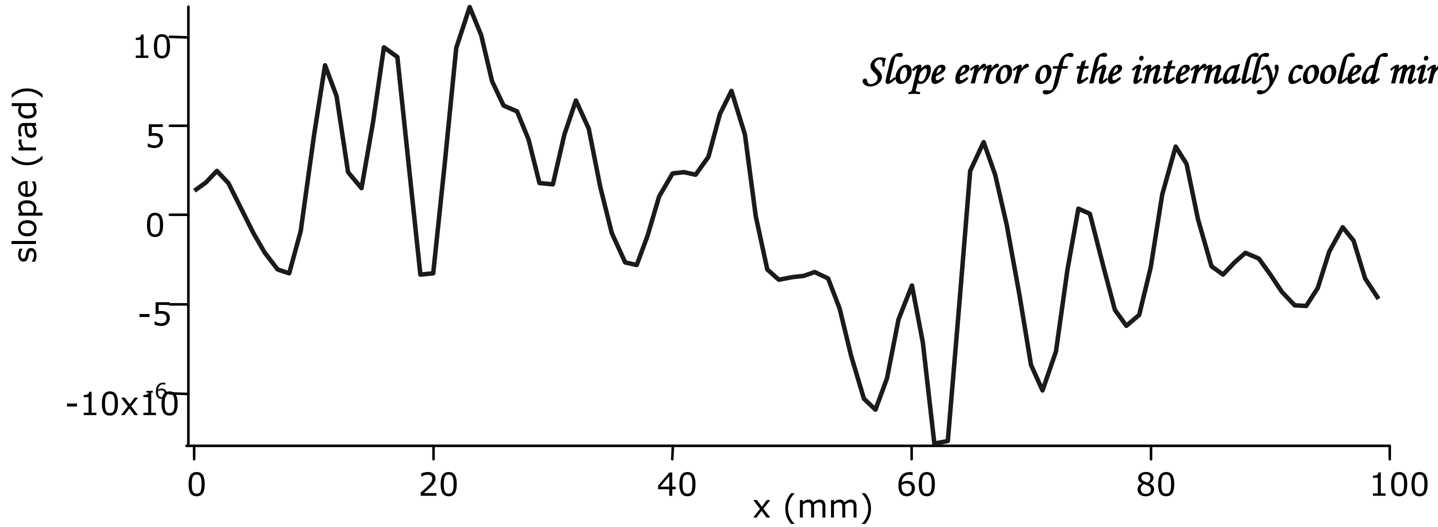


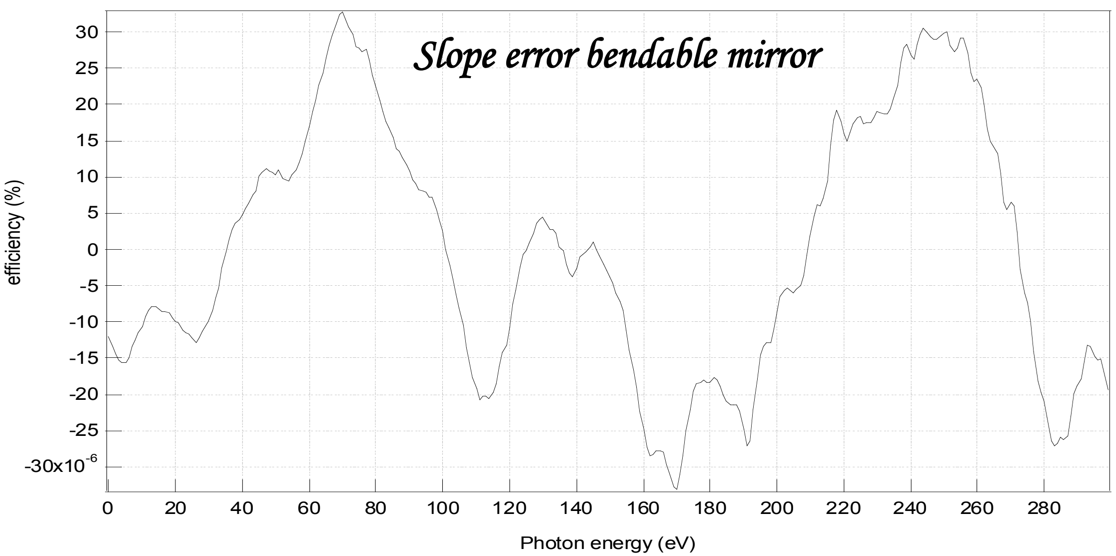


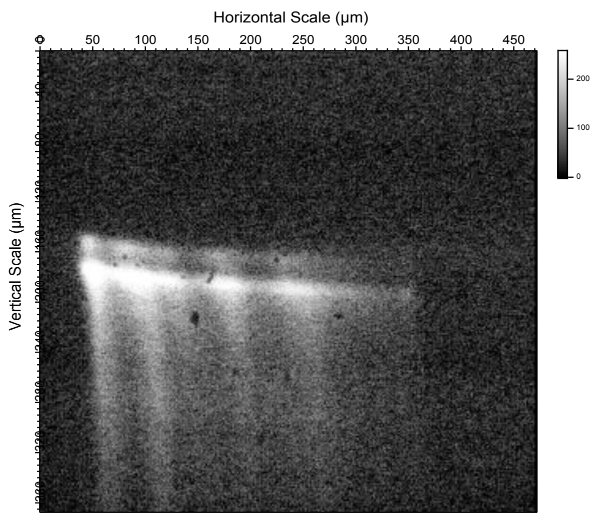
Out of focus


1 μrad slope errors
vertical position (μ m)
horizontal position (μm)
10
5
0
-5
-10
Bendable plane elliptical mirrors
in KPB configuration
Focusing beam
Horizontal Scale (μm)
50 100 150 200 250 300 350 400 450
Vertical Scale (μm)
200
100
0

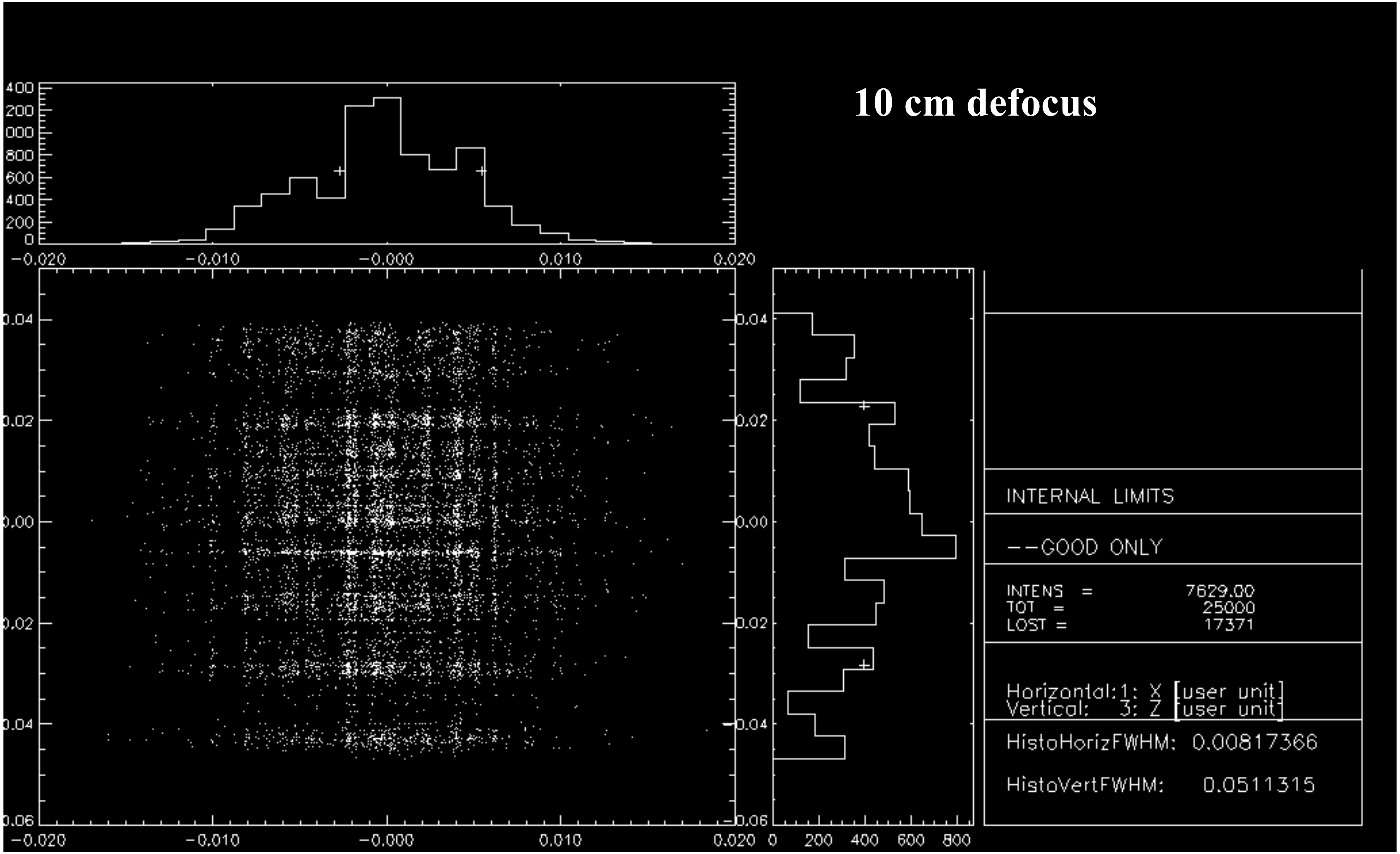
Out of focus


Slope error of the internally cooled mirror
slope (rad)
10
5
0
-5
-10x10-6
0
20
40
60
80
100
x (mm)

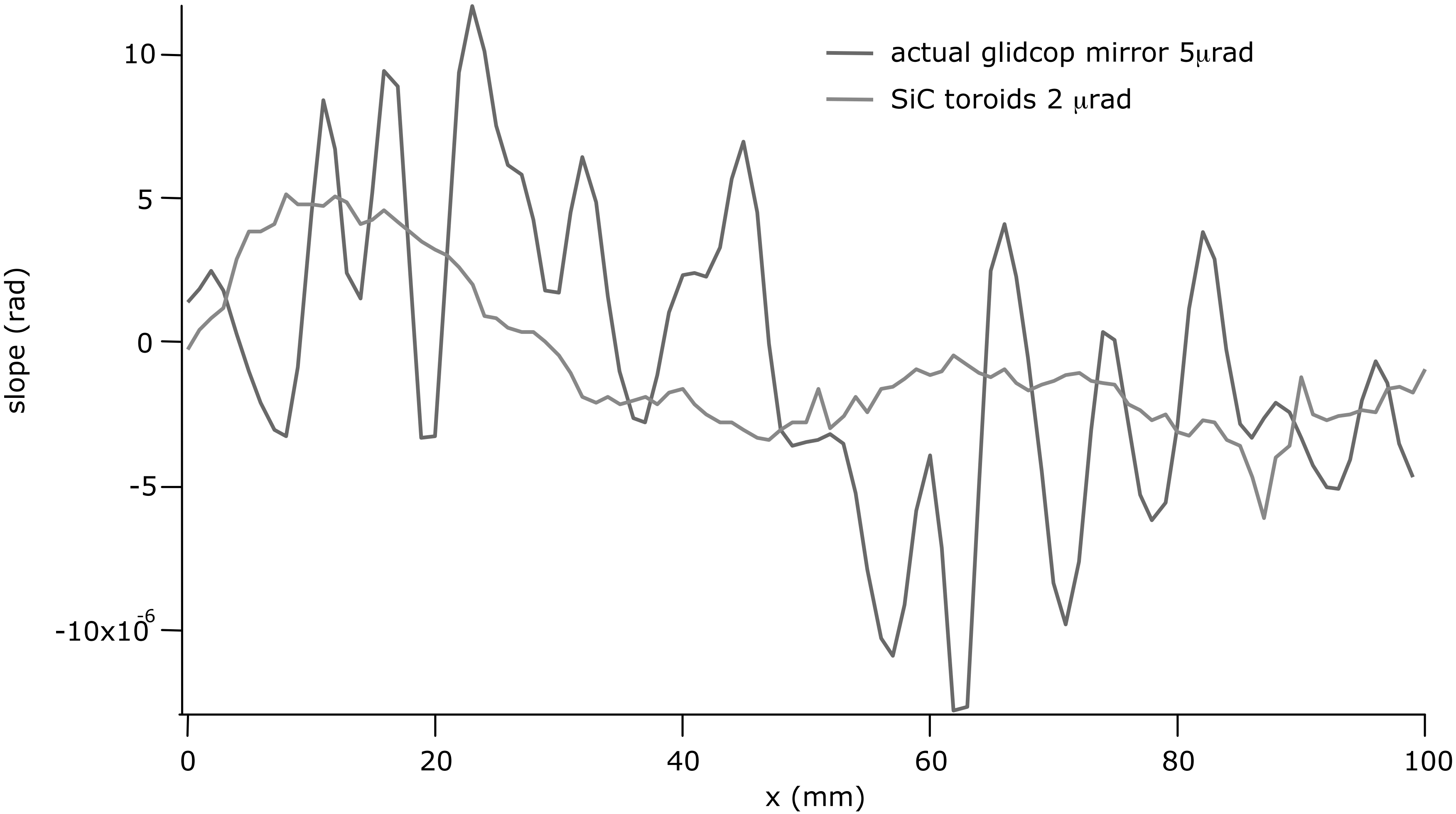

Slope error bendable mirror
efficiency (%)
Photon energy (eV)
-30x10-6


Horizontal Scale (μm)
Vertical Scale (μm)
50
100
150
200
250
300
350
400
450

Out of focus

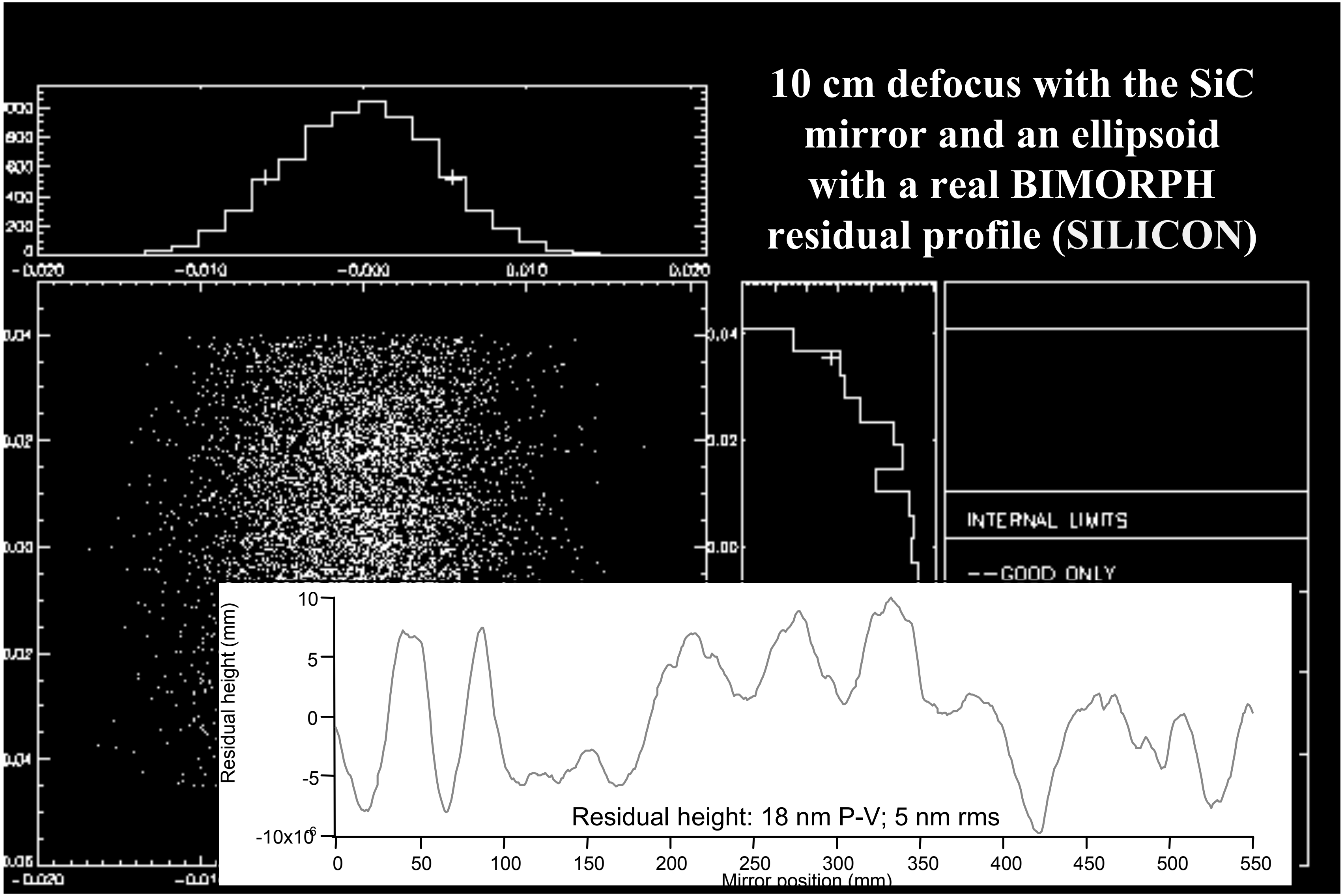

10 cm defocus
INTERNAL LIMITS
--GOOD ONLY
INTENS = 7629.00
TOT = 25000
LOST = 17371
Horizontal:1: X [user unit]
Vertical: 3: Z [user unit]
HistoHorizFWHM: 0.00817366
HistoVertFWHM: 0.0511315

