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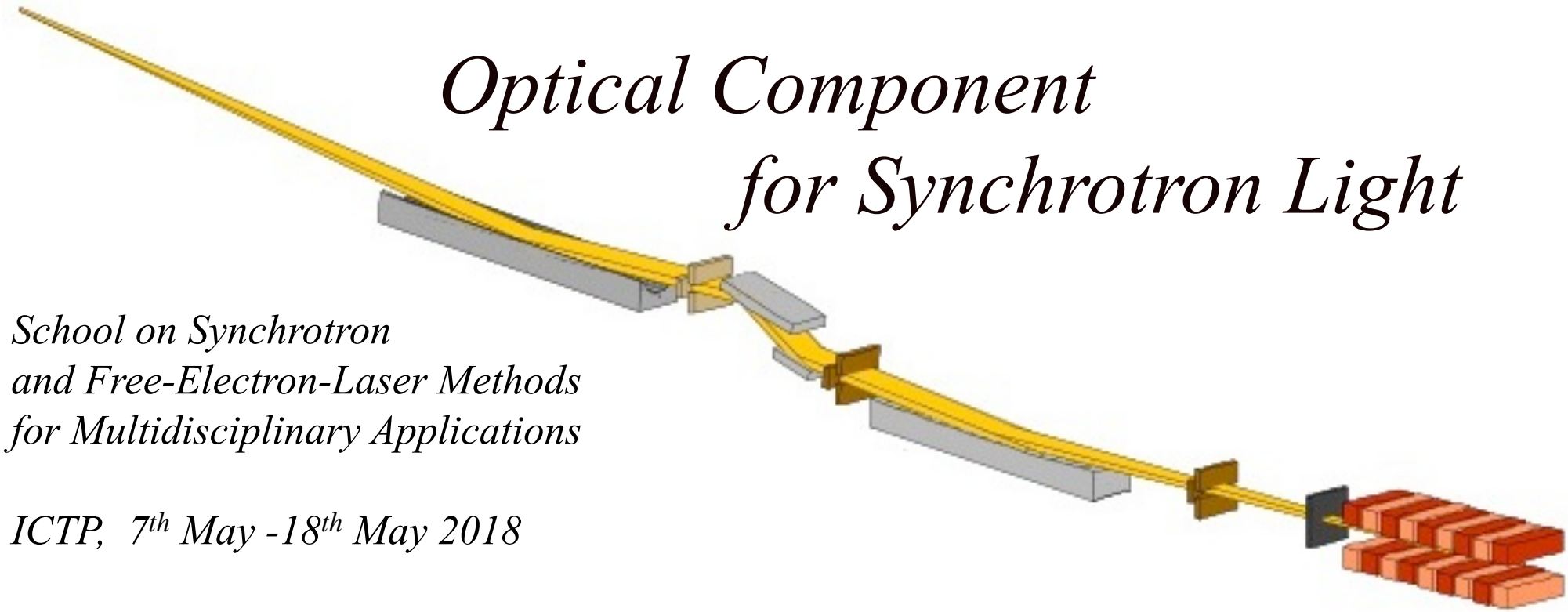
Optical Component for Synchrotron Light



School on Synchrotron and Free-Electron-Laser Methods for Multidisciplinary Applications

ICTP, 7th May -18th May 2018

Edoardo Busetto & Luca Rebuffi - MVO Group
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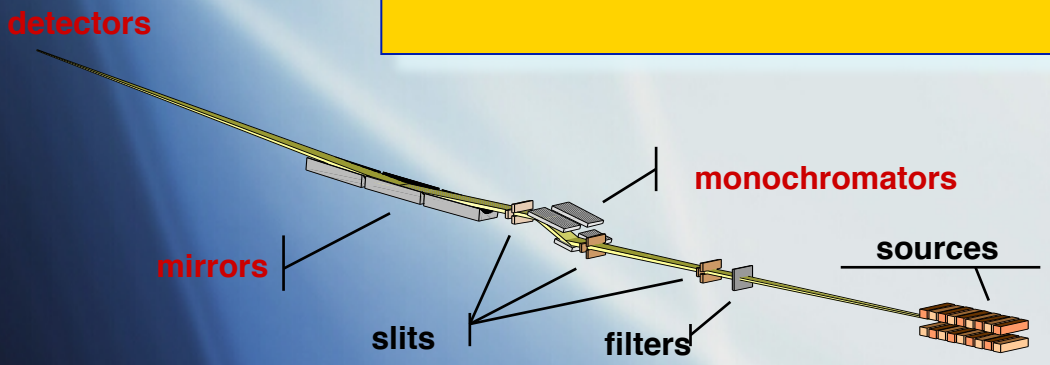
Optical components for SL: mirrors and monochromators

low emittance electrons beam produces a high brilliance x-ray photons beam.

" ...The finite quality and the fundamental limits of the optical components increase the emittance of the beam…….

The main aim of the optical design consists on minimizing the inevitable beam degradation…"

Jean Susini *"Design parameters for hard x-ray mirrors: the ESRF case"*
OPTICAL ENGINEERING/February 1995/Vol. 34 2/361



The most important optical elements for a beamline:

- mirrors
- monochromators

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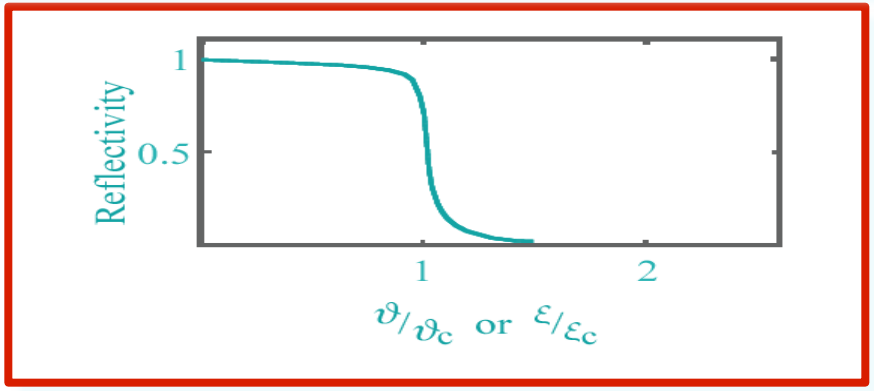
Optical components for SL
Mirrors: total reflection

If we consider θ as the angle between the incoming radiation and the mirror surface (grazing angle), the x-ray beam will be totally reflected when $\theta < \theta_c$



For x – rays the refraction index is **n** = 1- δ
where $0 < \delta < 1$, and therefore $0 < \mathbf{n} < 1$

$\theta < \theta_c$

$\theta = \theta_c$

$\theta > \theta_c$

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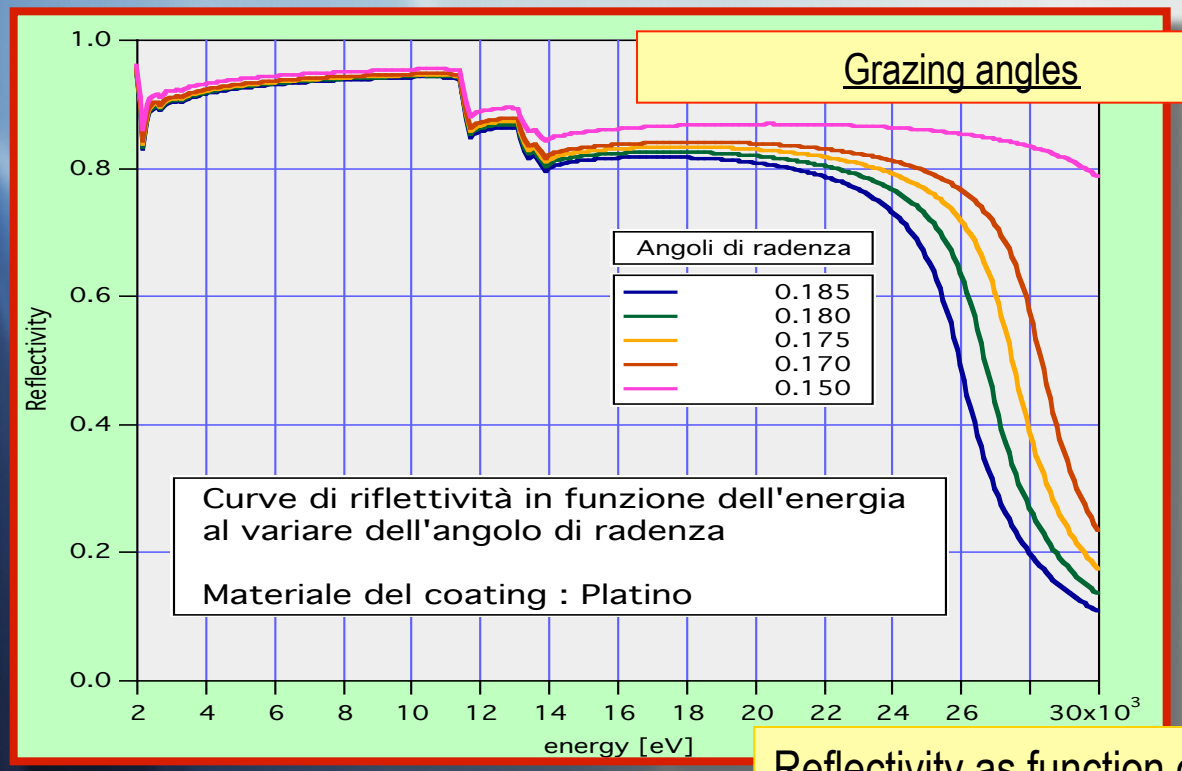
Optical components for SL
Mirrors: total reflection

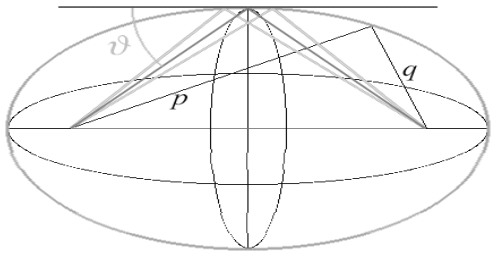
$$\theta_c = 1.66\ \lambda\ [A](\rho)^{1/2}[g/cm^3]$$



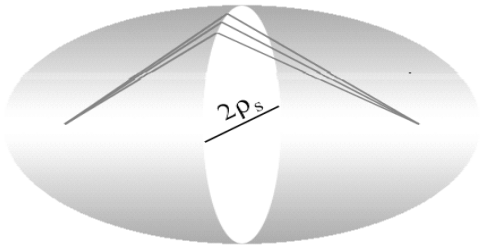
Reflectivity as function of the photons energy and the grazing angle in degrees Mirror coating: Platinum

Optical components for SL Mirrors: focusing

Ellipsoidal surface



Tangential focusing



Sagittal focusing

Best approximation circle

$$\rho_{tangential} = 2f / \sin\vartheta$$

an ideal focusing mirror will focus a point source into another point according to the formula $1/q+1/p=1/f$

$$\rho_{sagittal} = 2f \sin\vartheta$$

- *Bendin magnet*
- *Extended source (wiggler and undulators)*

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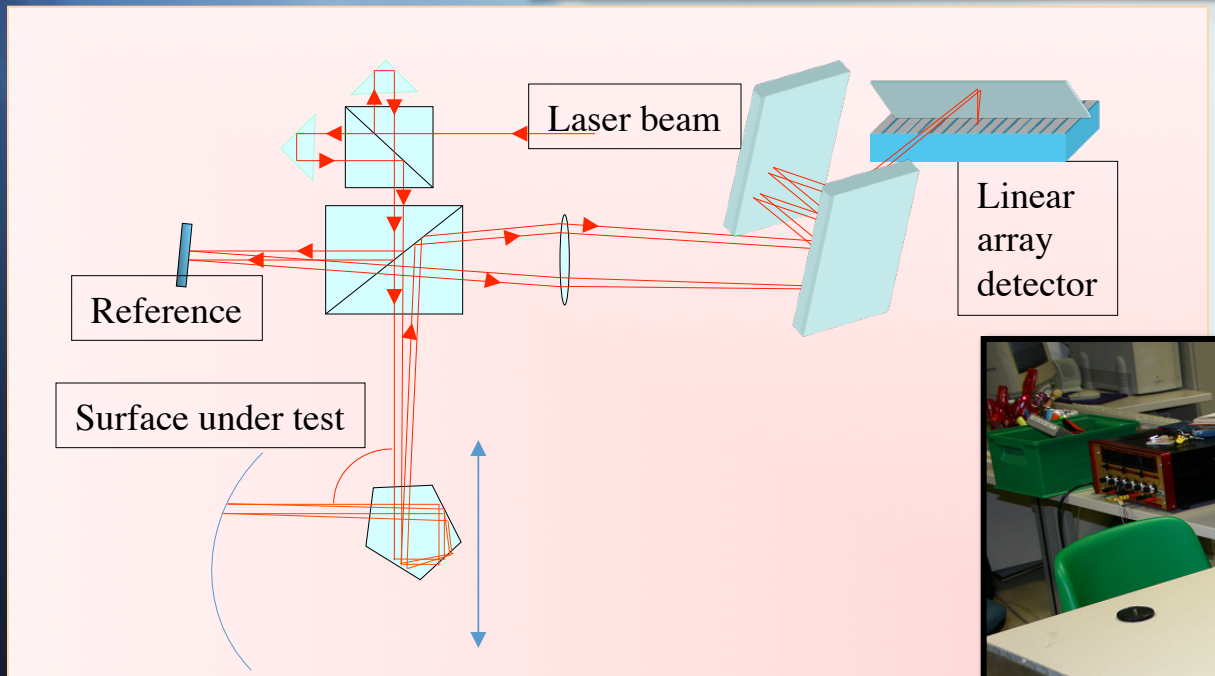
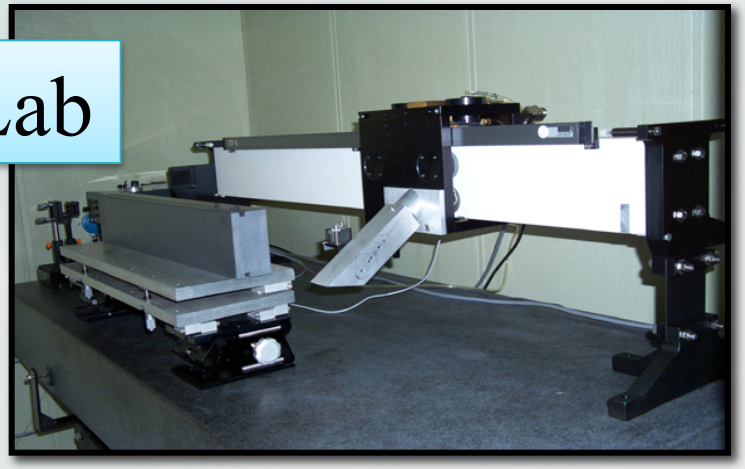
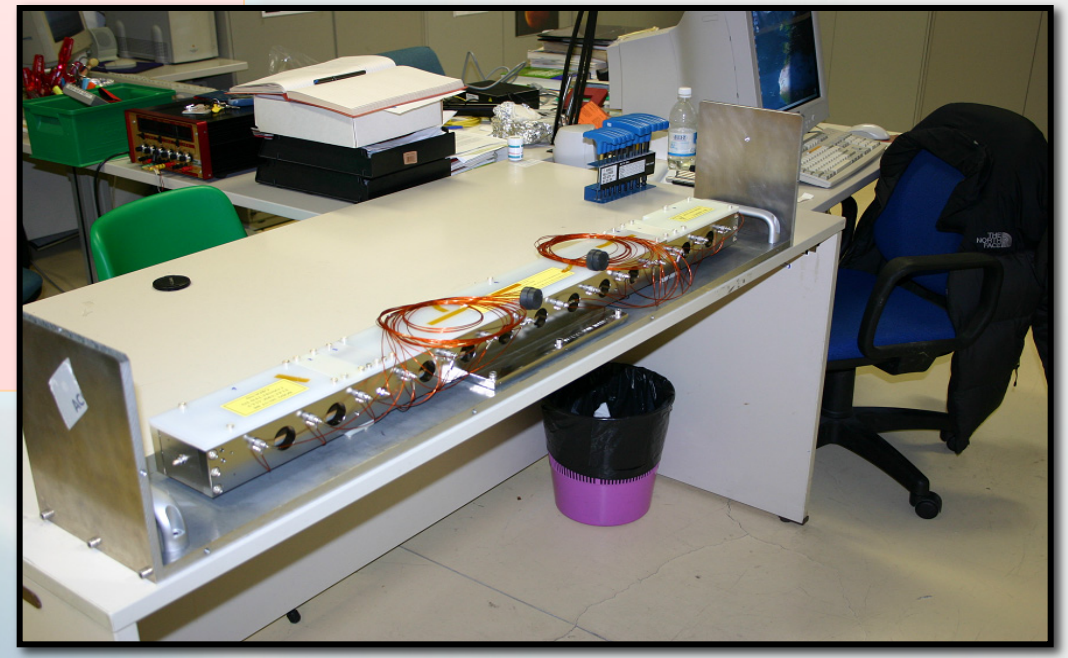
Optical Metrology Lab







