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Report on the preparation of novel K-B and LE X-ray optics modules

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Abstract

This deliverable represents the report on preparation of novel X-ray Kirkpatrick Baez (KB) and Lobster Eye (LE) X-ray optics modules at the Czech Technical University in Prague. These works involved the simulations, design, assembly and tests both in optical domain as well as in X-rays of several test modules of KB and LE arrangements. The works carried at the CTU in Prague were affected by the Covid-19 pandemic and related restrictions. Despite of this, we were able to perform works described briefly below which is presented in this report.

- Simulations and designs of LE and KB Systems
- Alternative simulation/ray tracing methods
- Design and assembly of new test modules
- Alternative LE and KB arrangements
- Studies of alternative/improved coatings
- Study of novel and improved substrates
- Measurements of LE and KB modules in X-rays and in optical light

1 Introduction.

In this report we describe the progress in design and development of novel X-ray optics of LE and KB type within the H2020 project.

The CTU contributes to the WP10 by developing and testing advanced novel Kirkpatrick Baez, Lobster Eye and Hybrid X-ray optics mirror technologies, and by performing the calibration and testing of the ongoing developments of Lobster Eye (LE) optics

Detailed simulations of novel X-ray optics are necessary to predict the in-orbit and ground based (finite source distance or parallel beam) performance (i.e. the point spread function and efficiency) of newly developed prototype optics with improved parameters. The designed optics was tested at PANTER and other test facilities. The work includes two basic parts as described below.

1. Kirkpatrick Baez X-Ray optics. We have simulated, designed, assembled and tested first advanced modules in KB arrangement. These modules were based on stacked (a) high quality glass foils and (2) superior quality silicon wafers. The work included the selection and detailed analyses of best substrates available. Such superior substrates may help to increase significantly the performance of the newly developed modules, with emphasis on improvement of FWHM, improvement of effective area, and extending the energy range.
2. Lobster Eye Optics in Schmidt arrangement. We have simulated, designed, assembled and tested first advanced modules in LE Schmidt arrangement. These modules were based on {a) high quality glass foils and (2) superior quality silicon wafers.

We note that Kirkpatrick-Baez (KB) based lenses as well as various types of lobster eye optics serve as an example of advanced future X ray telescopes . Analogously to Wolter lenses, all these systems use the principle that the X-rays are reflected twice to create focal images. Various future projects in X-ray astronomy and astrophysics will require large optics with wide fields of view. Both large Kirkpatrick-Baez modules and lobster eye X-ray telescopes may serve as solutions as these can offer innovations such as wide fields of view, low mass and reduced costs

2 Simulations of X-ray Optics.

Alternative simulation and ray tracing methods for LE optics were investigated and compared including Zemax (OpticStudio) based, Matlab (Optometrika toolbox) based, and Python code. They were compared with LESim house made Rigaku code. The new Python X-ray-tracing code PyXLA for Lobster-Eye Application is written in the Python language and supports Lobster-eye optics with coded rectangular mask. Point sources are used as sources of parallel beams for selected energy and material reflectivity based on the CXRO database.

We have newly developed novel ray-tracing simulator which models X-ray reflective optics with emphasis on Lobster Eye LE arrangements. The current version of the software represents a simulator for Lobster-Eye optics in a one-dimensional arrangement. The software for 2D arrangements is expected to follow. It utilizes real ray-tracing principles and the mirrors' arrangements and their surface finishing as input parameters to provide accurate results based on physical principles and thus allows for optimization of the system. The goal of the software is to verify the properties and behavior of X- ray optics for different conditions and spectra.

There are several simulators of X-ray optics based on different evaluation methods such as ray-tracing or mathematical analysis. The newly developed software was compared with the available software: Zemax (ray-tracing), LeSim (ray-tracing and mathematical analysis) and the Optometry toolbox from MATLAB (Figure 1).

The developed software respects the dependence of the reflectivity of individual mirrors with regard to their coating and its thickness, angle of incidence and energy of incident radiation. The program is able to distinguish individual rays based on the number of reflections in the optical module. The energy of incoming radiation has a substantial impact on the reflectivity and thus the sensitivity of the X- ray telescope.

Main features of PyXLA Python X-ray-tracing for Lobster-Eye Application [1]:

- Written in Python language
- Support Lobster-eye optics with coded rectangular mask
- Point sources as parallel beams for selected energy and material reflectivity based on CXRO database
- Outputs
- Image created by ray-tracing process
- Simplified 3D model (optionally direct or reflected rays)

An example of the with PyXLA simulated image for LE optics with parameters in Table 1 is presented in Figure 2. The example of simulation results by LeSIM cod efor the KB systém is in Figure 3 (focal images) and in Figure 4 (effective area calculation).

The 2D LE systems designed and assembled within the project were primarily simulated by LeSIM code, see Figure 2.

Table 1 Example parameters of LE Optics used for various ray tracing method tests and comparison

<table>
<tr><th></th><th>1D</th><th>2D (H | V)</th><th></th></tr>
<tr><td>Focal length</td><td>250 mm</td><td>1345 mm</td><td>| 1079 mm</td></tr>
<tr><td>Mirror thickness</td><td>0.145 mm</td><td>0.35 mm</td><td>| 0.35 mm</td></tr>
<tr><td>Mirror spacing</td><td>0.3 mm</td><td>0.75 mm</td><td>| 0.75 mm</td></tr>
<tr><td>Number of mirrors</td><td>56</td><td>47</td><td>| 47</td></tr>
<tr><td>Reflective surface</td><td>Au</td><td>Au</td><td>| Au</td></tr>
<tr><td>Field of view</td><td>2.75°</td><td>1.04°</td><td>| 1.29°</td></tr>
<tr><td>Angular resolution</td><td>6.12 arcmin</td><td>1.40 arcmin</td><td>| 1.59 arcmin</td></tr>
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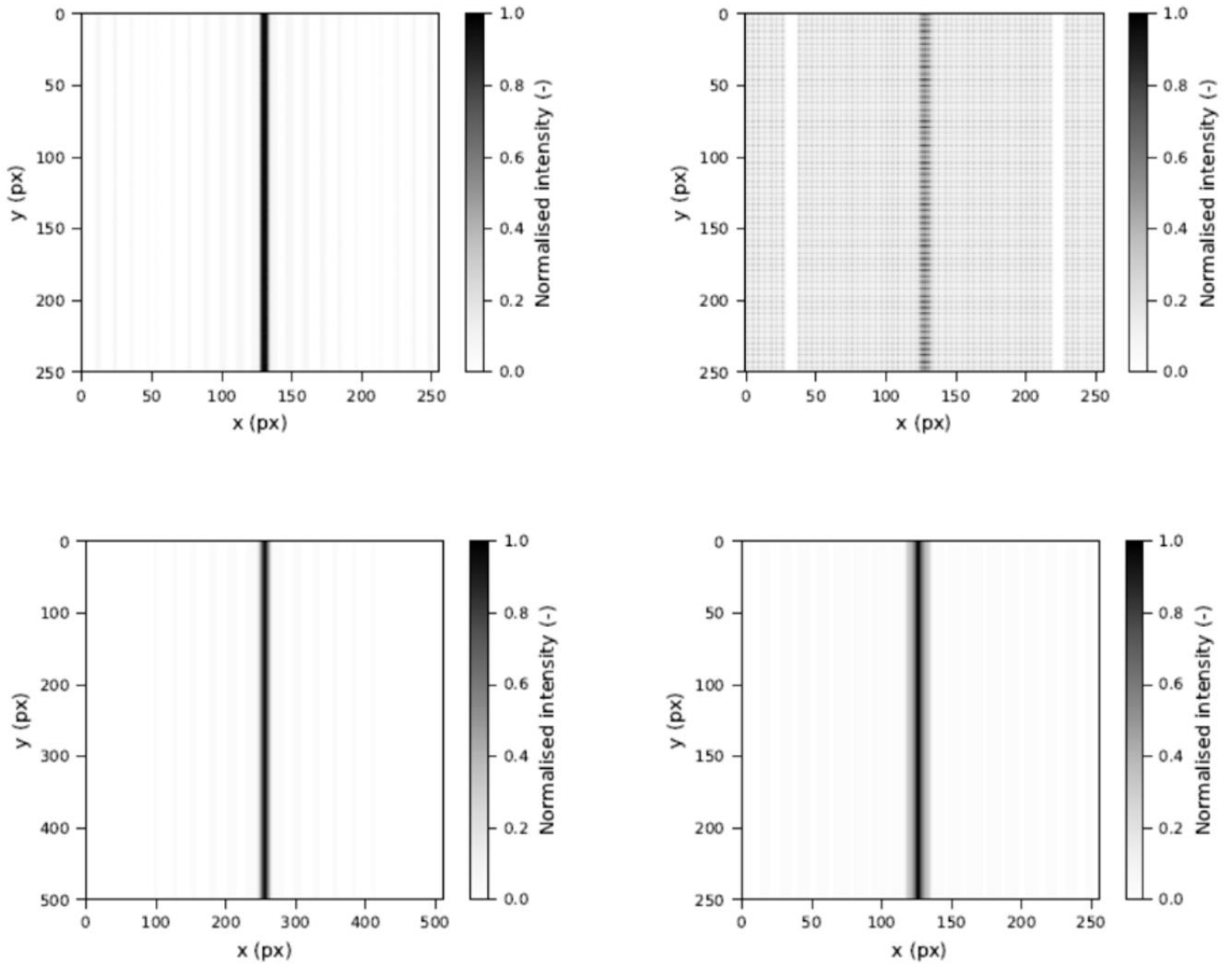