Different mirror materials



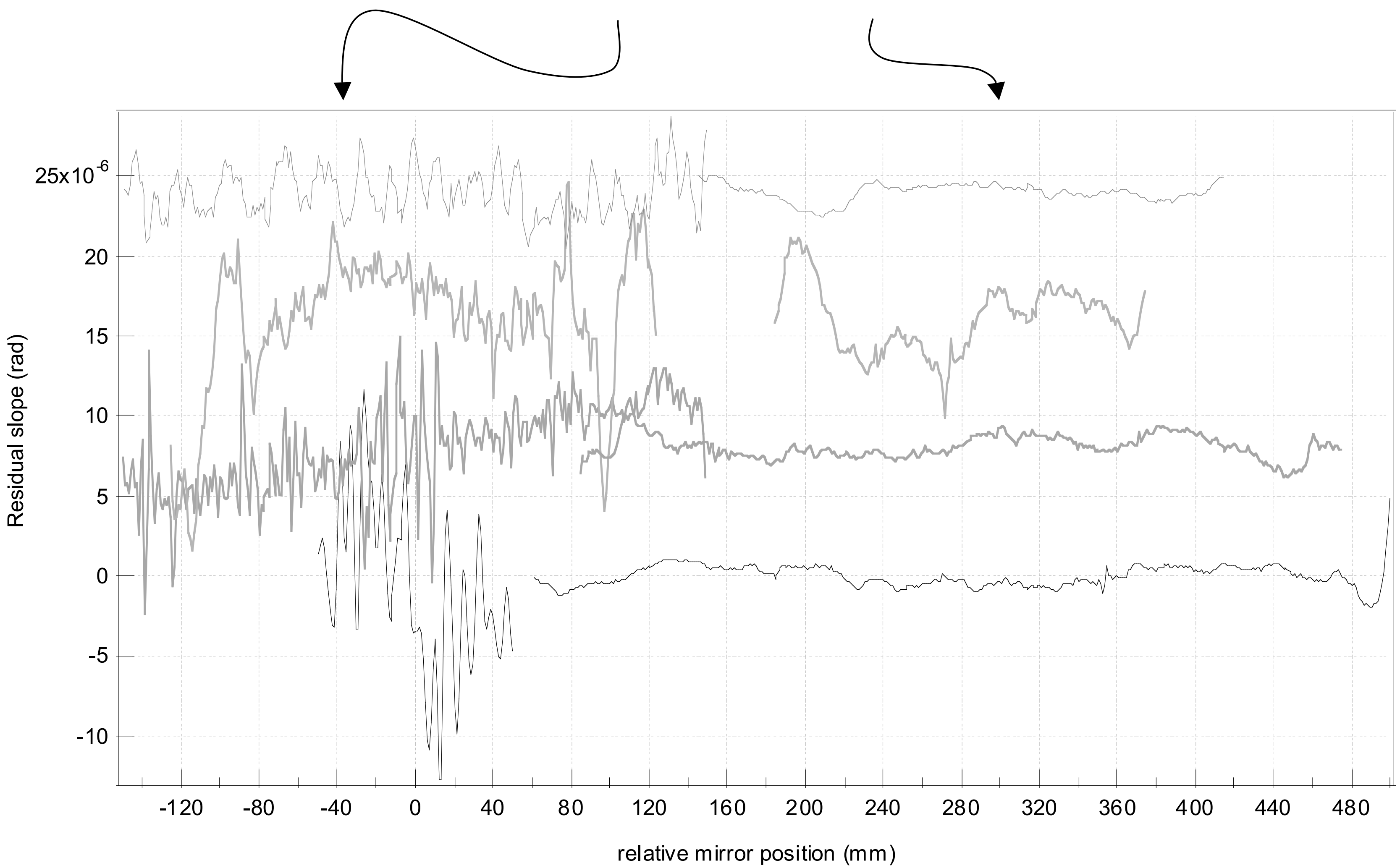
D. Cocco *X-Ray optics*, Erice, 6-15 April 2011

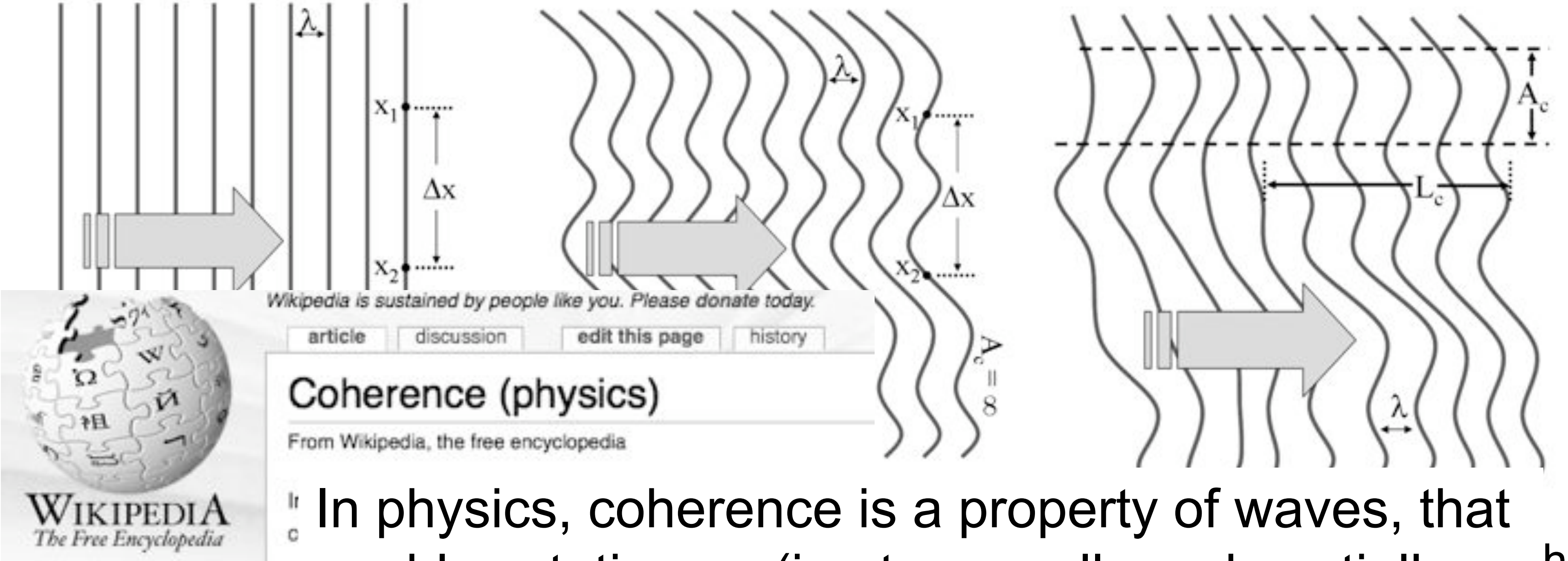
Out of focus with Silicon mirrors



The bimorph mirror is property of GM/CA CAT at the APS (funded in whole or in part with Federal funds from the National Cancer Institute (Y1-CO-1020) and the National Institute of General Medical Science (Y1-GM-1104)). ACCEL instruments GmbH is the main contractor for the realization of the GM/CA CAT beamlines.

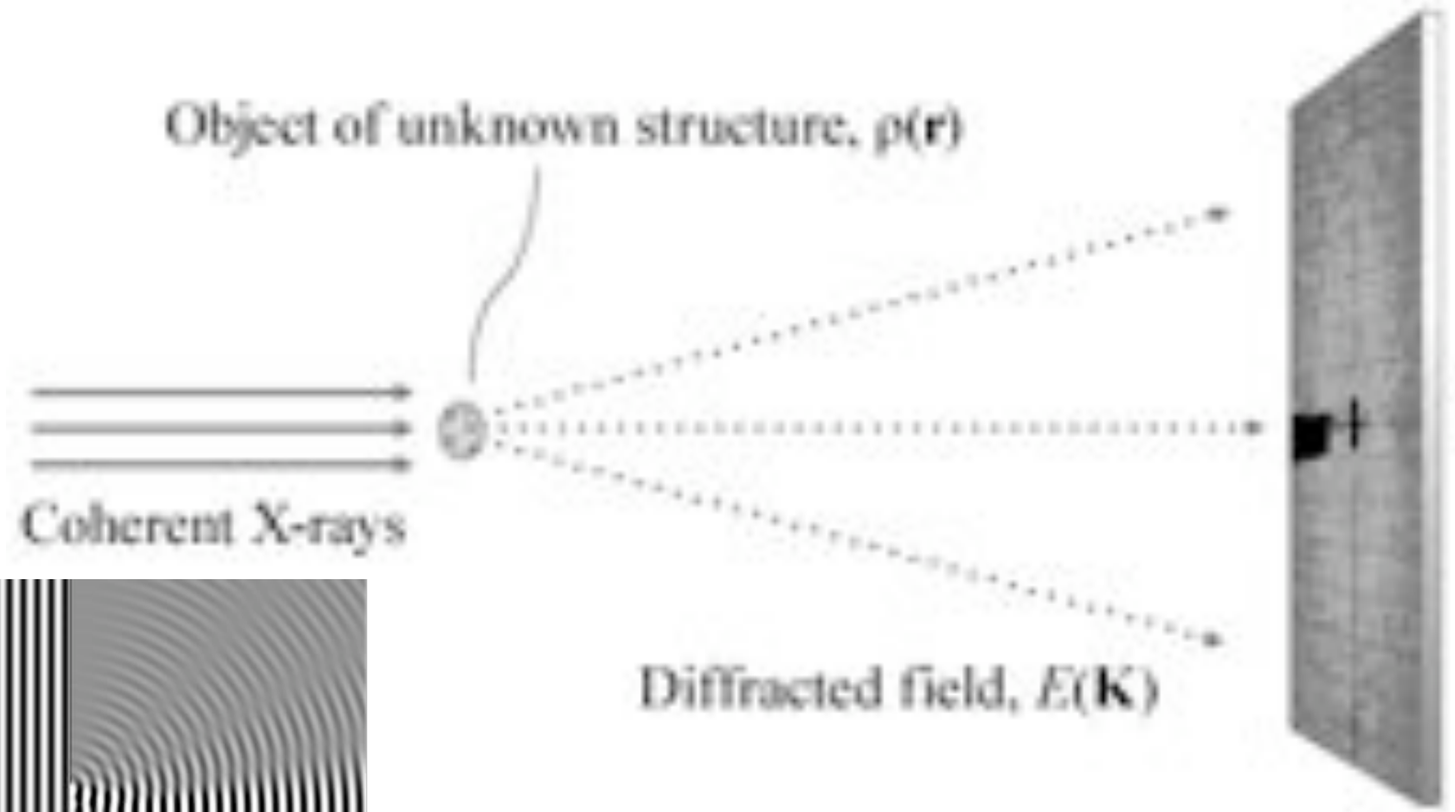
Metallic vs Silicon

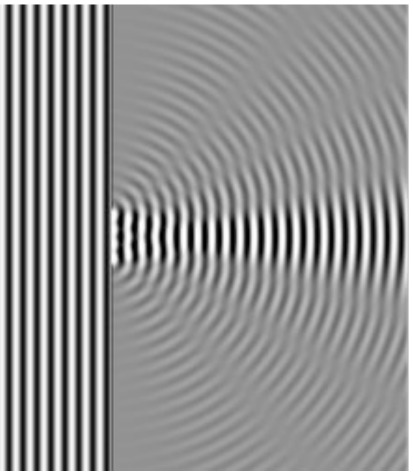




In physics, coherence is a property of waves, that enables stationary (i.e. temporally and spatially constant) interference. More generally, coherence describes all correlation properties between physical quantities of a wave.

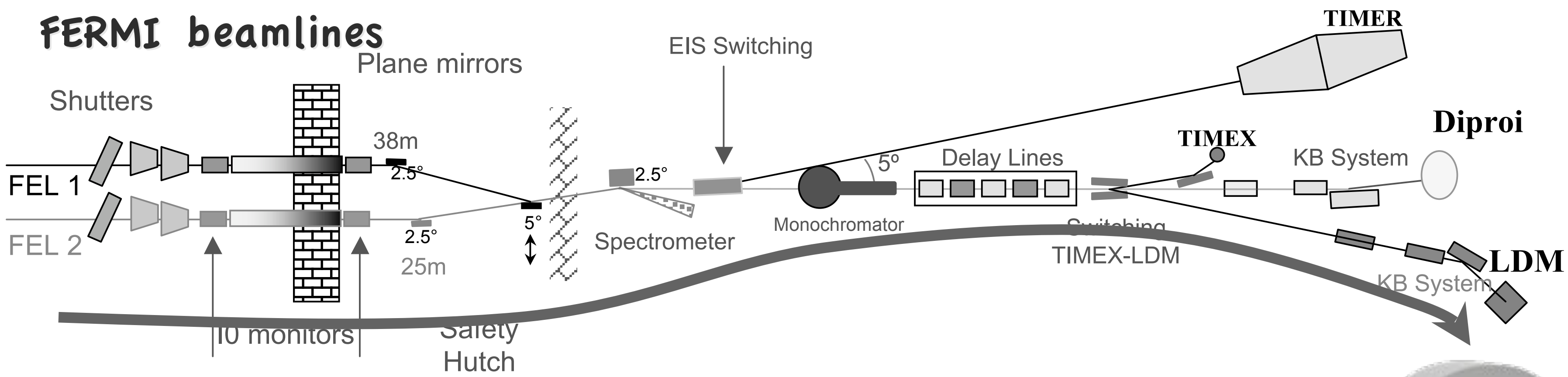
Coherence

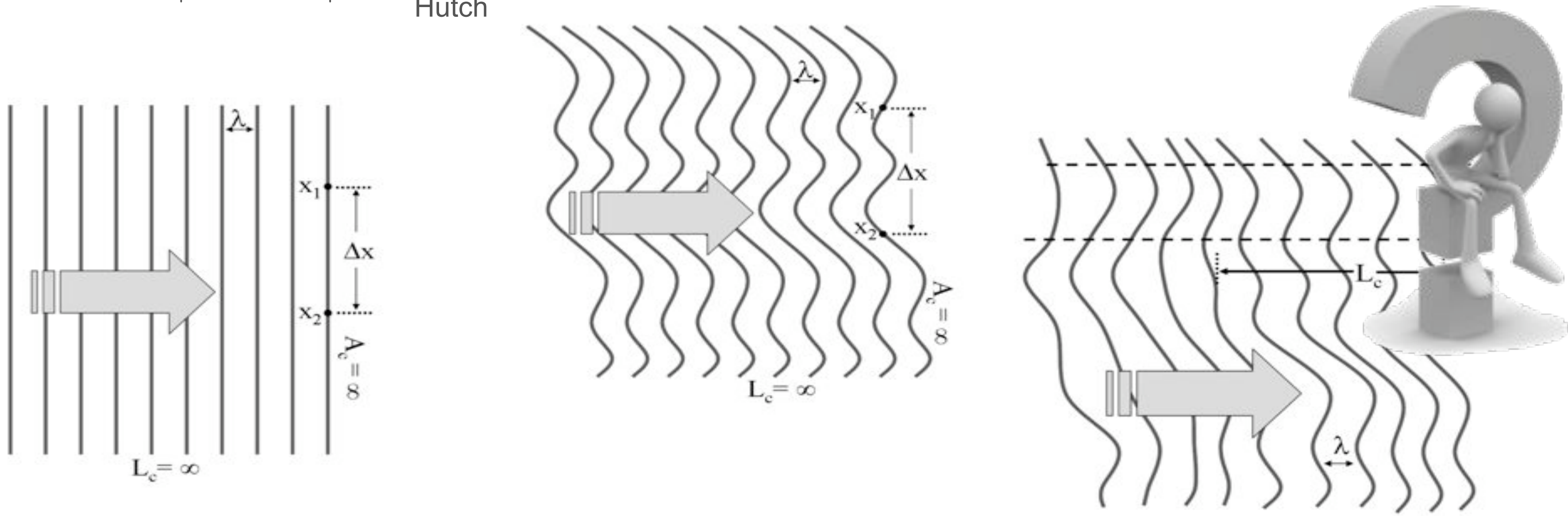




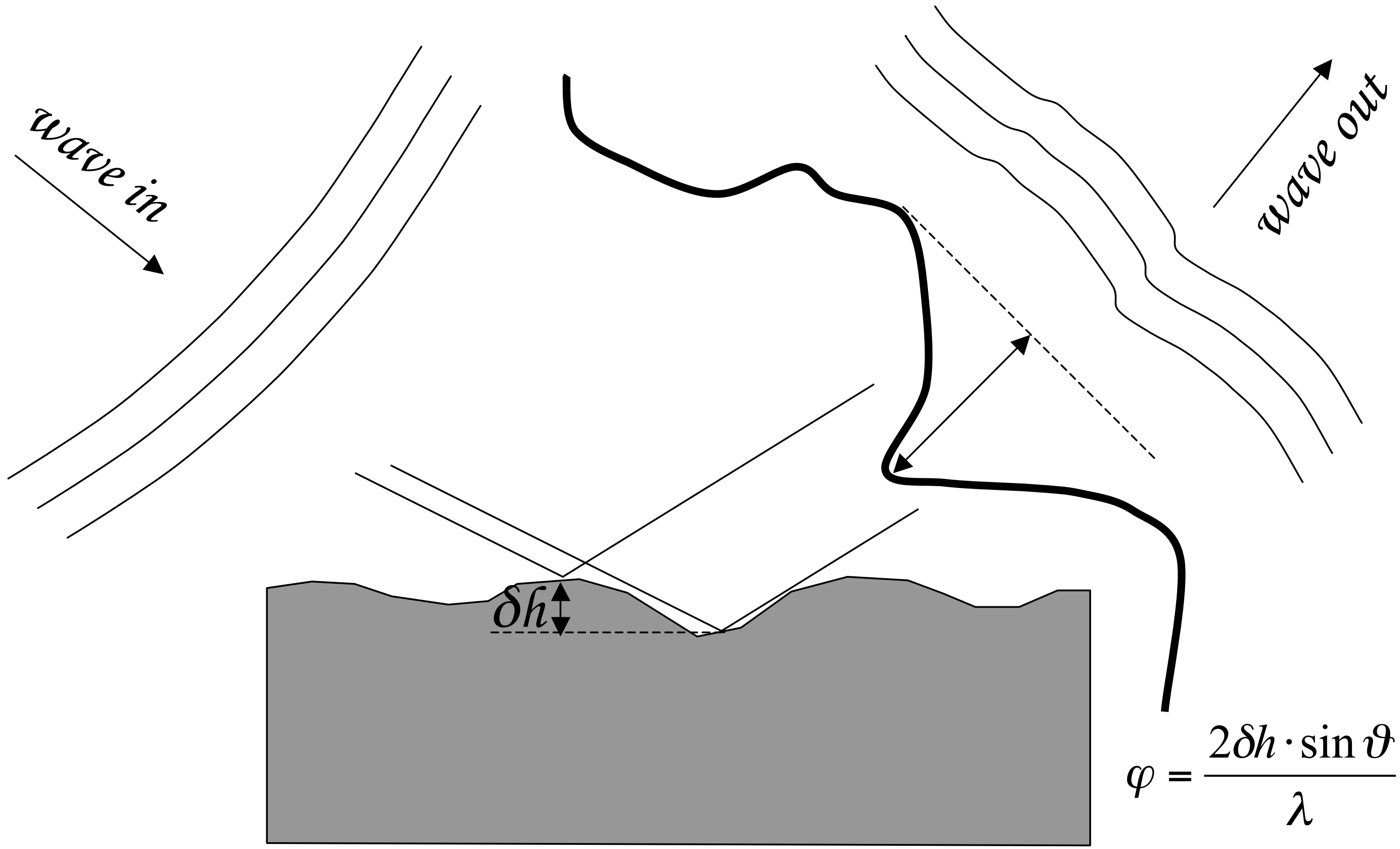
H. Chapman et al. Nature Physics 2, 839 - 843 (2006)

