Czech Technical University
in Prague

X-ray Optics for Astrophysical Applications

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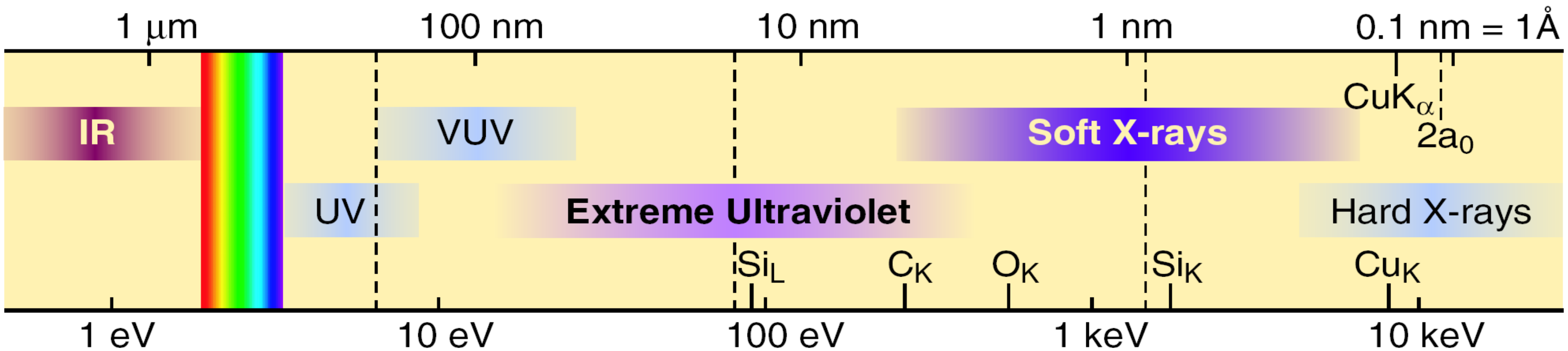
Introduction

- X-ray spectrum
- X-ray grazing incidence optics in Czech Republic
- X-ray grazing incidence optics basics
- Rotational symmetric and Multi-foil X-ray mirrors
- Selected space applications of X-ray mirrors

Electromagnetic radiation spectrum



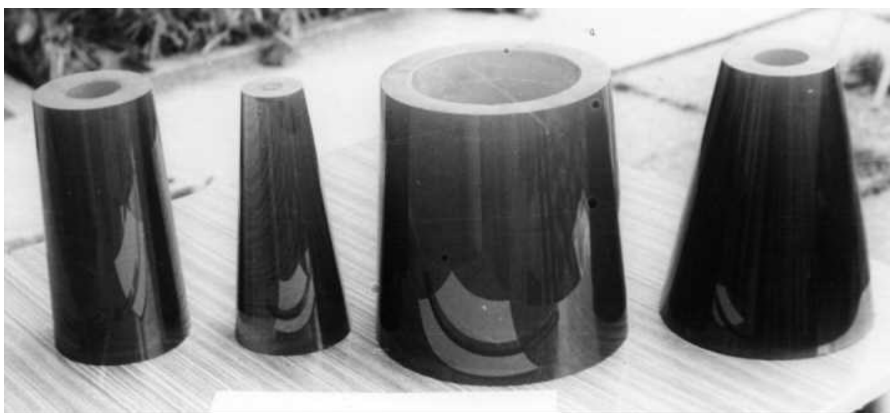
D. T. Attwood *Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, Cambridge, 1999)

13.5 nm / 92 eV	**EUV Lithography**
6.2 nm / 200 eV	**BEUV Lithography**
2.34 – 4.39 nm / 283 – 531 eV	**Water Window Microscopy**
5 – 17 keV	**X-ray Microscopy**

Laboratory → 50 eV – 10 keV Space applications

Grazing Incidence (GI) replicated X-ray Optics
49 years of research and development in Czech Republic

Replication Technology for X-ray Optics Manufacturing



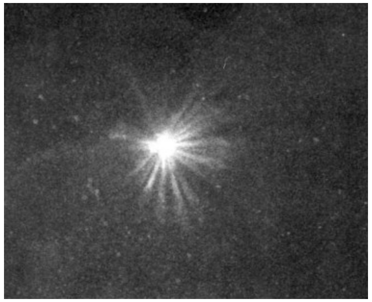
Mandrels used for the manufacture of X-ray mirrors (Glass ceramics Sital, Acad of Sci, Prague, 1969)

Replicated X-ray mirrors (hyperbolas, Ni surfaces, Acad of Sci, Prague)

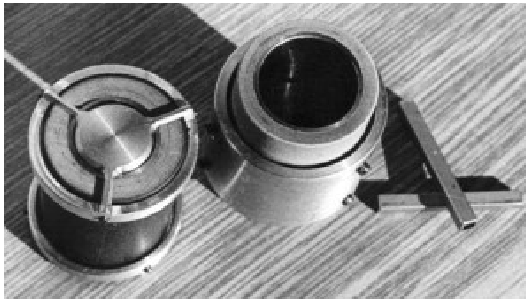
History – milestones and examples of projects
(Academy of Science, Czech Technical University, Reflex, Rigaku)

- **1969 First considerations started**
- **1970 First X-ray mirror produced (Wolter 1, 50 mm)**
- **1971 Wolter 1, 80 mm**
- **1976 Wolter 1, 115 mm**
- **1979 First mirrors flown in space (two Wolter 50 mm, Vertikal 9 rocket)**
- **1980 Vertikal 11 rocket (two Wolter 50 mm)**
- **1981 First large Wolter mirror (240 mm)**
- **1981 Salyut 7 orbital station (Wolter 240 mm nested)**
- **1985 Applications for plasma physics, EH 17 mm, PP 20 mm**
- **1987 First high quality X-ray foils for foil mirror X-ray telescope (SODART)**
- **1988 Fobos 1 Mars probe, TEREK X-Ray Telescope**
- **1989 KORONAS I X-ray mirror, Wolter 80 mm**
- **1990 First Micromirror (aperture less than 1 mm, Bede Ltd.)**
- **1993 Collaboration with SAO, USA, WF X-ray optics started**
- **1996 First Lobster Eye test module produced, Schmidt geometry**
- **1997 Double-sided X-ray reflecting flats (SAO MA USA, CTU Prague)**
- **1997 Lobster Eye Angel geometry project started**
- **1999 First Lobster Eye test module produced, Angel geometry**
- **2001 Thin segmented X-ray mirrors**
- **2005 Replicated Image Slicers for LEO, EU FP6 projects, Cambridge**
- **2006 MFO Kirkpatrick-Baez optic, University of Boulder, CO, NASA, USA**
- **2007 Innovative technologies for X-ray telescopes, PECS, ESA XEUS projects**
- **2008 – 2018 EUV/BEUV/WW/SXR/XR Grazing Incidence mirrors …**

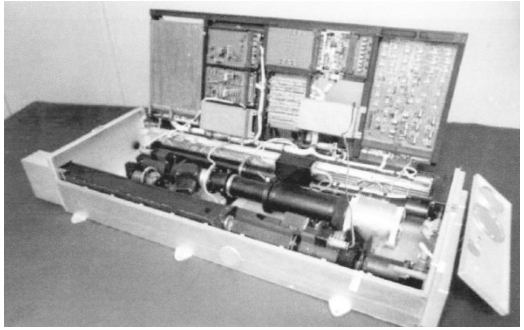
Examples of Imaging GI X-ray optics



X-ray image of the
laser plasma by the
17 mm EH microscope
(IPPLM Warsaw)

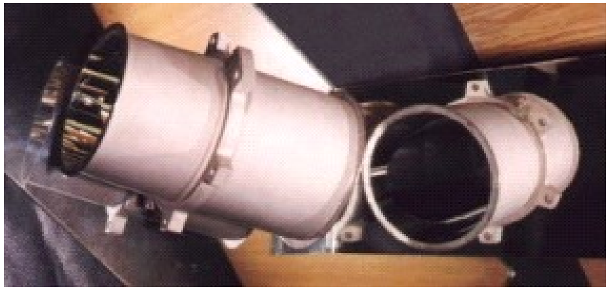


1985 Applications for plasma physics
(EH 17 mm, PP 20 mm)



1988 FOBOS 1 Mars probe,
TEREK X-ray telescope

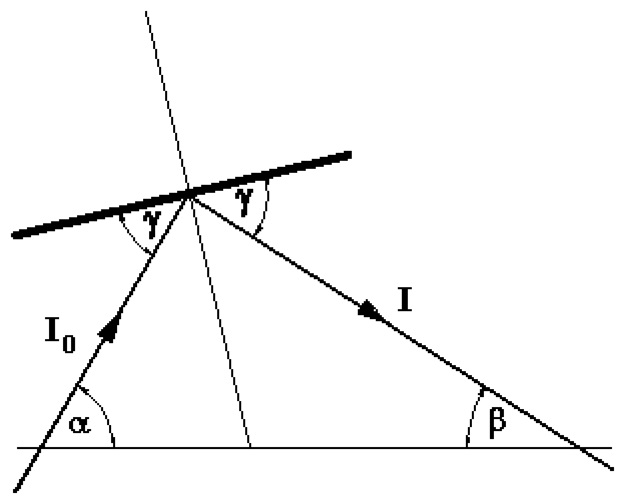
1989 KORONAS I
(Wolter 80 mm)



GRAZING INCIDENCE X-RAY MIRRORS

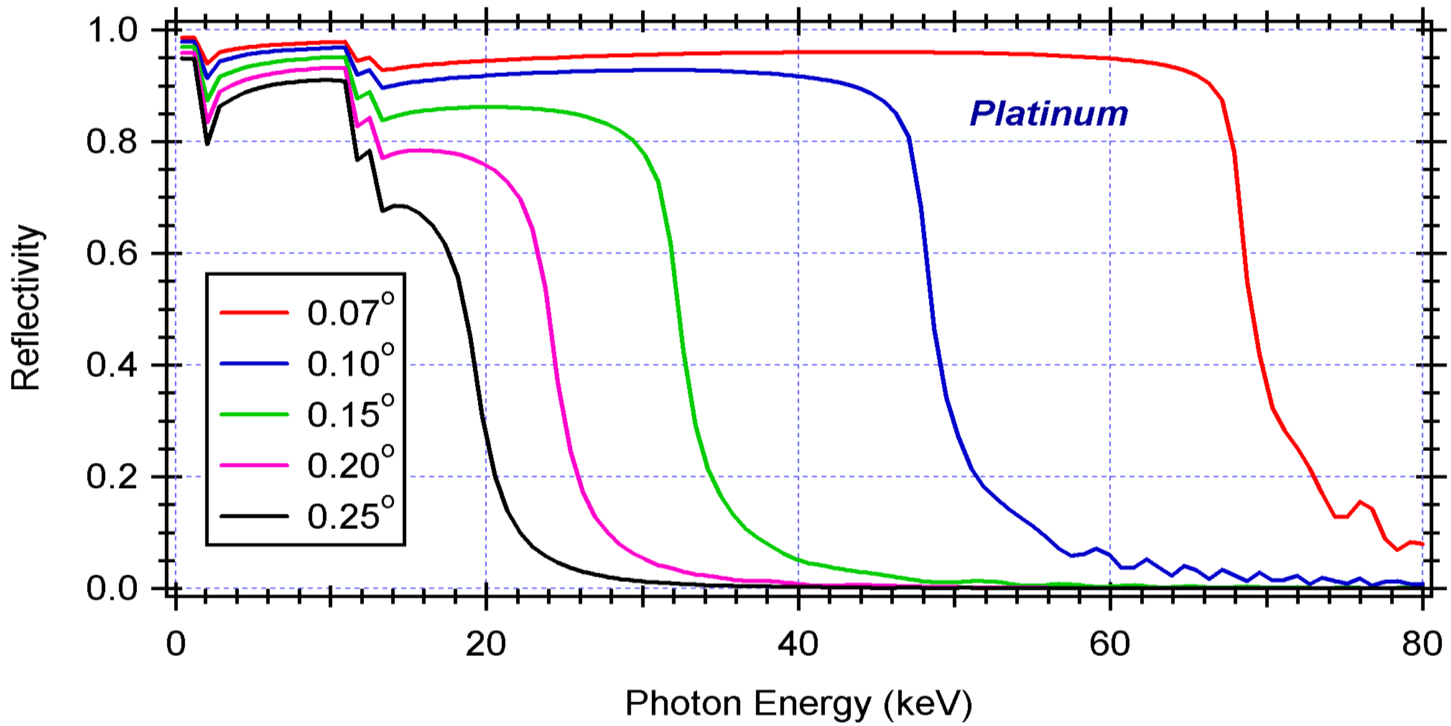
Flat X-ray Mirror

FLAT MIRROR

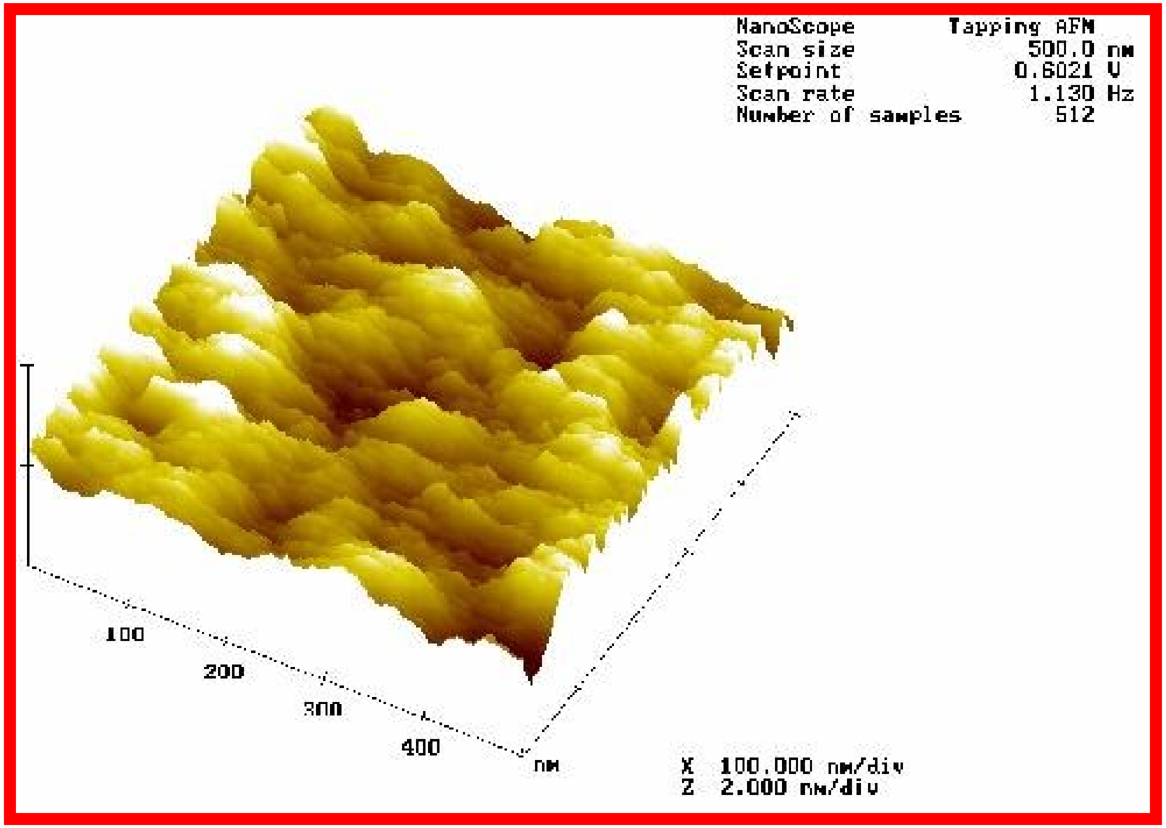


$$\gamma = \frac{\alpha + \beta}{2}$$

Variation of reflectivity with X-ray energy and grazing angle (Pt)