Figure 1 from top left to bottom right results of the geometric approach of: optic studio software, Optometrica Toolbox for Matlab, leSim, and PyXLA software. This approach does not take the angular dependence of the reflectivity into account.

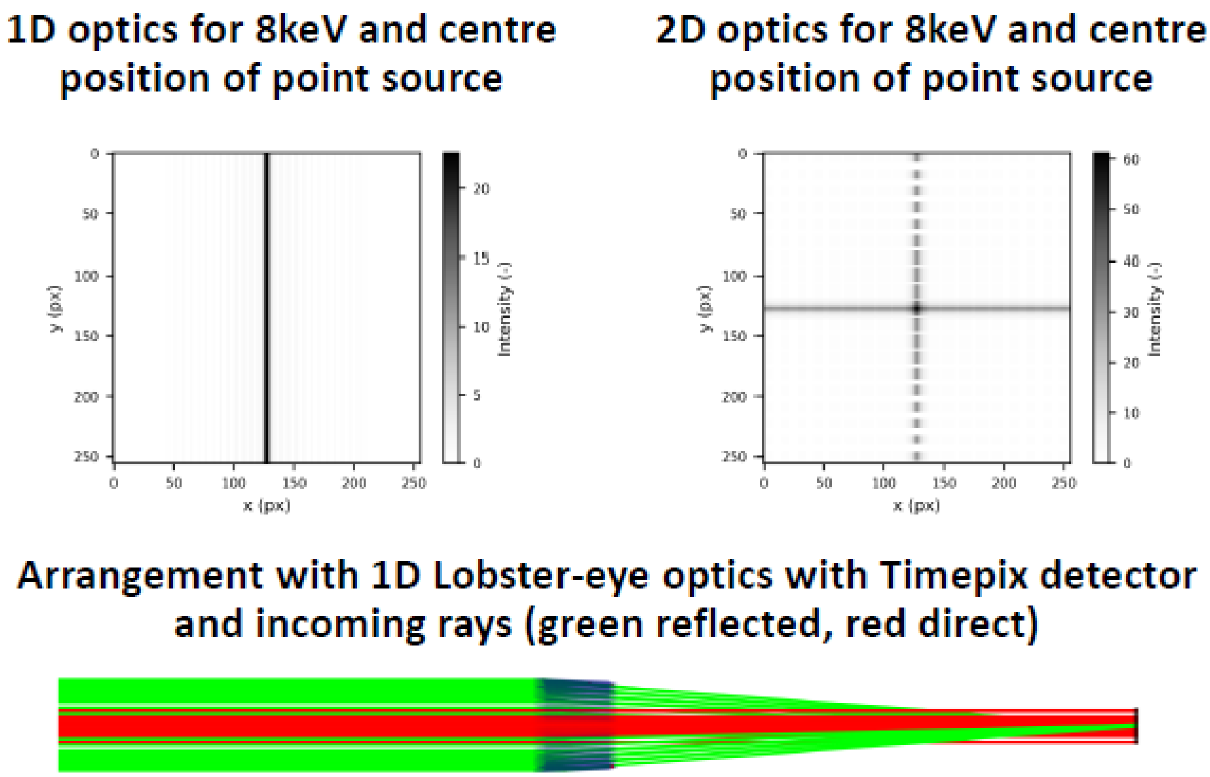

Figure 2 Images from PyXLA, arrangement with 1D LE optics are shown here.

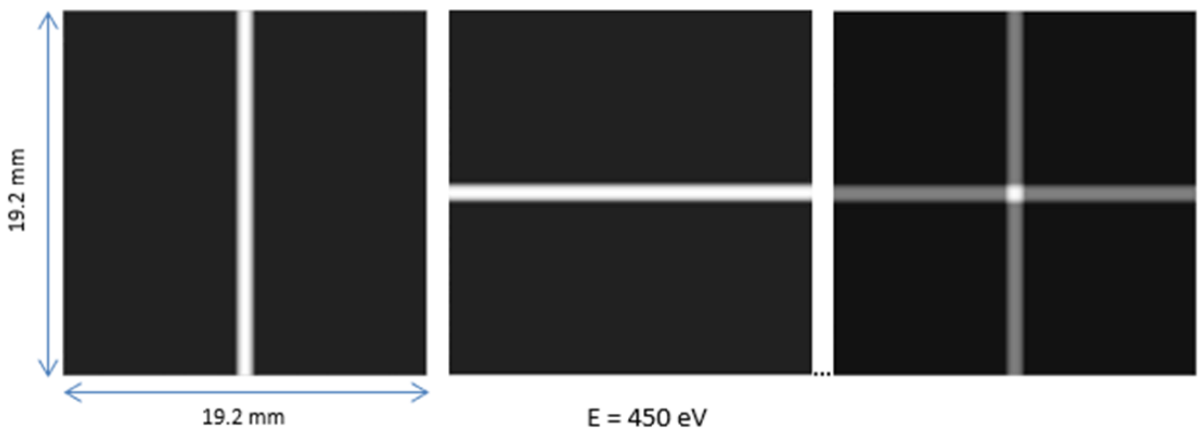

Figure 3 Large KB module. The example of the line focus from horizontal 1D sub-module A (left), line focus from vertical 1D sub-module B (center) and focus from 2D optics (right) in the logarithmic scale. The size of the detector image is 19.2 x 19.2 mm. By Rigaku Prague ray tracing code LeSIM.

