



Development and tests of novel X-ray optical systems for space applications

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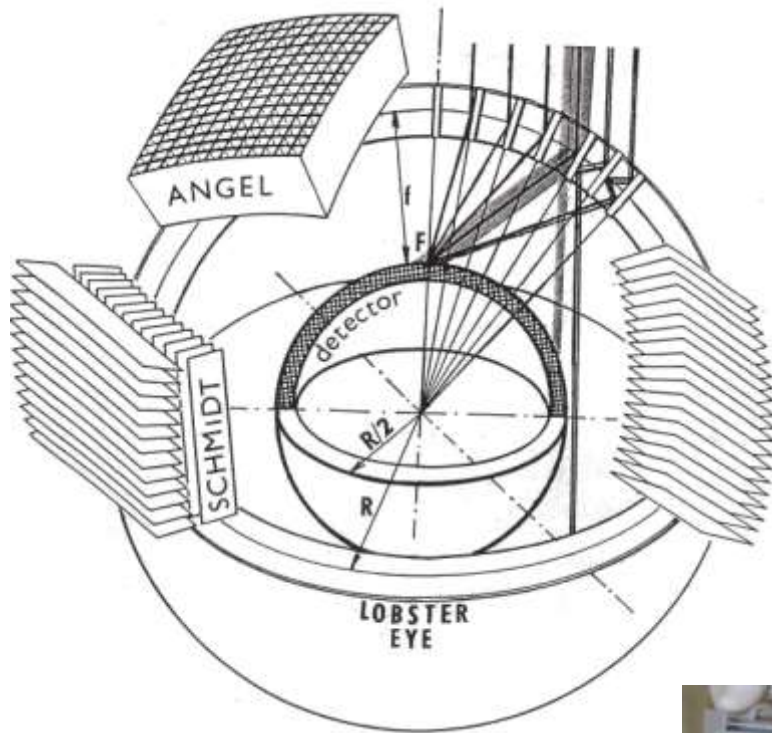
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Lobster Eye & MFO Optical Systems



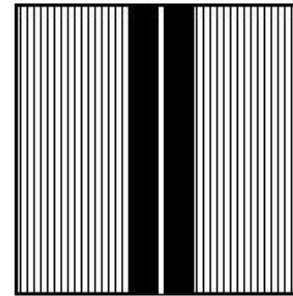
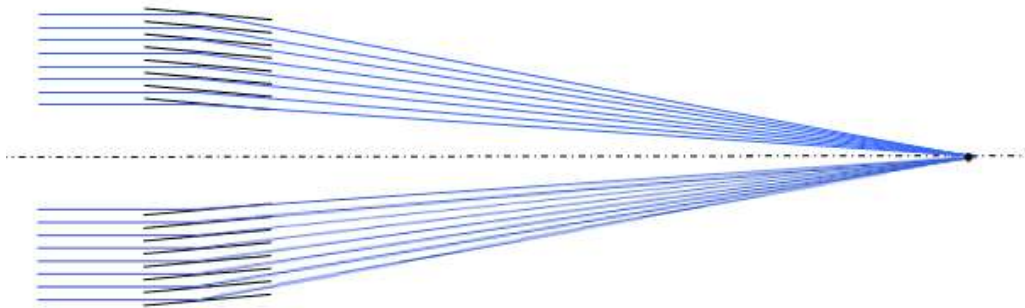
- Wide FOV
- Glass and / or silicon substrates for soft X-rays
- Planar & ellipsoidal mirrors
- Foils 3×3 mm to 300×300 mm
- Foil thickness from $30 \mu\text{m}$ to 1 mm



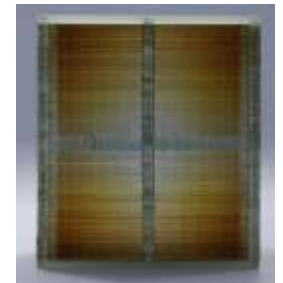
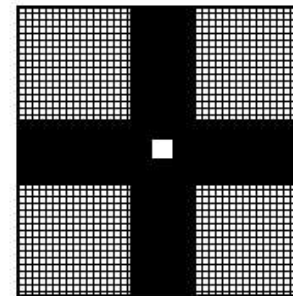
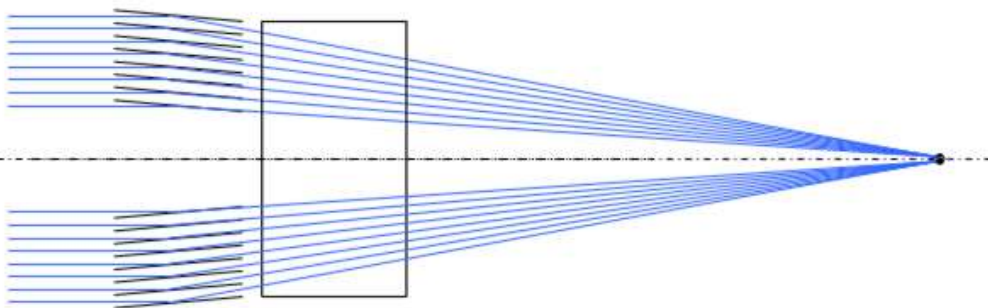
LE optic - Schmidt layout

1D and 2D systems

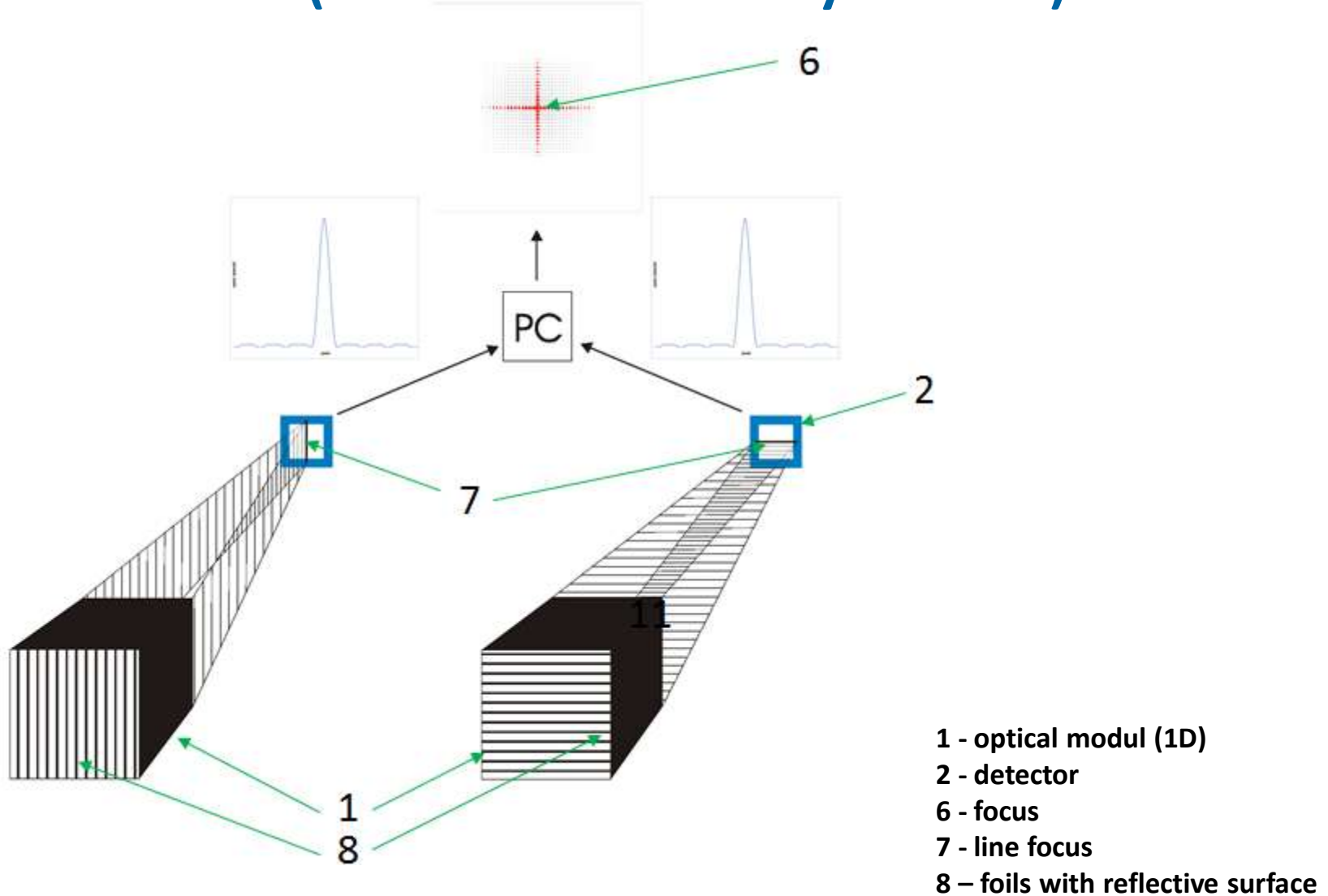
1D optic - 1 reflection, energy range optical to 30 keV