Coherence & Wave front Preservation





Coherence & Wave front preservation



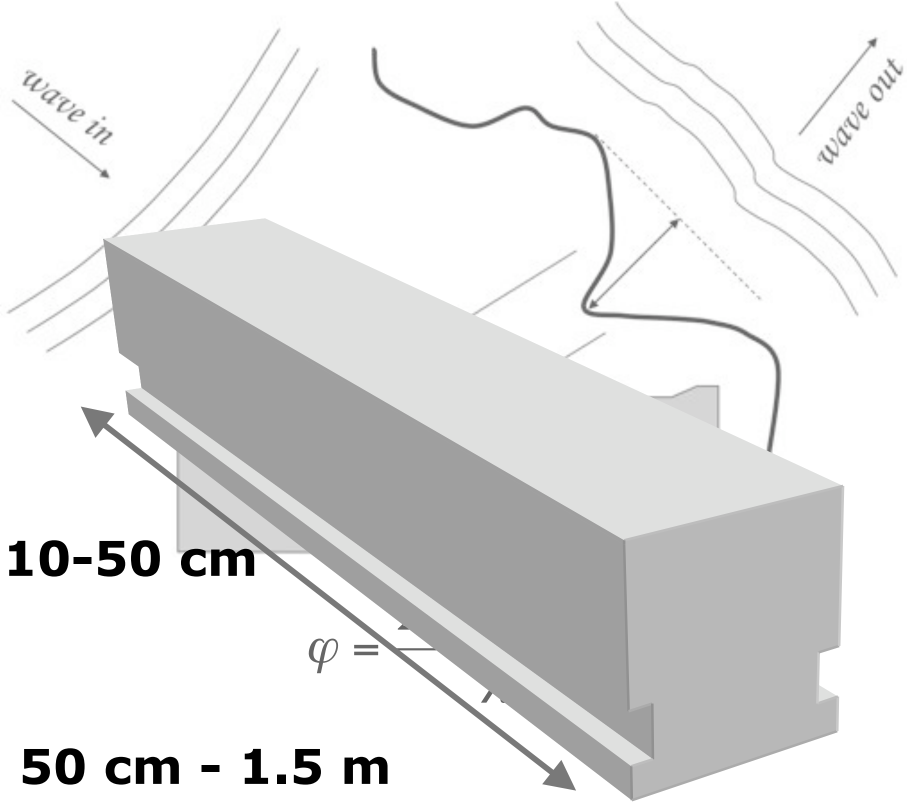
$$\varphi = \frac{2\delta h \cdot \sin\vartheta}{\lambda}$$

λ/4 deformation (after <u>all</u> mirrors) needed
λ/10 deformation (at <u>each</u> mirrors) acceted

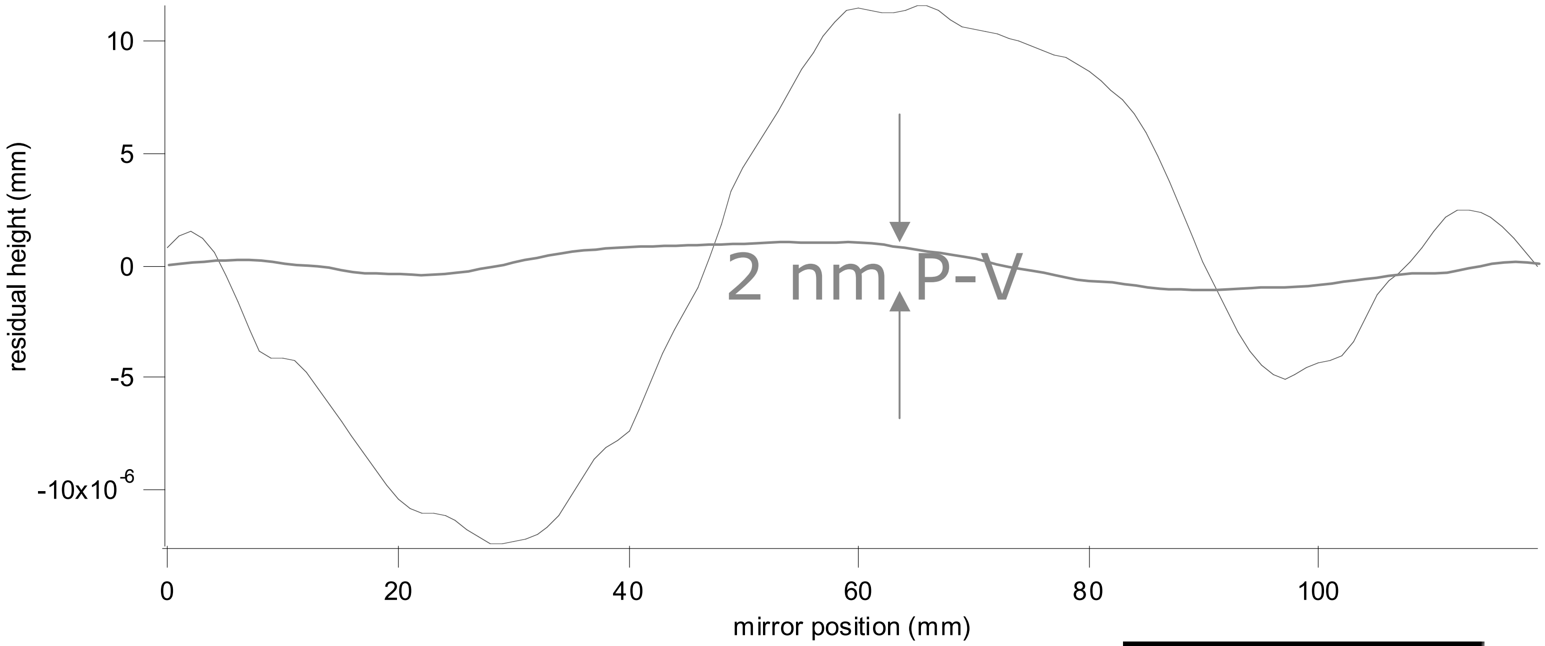
Coherence & wave front preservation

Fermi@elettra case			
Wavelength	Angle of incidence	shape error p-v φ =**0.25**	shape error p-v φ =**0.1**
40 nm	6°	47	18
40 nm	3°	95	38
40 nm	1.5°	191	76
10 nm	3°	23	9
10 nm	2°	35	14
10 nm	1°	71	28
5 nm	3°	12	5
5 nm	2°	18	7.2
5 nm	1°	36	14
1.67 nm	3°	4	2

Xfel(s) case			
Wavelength	Angle of incidence	shape error p-v φ =**0.25**	shape error p-v φ =**0.1**
1 nm	1°	7	3
0.5 nm	1°	3.6	1.4
0.1 nm	0.33°	2	<1

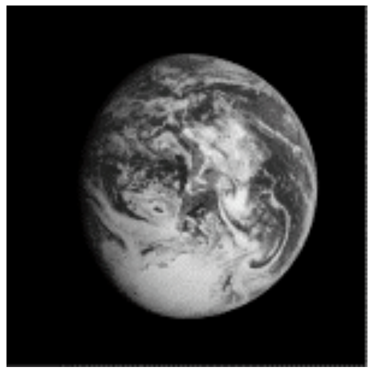


Mirror shape errors

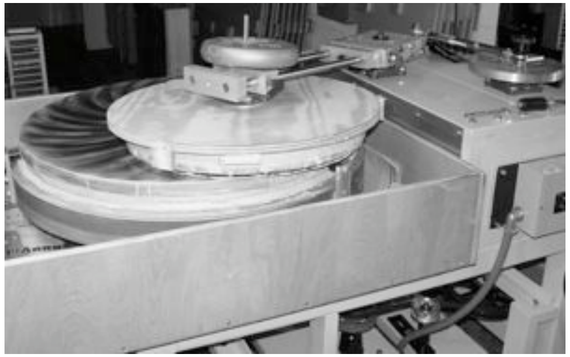


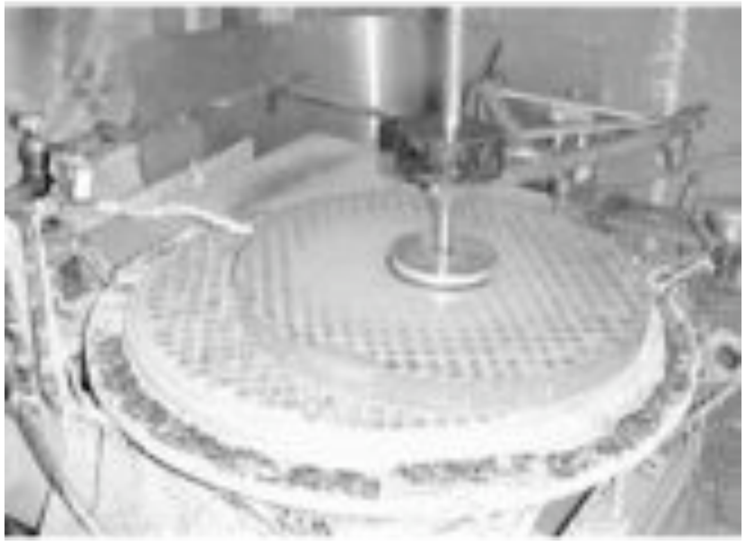
Typical SR mirrors

Required FEL mirrors



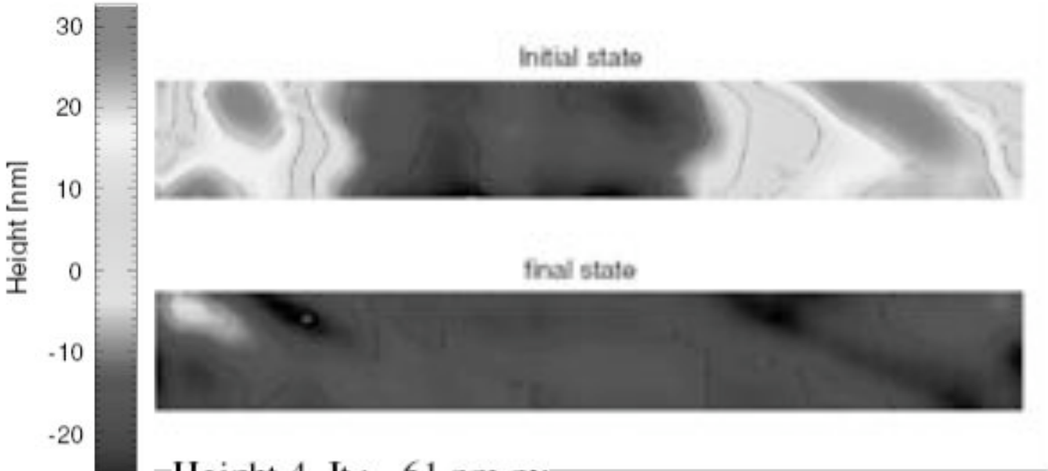
Mirror polishing



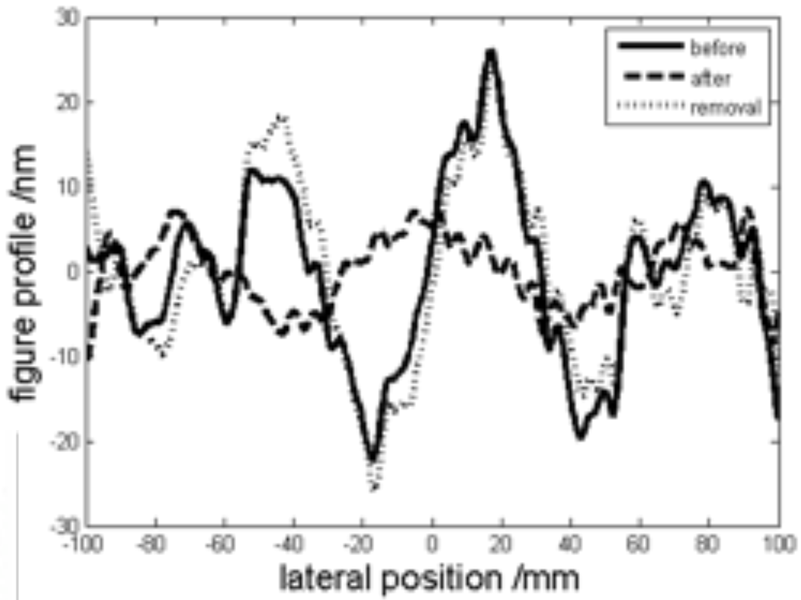


Classical polishing

1) Classical polishing (Computer Controlled Polishing-CCP)
2) High precision metrology (NOM-Bessy)
3) Ion Beam Figuring or CCP
4) Second itaration with metrology
5) Second IBF or CCP
6) Third.....
7) ......
8) ....

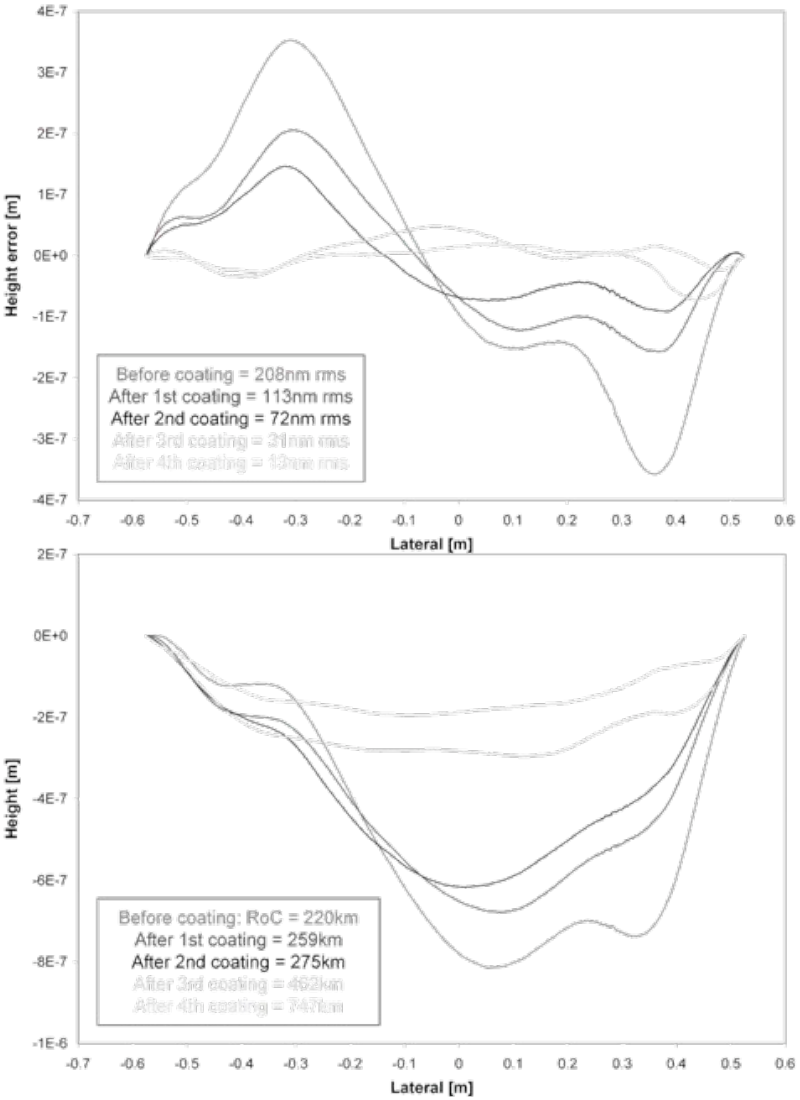


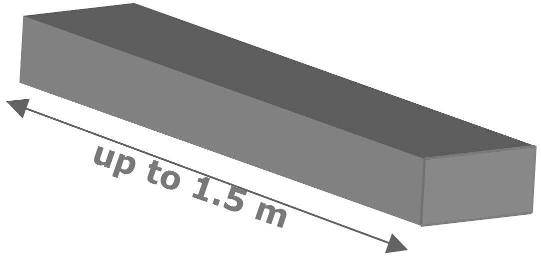
Height 4. It.: 61 nm pv
Height final.: 22 nm pv



	PV /nm	RMS /nm	slope RMS /arcsec
before	48.4	10.3	0.37
after	14.9	3.9	0.22
after -0.5mm	13.9	3.6	0.17
after +0.5 mm	18.5	4.4	0.31

Preferential coating techiques





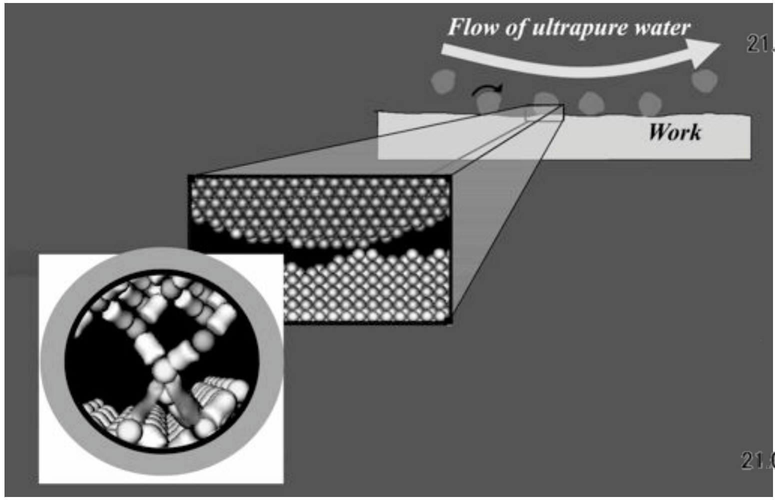
1) Classical polishing
2) High precision metrology
3) Error correction by Rh controlled deposition
4) Second itaration with metrology
5) Second differential coating deposition
6) Third.....
7) ......
8) ....
9)

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

Elastic emission machining

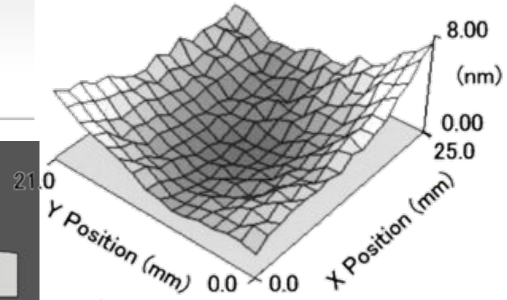
mirror substrate :Quarz Glass Silicon

JTEC CORPORATION



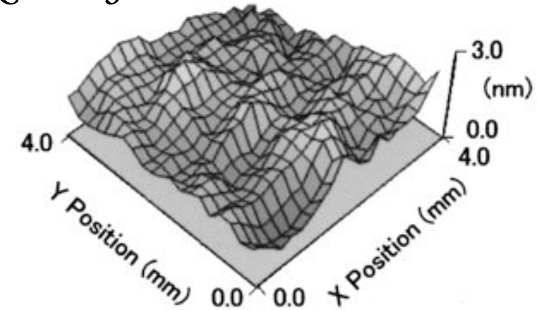
Chemical reaction are induced between top-site atoms of mirror and fine powders

Problem: max dimension 100mm (400 with lower precision)