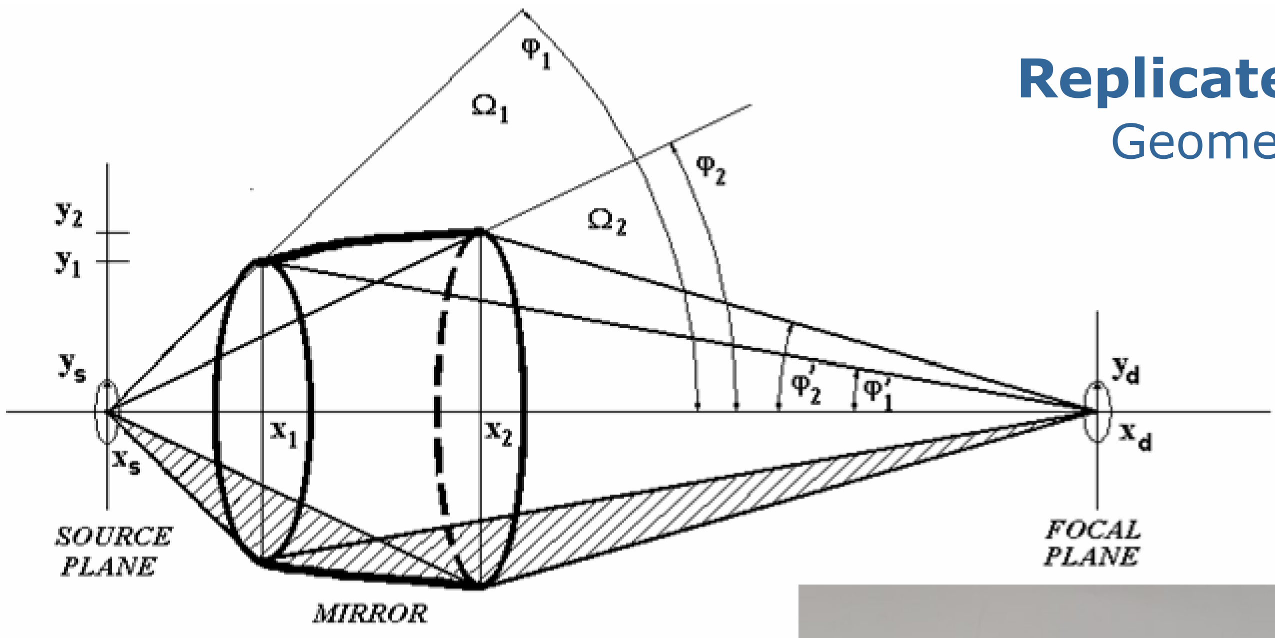


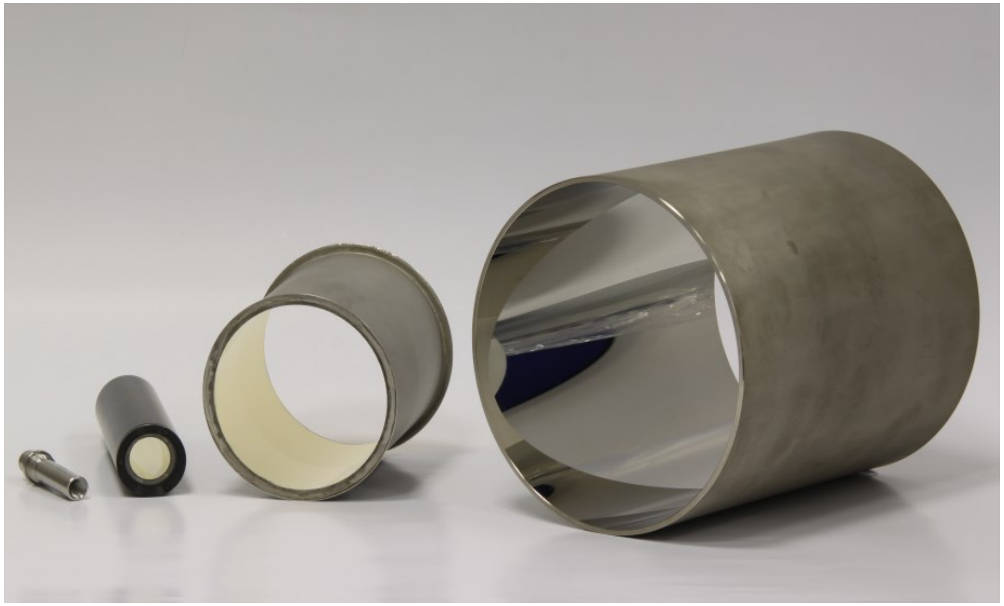
Microroughness of of Au coated X-ray mirror (AFM)



Tapping AFM images of the surface of the double - sided flats developed for Schmidt lobster-eye telescopes. The resulting microroughness RMS is 0.3 nm. Test facility at the Astronomical Observatory in Brera, Italy.

Replicated GI Mirrors
Geometry and size





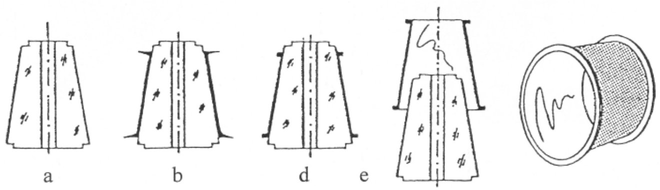
Example: Elliptical mirror

- **Mirror surface has shape of rotational ellipsoid**
- **Source is placed in left focus**
- **Detector or sample is placed in right focus**
- **Radiation strikes mirror surface at grazing angles 0,5° ÷ 20°**
- **Mirror is focusing radiation from left focus on right focus**

Replication technology

- Replication technology developments in the Czechoslovak Acad. of Sci., National Research Institute for Materials (1969)
  - 2-3 mirrors from one master

- Improvement of replication technology:
  - less damage of mandrel
  - reduced weight



a - master,
b - master with electroformed nickel layer
d - cutting/finishing of the edges
e - removing the Ni mirror shell

- Laboratory and space applications
  - Wolter objectives 17 mm and 20 mm dia
  - EH Wolter used (1985) for taking photographs of laser plasma in Institute of Plasma Physics and Laser Microfusion in Warsaw

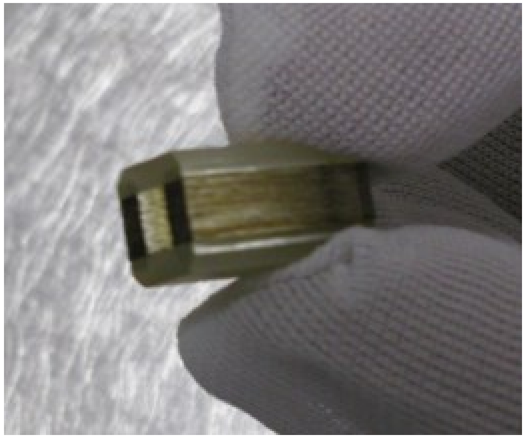
Replication technology

MANDREL
with Au surface
layer

Ellipsoidal mirror for
spectral region
10 – 15 nm

Now manufactured by Rigaku Innovative Technologies Europe

- A part of Rigaku Corporation group (Tokyo, Japan)
- Established in 2008 as European center for the design, development and manufacturing of **X-ray optics**, **X-ray detectors** and **X-ray sources**
- Colaboration with Czech academic institutions and high-tech companies
- Ellipsoidal and parabolic optics for EUV/BEUV/WW/SXR/XR
  (laser plasma research, EUVL, WW and X-ray microscopy, space, …)
- Slope error < 10 arcsec (5“), microroughness < 2 nm (0.5 nm)



Replicated GI Mirrors

Ellipsoidal GI mirror for WW application (2.3 – 4.4 nm)

Ellipsoidal GI mirror For EUVL applications (10-15 nm)