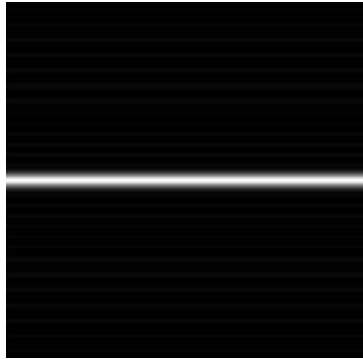
2D optic – composed of two 1D sub-modules, 2 reflections, energy range optical to 10 keV



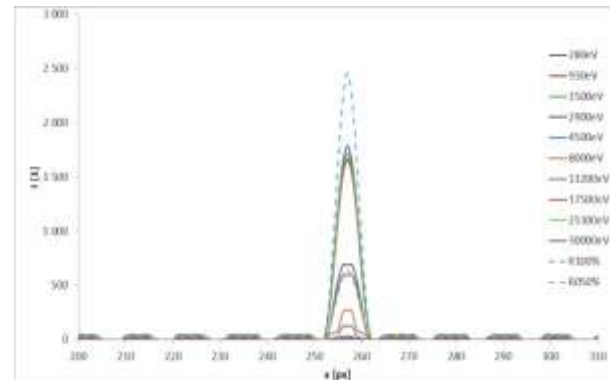
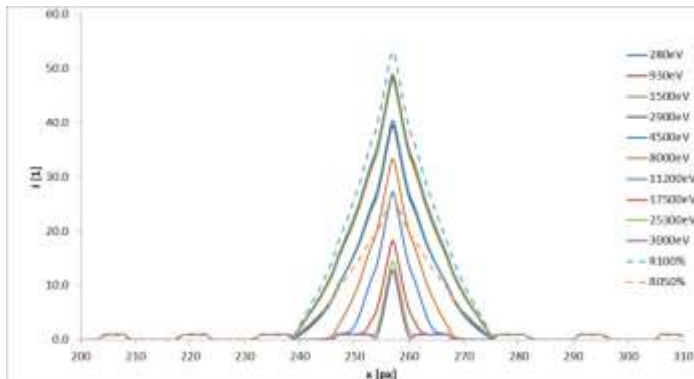
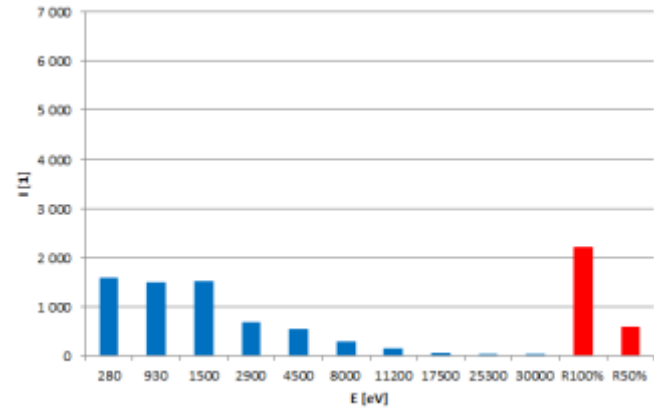
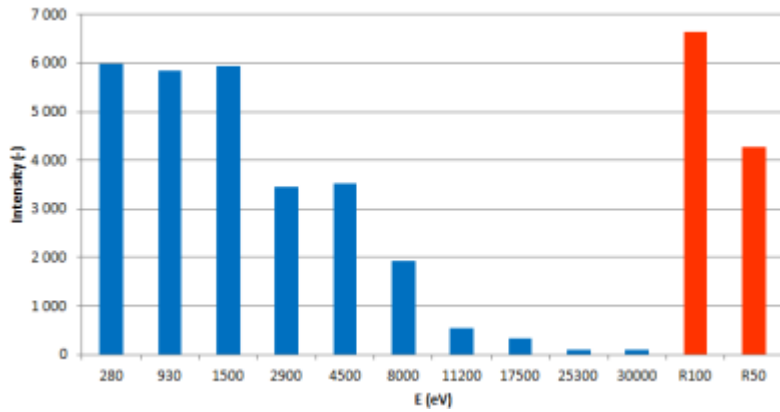
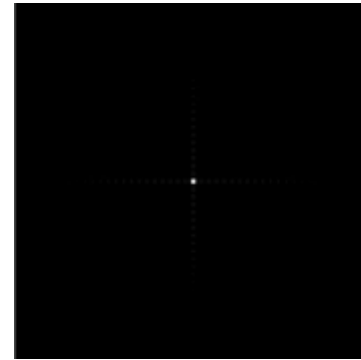
Monitoring system with two 1D units (fast location of X-ray sources)