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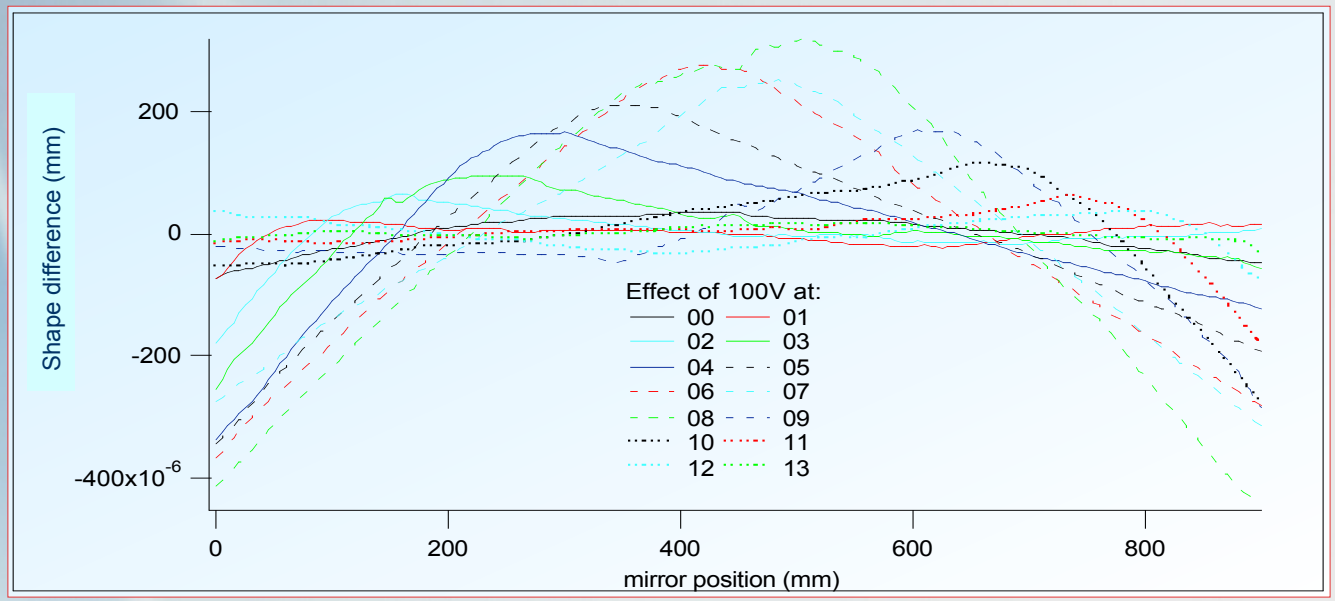

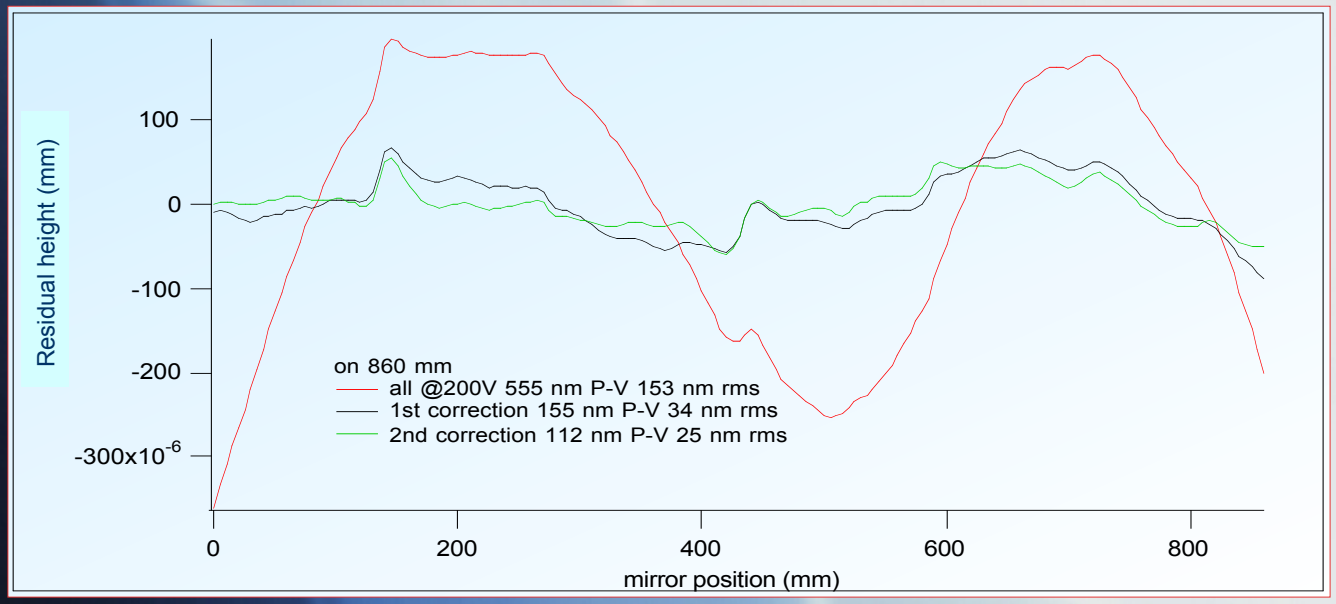

13 active mirror sections
10 minutes / measurement
Total time > 130 minutes

voltage stability

Optical Metrology Lab

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In last 10 years

- 200 - 400 mm long flat mirrors:
  from ~ 1 µrad to ~ **0.2 µrad** rms
  Ion beam figuring (IBF) now almost normally applied

- curved mirrors
  R=100 m , 100 mm long : **0.45 µrad** rms
  Toroid R=300 m, r = 100 mm, 200mm long **: 0.5 µrad** rms
- High quality ellipses
  IBF finished, 200mm long: **0.8/1 µrad** rms from best ellipse
  F=900mm / 500mm @ 2.5 / 2 deg
  Fluid jet polishing ,100 mm long: **0.07 µrad** rms from best ellipse
  F=180 mm / 280mm @ 2.5/ 3 mrad

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Goals for the next 10 years

Mirror shape errors
Slope errors < 50 nrad rms from best shape : flat and moderate curvature
height errors < 0.1 nm rms

Improvement of figuring technology
Convergence of iterative figuring process

Development of fast accurate metrology procedures
At synchrotrons
At manufacturers

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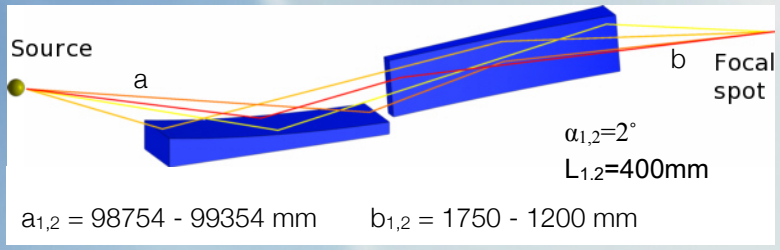
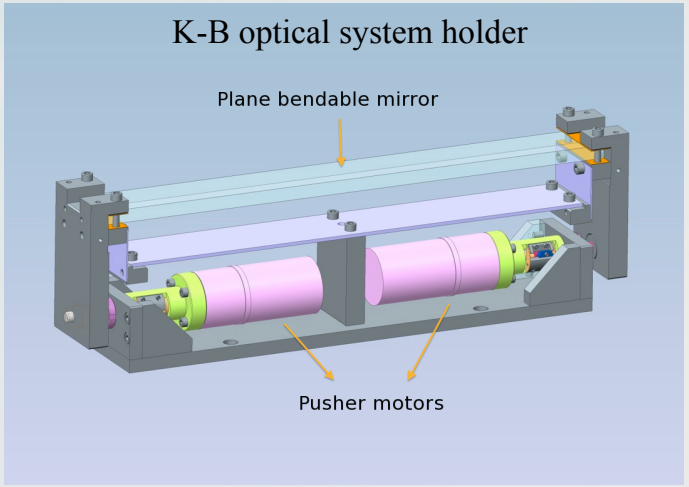
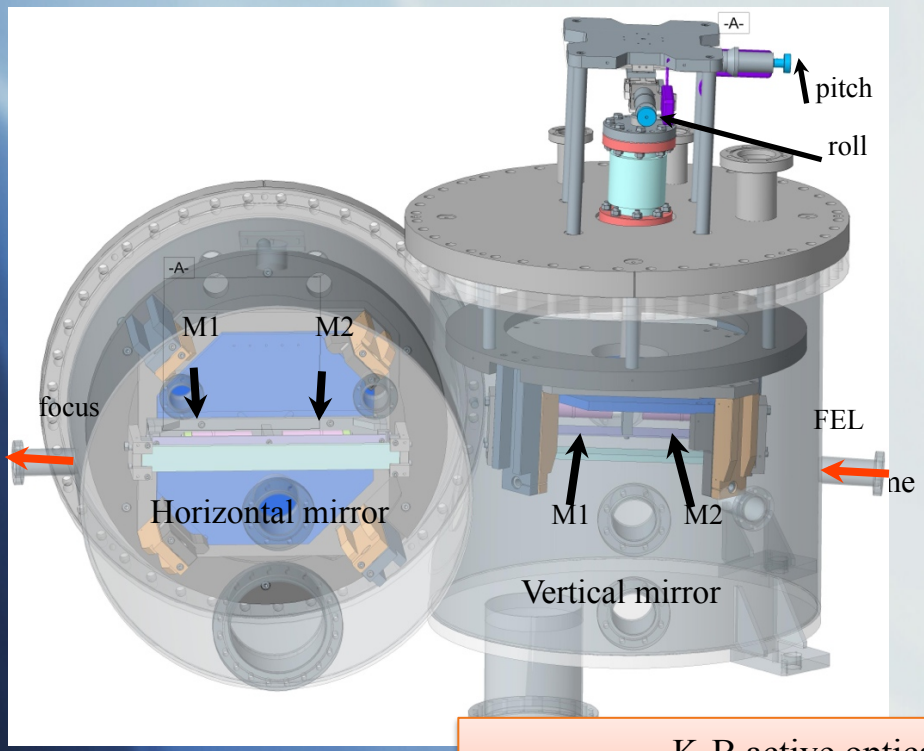
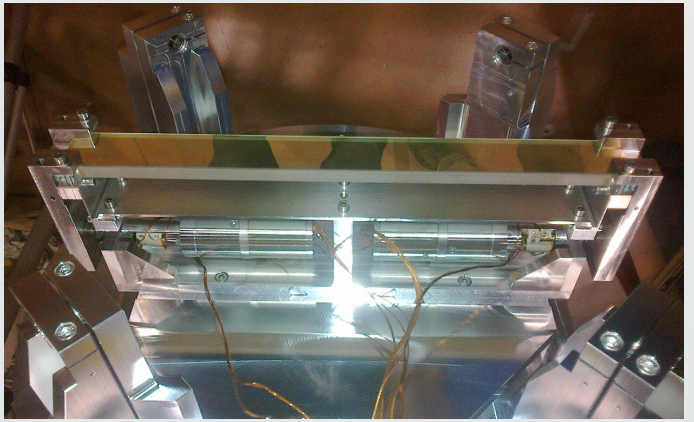
Optical components for SL
Mirrors: figure errors modification









K-B active optical system – DiProI

L. Raimondi et all. Status of the K-B bendable optics at FERMI@Elettra FEL
Proc. Of SPIE Vol.9208 920804-1

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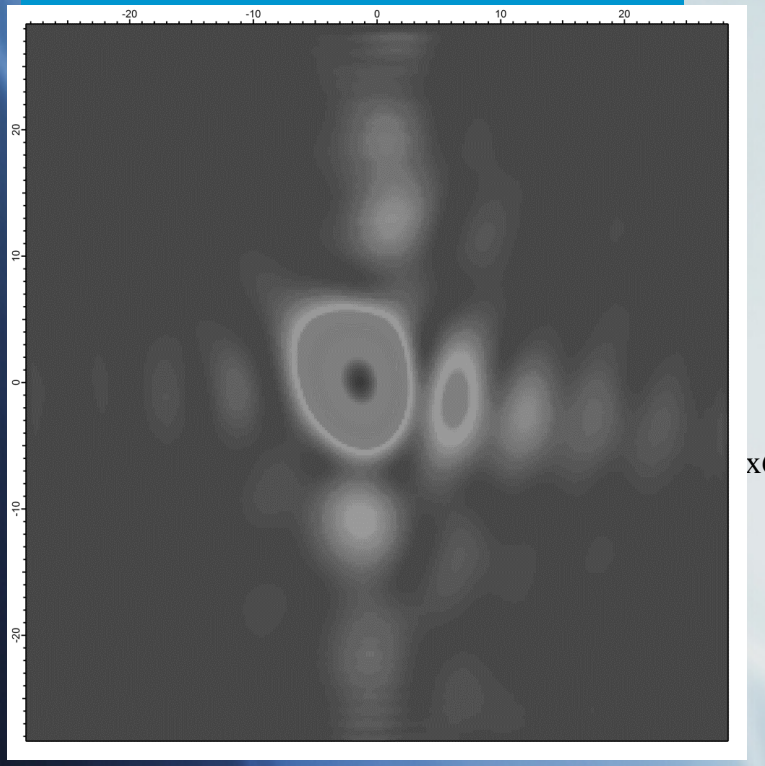
Focal spot simulations from metrology

Reconstruction from Hartmann WFS data

https://en.wikipedia.org/wiki/Shack–Hartmann_wavefront_sensor

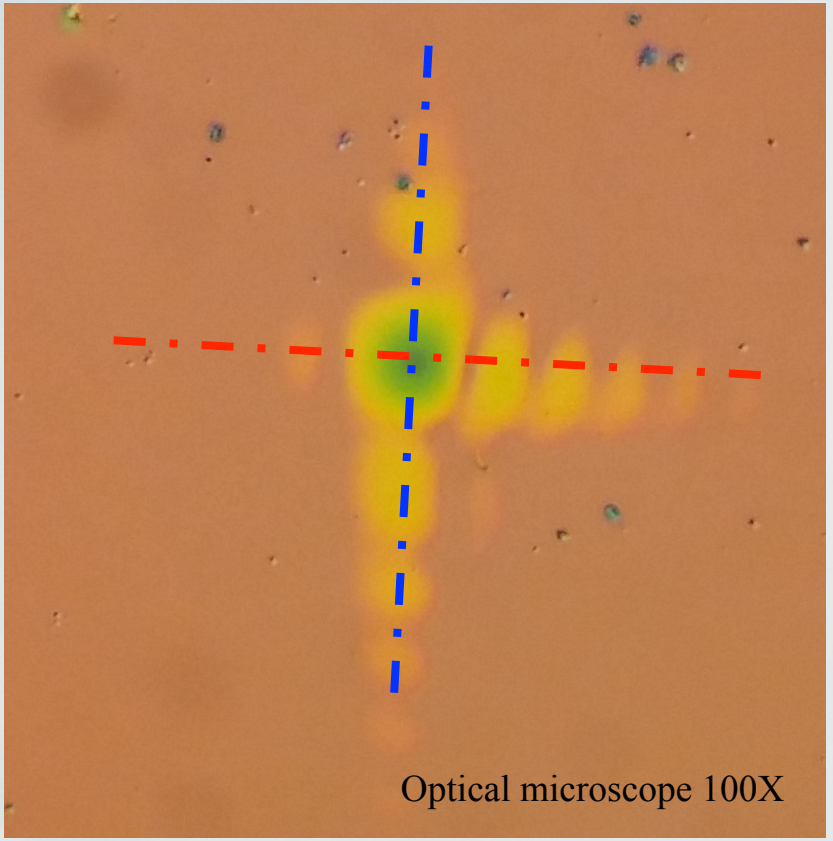


x6.5 μm²

KAOS

PMMA indentation / WFS measurement

PMMA ablation imprint



Good agreement between in-house reconstruction, PMMA, simulations (WISE, SRW)