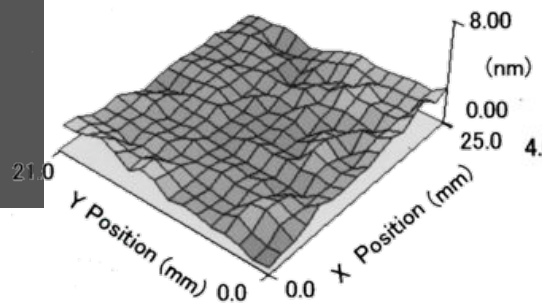
Before machining

1.3 nm rms



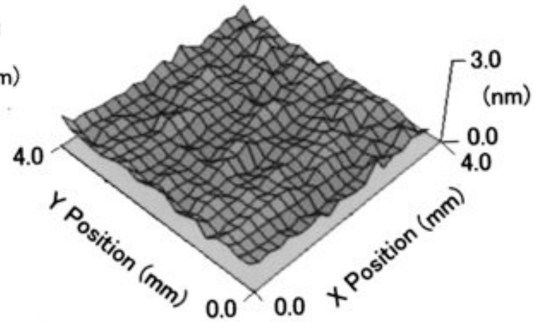
Before machining

0.32 nm rms



after machining

0.3 nm rms

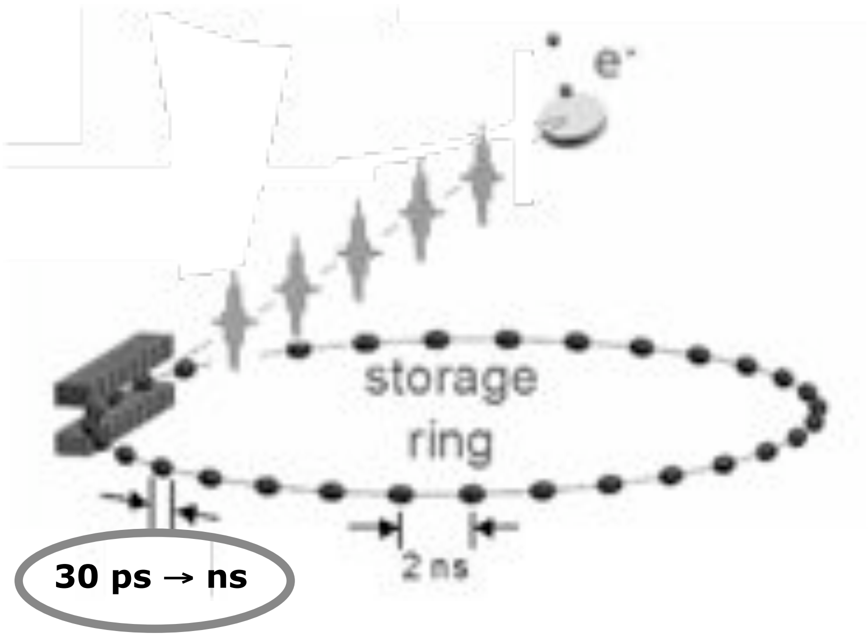


after machining

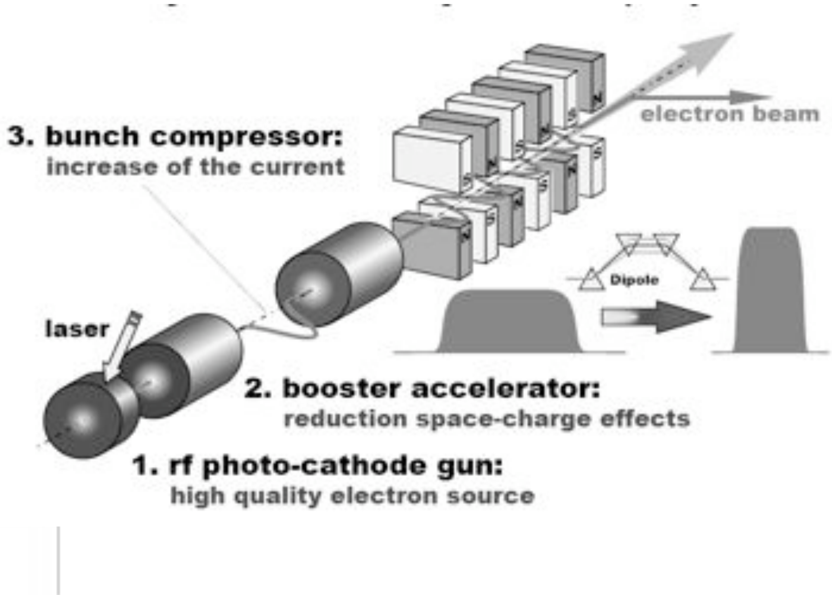
0.14 nm rms

Powder used: 0.1μm size SiO2 2μm size SiO2

SR sources vs FEL sources

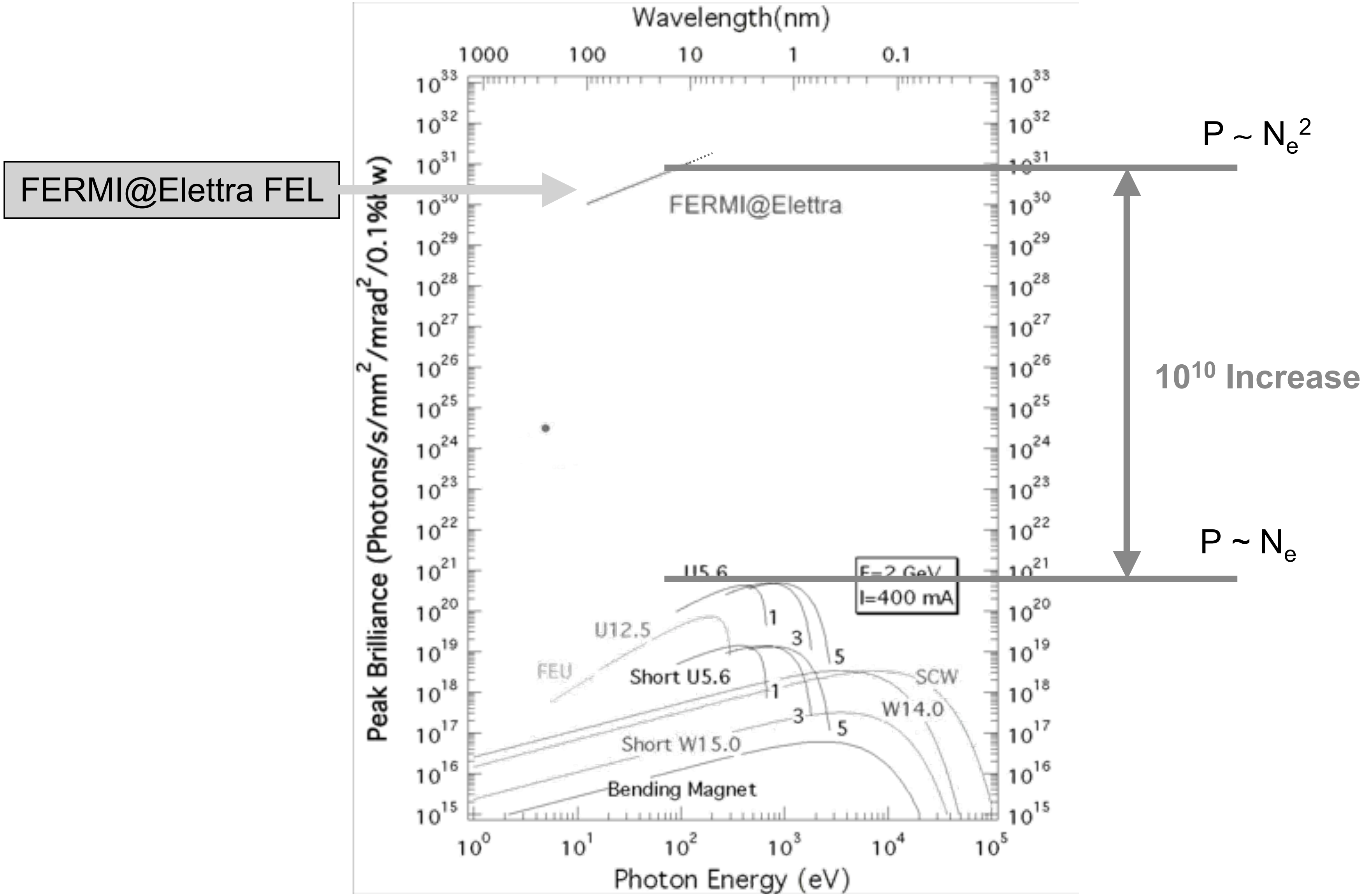


Synchrotron bunch distribution



Compress the bunch length and see what's happen

Brilliance



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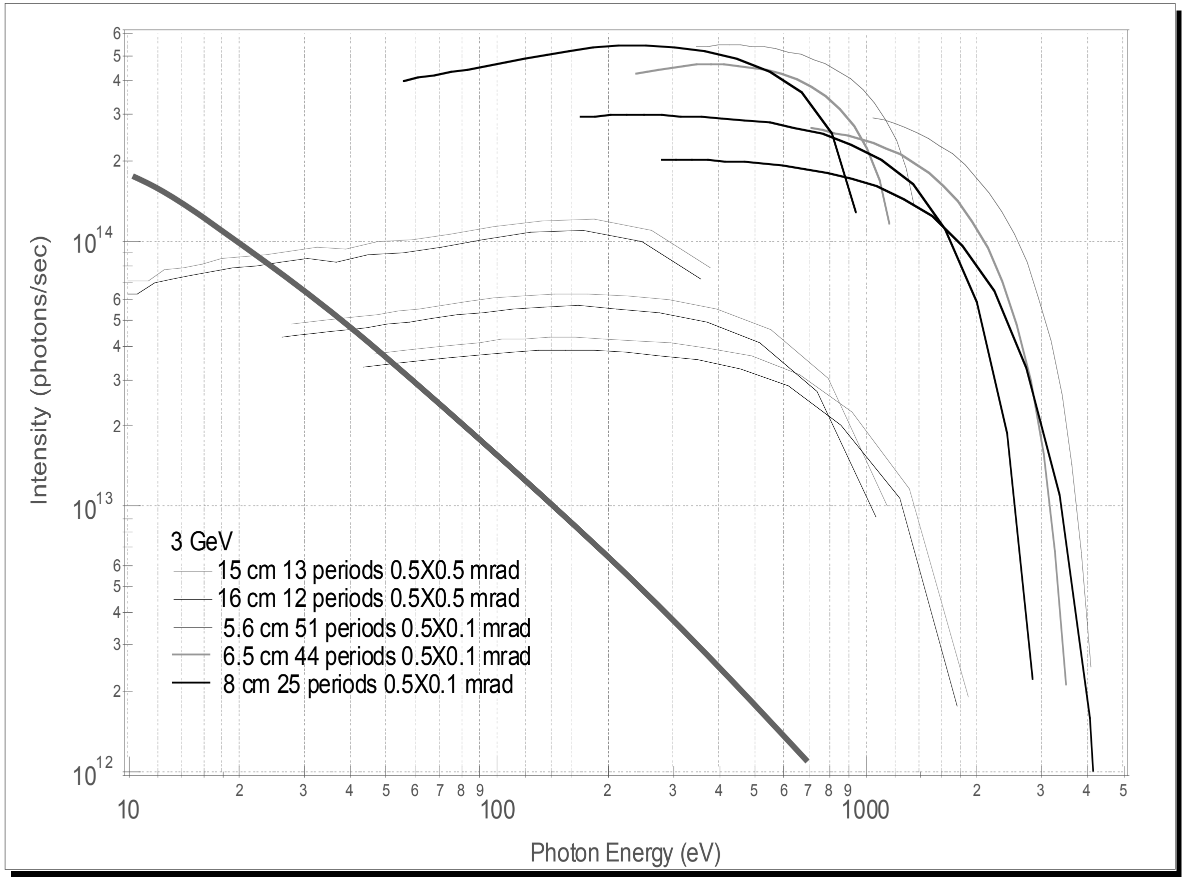
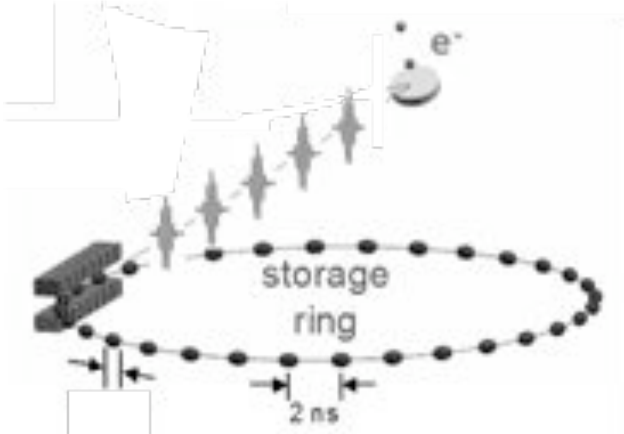
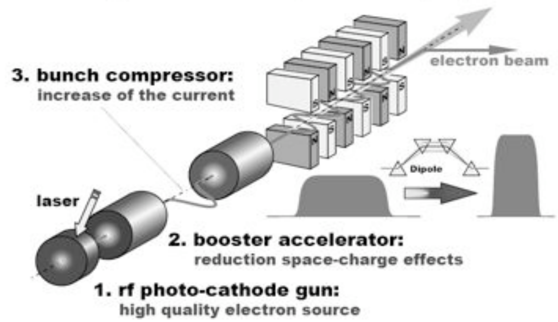
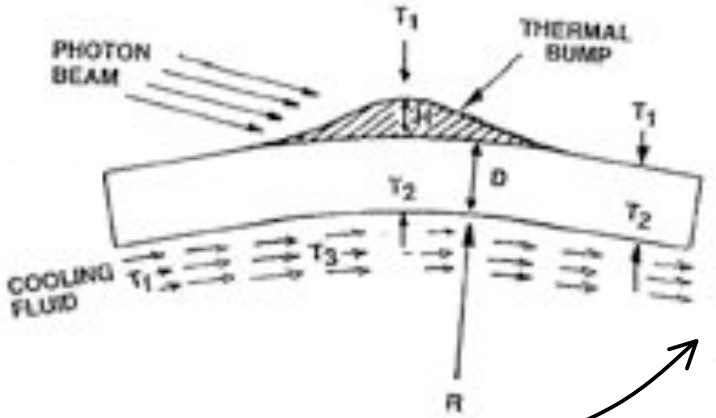
Differences

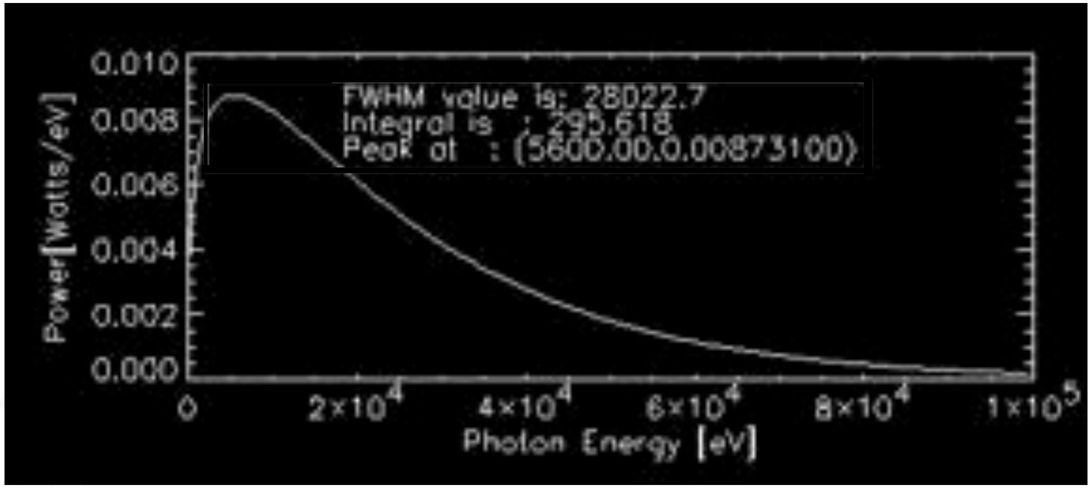


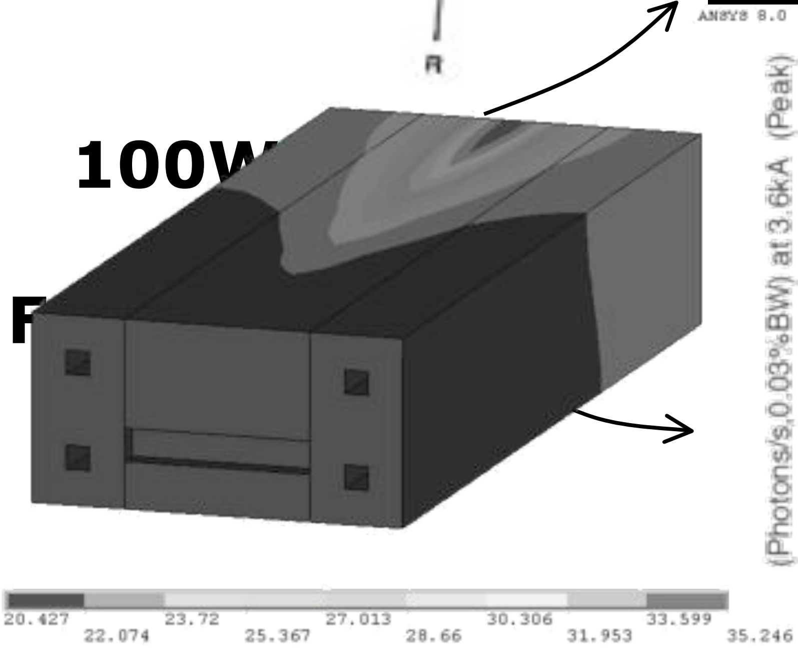


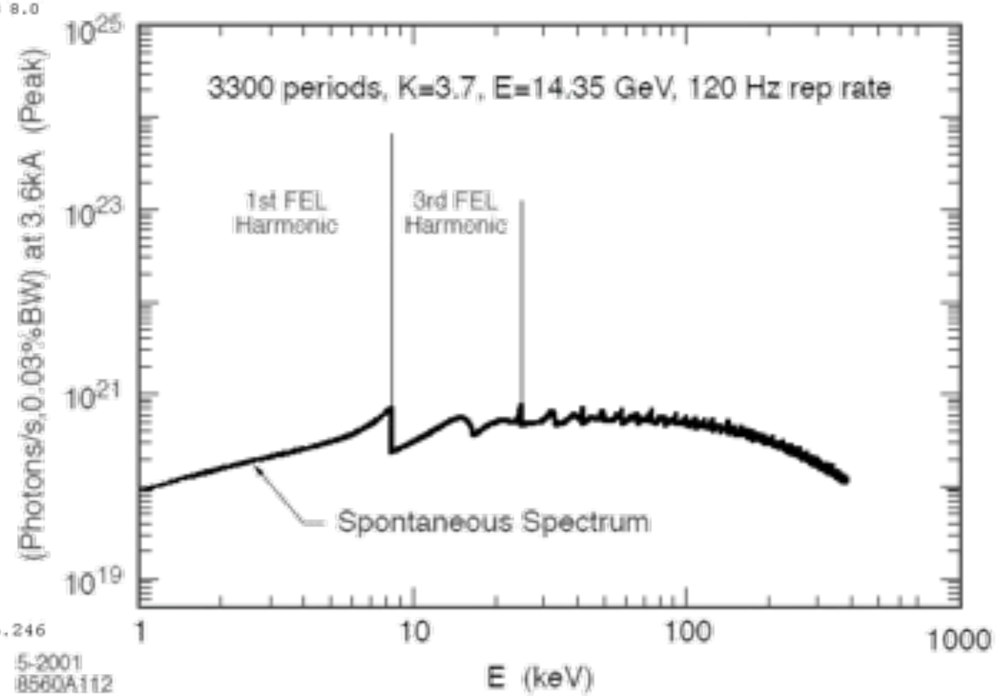


Thermal deformations

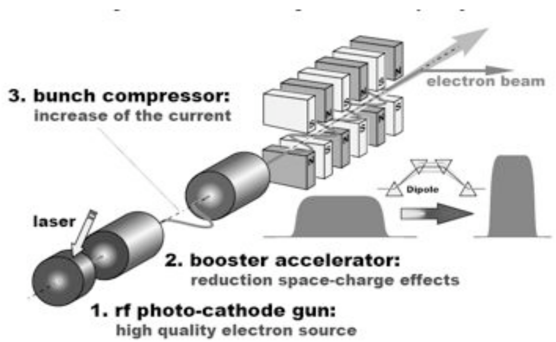






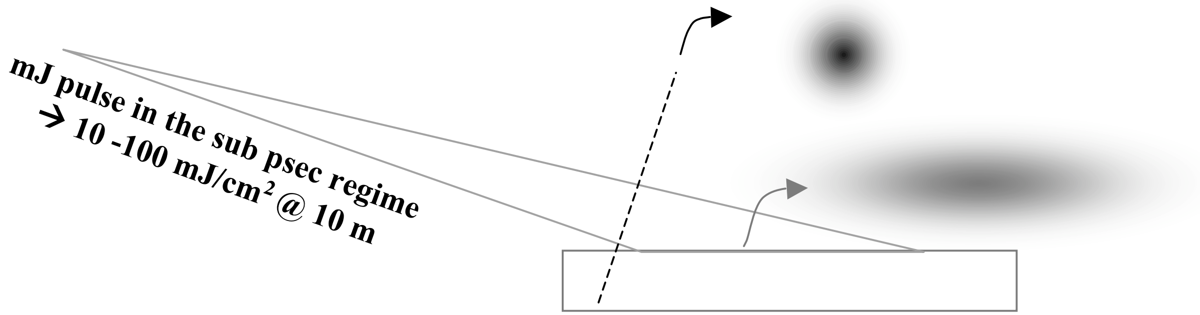


Fluence and damage treshold



Fluence (Joules/cm^2) = laser pulse energy (J) / focal spot area (cm^2)
Intensity (Watts/cm^2) = peak power (W) / focal spot area (cm^2)
Peak power (W) = pulse energy (J) / pulse duration (sec)