Rigaku

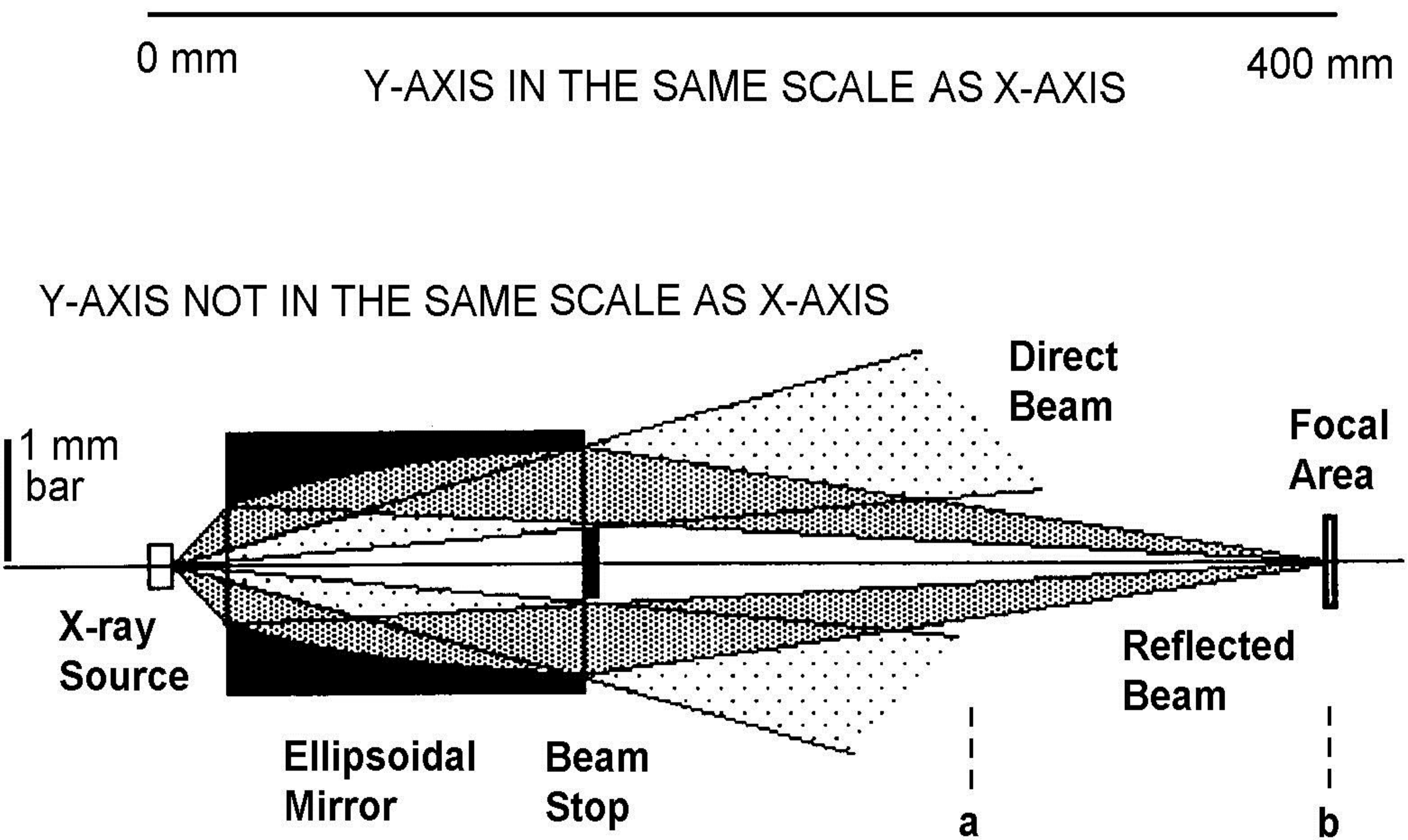
GI EUV Mirrors

Ellipsoidal GI EUV mirror for 13.5 nm

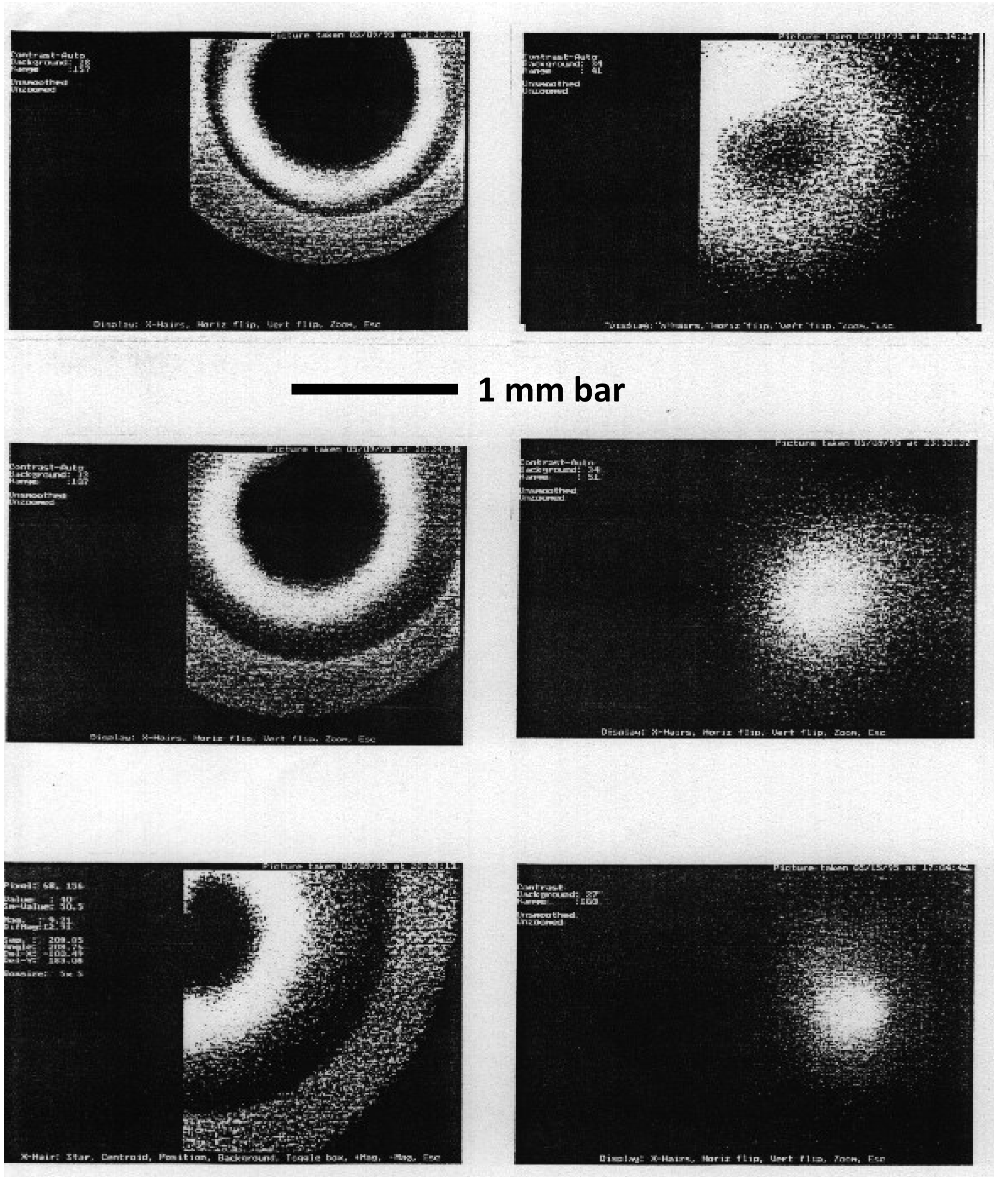
Ellipsoidal GI EUV mirror for 13.5 nm

Replicated GI Mirrors for Imaging and Analysis

Ellipsoidal optic for 8 keV microfocus source



Ellipsoidal optic for 8 keV microfocus source

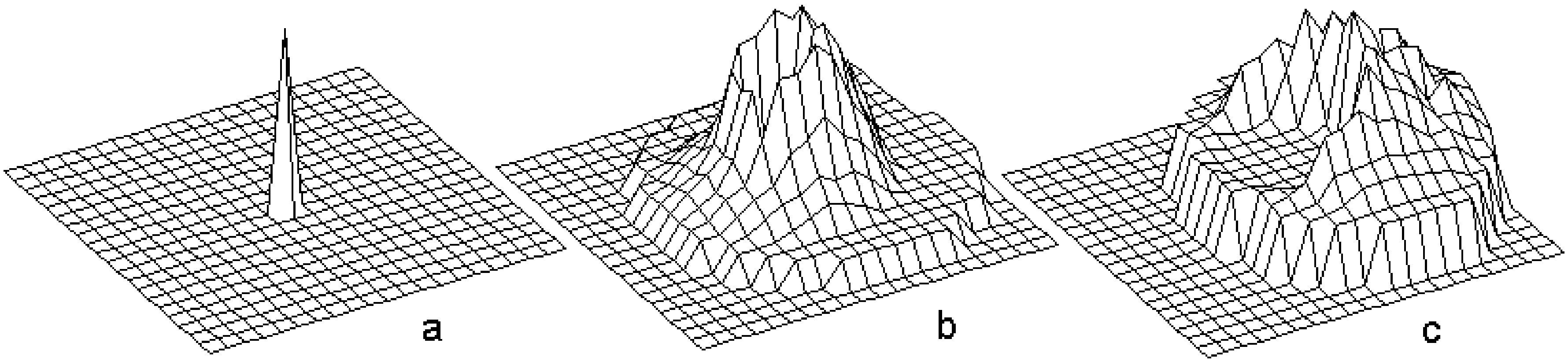


A series of X-ray beam images behind the output of ellipsoidal mirror with beam stop on the axis.

Converging reflected beam and diverging direct beam are clearly distinguishable.

Ellipsoidal optic for 8 keV microfocus source

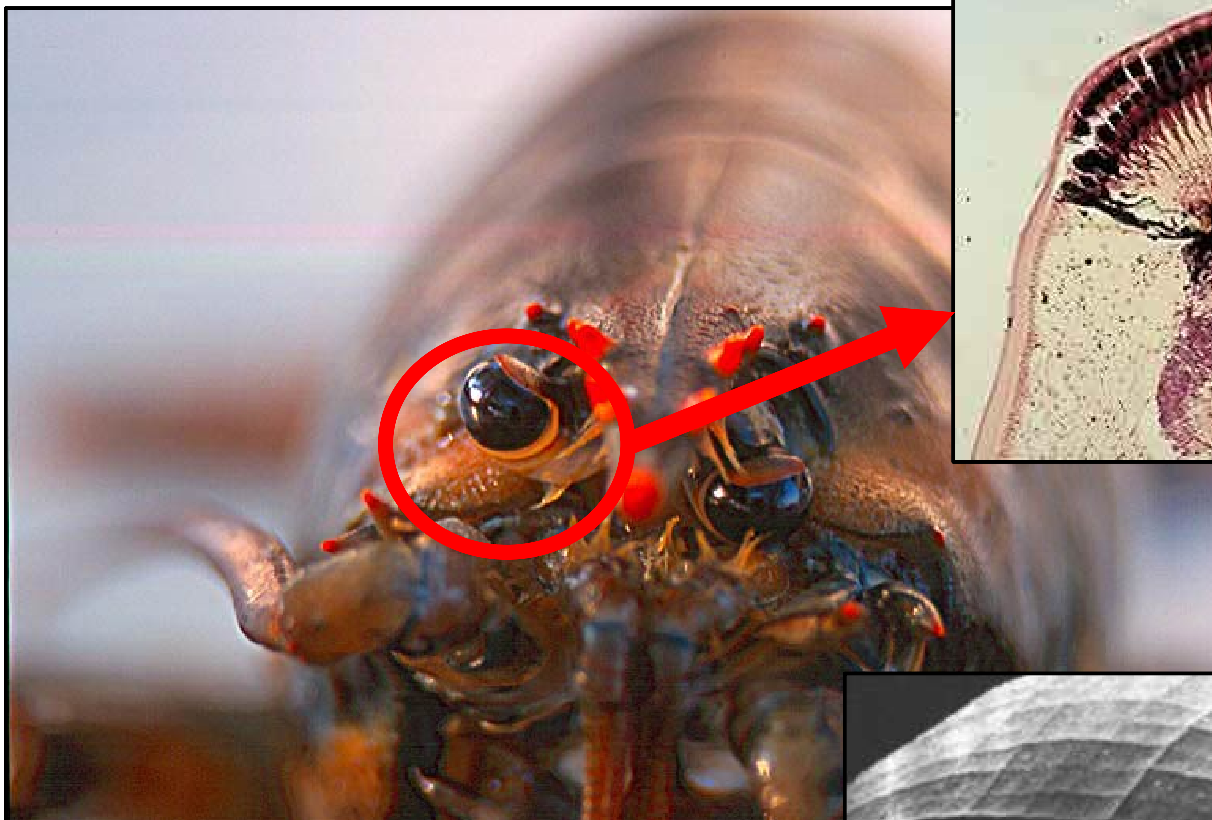
Focal spots for off-axis source position (ray-tracing model)

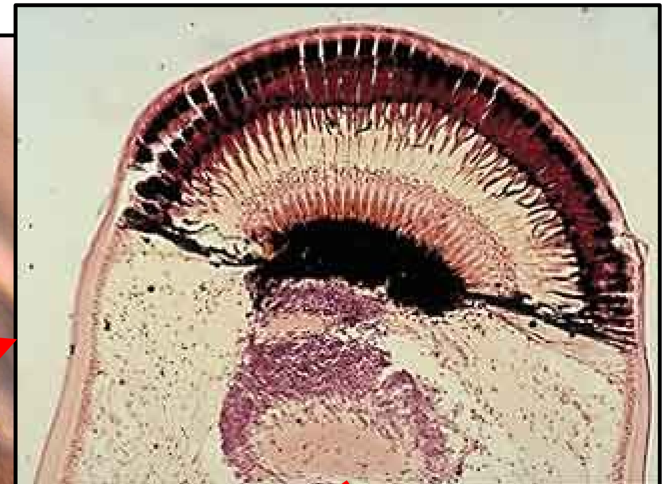


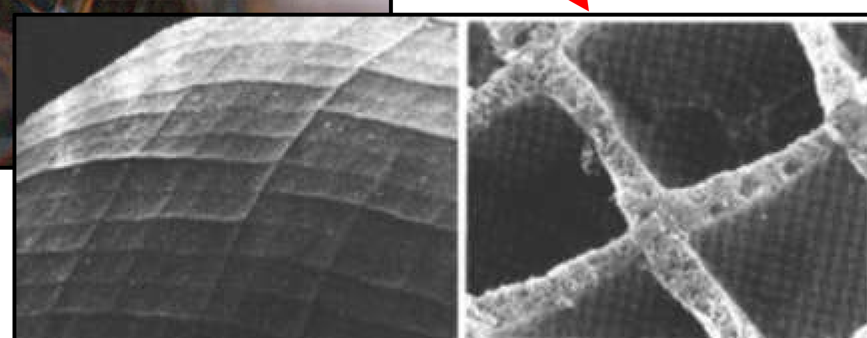
Graphs a to c showing the effect of point-like X-ray source off-axis displacement on the detector intensity distribution for ellipsoidal mirror.

a – 0 μm source displacement,
b – 200 μm displacement,
c – 400 μm displacement.