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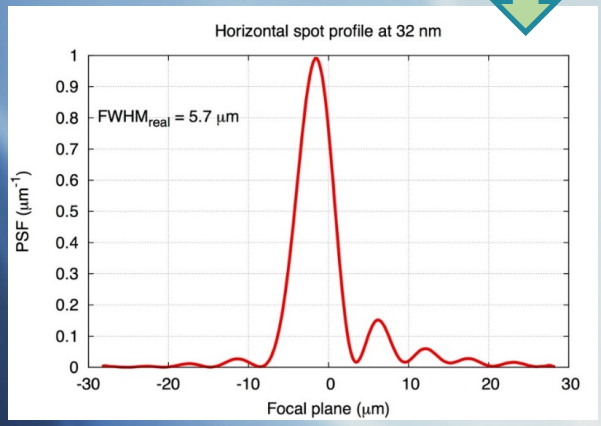
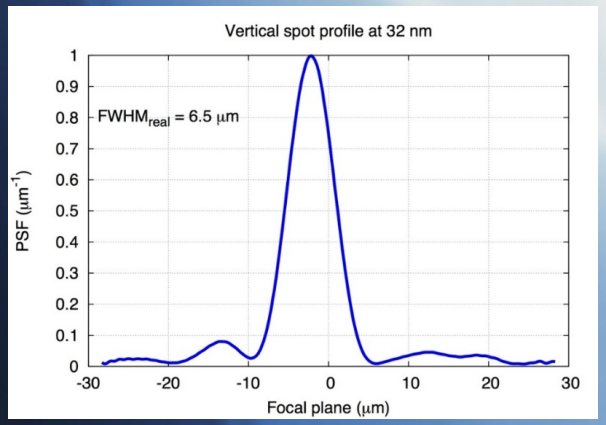
Focal spot simulations from metrology

Profilometry at best curvature (LTP) → Simulations (WISE, SRW)





KAOS
PMMA indentation / WFS measurement

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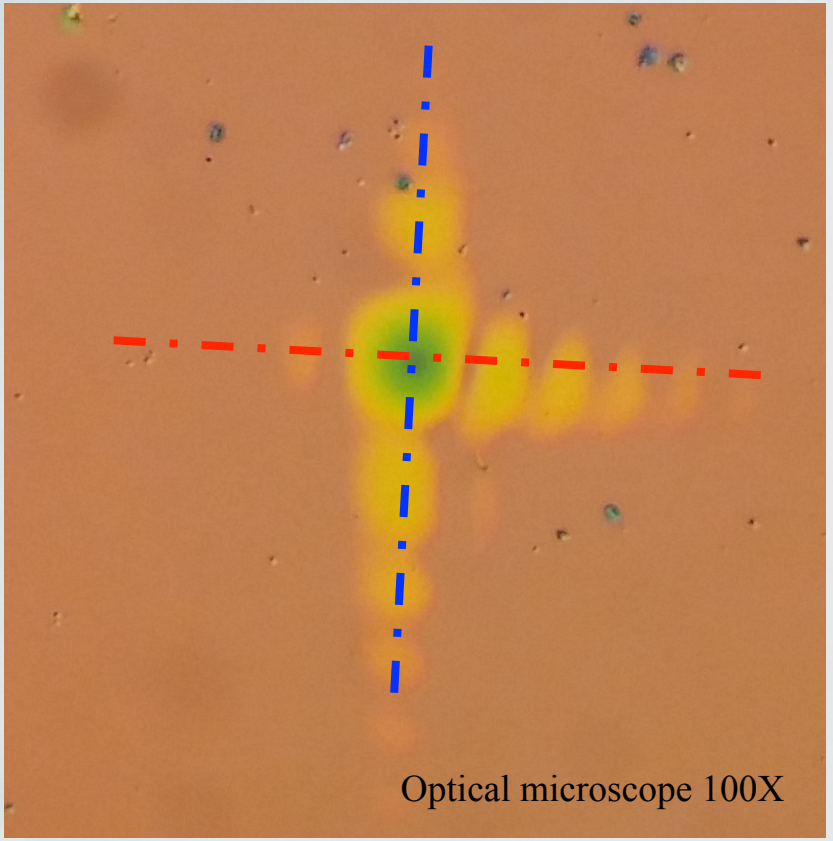

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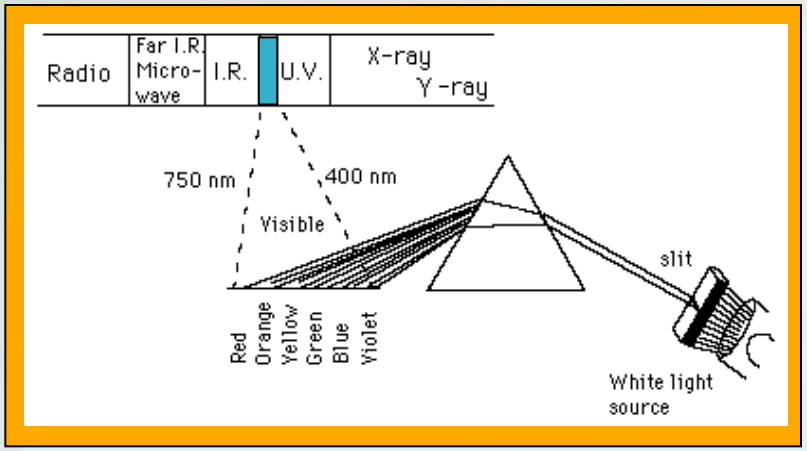
Optical component for SL: Visible light monochromators

Dispersion of radiation through the matter: the RIFRACTION

Visible radiation optical PRISM

The glass refraction index depends on the radiation wavelength,
the optical prism splits the visible radiation as function of the energy

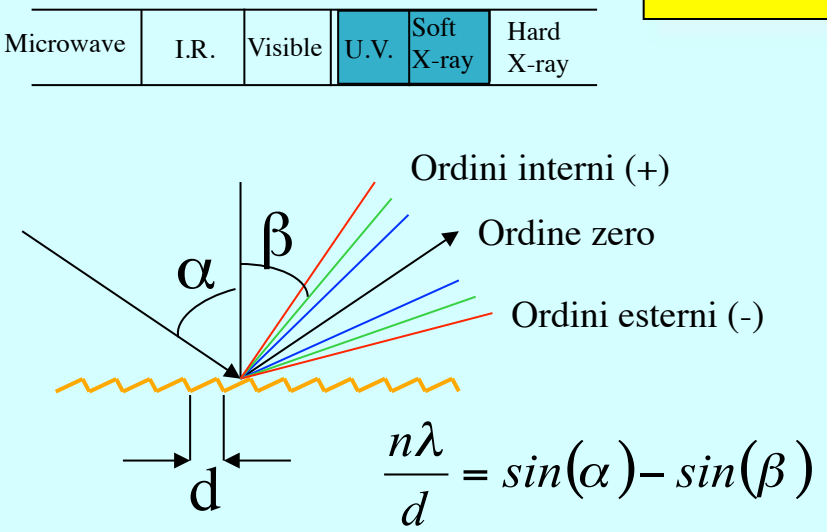


We can sample the dispersed beam with a slit selecting part of it. The spectral resolution will depend on the glass refraction index n, on the slit aperture and on the distance between slits and the optical prism.

Optical component for SL: Soft x-rays monochromators

Dispersion of radiation from a periodic structured surface: the surface DIFFRACTION

GRATINGS



The optical surface is machined with particular periodic structures that are origin of interference phenomena with the incoming radiation

Optical component for SL: Hard x-rays monochromators

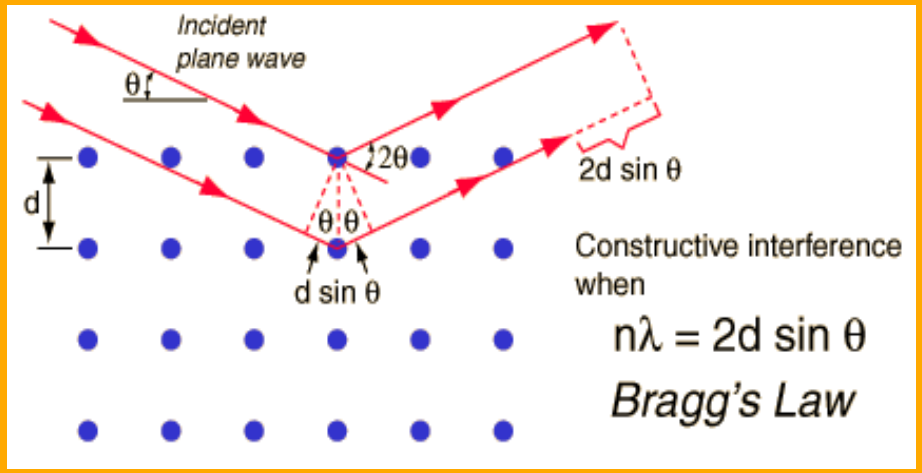
Dispersion of radiation from a bulk periodic atomic structure: The bulk DIFFRACTION

The Bragg's law

The radiation penetrates the material and is diffused by the atoms of the structure.
The diffused waves interfere.
The interference will be constructive if the difference in optical path will be a multiple of the wavelength λ:

Single crystal

Microwave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray



Optical component for SL: monochromators

From the Bragg's law $2d\sin\vartheta = n\lambda$

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

and the Bragg angle is 90º

$$\lambda_{max} = 2d$$

Optical component for SL: monochromators

from the derivative of the Bragg's low an important property of the hard x-ray monochromators

energy resolution

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

$\Delta\theta$ is the convolution of two contributes:

$\Delta\theta_{beam}$ - angular divergence of the radiation beam in the scattering plane

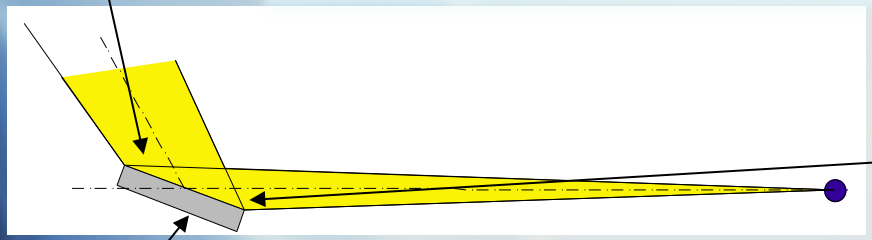
ω_s - the intrinsic angular bandwidth of the crystal monochromator known as Darwin width

Optical component for SL: monochromators

Case with $\Delta\theta_{beam} >> \omega_s$
white beam with divergence in the plane of scattering

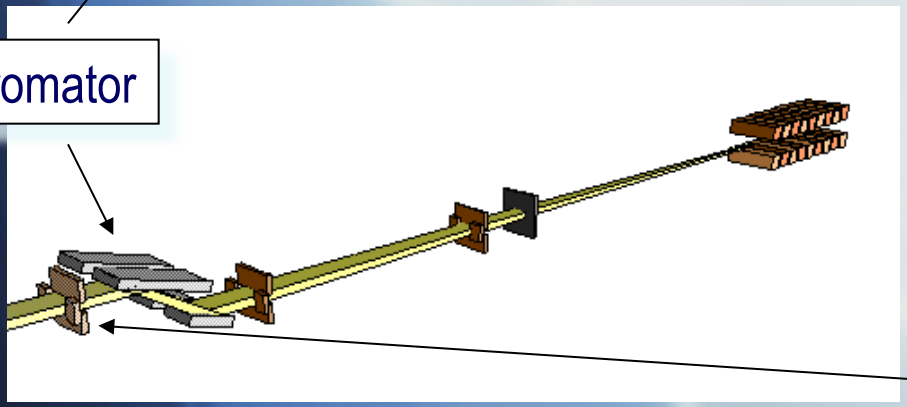
θ_{min} / E_{max}

The crystal will diffract all the rays with: $\theta_{min} \leq \theta_B \leq \theta_{max}$

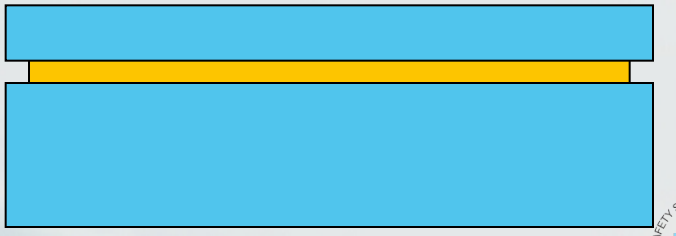


θ_{max} / E_{min}

monochromator

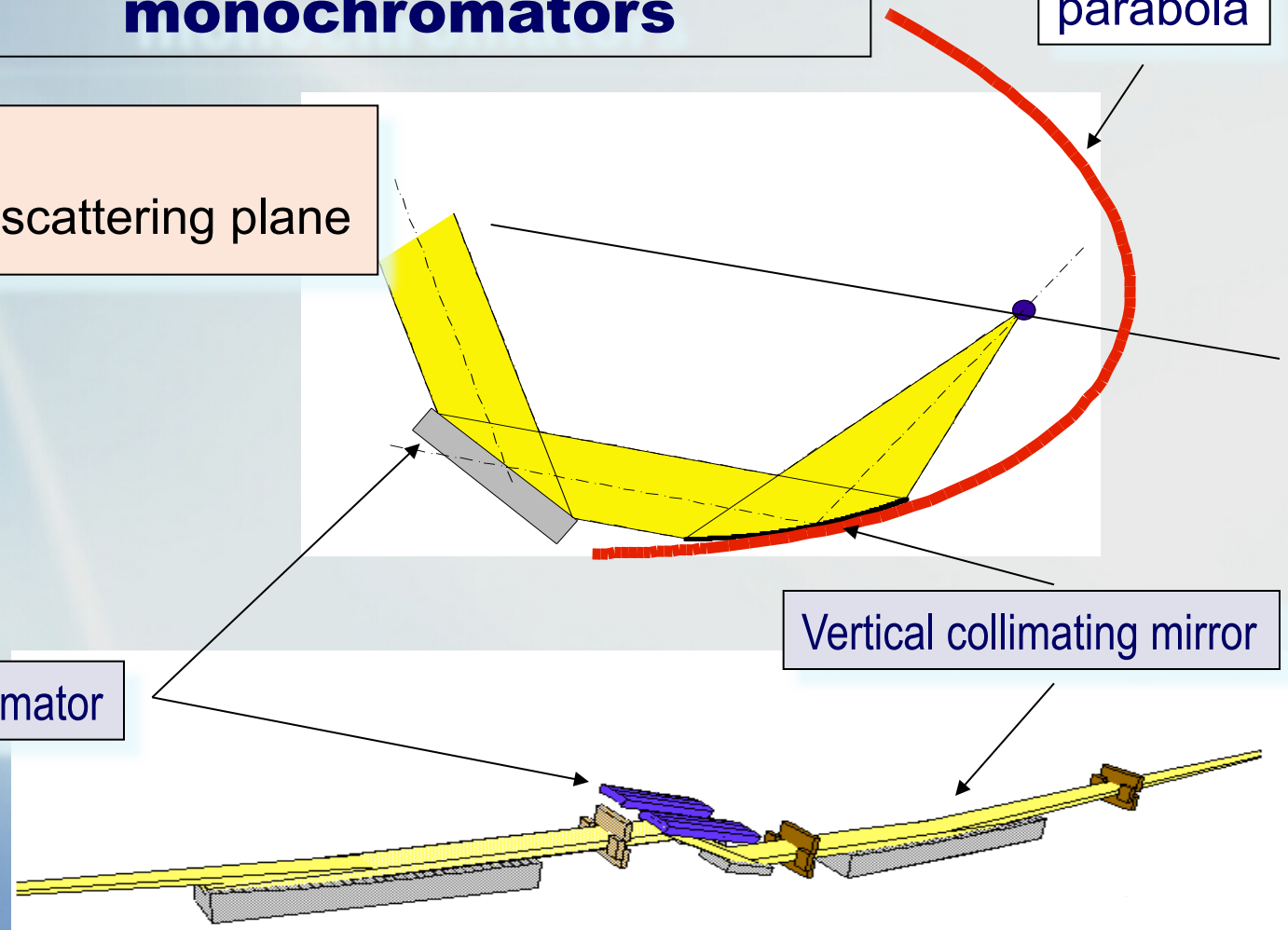


In this case the energy bandwidth is
$\Delta E \approx \Delta\theta_{beam}\ \mathrm{cotg}(\theta_B)\ E$



