AHEAD

eROSITA - Science and Data Analysis School

eROSITA Optics

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- *Optical Constants (Material depending)*

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2.1. Grazing Incident Telescopes

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- *Modified Wolter Optics*

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- *Focal Length f, Diameter (Radius r), Coating*

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- *Segmented Optics*
- *Multi-Optic Telescopes*

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- *Angular Resolution (Point-Spread Function)*
- *Surface Roughness (Micro-Roughness)*
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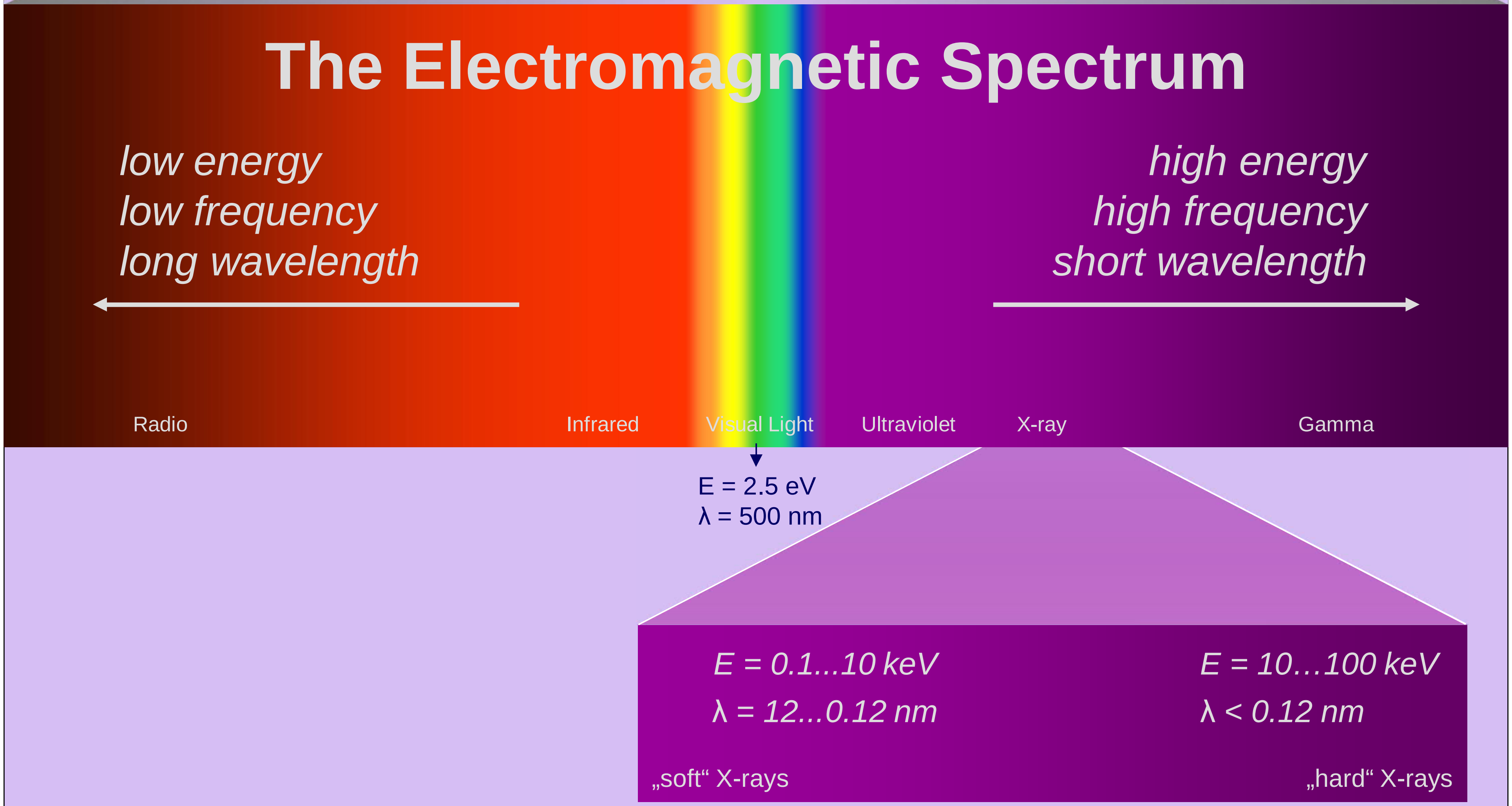
1.1. The X-Ray Band in the Electromagnetic Spectrum

The X-Ray Band in the Electromagnetic Spectrum



The Electromagnetic Spectrum

low energy
low frequency
long wavelength

high energy
high frequency
short wavelength

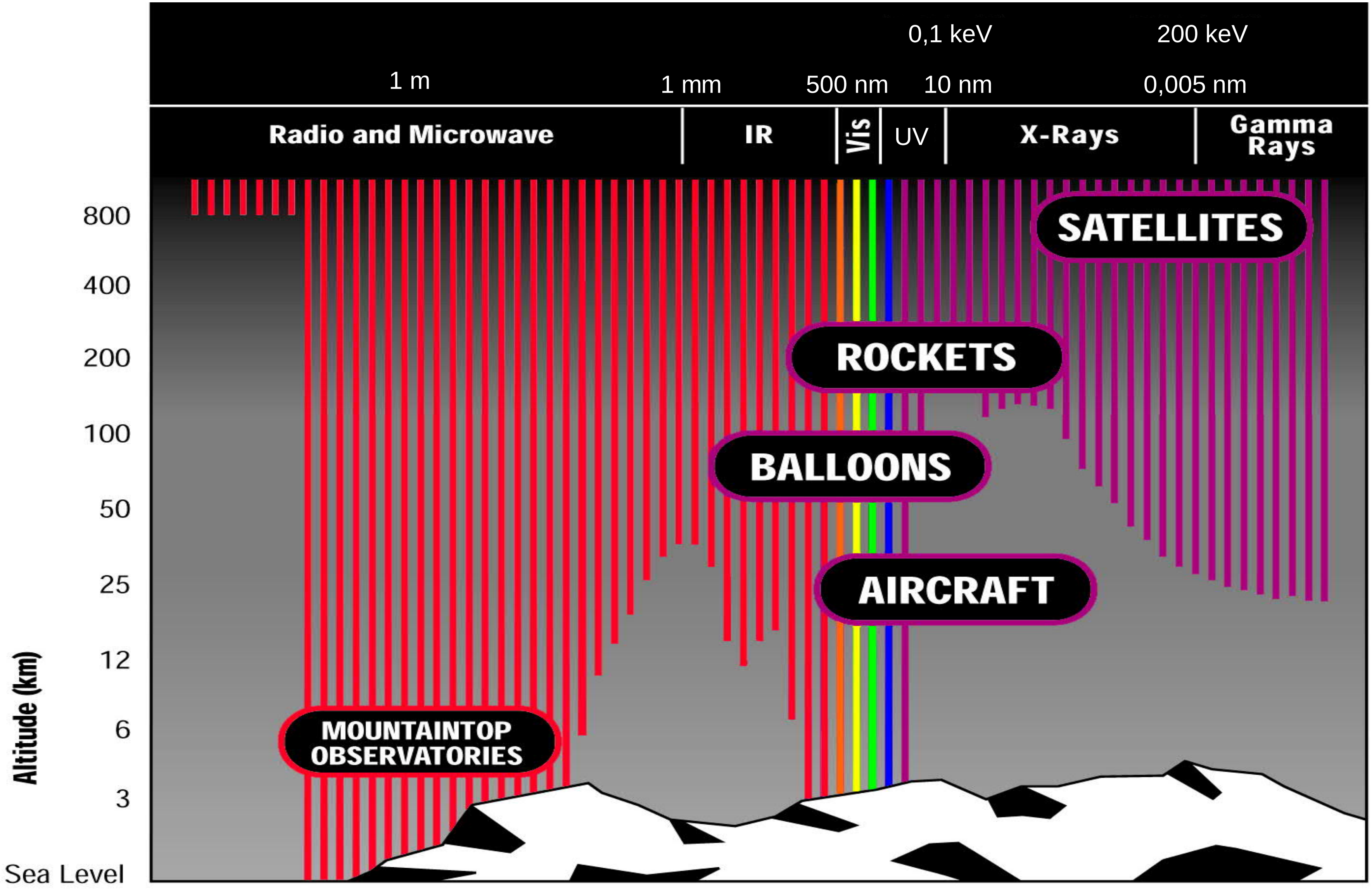
Radio | Infrared | Visual Light | Ultraviolet | X-ray | Gamma

E = 2.5 eV
λ = 500 nm

E = 0.1...10 keV
λ = 12...0.12 nm
„soft“ X-rays

E = 10…100 keV
λ < 0.12 nm
„hard“ X-rays

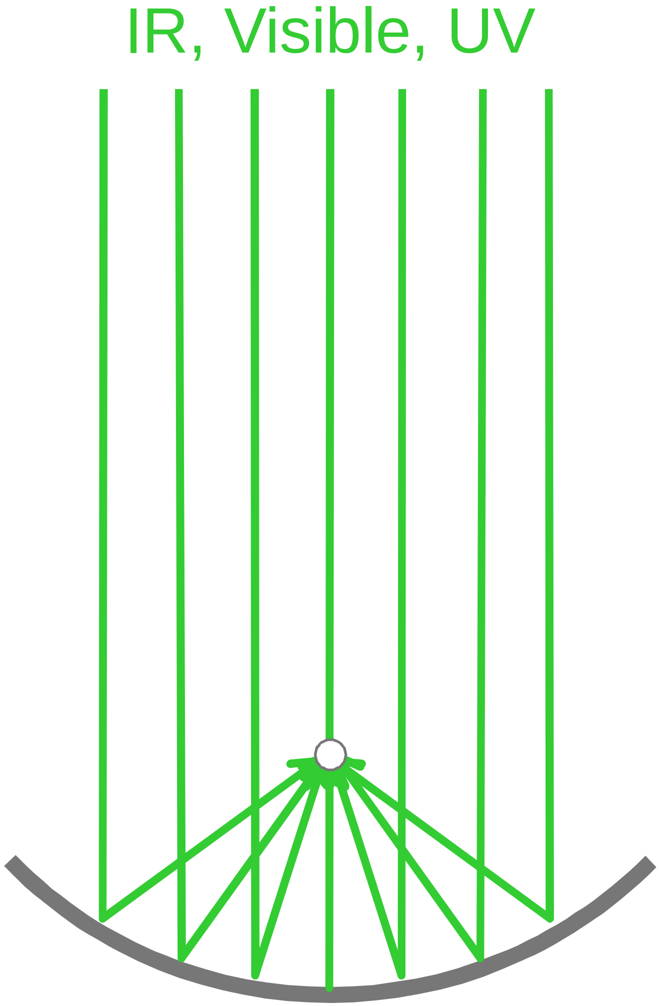
Absorption in the Atmosphere

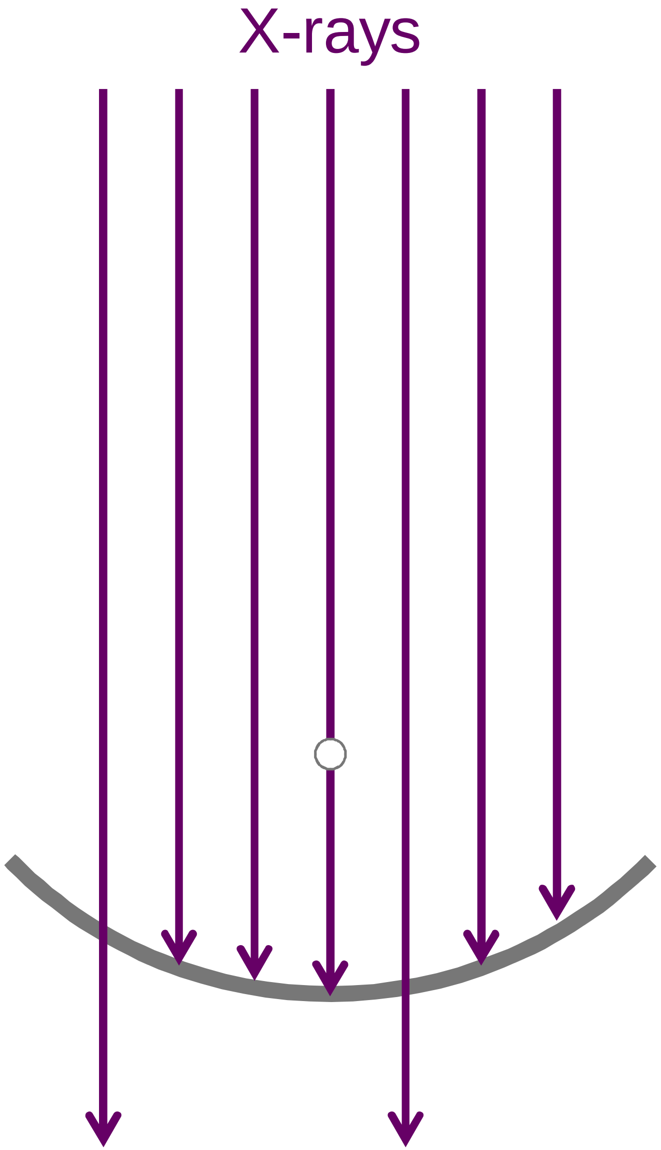


1.2. Reflectivity

- *Refraction Index, Grazing Angle, Photon Energy (Total External Reflection)*
- *Optical Constants (Material depending)*

Reflection and Absorption

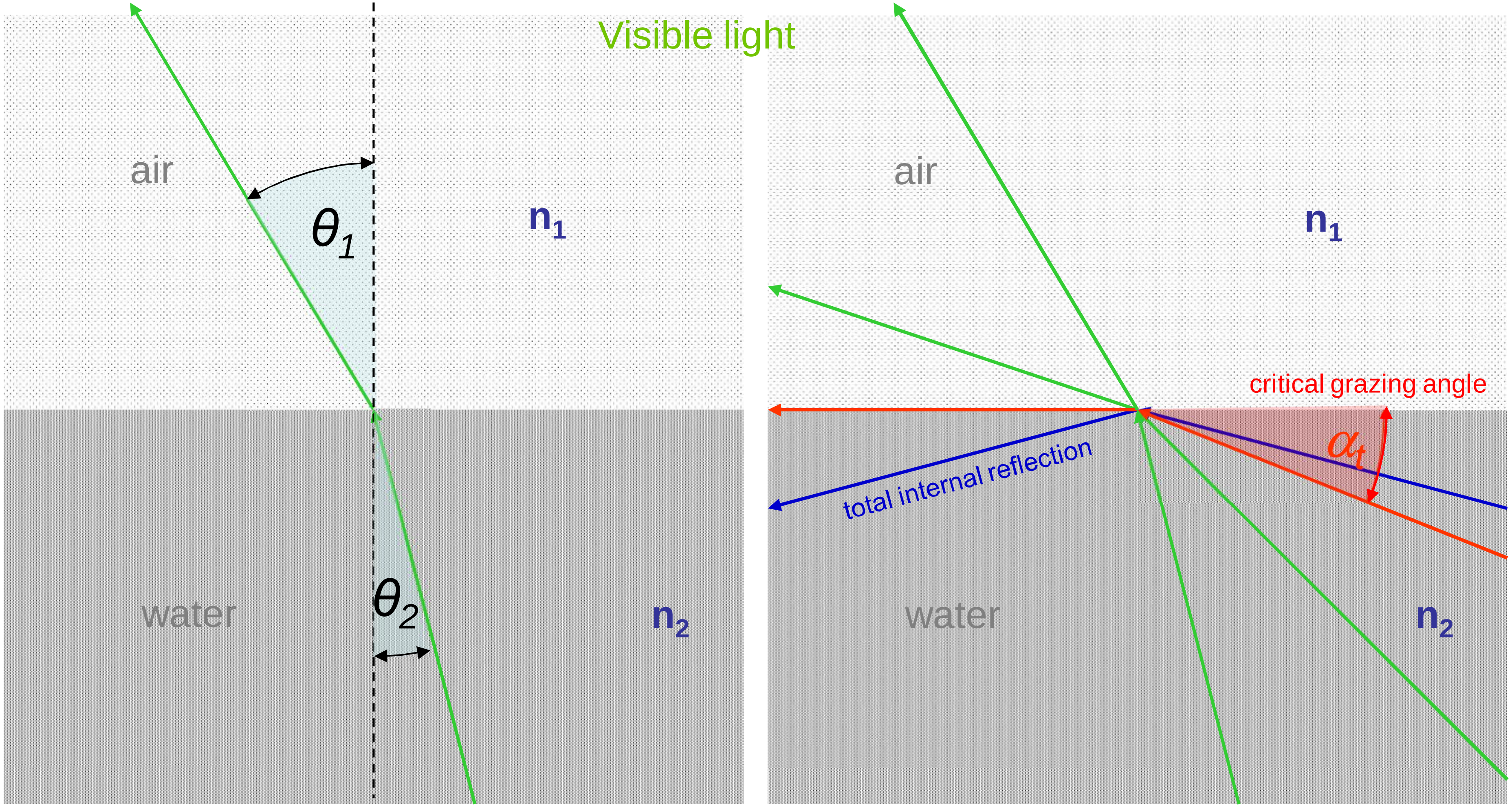




Index of Refraction and Total Internal Reflection

Snell's law: $\mathbf{n_1 \sin \theta_1 = n_2 \sin \theta_2}$

$\rightarrow \mathbf{\cos \alpha_t = n_1 / n_2}$



Index of Refraction and Grazing Angle

Complex refractive index *n*:

$$\mathbf{n = \underbrace{1 - \overset{\text{phase change}}{\delta}} - i\overset{\text{absorption}}{\beta}}$$

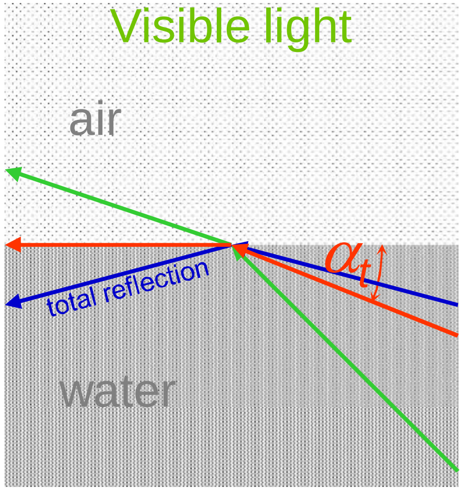
slightly less than 1
for X-rays in matter

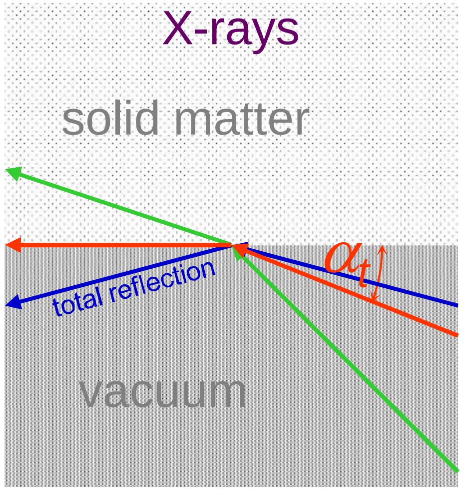
exactly 1 in vacuum

Critical grazing angle α_t:

$$\cos \alpha_t = 1 - \delta \quad \textit{(Snell's law)}$$

$$\text{for } \delta \ll 1: \quad \alpha_t = \sqrt{2\,\delta}$$





from theoretical atomic physics:

$$\delta \sim E^{-2} \qquad \delta \sim Z$$

$$\rightarrow \underbrace{\alpha_t \sim E^{-1} \qquad \alpha_t \sim \sqrt{Z}}$$

for practical use:

$$\alpha_t \approx 69\,\sqrt{\rho}\,/\,E$$

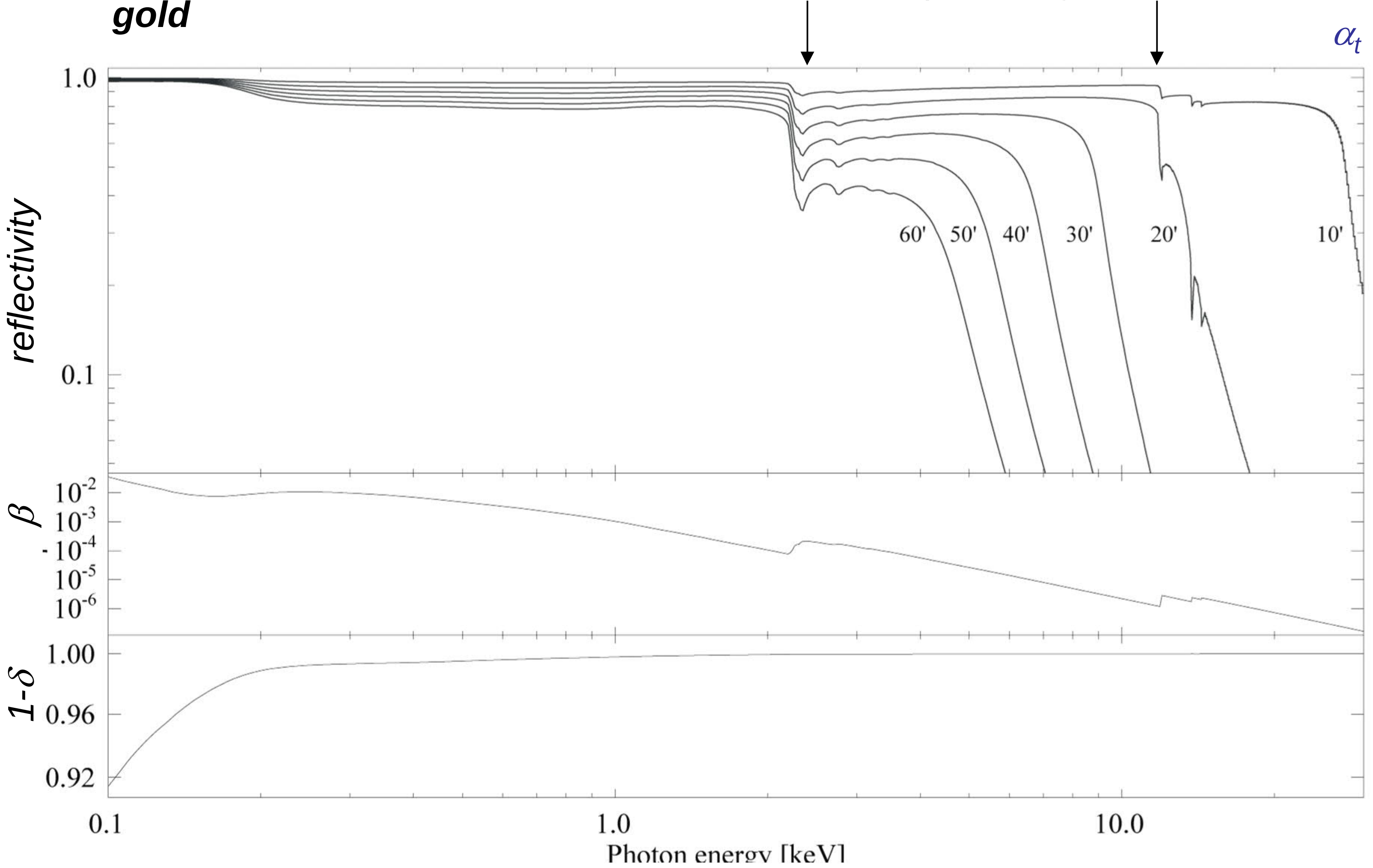
α_t in arc minutes
E in keV
ρ in g/cm^3

Optical Constants

gold

absorption edges

$\alpha_t \sim E^{-1}$

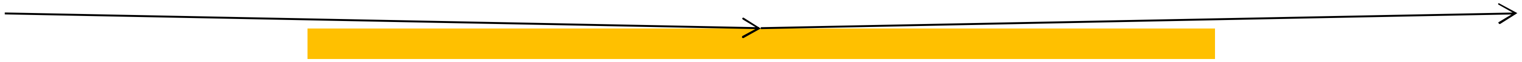


from http://henke.lbl.gov/optical_constants/

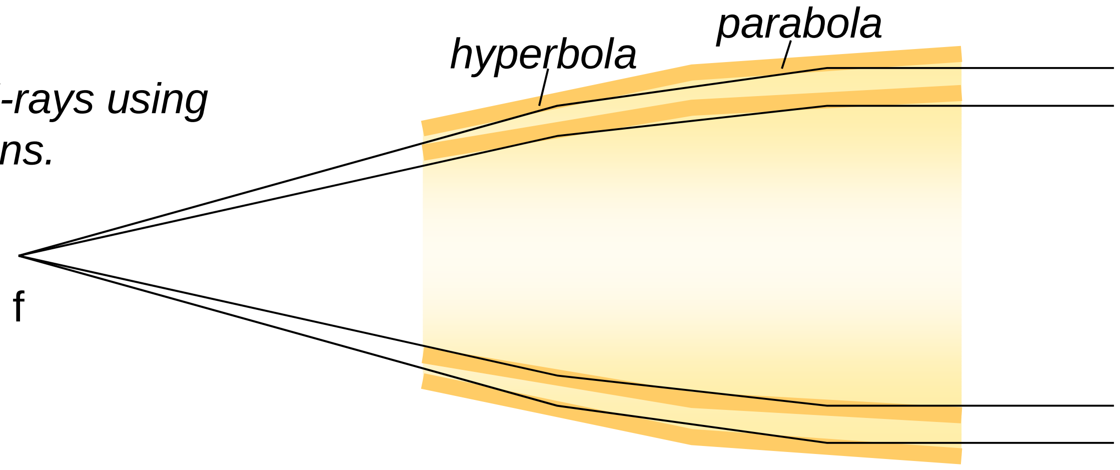
2.1. Grazing Incident Telescopes

- *Wolter Type Optics (I, II, III)*
- *Modified Wolter Optics*

Grazing Incidence Telescopes

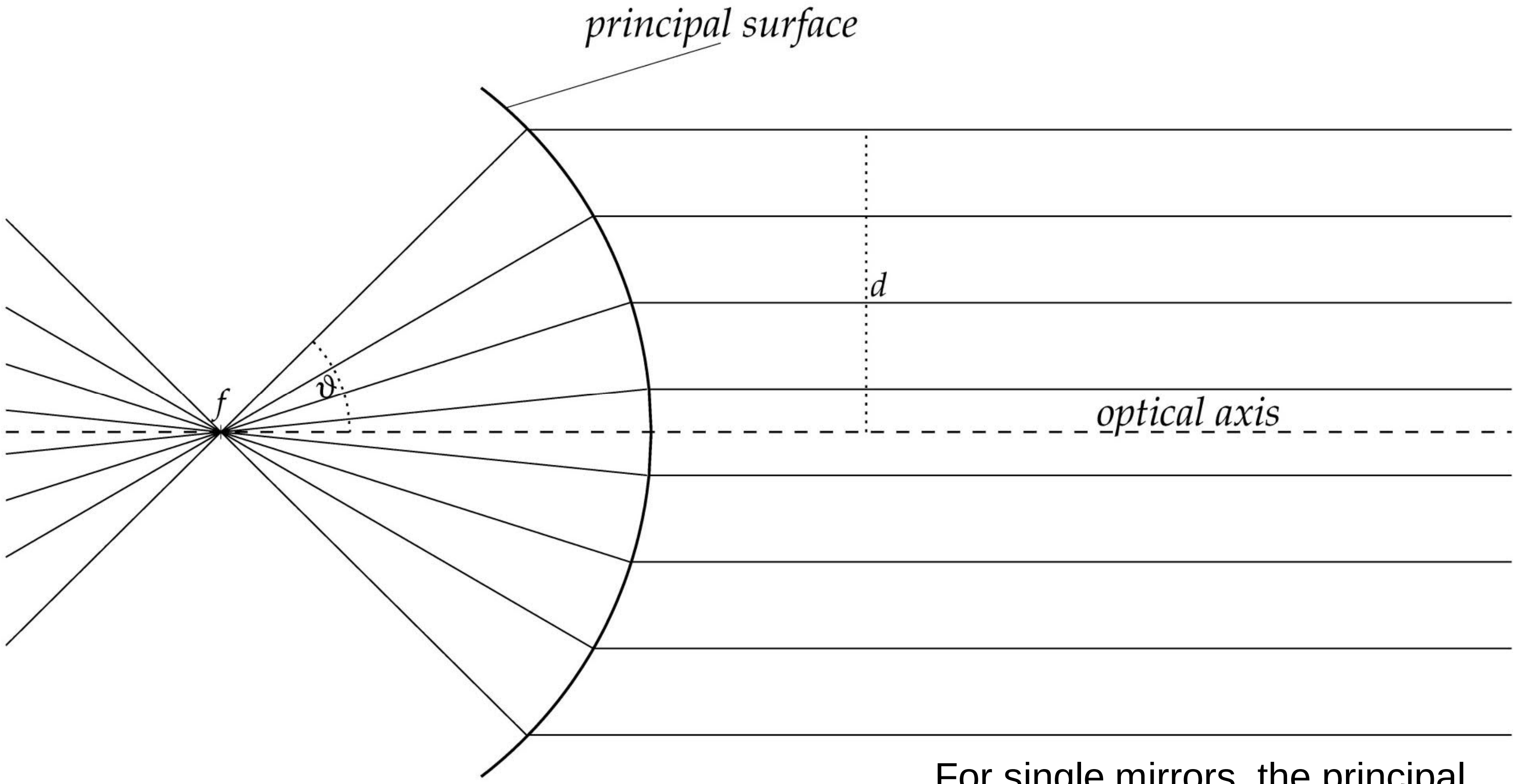


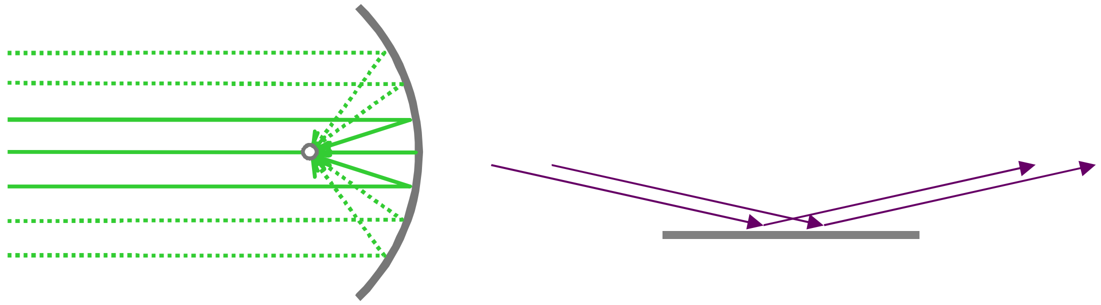
Wolter telescopes focus X-rays using grazing incidence reflections.