LE system - 1D vs. 2D

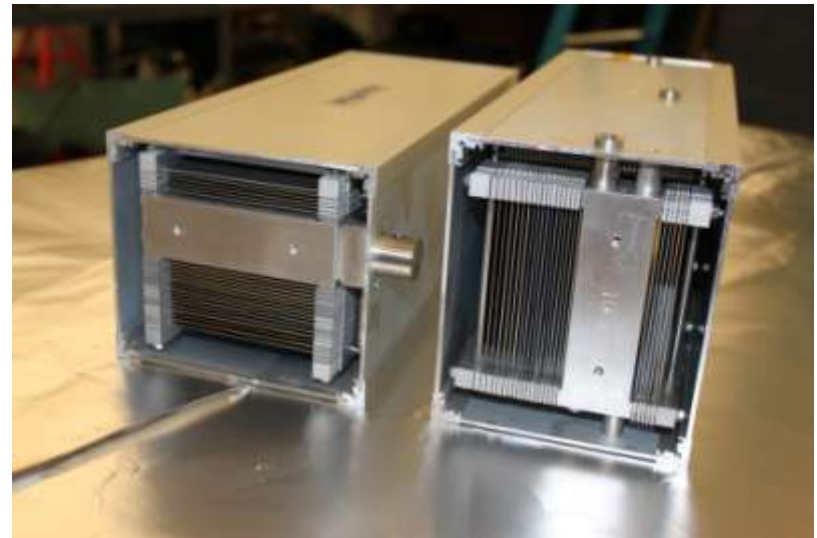


Ray-tracing



KB modules - specification

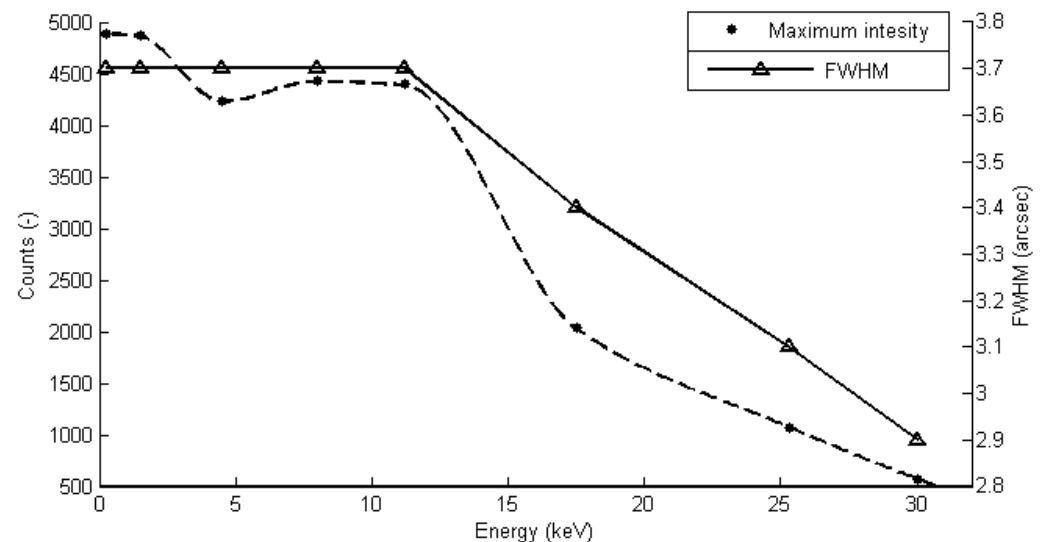
- Requirements:
 1. calculated angular resolution using ray tracing should be better than 5 arcsec
 2. possibility of testing at higher energies (10-30 keV), therefore a **module placed in the center was considered**
- 144 commercially available 525 μm thick Si wafers with Au surface coating
- Mirrors arranged into planar-ellipsoidal shape with axial symmetry
- 1st mirror is at a distance of approx. 16 mm from optical axis
- Mirror size 100 \times 100 mm
- 3 sets of 24 (18+6) mirrors in each module
- Spacing 1.5 \div 2.5 mm
- Wedge smaller than 10 μm
- Modules were designed for vacuum chamber at **CASA UC at Boulder)**



KB modules – ray tracing simulations

Dependance on energy

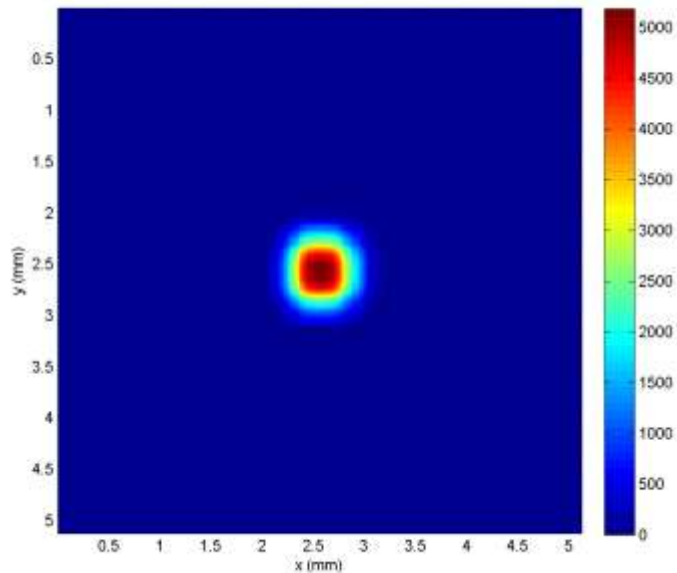
Energy (eV)	Maximum Intensity (counts)	FWHM (arcsec)
100% reflection	5329	3.8
280 (C)	4893	3.7
1 500 (Al)	4865	3.7
4 500 (Ti)	4235	3.7
8 000 (Cu)	4432	3.7
11 200 (Se)	4394	3.7
17 500 (Mo)	2036	3.4
25 300 (Sn)	1075	3.1
30 000	575	2.9



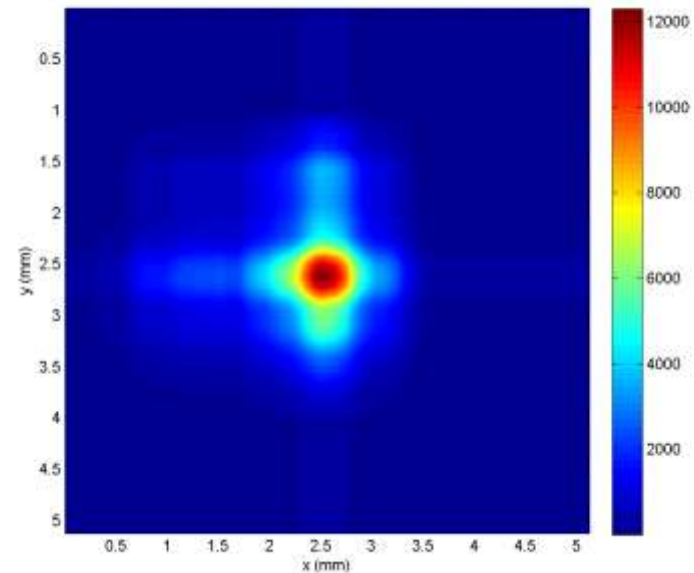
- Input parameters (mirror material properties, arrangement of mirrors in modules, experiment geometry, ...) are the same as in the experiment
- Point source was considered

KB modules – ray tracing simulations

- Input parameters (mirror material properties, arrangement of mirrors in modules, experiment geometry, ...) are the same as in the experiment
- Energy 453 eV (Ti $L\alpha$)