Lobster Eye

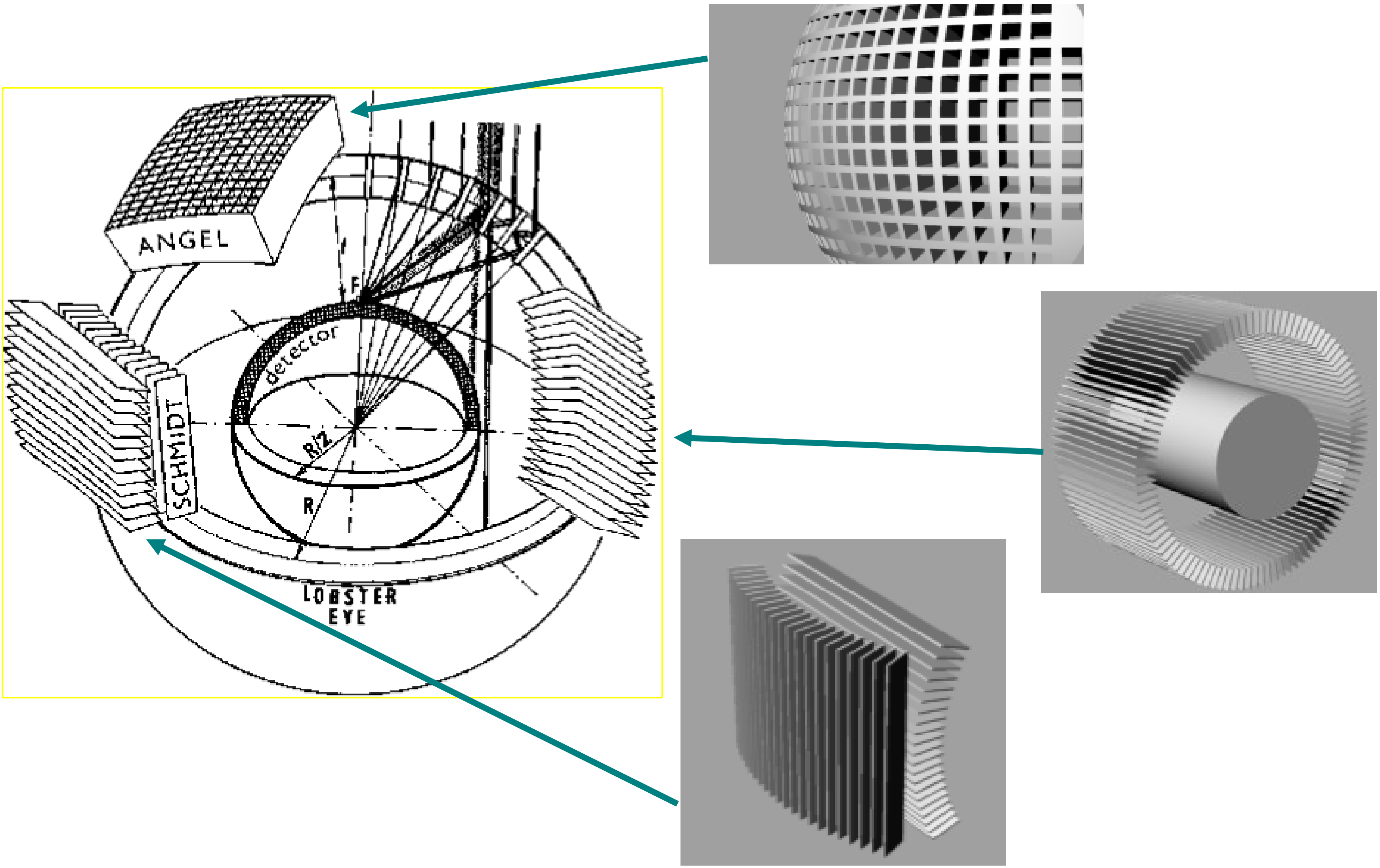




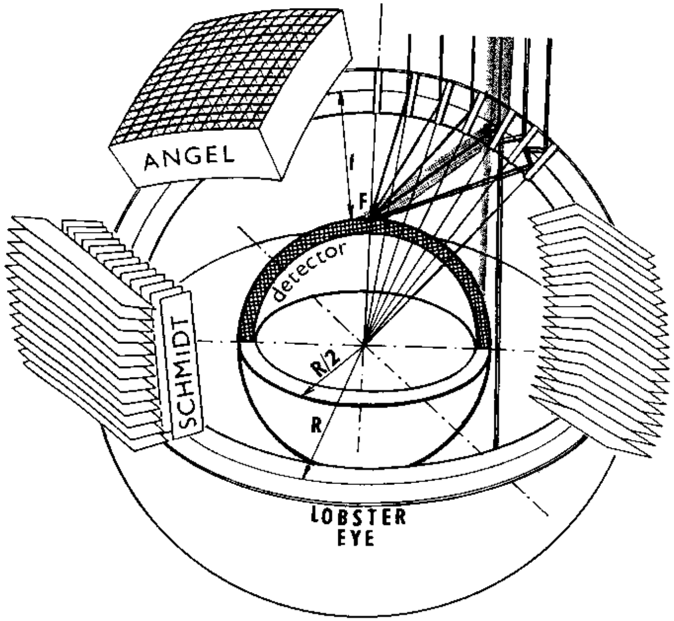


Channels – optical elements
Wide field optic

Lobster Eye (MFO) Optic Concepts

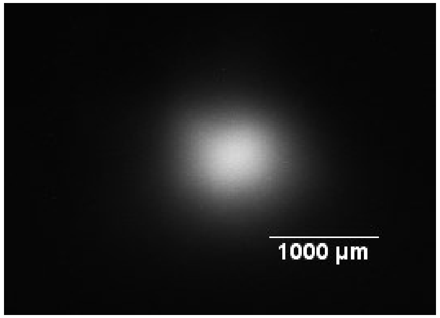


RITE multifoil optics



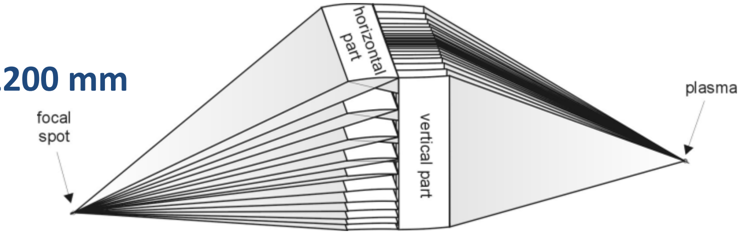
Wide FOV

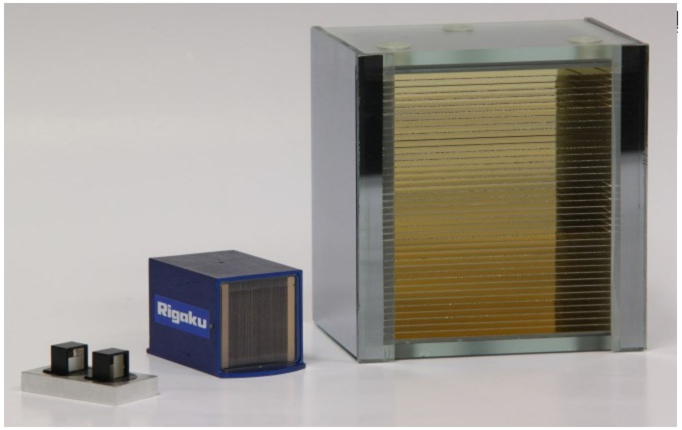
- Glass or silicon substrates
- Planar or ellipsoidal mirrors
- Foils 3×3 mm to 300×300 mm
- Thickness from 30 μm – 1 mm
- Wavelength: EUV – soft X-ray
- Surface: Au, Ni, Mo, Pt, W, ...



Lobster Eye

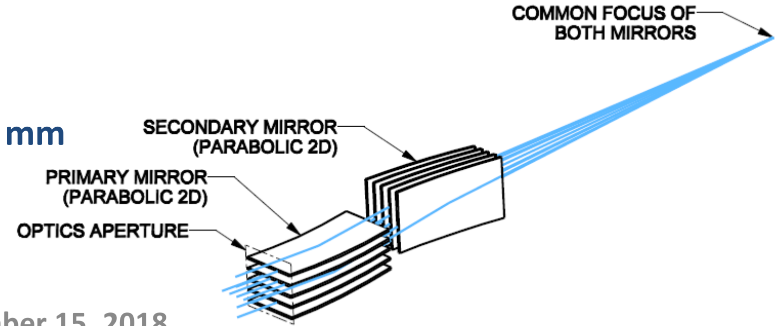
- 5 – 10 keV
- Focal length: 1000 – 1200 mm
- Imaging: 1:1
- Spot size: 0.5 mm
- FOV: 2°





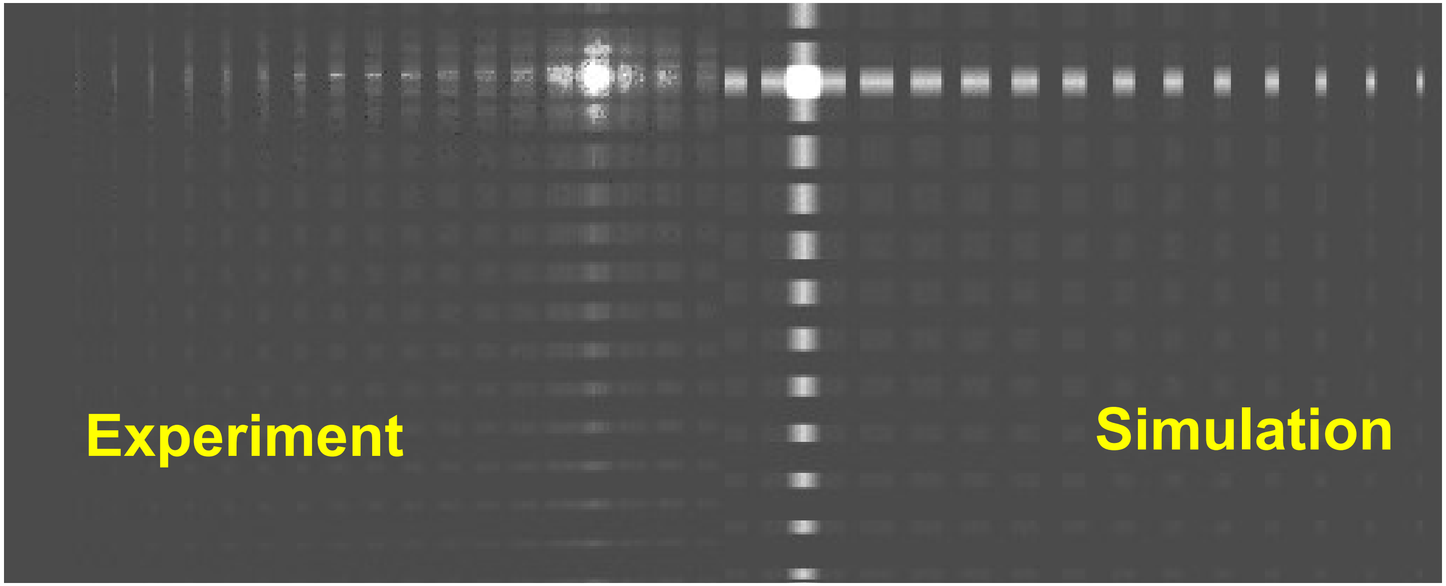
MFO KB system

- 80 – 120 eV
- FOV: 20°
- Spot size: 0.5 – 1.0 mm

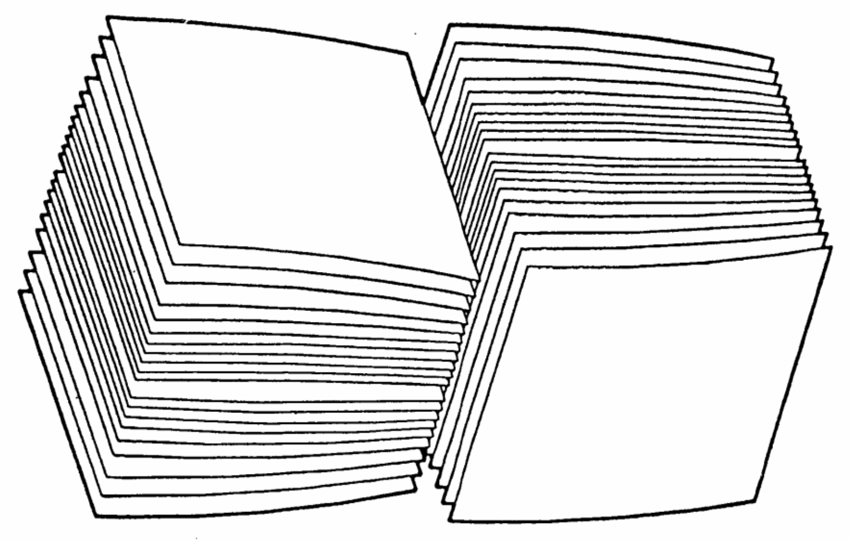


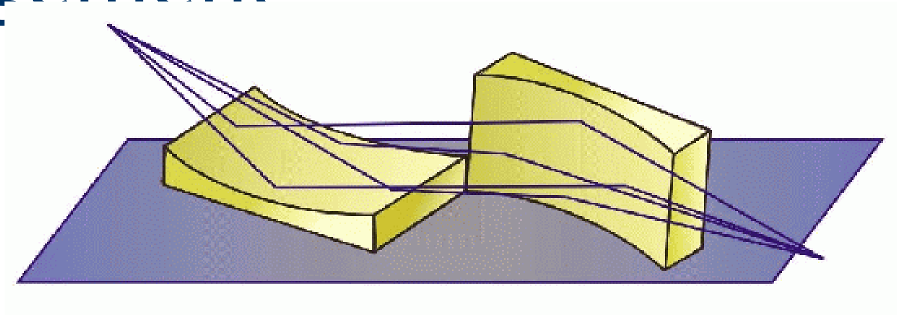
X-ray LE - experiment vs theory

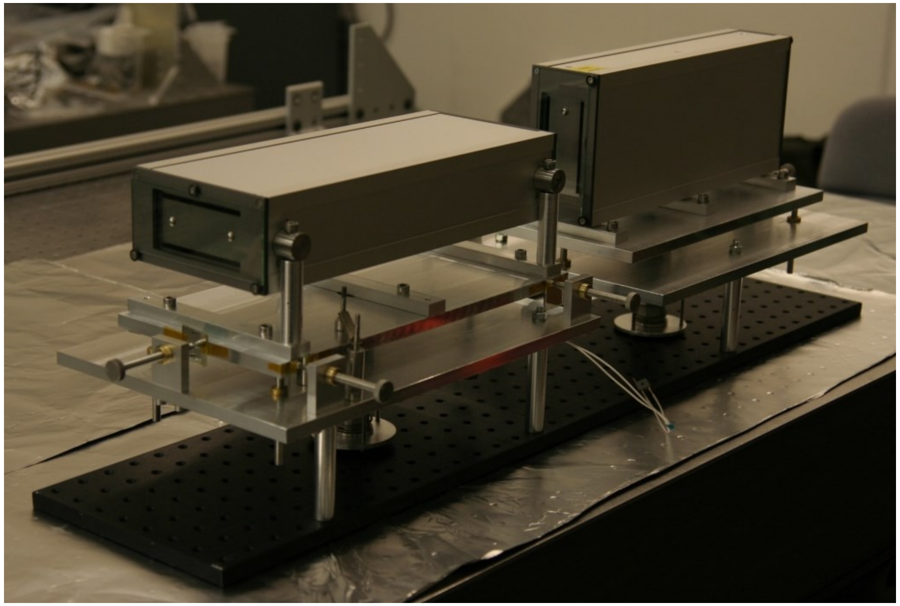
- Point-to-point focusing system
- Source: 20 μm size, 8 keV photons
- Source-detector distance: 1.2 m, 8 keV photons
- Detector: 512x512 pixels, 24x24 μm pixel size
- Intensity Gain: G=570 (experiment) vs. G=584 (comp. simulation)