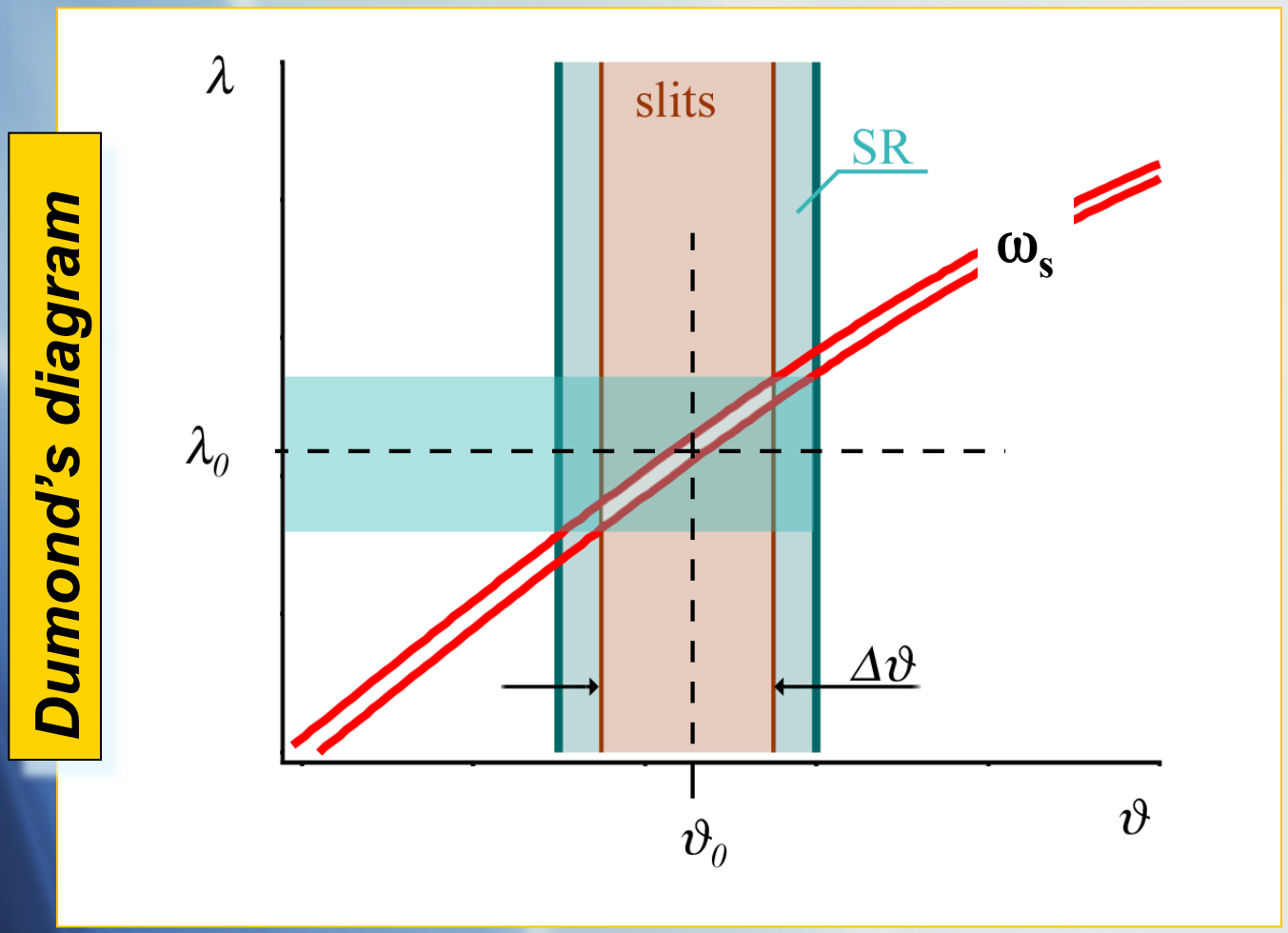
Optical component for SL: monochromators

Case with $\Delta\theta_{beam} << \omega_s$
white parallel beam in the scattering plane



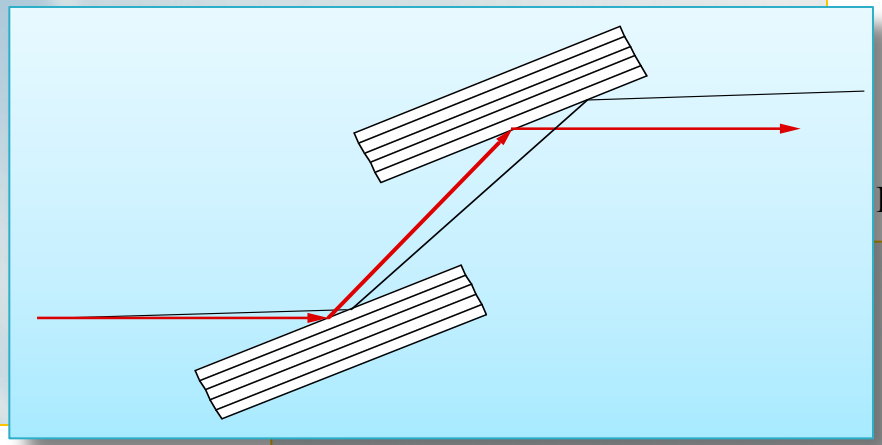
In this case the energy bandwidth will be the crystal Darwin width, function of the Miller indexes: $\Delta E \approx \omega_s \, \mathrm{cotg}(\theta_B) \; E$

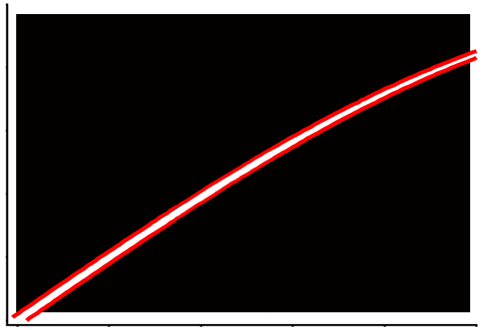
Optical component for SL: monochromators



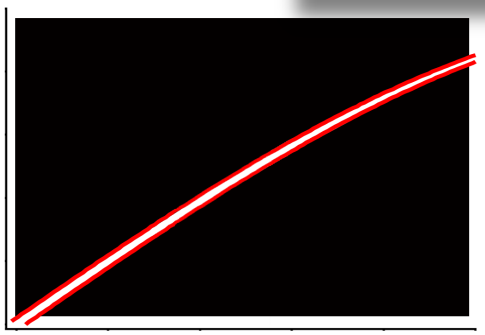
Optical component for SL: Hard x-rays monochromators

Second crystal in ***non dispersive*** configuration to achieve a fixed exit beam





Dumond diagram of the second crystal

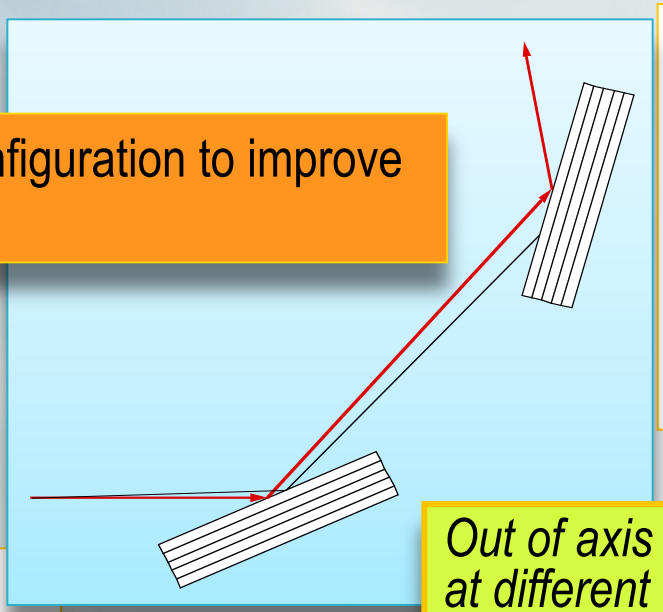


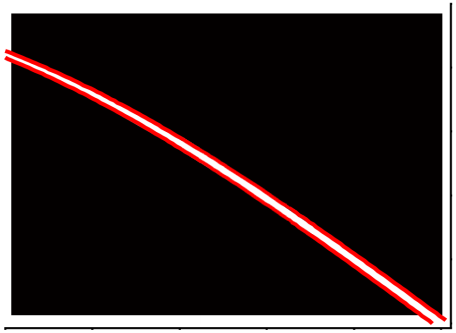
Dumond diagram of the first crystal

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

Optical component for SL: Hard x-rays monochromators

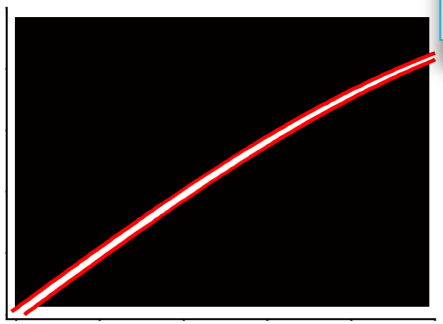
Second crystal in ***dispersive*** configuration to improve energy resolution





Dumond diagram of the second crystal

Out of axis rays on the first crystal are incident at different angles on the second one.



Dumond diagram of the first crystal

Dumond diagram of both crystals

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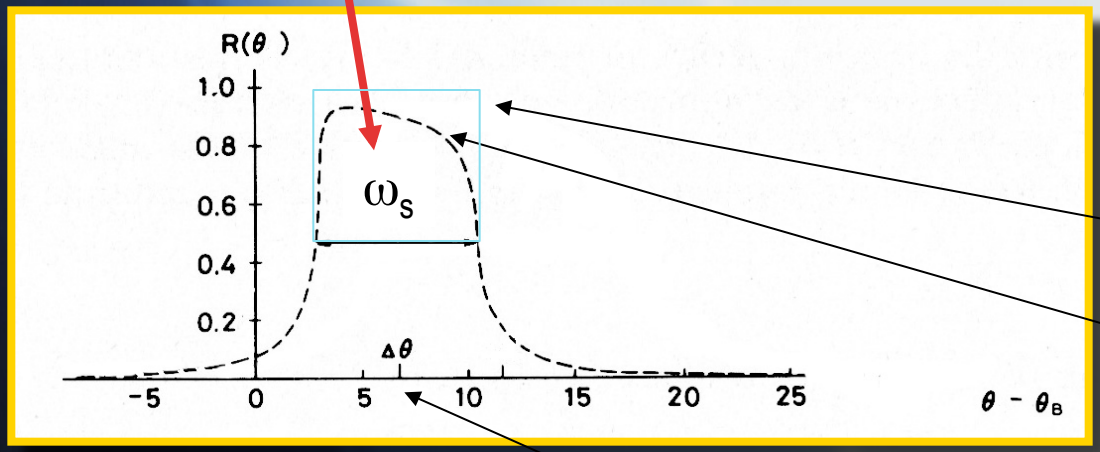
INTENSITY OF THE	- reflectivity or peak reflectivity
REFLECTION	- integral reflecting power

The Darwin curve

$$\omega_S = \frac{2}{\sin 2\vartheta_B} \frac{r_e \lambda_1^2}{\pi V} C |F_{hr}| e^{-M(n)}$$

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)



predicted by the dynamical theory

absorption effects

angular shift due to the refractive effect

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the **b** parameter defined as :

$$b = \frac{\sin(\alpha - \vartheta_B)}{\sin(\alpha + \vartheta_B)}$$

α is the angle between the Bragg plane and the crystal surface

T. Matsushita and H. Hashizume ***X-Ray Monochromators***
Handbook on Synchrotron Radiation, Vol. 1

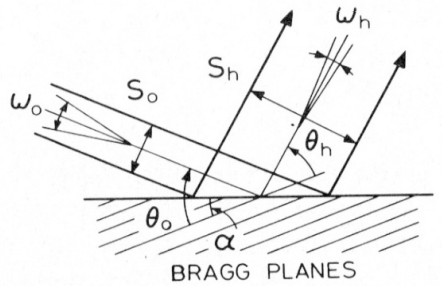

Fig. 3. Geometry of X-ray reflection by a perfect single crystal. θ_0: incidence angle; θ_h: reflection angle. For a non-zero asymmetry angle α ($0 < |\alpha| < \theta_B$), the angular width ω_0 for acceptance is not equal to the angular width ω_h for emergence. The figure is drawn for $b < 1.0$, where $\omega_0 > \omega_s > \omega_h$. Note also the change of beam cross sections, S_0 and S_h.

$$\omega_o = \frac{\omega_s}{\sqrt{b}}$$

the angular acceptance as function of the intrinsic width and the **b** parameter:

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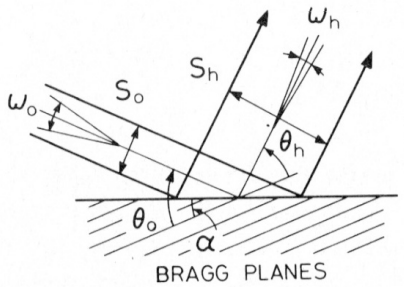


Fig. 3. Geometry of X-ray reflection by a perfect single crystal. θ_0: incidence angle; θ_h: reflection angle. For a non-zero asymmetry angle α ($0 < |\alpha| < \theta_B$), the angular width ω_0 for acceptance is not equal to the angular width ω_h for emergence. The figure is drawn for $b < 1.0$, where $\omega_0 > \omega_s > \omega_h$. Note also the change of beam cross sections, S_0 and S_h.

T. Matsushita and H. Hashizume ***X-Ray Monochromators***
Handbook on Synchrotron Radiation, Vol. 1

Bragg reflection width in case of asymmetric cut crystal is defined by:

$$\omega_h = b\omega_o$$

the angular acceptance as function of the Bragg reflection width

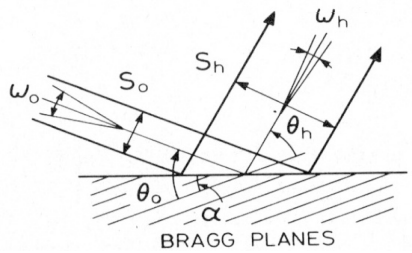
$$\omega_h = \omega_s\sqrt{b}$$

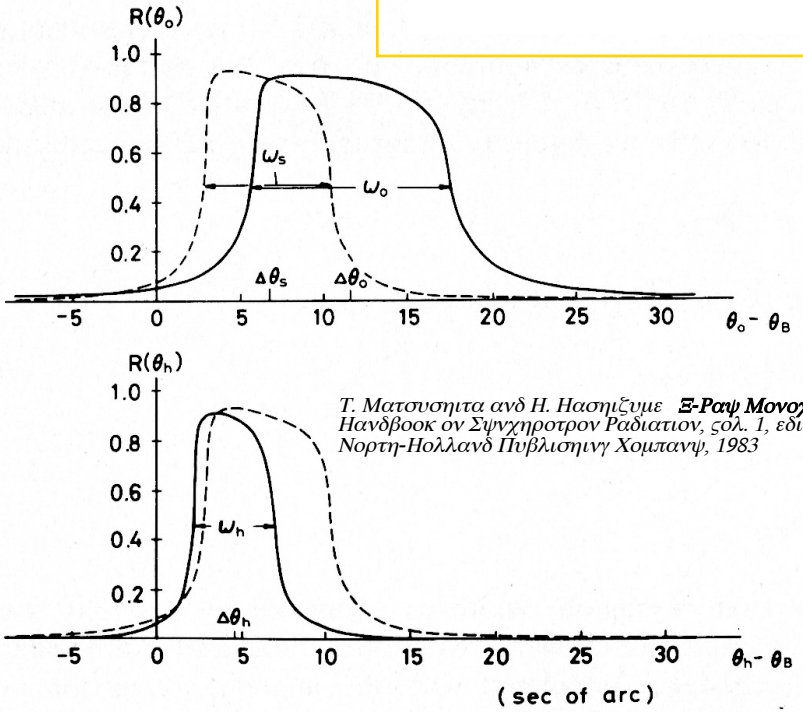
also for the beams sections

$$S_h = \frac{S_o}{b}$$

combining the two formulas we have the well known Liouville's theorem

$$\omega_h S_h = \omega_o S_o$$





Τ. Ματσυσηιτα ανδ Η. Ηασηιζυμε ***Ξ-Ραψ Μονοχηροματορσ***
Ηανδβοοκ ον Σψνχηροτρον Ραδιατιον, ϛολ. 1, εδιτεδ βψ Ε.Ε. Κοχκ
Νορτη-Ηολλανδ Πυβλισηινγ Χομπανψ, 1983

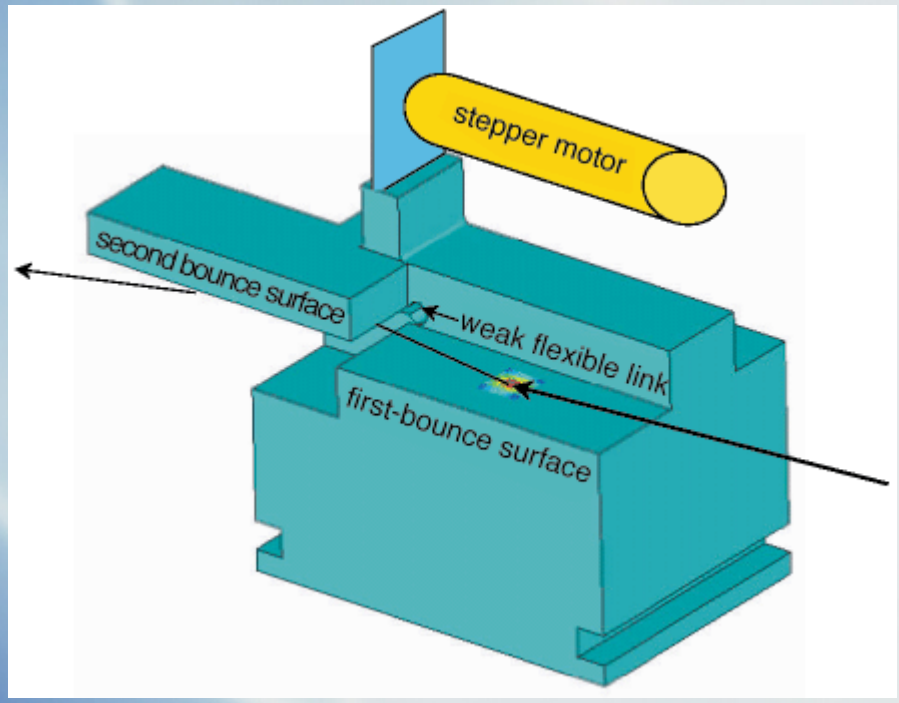
Fig. 4. Perfect-crystal reflection curves for the (111) reflection of silicon at 1.6 Å. $R(\theta_0)$ shows the reflectivity for the ideal plane wave as a function of the incidence angle θ_0, while $R(\theta_h)$ represents the intensity reflected at a reflection angle θ_h for a plane wave incident at θ_0, θ_0 and θ_h being related by $(\theta_h - \theta_B) = b(\theta_0 - \theta_B)$. The solid curves are calculated for an asymmetric case of $b = 0.4$, while the broken curves for the symmetric case ($b = 1.0$) where $R(\theta_0) \equiv R(\theta_h)$.