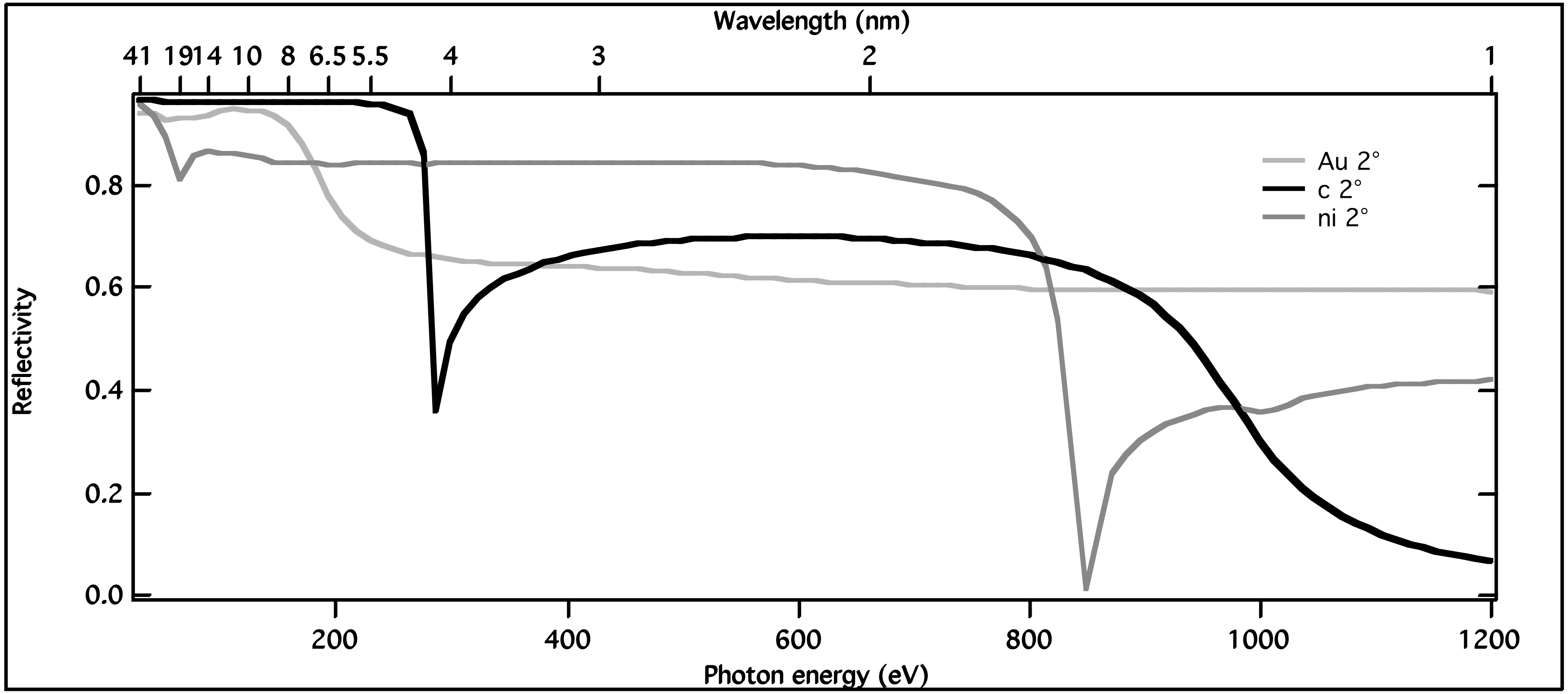
FEL 1:
100 fsec; 5 GW → ~ 0.5 mJ
FEL 2:
200 fsec; 1 GW → ~ 0.2 mJ



Matrial	***Damage threshold @ 90 nm***	***Safety angle 100 nm (10 /20/40 m)***	***Estimated damage threshold @ 40 nm***	***Safety angle 40 nm (10 /20/40 m)***
Cu/Glidcop bilk	~ 500 mJ/cm^2	24° / 90°/ 90°	~ 1000 mJ/cm^2	41° / 90°/ 90°
Au coating	40 mJ/cm^2	1.9° / 7.6°/ 32°	50 mJ/cm^2	4.8° / 20°/ 77°
Silicon bulk	30 mJ/cm^2	1.5° / 6°/ 23°		
Graphite coating	60 mJ/cm^2	2.9° / 11.5°/ 53°	240 mJ/cm^2	9° / 40°/ 90°
YAG bulk	70 mJ/cm^2	3.3° / 13.4°/ 68°		

Fluence and damage treshold

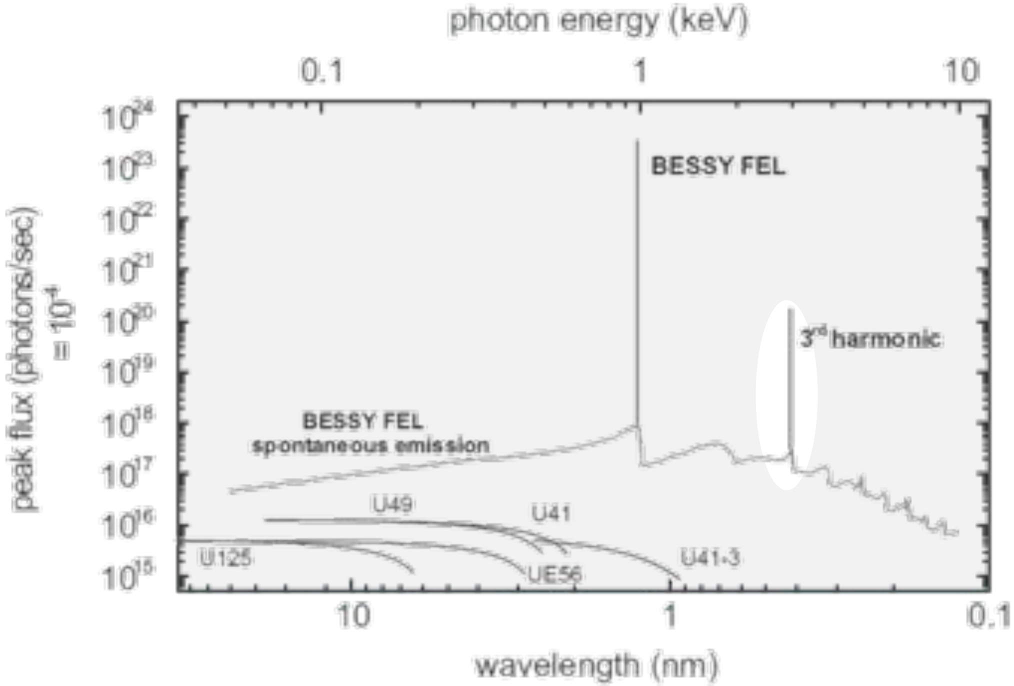
High density carbon (or B4C) are very "strong" materials but...

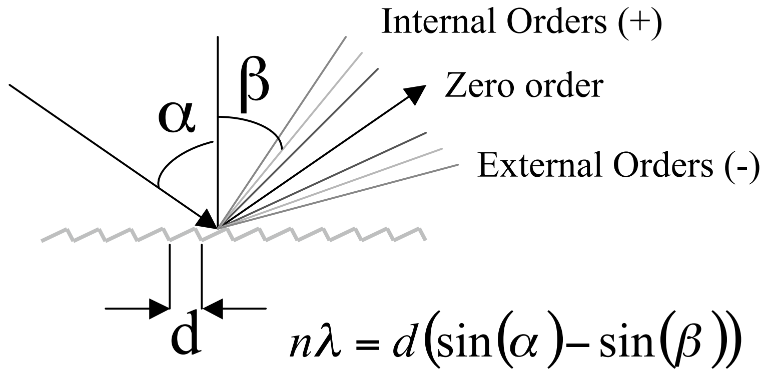


Proper mirror coatings (and multilayers) must be made.
Binding layers are very very important

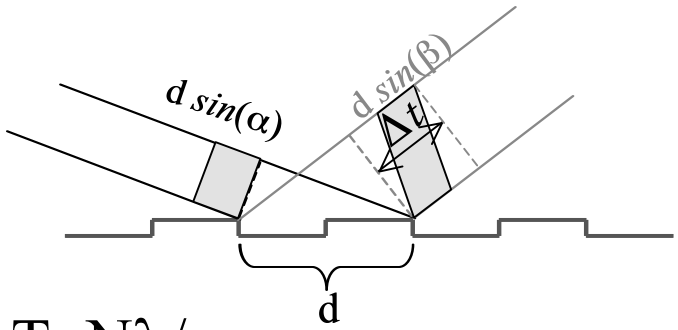
Gold or platinum are "soft" or "tender" materials.....

Harmonic rejection and monochromatisation





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

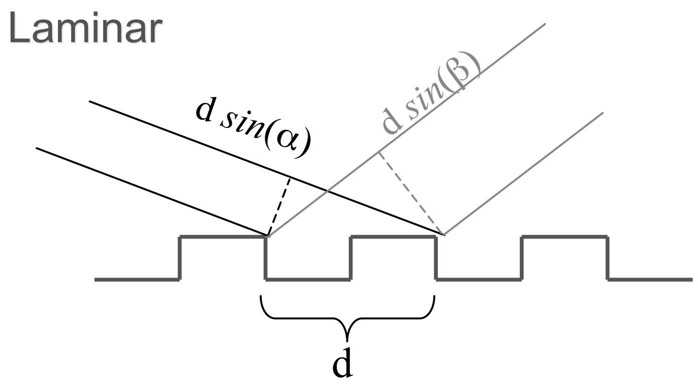


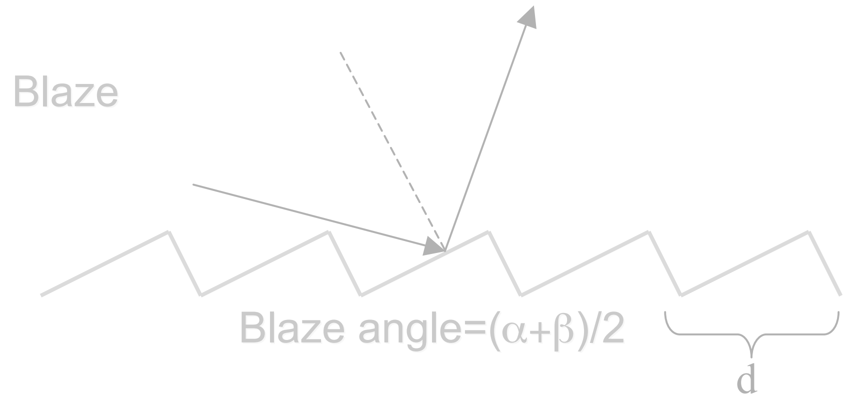
$\Delta T = N\lambda/c$

Examples:

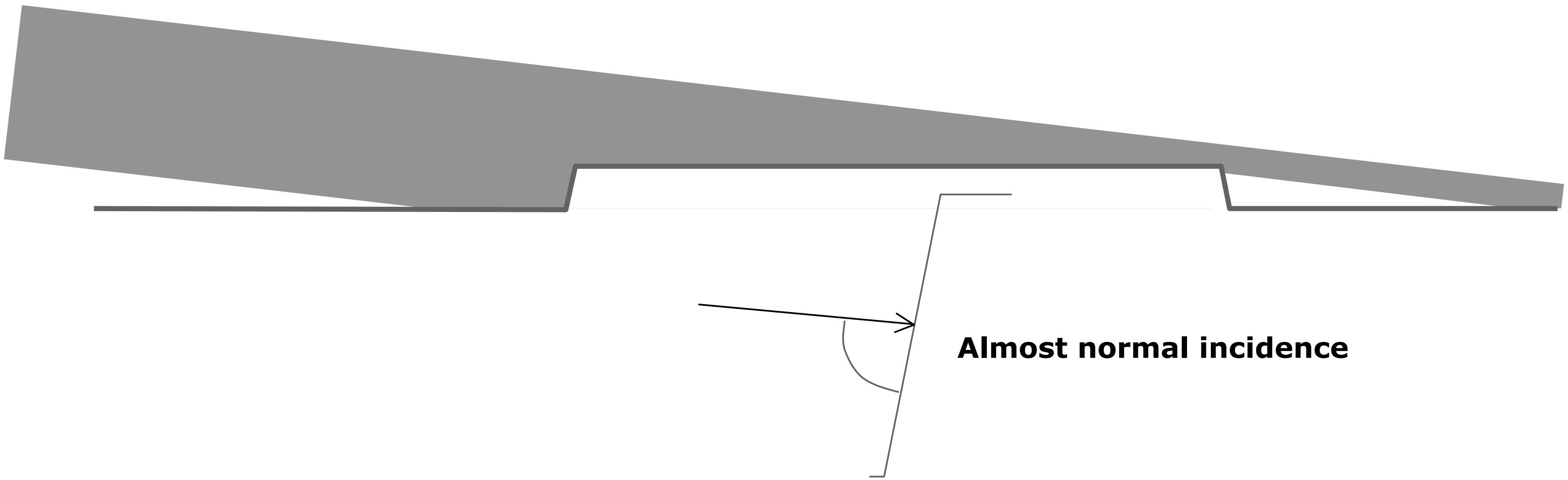
100 nm cff 0.98 α 80.41 11.1 l/mm Δt=74 fsec FWHM
40 nm cff 0.93 α 81.8 33.3 l/mm Δt=65 fsec FWHM
30 nm cff 1.25 α 82.65 150 l/mm Δt=300 fsec FWHM
10 nm cff 1.73 α 85.5 600 l/mm Δt=236 fsec FWHM

Grating's groove



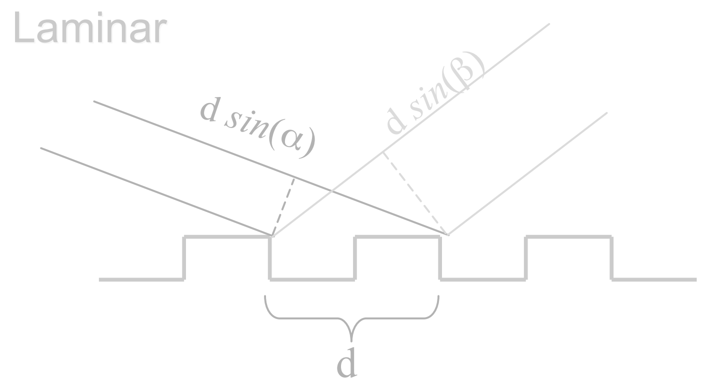


A lot of energy deposited on the grating facet

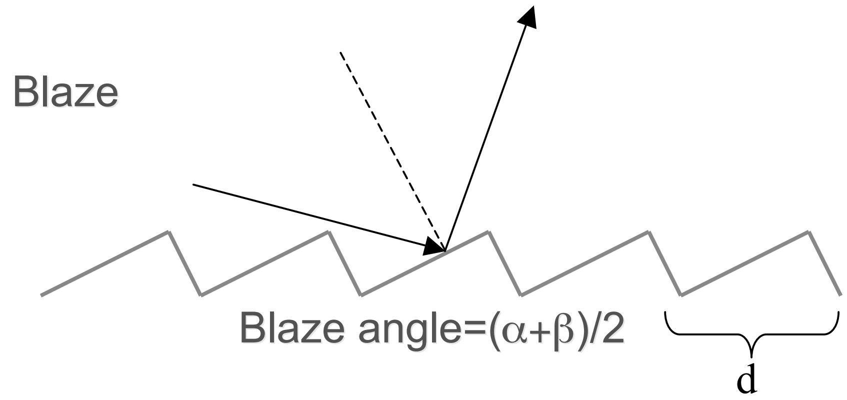


Almost normal incidence

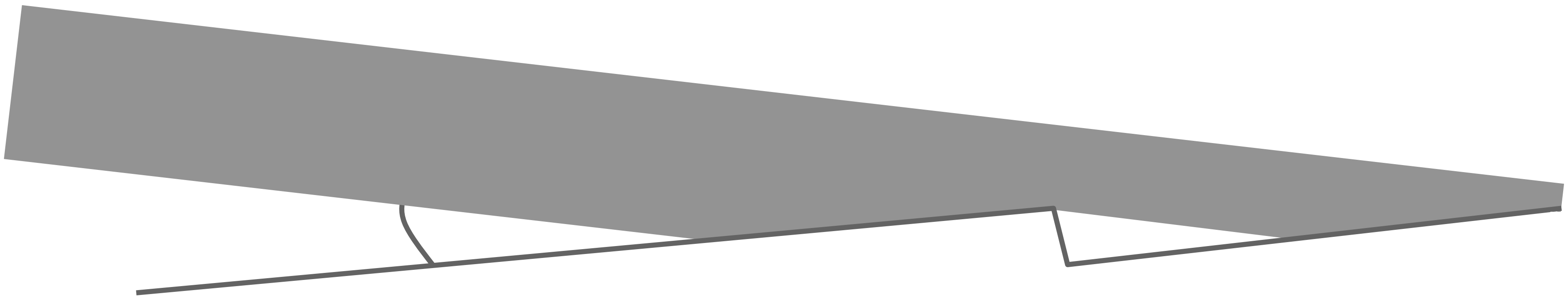
Grating grooves



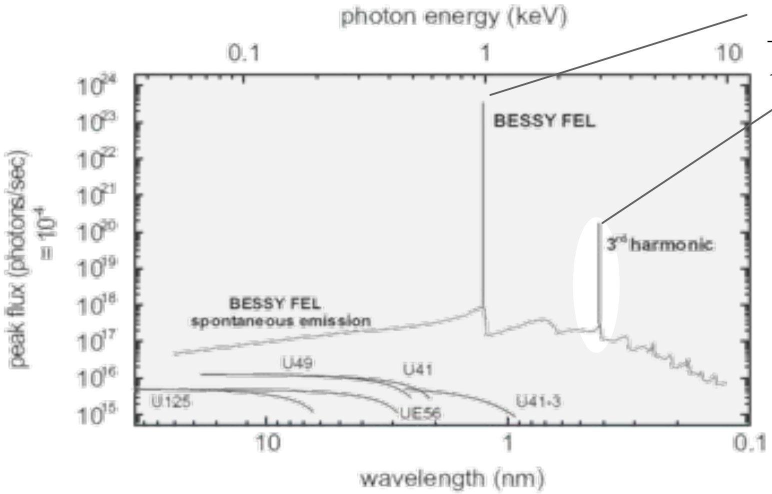
A lot of energy deposited on the grating facet