Multifoil optics – Kirkpatrick-Baez Arrangement

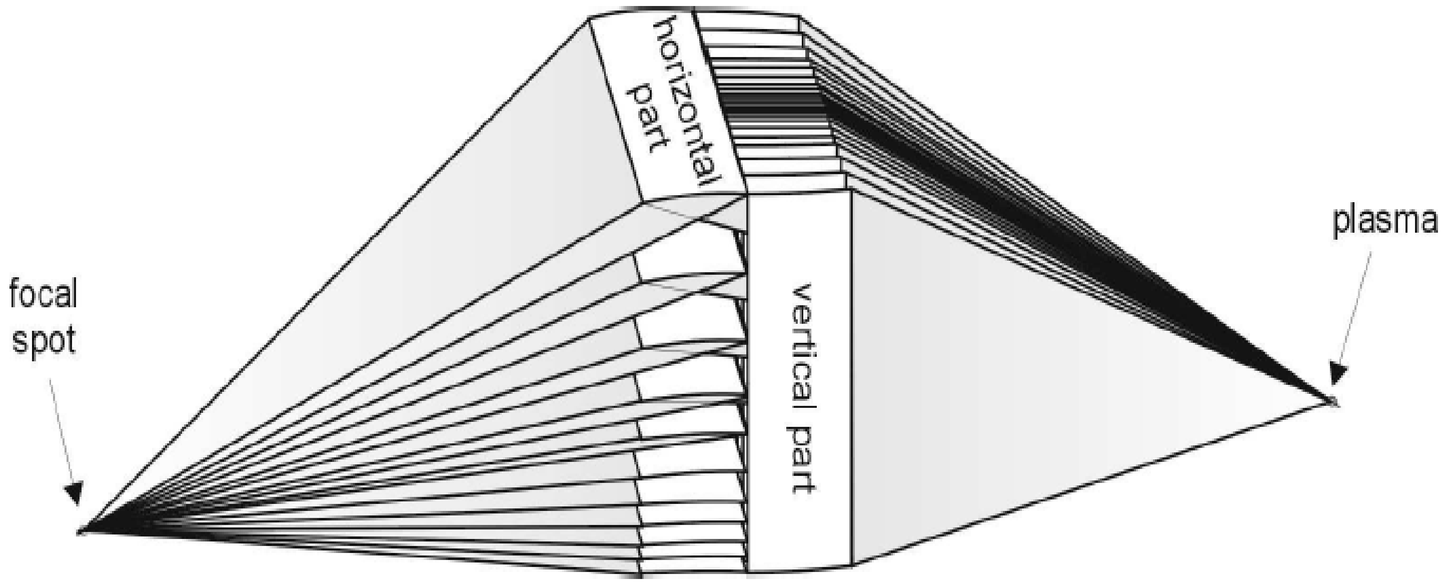




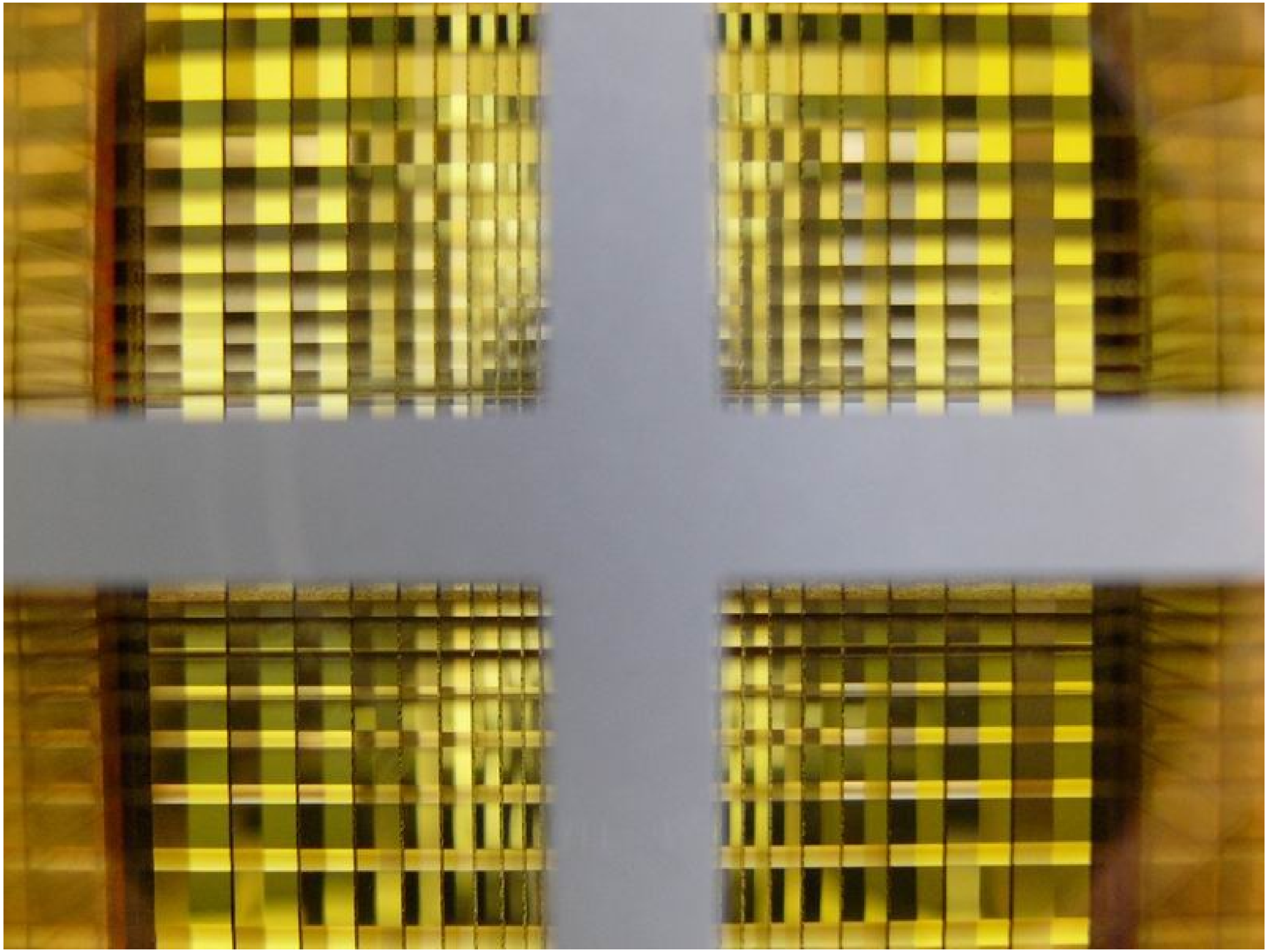


Kirkpatrick-Baez mirror consisting of orthogonal stacks of reflectors. Each reflector a parabola in one dimension.

Focusing of XUV radiation and XUV modification of materials (experiments at CTU, PALS and WAT)

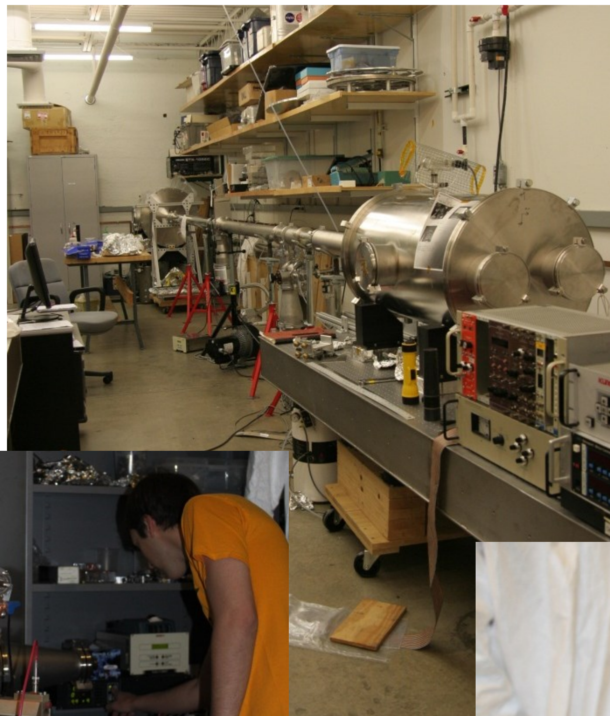


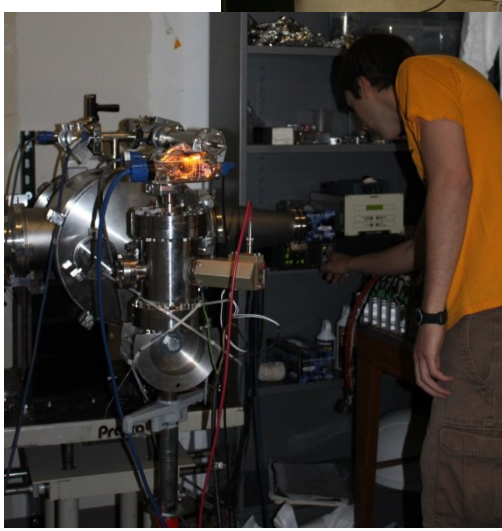
Schematic view of one half of the multi–foil (MFO) XUV bifacial Kirkpatrick-Baez condenser – experiments at WAT, Warsaw.

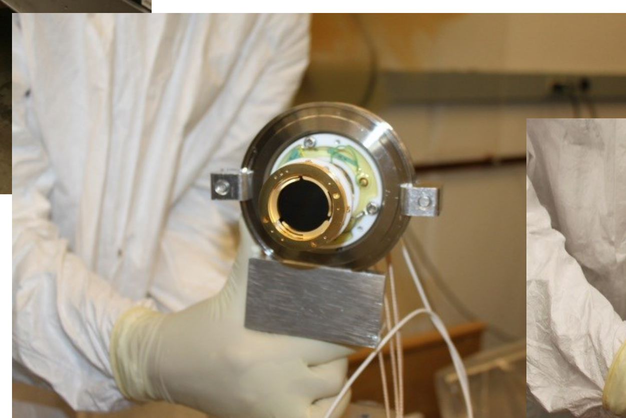


MF K-B system for EUV lithography

Vacuum chamber at CASA UC – testing in 2014



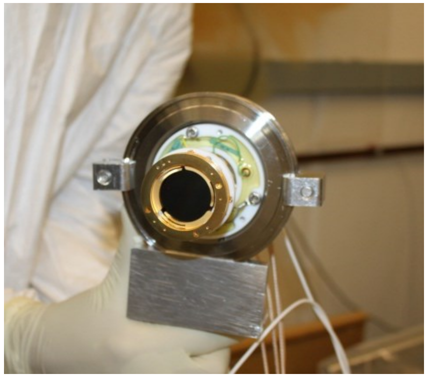




- X-Ray source with Ti anode
  (Lα, 453 eV, 2.73 nm)
- X-Ray beam diameter
  (diameter of vacuum tube) 8 cm
- Total vacuum chamber length 20 m
- MCP detector, diameter 1’’
- TIMEPIX detector, (MEDIPIX)

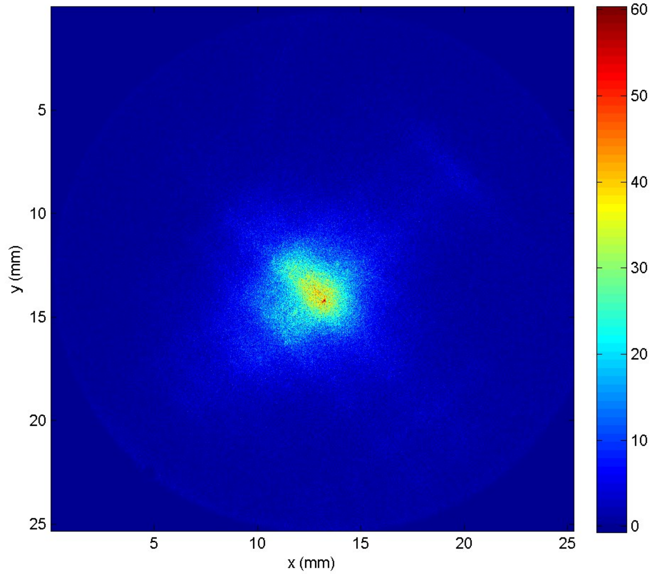
KB modules - test results

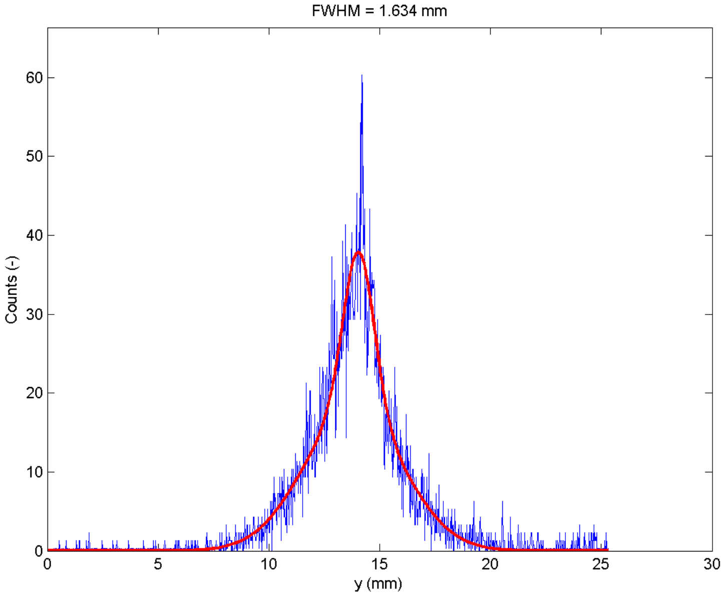
- MCP detector, diameter 1’’
- Energy of X-rays: **453 eV**



- FWHM = 1.63 mm

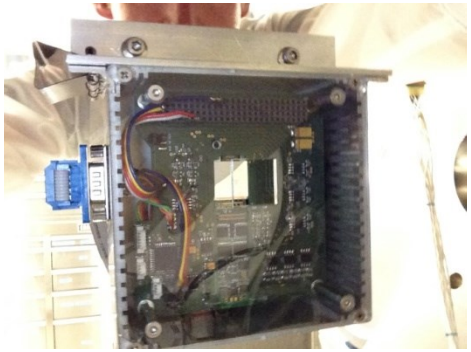
  Anglular resolution: **10.2 arcsec** (after ellips. correction)





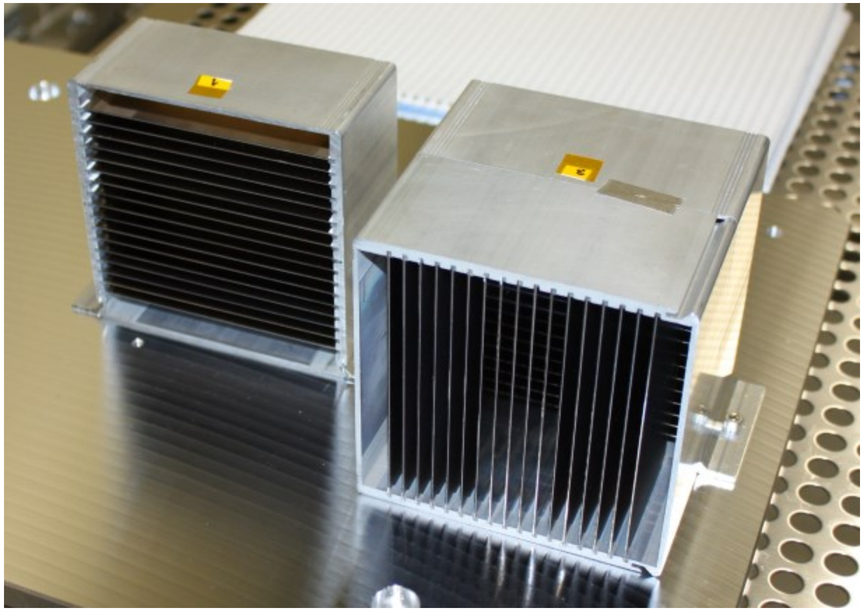
Optics for rocket experiment – testing in 2015

- X-ray testing with Timepix detector in vacuum chamber at the **University of Iowa**
- Energy: 8 keV (Cu Kα)
  1.25 keV (Mg Kα)
- Source-to-detector distance: 10 m



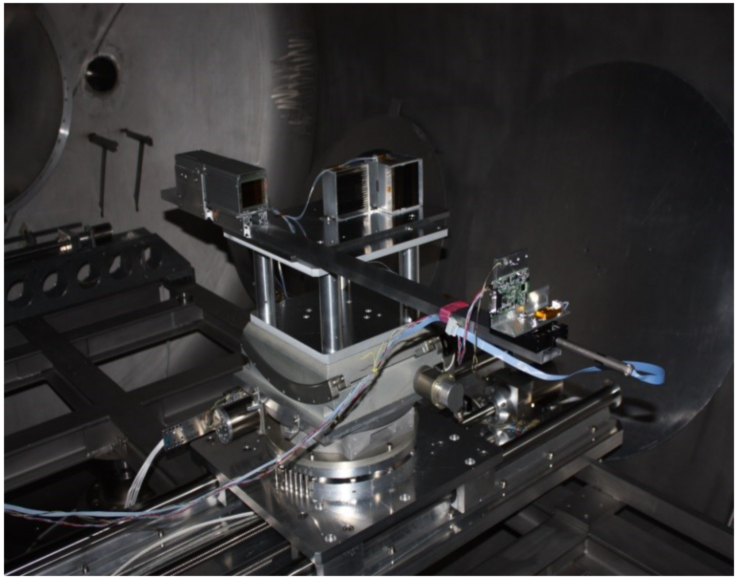
KB modules for Panter experiments

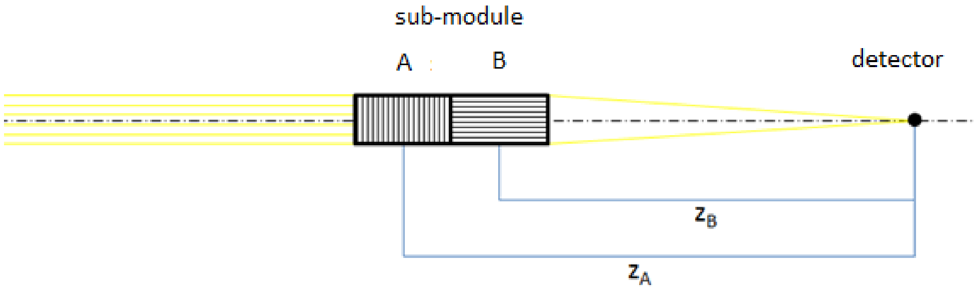
- Requirements:
  1. Calculated angular resolution using ray tracing should be better than 5 arcsec
  2. Possibility of testing at higher energies (1.5-30 keV),
- Commercially available 625 µm thick Si wafers with Au surface coating
- Foils arranged into planar-elliptical shape with axial symmetry
- Foils size 100 × 50 mm
- Spacing 4.5 mm
- Modules were redesigned for vacuum chamber at Panter facility, MPI