Abbe‘s Sine Condition

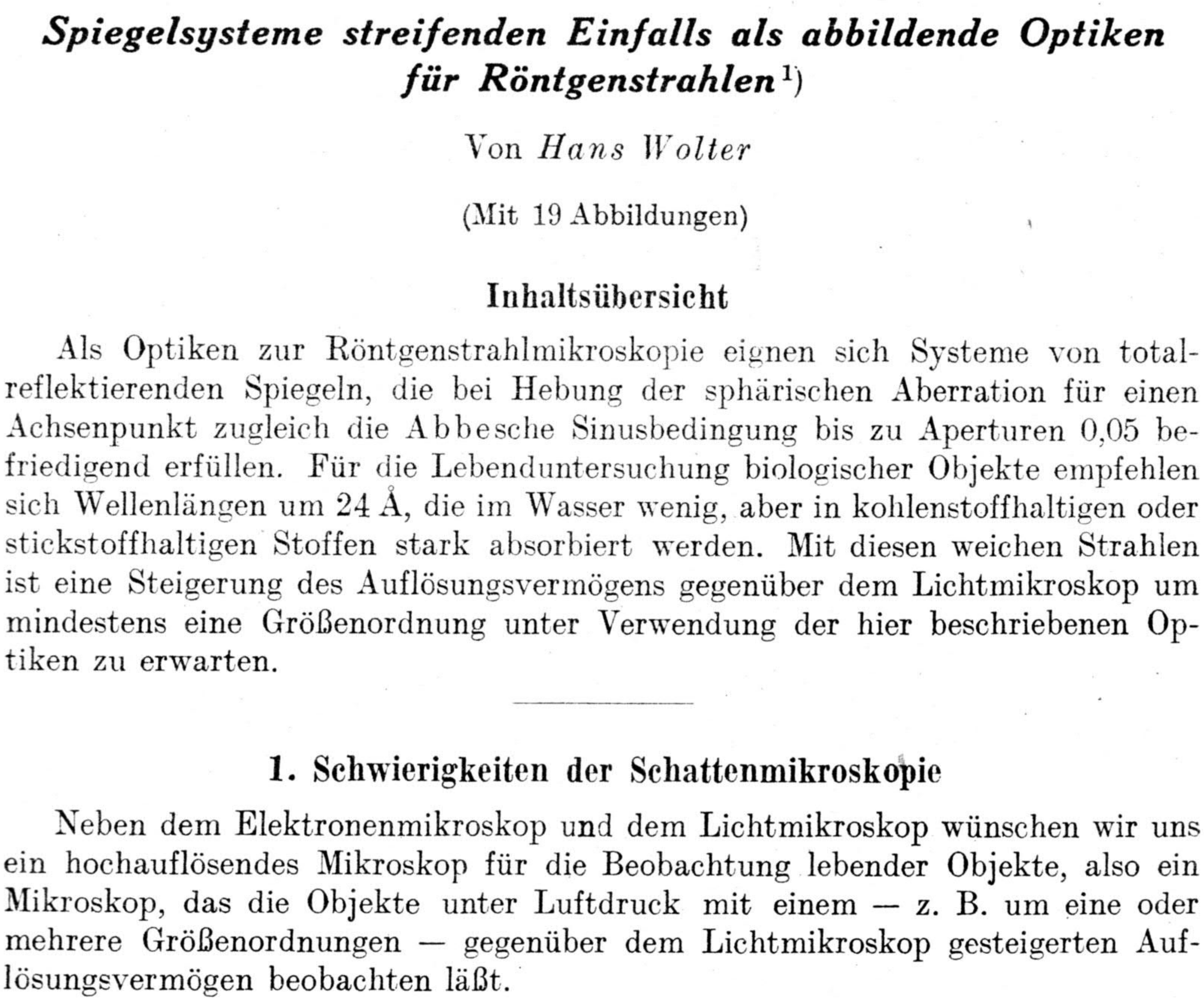
$$d\,/\,\sin\vartheta = \mathrm{f}$$





For single mirrors, the principal surface of is always identical to the mirror surface itself.
That means that the sine condition is approximately satisfied only if the reflection is almost perpendicular to the mirror‘s surface.

Wolter‘s Publication in 1952 (Annalen der Physik)



*Spiegelsysteme streifenden Einfalls als abbildende Optiken für Röntgenstrahlen*1)

Von *Hans Wolter*

(Mit 19 Abbildungen)

Inhaltsübersicht

Als Optiken zur Röntgenstrahlmikroskopie eignen sich Systeme von totalreflektierenden Spiegeln, die bei Hebung der sphärischen Aberration für einen Achsenpunkt zugleich die Abbesche Sinusbedingung bis zu Aperturen 0,05 befriedigend erfüllen. Für die Lebenduntersuchung biologischer Objekte empfehlen sich Wellenlängen um 24 Å, die im Wasser wenig, aber in kohlenstoffhaltigen oder stickstoffhaltigen Stoffen stark absorbiert werden. Mit diesen weichen Strahlen ist eine Steigerung des Auflösungsvermögens gegenüber dem Lichtmikroskop um mindestens eine Größenordnung unter Verwendung der hier beschriebenen Optiken zu erwarten.

1. Schwierigkeiten der Schattenmikroskopie

Neben dem Elektronenmikroskop und dem Lichtmikroskop wünschen wir uns ein hochauflösendes Mikroskop für die Beobachtung lebender Objekte, also ein Mikroskop, das die Objekte unter Luftdruck mit einem — z. B. um eine oder mehrere Größenordnungen — gegenüber dem Lichtmikroskop gesteigerten Auflösungsvermögen beobachten läßt.

3. Annähernde Erfüllung der Abbeschen Sinusbedingung durch ein Zweispiegelsystem

Ein System aus 2 sich schneidenden Spiegelflächen hat eine Knickfläche, die so durch die Schnittkante der beiden Spiegel geht, wie Abb. 5 das andeutet. Um mit 2 Spiegeln bei streifendem Einfall alle achsenparallelen Strahlen in einem Punkt zu sammeln, verwenden wir ein Rotationsparaboloid (Abb. 6) und ein

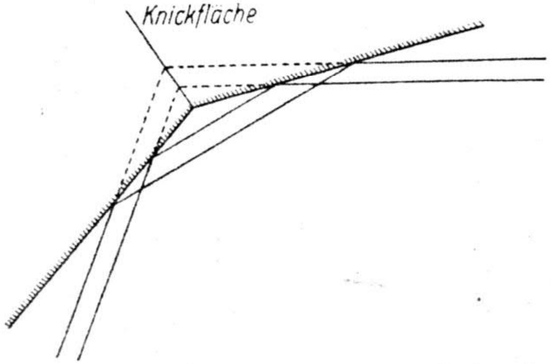


Abb. 5. Knickfläche bei zwei Spiegeln

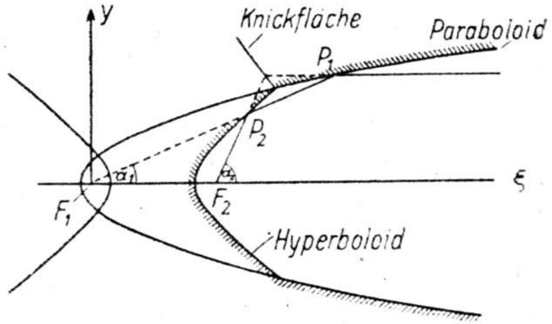


Abb. 6. Paraboloid und Hyperboloid in konfokaler Lage als Spiegelsystem für streifenden Einfall

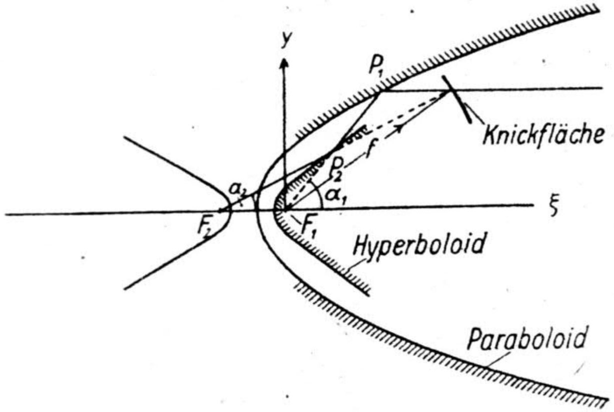


Abb. 15. Spiegelsystem 2. Art

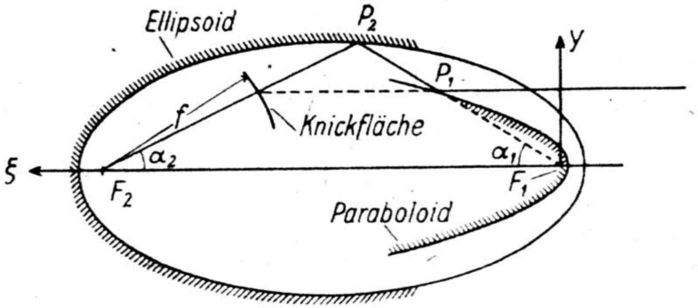
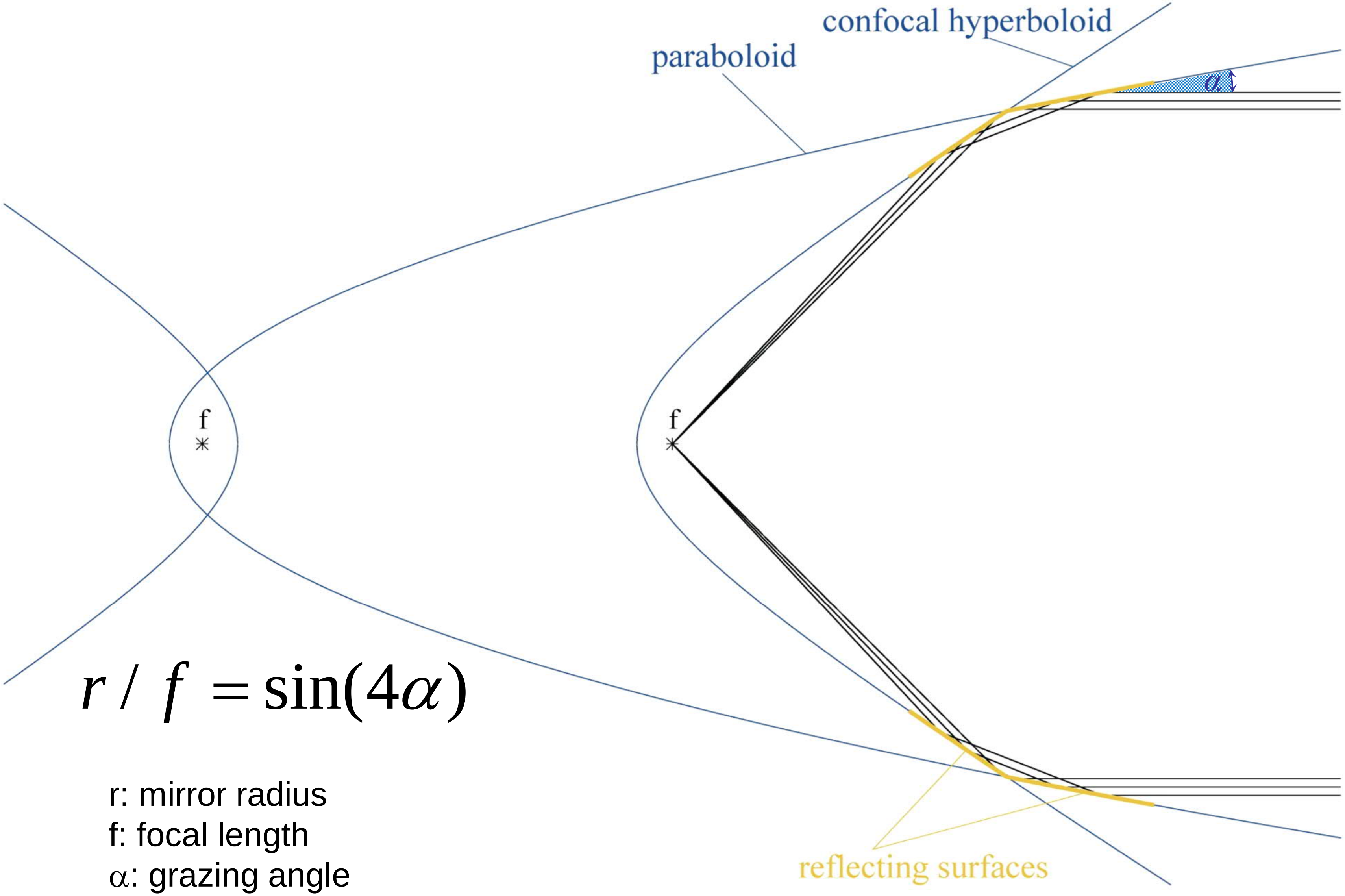


Abb. 16. Spiegelsystem 3. Art

Wolter I Design



$$r / f = \sin(4\alpha)$$

r: mirror radius
f: focal length
α: grazing angle

Modified Wolter Optics: Wolter-Schwarzschild, Wide Field Imager

Mathematical sequence to describe Wolter optics and modifications:

Equation for parabolic mirror:

$$r_a^2 = r_0^2 \cdot \sum_{i=0}^{1} a_i \cdot \left(\frac{x - x_0}{r_0} \right)^i \quad \text{with} \quad a_0 = 1, \quad a_1 = 2 \cdot \tan\alpha \quad \textit{for Wolter optics}$$

Equation for hyperbolic mirror:

$$r_b^2 = r_0^2 \cdot \sum_{i=0}^{2} b_i \cdot \left(\frac{x - x_0}{r_0} \right)^i \quad \text{with} \quad b_0 = 1, \quad b_1 = 2 \cdot \tan\beta, \quad b_2 = \frac{2 \cdot r_0 \cdot \tan\beta}{f + r_0 \cdot \cot(2 \cdot \alpha)} \quad \textit{for Wolter optics}$$

The Wolter systems satisfy Abbe's sine condition approximately only near the optical axis and near the intersection of the primary and secondary.

Modified equations were also developed which satisfy the Abbe sine condition strictly and hence exhibit no comatic aberration. These are called Wolter-Schwarzschild designs.

Other modifications are proposed in order to optimize the PSF over the field-of-view.

equations from C. J. Burrows, R. Burg und R. Giacconi (APJ 1992, 392, 760)

2.2. Basic Telescope Parameters (for Wolter Telescopes)

- Focal Length f, Diameter (Radius r), Coating

$$r / f = \sin(4\alpha)$$

or

$$\alpha = 0.25 \times \arcsin(r / f)$$

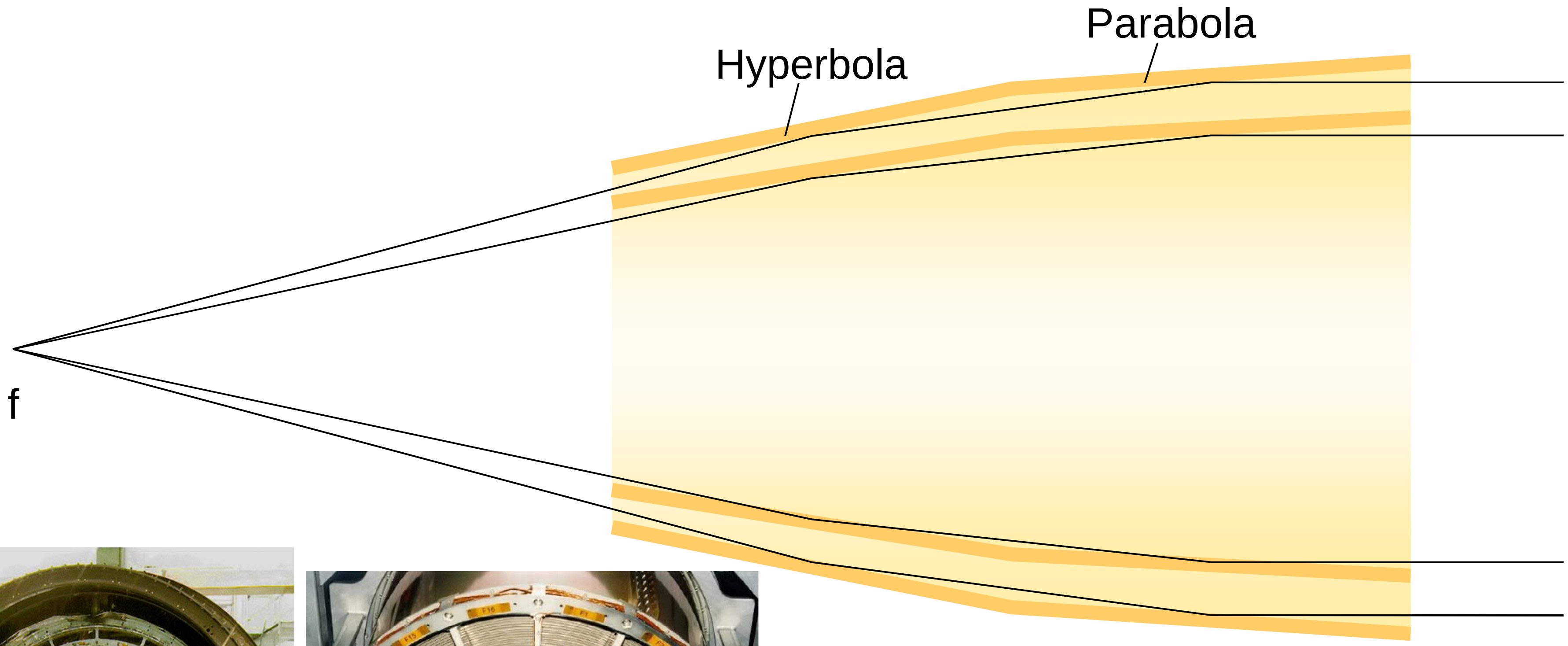
$$\alpha_t \approx 69 \sqrt{\rho} / E$$

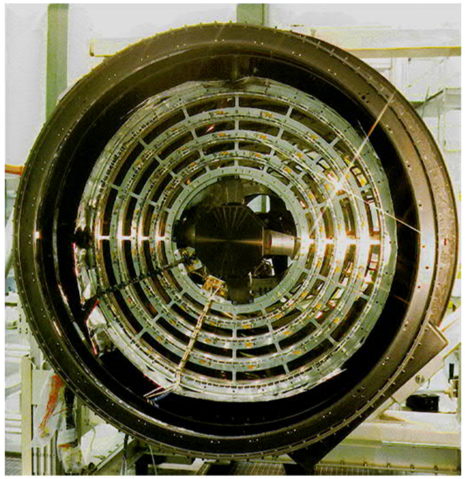
α_t *in arc minutes*
E in keV
ρ *in* g/cm^3

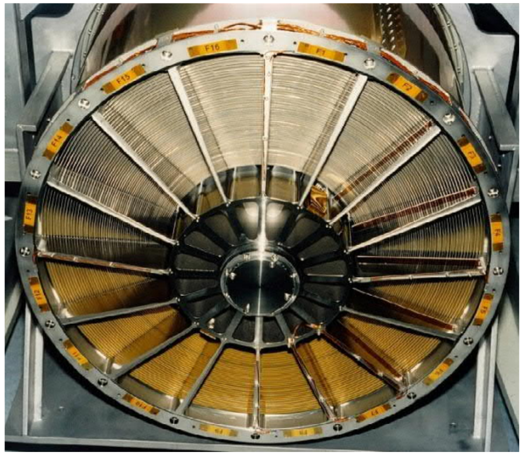
2.3. Design Options

- *Nesting of Mirror Shells*
- *Segmented Optics*
- *Multi-Optic Telescopes*

Nesting of Wolter 1 Mirror Shells



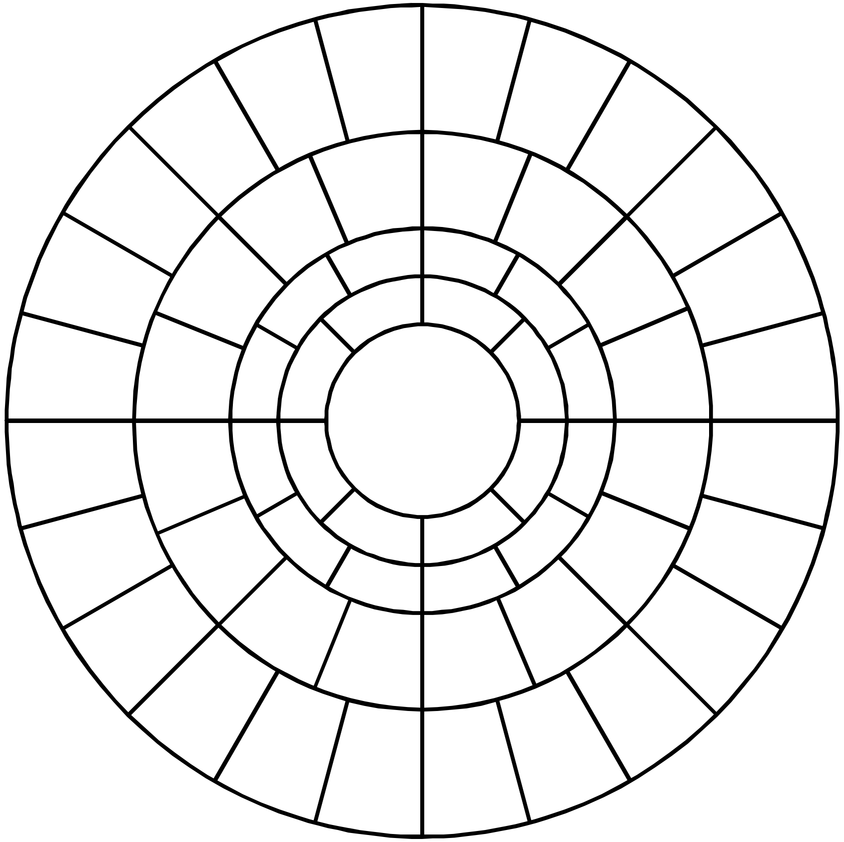


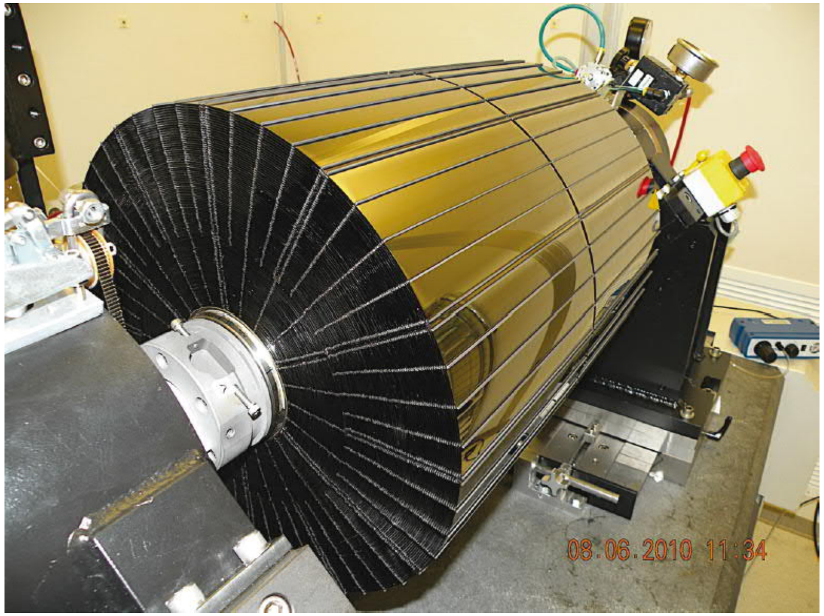


$$a \approx 2\pi r \times l \sin \alpha$$

a: projected area of one shell
l: length of a mirror element
α: grazing angle

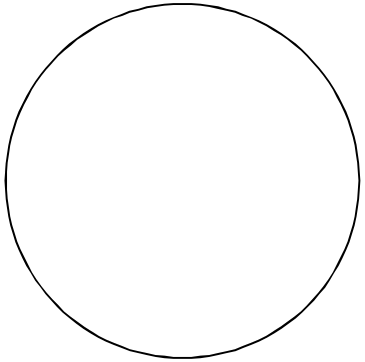
Segmented Wolter Mirrors

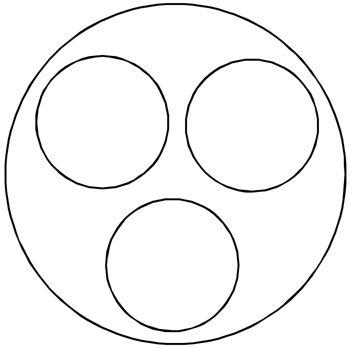


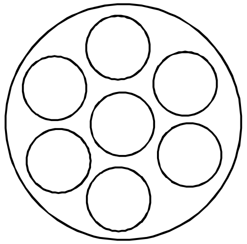


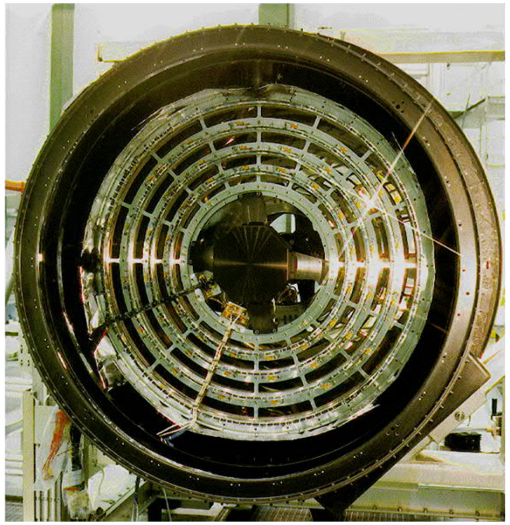
Example: NuSTAR

Multi-Optic Telescopes

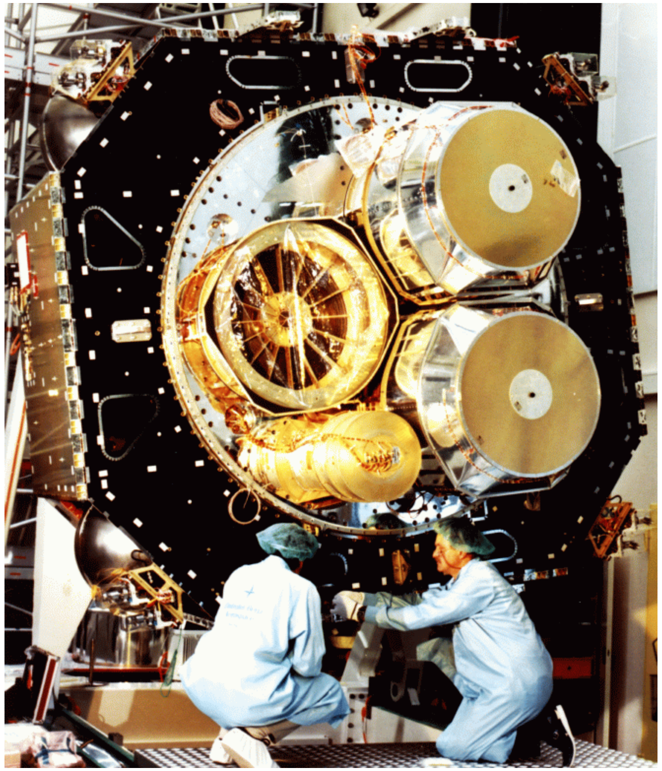




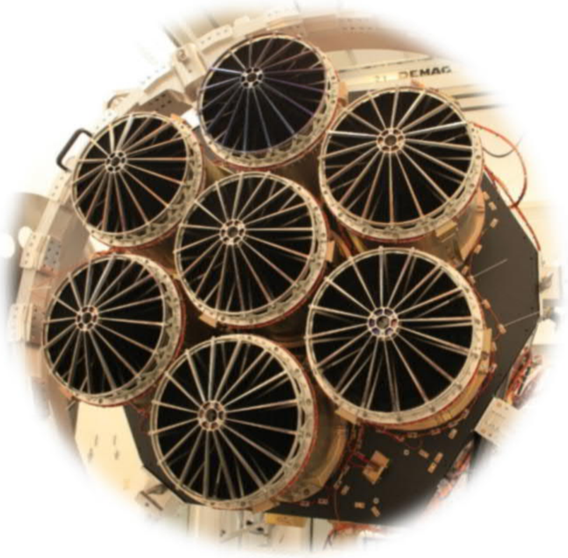




Example: ROSAT



Example: XMM-Newton

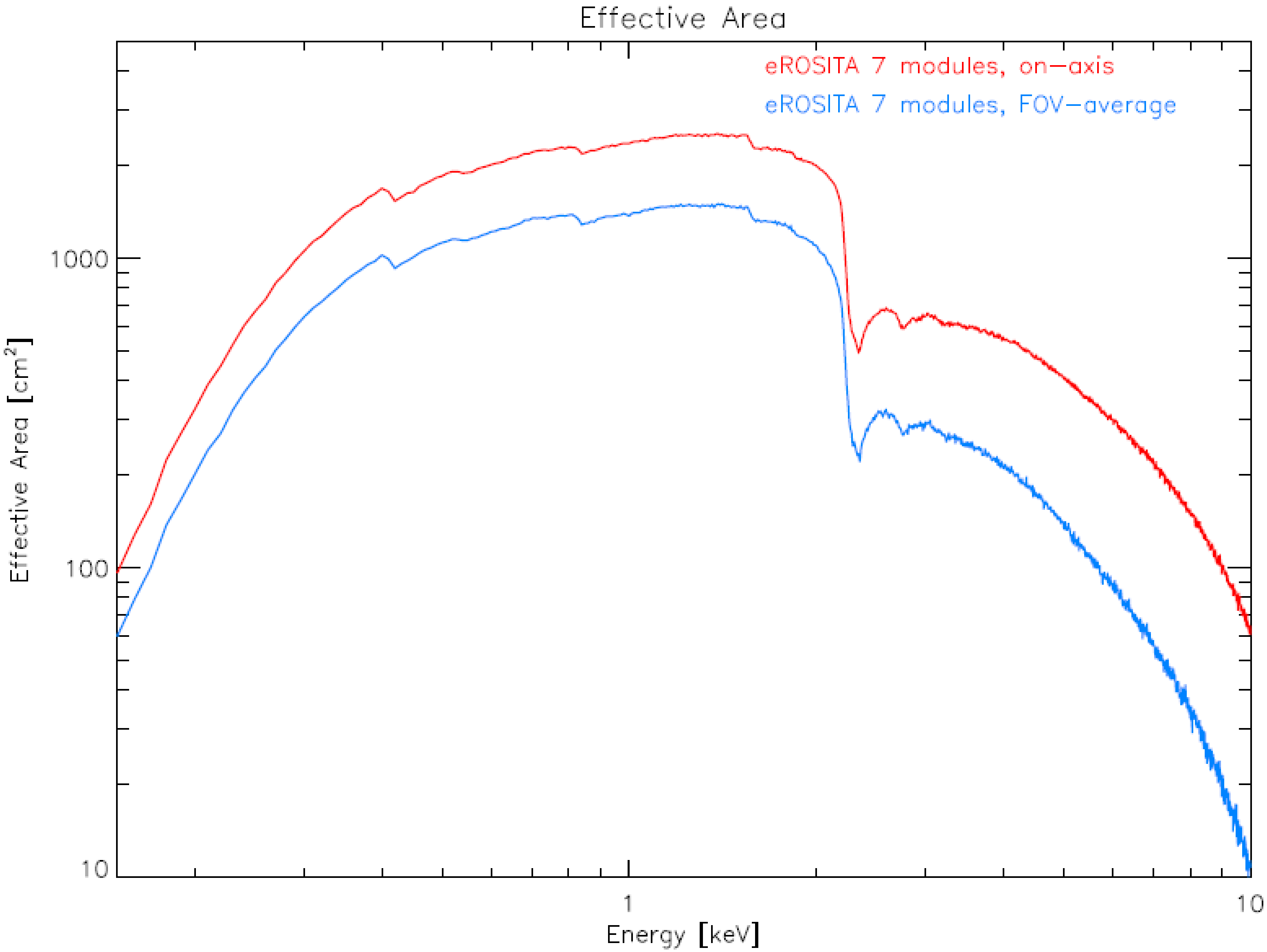


Example: eROSITA

2.4. Characteristics of X-Ray Telescopes

- *Effective Collecting Area*
- *Angular Resolution (Point-Spread Function)*
- *Surface Roughness (Micro-Roughness)*
- *Field-of-View: Vignetting and Off-Axis Blurring*
- *Straylight: Single Reflections (and how to prevent them)*