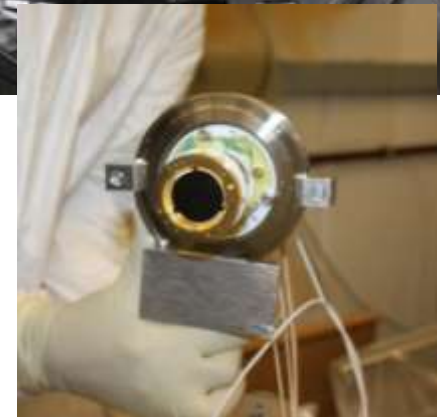
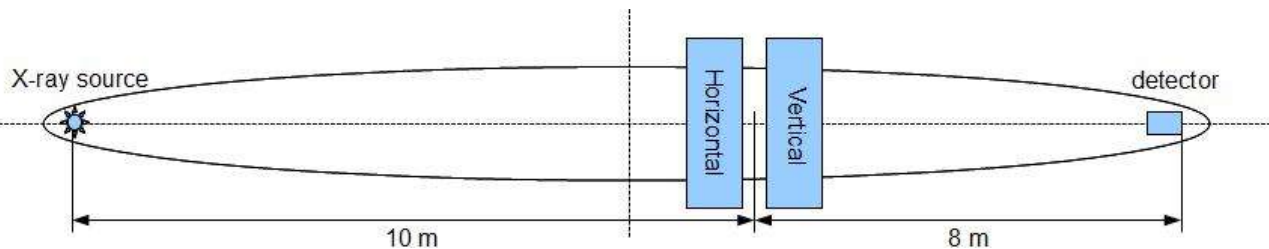
Theoretical focus:
FWHM = 0.58 mm
 \approx **3.7 arcsec**



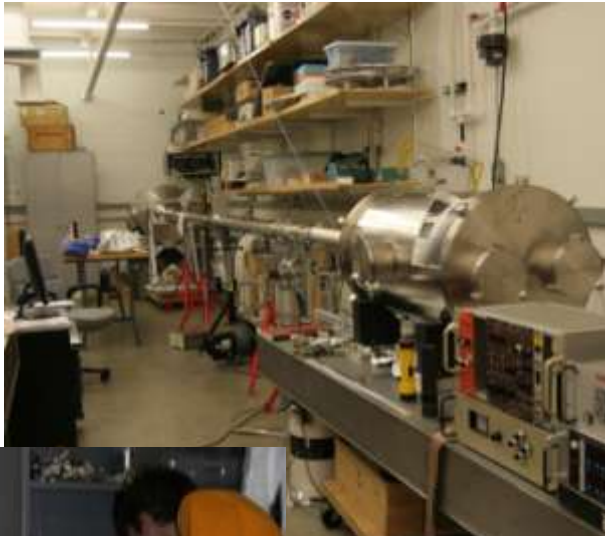
Theoretical focus with 0.2 mm source diameter
and 2 μ m manufacturing errors:
FWHM = 0.59 mm

KB modules - experimental arrangement

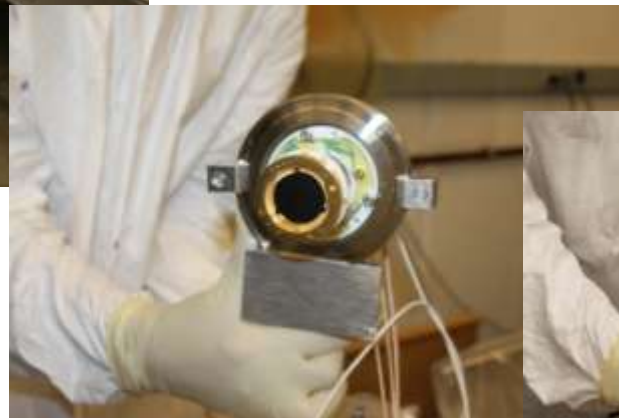
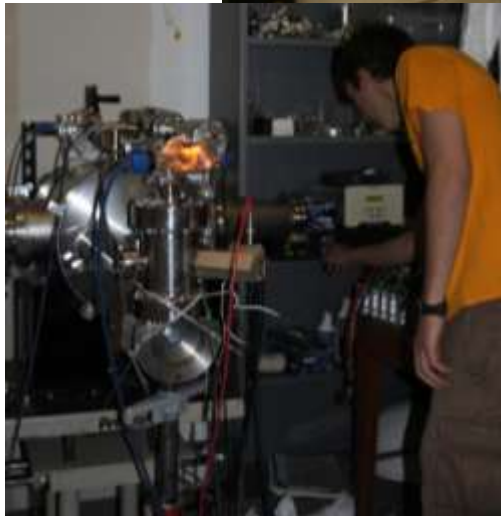
- Modules were tested in vacuum chamber at CASA (University of Colorado at Boulder)
- Elliptical geometry
- Source to optics distance: 10 m
- Optics to detector distance: 8 m
- Module position adjustment done with visible light (Xe lamp)
- MCP detector, diameter 1"



Vacuum chamber at CASA UC – testing in 2014

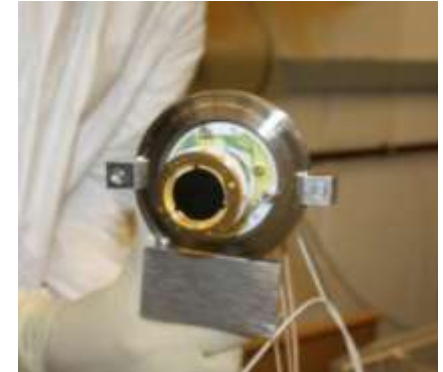


- X-Ray source with Ti anode ($L\alpha$, 453 eV, 2.73 nm)
- X-Ray beam diameter (diameter of vacuum tube) 8 cm
- Total vacuum chamber length 20 m
- MCP detector, diameter 1''
- TIMEPIX detector, (MEDIPIX)

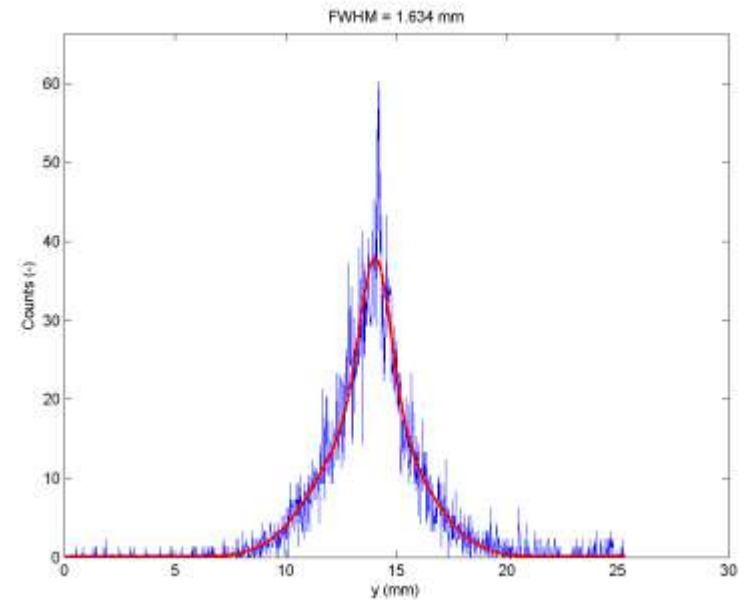
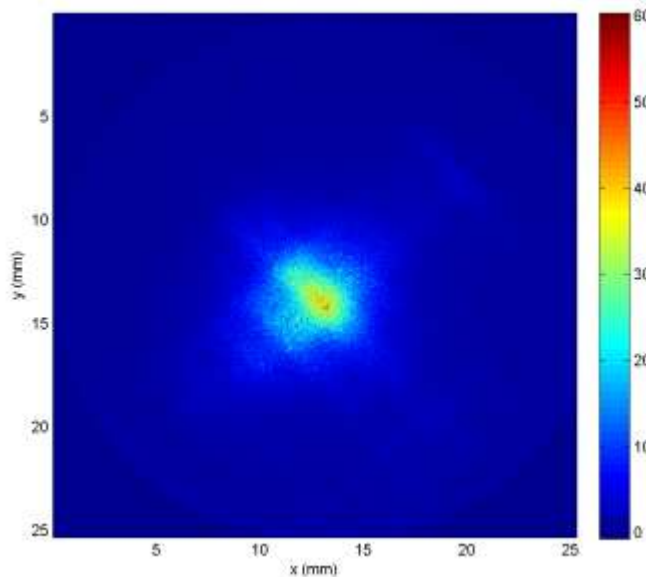