Panter experiments

- Source Energies:
  - Al Kα (1.49 eV)
  - Ti Kα (4.51 eV)/ Ti Kβ (4.93 eV)
  - Cu Kα (8.04 eV)
- Detector:
  - TroPIC detector
  - 256x256 px (75 μm pixel size)
  - Exposure time: 15 min





Source spectra

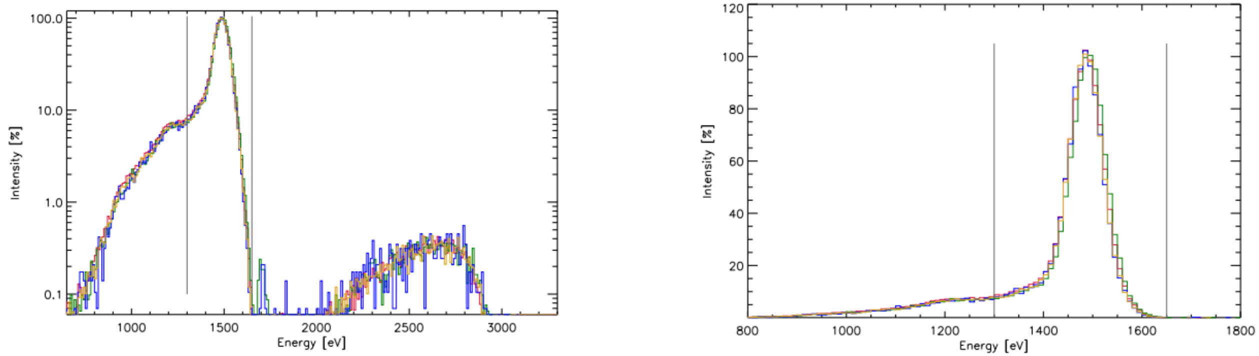


Figure 5: Spectrum – Al Kα, 1.49 keV @PANTER (left – range from 700 to 3300 eV, right – detail 800 – 1800 eV)

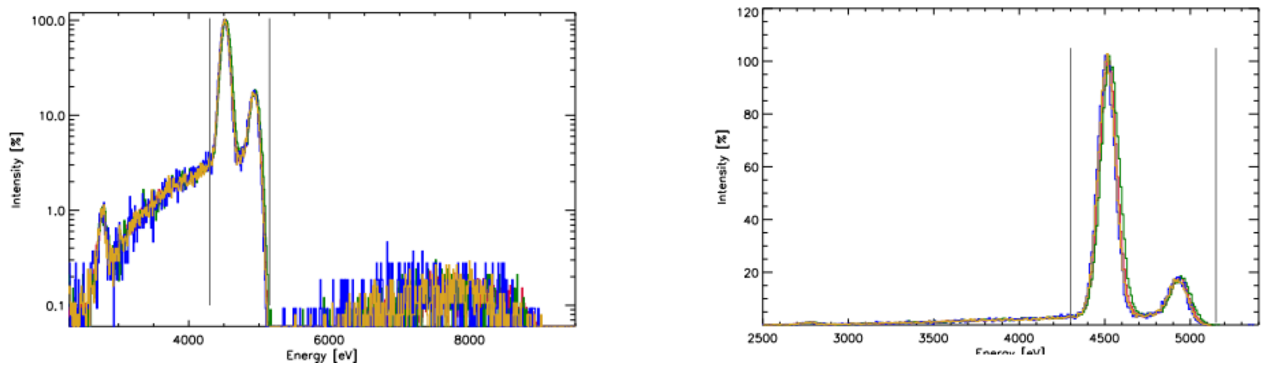


Figure 6: Spectrum – Ti Kα 4.51 keV/Ti Kβ 4.93 keV @PANTER (left – range from 2500 to 10000 eV, right – detail 2500 – 5400 eV)

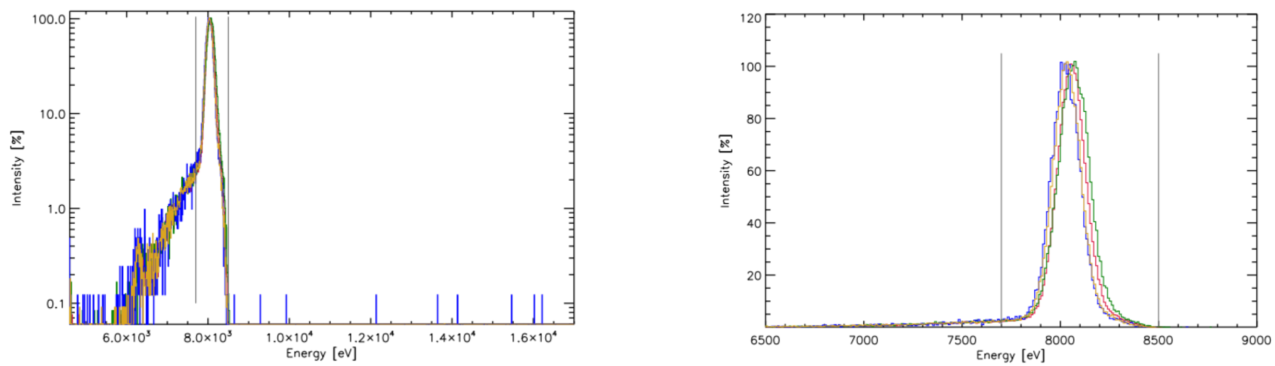
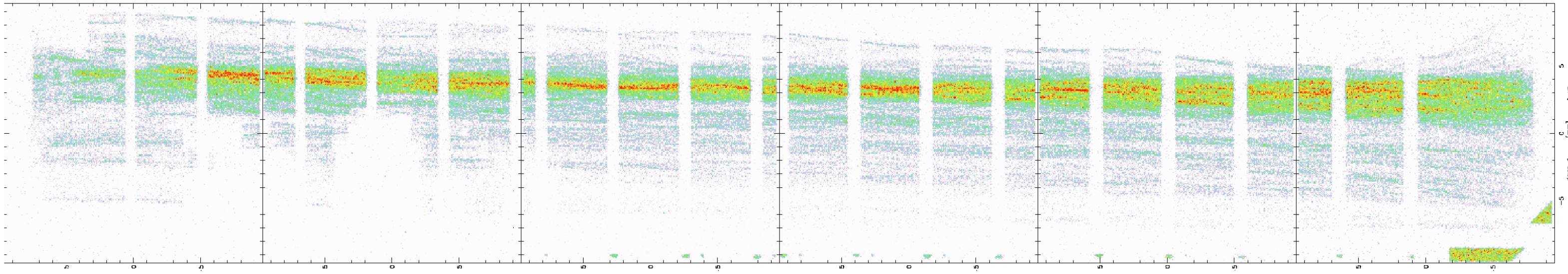
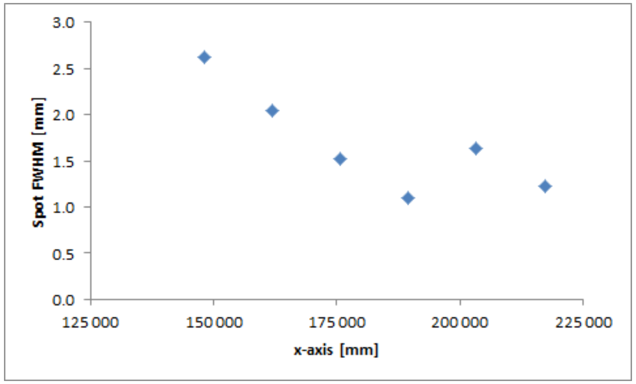
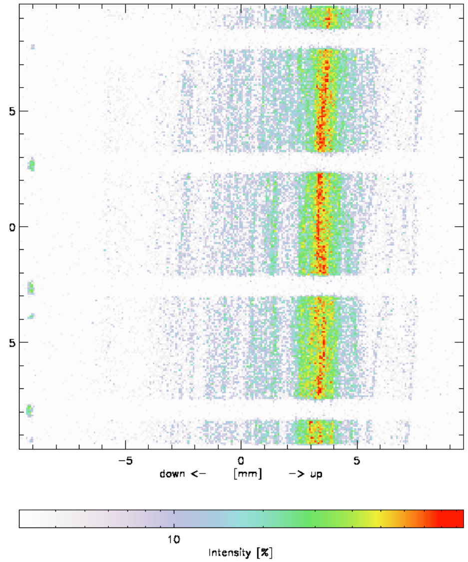


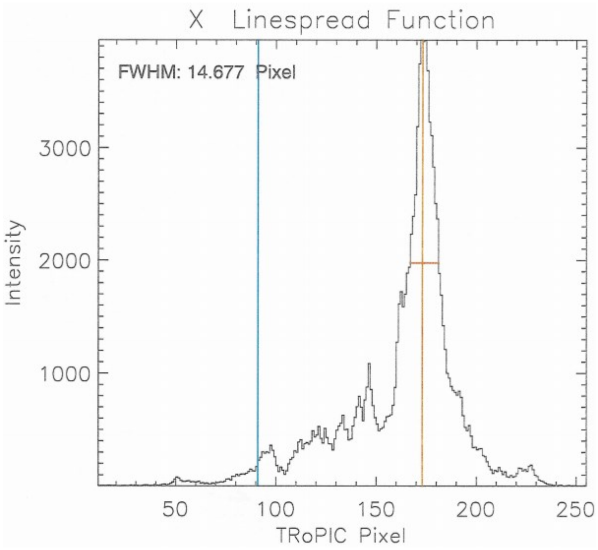
Figure 7: Spectrum – Cu Kα, 8.04 keV @PANTER (left – range from 4500 to 16000 eV, right – detail 6500 – 9000 eV)

Results - 1D horizontal module



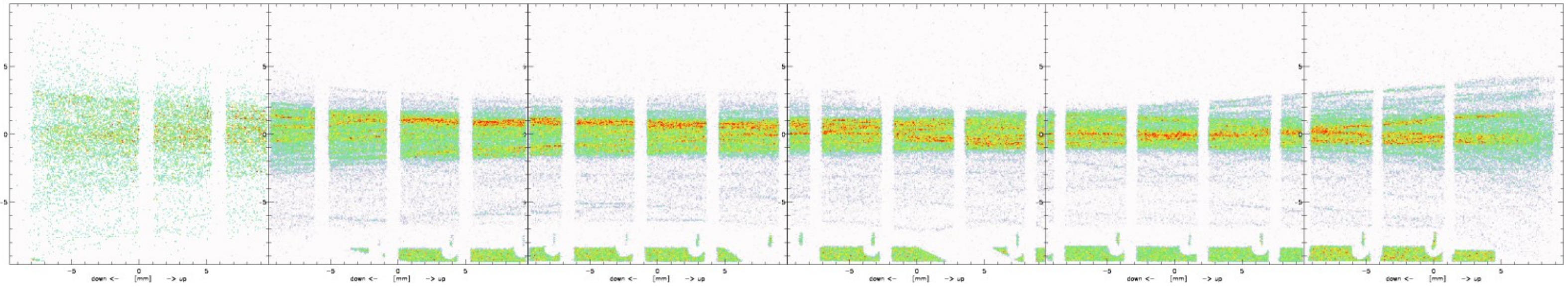


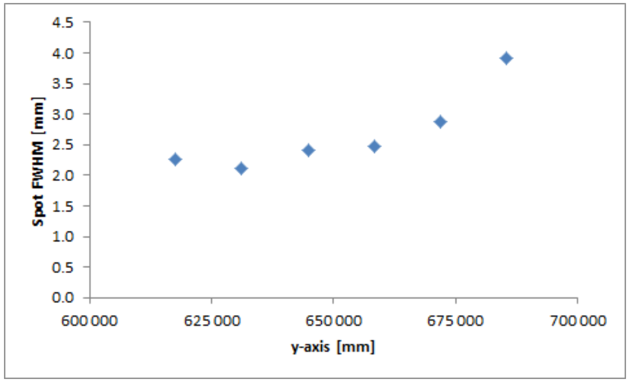


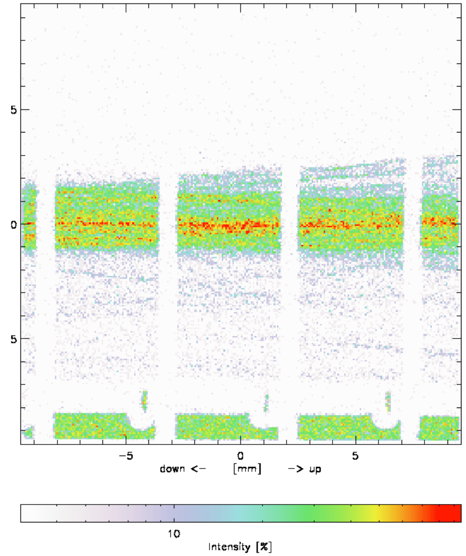


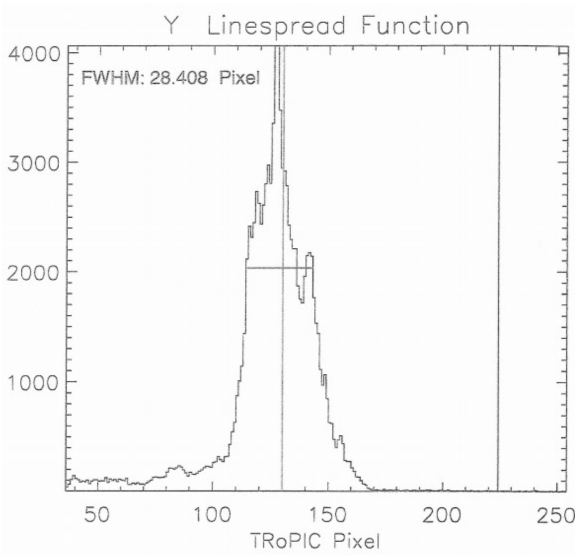
The best 1D focus in y direction (horizontal), line profile FWHM = 1.2mm at 1.49 keV