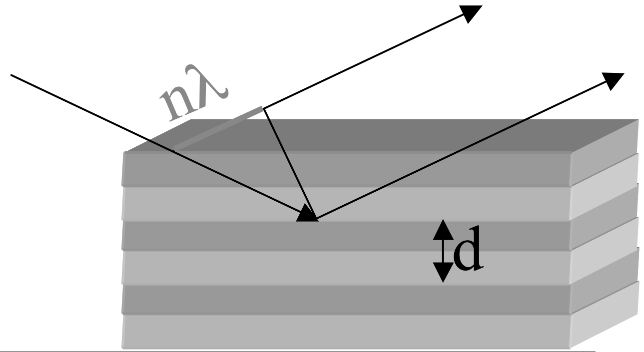
Energy distributed on the grating facet



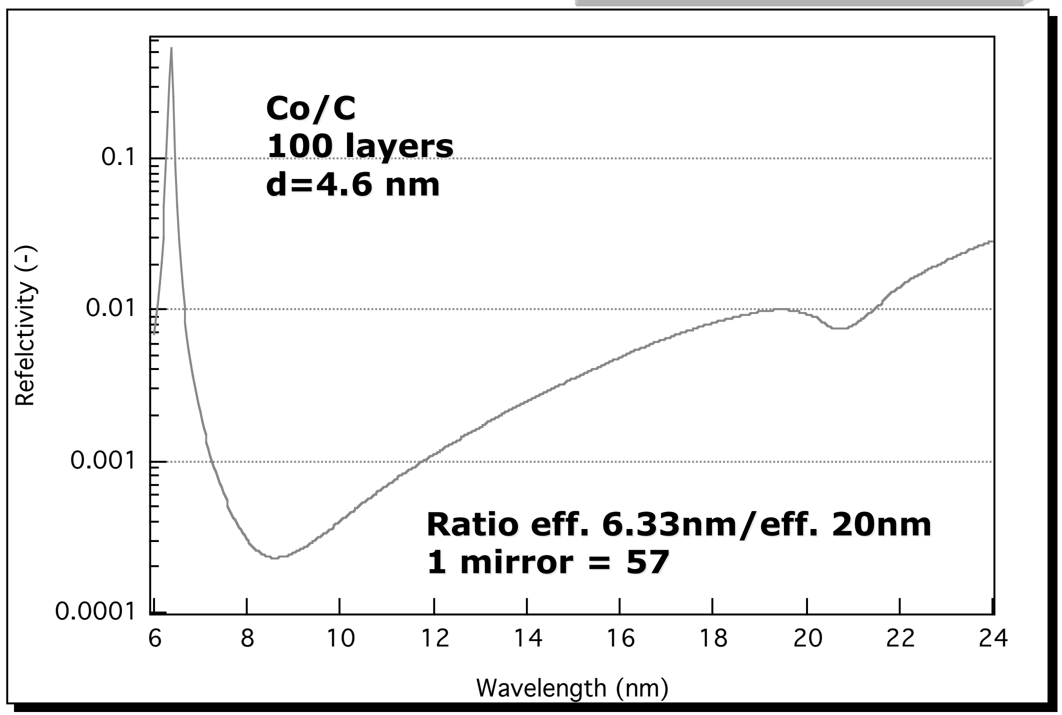
Multilayers

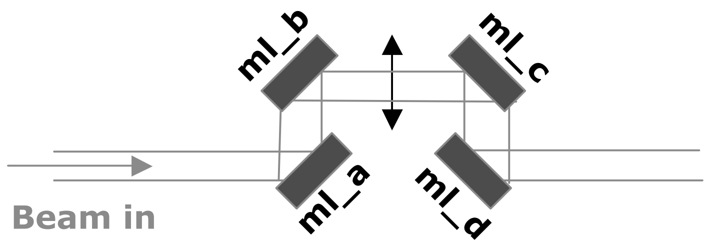


$$\frac{Intensity\ 20nm\ \left(1^{st}\ harm\right)}{Intensity\ 6.33nm\ \left(3^{rd}\ harm\right)} \geq 100$$

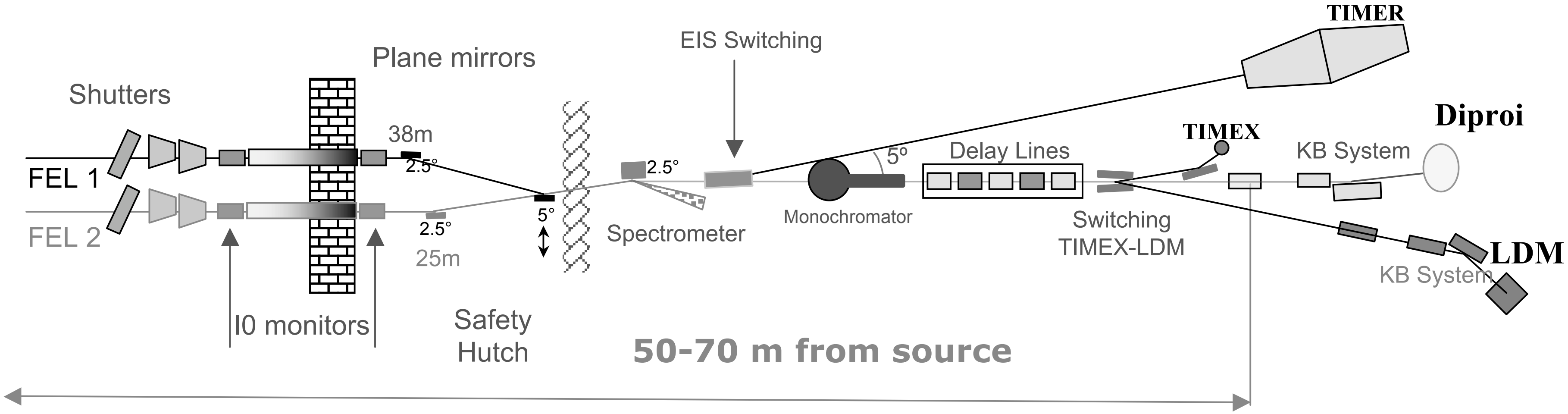


Ratio eff. Multilayer	Total
6.33nm/eff. 20nm	6.33nm/eff. 20nm
1 mirror → 57	1 mirror → 0.6
2 mirrors → 3300	2 mirrors → 33
4 mirrors → 10^7	4 mirrors → 10^5





Multilayers



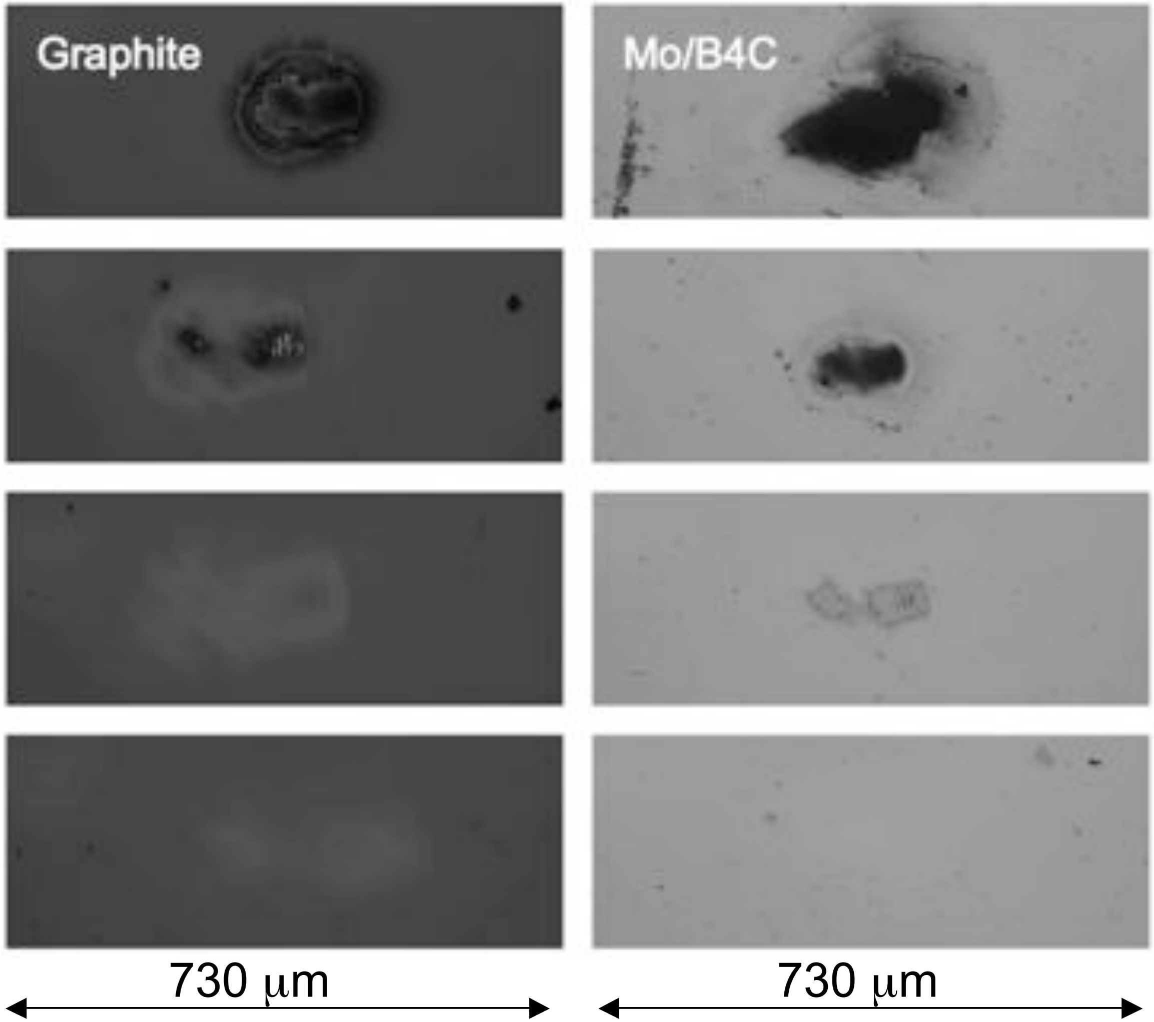
0.9-1.8 mJ/cm² on the 45° mirror surface at 20 nm
0.9-1.8 mJ/cm² adsorbed

Matrial	*Damage threshold @ 32 nm*	*Safety margin @ 50 m, 45° Full beam Absorbed*
Silicon bulk	87 mJ/cm^2	48 - 48
α-C	60 mJ/cm^2	33 - 33
SiC	140 mJ/ cm^2	77 - 77
B4C	200 mJ/cm^2	111 – 111

Multilayers suffer from fast aging effect

	Material	Efficiency
40 nm	Sc/Si	70%
20 nm	Mo/Si	70%
13.3 nm	Mo/Si	75%
6.33 nm	Co/C	50%

Multilayers



In focus
Fluence: 180 mJ/cm2

1 mm out of focus
Fluence: 60 mJ/cm2

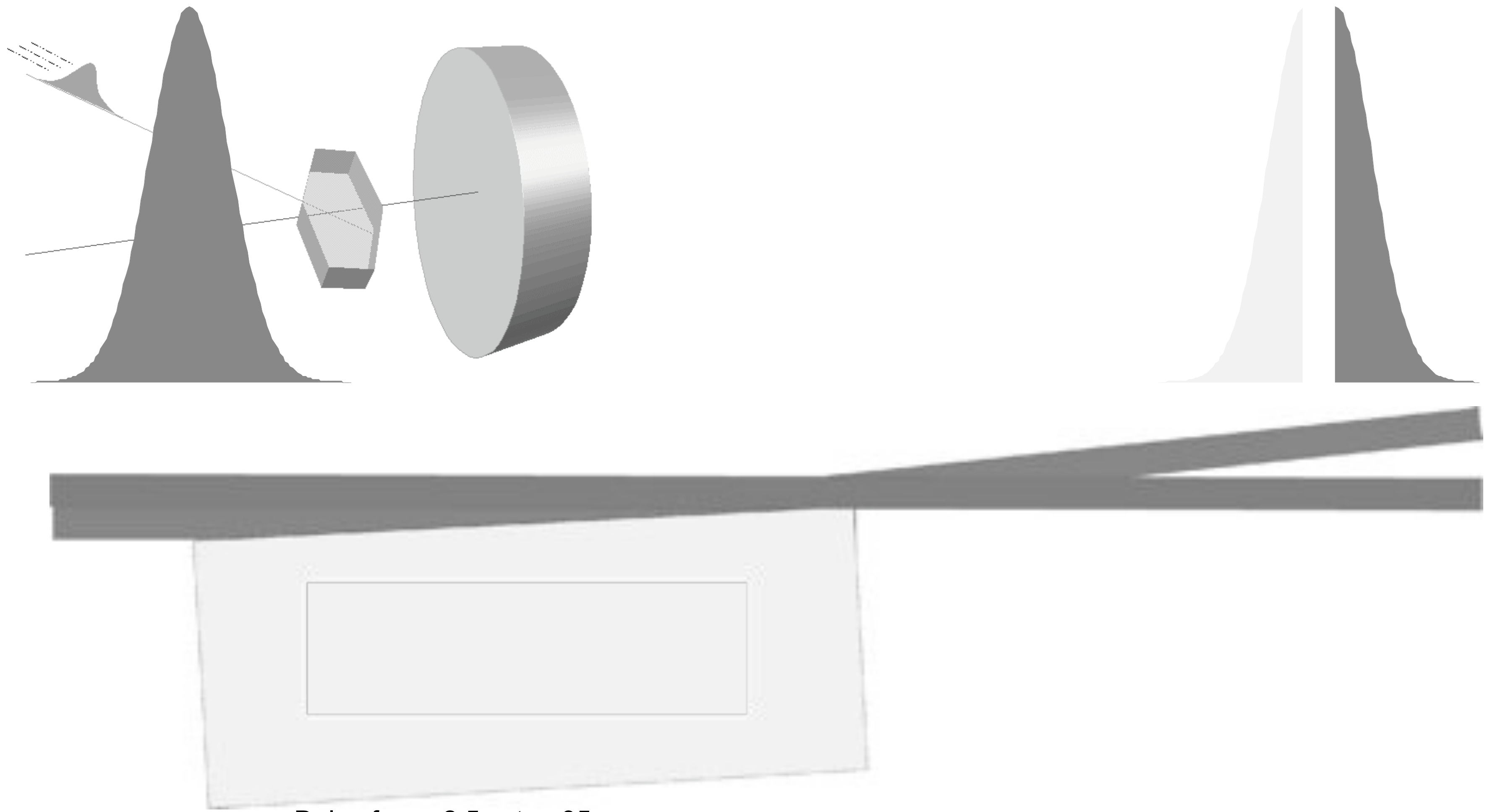
2 mm out of focus
Fluence: 25 mJ/cm2

3 mm out of focus
Fluence: 12 mJ/cm2

α-C	60 mJ/cm^2
B4C	200 mJ/cm^2

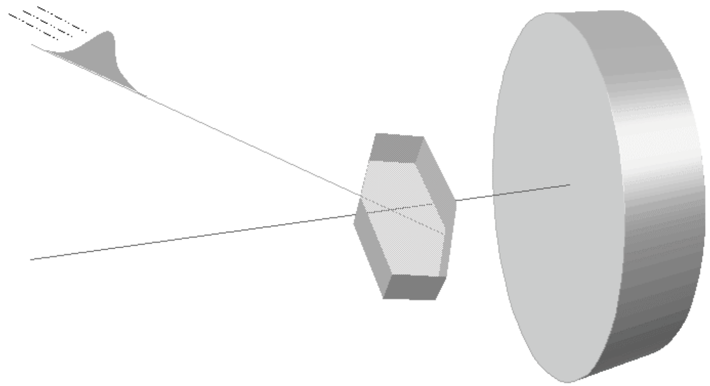
Measured at 400 nm at the EIS laser lab

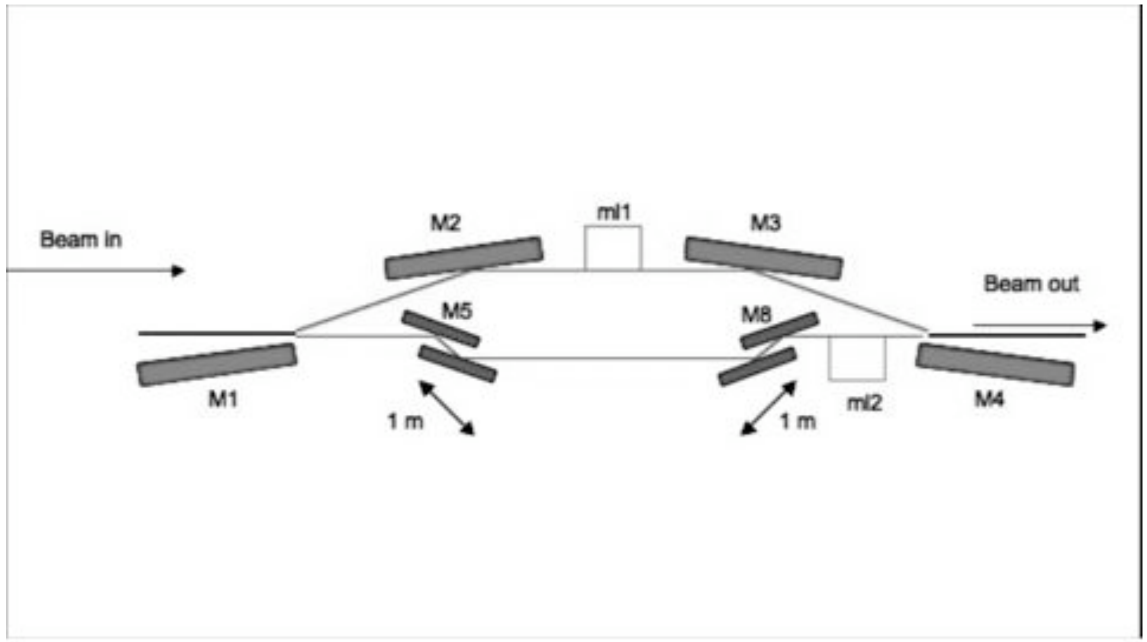
Pump and probe - delay line



Delay from -2.5ps to +35 ps
Pump with 1st Probe with 1st or 3rd (multilayer positioned in the fixed “probe” line