KB modules - test results

- MCP detector, diameter 1''
- Energy of X-rays: **453 eV**
- FWHM = 1.63 mm



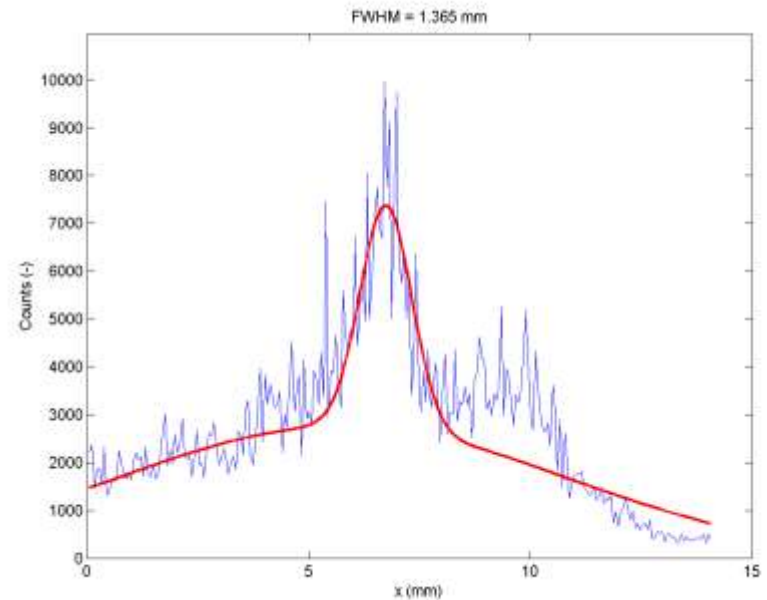
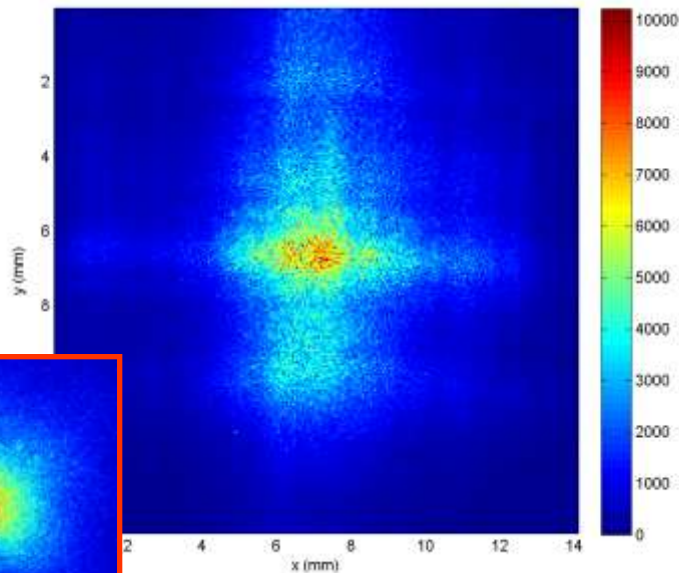
Angular resolution: **10.2 arcsec** (after ellips. correction)



KB modules - test results

- Timepix detector (IEAP CTU in Prague), size 14 mm, 500 nm Al filter
- Energy of X-rays: **4.5 keV**
- FWHM = 1.63 mm

Angular resolution: **8.7 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 $K\alpha$)**
1.25 keV (Mg $K\alpha$)
- Source-to-detector distance:
10 m

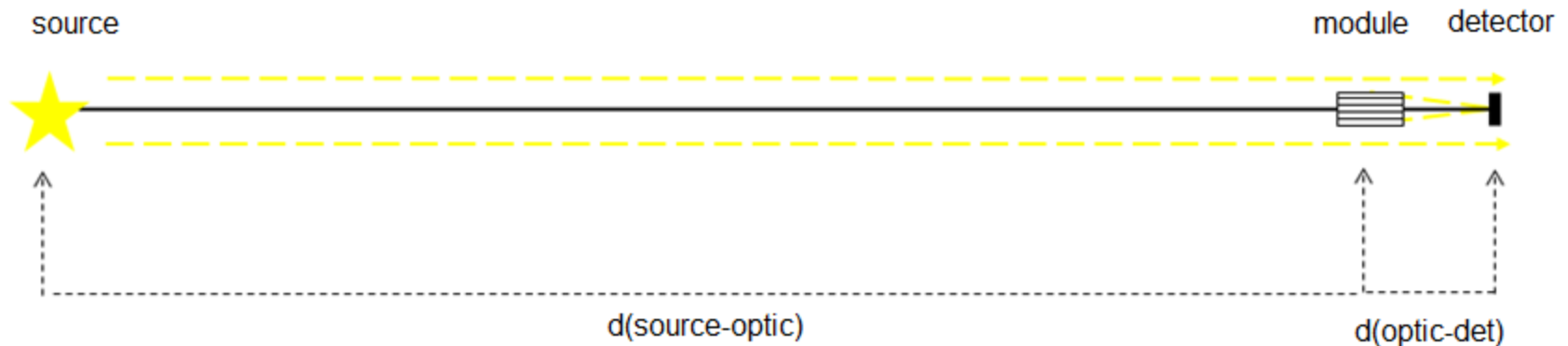


MFO for rocket experiment – testing in 2016

Testing in Penn State University vacuum tunnel

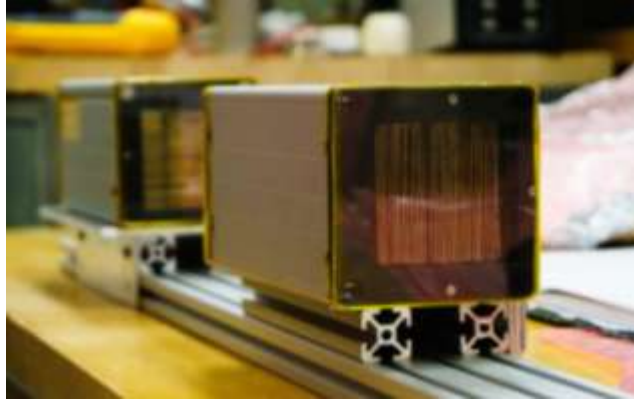
- First preliminary experiments at Penn State University
- Source - Fe-55 (5.9 keV)
- Detector - Timepix (256x256 px, 55 μm), no cooling
- Source-to-detector distance - 47 m