Results - 1D vertical module



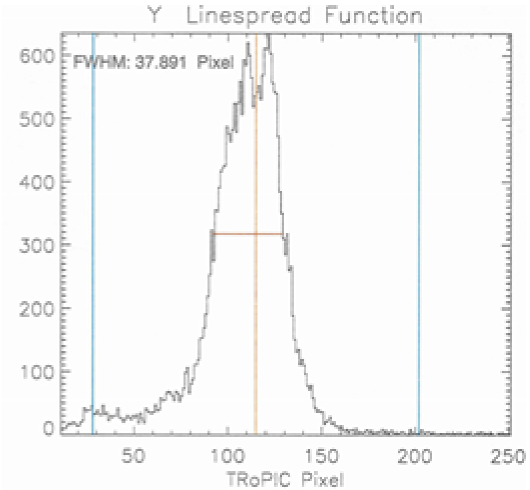


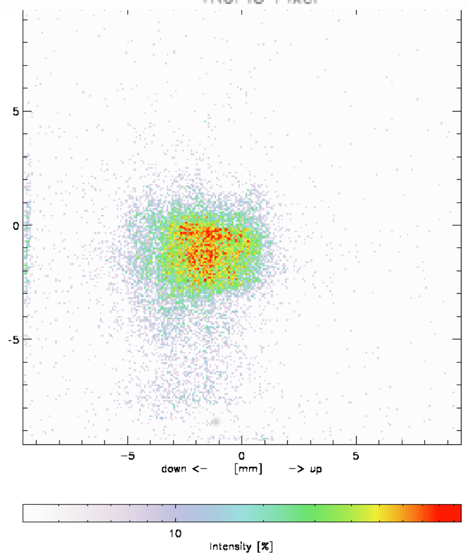


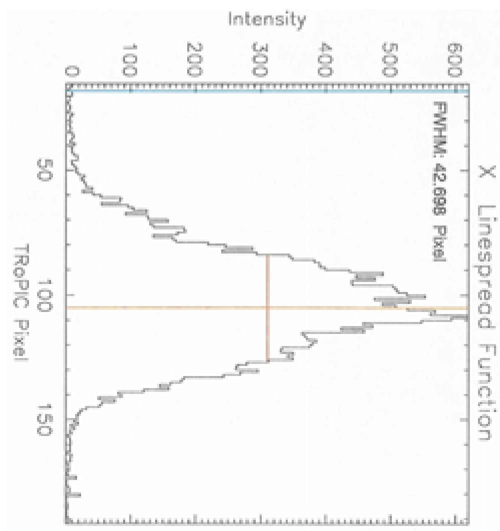


The best 1D focus in y direction (horizontal), line profile FWHM = 2.1mm at 1.49 keV

2D KB X-ray optical system







The best 1D focus in y direction (horizontal), line profile FWHM = 2.1mm at 1.49 keV

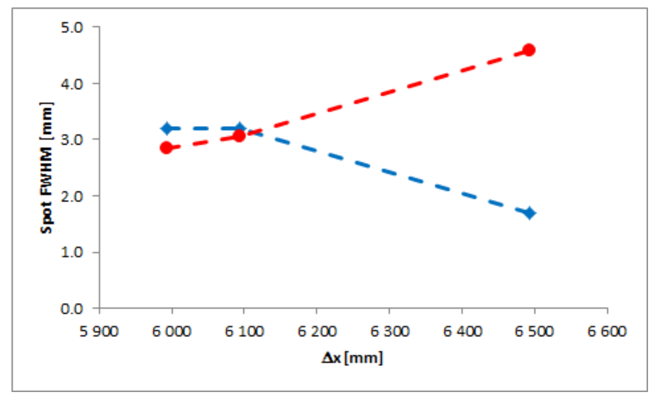
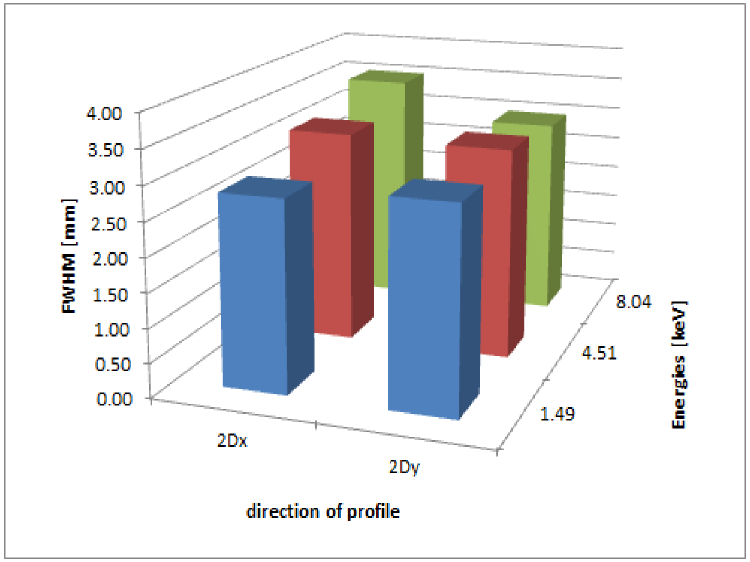


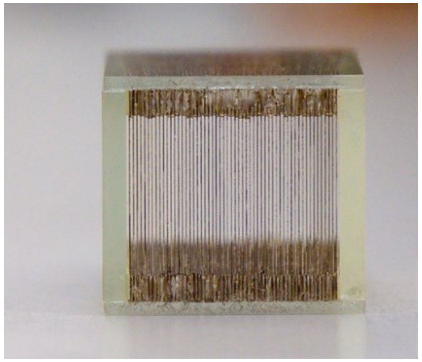
Figure 17: 2D X-ray optics – the best 2D focus at different energies

The 2D X-ray optics was tested at 3 different energies. The graph shows that the modules work up to 8 keV photon energy.

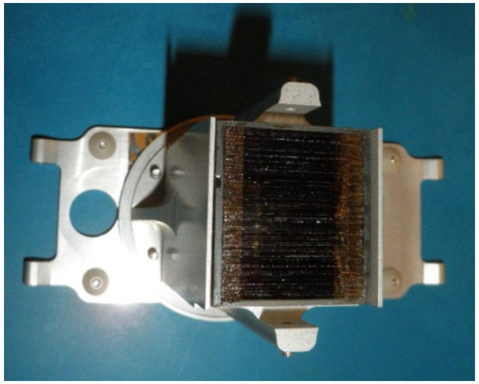


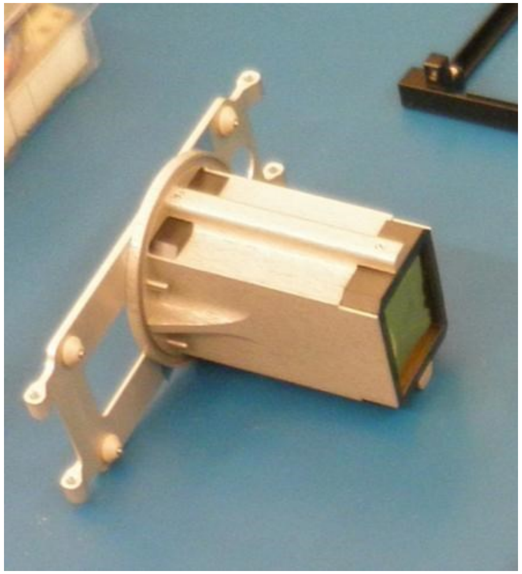
E [keV]	FWHMx [mm]	FWHMy [mm]
1.49	2.80	2.98
4.51	3.17	3.13
8.04	3.52	2.98

Lobster Eye for VZLUSAT-1



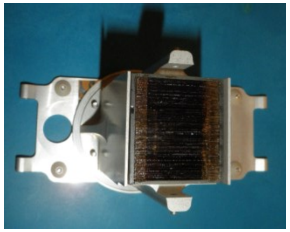
- 1D Lobster Eye module with focal length 250 mm
- Composed of 182 wedges and 90 reflective double-sided gold-plated foils (thickness 150 μm)
- Input aperture: 29x19 mm, outer dimensions: 29x31x60 mm
- Active part of the foils: 19 mm in width and 60 mm in length
- Energy range 3 to 20 keV

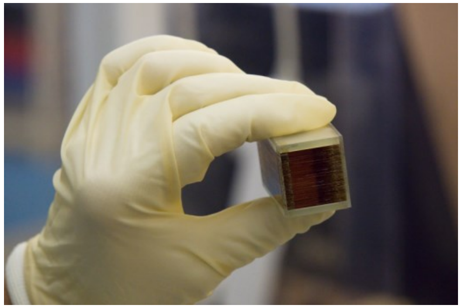


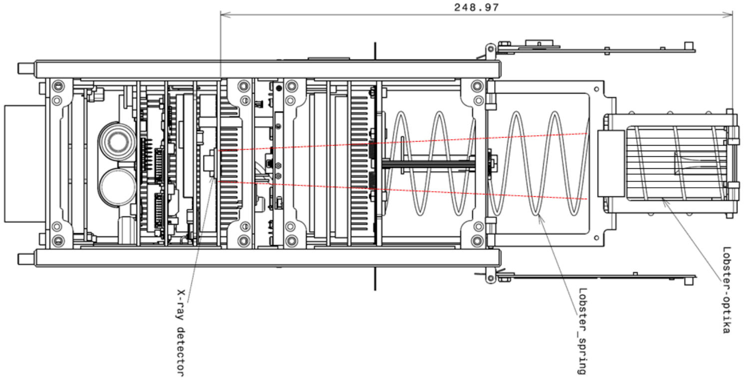


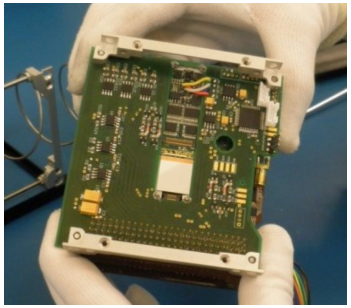
X-ray optical system onboard VZLUSAT-1

- X-ray optical system designed and tested in RITE includes folded X-ray optical module, detector and electronics.
- One dimensional RITE Lobster Eye optic (250 mm focal length).
- Timepix Detector for the optical system was designed and tested in collaboration with CTU UTEF (Jan Jakubek, Ph.D.).
- Electronics was designed and tested in collaboration with CTU FEL (Ing. Tomáš Báča, Ing. Ladislav Sieger, doc. Ing. René Hudec, Ing. Martin Urban, Ing. Ondřej Nentvich, Ing. Veronika Stehlíková).

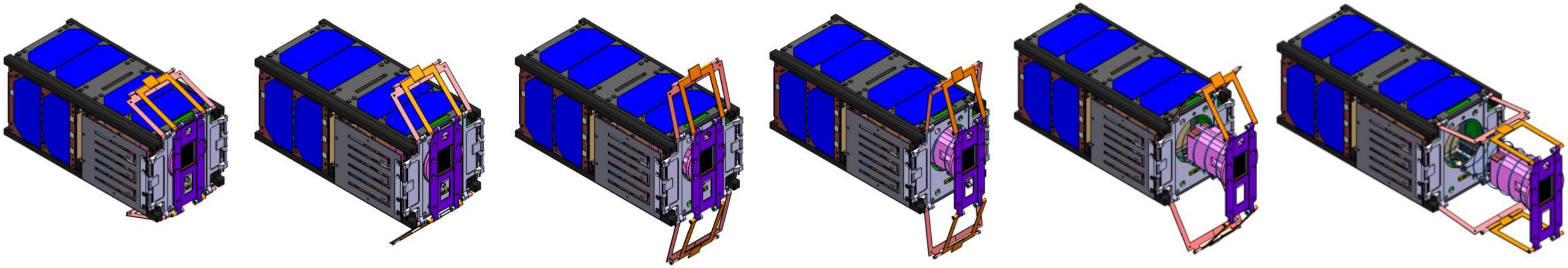


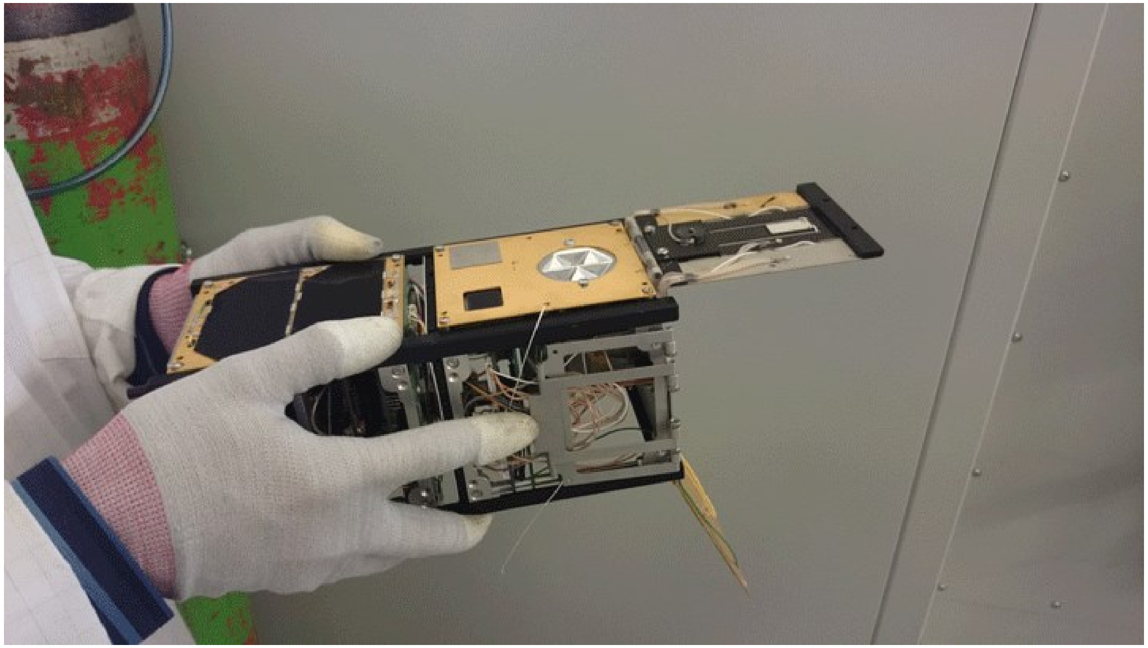






Deployable mechanism





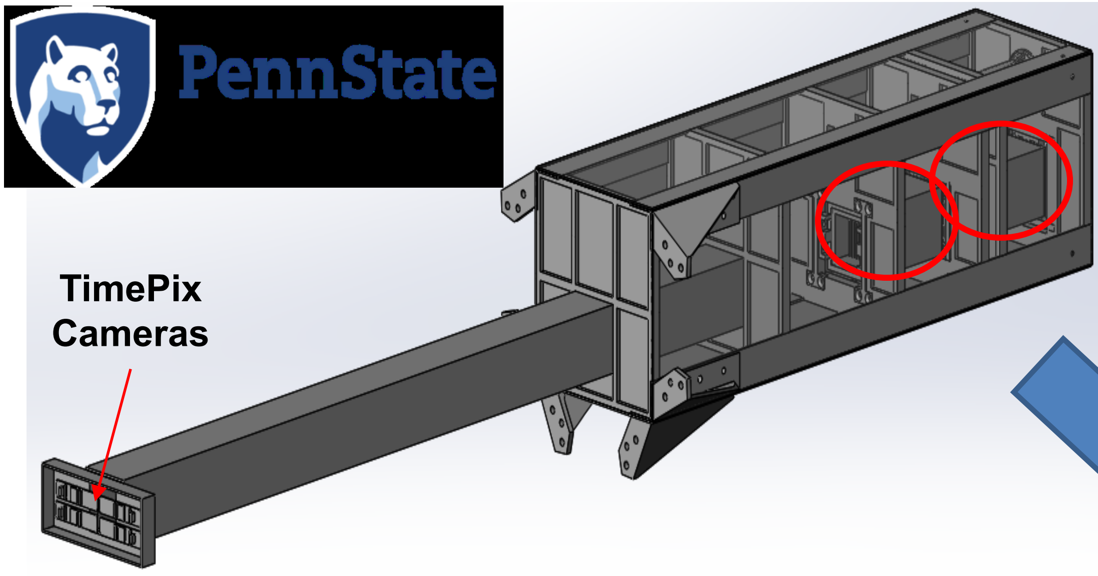
Sub-orbital rockets and Lobster Eye instruments