Effective Area

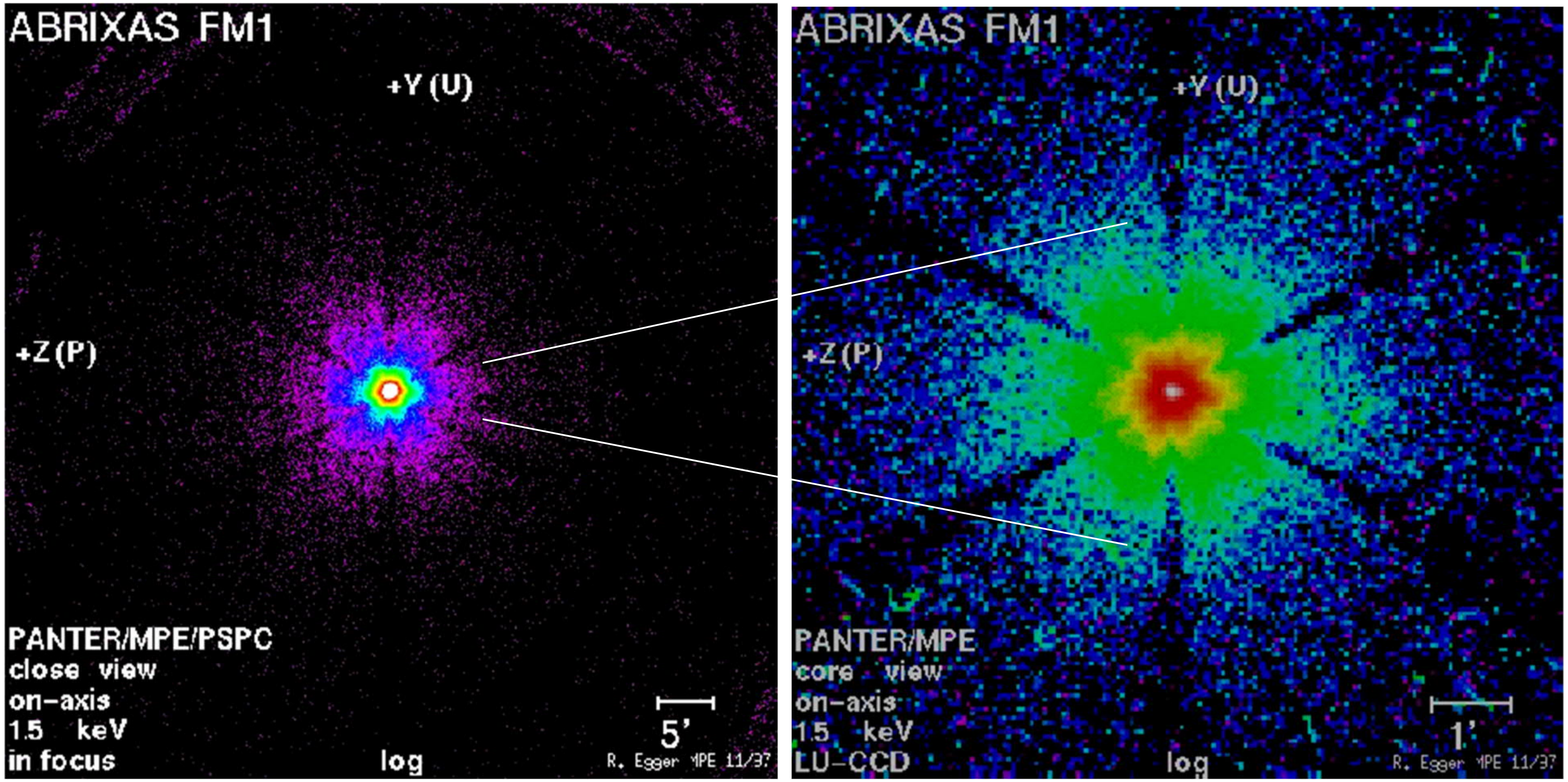


Point Spread Function (PSF)

The wings of the PSF are due to

- figure errors (lower spatial fequencies) → geometrical optics

- microroughness (higher spatial frequencies) → interference



Surface Roughness (Micro-Roughness)

A: Fractional energy in core: $A = e^{-(2k\,\sigma \sin\alpha)^2}$

B: Total integrated scatter (TIS): $B = 1 - A \rightarrow B = (2k\,\sigma \sin\alpha)^2$ *for small B*

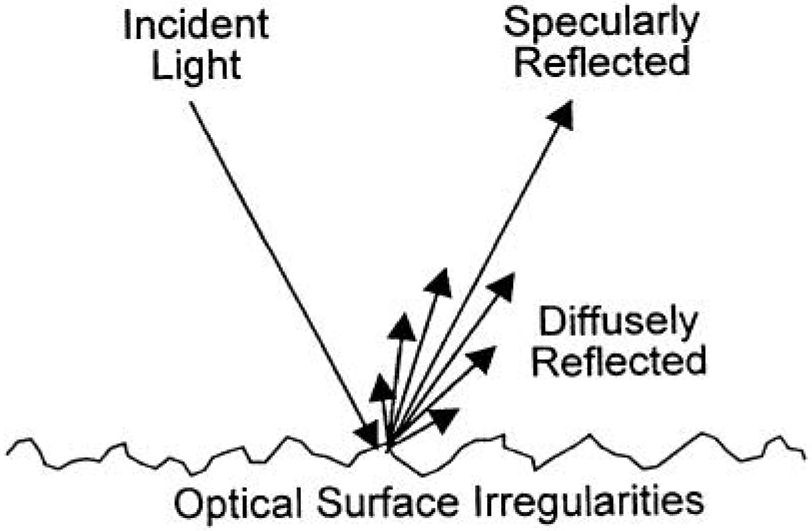


Figure 3. Optical surface irregularities result in both specularly reflected and diffusely reflected light.

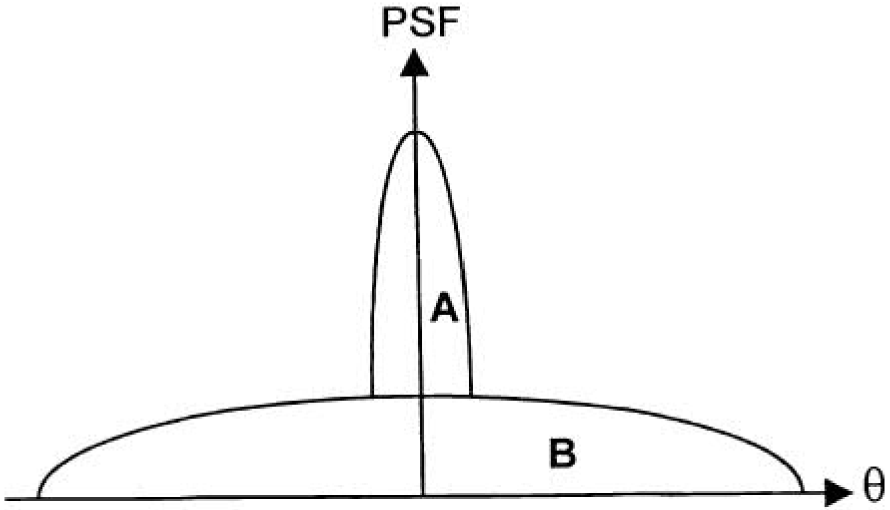
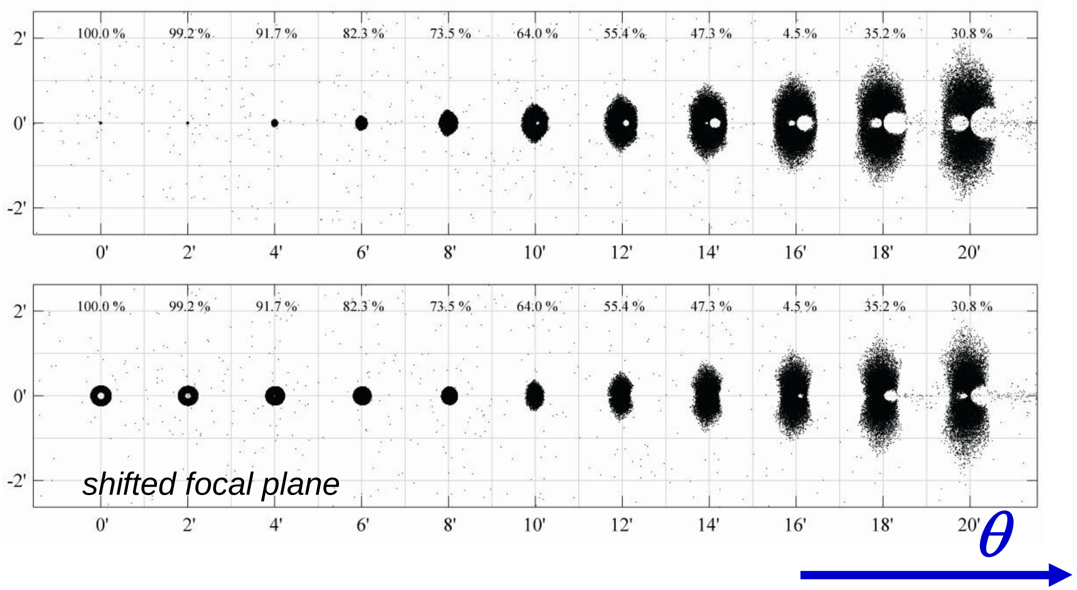


Figure 4. The image of a point source consists of a narrow image core surrounded by a scattered halo.

From J.E.Harvey et al., SPIE proceedings 3447

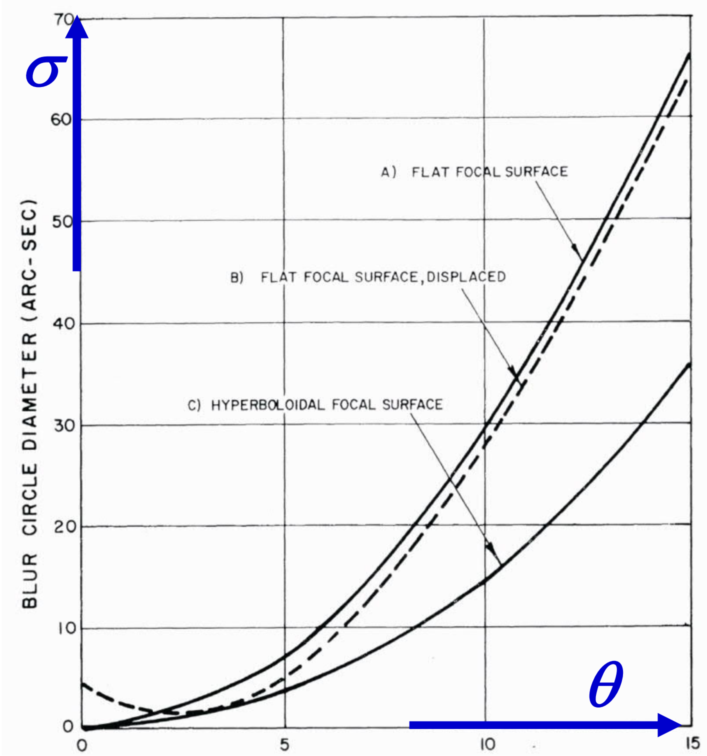
Off-Axis Blurring

and Vignetting

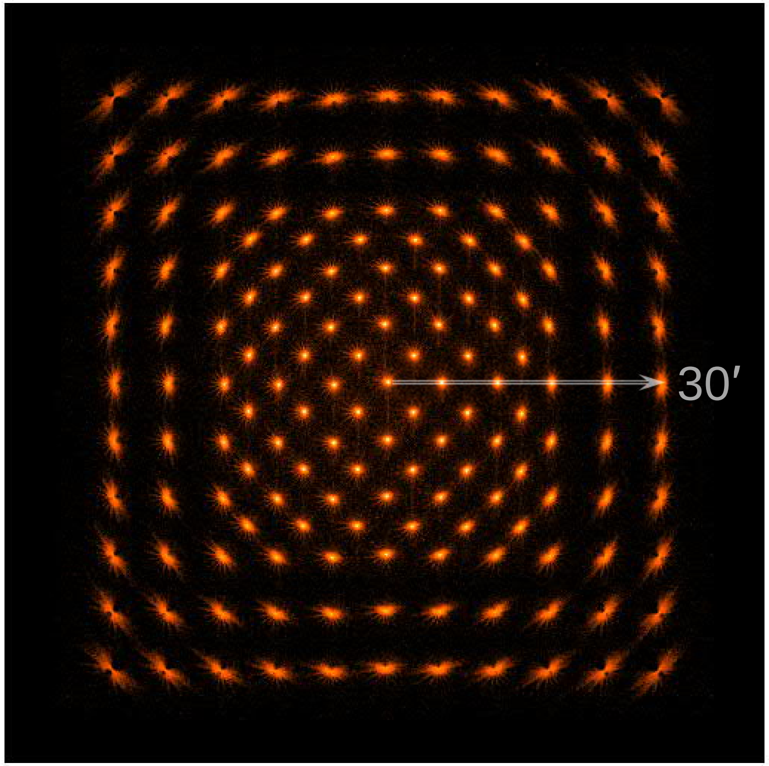


rms blur circle σ:

$$\sigma = 5 \times \frac{l}{f} \times \frac{\tan^2\theta}{\tan\alpha} + 4\tan\theta\tan^2\alpha$$

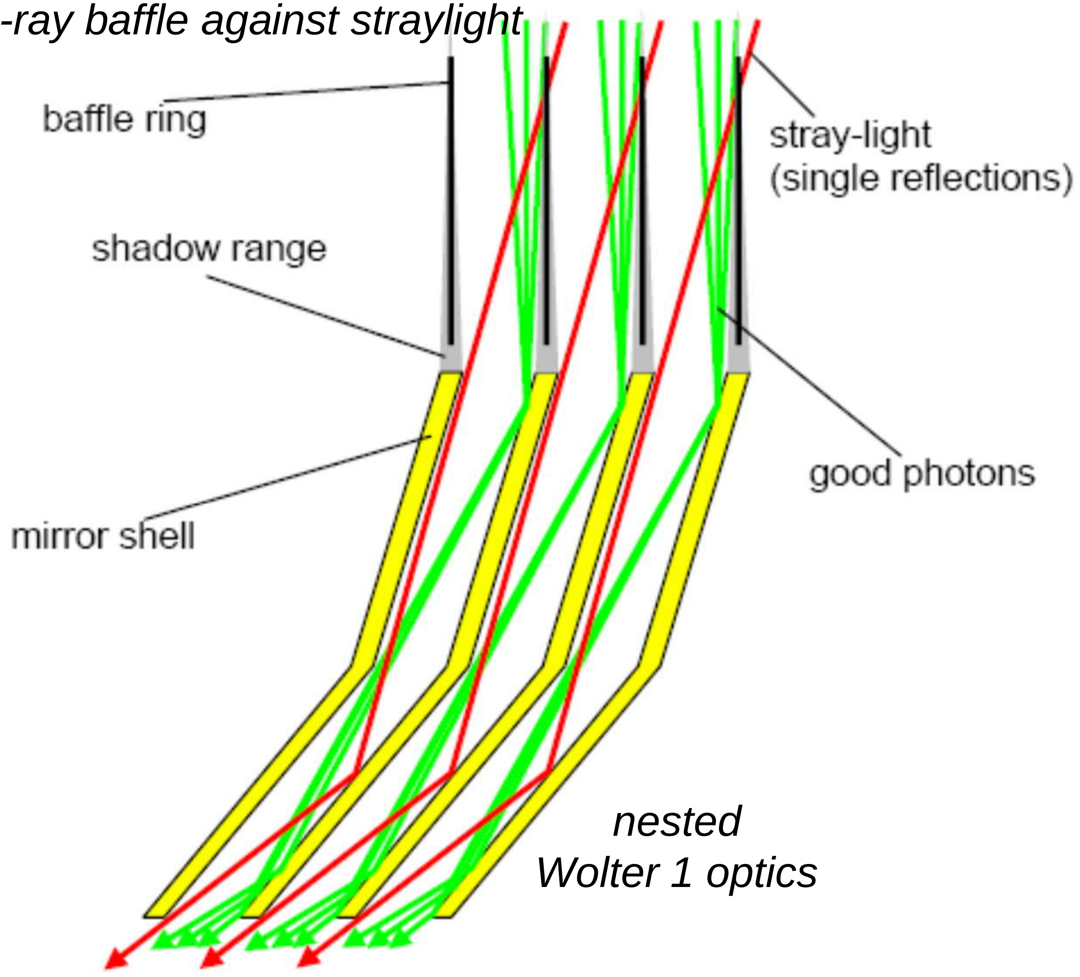


From R. Giacconi et al. 1969



Straylight: Single Reflections (and how to prevent them)

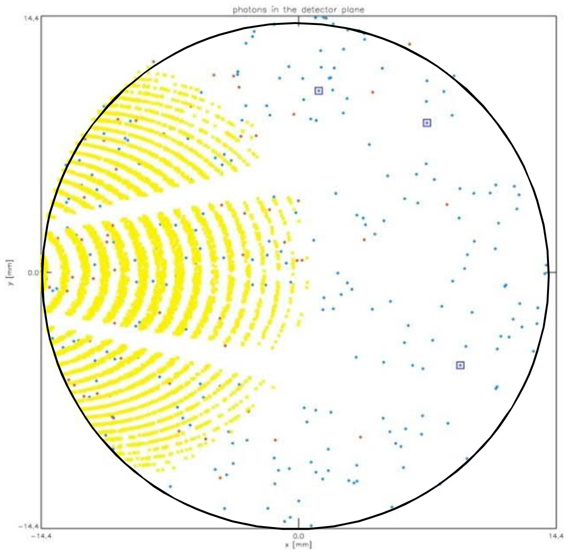
X-ray baffle against straylight



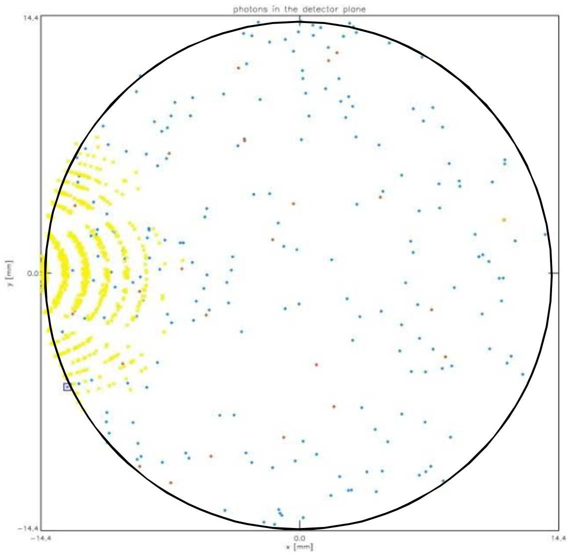
nested
Wolter 1 optics

source 1° off-axis

without baffle

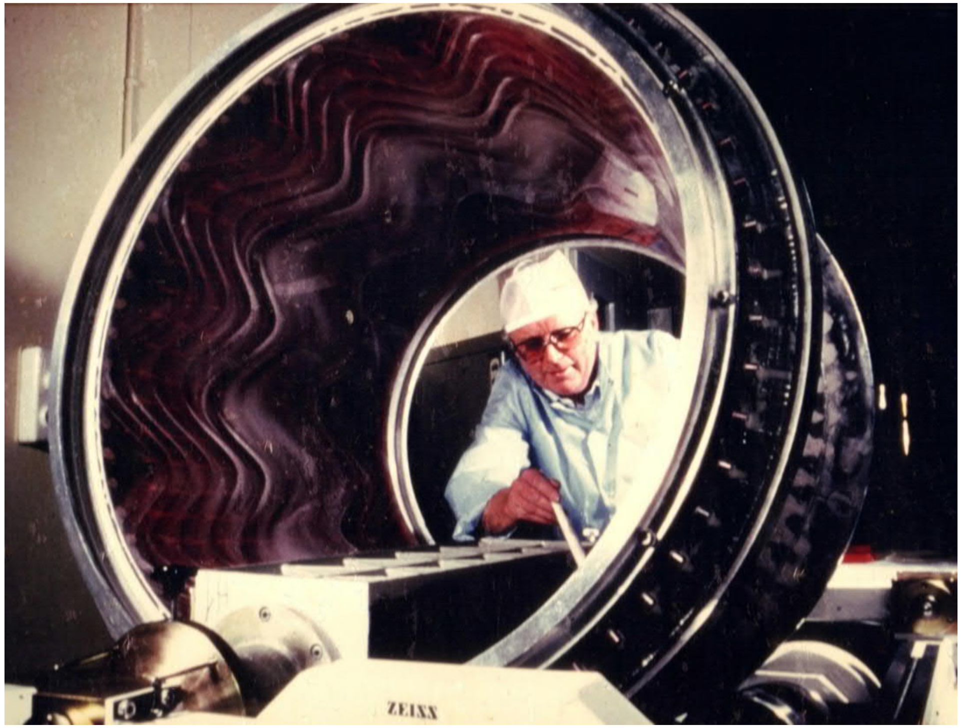


with baffle

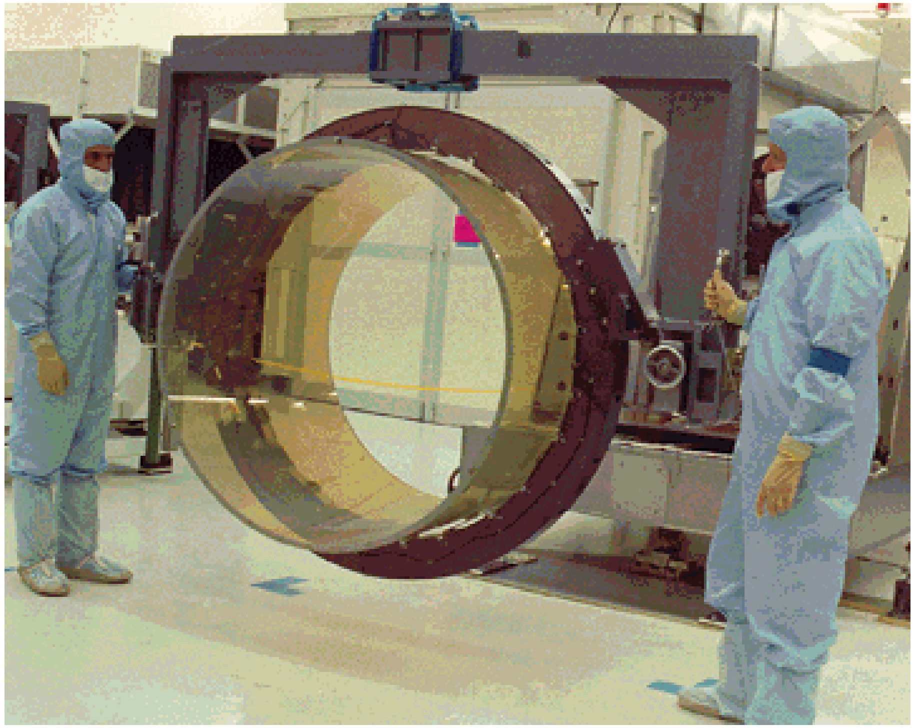


3.1. Zerodur and Quartz Mirrors

X-Ray Mirrors made of polished Zerodur: ROSAT and Chandra



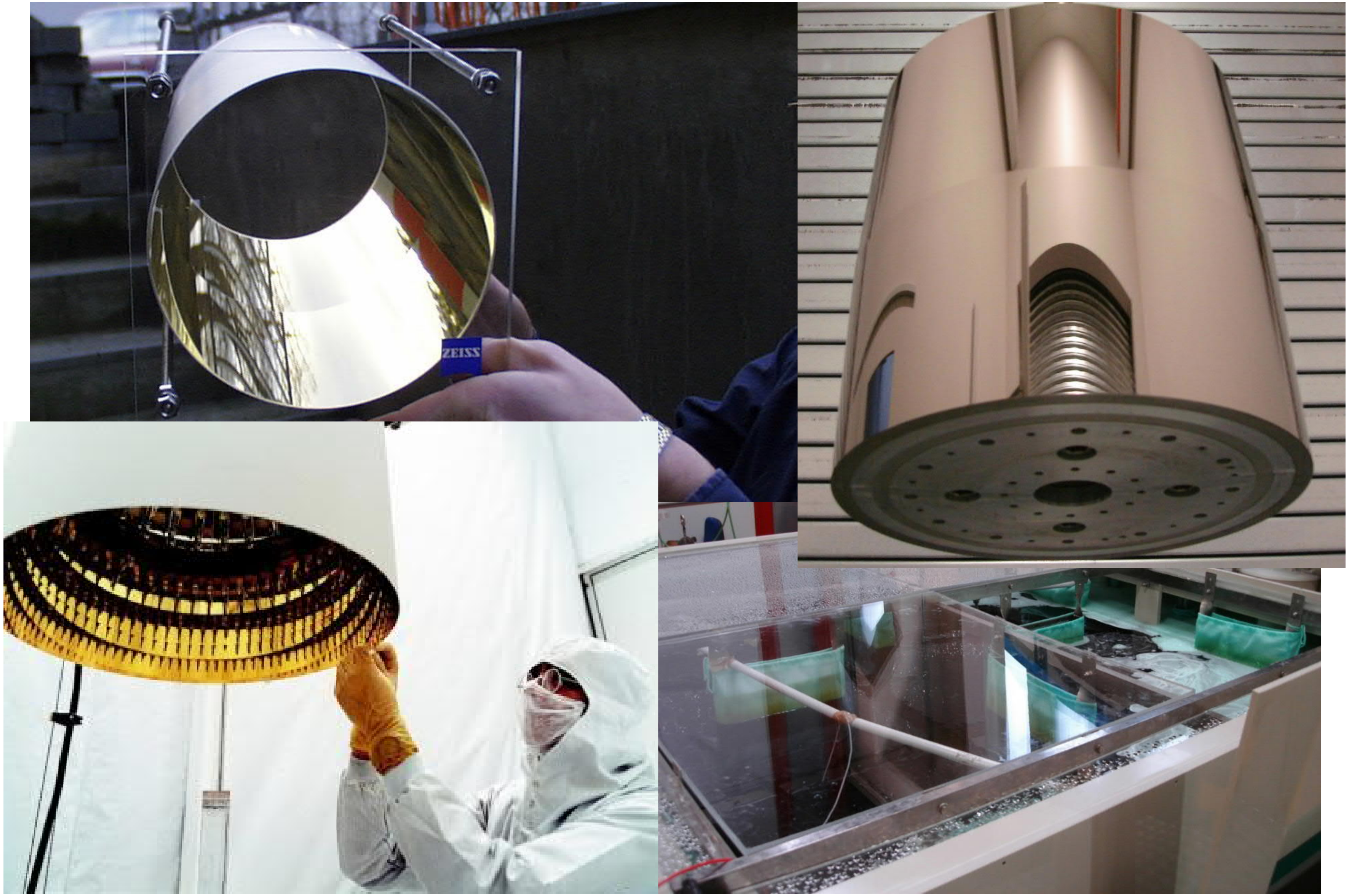
ROSAT X-ray mirror (1 of 4)