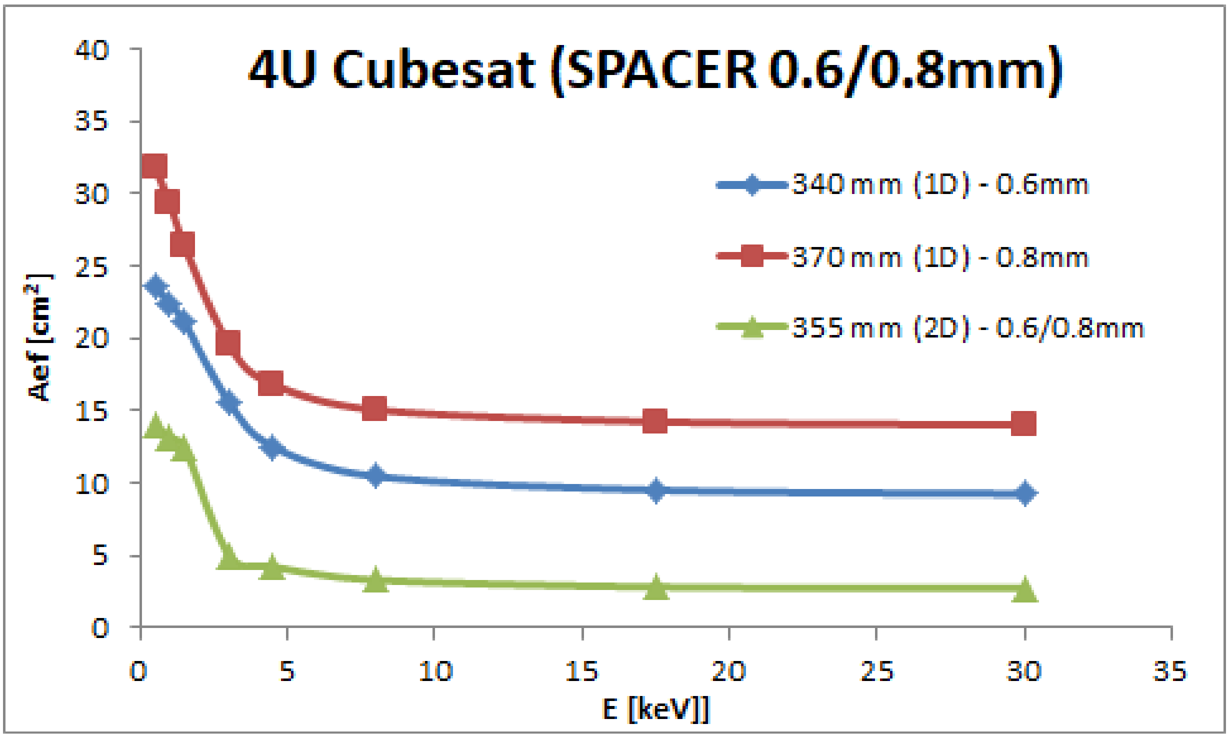

Figure 4 The comparison of the calculated effective area (for 1D sub modules and 2D optics) for a point source that is on the optical axis, at infinity. Test LE module with f 400 mm. *By Rigaku Prague ray tracing code LeSIM.*

3 Design of X-ray Optics of Lobster Eye type.

The Lobster Eye X-ray optics was first desribed by Angel (1979) [11] and by Schmidt (1975) [12]. In Figure 5 the different types of Lobster Eye X ray optics (Angel, Schmidt 1D and Schmidt 2D) are shown. Due to manufacturing difficulties, the realization of LE lenses was achieved only relatively recently, with still limited applications in space, see Hudec and Feldman [5] for a review. For additional details on past developments see [6][7][8][10][13]. In this report we focus on LE in Schmidt arrangement based on planparallel sets of thin reflecting surfaces.

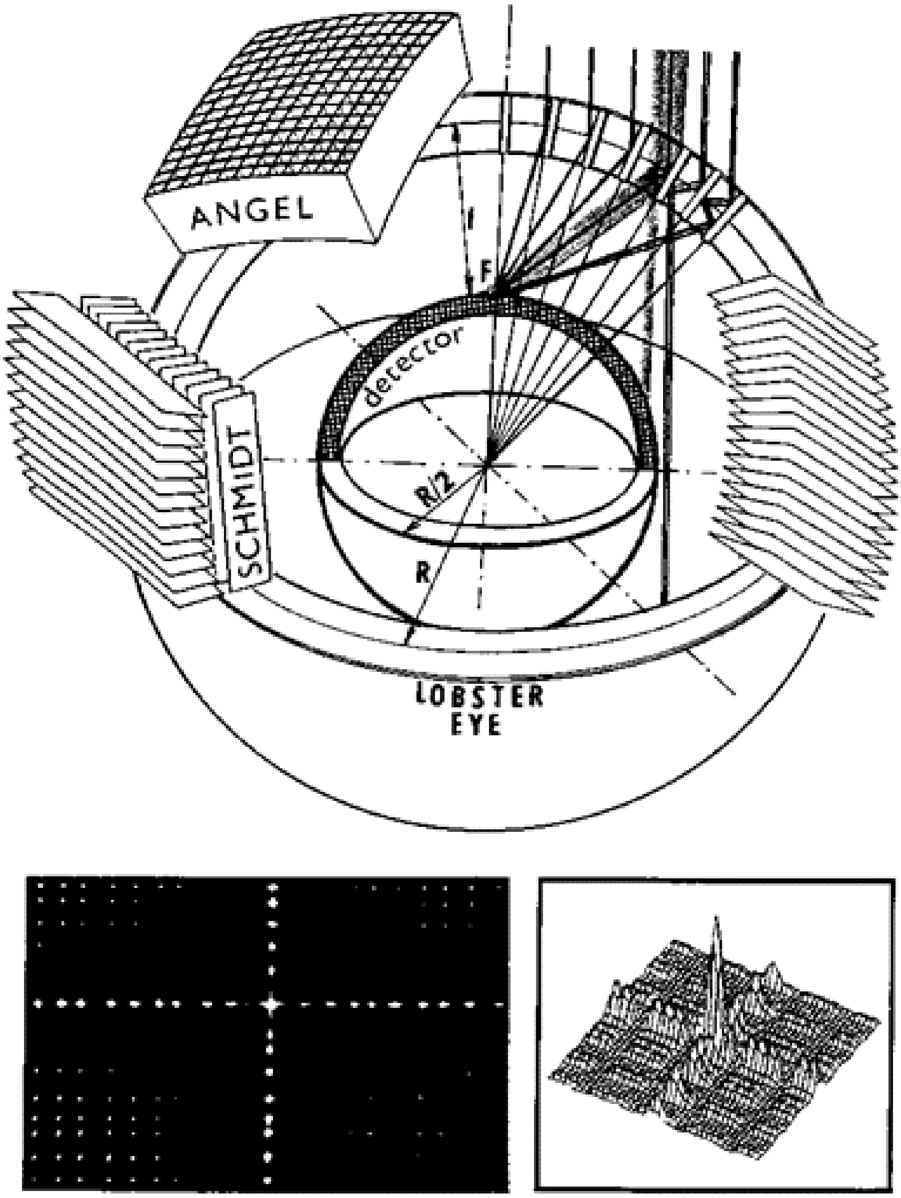

Figure 5 The principle of Lobster Eye X ray optics of Angel and of Schmidt type in 1D and in 2D arrangements. Both 2D as well as 2D Schmidt modules are deesribed in this report.

3.1 Alternative LE Arrangements

In addition to the commonly considered LE 2D arrangements, we have investigated novel arrangement of parallel 2 x 1D LE modules (Figure 6) with relevant image reconstruction methods (2x line focus). This arrangement allows to increase the energy range towards higher E due to 1 reflection only instead of 2.