Experiment geometry



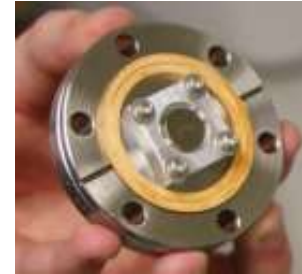
MFO for rocket experiment

Testing in Penn State University vacuum tunnel



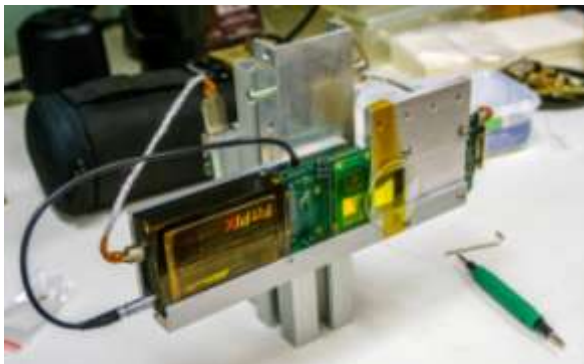
LE system

- MFO, glass foils



Source

- Fe-55
- $K\alpha = 5.9 \text{ keV}$

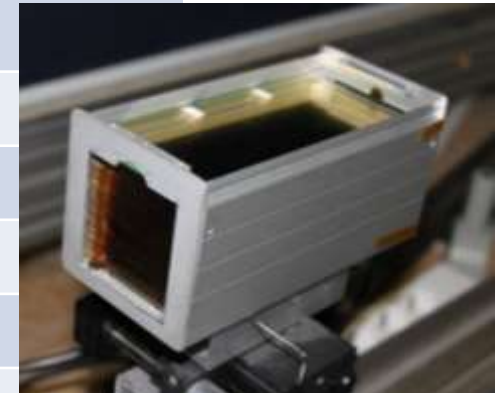


Detector

- pixel detector with 256×256
- $55 \mu\text{m}$ pixel size
- $14 \times 14 \text{ mm}^2$

MFO for rocket experiment

Aperture [mm]	54 x 54
F [mm]	1190 (L), 960 (M)
R [mm]	2380 (L), 1920 (M)
t [mm]	0.1
N [/]	55
l [mm]	150
w [mm]	75
h [mm]	55
Distance between foils [mm]	0.75
Surface	Au
Detector	Timepix
Pixel size [μm]	27.5
Detector size [px]	512x512



MFO for rocket experiment - Simulation

for source-detector distance 10 m at 8 keV

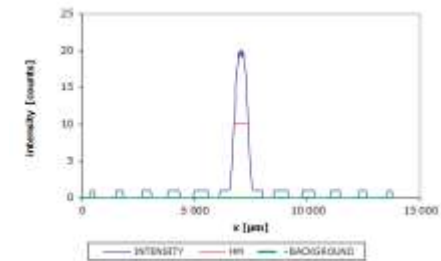
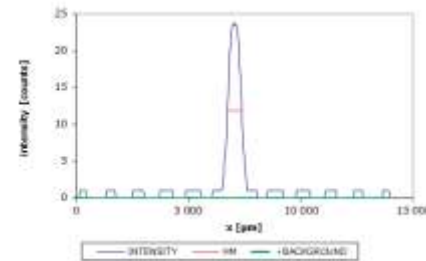
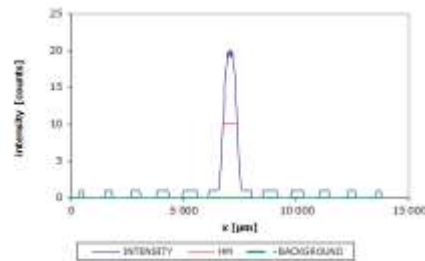
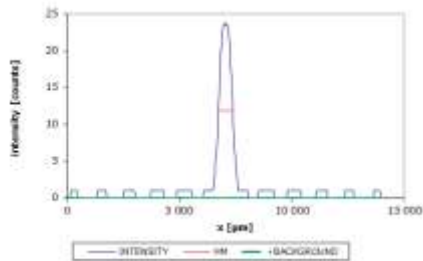
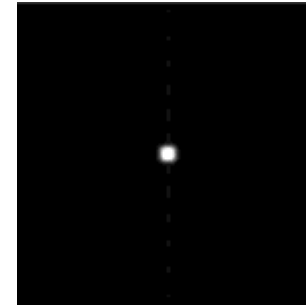
Sub-Module A



Sub-Module B



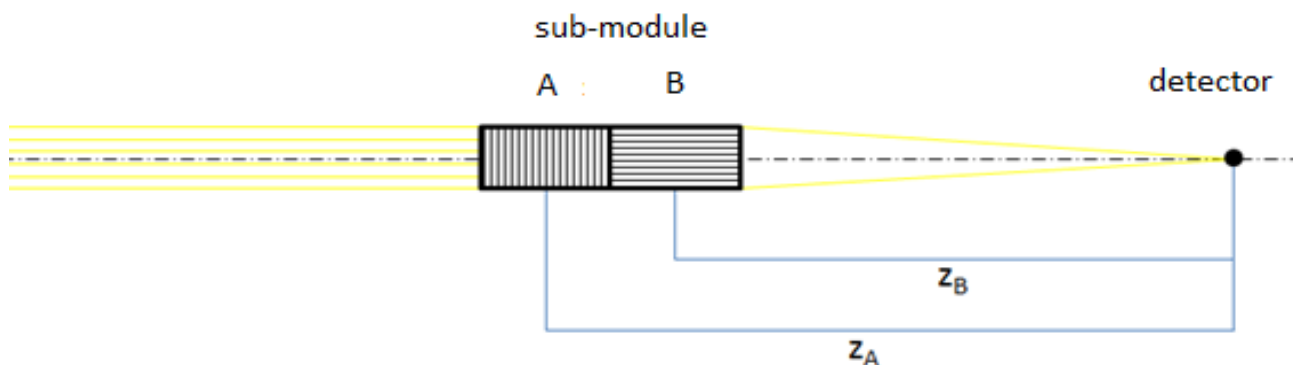
A&B



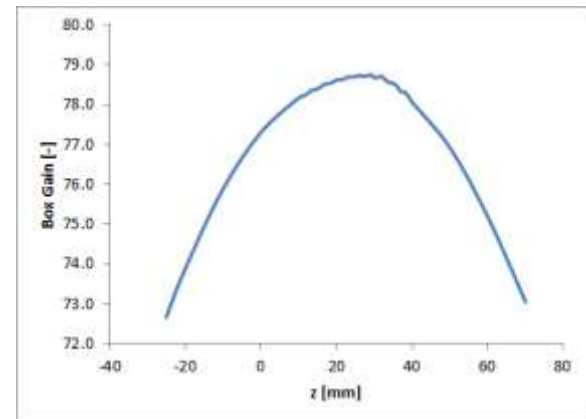
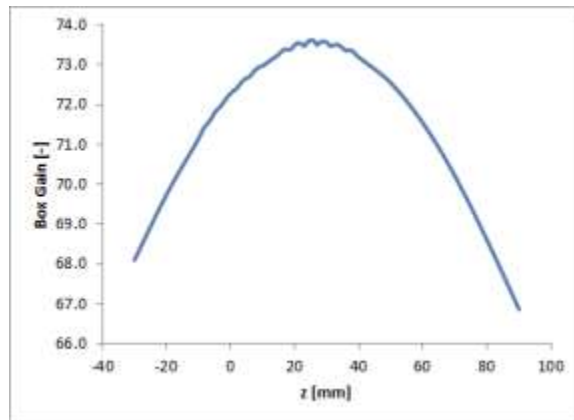
	Sub-module A / horizontal	Sub-ModuleB / vertical
FWHM [mm]	0.645	0.630
G_{max} [1]	17.2	20.6
φ [arcmin]	1.50	1.48