The Pennsylvania State University

James Tutt
On behalf of the McEntaffer group

Collaboration with the Czech Technical University

- OGRESS had a problem with the GEM detectors accelerating electrons
- First channel, change out the detectors for Hybrid CMOS Detectors
- Second channel is a Lobster Eye instrument from the Czech Technical University (LE optic manufactured by RITE)
- Water recover
    - Opens ability to launch recoverable rockets from locations such as Kwajalein and Wallops Island
- Southern hemisphere sky target
- Launch in April 2018

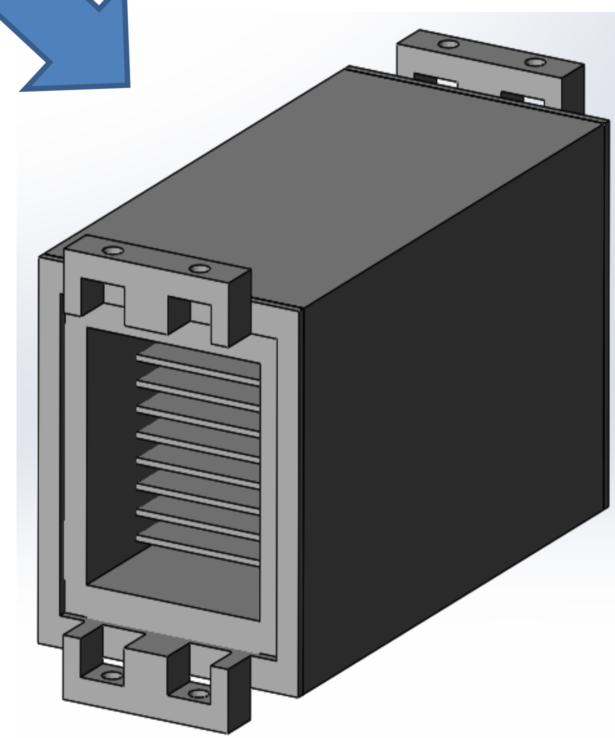


- Self-contained instrument
- 1.3 m focal length
- TimePix cameras on focal plane
- Designed for CubeSats

Collaboration with the Czech Technical University in Prague

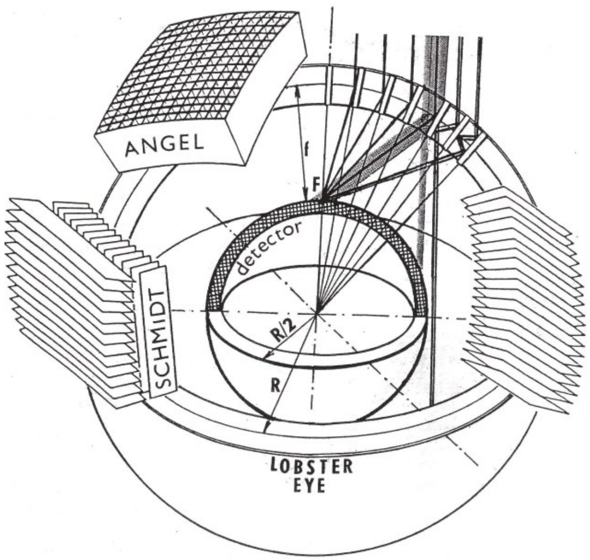
TimePix camera

- Designed for high energy particle tracking at the LHC
- CMOS readout
- Optimized for high energy X-ray detection in lobster eye
- USB connection
- No cooling required
- 55 μm pixels and a single chip is 256 x 256 pixels

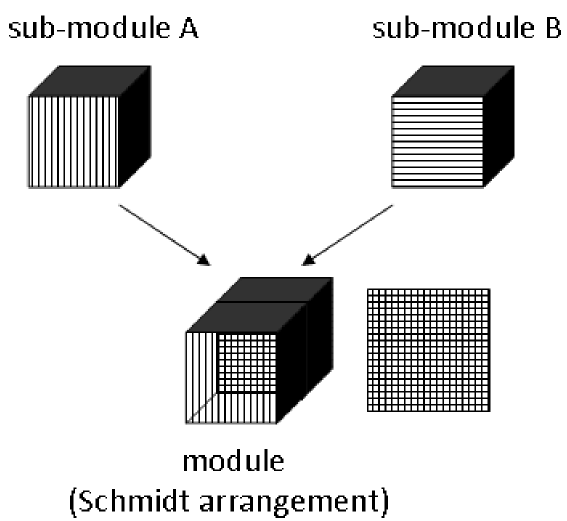


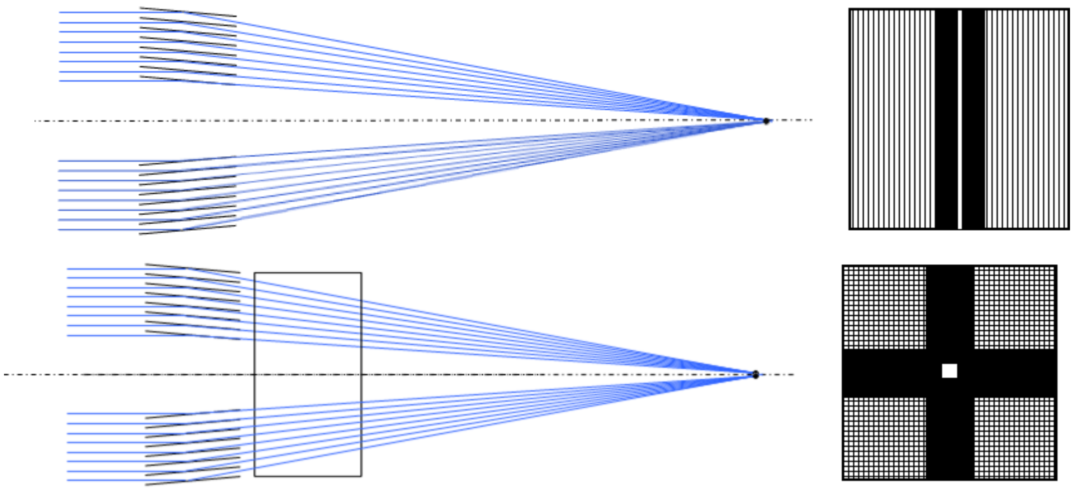
ROCKET EXPERIMENT
Installation at Pensylvania State University

MFO Optical Systems

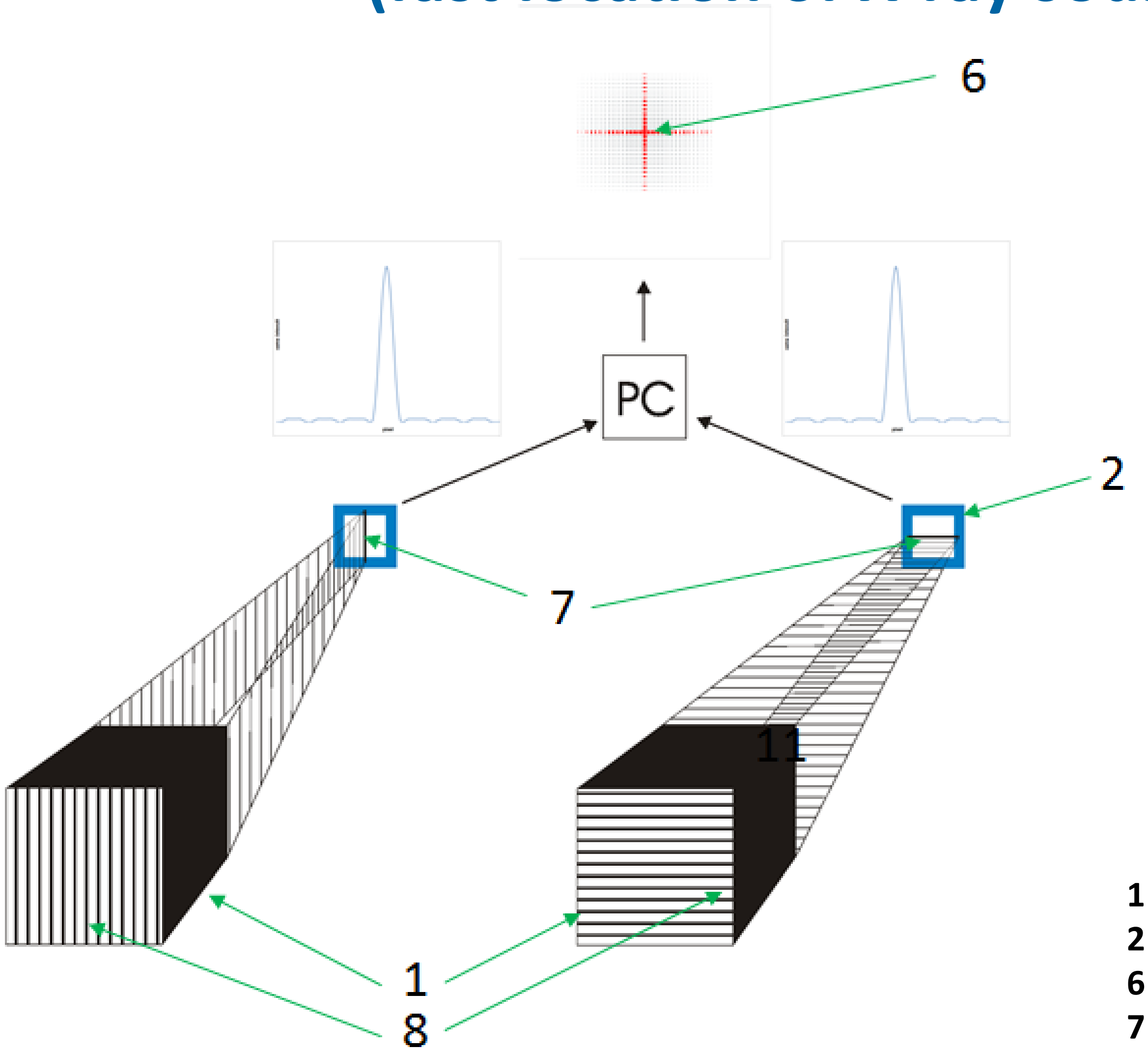


- Optical system assembled from thin foils
- Glass or silicon foils
- X-ray optics type
  - Lobster Eye
  - Kirkpatrick-Baez



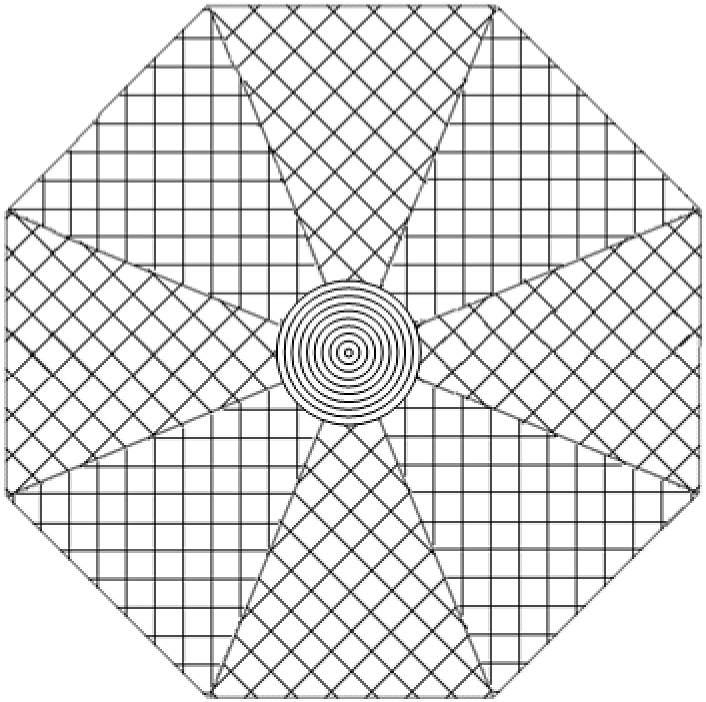


Monitoring system with two 1D units (fast location of X-ray sources)



1 - optical modul (1D)
2 - detector
6 - focus
7 - line focus
8 – foils with reflective surface

Novel arrangement of KB modules with high resolution



- Development of KB modules for big space telescope with high resolution of 10 arcsec
- Non-functional (blind) central area of KBF system can be filled with thin rotationally symmetric foils (classical nested mirrors with parabolic shape P)

  => **improvement of KBF optical system aperture effective area for higher energies**
- Patent pending (PV 2011-297)

Conclusion

- X-ray grazing incidence mirrors have been studied, manufactured and analyzed
- Selected space applications of X-ray mirrors have been studied and two missions have been realized
- Current activities include ESA project ‘’Space radiation capabilities, technologies and platforms for small spacecraft and CubeSats (SR-CTP)’’ – Rigaku as prime contractor

Rigaku, VZLU, ADVACAM Imaging the Unseen, 5M, THIN FILM TECHNOLOGICAL SERVICE, BD SENSORS Space, CSRC, HVM PLASMA	Doc. No:	SR-VZL-RP-002
	Issue:	1.0
	Date:	24.09.2018
	Page:	1 of 18
Space radiation capabilities, technologies and platforms for small spacecraft and CubeSats (SR-CTP)	**ESA contract 40001250020/18/NL/GLC /hh**	

THANK YOU FOR ATTENTION

Prague