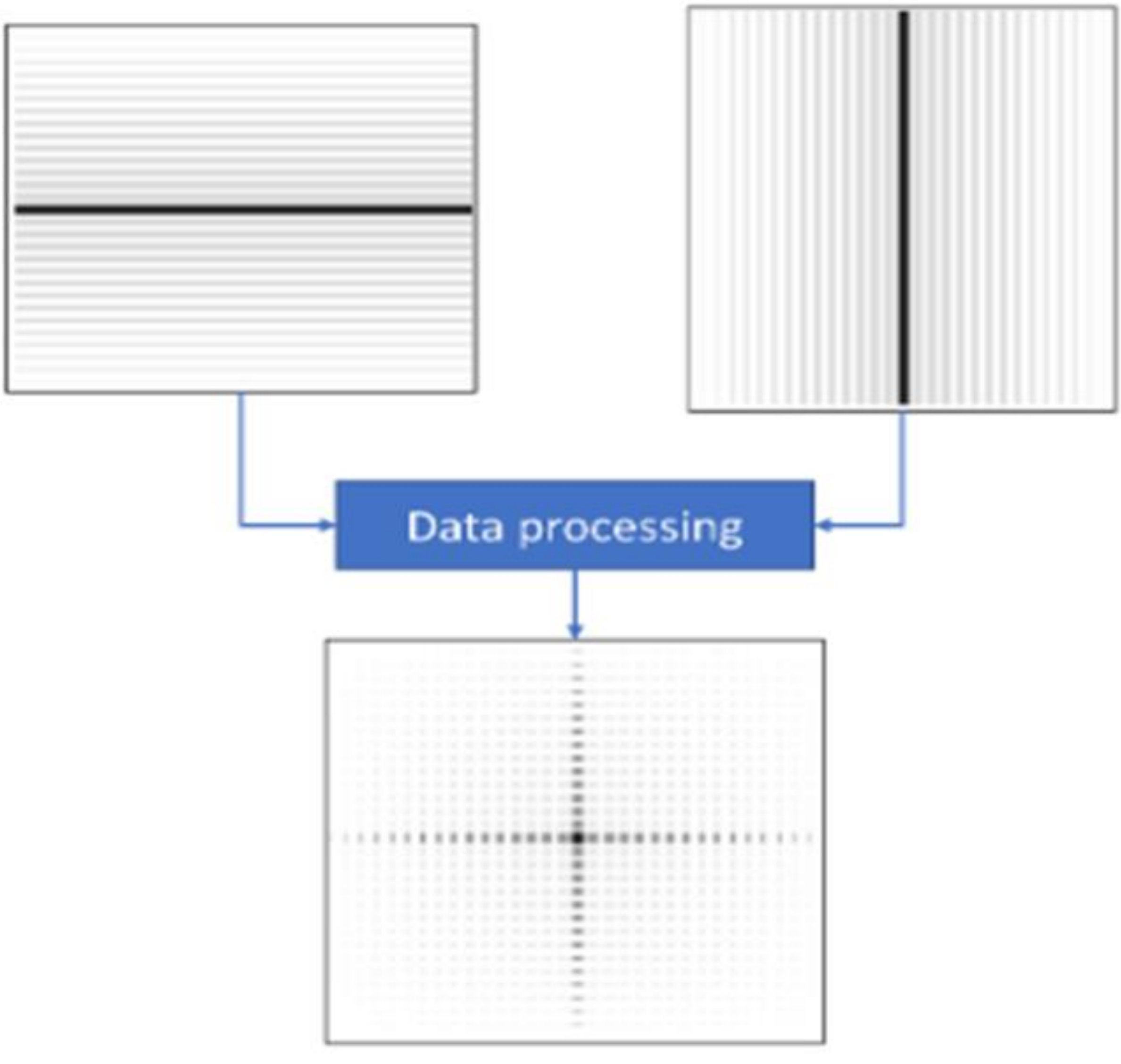

Figure 6 The principle of two LE 1D arrangements. It requires Min and Max search and mathematical processing.

3.2 Effective area simulations of LE optics

This parameter (effective area) is one of the principal parameters when it comes to optical systems. Indeed, the larger the area is, the more efficient the optical system is. We have estimated the effective collecting area by two different methods and then compared the results: the analytical method and then the simulation algorithm [2].

A. The analytical method to determine effective collecting area

We consider that the source of the X-ray is taken to be at an infinite distance and is on the convex side of LE optic, for the application of the telescope. Analytical models [9] are useful to approximate, even if the estimation of performance may be fast. It is also useful to determine the different parameters that impact the results.

As we have seen in the last part, LE optical system depends on radius of the system r (r1 and r2 for Schmidt technology as in REX1 and REX2), size of space between centers of surfaces of adjacent mirrors (pore width) a, plate thickness (or width of wall of pore) t , plate (or pore) depth h and number of plates (number of pores in one dimension) N (Figure 7). Variable beta represents the angular position of a mirror. The incoming rays are considered to be parallel and therefore beta is equal to theta, where theta is a grazing angle. We also have to define the effective angle epsilon of the system, which is the maximal grazing angle when the mirror does not lay in a shade of the adjacent mirror. Thus, if the grazing angle of the system theta is less or equal to epsilon, then the mirror is fully illuminated. Else, if the grazing angle of the system theta is less or equal to 2*epsilon and greater than epsilon, the active area of the mirror is limited by the adjacent one as we said before. The Figure 7 describes both of the cases.

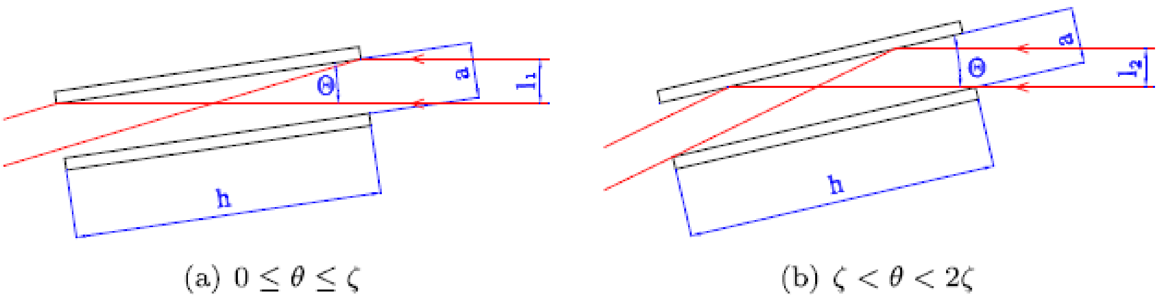

Figure 7 The passage of X-rays through the plates of the Schmidt LE module.

Depending on l1 and l2, we can get the total effective collecting length L [9] which is equal to the sum of effective lengths of all active mirrors but also of the reflectivity R(theta).

3.3 Design of Lobster Eye Test Modules

Alternative LE arrangements were studied, including a feasibility study of parallel 2 x 1D LE modules with image reconstruction methods (2x line focus). Such arrangement is assumed to increase the energy range towards higher energies due to just one reflection only instead of two. Design of two test LE modules was performed one with frontal aperture of 140 x 140 mm based on Au coated glass foils with dimension of 150 x 60 mm and the other one double test module with 4 x 17 Si wafers 0,625 mm thick aperture 85 x 65 mm f 2 m for comparison of various surface coatings based on Si wafers with thickness of 0.65 mm. The later modules were tested at PANTER in April 2021.
The relevant parameters of the LE module with short focal length are summarized in Table 1.

In total 4 LE modules were designed assembled and tested, one double with two paralell parts with different coatings (HORUS, Figure 9,Figure 10, Figure 11), one with f 900 mm (Figure 8) and the last one with f 400 mm (Figure 13).

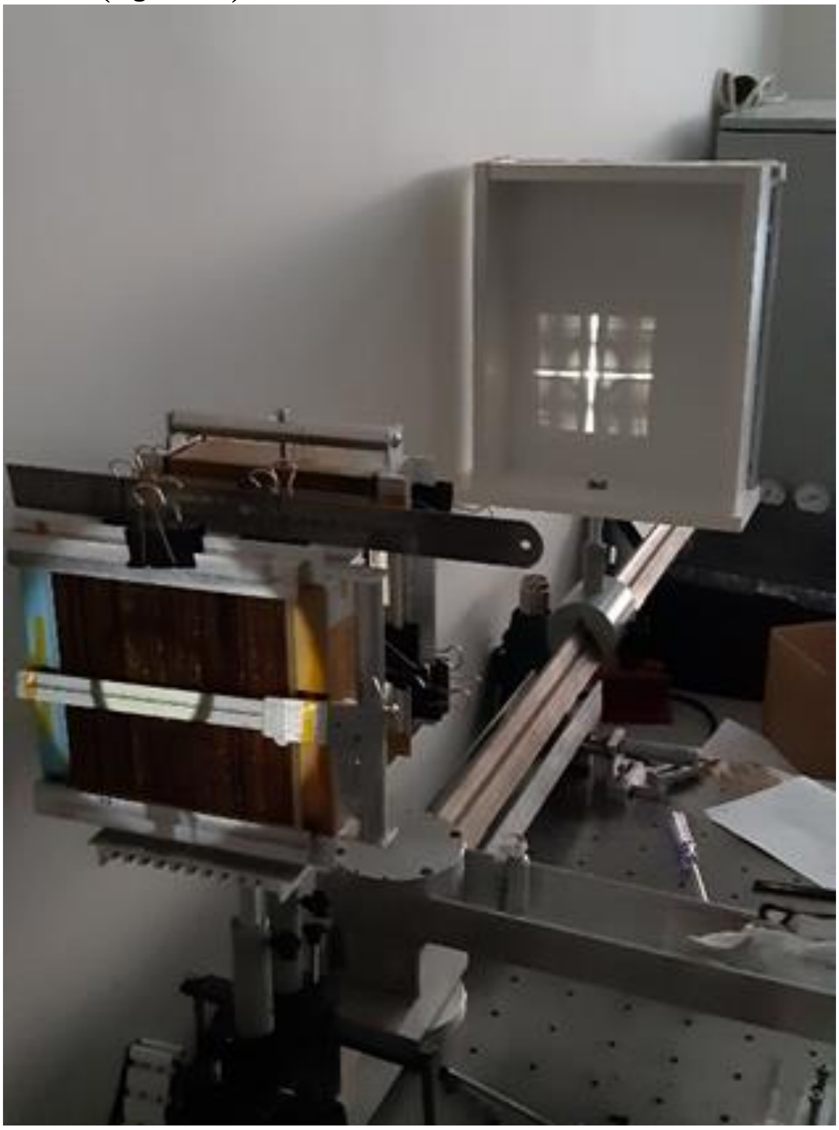

Figure 8 The LE test module with f=0.9m during testing in visible light.