T. Matsushita and H. Hashizume ***X-Ray Monochromators***
Handbook on Synchrotron Radiation, Vol. 1

Table 2
Intrinsic Bragg reflection widths ω_s, energy resolutions $\Delta E/E$ and integral reflecting powers I of perfect crystals of silicon, germanium and α-quartz at 1.54 Å.

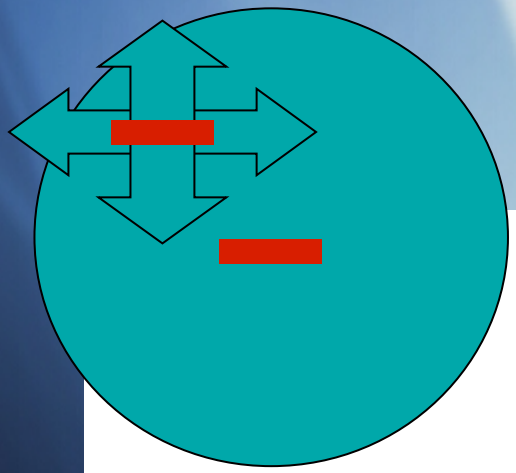
Crystal	*hkl*	ω_s (second or arc)	$\Delta E/E$ ($\times 10^5$)	I ($\times 10^6$)
Silicon	111	7.395	14.1	39.9
	220	5.459	6.04	29.7
	311	3.192	2.90	16.5
	400	3.603	2.53	19.3
	331	2.336	1.44	11.8
	422	2.925	1.47	15.5
	333 (511)	1.989	0.88	9.9
	440	2.675	0.96	14.0
	531	1.907	0.60	9.3
Germanium	111	16.338	32.64	85.9
	220	12.449	14.46	67.4
	311	7.230	6.92	37.1
	400	7.951	5.94	42.3
	331	5.076	3.34	25.4
	422	6.178	3.34	32.4
	333 (511)	4.127	2.00	20.2
	440	5.339	2.14	27.5
	531	3.719	1.33	17.7
α-quartz	100	3.798	10.00	18.8
	101	7.453	15.26	40.9
	110	2.512	3.69	12.2
	$10\bar{2}$	2.488	3.36	12.9
	200	2.252	2.81	11.5
	112	2.927	3.03	15.5
	202	2.072	1.93	10.6
	212	2.042	1.47	10.7
	$20\bar{3}$	2.430	1.74	12.9
	301	2.368	1.69	12.6

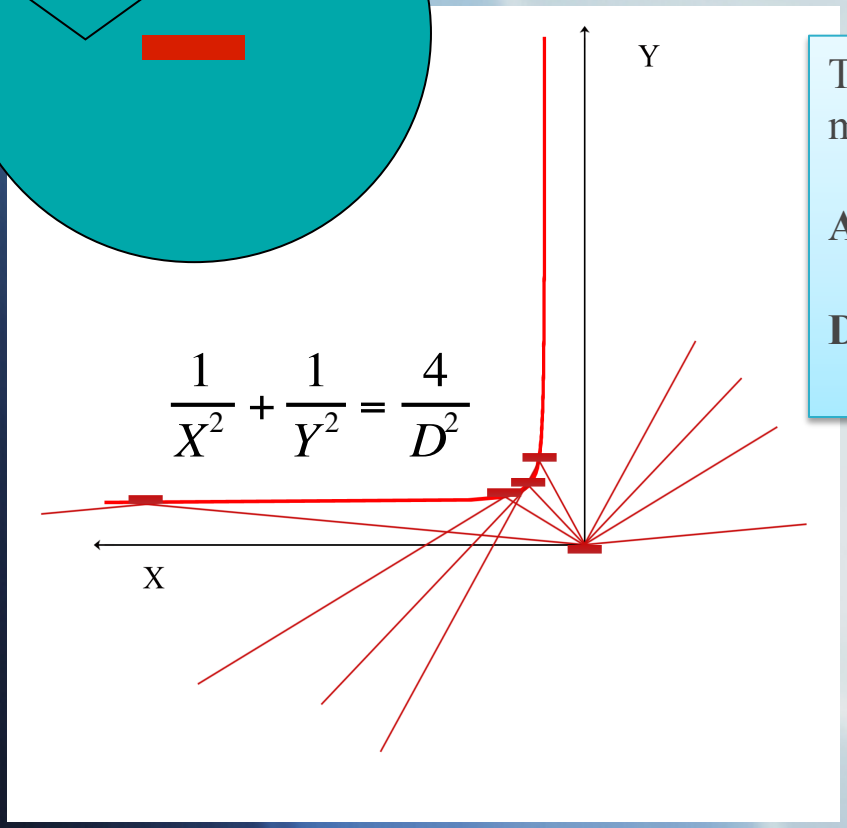
The simplest DCM, the **channel-cut**



The chanel-cut DCM is made from a single crystal monolith.
Advantages: simple, intrinsically aligned
Disadvantages: not fixed height beam output changing the energy

Pseudo channel-cut Double Crystal Monochromator



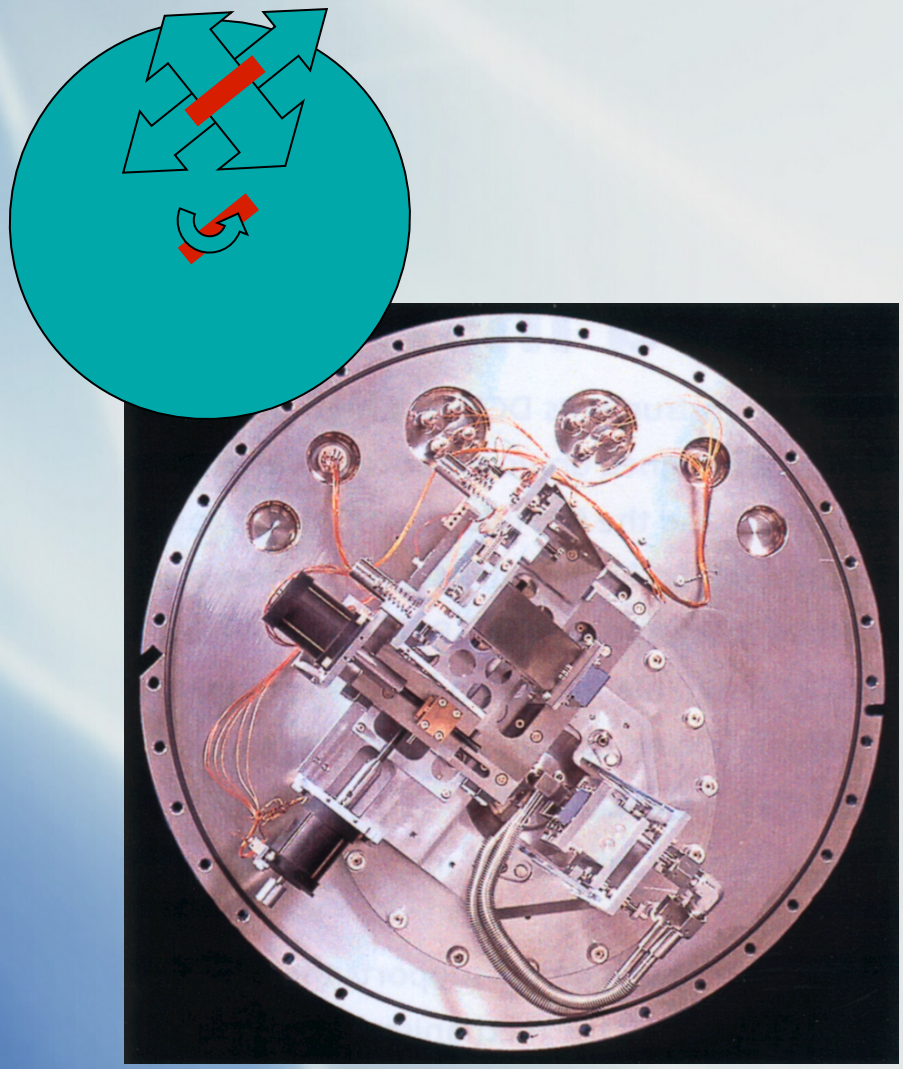


The pseudo chanel-cut DCM is made from two single crystals mounted on to a common rotating table.

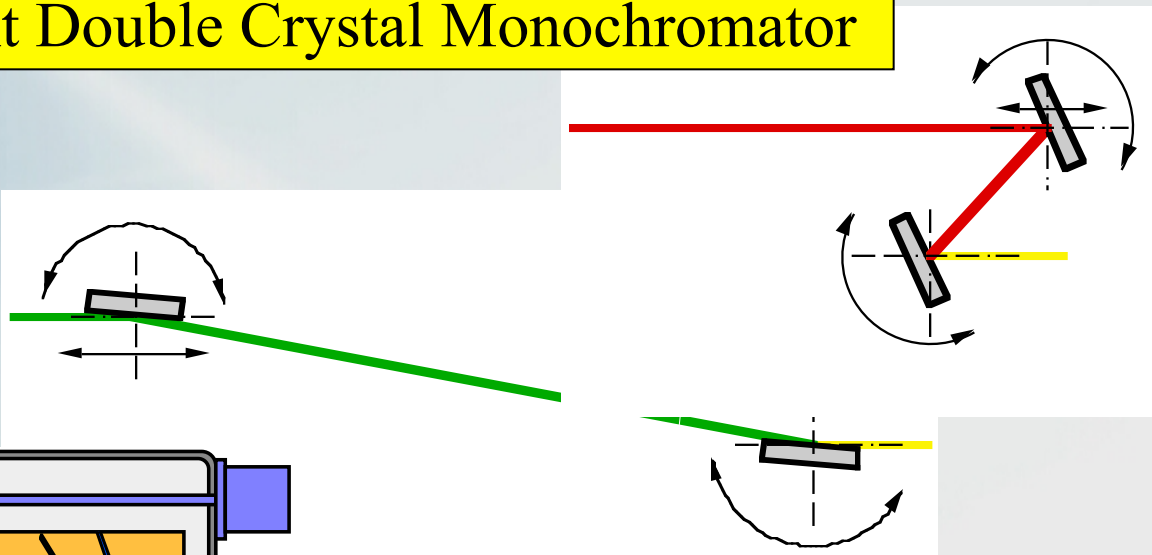
Advantages: fixed height beam output changing the energy

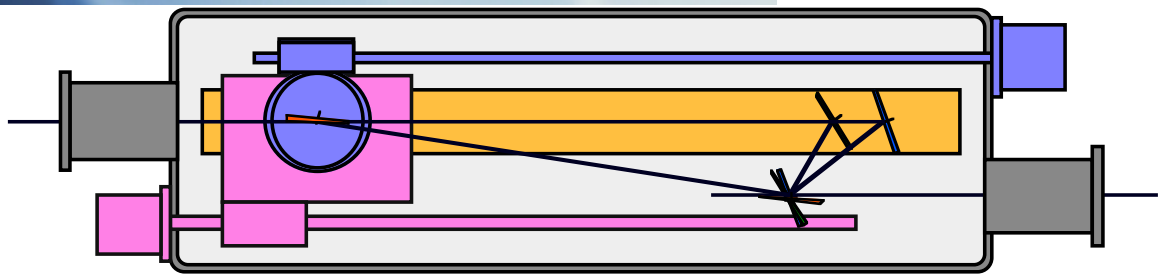
Disadvantages: it needs course and fine regulations for the second crystal

Pseudo channel-cut Double Crystal Monochromator



Independent Double Crystal Monochromator





Si(111)
crystal positions:
- 2100 eV θ =70.3°
- 2300 eV θ =59.3°
- 25000 eV θ =4.5°

II crystal movements:
- II crystal translation
- II crystal rotation
- linear slide

The first crystal can rotate. The second crystal can rotate and translate.

Advantages: fixed height beam output due to the mechanical construction along a wide energy range

Disadvantages: it needs course and fine regulations for the second crystal

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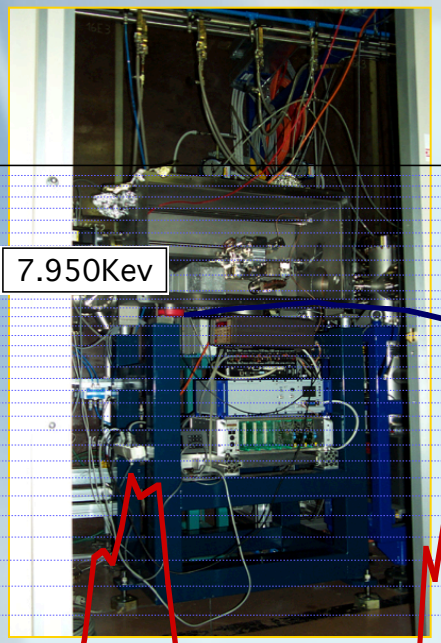

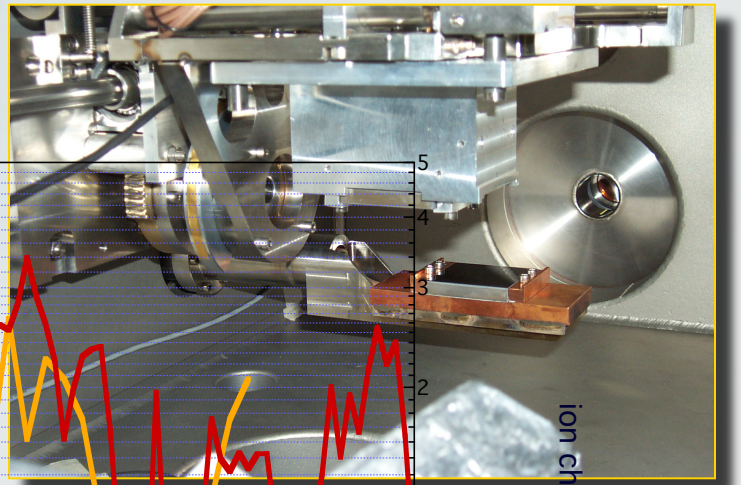

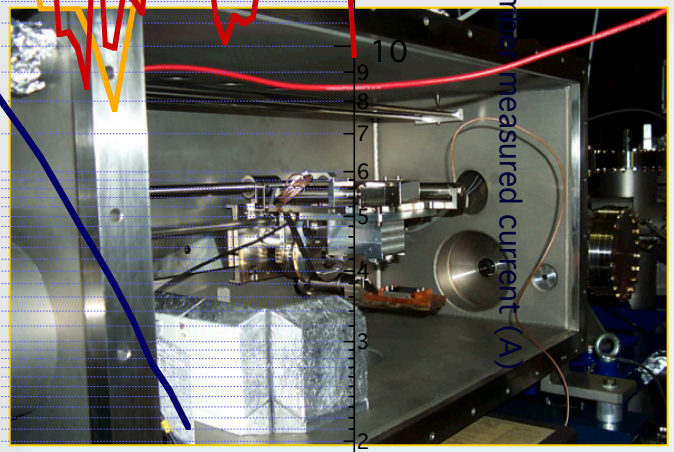

7.950Kev

18.545Kev

autocollimator pitching parllelism error (arc sec)

piezo correction (arc sec)

ion chamb. measured current (A)

20
10
0
-10
-20

5
4
3
2
10
9
8
7
6
5
4
3
2

10^{-10}

20 18 16 14 12 10 8 6

bragg angle (deg)