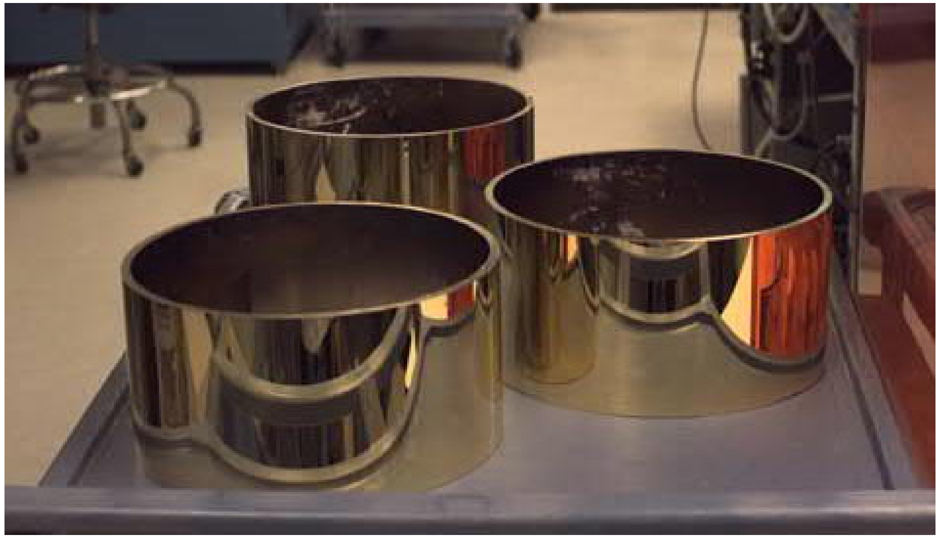
Chandra X-ray mirror (1 of 4)

3.2. Nickel Replication (Electroforming)

- *Super-Polished Mandrels*
- *Coating*
- *Galvanic Nickel Electroforming*



Segmented Foil Mirrors: Suzaku



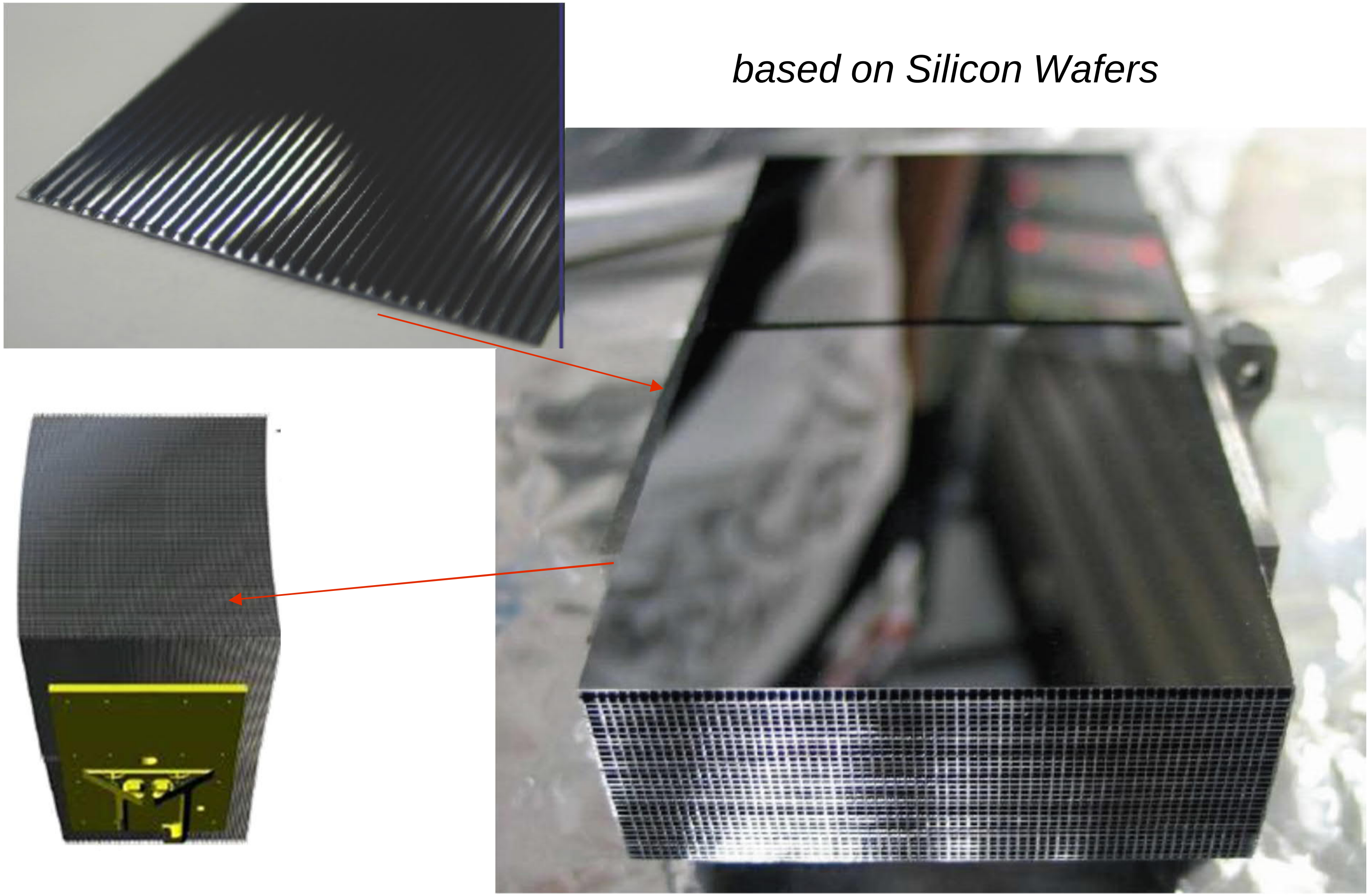
mandrels

replicated foil mirror segment

The Japanese X-ray satellite Suzaku and its precursers have telescopes made of aluminum foil segments which are replicated from glass mandrels using an epoxy layer in between.
The coating is transferred from the mandrel to the foils.

The European X-ray satellite EXOSAT had two Wolter telescopes made in a similar way but with a beryllium substrate instead of aluminum foil.

3.4. Silicon Pore Optics



based on Silicon Wafers

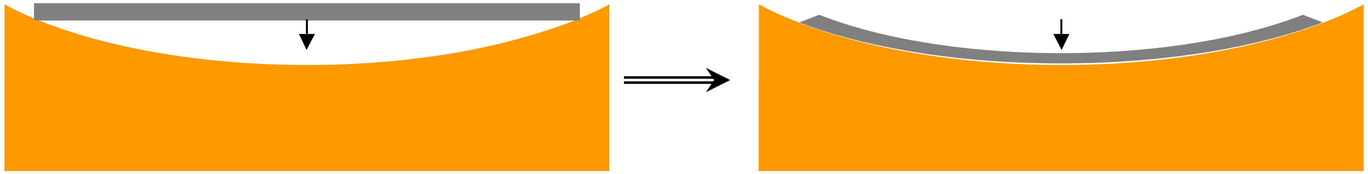
prototype pore optics element with 2 reflections

3.5. Slumped Glass

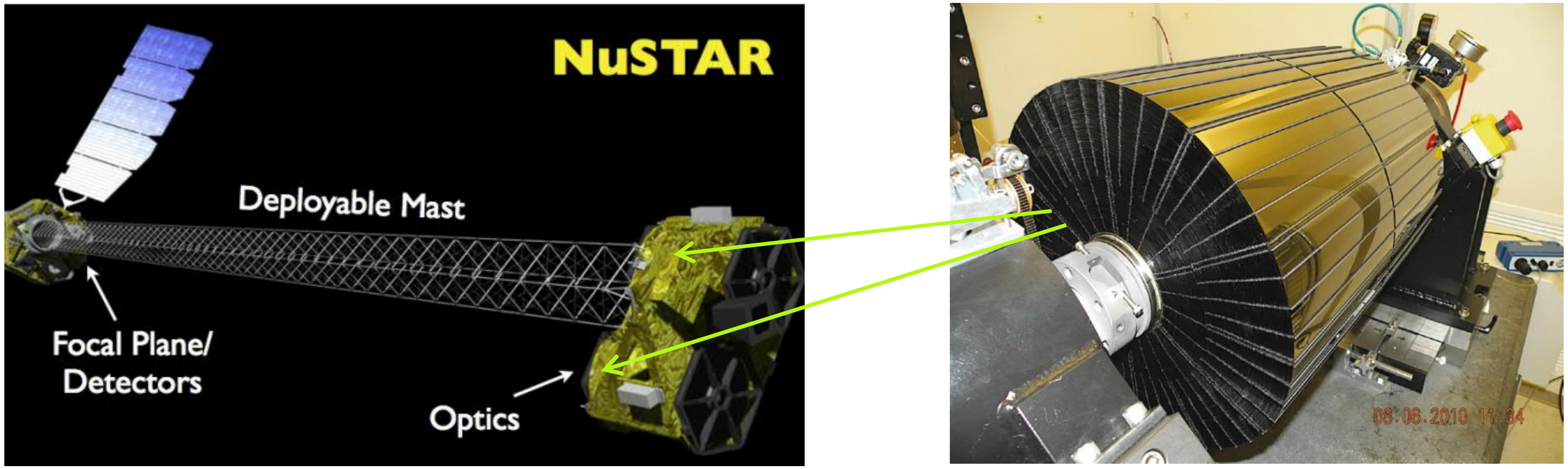
Technique:

Glass sheets are heated above the annealing point (but below the melting point), the lowering viscosity let them slump into a given mould.

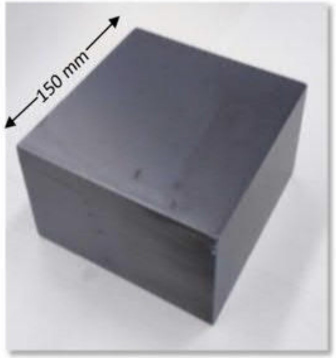
The glass used for this process has a micro-roughness which is already good for X-ray reflection.



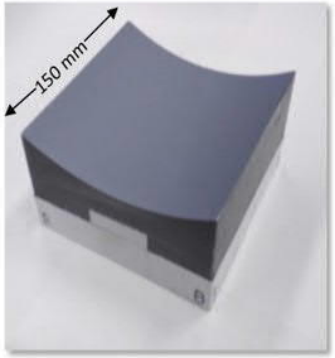
NuSTAR is the first X-ray satellite in orbit with telescopes made of slumped glass (angular resolution: ~50 arc seconds).



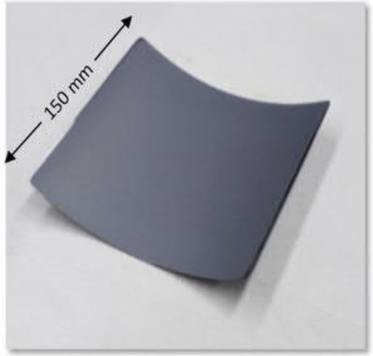
3.6. Polished Silicon Optics



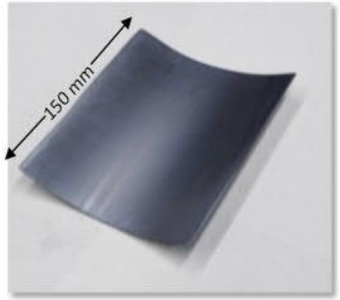
1. Mono-crystalline silicon block



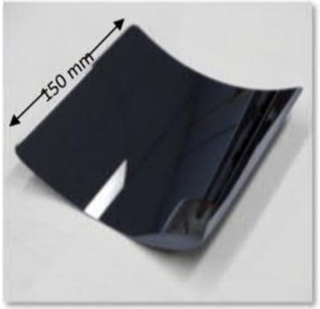
2. Conical form generated



3. Light-weighted substrate

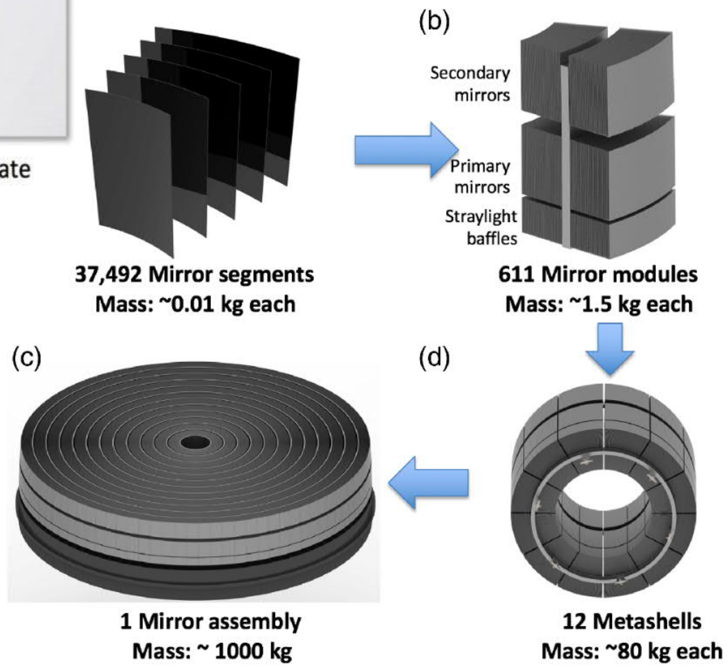


4. Etched substrate

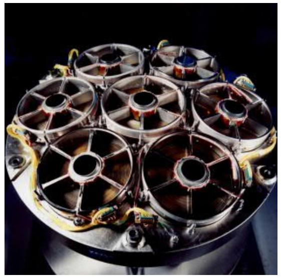


5. Polished mirror substrate

6. Trimmed mirror substrate

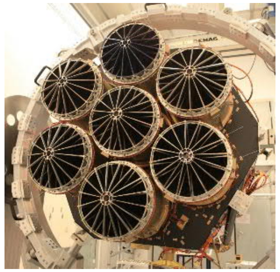


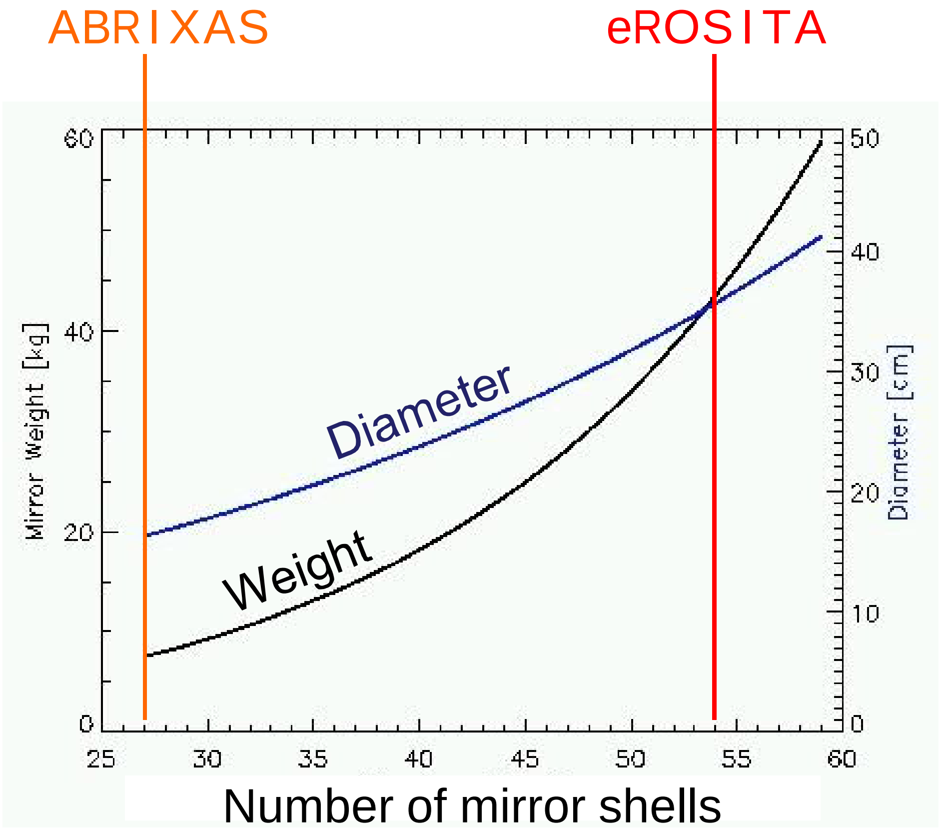
4.1. eROSITA Optics Design

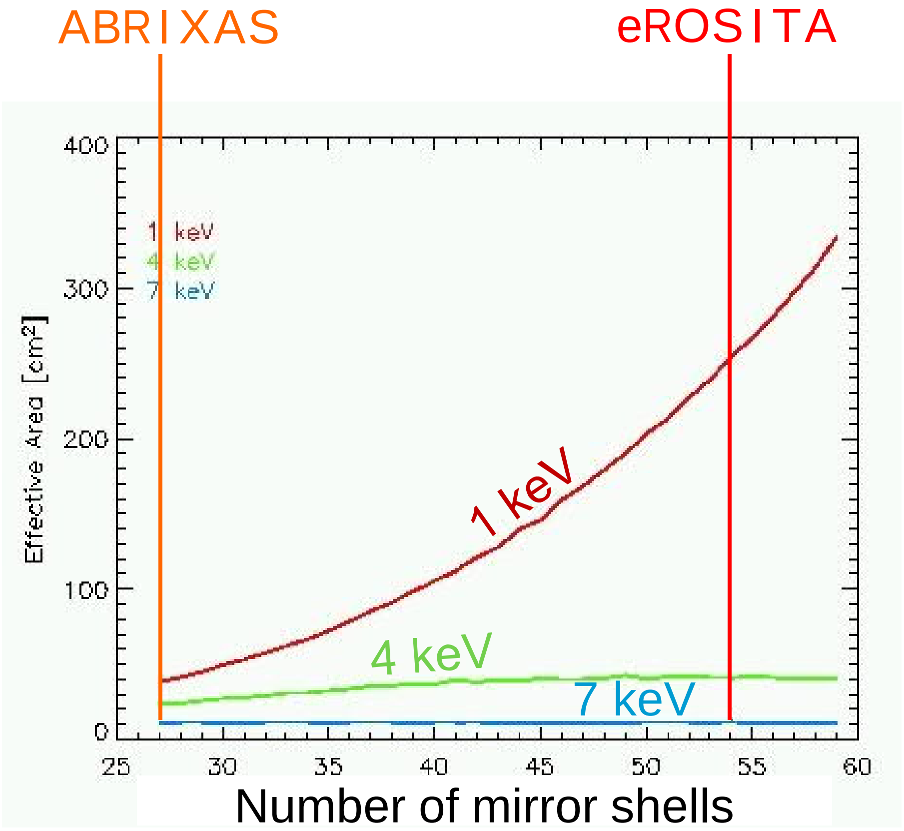


Mirror Design

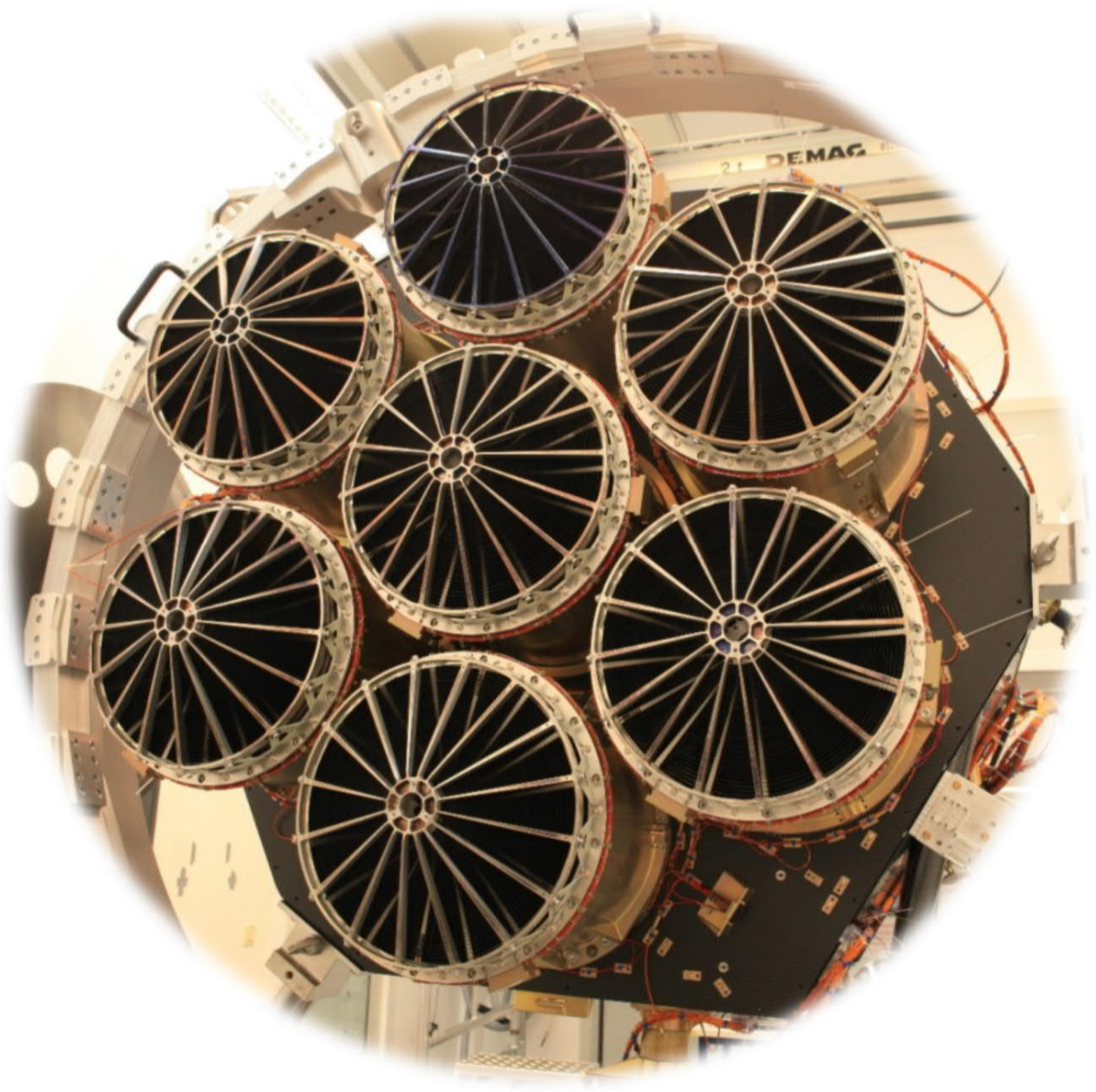
From ABRIXAS to eROSITA





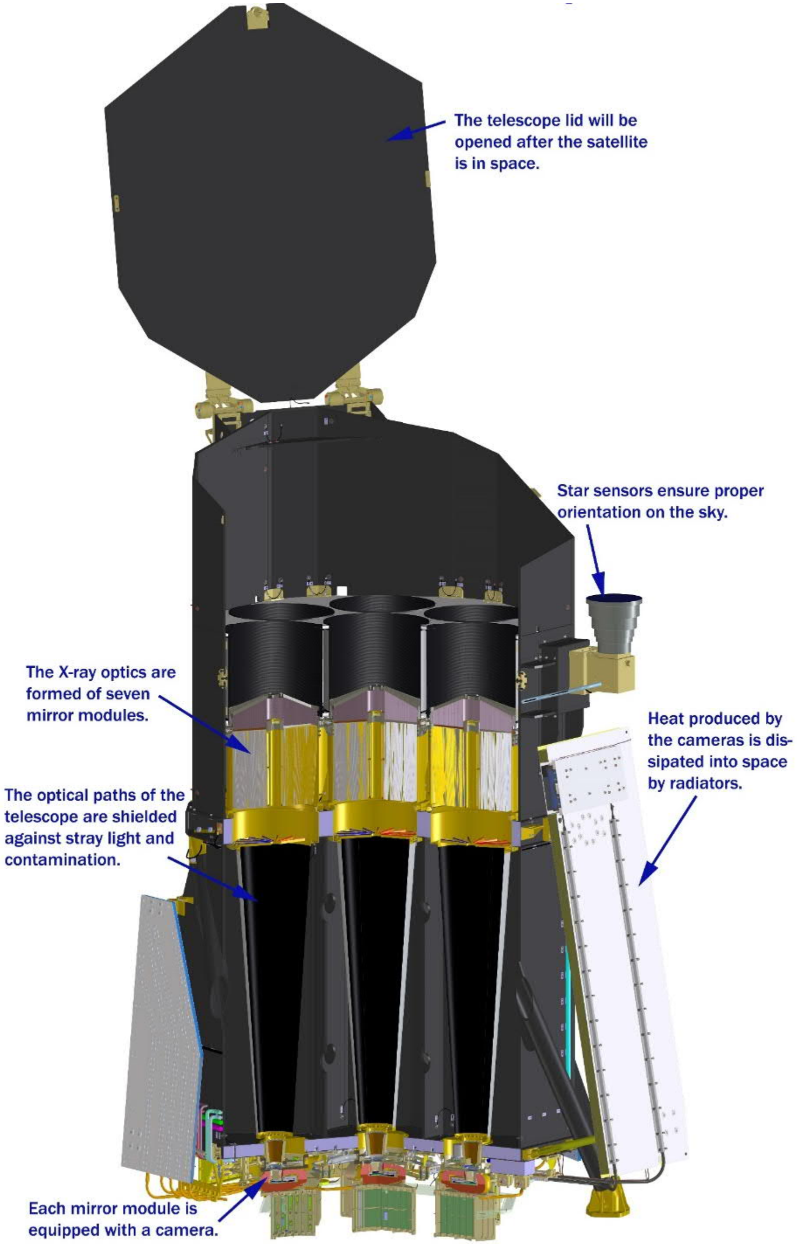


The X-Ray Telescope eROSITA with its 7 Modules



eROSITA’s X-ray telescope consists of 7 co-aligned mirror assemblies, each with 54 nested Wolter-1 electroformed mirror shells and an X-ray baffle made of concentric invar foils.

The X-Ray Telescope eROSITA



The telescope lid will be opened after the satellite is in space.

Star sensors ensure proper orientation on the sky.

The X-ray optics are formed of seven mirror modules.

Heat produced by the cameras is dissipated into space by radiators.

The optical paths of the telescope are shielded against stray light and contamination.

Each mirror module is equipped with a camera.