Pump and probe - delay line

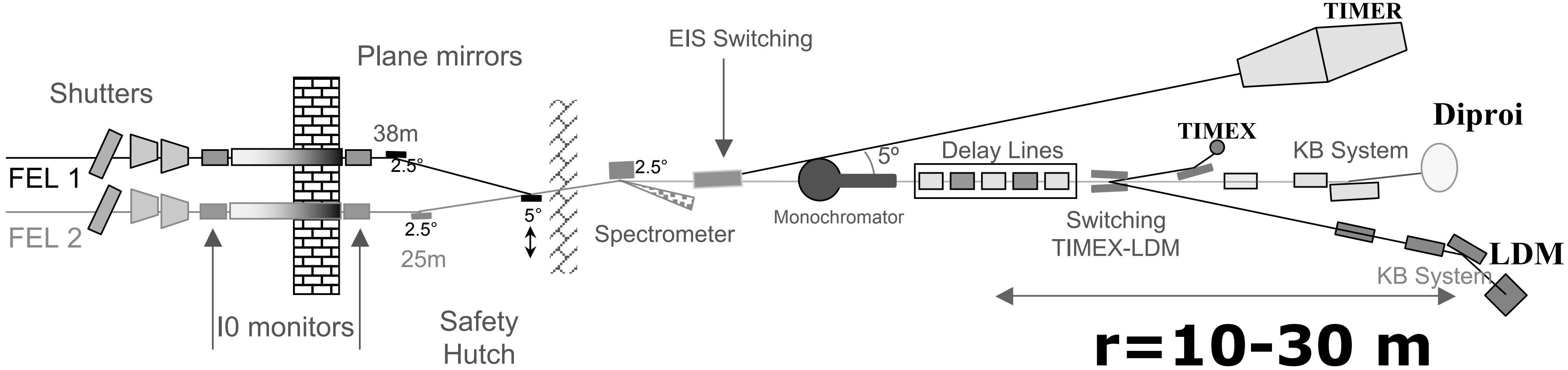




Delay from -2.5ps to +35 ps
Pump with 1st Harmonic
Probe with 1st or 3rd (multilayer positioned in the fixed "probe" line

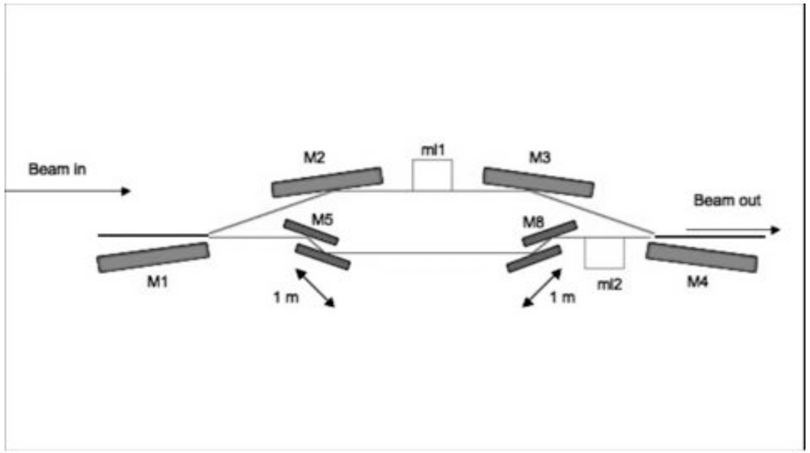
Required movement range and step: ≈ 1m. few μm

Precision required



Spot dimension < 10 μm (could easly be less)

Beam offset = 2δθ(angular error on mirror) * r ➔

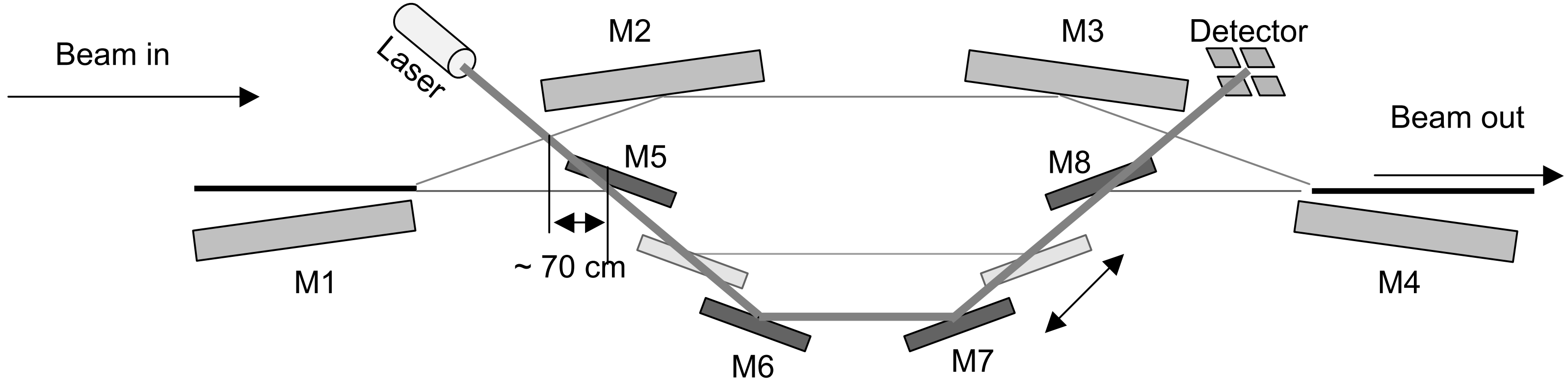


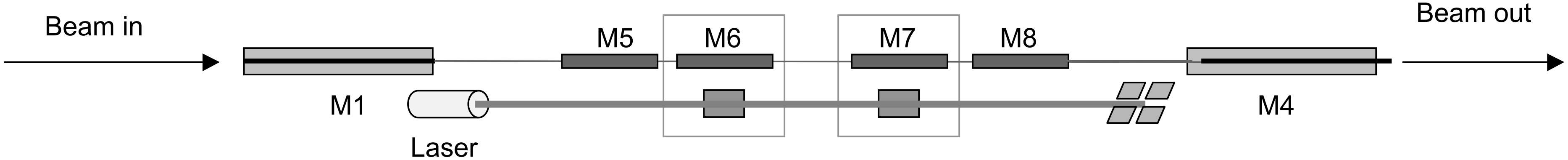
δθ=1μrad

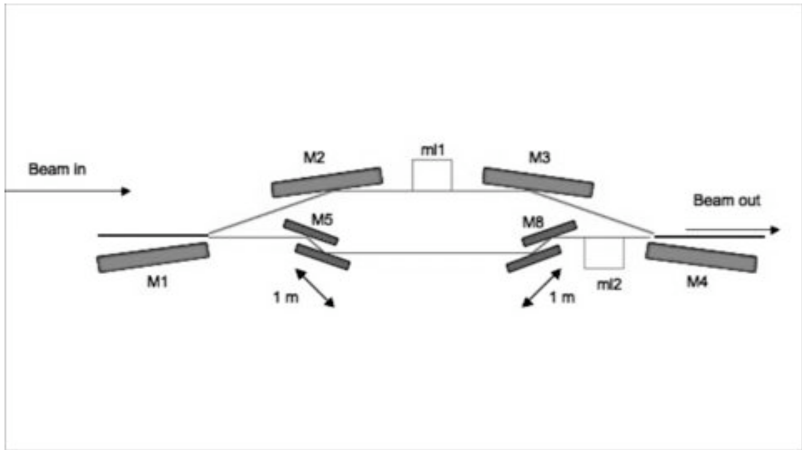
δθ=0.3μrad

δθ=0.1μrad

Precision required



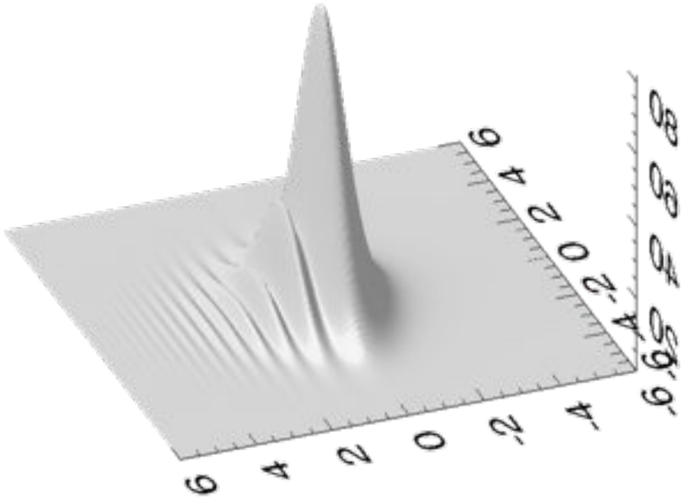


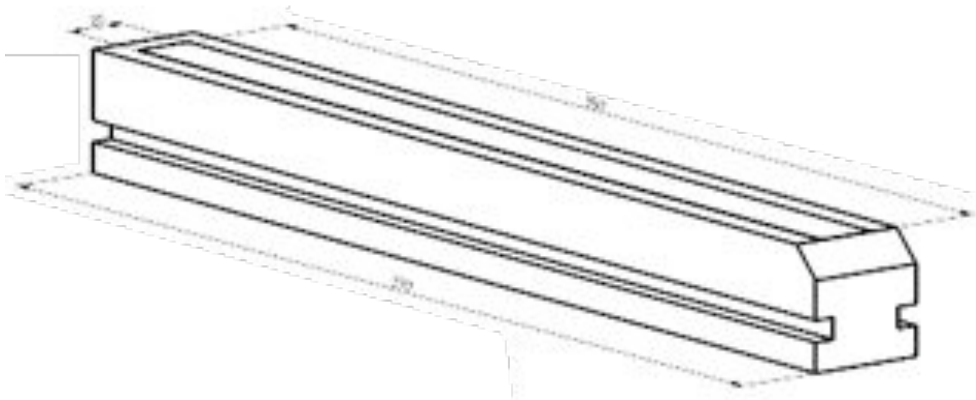


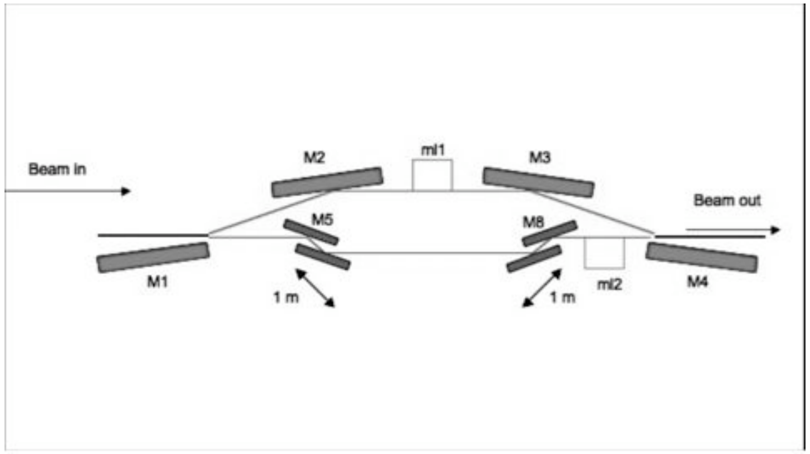
$\delta\theta$=**0.3**μ**rad**

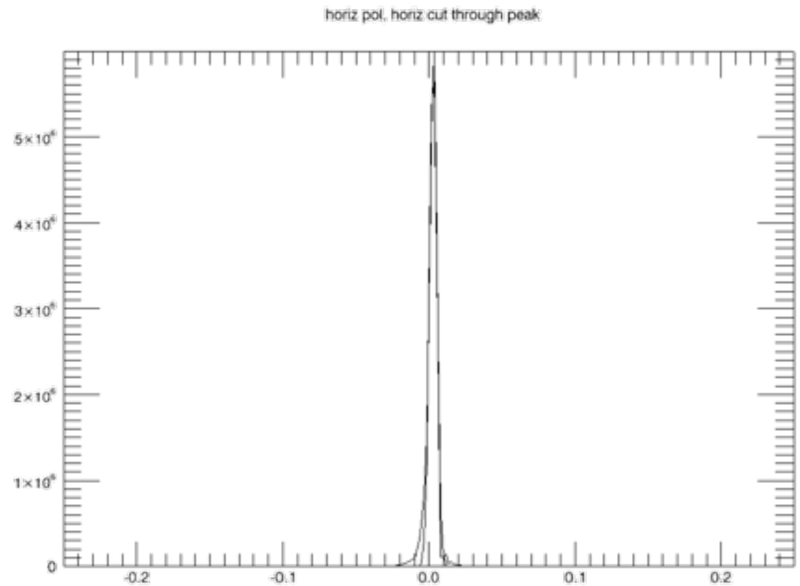
$\delta\theta$=**0.1**μ**rad**

Delay line - Choerent beam diffraction effect

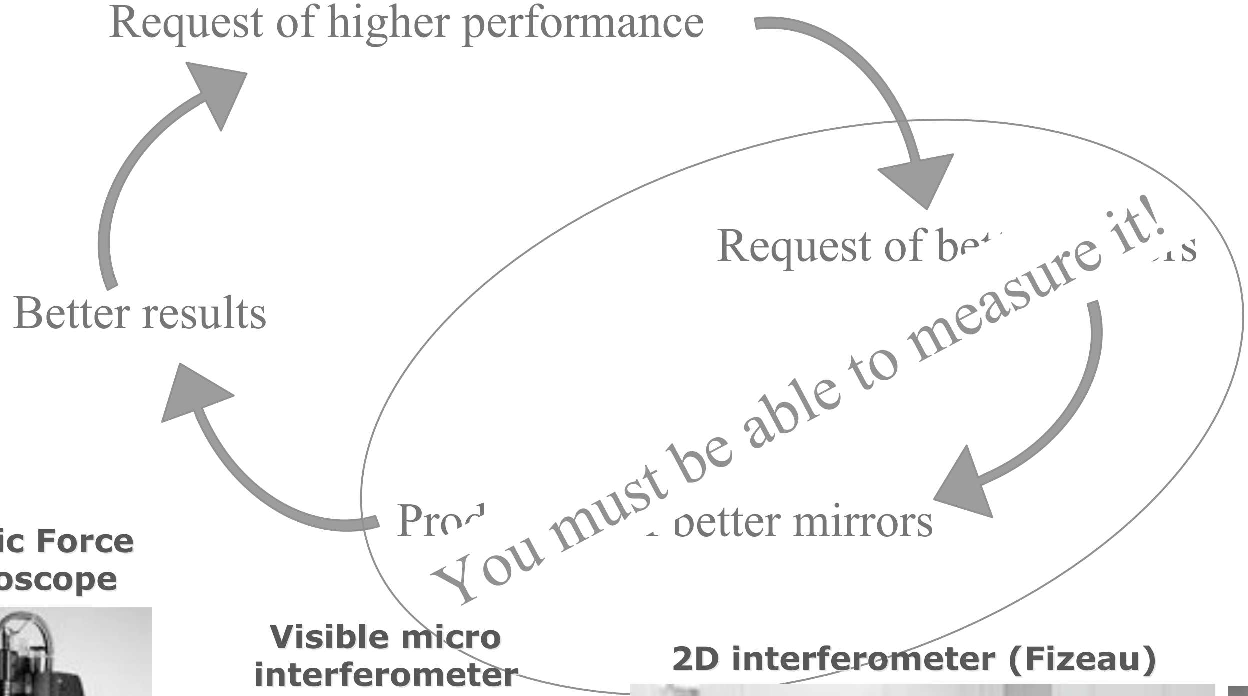








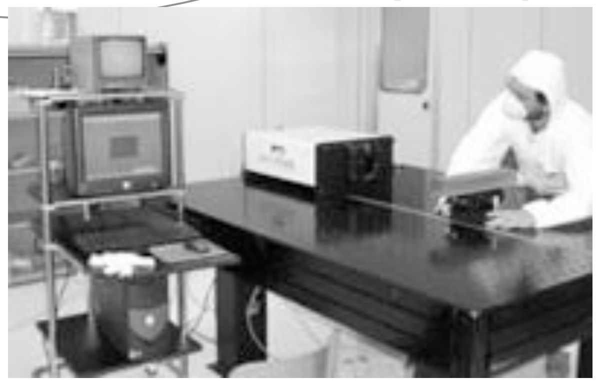
Metrology



Atomic Force Microscope

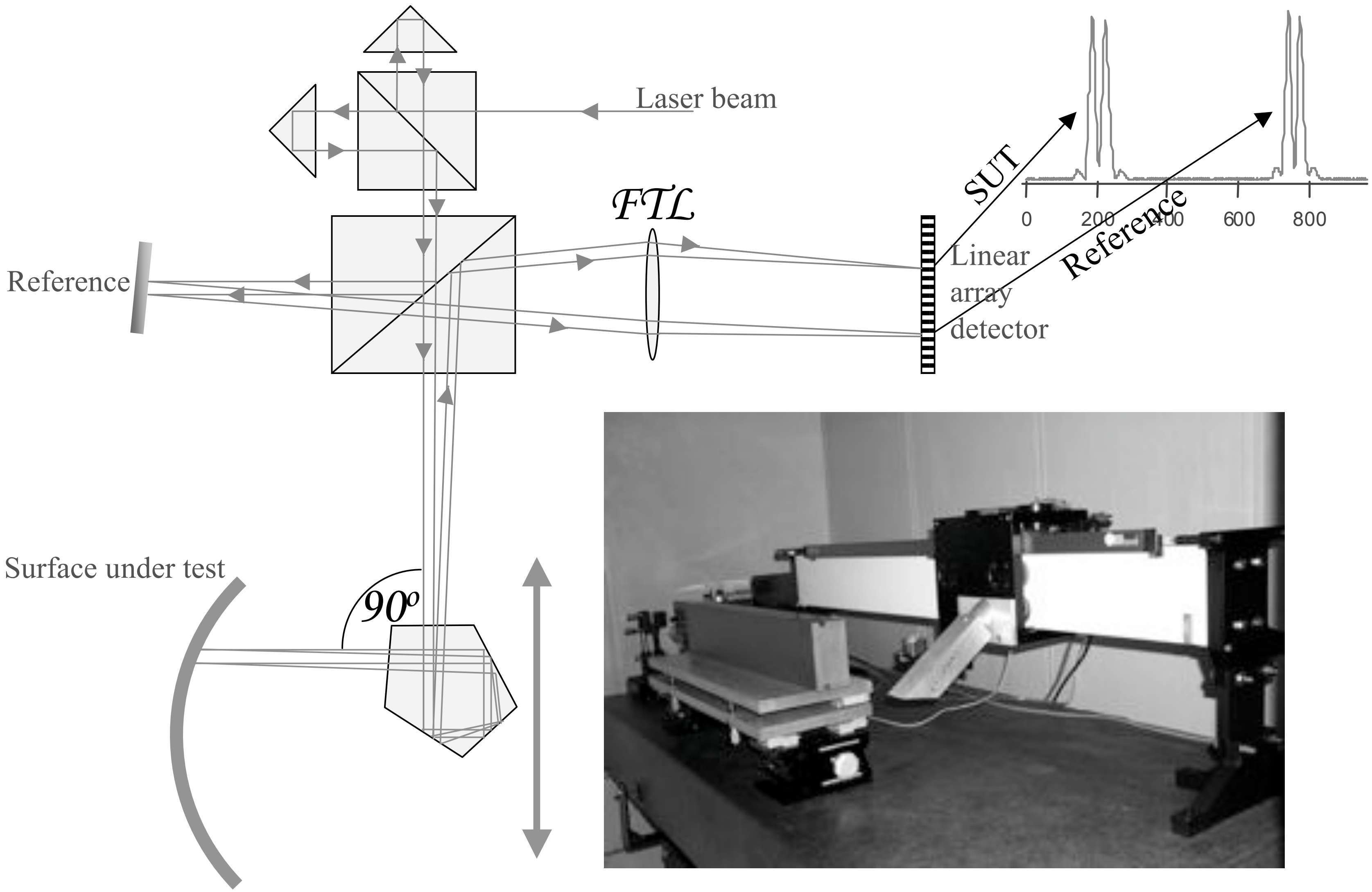
Visible micro interferometer

2D interferometer (Fizeau)