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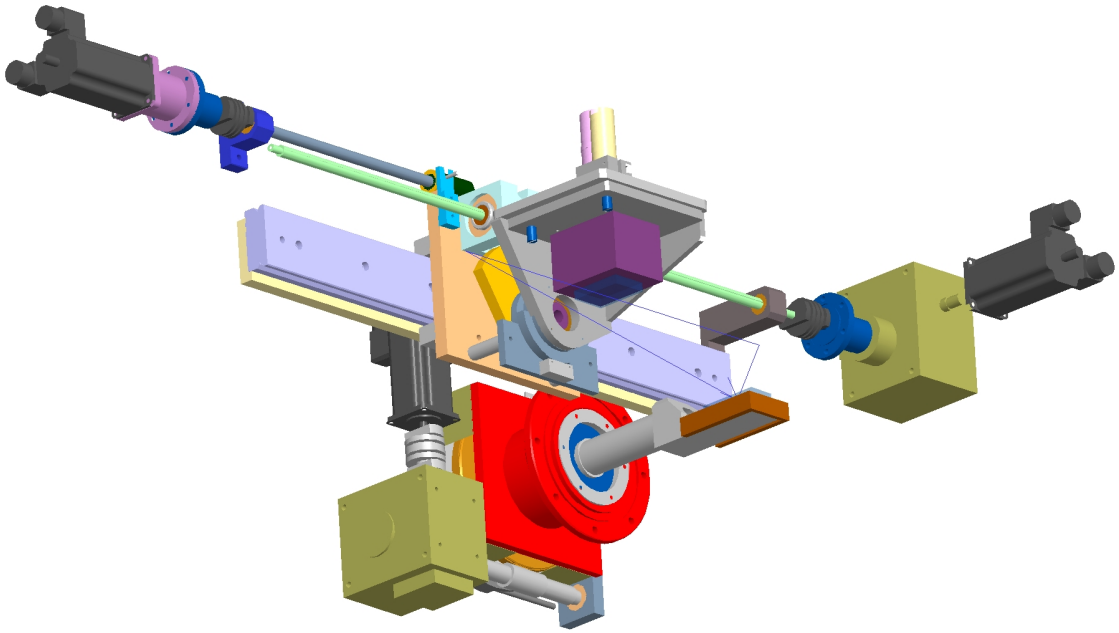
Final design 3D view
The monochromar equipped with a sagittal bender is operating at the powder diffracion beamline @ Elettra



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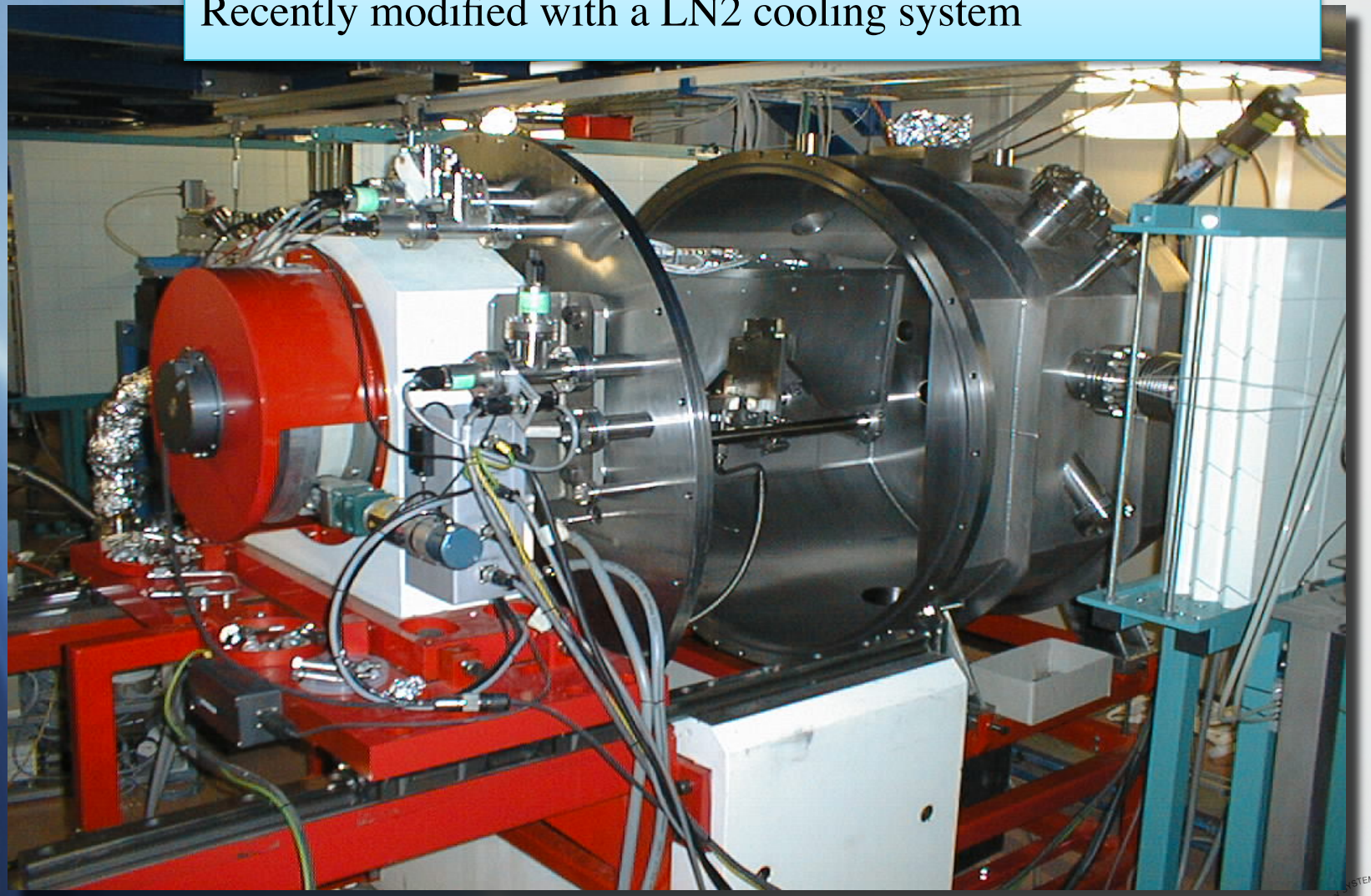
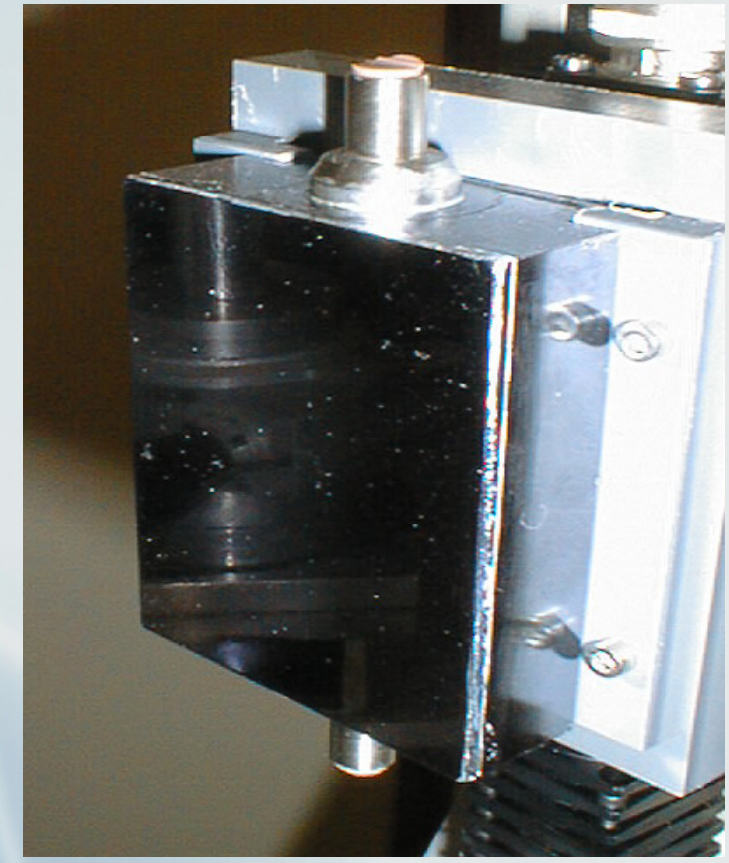
The XRD1 Double Crystal monochromator @ Elettra
it has been designed in Elettra in 1991. It operates since 1994.
Recently modified with a LN2 cooling system

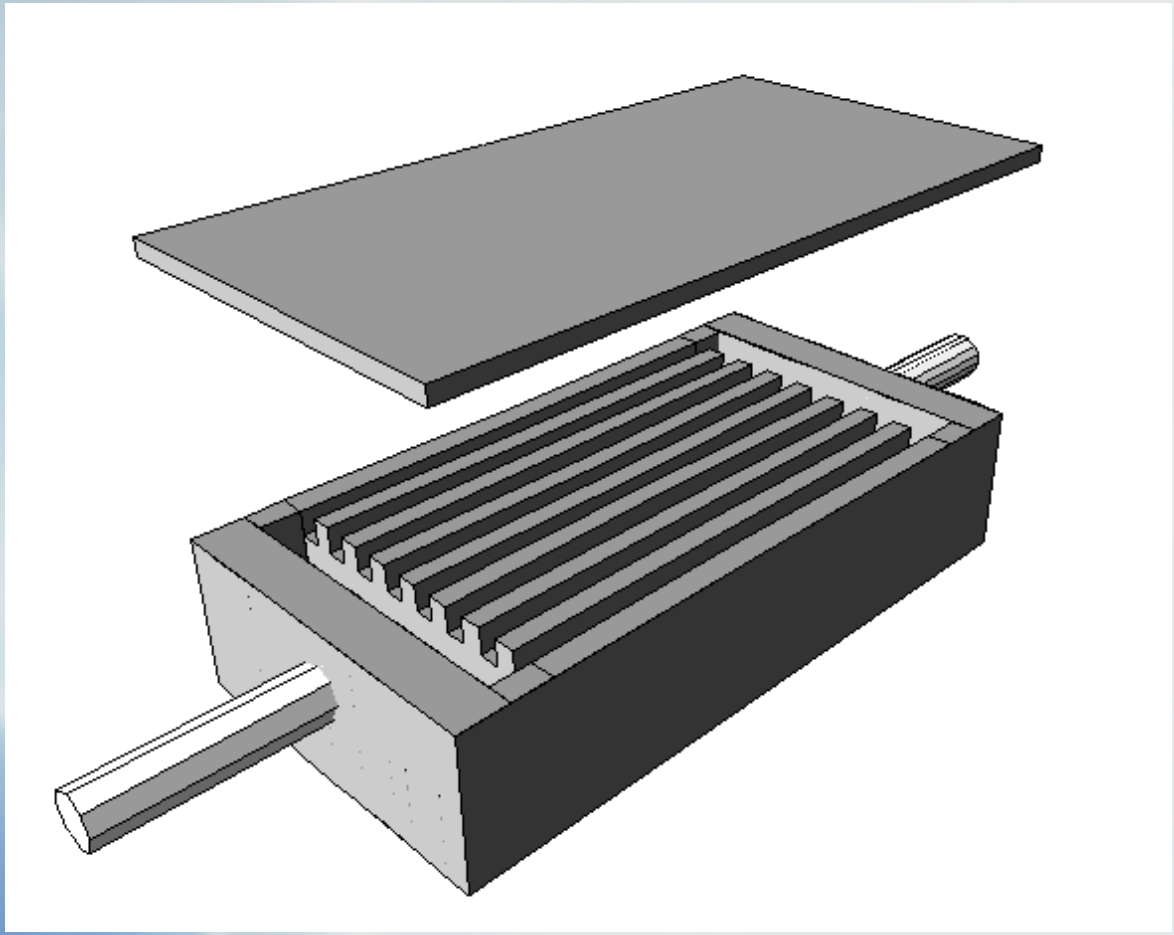


Monochromator optics and thermal load XRD1

Absorbrd power 0.4 kW*

* 1.5 x 0.28 mrad^2





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The two crystal elements before brazing in vacuum oven (first prototype)

Channels	thickness:	300 μm
	depth:	2 mm

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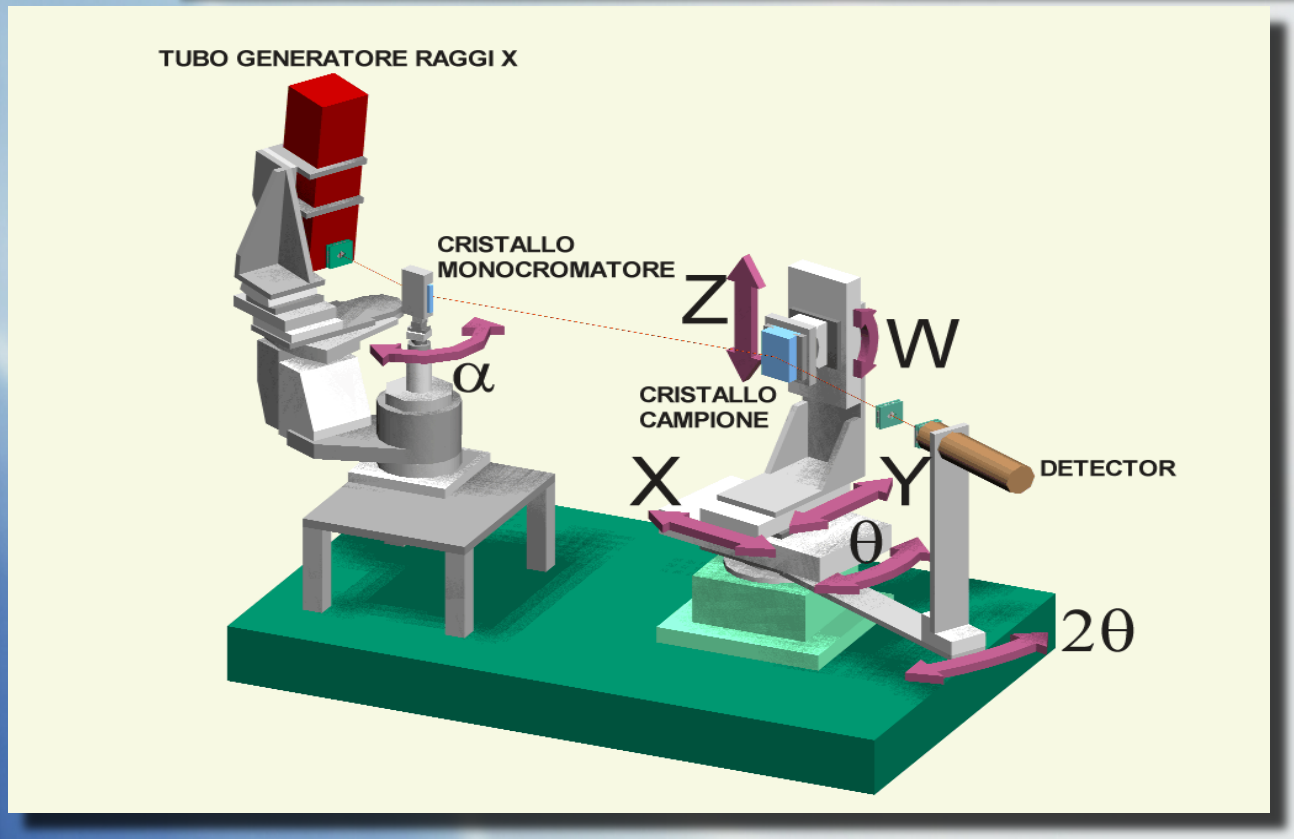
Metrology station with X-rays