4.2. Development phase and Demonstrator Model

- *Mandrel polishing and refurbishment*
- *Galvanic Nickel Electroforming (based on XMM experience)*
- *Vertical optical bench for mirror shell integration*
- *X-ray tests*

Mandrels

Refurbished ABRIXAS mandrels

Polishing of new mandrels at Media Lario on on a Zeeko polishing machine

Early 2007: First Mirror Replications
with refurbished ABRIXAS Mandrels #44 and #46

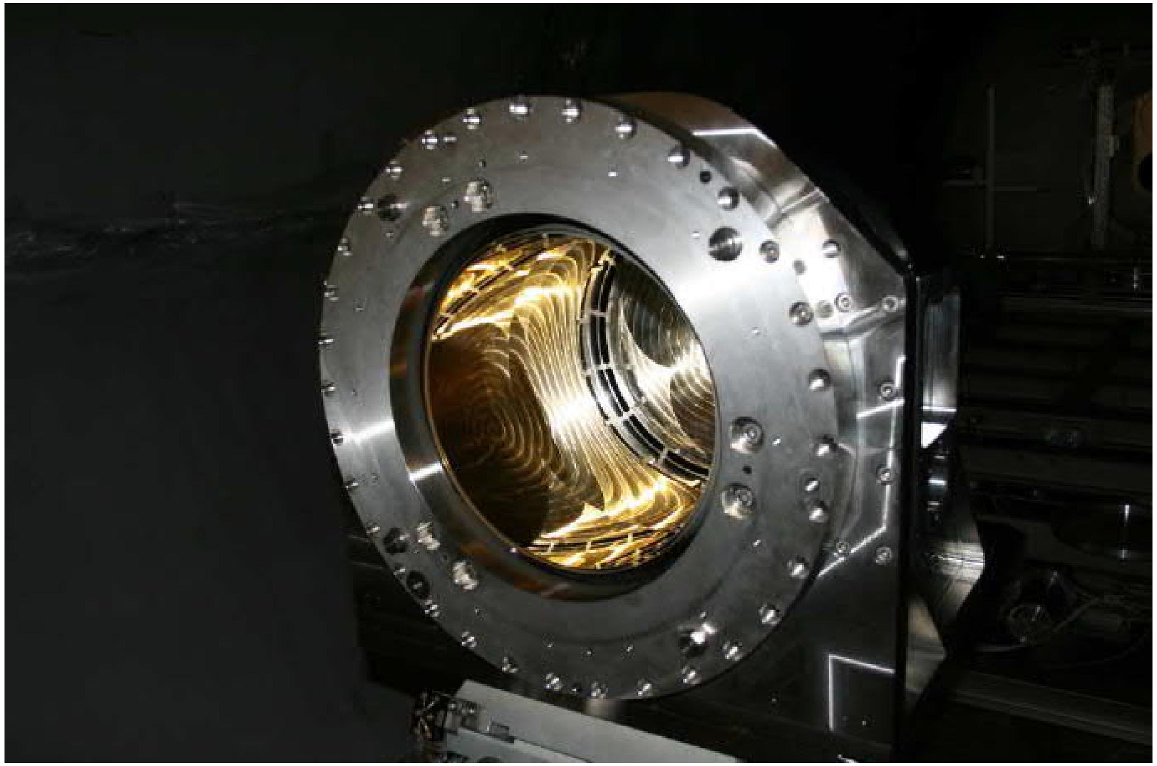
- **Mandrel #44 (Zeiss)**
  - refurbished ABRIXAS mandrel #17
  - first 2 replications with release problems
  - good release after outgassing procedure but shell has still large roundness errors
  - X-ray test: ~50’’ HEW


Integration on modified XMM facility

- **Mandrel #46 (Zeiss)**
  - refurbished ABRIXAS mandrel #19
  - 6 replications performed without problems
  - X-ray test: ~24’’ HEW

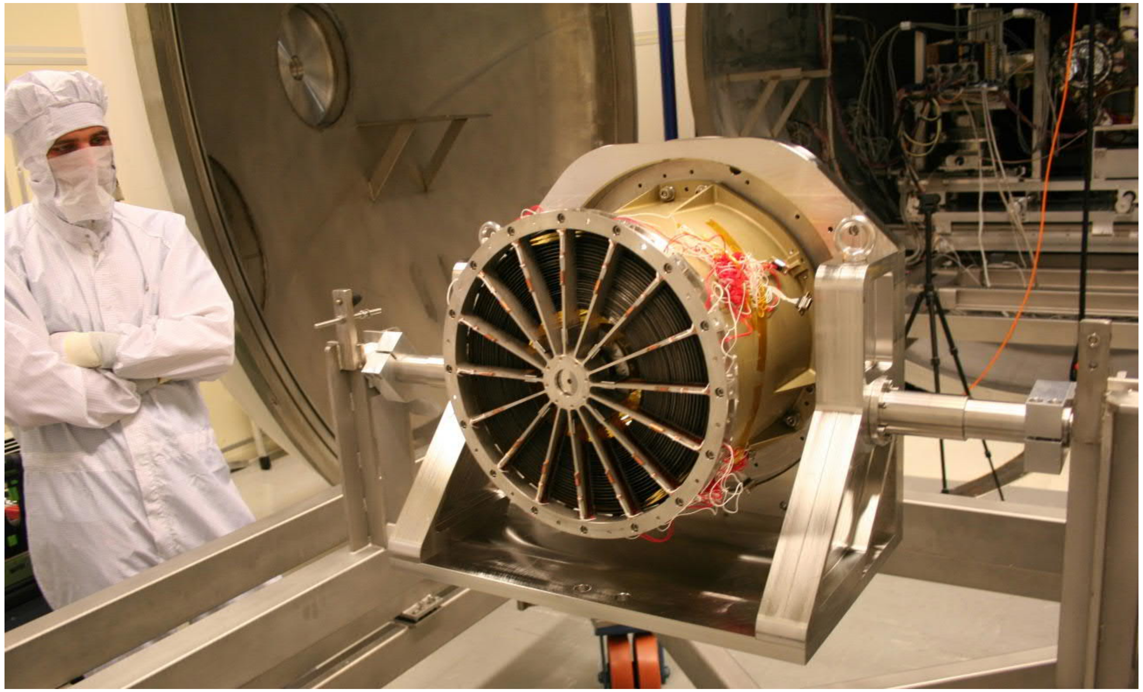
Shells #44 and #46 in PANTER fcility

May 2008: Test Mirror Module „DU6“ with mirror shells #1 and #2



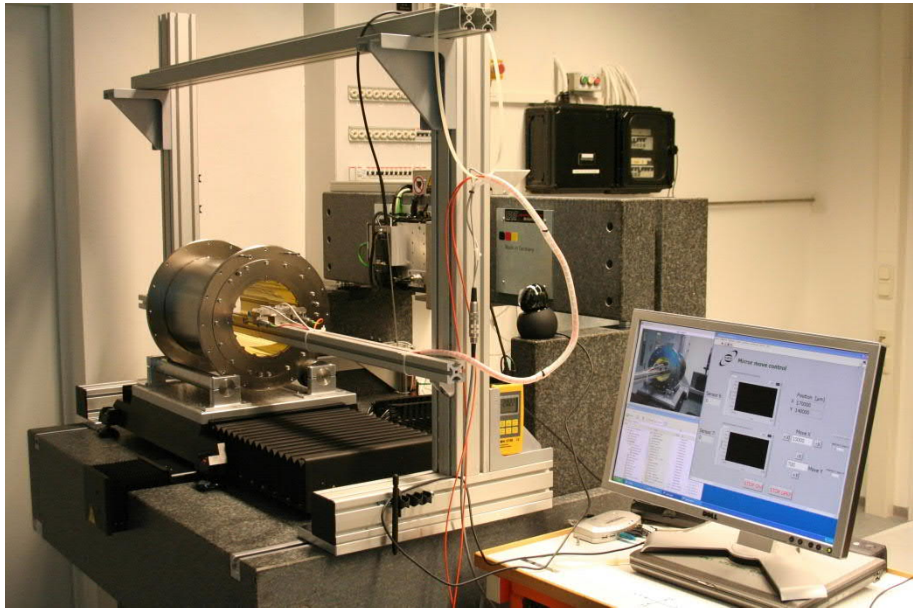
	HEW @ 0.28 keV	HEW @ 1.49 keV	HEW @ 2.98 keV
Shell #1	21.2″	36.2″	61.5″
Shell #2	29.4″	31.9″	43.0″

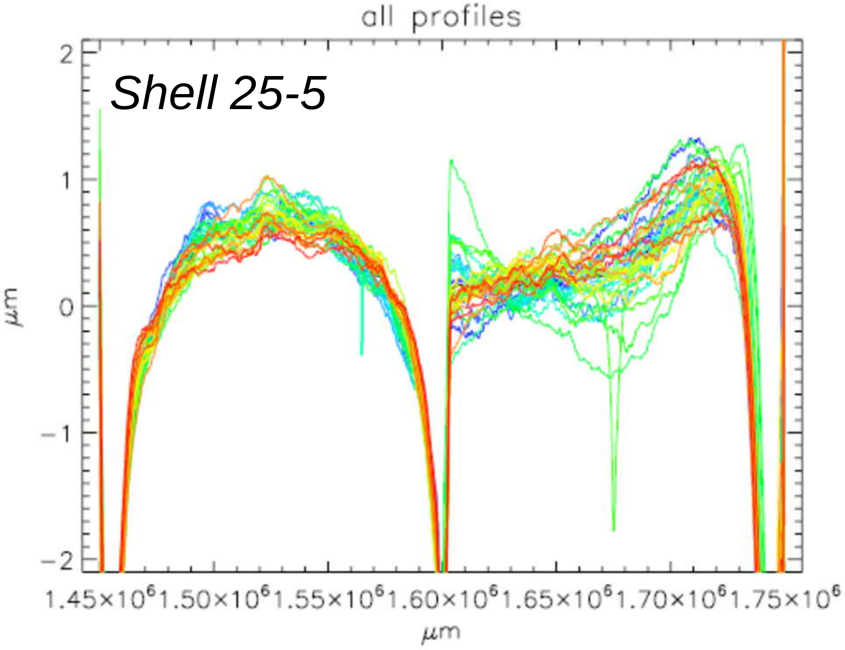
2009: X-ray tests with Demonstrator Model (Shells #1, #2, #27)

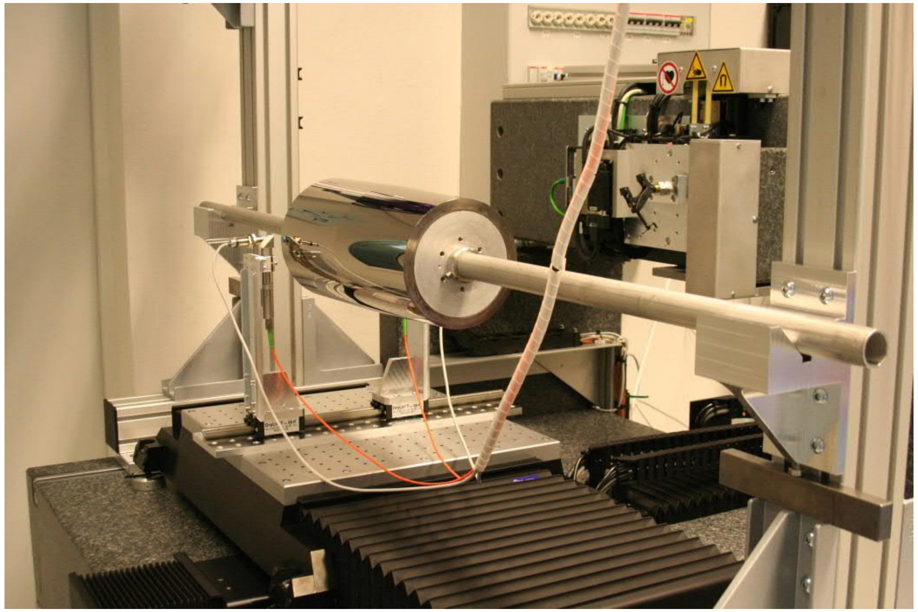


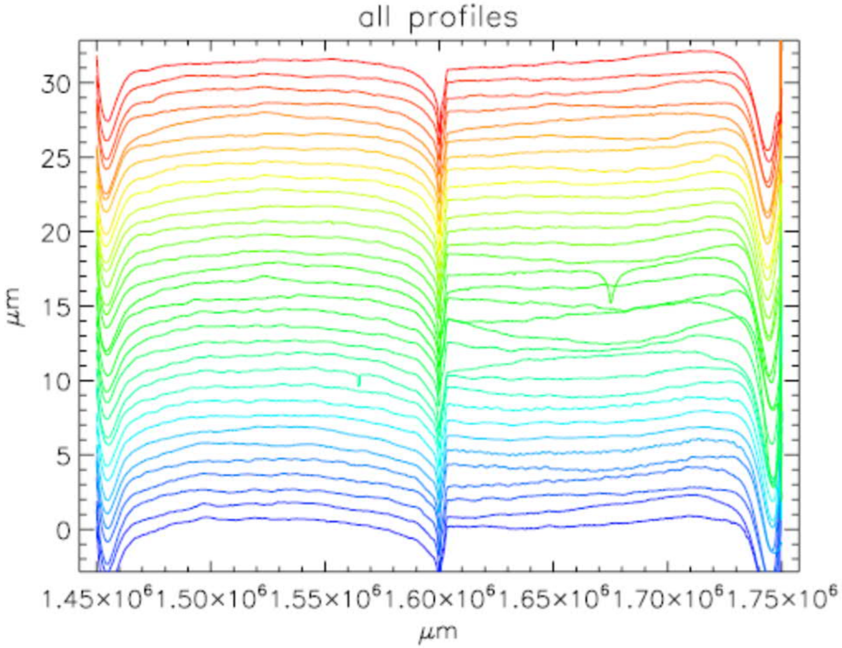
	HEW @ 0.28 keV	HEW @ 1.49 keV	HEW @ 2.98 keV
Shell #1	25.0″	33.5″	55.6″
Shell #2	33.0″	36.9″	58.2″
Shell #27	21.2″	27.7″	31.3″
all	40.0″	40.0″	

2009/10: Mirror Verification Phase, Metrology at MPE

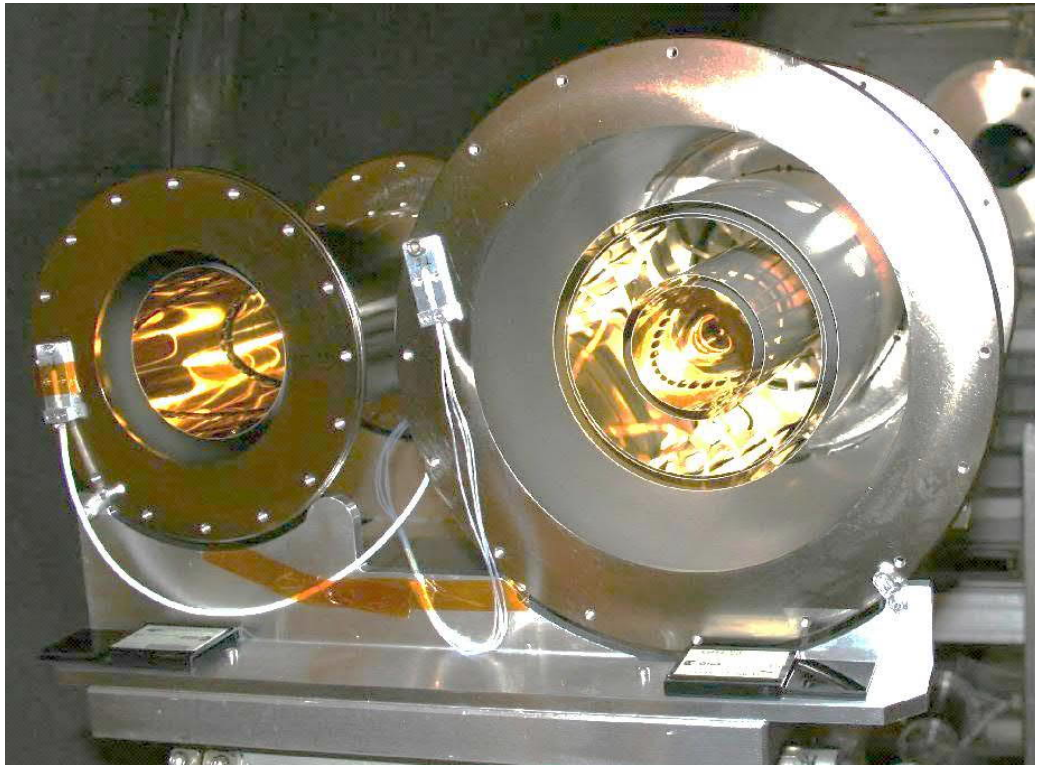


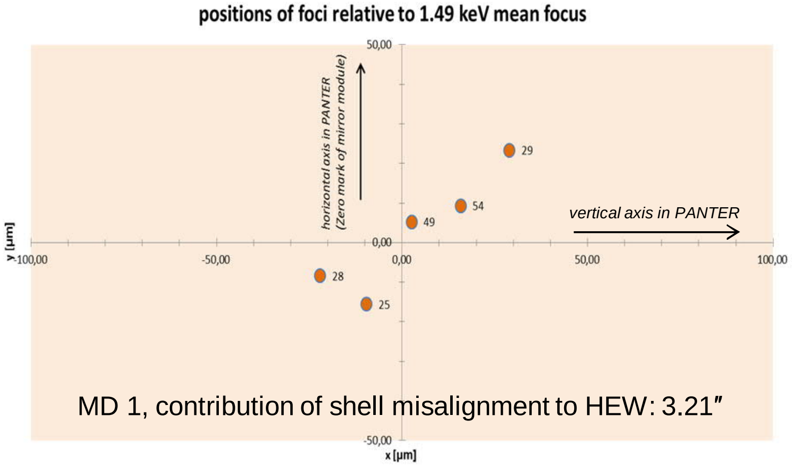






2009/10: Mirror Verification Phase, X-Ray Tests with “Drums”



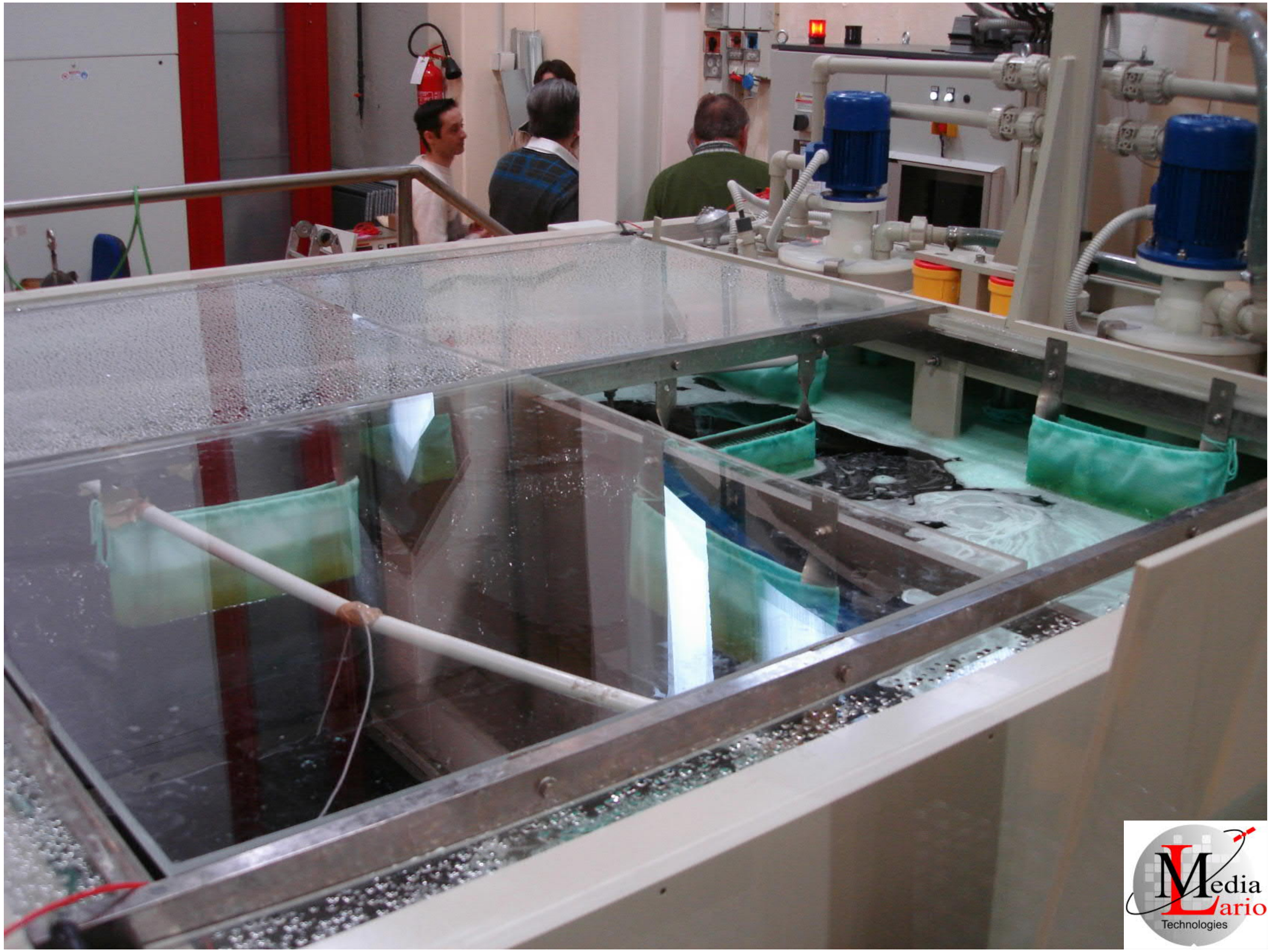


MD 1, contribution of shell misalignment to HEW: 3.21″

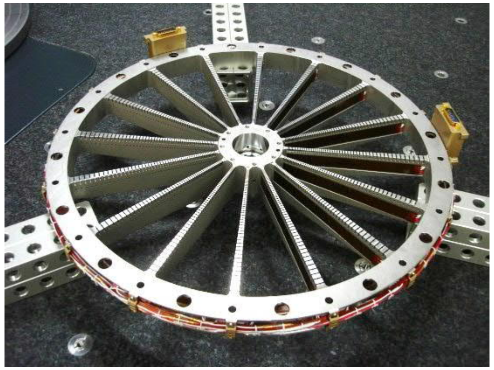
	HEW @ 1.49 keV	**HEW @ 8.04 KeV**
MD 1	18.4″	17.7″
MD 2	23.4″	20.5″
MD 3	25.6″	28.8″
MD4	19.6″	21.8″

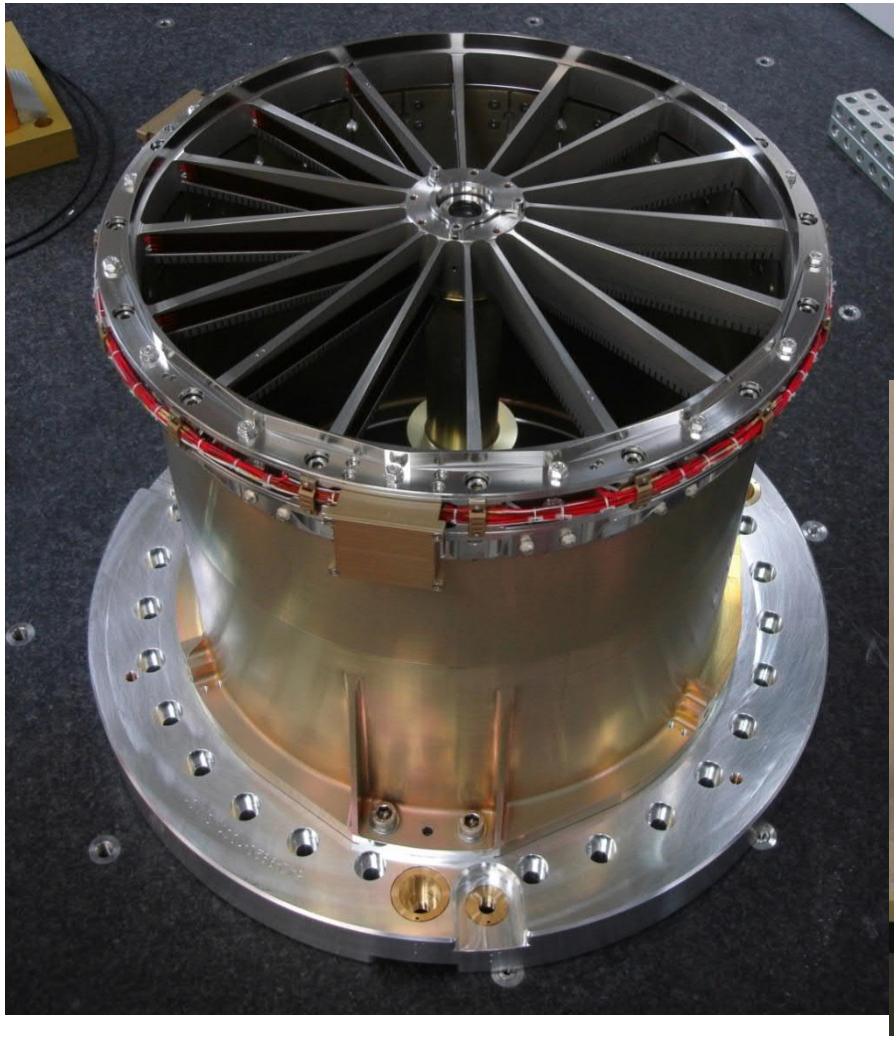
4.3. Mirror shell production and integration

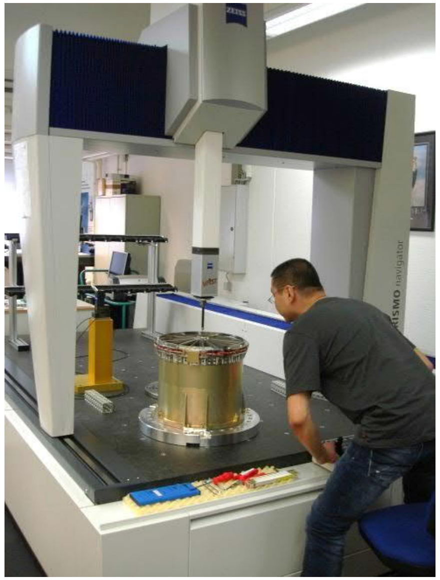
Electroforming Baths



Mirror Module Structure

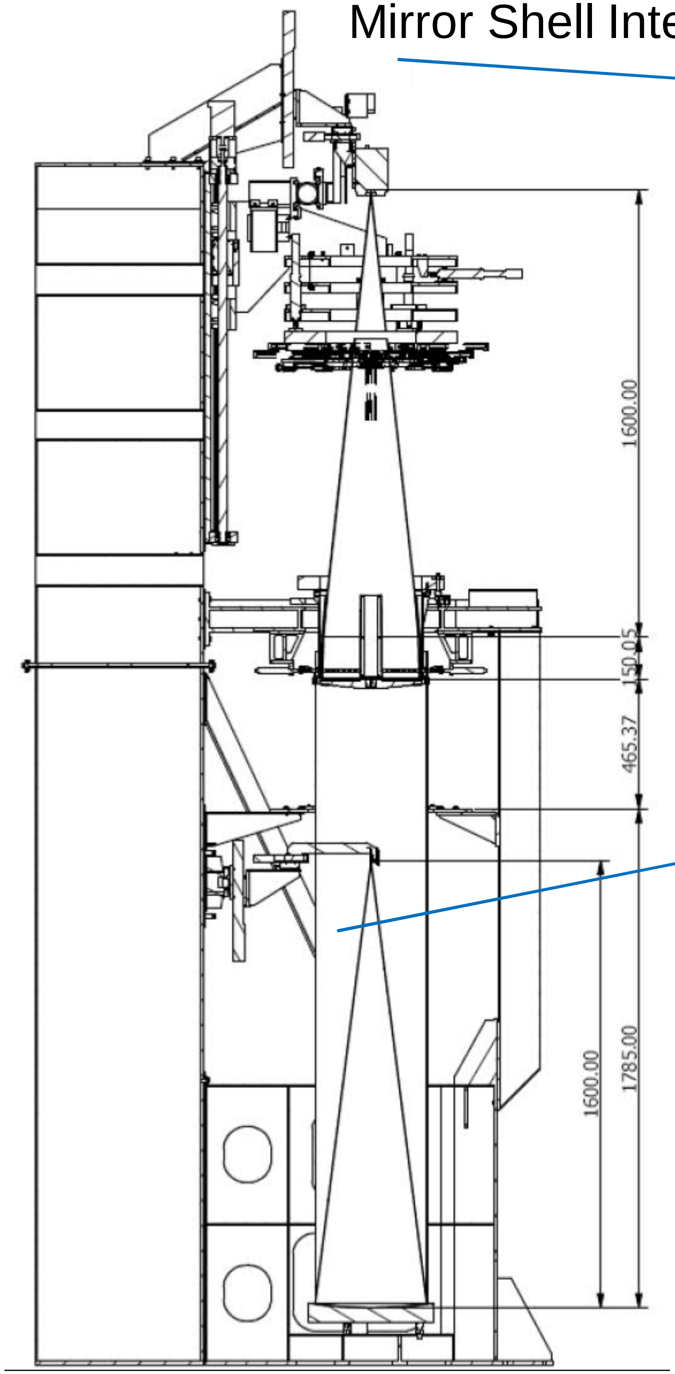


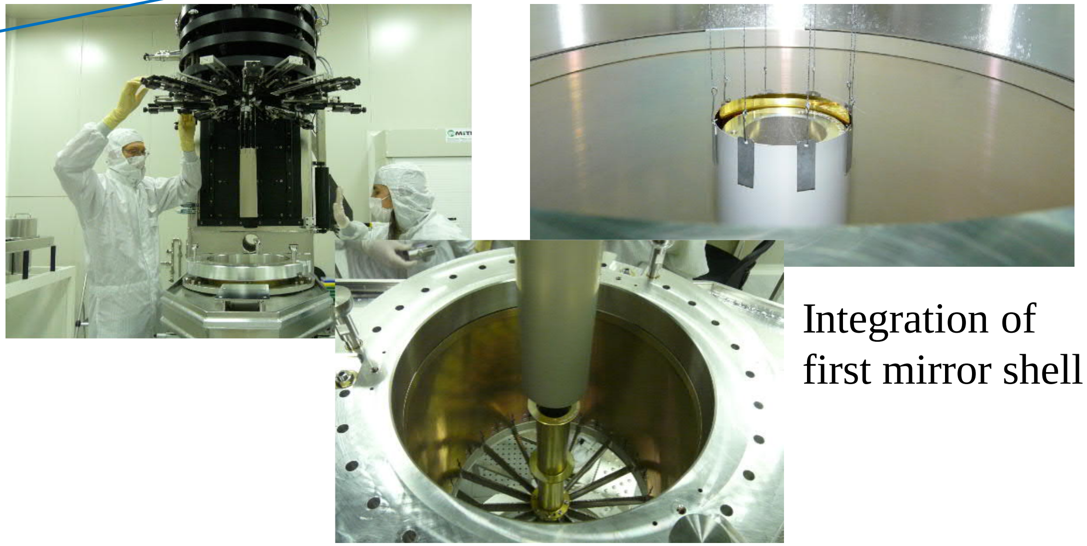




KAYSER-THREDE

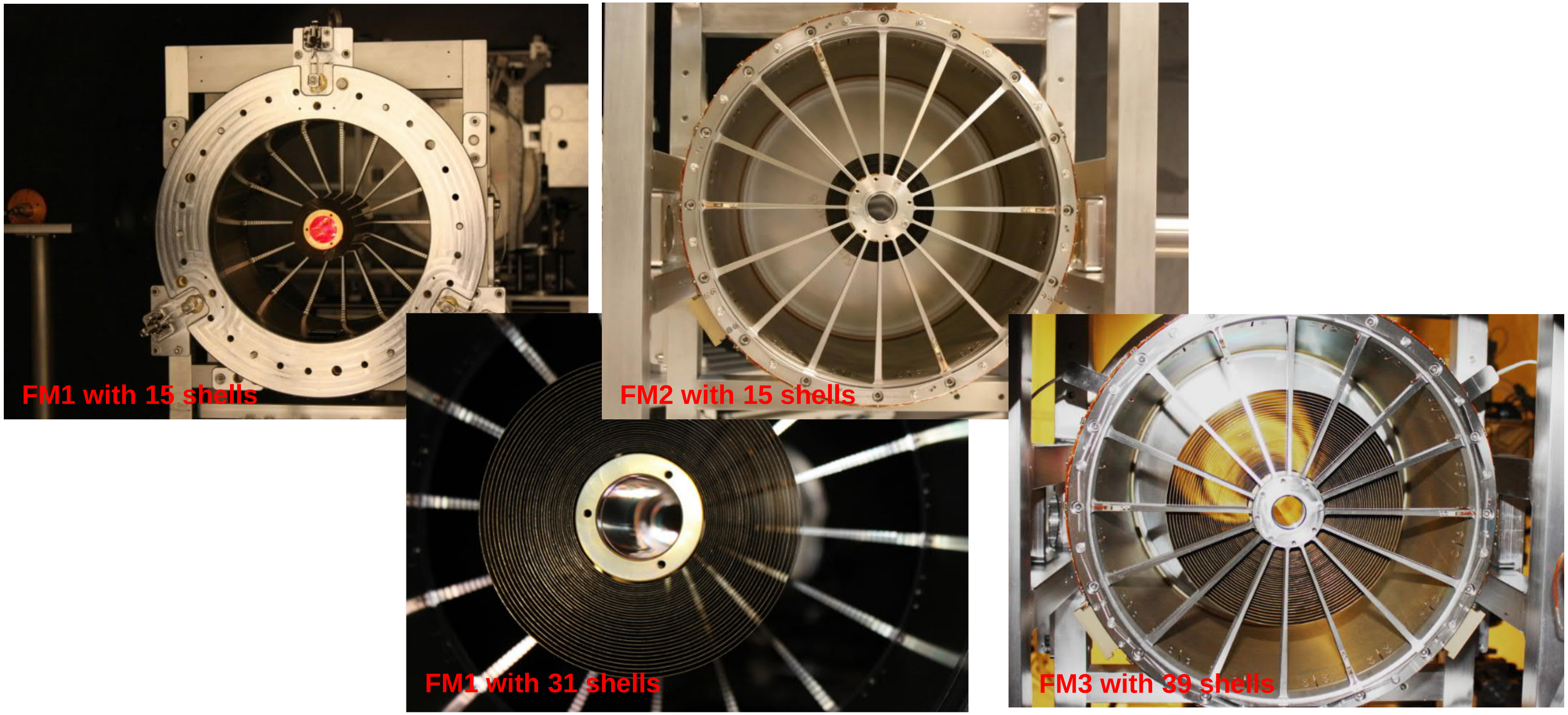
Mirror Shell Integration on Vertical Optical Bench