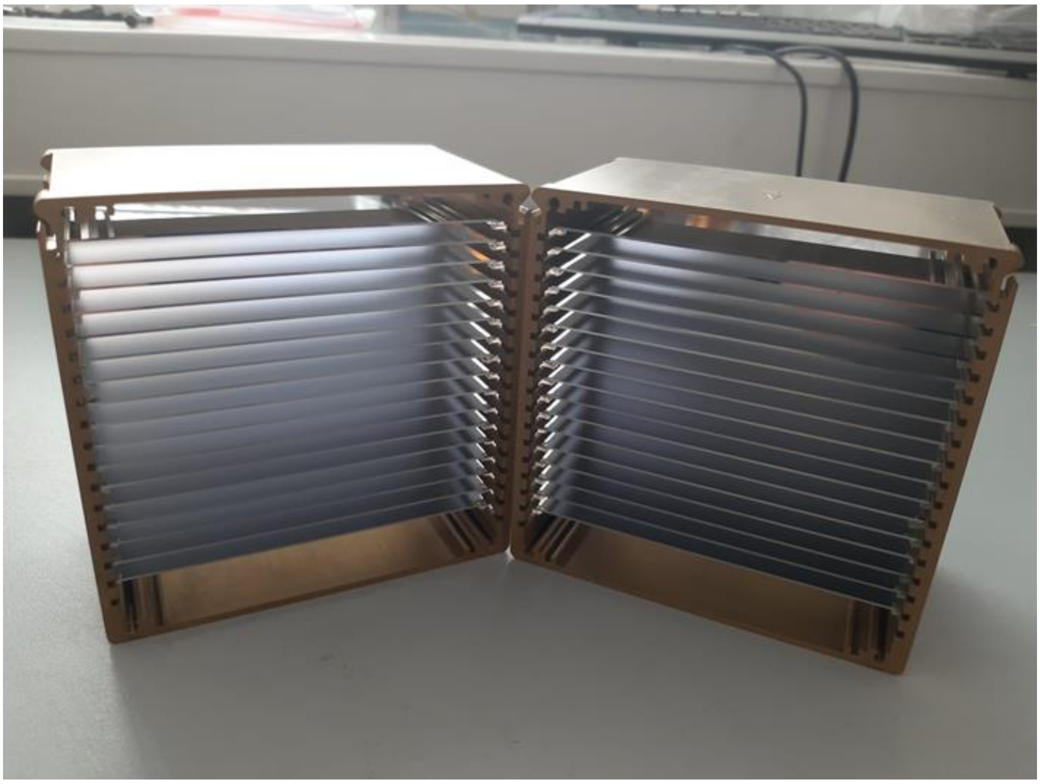

Figure 9 The double LE test module to experimentally compare different reflective layers with 4 x 17 Si wafers 0,625 mm thick, aperture 85 x 65 mm and f 2 m. Collaborative effort of CTU in Prague, Rigaku Prague, and Aschaffenburg University

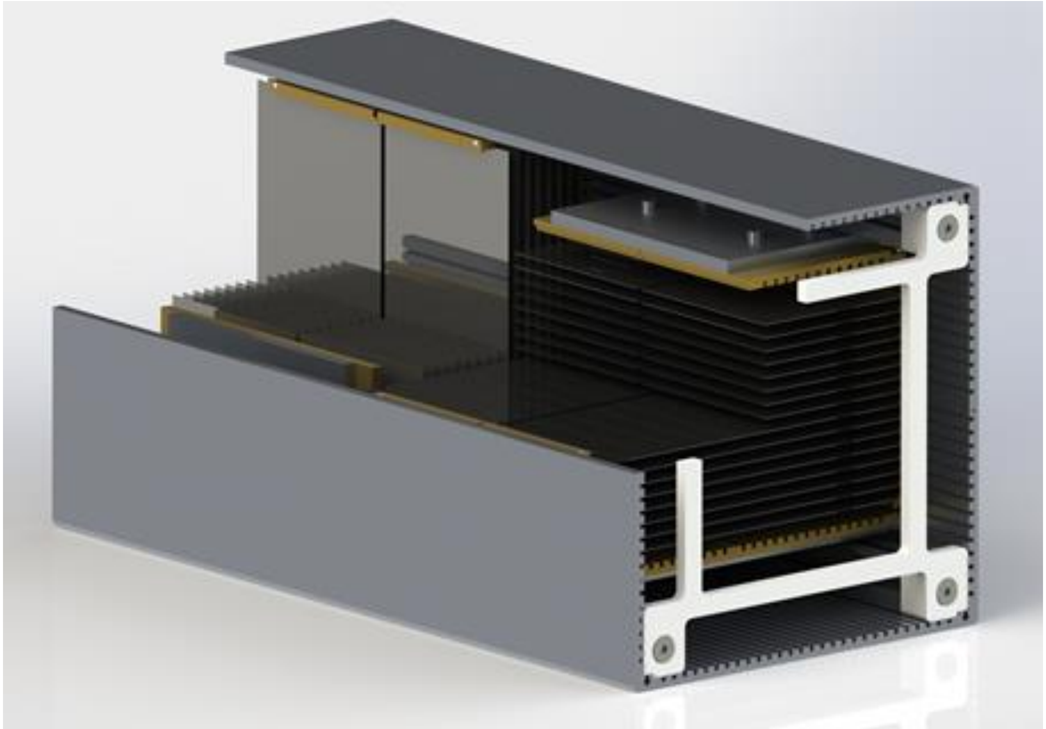

Figure 10 CAD drawing of the HORUS double LE test module.

Figure 11 The frame of the double LE HORUS module.

Effective area of the double LE HORUS optics was calculated for different angles for double and single reflection. As the optical channels close with rising angle, also effective area drops. For 1°tilt of optics, the double reflection effective area was 3.42 cm^2, for 2.2° then 0.25 cm^2. Calculated angular resolution of the optical system corresponds to 1.6 arc min.

Because the modular design provides freedom of different configurations, for experimental reasons of testing different coating layers were used two types of reflective coatings (Figure 12). Therefore two sub-modules are coated using pure golden layer, while two are equipped with a sandwich of chromium and iridium [2][3].

This combination of main iridium reflective layer and complementary chromium nano layer proved to provide better overall reflectivity in comparison with pure golden layer. This factor can be seen in Figure 12. All the samples have carrying chromium underlayer, which compensates the stress and prevents layer degradation over time.