Optics for AHEAD

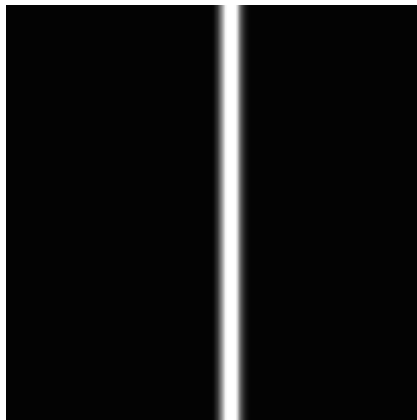
Number of foils	10 x 3
Dimension of foils	100 x 100 x 0.4 mm
Spacing	7 - 8 mm
Reflective surface	Au
Dimension of sub-module	100 x 100 x 300 mm
Aperture	70 x 70 mm
Focus z_A/z_B	7 155 / 6 825 mm
Source	Parallel beam
Detector	512 x 512
Detector pixel size	37.5 μm



Optics for AHEAD

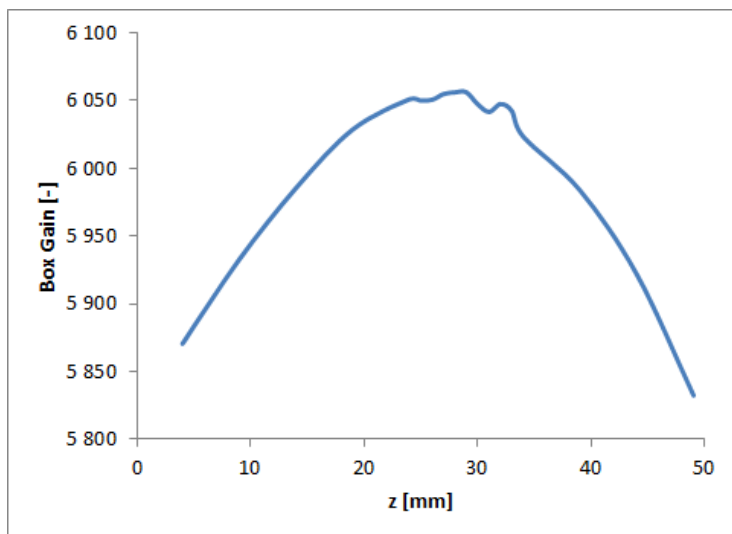


Looking for optimal position for 1D module A (left) and 1D module B (right) – dependence of gain in focus on detector position



Ray-tracing simulation of 1D LE optics for sub-module A (left) and sub-module B (right) for source-detector distance of 7 m for ideal mirrors, ideal position.

Optics for AHEAD



Looking for optimal position of 2D X-ray optics

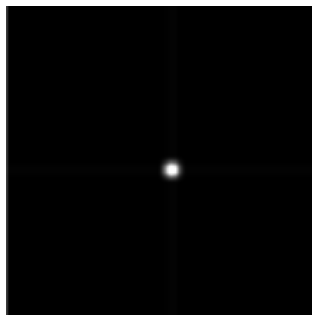


Ray-tracing simulation of 2D X-ray optics for source-detector distance 7 m for ideal mirrors.

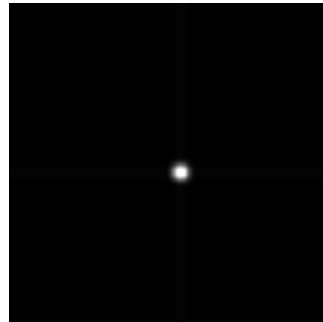
	vertical	horizontal
FWHM [μm]	725.5	705.7
G [1]	6 054	
φ [arcsec]	21.4	20.8

Optics for AHEAD

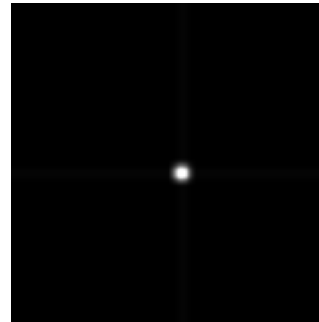
Ray-tracing simulation of 2D LE optics for source-detector distance 7 m for various energies.