Integration of
first mirror shell

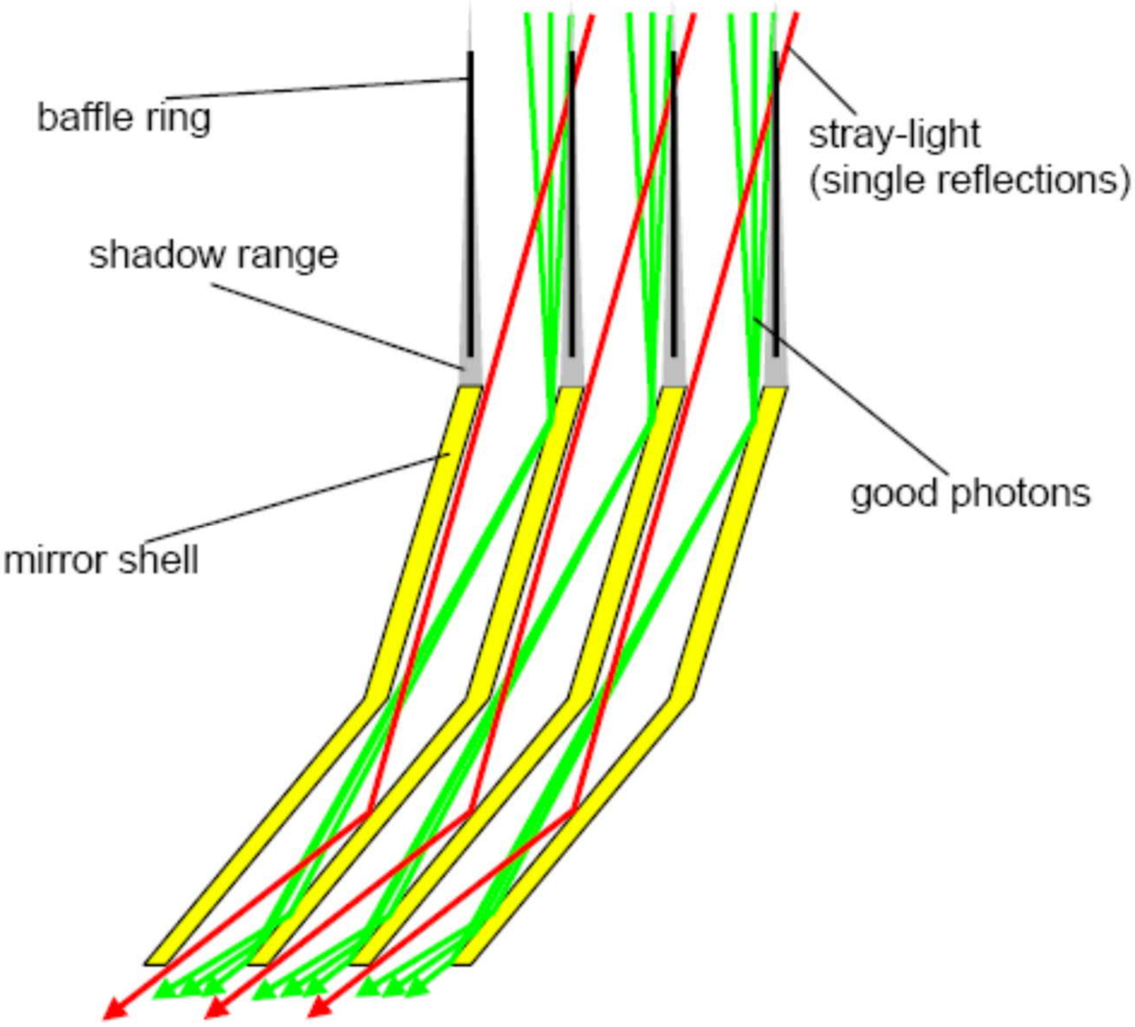
2011/12: FM X-Ray Tests with partially integrated modules



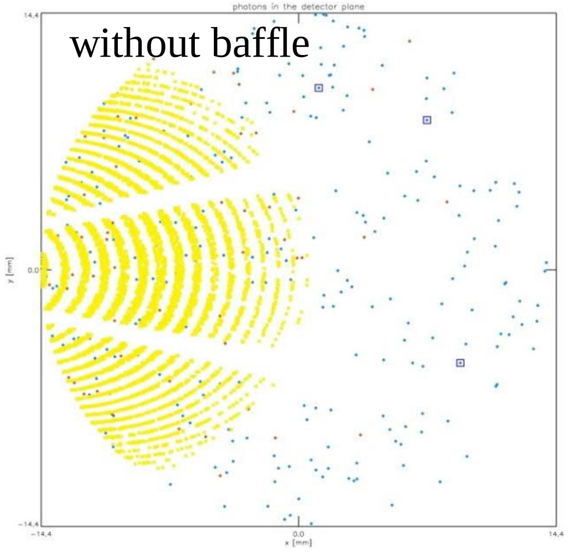
Mirror Module	Test Date	PSF	
		HEW @ 1.5 keV	**HEW @ 8.0 keV**
FM1 (shells 40-54)	March 2011	13.9±0.1 arcsec *	15.0±0.3 arcsec (all)*
FM2 (shells 40-54)	May 2011	14.4±0.1 arcsec *	15.7±0.4 arcsec (all)*
FM1 (shells 24-54)	June 2011	16.2±0.4 arcsec *	15.5±0.3 arcsec (all)*
FM3 (shells 16-54)	January 2012	16.2±0.4 arcsec *	15.7±0.4 arcsec (all)*

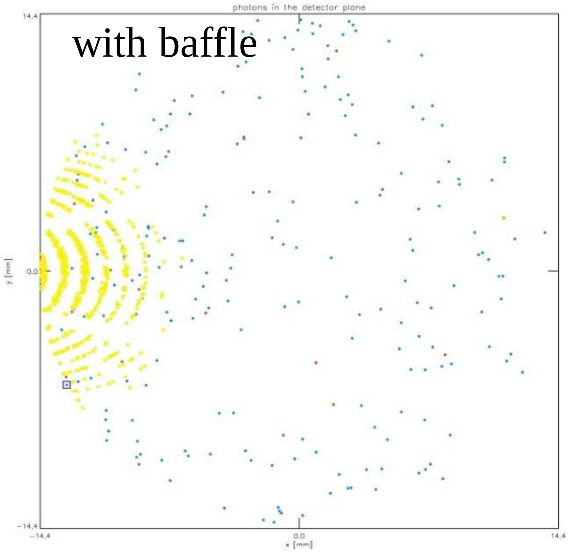
4.4. X-ray baffle against straylight

X-Ray Baffle Functionality (Ray-Tracing Simulations)



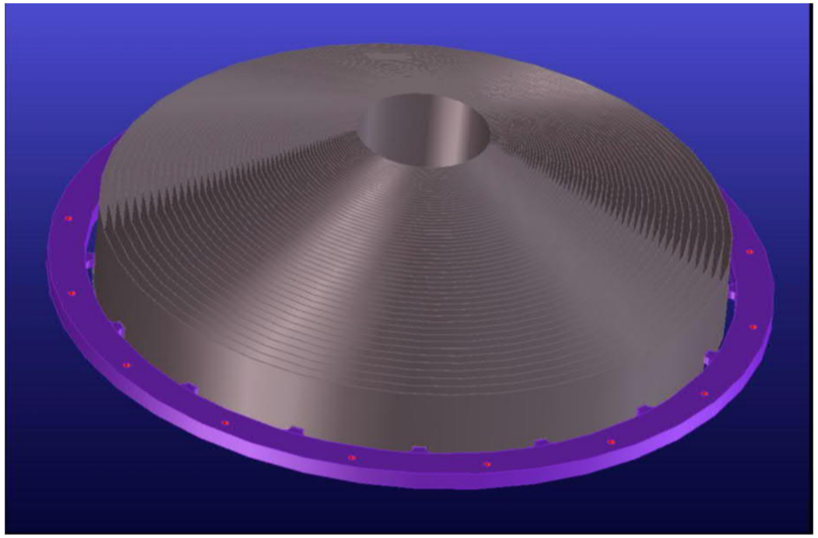
Light source 1° off-axis (i.e. out of FoV)

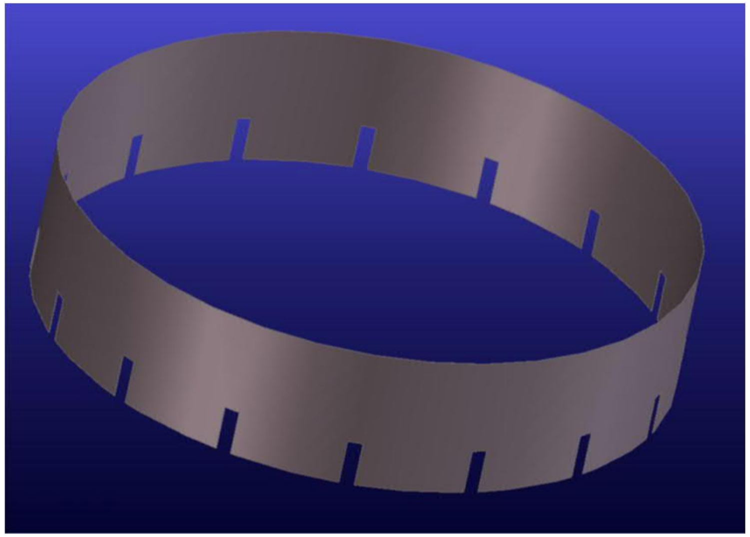




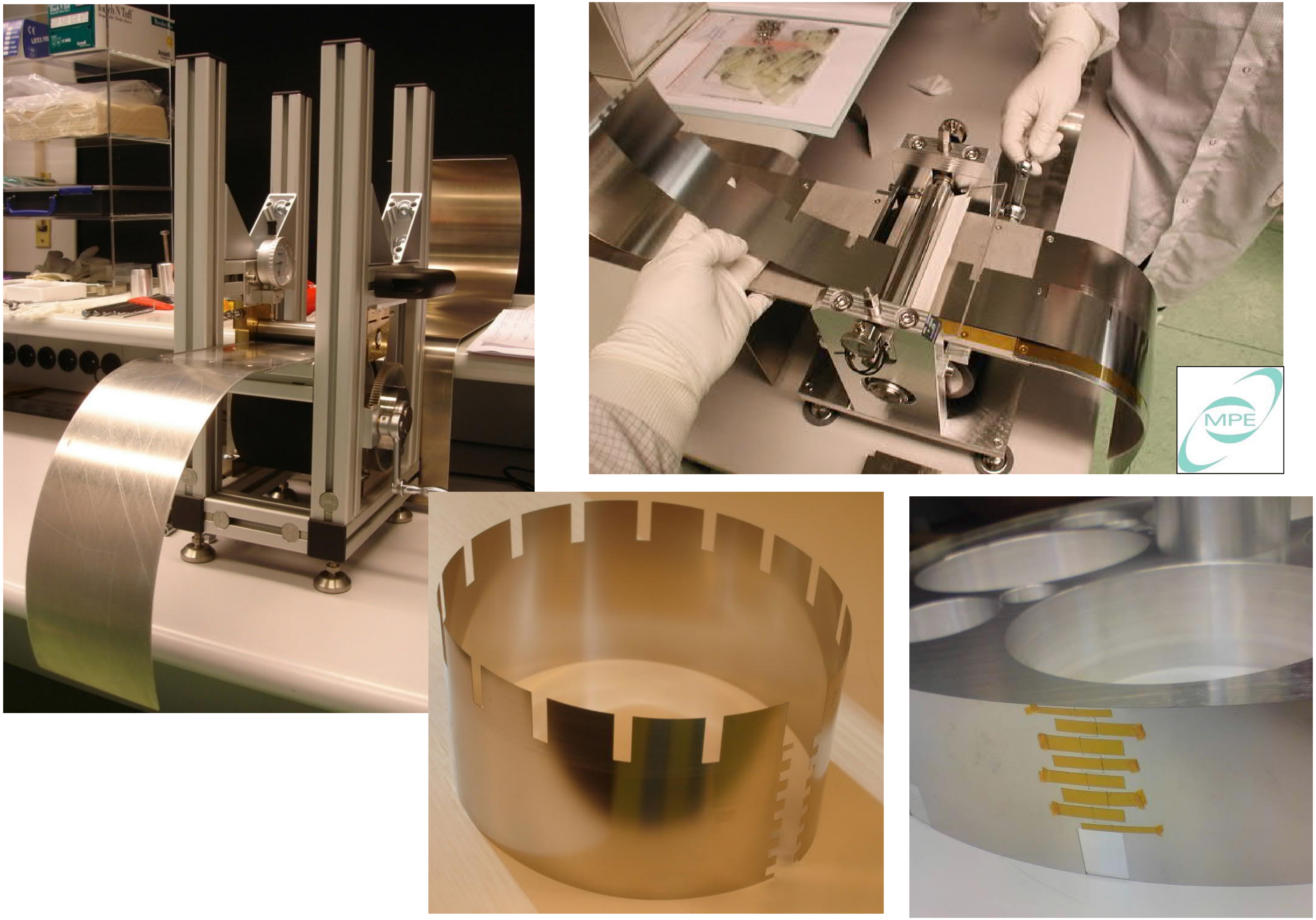
X-Ray Baffle: Basic Design

- System of 54 cylindrical shells
  - height outer 50 mm, height inner 110 mm, wall thickness 125 µm
- Straylight reduction of 95% @1keV (~90% @4keV)

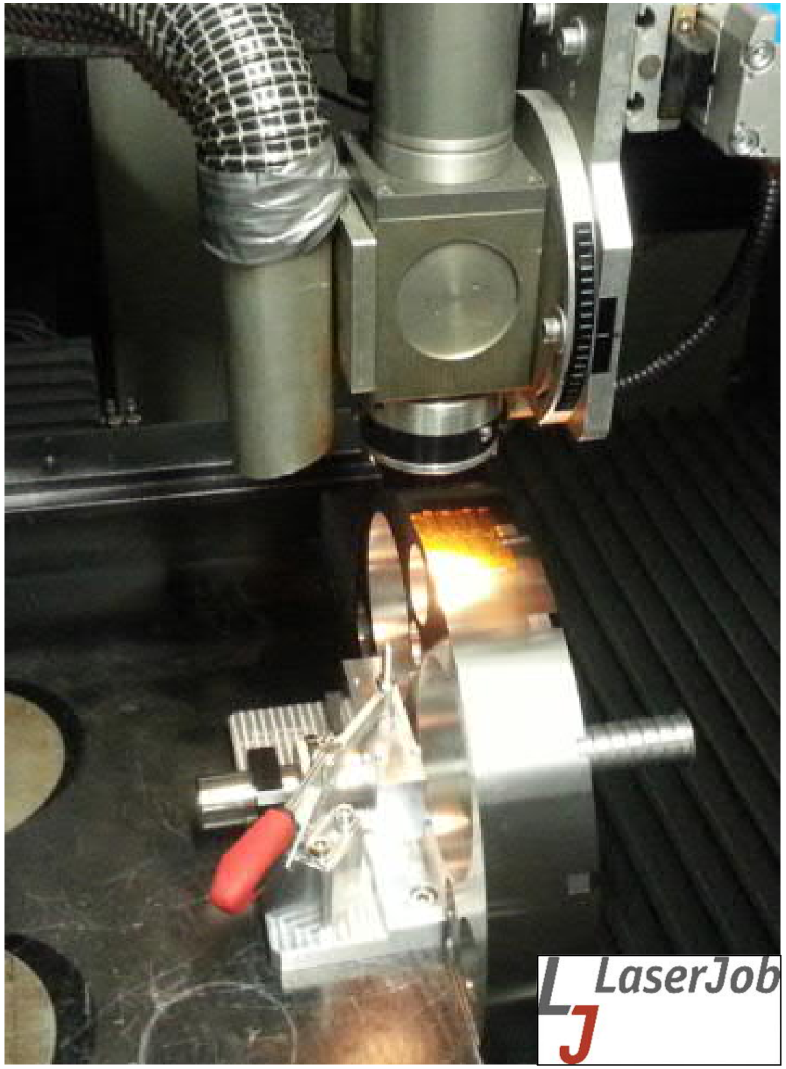




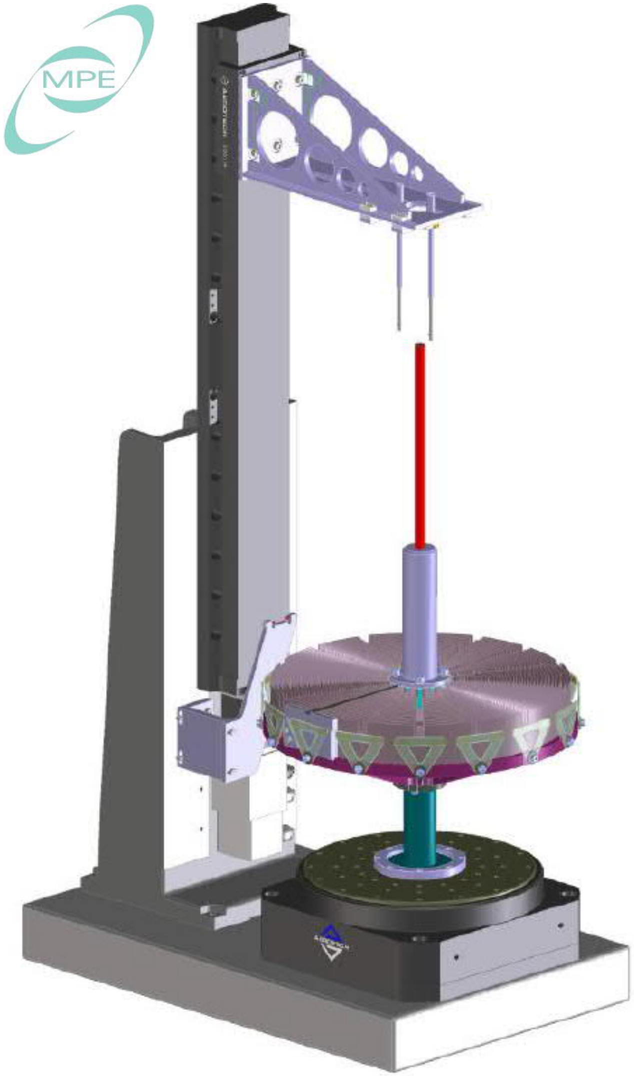
X-Ray Baffle Manufacturing: Rolling

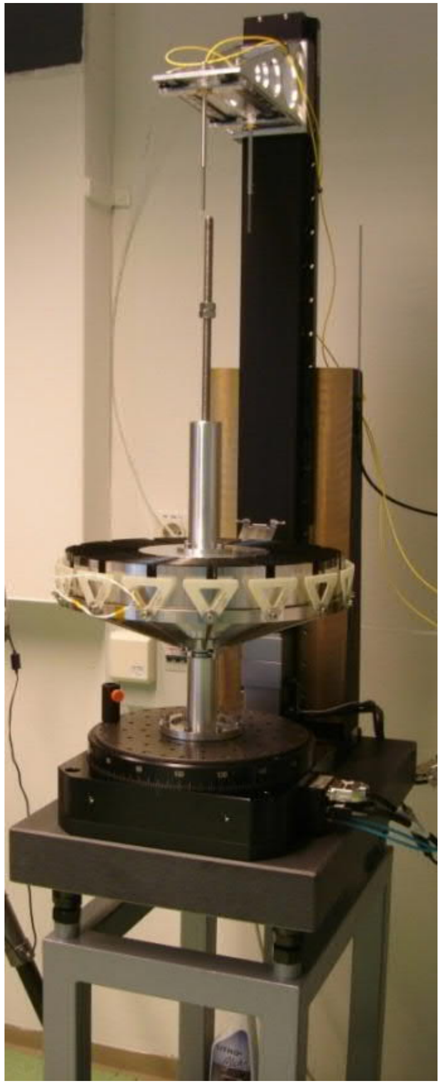


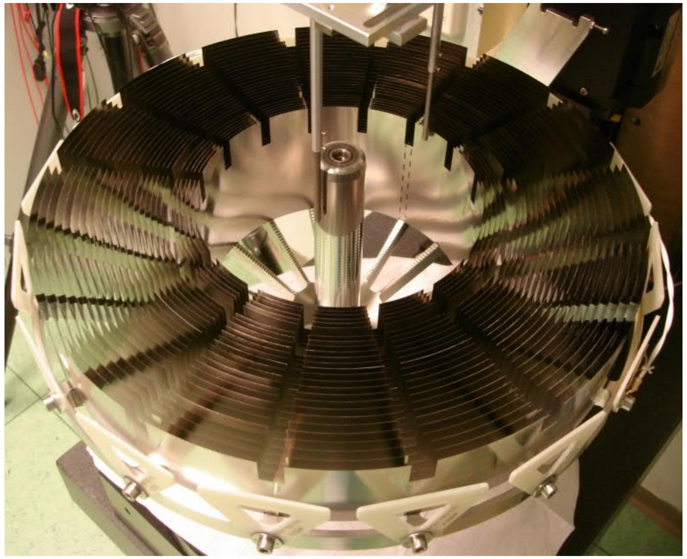
X-Ray Baffle Manufacturing: Laser Welding

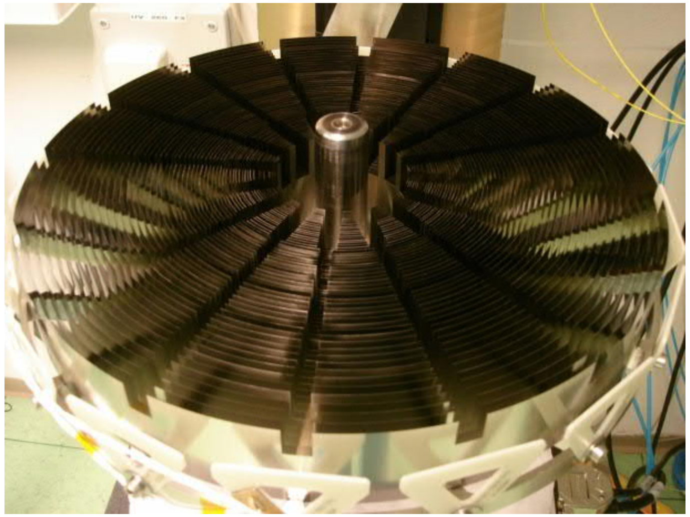


X-Ray Baffle Integration Stand

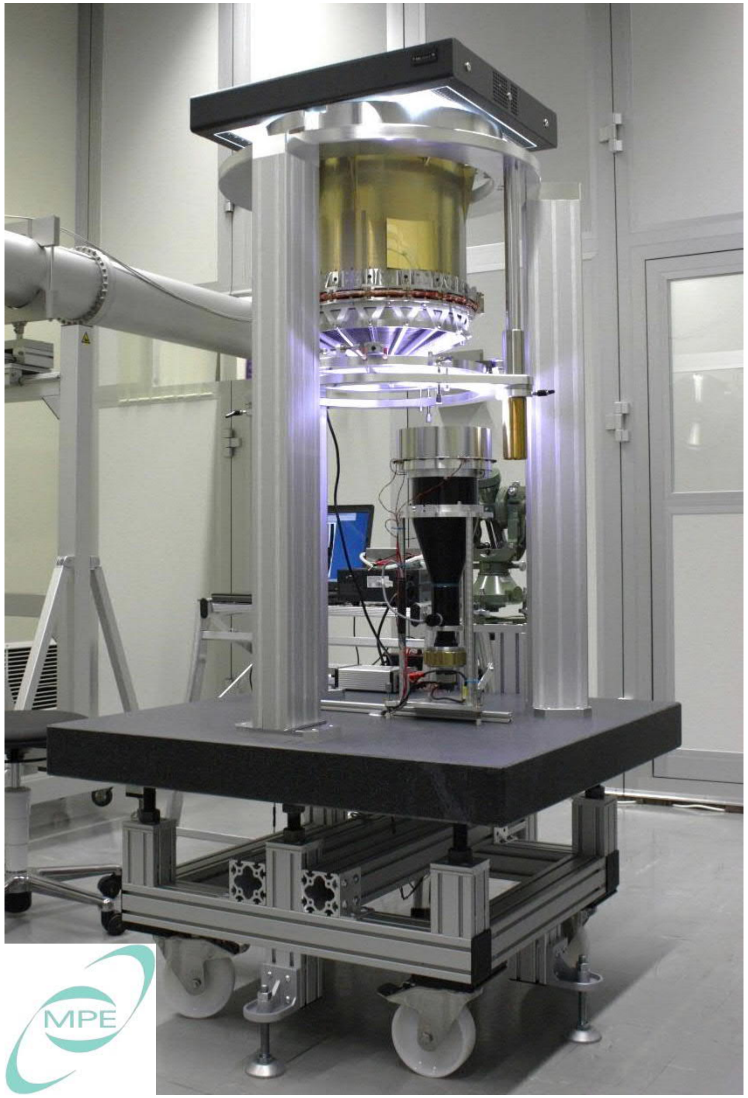




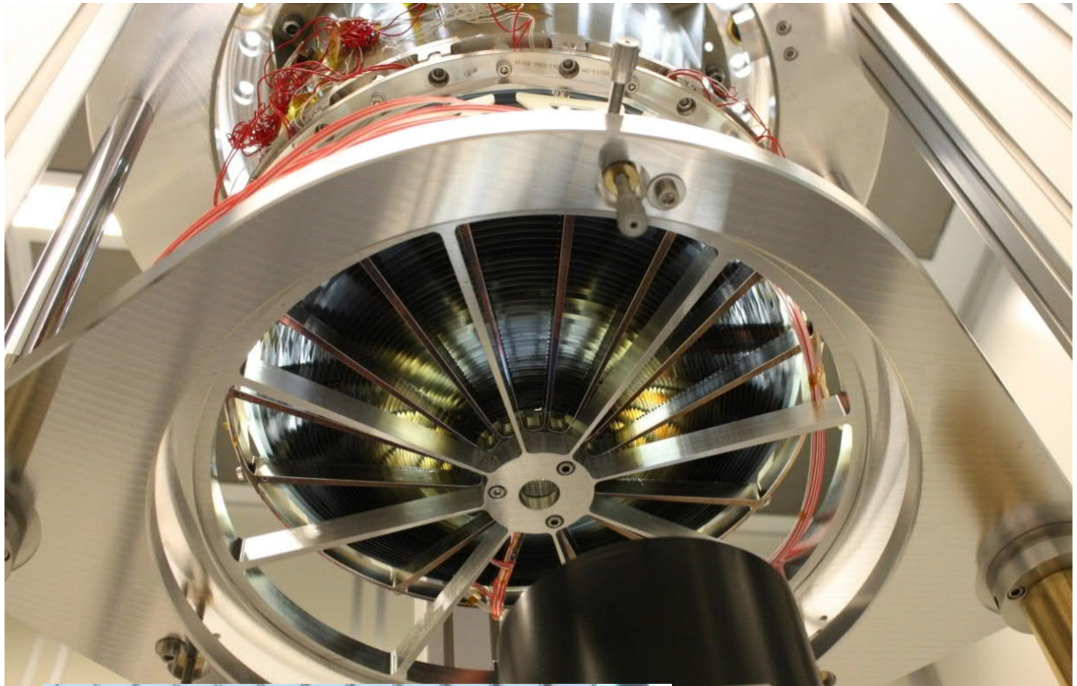


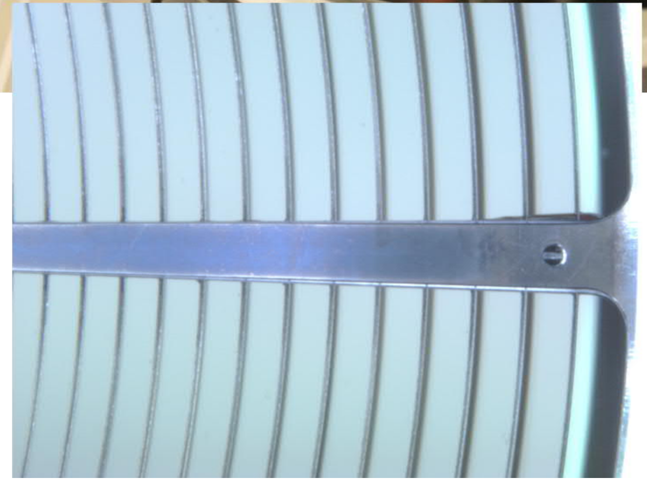


X-Ray Baffle Alignment / Mounting



alignment to MM…

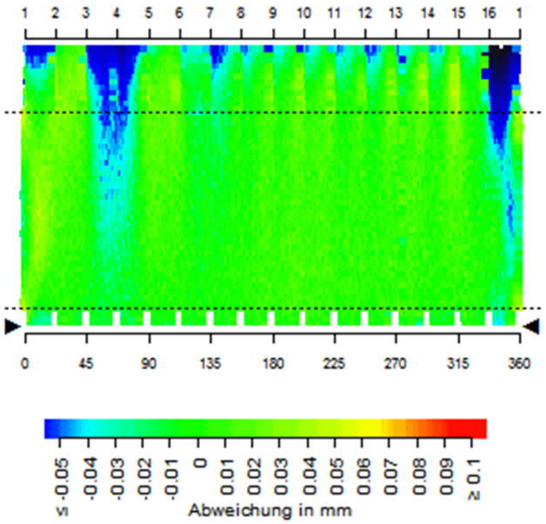




control

X-Ray Baffle Performance

Performance prediction from roundness measurements on baffle integration stand:

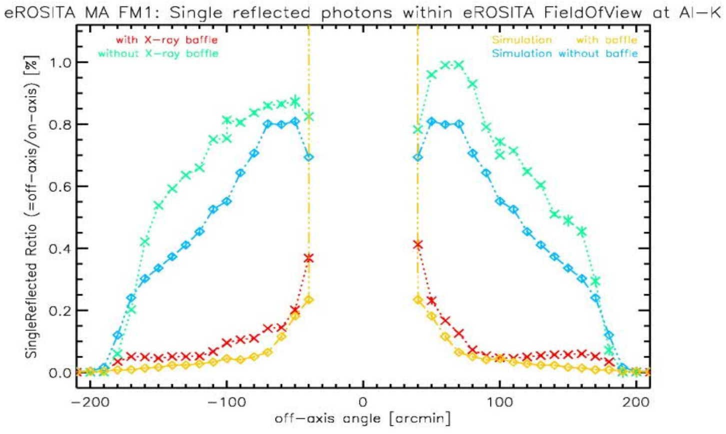


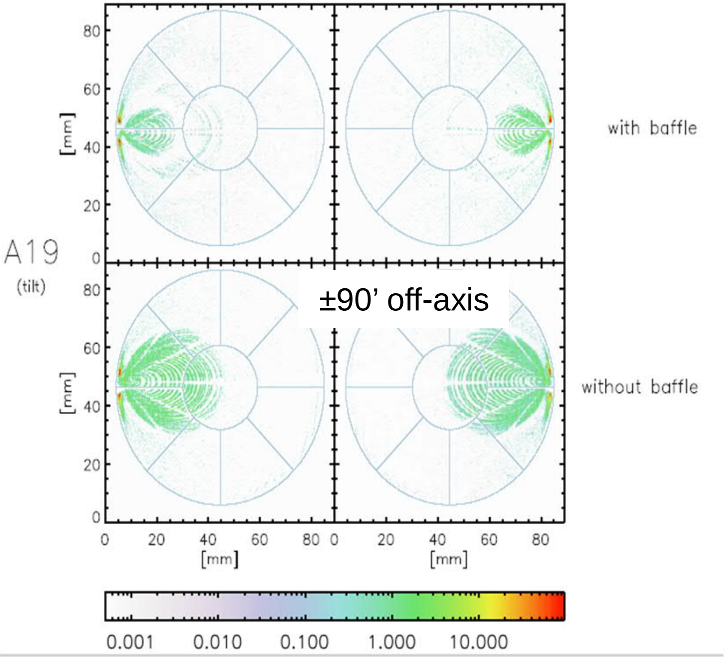
Stray-light (single refl.) reduction: 91-92% (ideal: 95%, accepted 90%)

Relative Loss of effective area: ~2% (still above specification)

X-Ray Baffle	Mirror Assembly	Loss of collecting area	Stray-light reduction
FM1	FM1	2,4%	91,3%
FM3	FM2	2,4%	91,5%
FM4	FM3	2,6%	92,1%
FM5	FM5	2,2%	91,4%
FM6	FM4	2,5%	91,2%
FM7	FM6	2,3%	91,0%
FM8	FM8	2,4%	90,6%
FM9	FM7	2,1%	91,9%

MA FM1 X-ray measurements





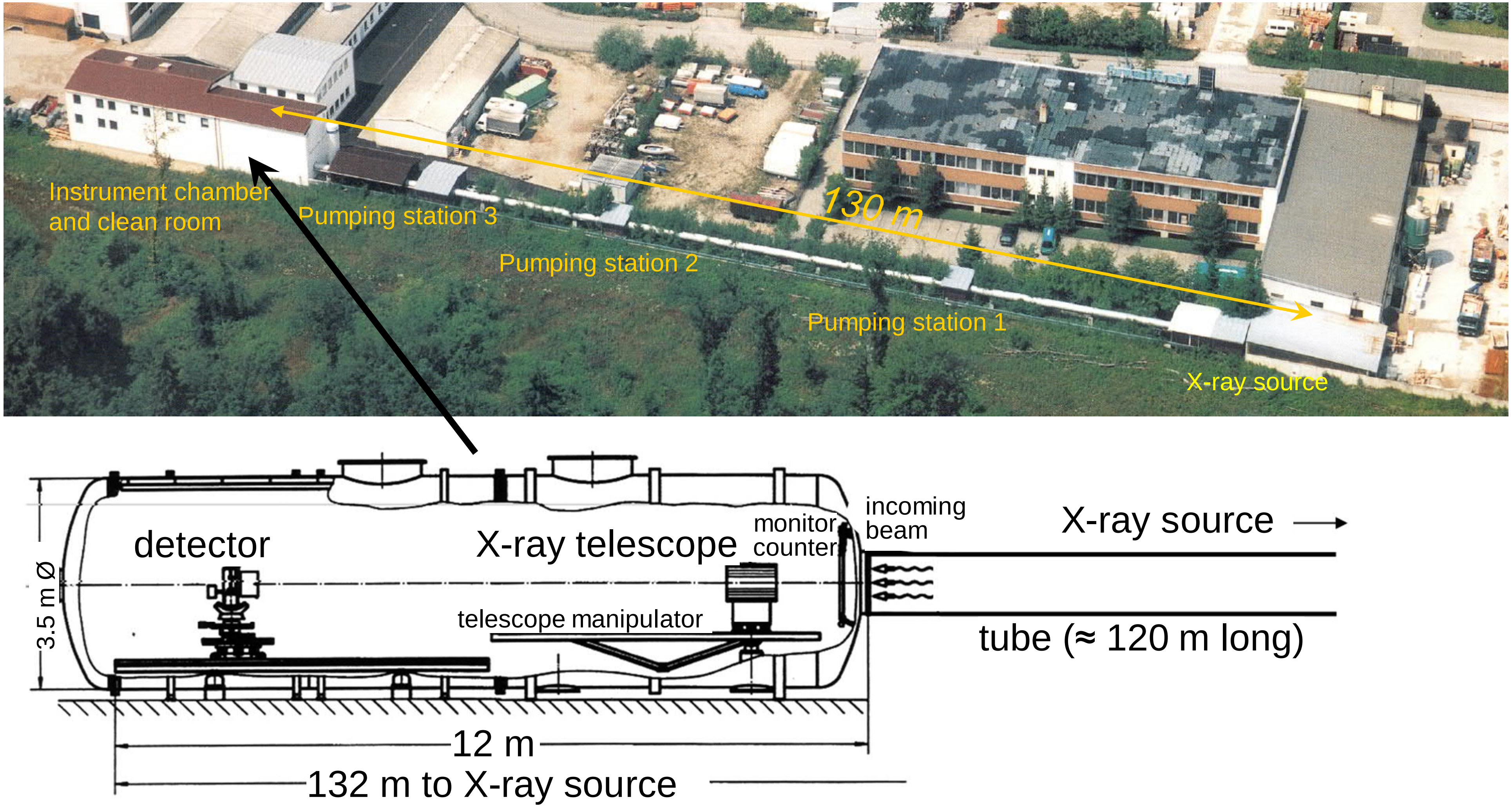
4.5. Tests and Calibration

- *X-ray test facility*
- *Imaging performance (PSF)*
- *Effective collecting area*
- *Focal length measurements*

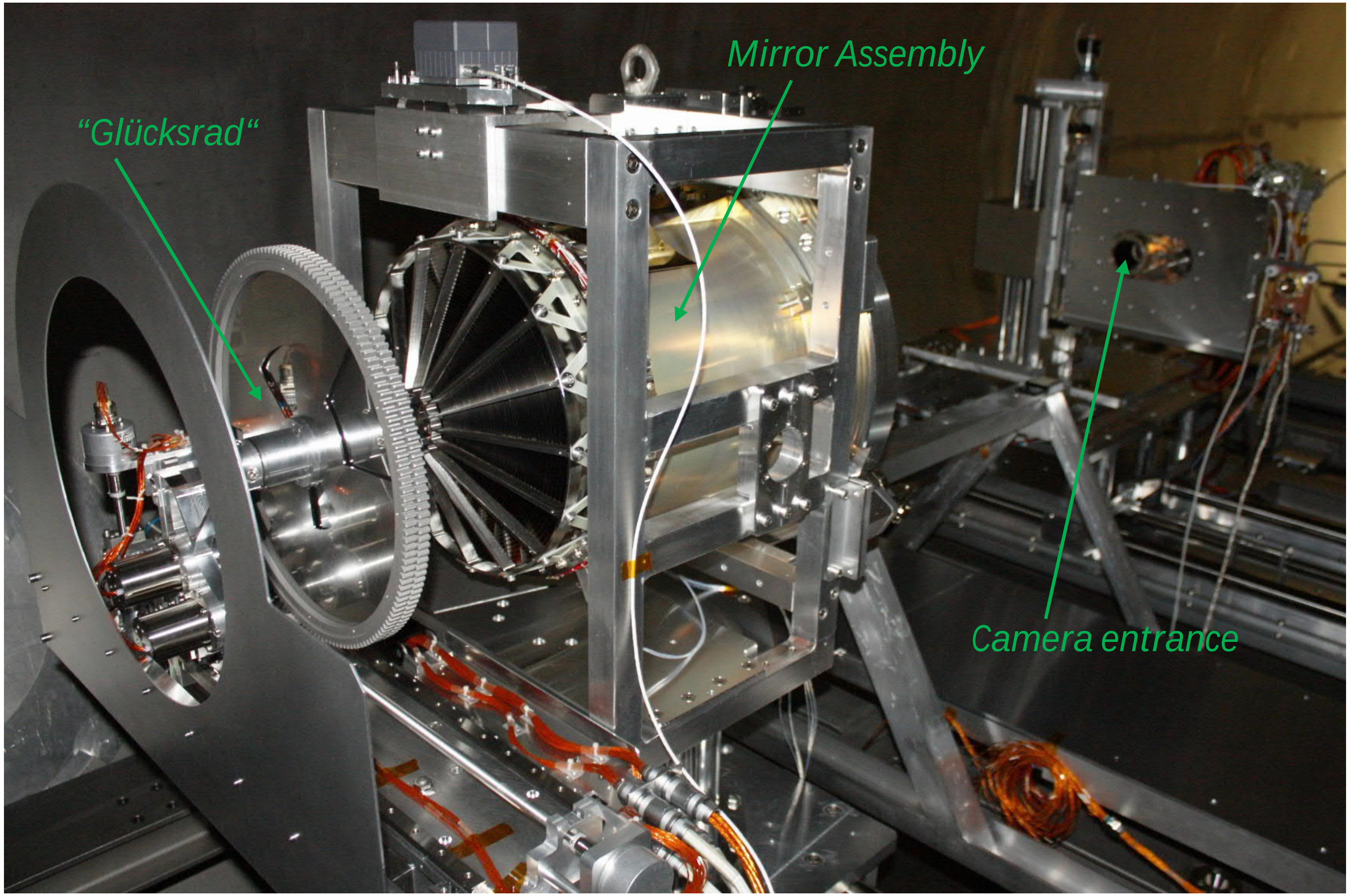
Calibration: Overview

PSF	– on-axis	→ verification of performance
	– off-axis mapping	→ Input for eSASS and simulations (shapelet reconstruction of PSF)
Effective Area (on- /off-axis) (difficult / time consuming in orbit)		→ Input for eSASS and for more realistic simulations, for prediction of sensitivity, number of detectable objects
Focal length		→ Essential input for positioning of the cameras in focus, tolerance <0.2 mm

MPE X-Ray Test Facility „PANTER“

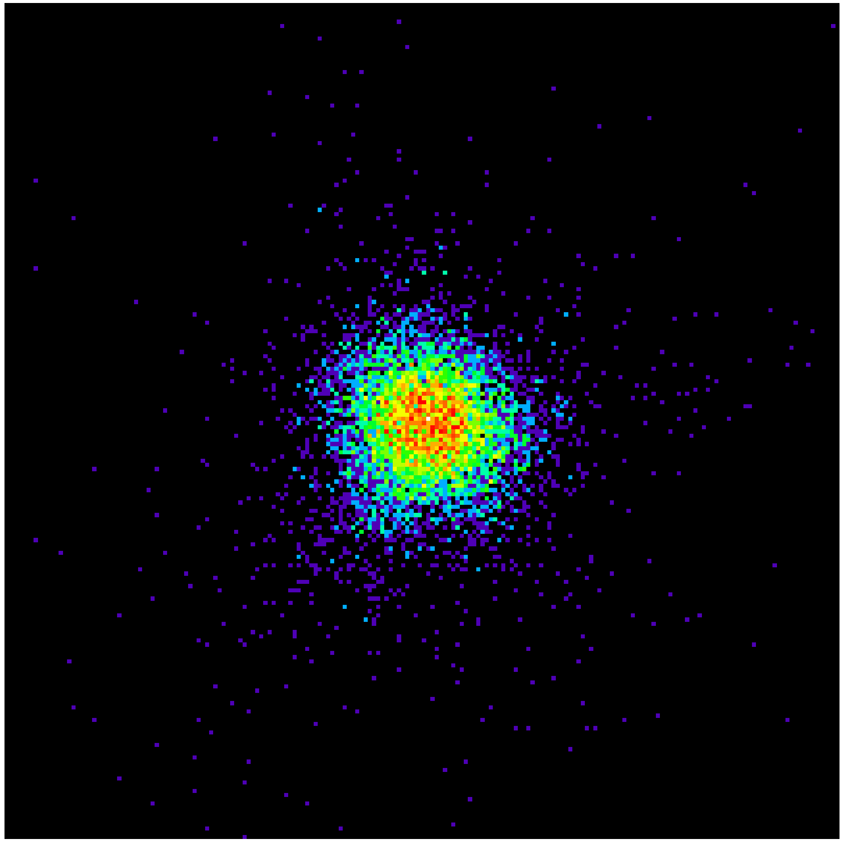


Setup in PANTER for FM Calibration

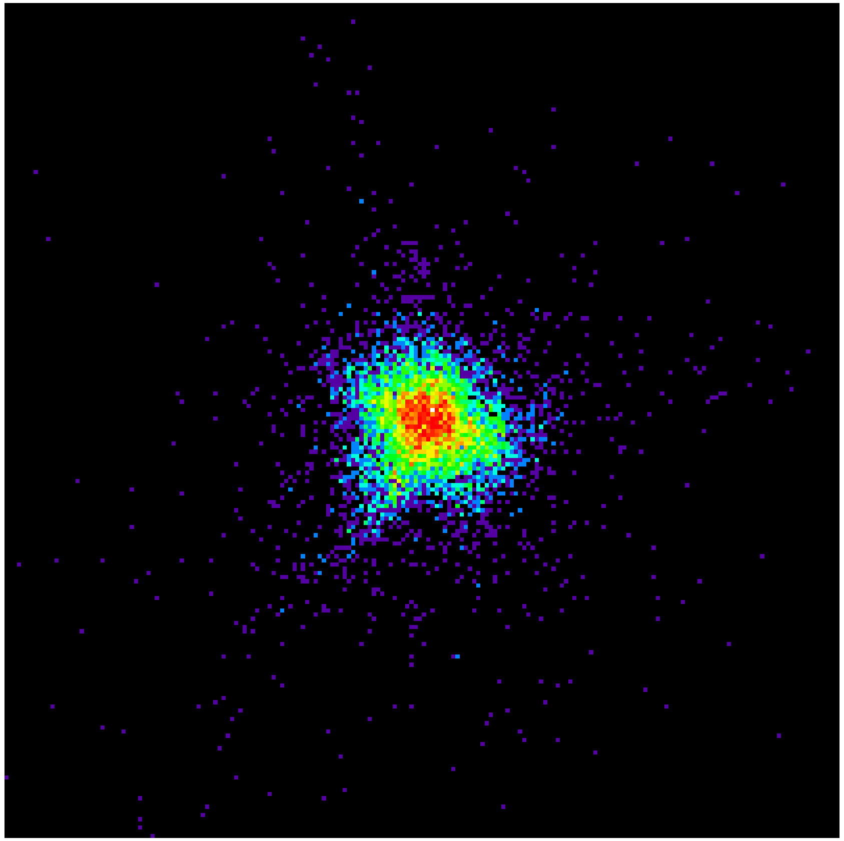


Setup in PANTER vacuum chamber, here Mirror Assembly FM1

Point spread function (PSF)

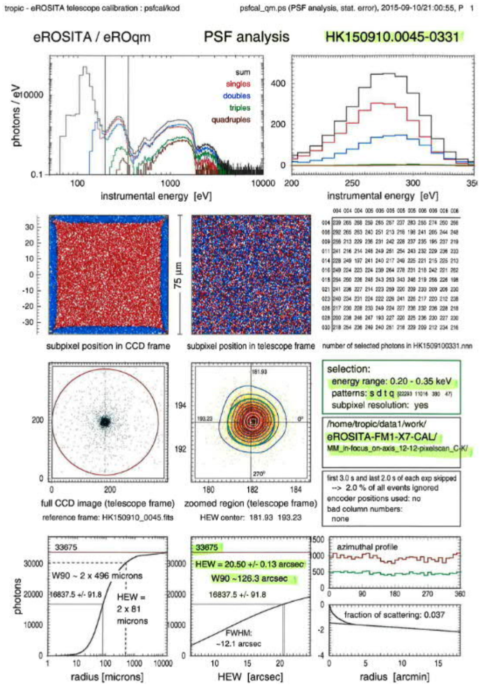


75 µm pixel (ca. 10") resolution: 17.3" HEW



Sub-pixel resolution: 14.7" HEW

PSF on-axis


tropic - eROSITA telescope calibration : psfcal/kod psfcal_qm.ps (PSF analysis, stat. error), 2015-09-10/21:00:55, P 1

eROSITA / eROqm PSF analysis HK150910.0045-0331

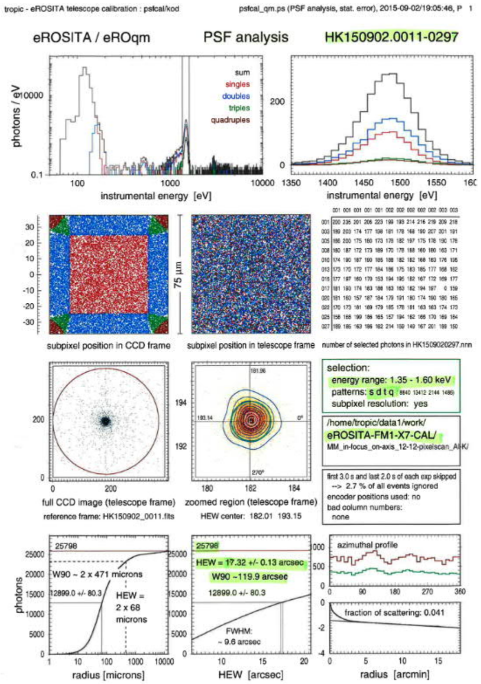
number of selected photons in HK1509100331.nnn

selection:
energy range: 0.20 - 0.35 keV
patterns: s d t q (22293 11016 390 47)
subpixel resolution: yes

/home/tropic/data1/work/
eROSITA-FM1-X7-CAL/
MM_in-focus_on-axis_12-12-pixelscan_C-K/

first 3.0 s and last 2.0 s of each exp skipped
--> 2.0 % of all events ignored
encoder positions used: no
bad column numbers:
none

reference frame: HK150910_0045.fits
HEW center: 181.93 193.23


tropic - eROSITA telescope calibration : psfcal/kod psfcal_qm.ps (PSF analysis, stat. error), 2015-09-02/19:05:46, P 1

eROSITA / eROqm PSF analysis HK150902.0011-0297

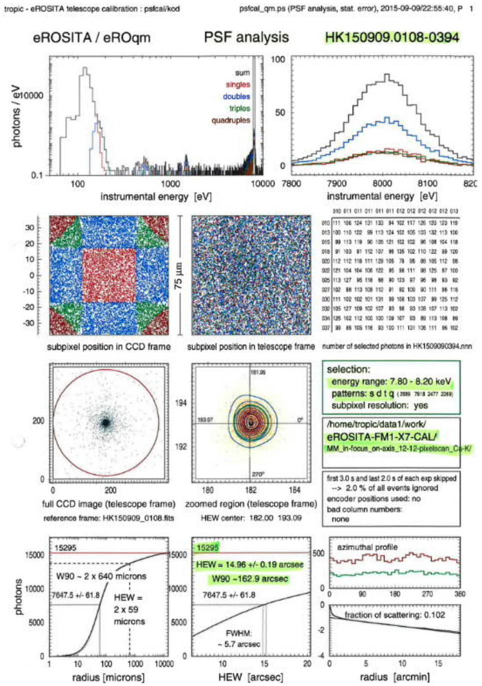
number of selected photons in HK1509020297.nnn

selection:
energy range: 1.35 - 1.60 keV
patterns: s d t q
subpixel resolution: yes

/home/tropic/data1/work/
eROSITA-FM1-X7-CAL/
MM_in-focus_on-axis_12-12-pixelscan_Al-K/

first 3.0 s and last 2.0 s of each exp skipped
--> 2.7 % of all events ignored
encoder positions used: no
bad column numbers:
none

reference frame: HK150902_0011.fits
HEW center: 182.01 193.15


tropic - eROSITA telescope calibration : psfcal/kod psfcal_qm.ps (PSF analysis, stat. error), 2015-09-09/22:55:40, P 1

eROSITA / eROqm PSF analysis HK150909.0108-0394

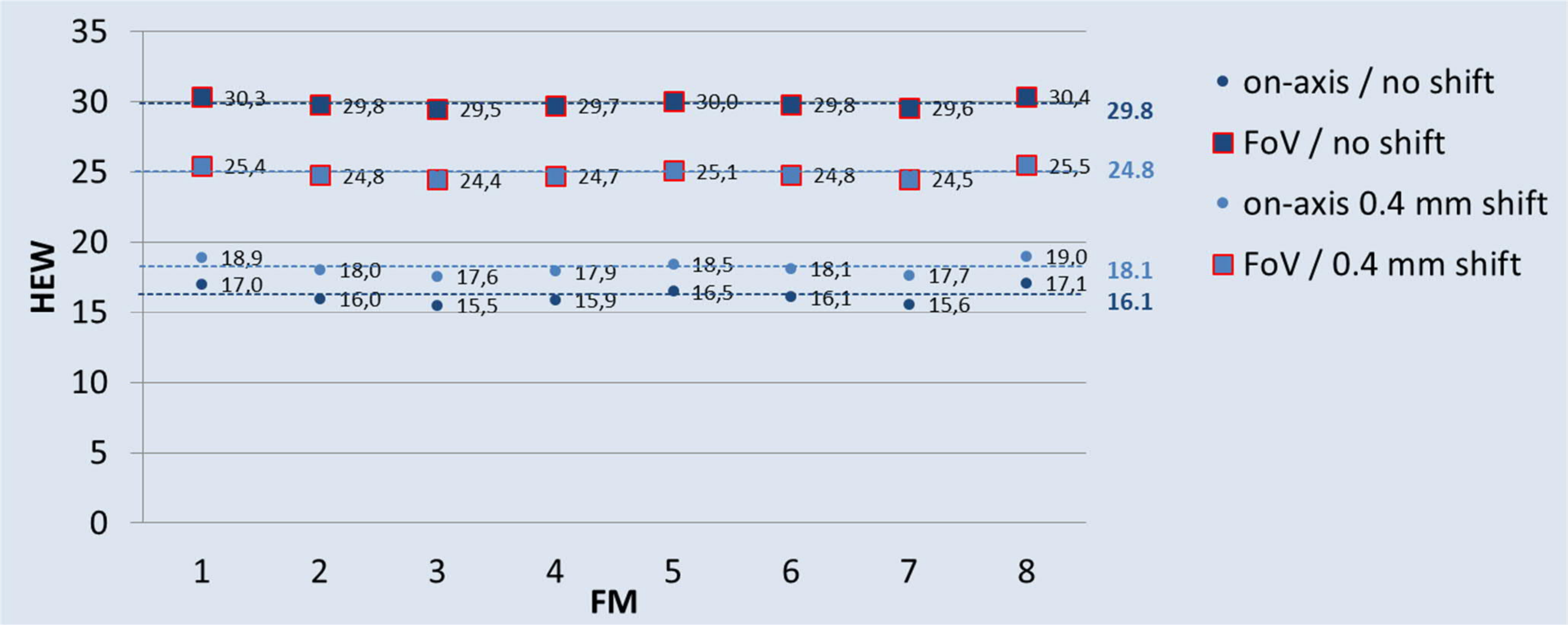
number of selected photons in HK1509090394.nnn

selection:
energy range: 7.80 - 8.20 keV
patterns: s d t q
subpixel resolution: yes

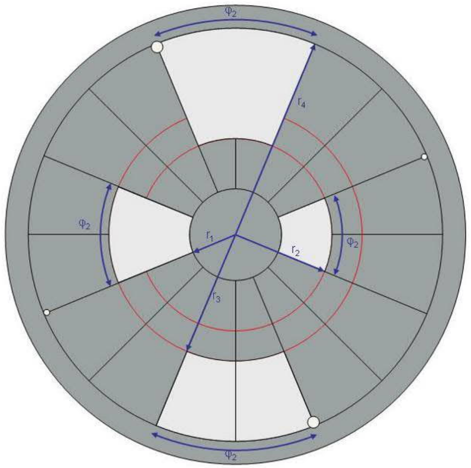
/home/tropic/data1/work/
eROSITA-FM1-X7-CAL/
MM_in-focus_on-axis_12-12-pixelscan_Cu-K/

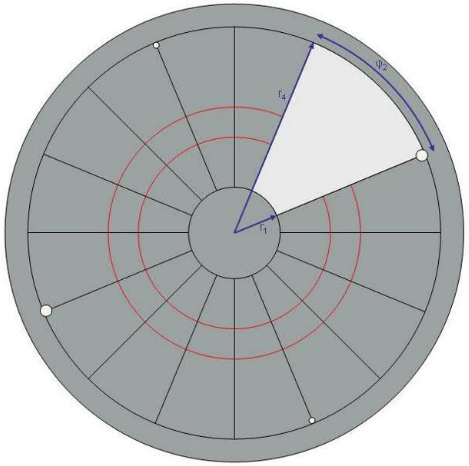
first 3.0 s and last 2.0 s of each exp skipped
--> 2.0 % of all events ignored
encoder positions used: no
bad column numbers:
none

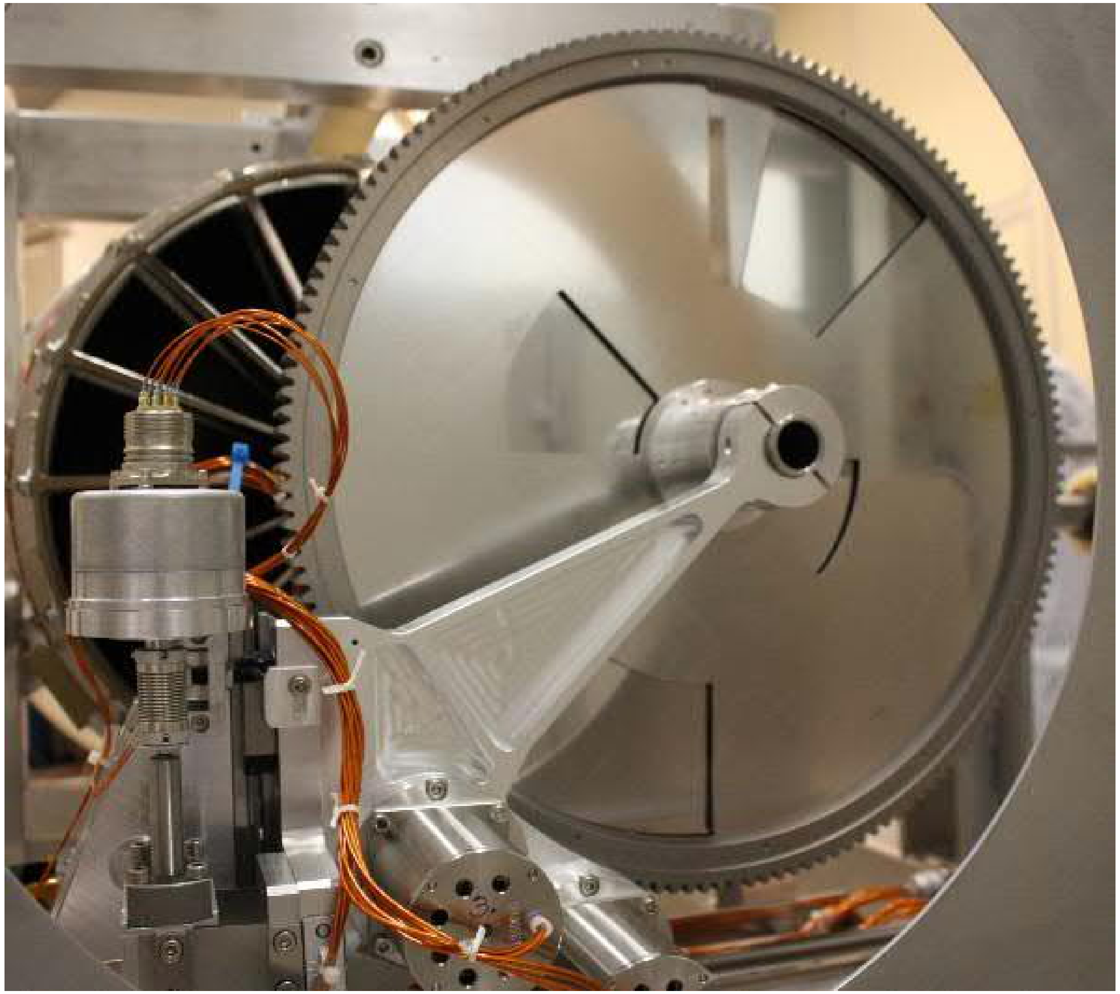
reference frame: HK150909_0108.fits
HEW center: 182.00 193.09