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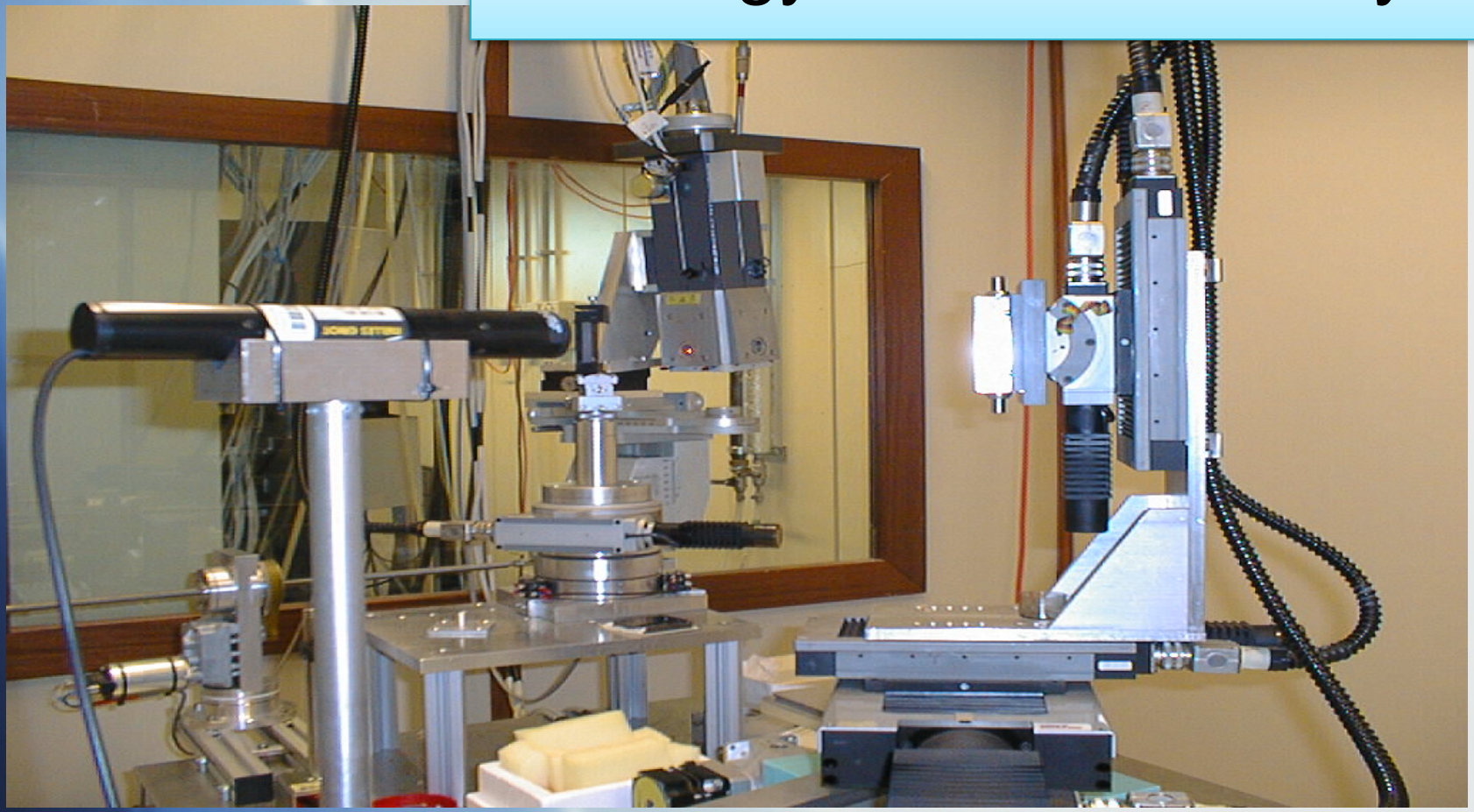
Metrology station with X-rays



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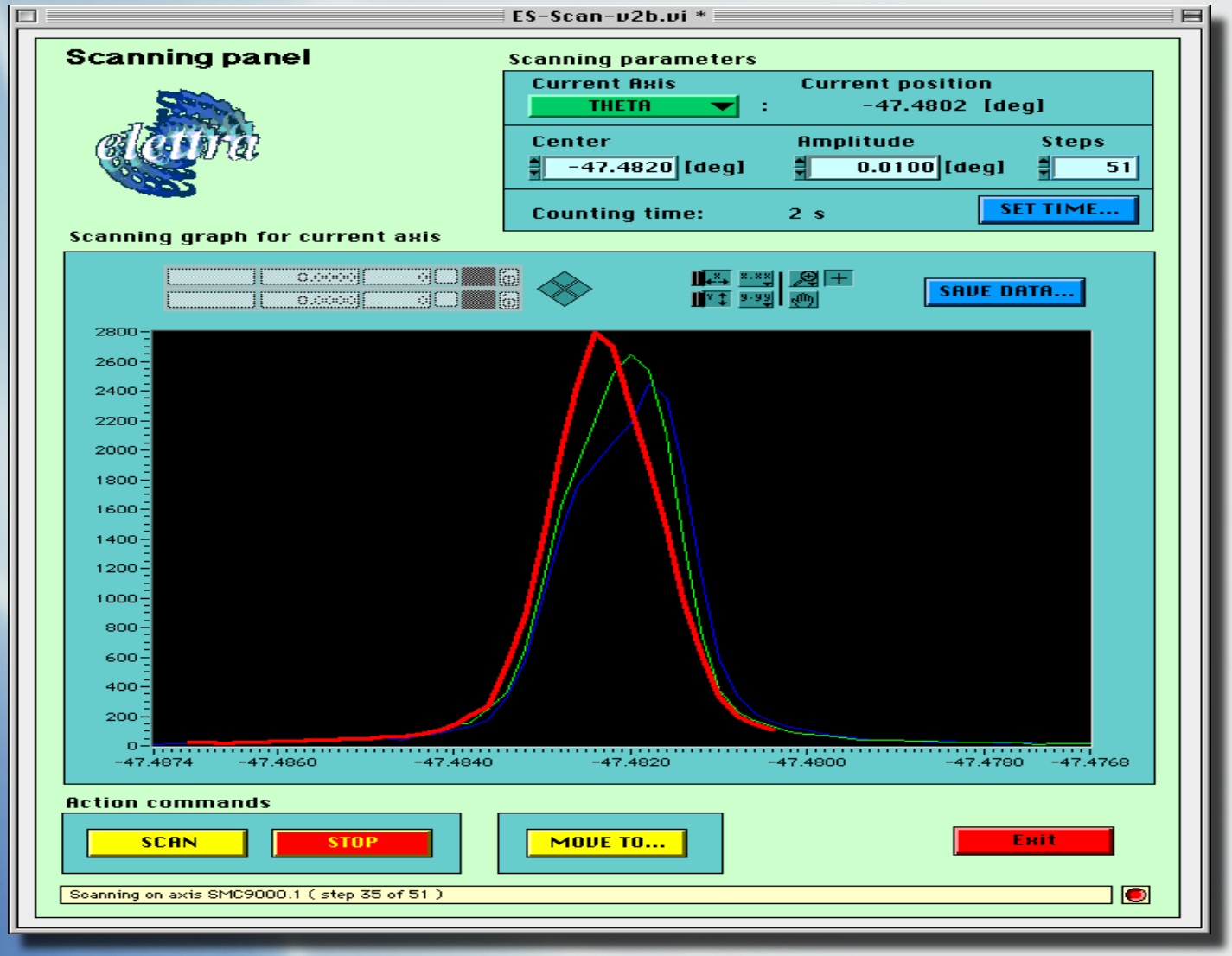
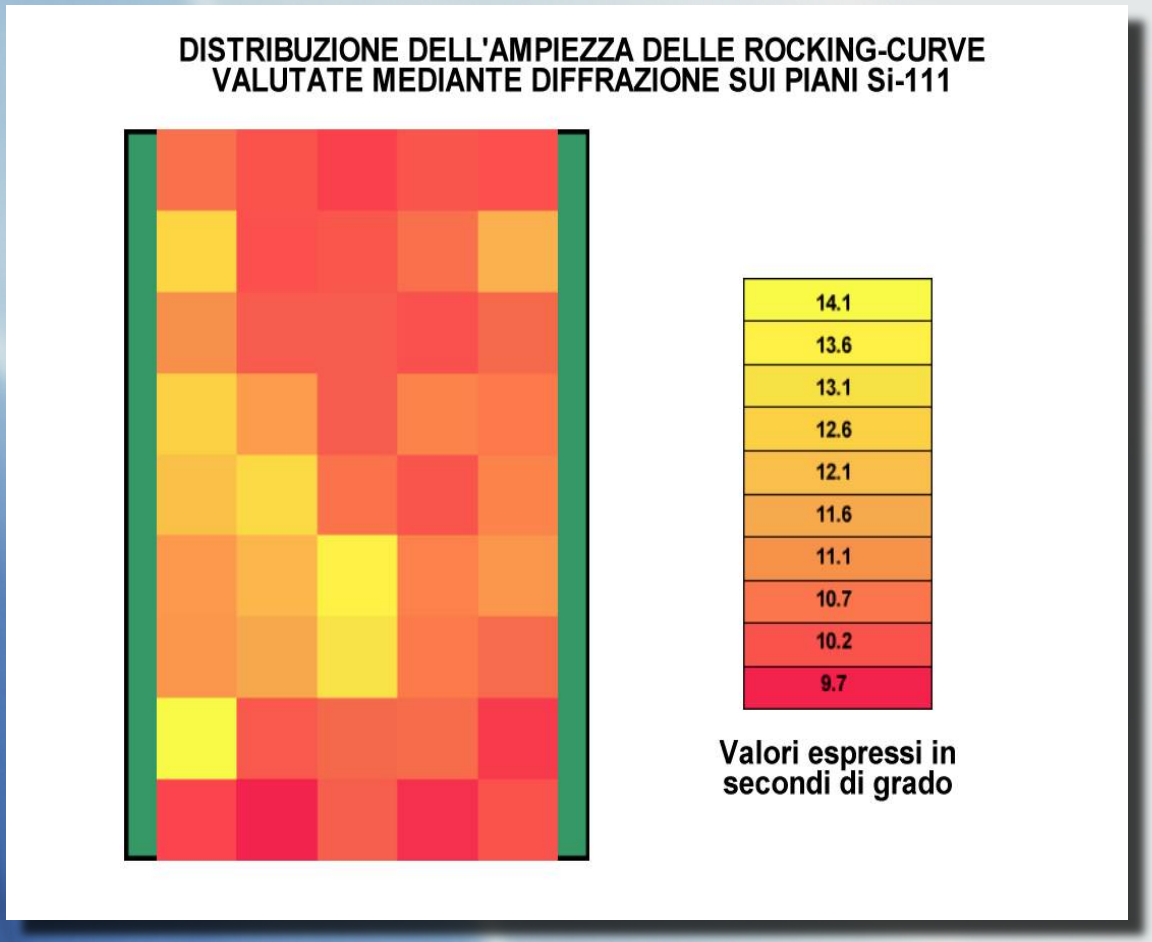


Rasterized crystal point rocking curve @ 1.54 Å Si111 FWHM 10.3 arcsec.



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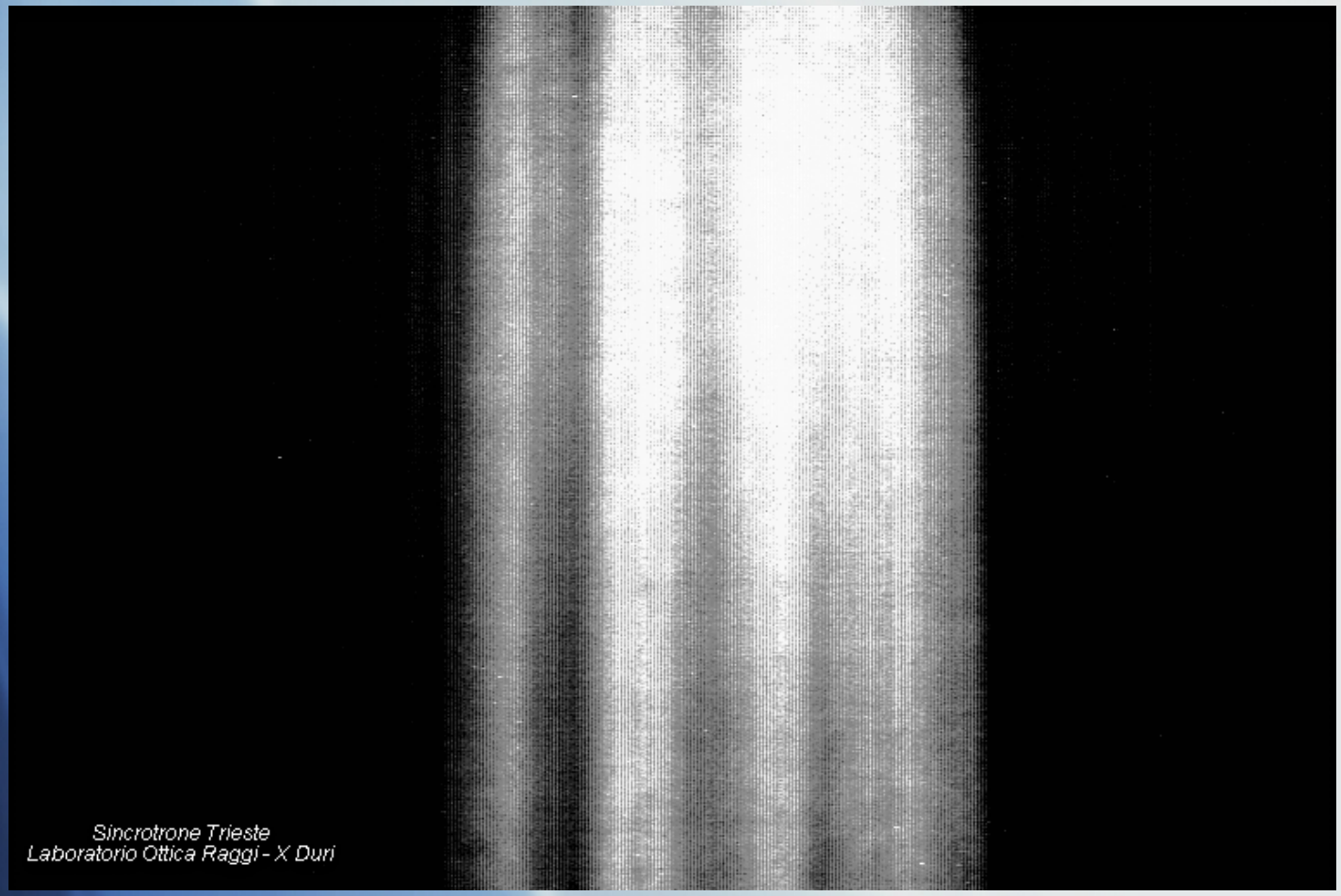
Topography of the internal cooled Si-crystal with channels perpendicular to the scattering plane



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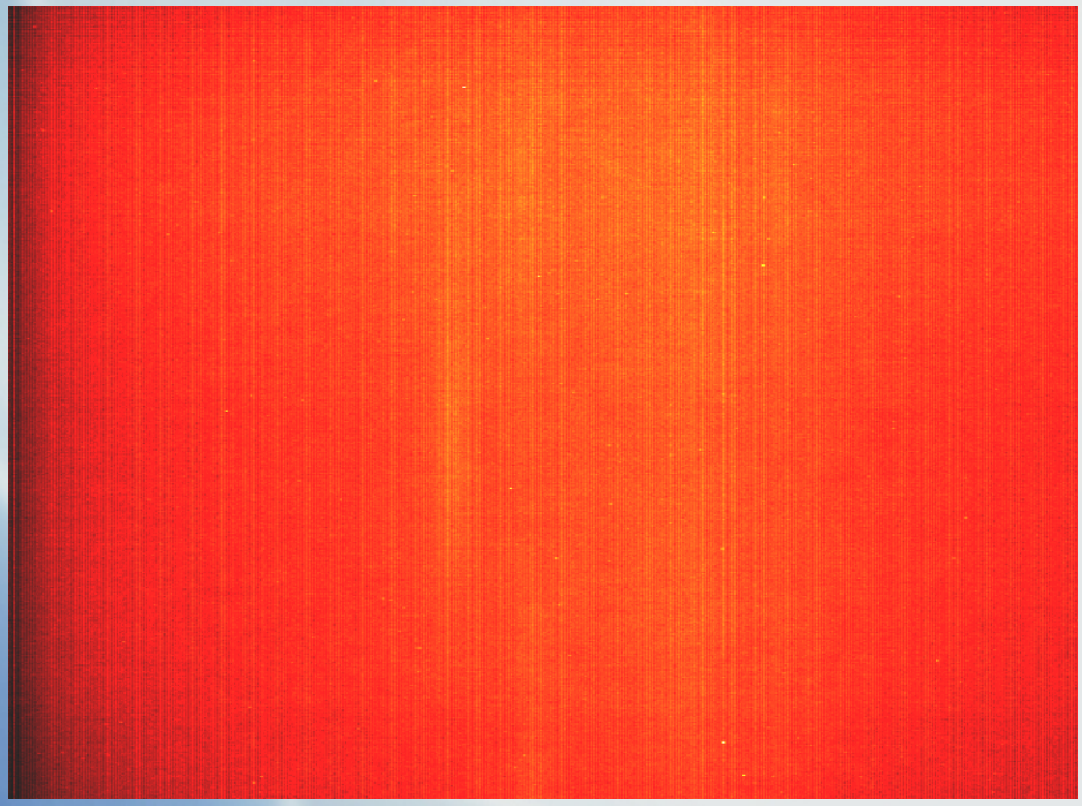
Topography live