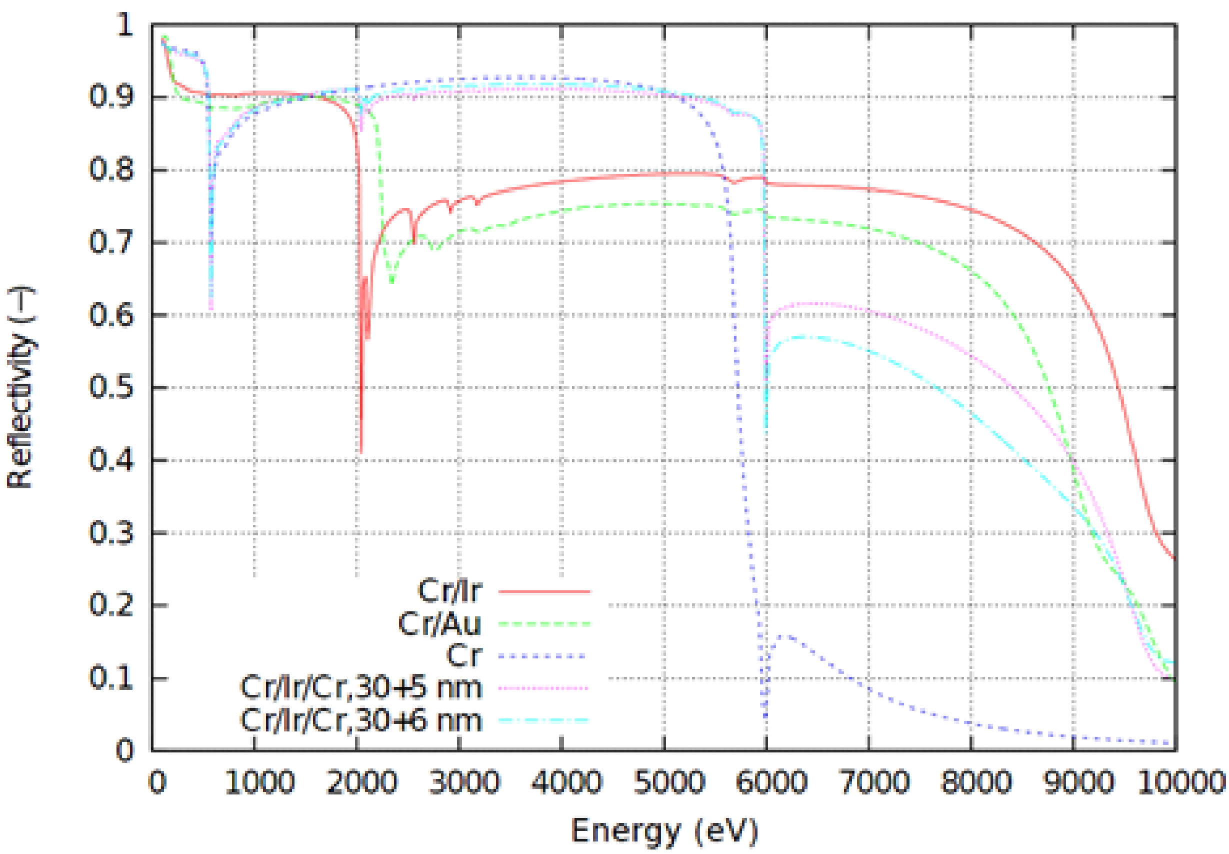

Figure 12 Comparison of reflectivity of the double LE module for different material combinations

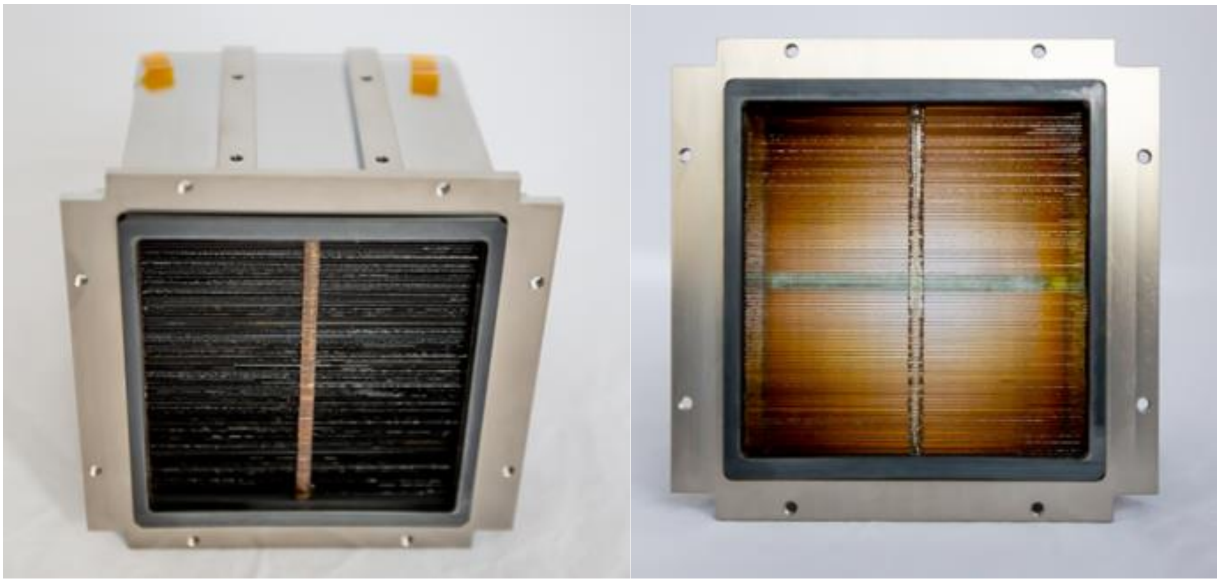

Figure 13 Small LE test module with f 400 mm for cubesat applications

4 Design of X-ray Optics of Kirkpatrick Baez type.

4.1 Design of Kirkpatrick-Baez Test Modules

The design of Kirpatrick-Baez (KB) X-ray optics dates back to 1948 [9]. The KB systems were used in the early era of X-ray astronomy on sounding rockets however later on mostly Wolter systems were used in space applications. However the KB systems offer some advantages for future large space X ray telescopes mainly due to no need to polish expensive mandrels and this is why we have in detail analysed and designed such systems based only on very slightly bent substrates (Figure 14).

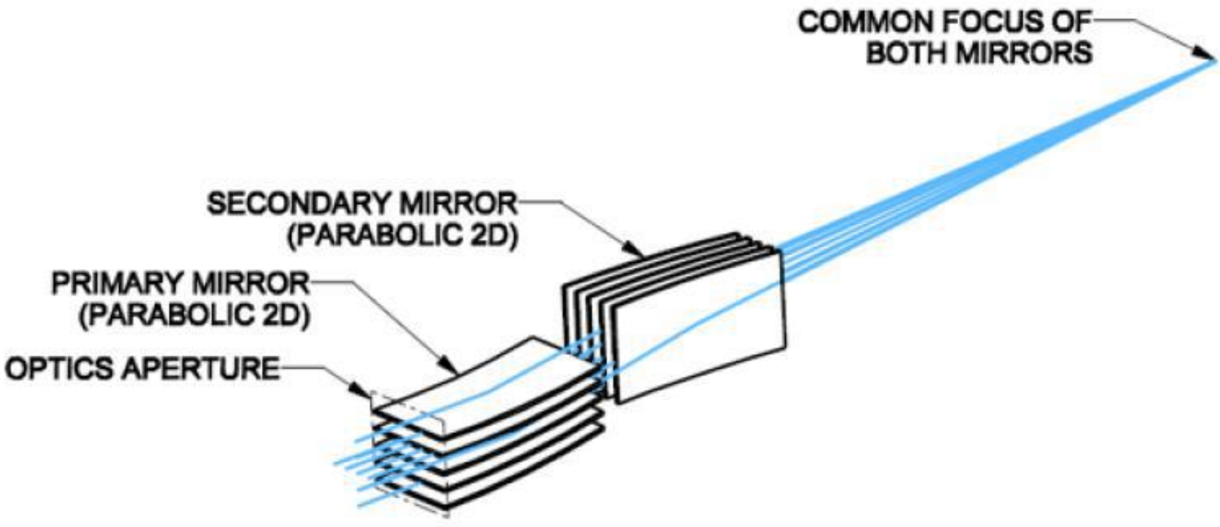

Figure 14 Principle of the KB X-ray multifoil optical system

Large KB multi-module array with long focal length of 6155 mm (due to the requirements at the PANTER test facility) has been developed in collaboration with Rigaku Prague (Figure 15 and Table 2 and Table 3) and tested in the PANTER X-ray facility at the end of 2021. In addition to that, the large KB module was also tested at the X ray test facility in Prague and in visible light in the optical laboratory of CTU in Prague. These results will be described later in the relevant section.