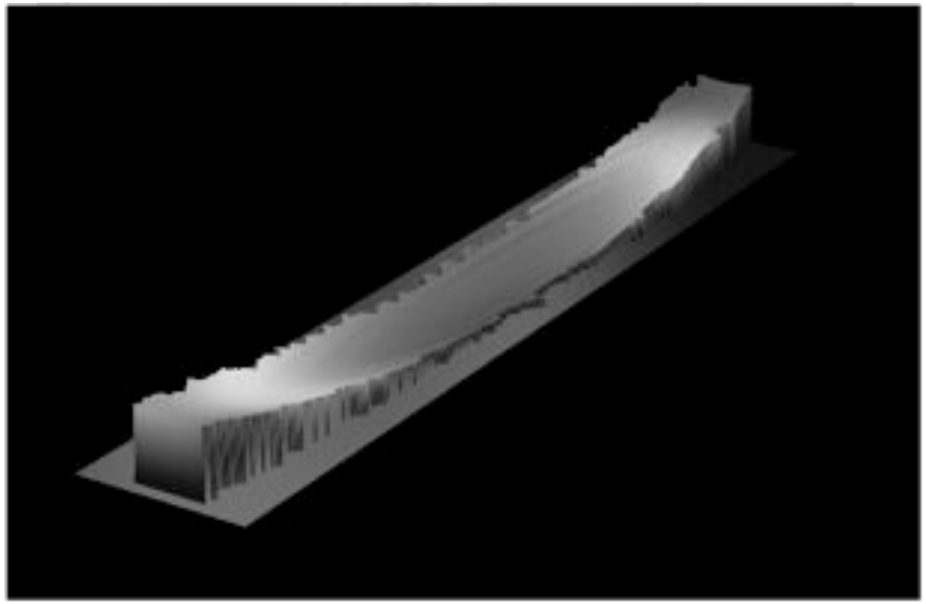


Long Trace Profiler (LTP II)

Long trace profiler



Fizeau Interferometer



3D measurement of optical surfaces

λ/100 precision

λ/2000 repeatability

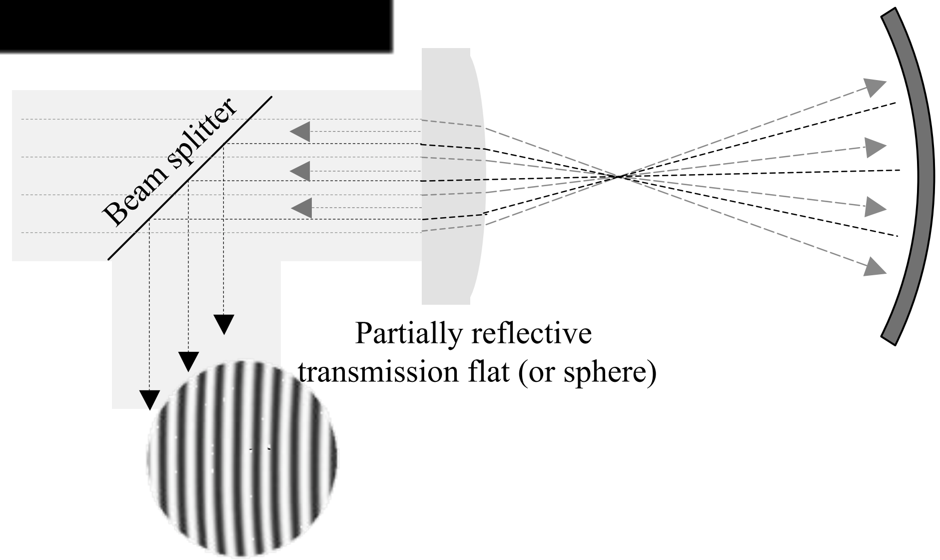
λ usually 632.8 nm or 1100 nm

Accessories

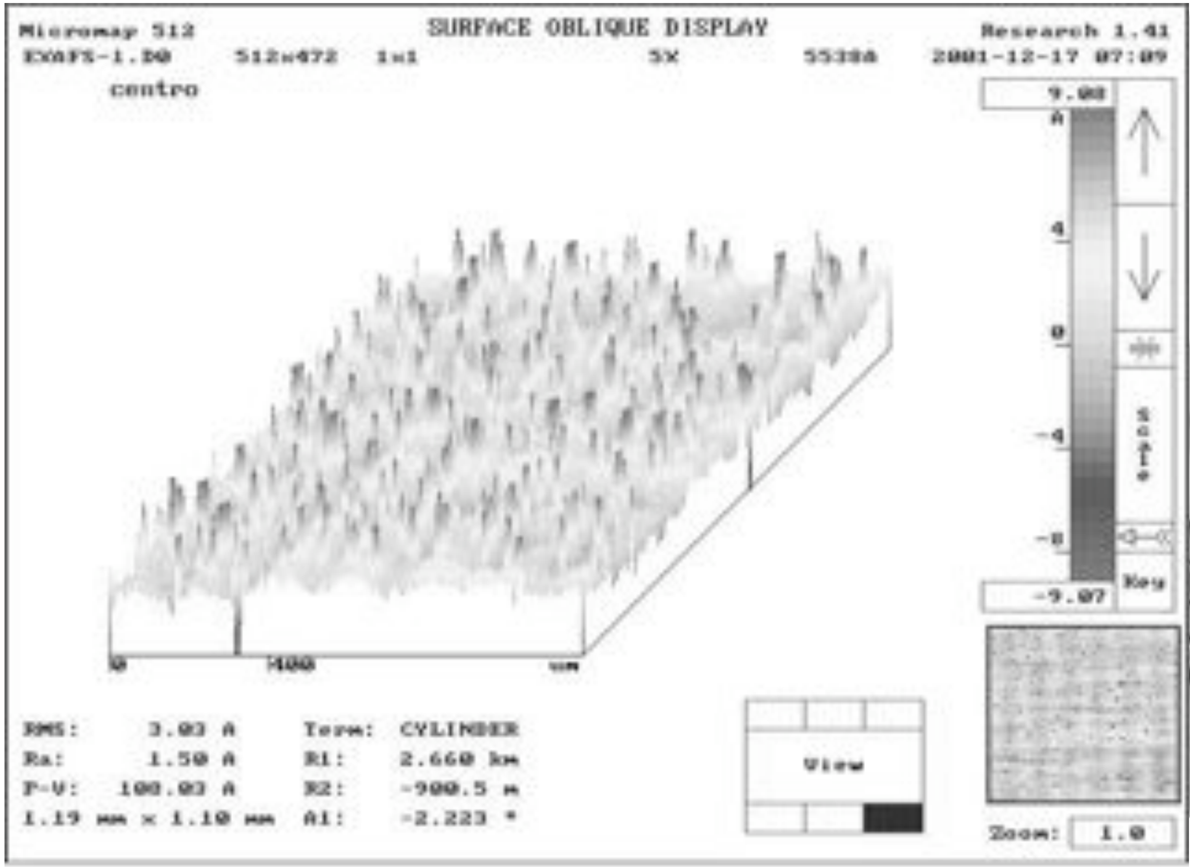
Transmission spheres

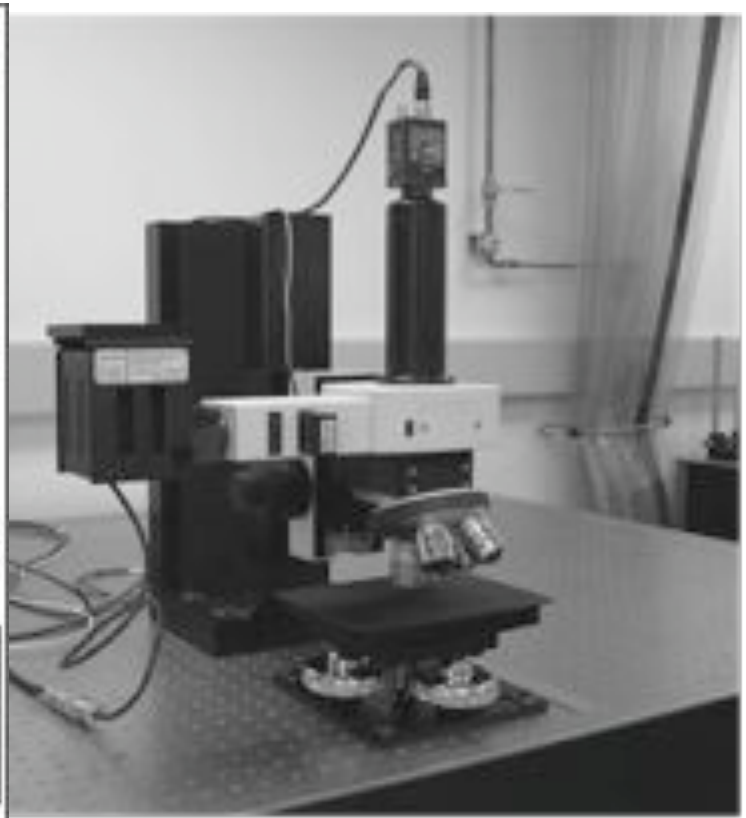
Converger for sagittal radii and NI mirrors

Diverger for NI mirrors with R>2 m



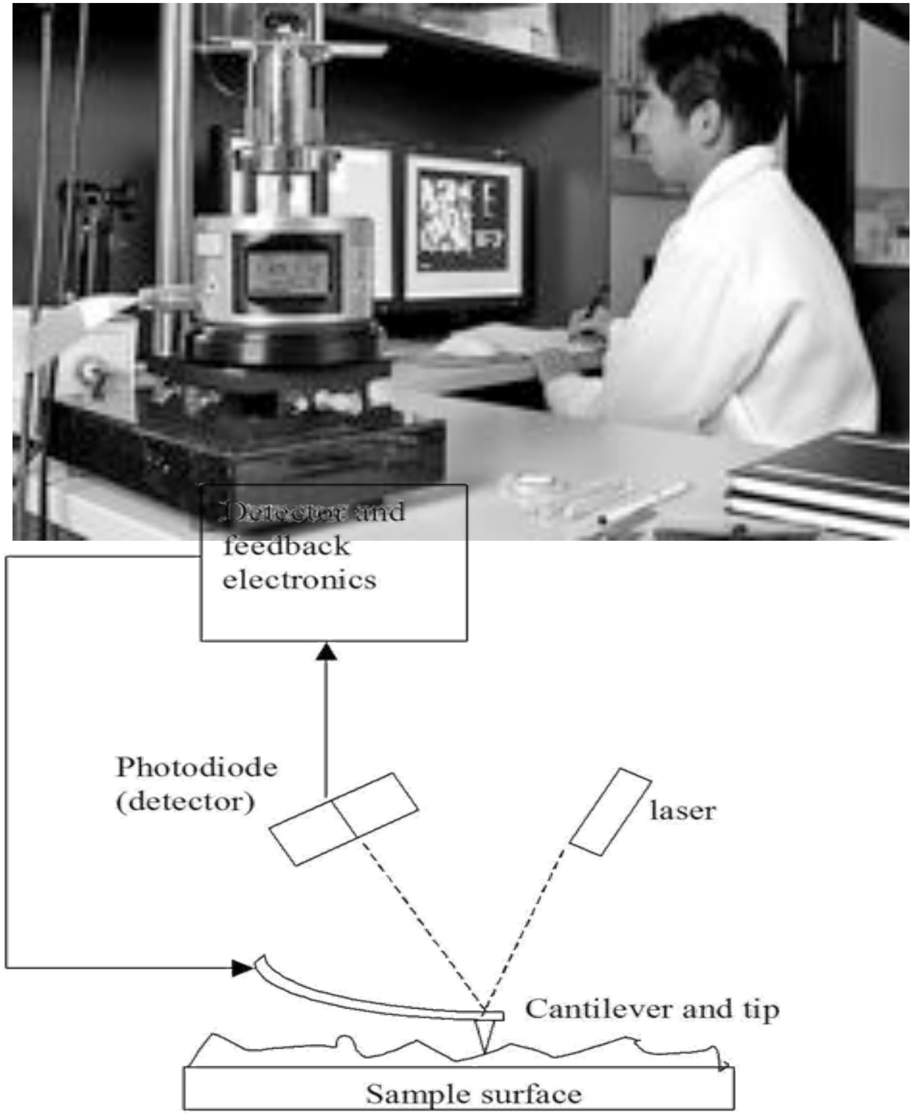
Roughness measurement

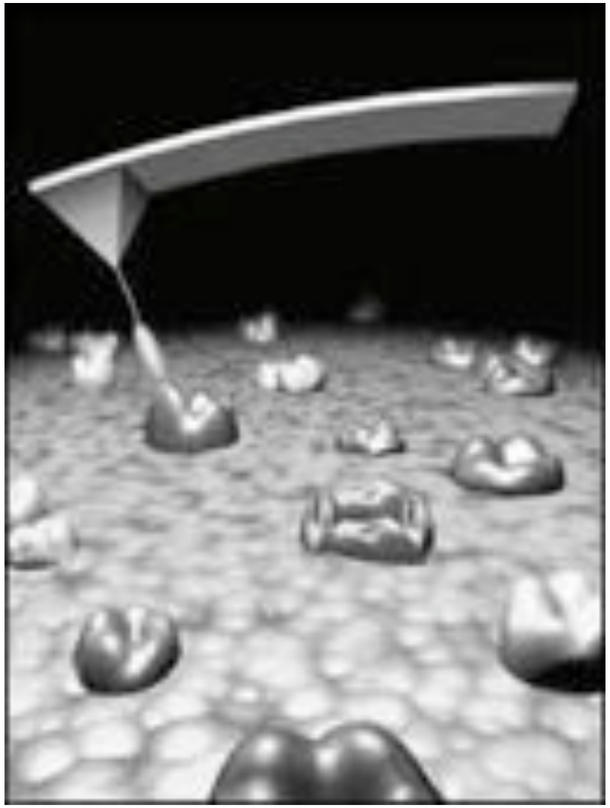




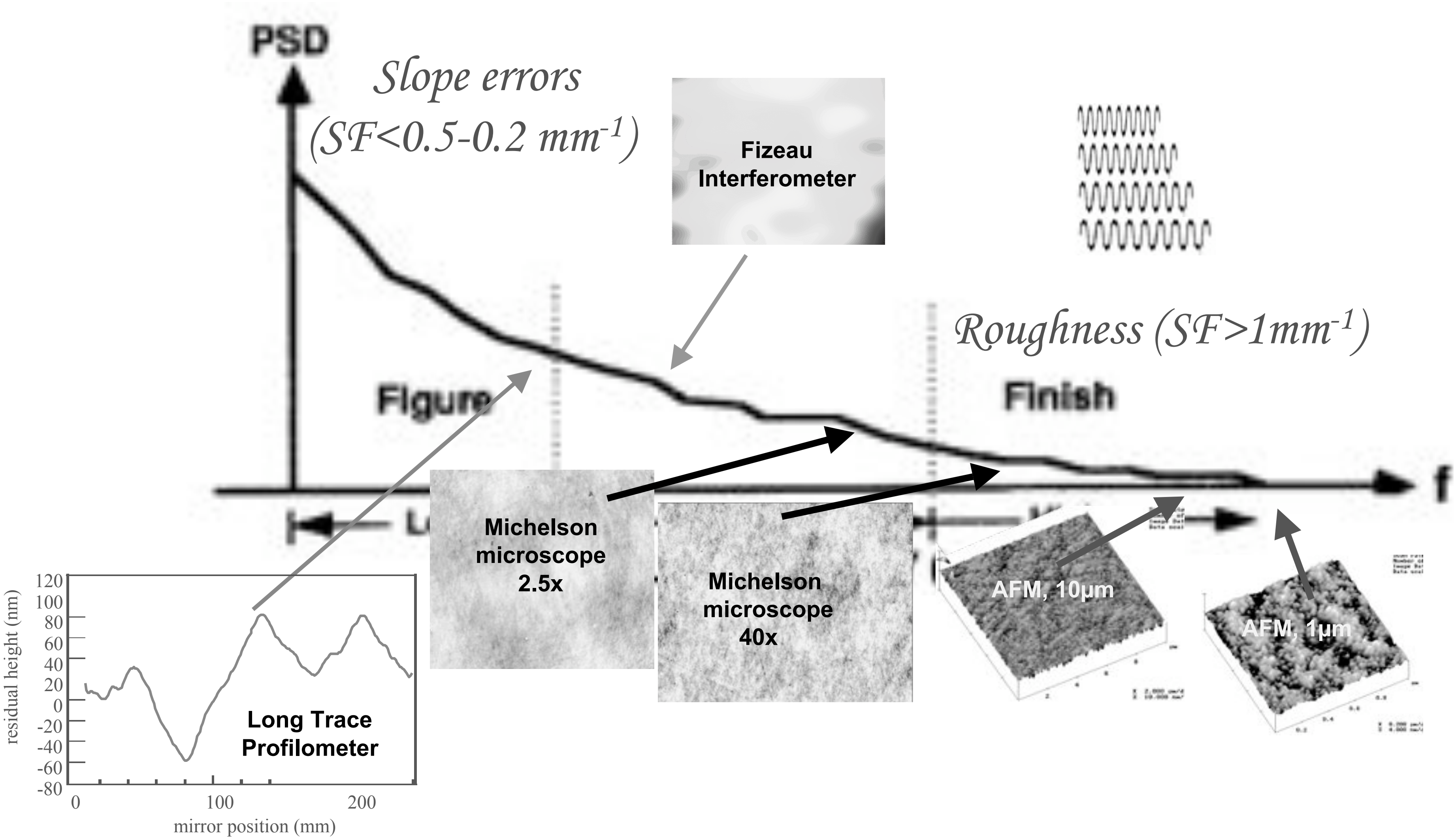
Michelson Interferometer

Atomic force microscope





Power spectral density



Bibliography

Books:
W. B. Peatman: **Gratings Mirrors and Slit** Gordon Sci. Publ. Amsterdam (1997) (Soft X.ray opitcs, introduction to SR sources)
D. Attwood, **Soft X-Rays and Extreme Ultraviolet Radiation**, Cambridge University Press (Interaction radiation-matter, SR sources, UV and Soft X-Ray optics)
A.A. **Modern Developments in X-ray and Neutron Optics** (Recent achievment in multilayer, metrology, ray tracing and X-ray lenses)
CXRO **X-ray data booklet** Lawrence Berkeley Nat. lab. (2001) free (general information and table useful when using X-ray)

Programs: Shadow (ray tracing) http://www.nanotech.wisc.edu/shadow/shadow.html
XOP (general optical calculation) http://www.esrf.fr/computing/scientific/xop
SPECTRA (synchrotron source) http://radiant.harima.riken.go.jp/spectra/index_e.html

Links: Centre for X-ray Optics http://www-cxro.lbl.gov/ *(general information and on line software)*
The international society for Optical Engineering http://www.spie.org
Optics.org http://optics.org
Photonics.com http://www.photonics.com/