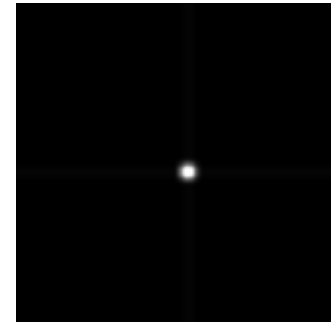
110 eV



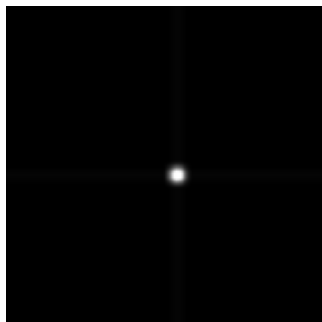
277 eV



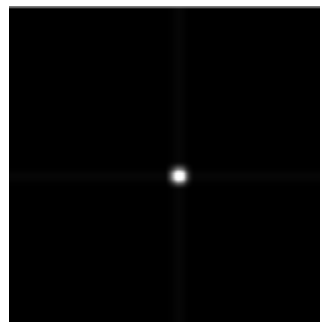
453 eV



930 eV



1487 eV



2123 eV

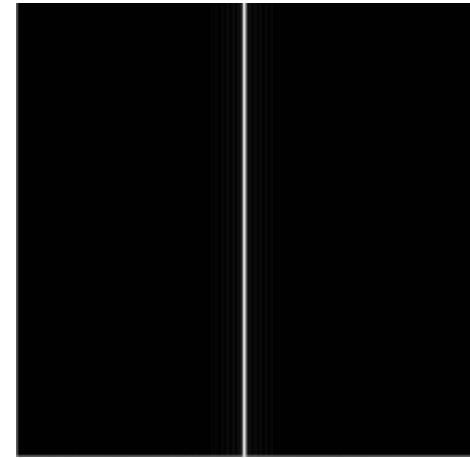


2839 eV

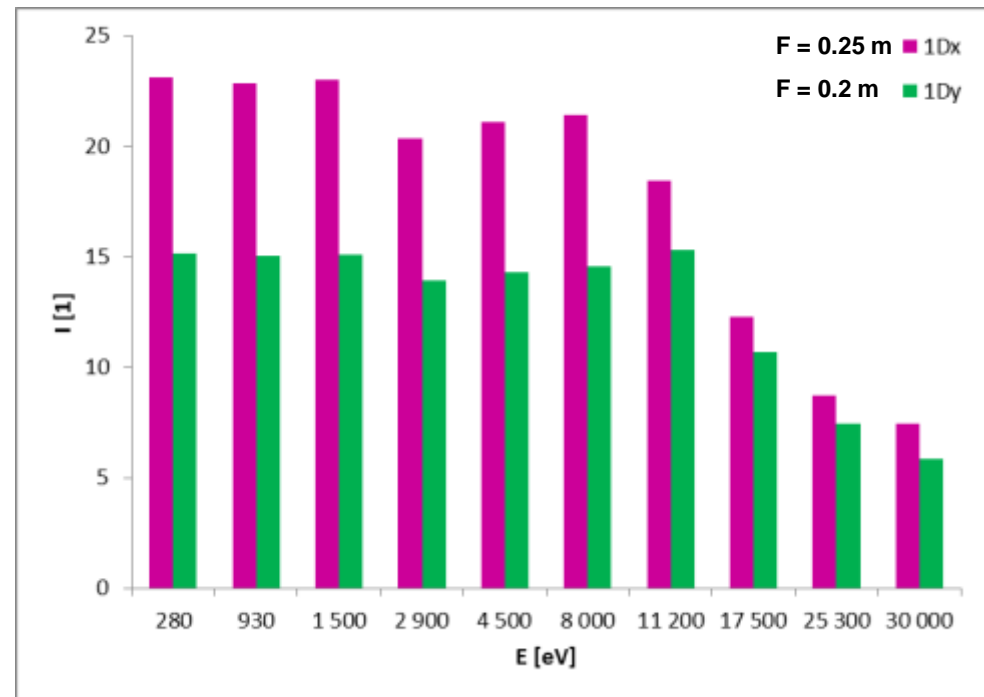


4511 eV

Study of LE with $F = 0.2 / 0.25 \text{ m}$



Aperture (mm)	100 x 100
Focal length (mm)	250 / 200
Radius (mm)	500 / 400
Foil thickness (mm)	0.075
Number of foils	444
Length (mm)	50
Width (mm)	100
Height (mm)	100
Foil spacing (mm)	0.15
Foil reflection surface	Au 50 nm
Detector	CCD
Pixel size (μm)	36
Number of detector pixels	512 x 512



Experimental tests of LE optics

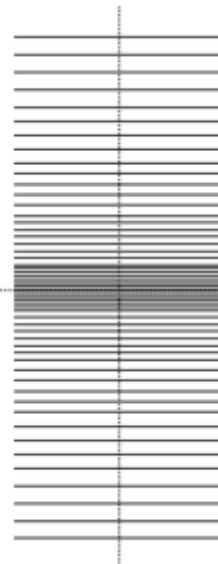
- CuK α X-ray tube
- Timepix detector



X-ray source



- LE optics was placed in the middle between source and detector

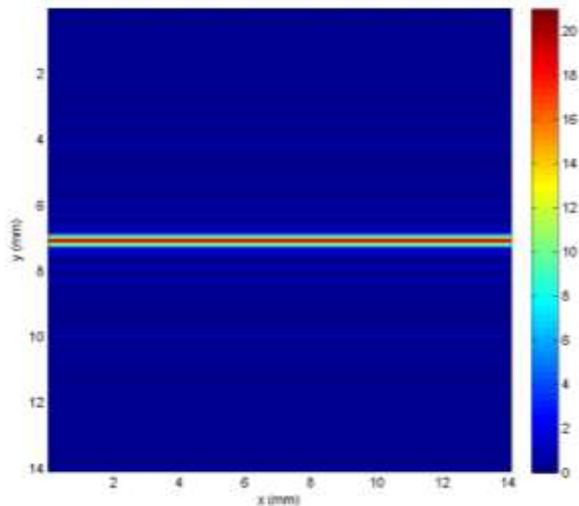


detector

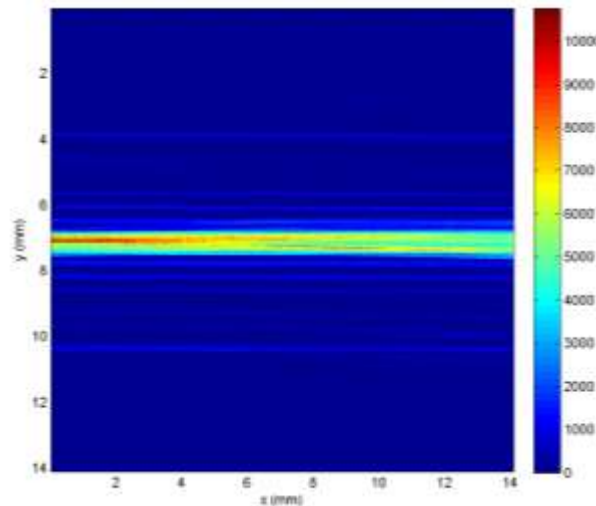
Experimental tests of LE optics

- Source - detector distance ... 600 mm
- Exposure time ... 0.4 s
- Maximum signal = 10^4 , after summation 18×10^5

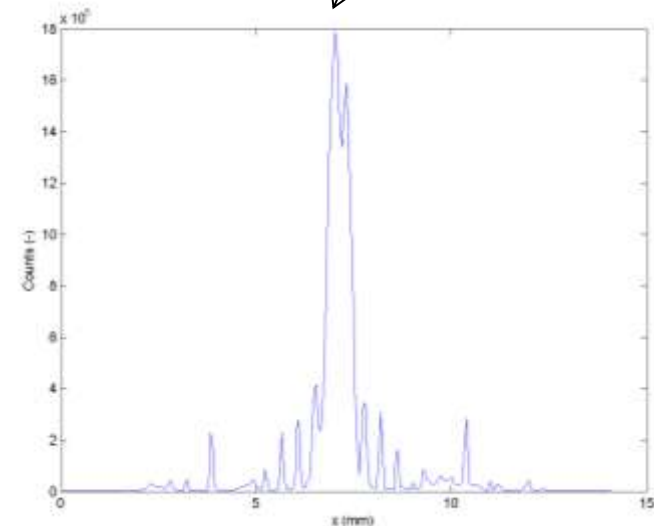
Ray-tracing



Measured focus



Horizontal sum
(sum of columns)



Conclusion

- The main aim of our international group is to verify the X-ray Lobster Eye (LE) optics with uncooled silicon pixel detector Timepix in orbit
- VZLUSAT-1 mission is designed to get higher Technology Readiness Level (TRL) for onboard products and technologies
- VZLUSAT-1 mission was planned for 6 months with launch in June 2016
- The rocket experiment is planned for launch in 2017

- MFO optics is suitable both for wide-field monitoring and big space telescopes with high resolution
- Resolution of MFO optics highly depends on assembling technology
- For long-focal MFO Si substrates are more suitable, while for wide-field optics with moderate resolution glass is convenient

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- **Team of W. Cash, University of Colorado at Boulder**

THANK YOU FOR ATTENTION



Prague