Calibration: Setup for Effective Area on-axis measurements

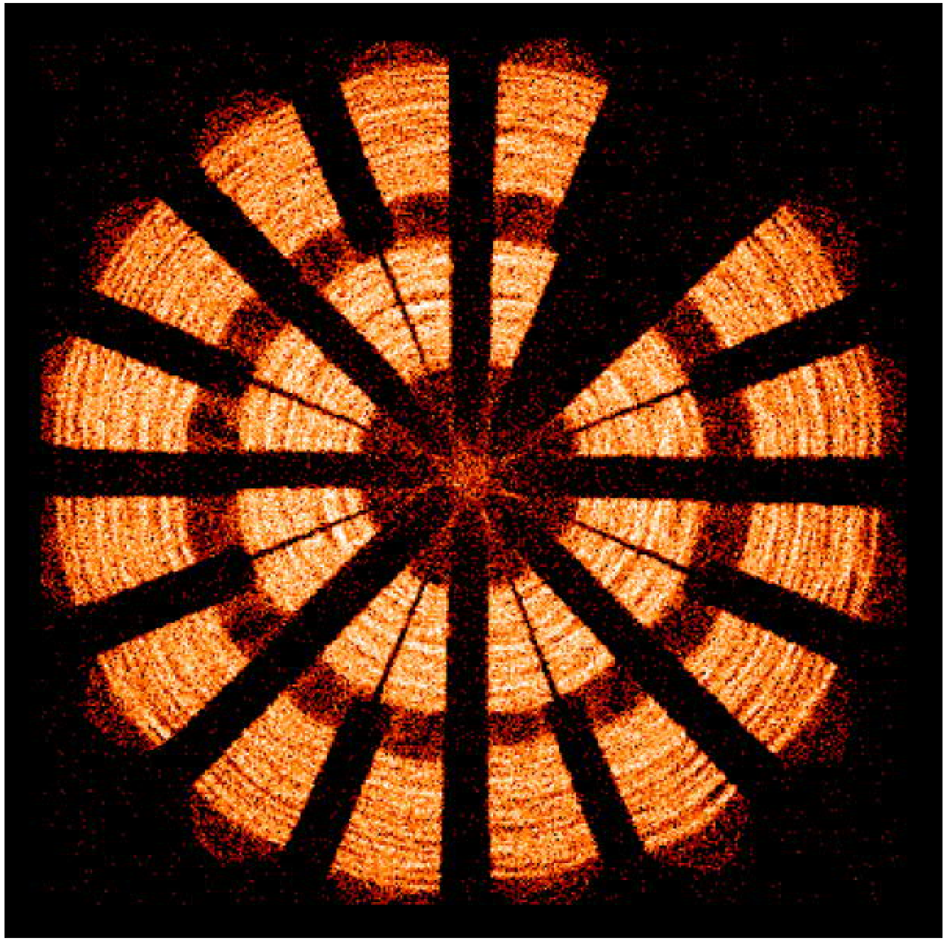




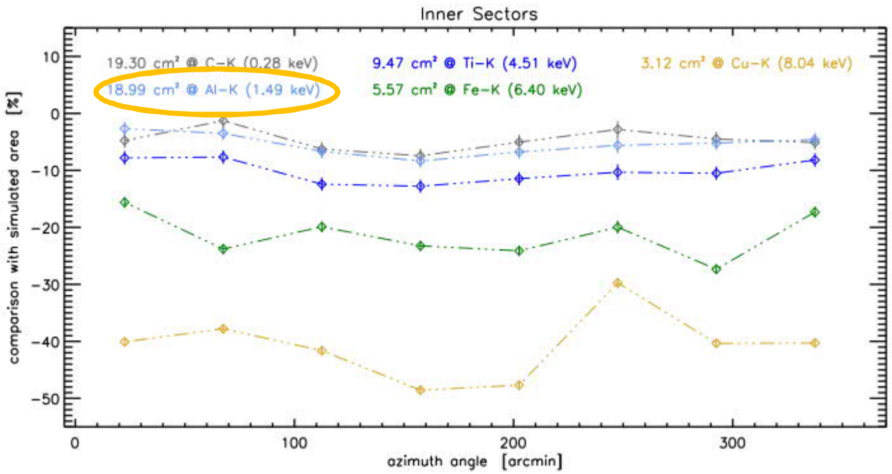


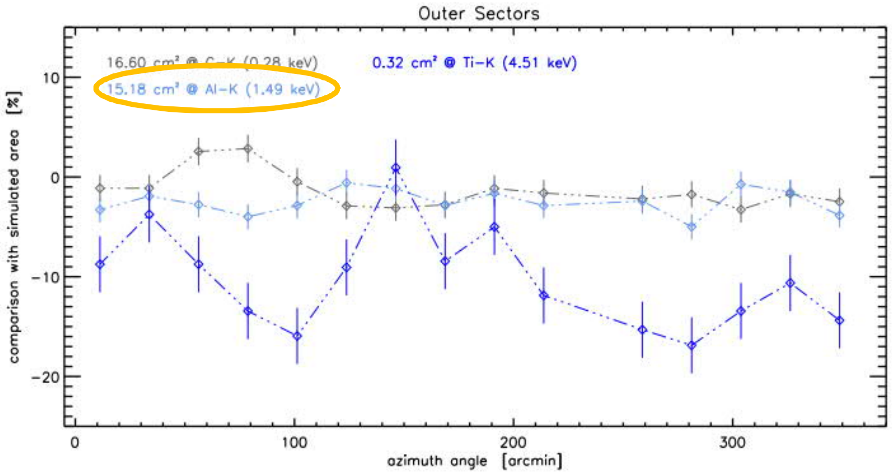
Quasi parallel beam with the “Glücksrad” configuration

Calibration: Effective Area on-axis, results for 1.5 keV



Al-K 1.49 keV

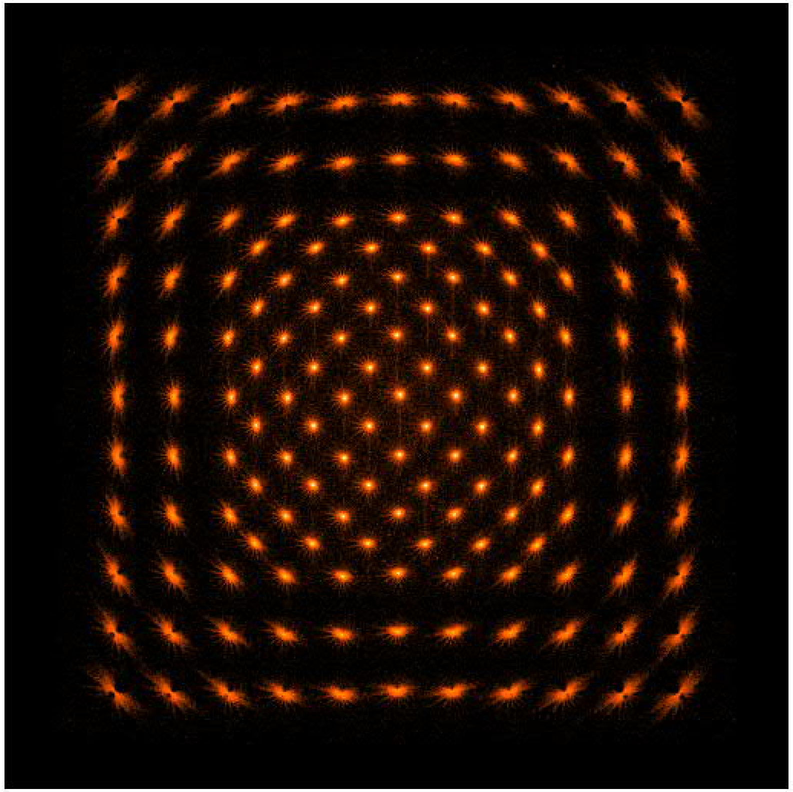




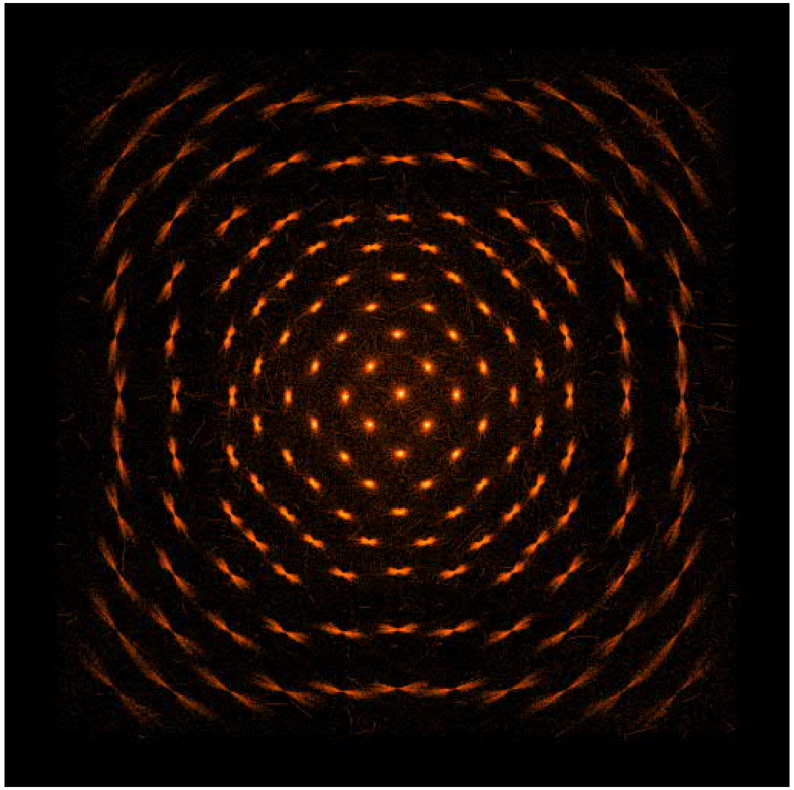
from Gisela Hartner (MPE, PANTER)

Quasi parallel beam with the “Glücksrad” configuration

Calibration: Effective Area off-axis



Al-K 1.49 keV

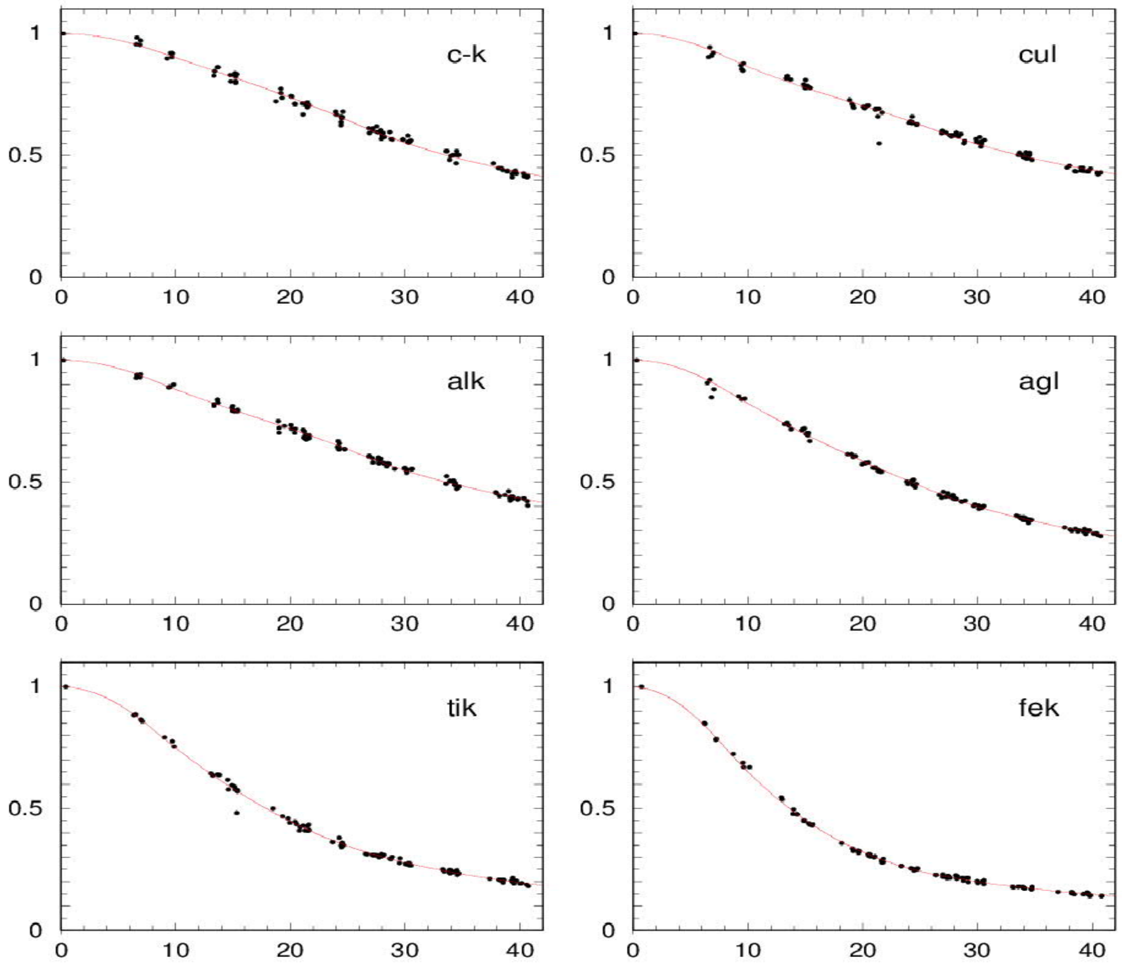


Fe-K 6.40 keV

from Konrad Dennerl (MPE)

Focal plane mapping for different energies

Calibration: Effective Area off-axis

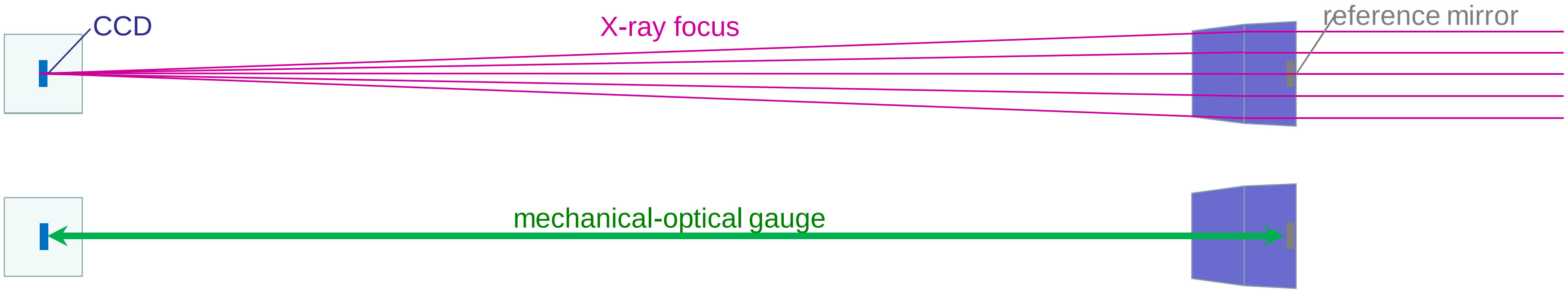


from Konrad Dennerl (MPE)

Focal plane mapping for different energies → vignetting function

Focal Length

(1) X-Ray Calibration



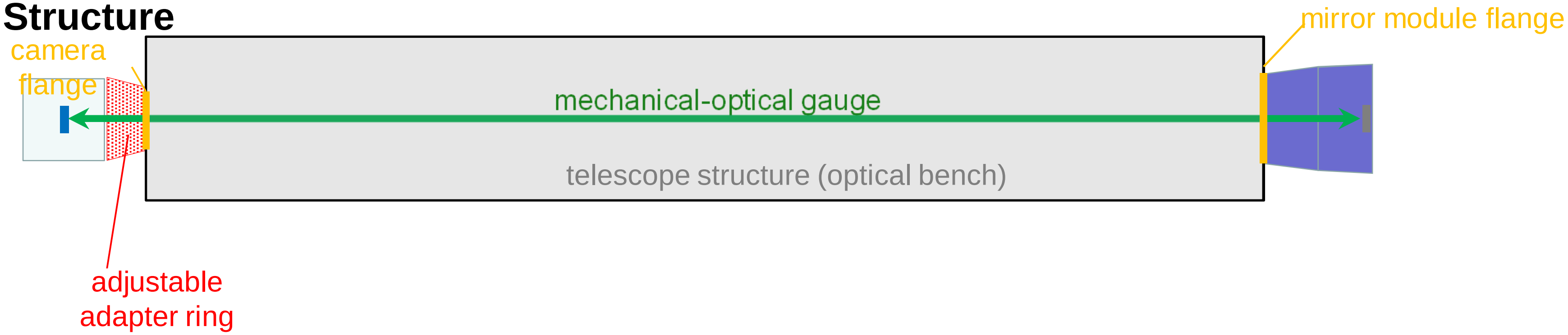
CCD

X-ray focus

reference mirror

mechanical-optical gauge

(2) Mounting into Telescope Structure



camera flange

mirror module flange

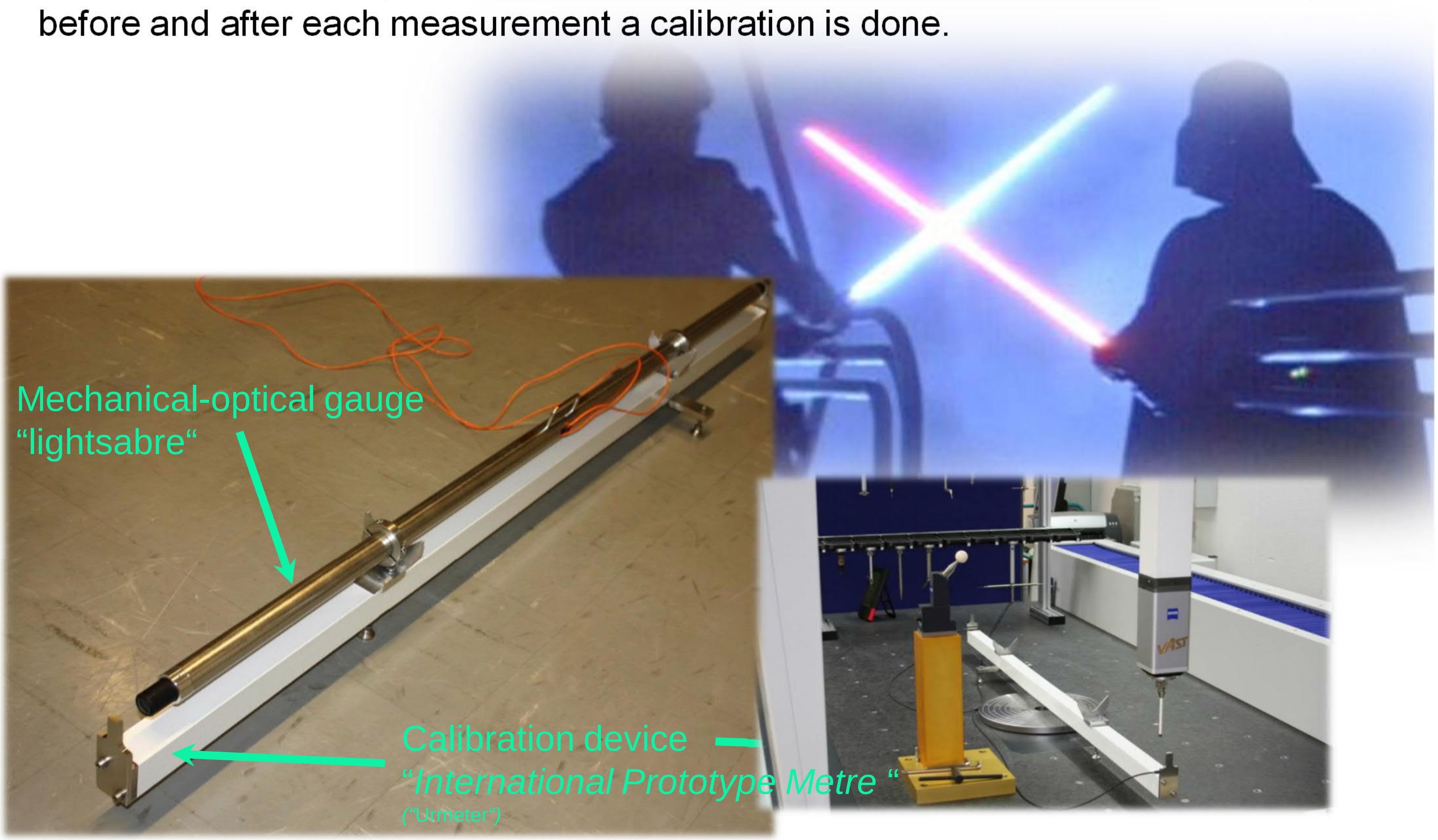
mechanical-optical gauge

telescope structure (optical bench)

adjustable adapter ring

Focal Length Gauge

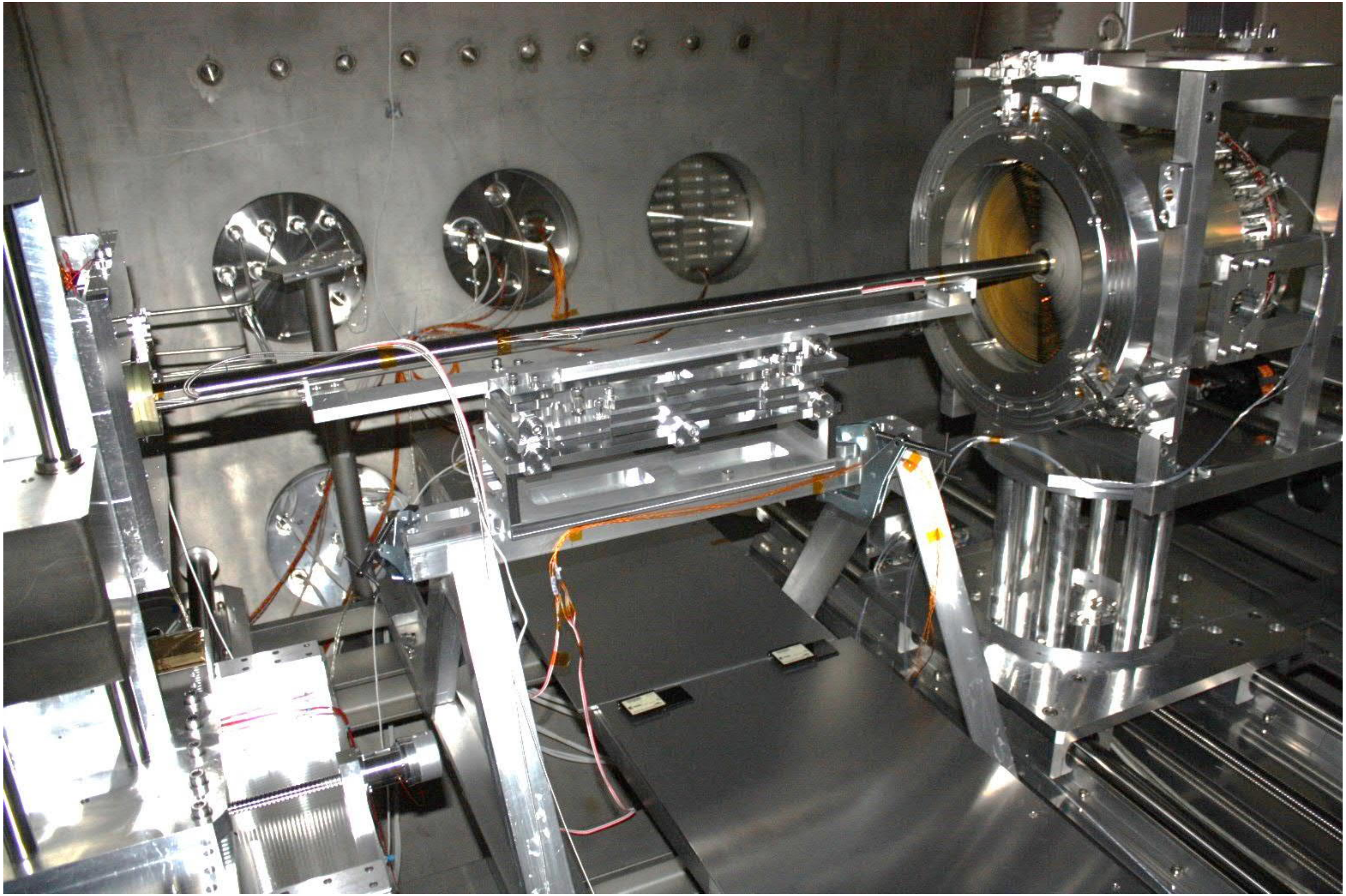
The focal length is measured with a mechanical-optical gauge giving the distance between the in-focus position of the detector and the reference mirror in the MM; before and after each measurement a calibration is done.



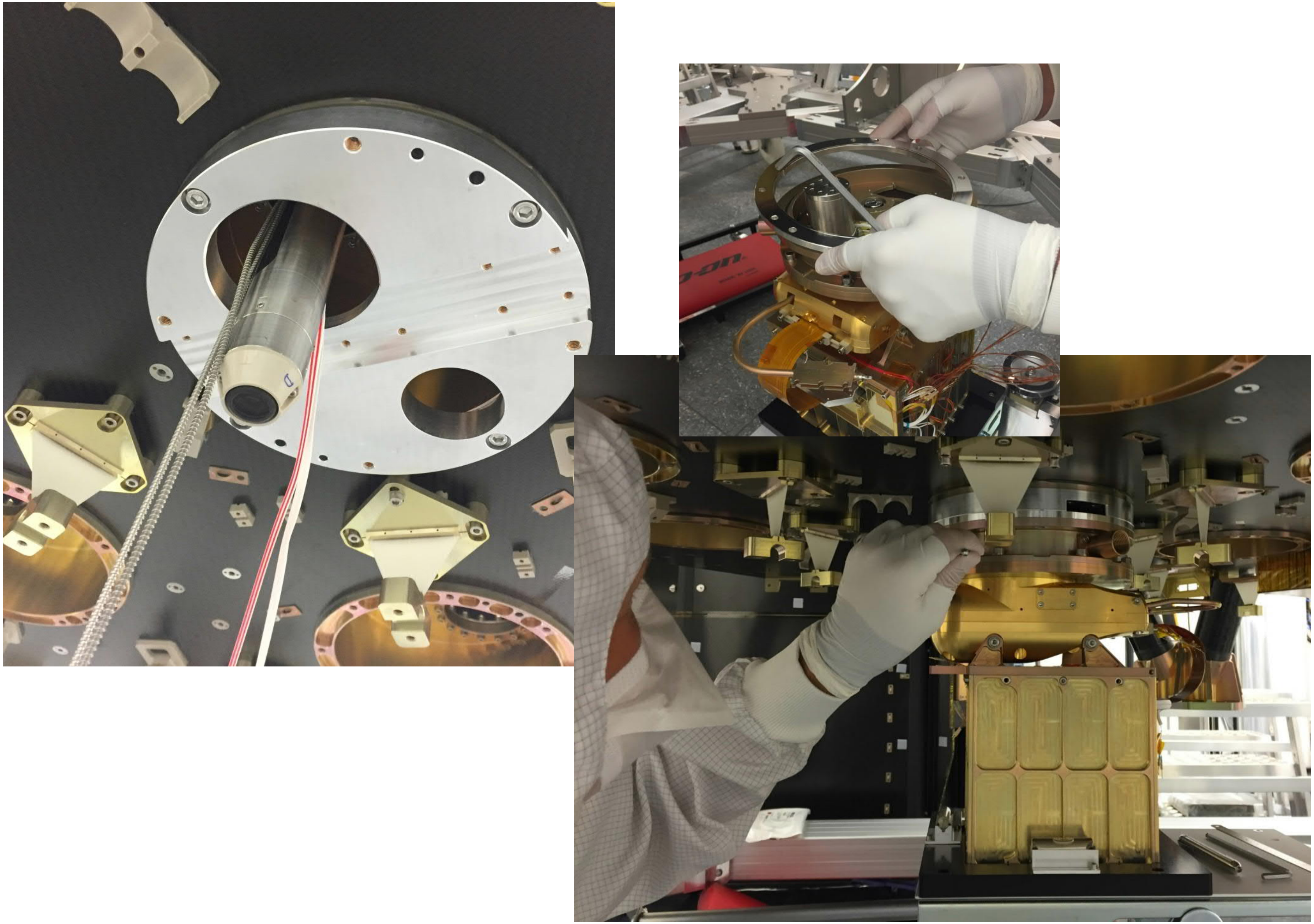
Mechanical-optical gauge
“lightsabre“

Calibration device
“International Prototype Metre “
(“Urmeter”)

New Gauge (vacuum proof)



Focal Length Adjustment in the Telescope Structure



4.6. Telescope assembly

Movie: Integration of the final Telescope Module

eROSITA at NPO Lavochkin in Moscow