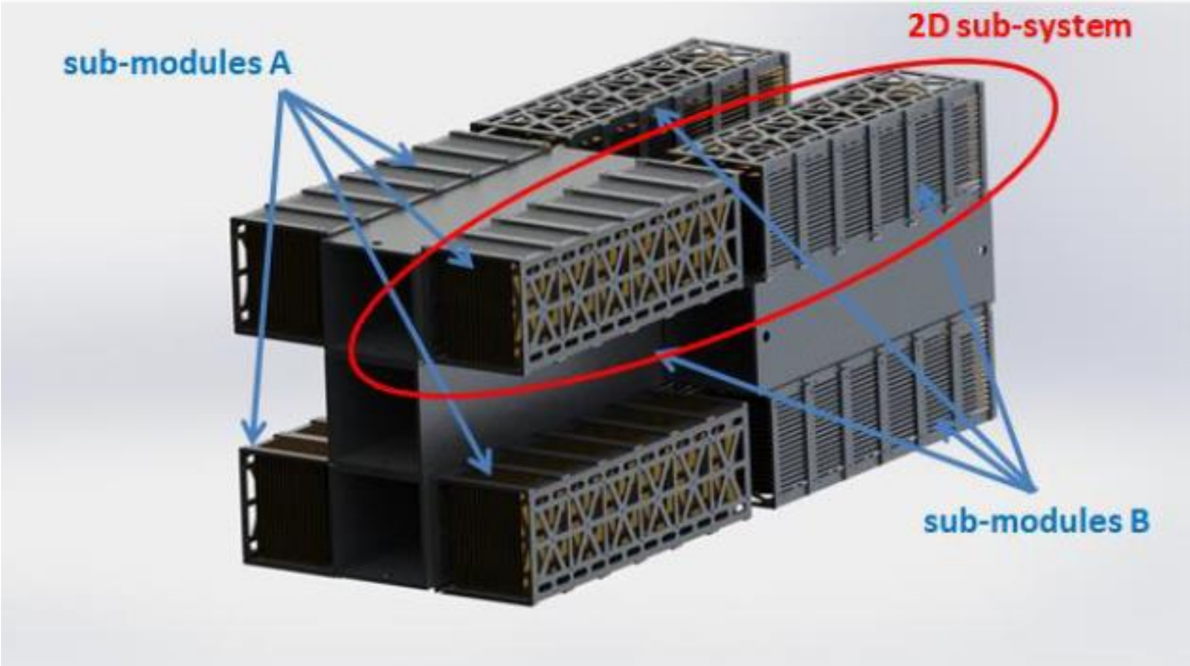

Figure 15 The CAD drawing of the large multi-module array KB optical system. The KB system designed, developed and manufactured in collaboration with RITE Prague consists of four 2D sub systems, i.e. 4 sub modules A and 4 sub modules B.

Table 2 The main parameters of the multi-modular KB system.

			sub-module B	sub-module A
Optical aperture	A_{opt}	[mm]	72.0 x 72.0	72.0 x 72.0
Dimensions of the foils:	T	[mm]	0.65	0.65
	H	[mm]	50	50
	W	[mm]	100	100
Foil material			silicon	
Reflective surface			multilayer based on the Au	
Number of foils in one sub-module	N	[-]	6 x 15	6 x 15
Focal length	F	[mm]	6 335	5 975
Field of view - optics	FOV_O	[deg]	1.3	1.4
Field of view – optical system	FOV_{OS}	[deg]	10.4	11.1
Angular resolution for closest profile*	ω_1	[arcmin]	9.6	10.1
Angular resolution for furthest profile*	ω_2	[arcmin]	20.7	21.9
Effective angle for closest profile*	β_{E1}	[rad]	18.5	18.5
Effective angle for furthest profile*	β_{E2}	[rad]	38.0	38.0
Limit angle for closest profile*	β_{L1}	[rad]	37.0	37.0
Limit angle for furthest profile*	β_{L2}	[rad]	75.8	75.8

*from the optical axis

Table 3 The key parameters of the large KB optics.

			module A	module B
Focal length	F	[mm]	6 335 (± 750)	5 975 (± 750)
Field of view	FOV	[deg]	≥ 1	≥ 1
FWHM @ 1.5 keV	FWHM	[mm]	2 (± 0.5)	
Angular resolution @ 1.5 keV	ω	[arcsec	≤ 45 (± 10)	

In addition to that, simple KB module with superior angular resolution was studied with aseembly and tests in the coming months.

5 Novel substrates and reflecting layers

5.1 Selection of reflecting substrates

The possibility of use of newly developed by external collaborator superior quality Si wafers with TTV of order of 0.2 microns was investigated. The optimized methods for substrates cutting was exploited too. Selected substrates were measured with the AFM machine. In collaboration with ON Semiconductor Czech Republic, the improved Si wafers with TTV <0.5 micron were studied (Figure 16). The use of such high quality substrates is expected to help to improve the angular resolution of future modules.

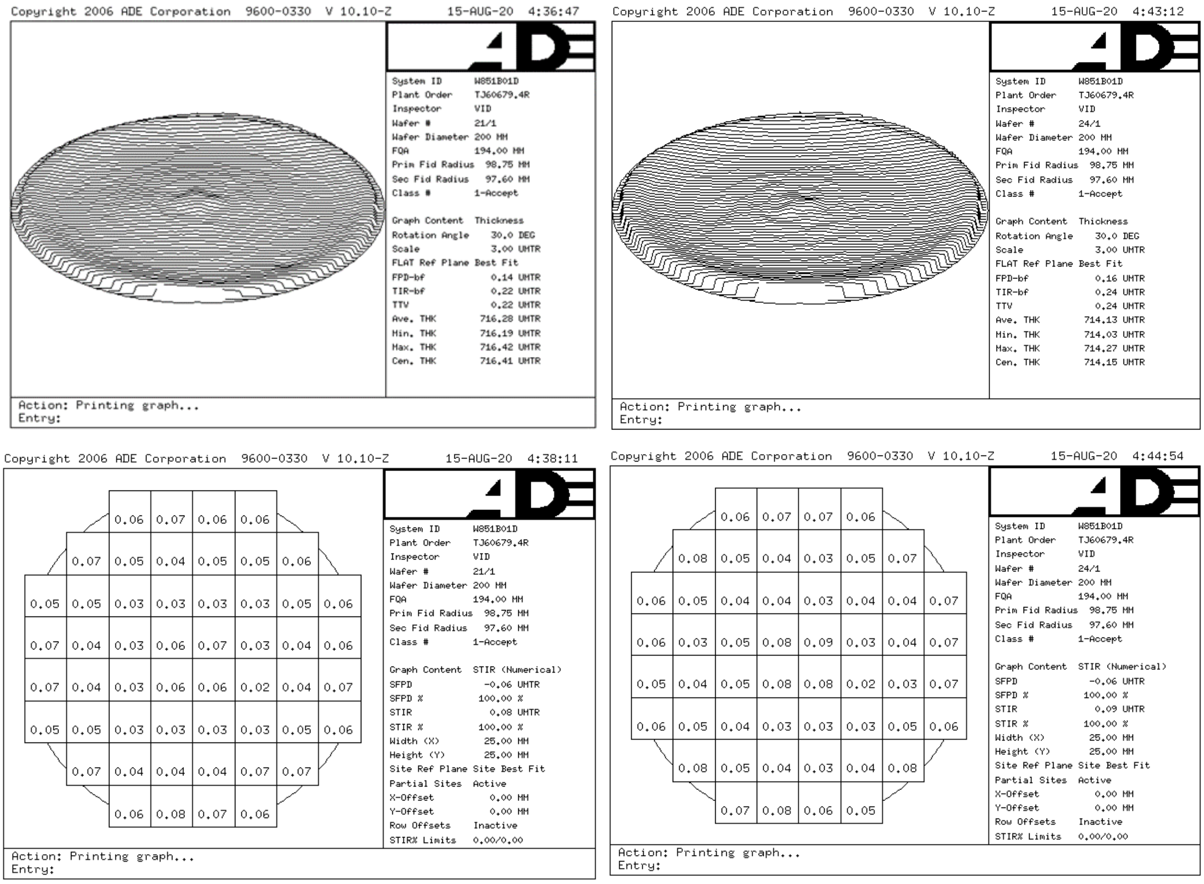

Figure 16 Advanced Si wafers type: W805B00 (diameter 200mm, dopant bor, orientation <100>, with iproved TTV <0,5um, by ON Semiconductor Czech Republic. Result of scintific collaboration with ON Semiconductor Czech Republic research department, Dr J. Sik.

5.2 Studies of alternative/improved coatings

In collaboration with Aschaffenburg University, Rigaku Prague and MPE, alternative and improved coatings were simulated, applied and recently tested (Figure 17). This includes the assembly of double test double hybrid LE module with Ir and Au reflecting surfaces deposited on identical substrates namely silicon wafers [3]. These studies are important for future advanced X-ray telescopes because of performace imporvements (effective area. reflectivity, energy range).