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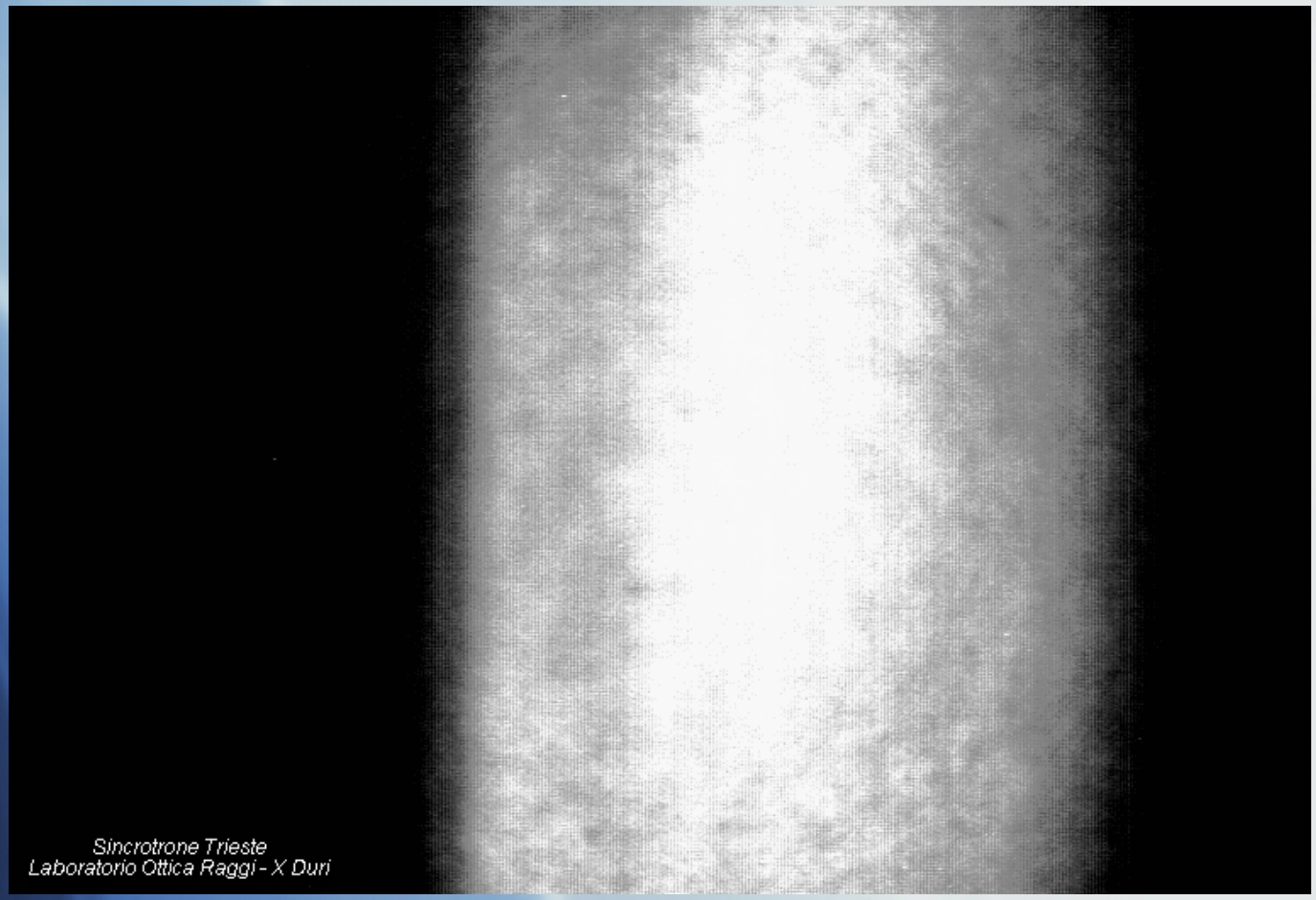
Same topography but with channels in the same direction of the scattering plane



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- Detector for Hard X-rays

- Two large families:

  single counters

  integrators

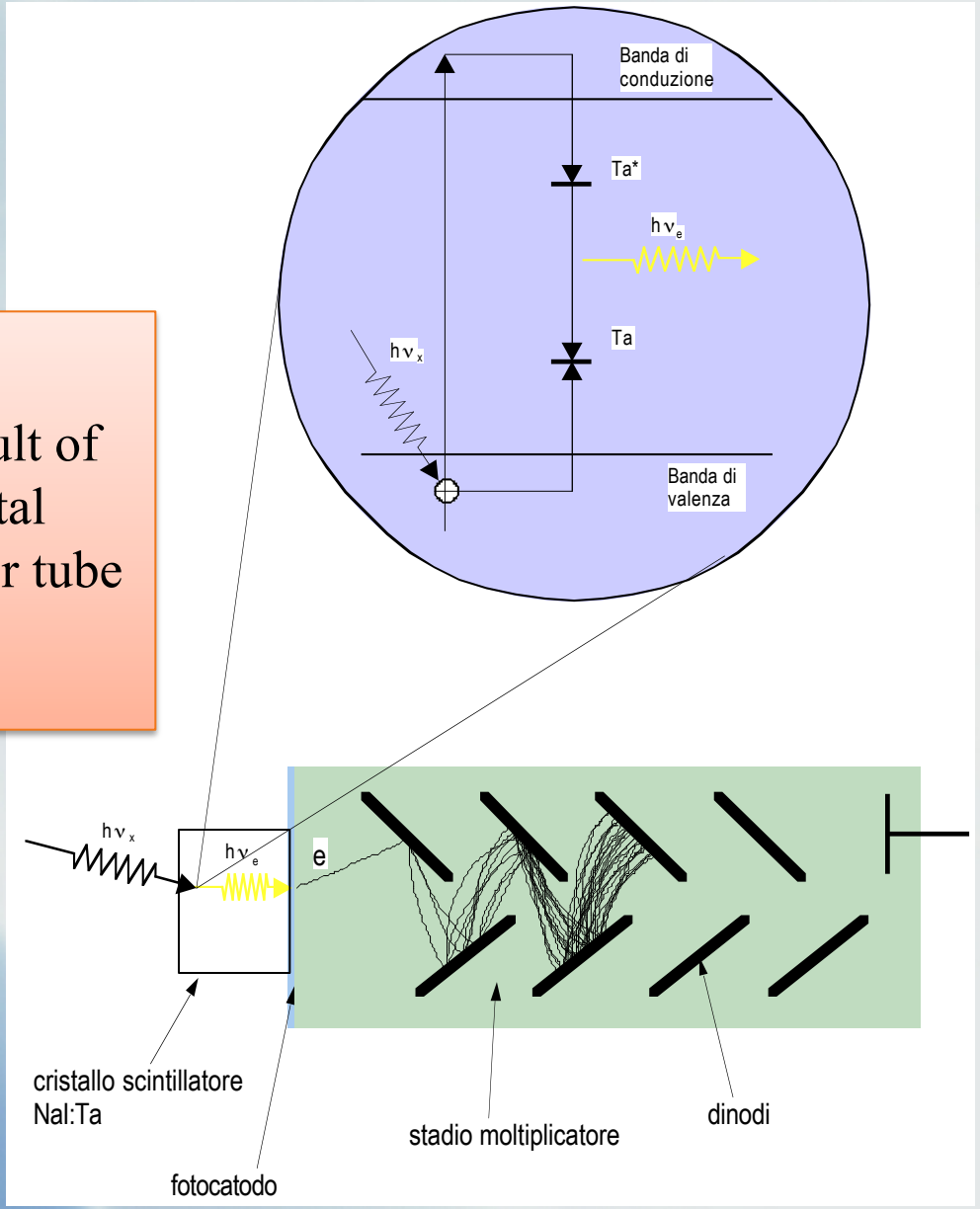
- **Single counters** :

- These systems allow to collect all the electrons produced by the absorption of an x-ray.
- The mean number of electrons produced during the absorption process is proportional to energy of the single x-ray.
- Used in spectroscopy

Scintillators

These kind of detectors are the result of the coupling between a doped crystal (i.e. NaI:Ta) and a photo-multiplier tube

https://en.wikipedia.org/wiki/Scintillation_counter



2D Integrators detectors

- They integrates the charge. Generally losing the direct correlation between electrons produced and energy of the absorbed photon.
- The signal local intensity has to be proportional to the dose absorbed in the same region.
- Correlation is possible in case of monochromatic beam

Radiographic film (totally analogic)

It is still one of the most used detector.
Due to the photocemical reaction AgBr –> Ag+ with a density of Ag+ that is proportional to the absorbed radiation. The developer bath reduces Ag+ –> Ag with the tipical gray scale we are used to see .

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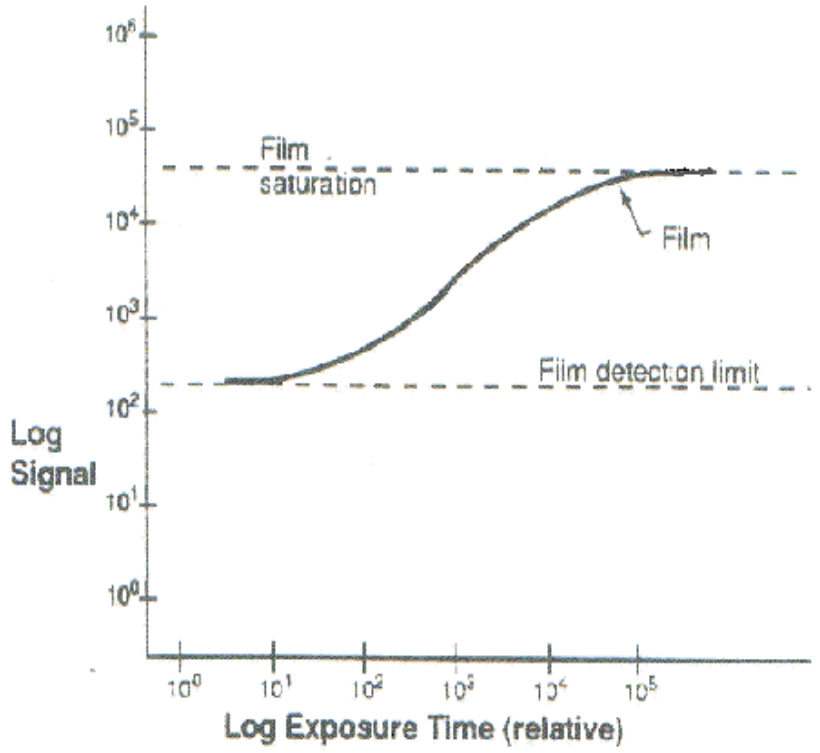
Characteristic curve of the film density versus the time esposure (log/log)

Dynamic range
Linearity

Linearità e range dinamico delle emulsioni fotografiche



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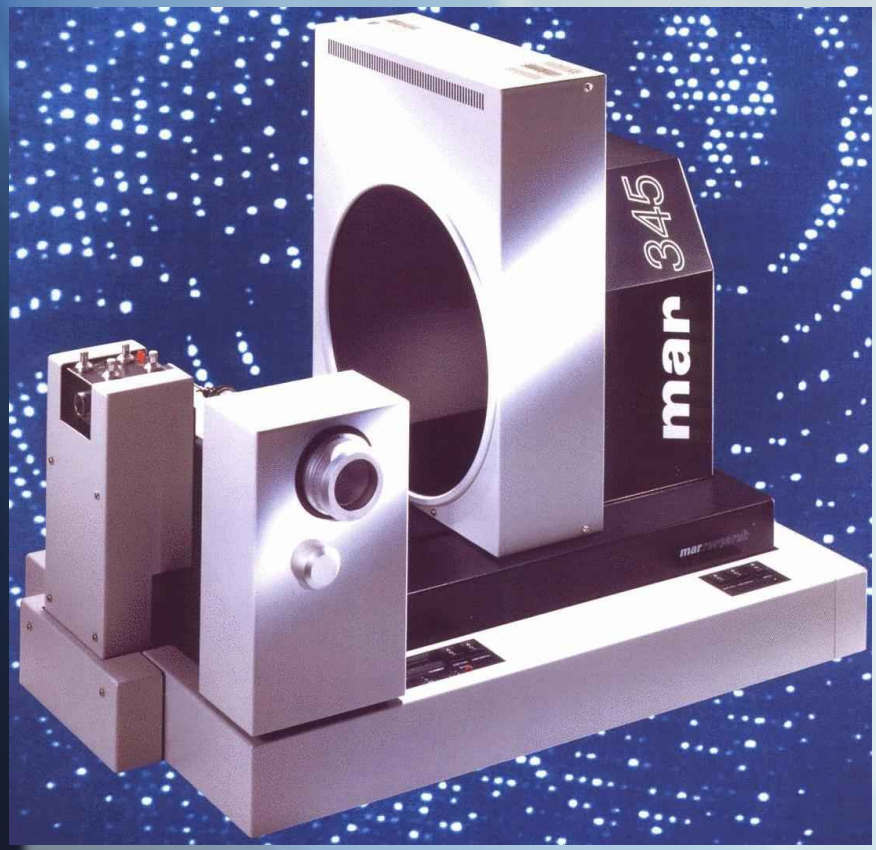
2D integrator detectors (analogic/digital)



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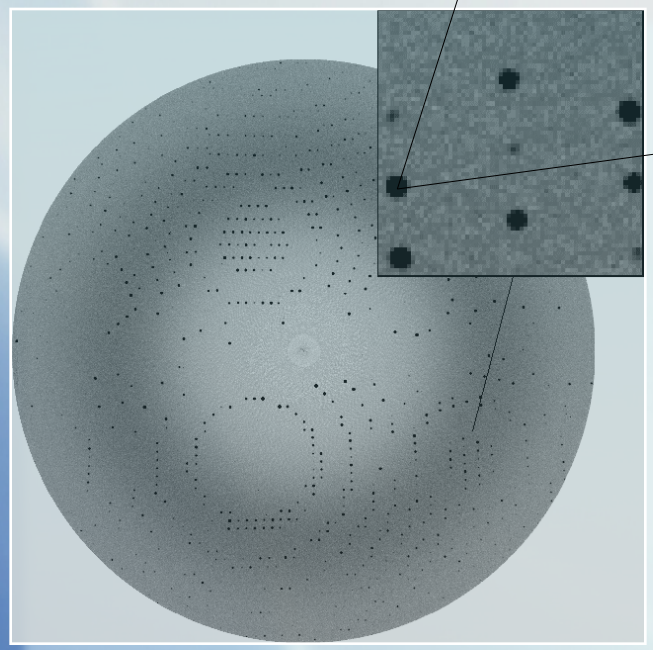
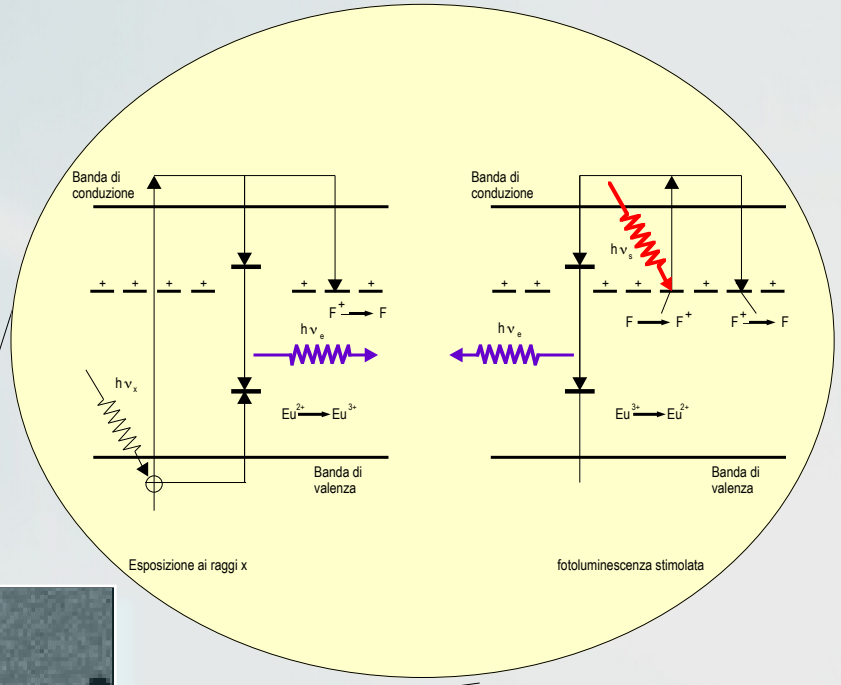
Imaging Plate… analogical detector with digital readout





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2D integrator detectors (totally digital)

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Sincrotrone
Trieste

PILATUS 6M: Specifications

No of Modules: 60
Module arrangement: 5 x 12
Detector Size: 431 x 448 mm^2
Format: 2527 x 2463 pixels
Spatial resolution: 0.172 x 0.172 mm^2
Dynamic range/pixel: 20bits
Count rate/pixel: <8 Mcps/pixel
Readout time: 3.5 ms
Frame rate: 12.5 Hz
Compressed dimension: ≈ 6M/frame
Mechanical positioning: Flat geometry
Intermodule gap x: 7 pixels, y: 17 pixels, 8.4% of total area

Data storage?…….. Hops! we have a problem!

DECTRIS
Next Generation X-Ray Detectors

Elettra
Sincrotrone
Trieste

THANK YOU!