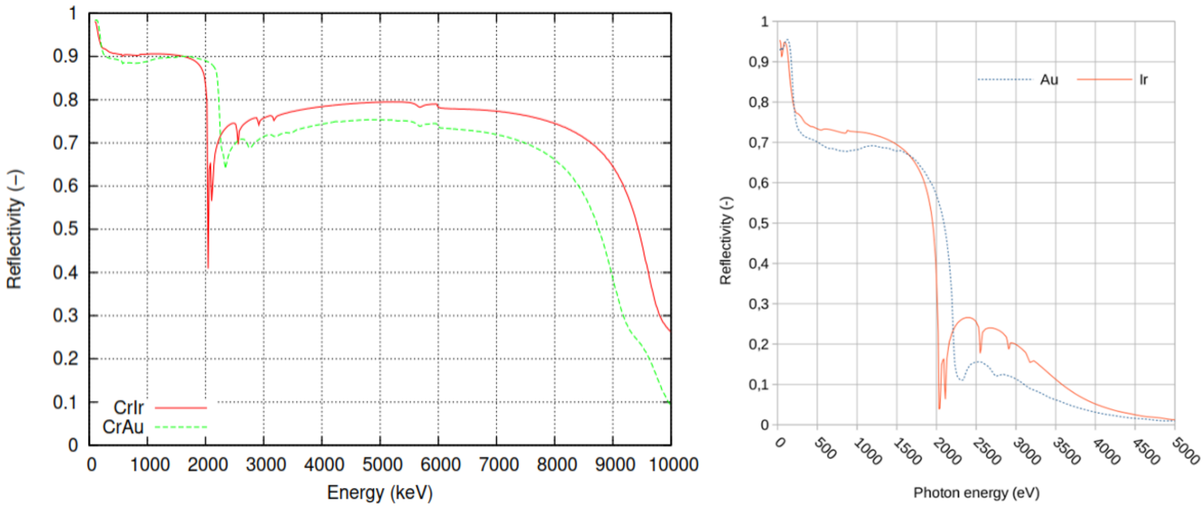

Figure 17 Study of alternative coatings. Multiple layers system - a sandwich of two metals

6 Tests of Kirkpatrick Baez (KB) and Lobster Eye (LE) modules

Tests of both KB as well as LE modules were performed in optical light at the CTU optical laboratory in Prague, and in X rays at the X ray laboratory in Prague in collaboration with the VZLU Institute and at the MPE PANTER facility. Some selected results are presented and discussed in the following sections. For all the measurements very detailed reports are available.

6.1 Tests in optical light

Tests in optical visible light (and in addition to that in UV light) were performed at the optical bench in the optical laboratory of CTU in Prague, using a large aperture optical lenss/collimator (Figure 18 and Figure 19). Examples of obtained focal images for 1D arrangement are presented in Figure 20 and Figure 21. More extended report is available at the CTU. CTU students were involved in these measurements [17].

The measurement setup is illustrated in Figure 19. First, the two KB submodules A and B were tested as 1D imaging devices, with 1D linear focus recorded by a CCD camera system. Then the full 2D KB system was arranged with both A and B modules and also tested.

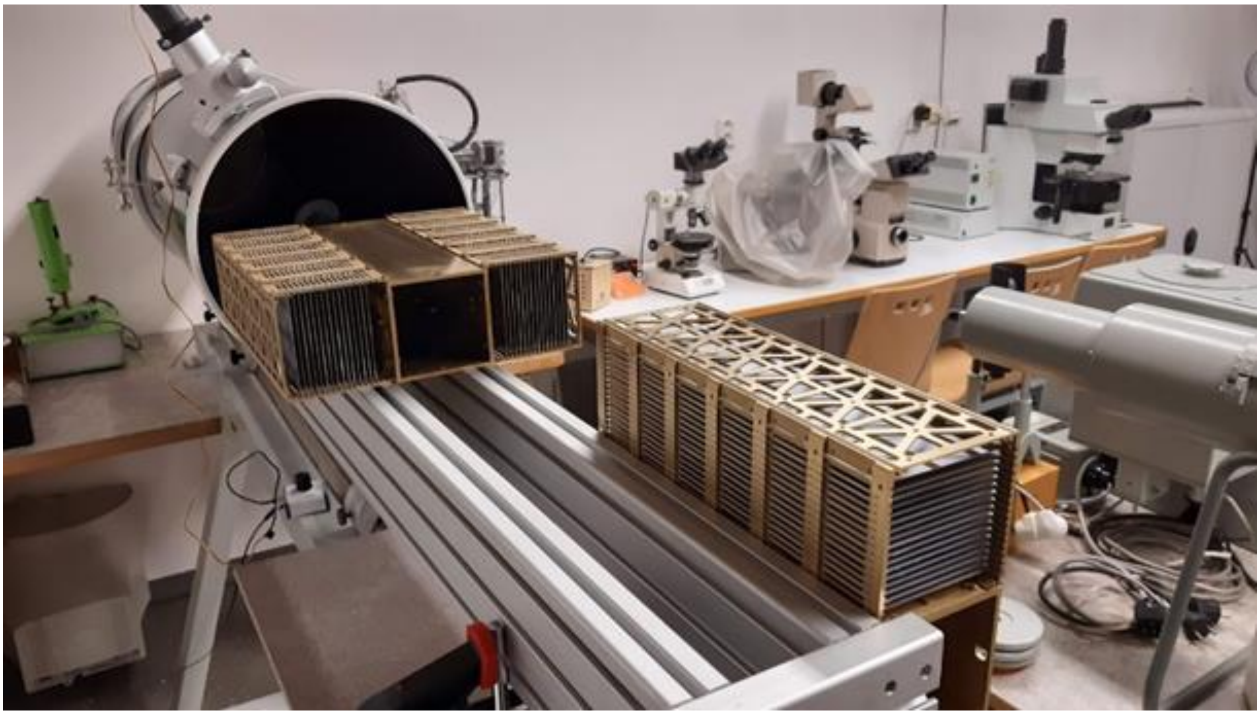

Figure 18 Large Kirpatrick Baez Array during optical tests at the Prague CTU laboratory.

It should be noted that the optical tests are influenced by optical diffraction, this is why also UV light illumination was tested.

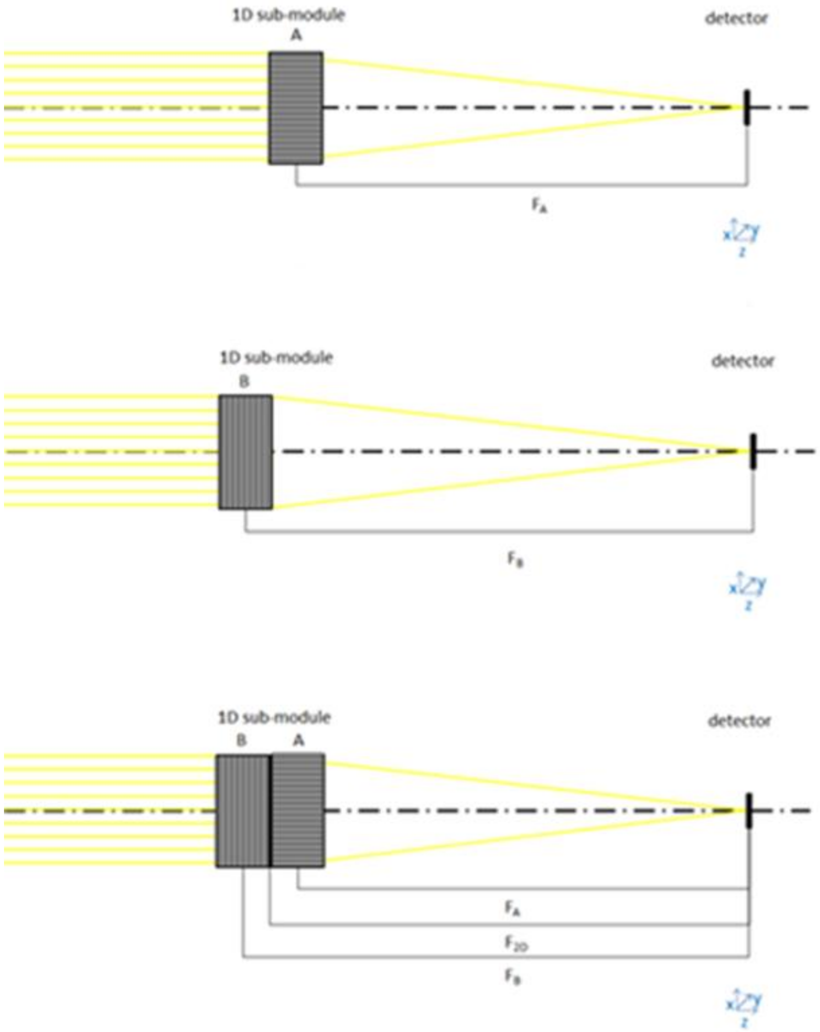

Figure 19 The setup of the optical experiment (large KB module) at CTU Prague Both 1D KB modules were tested separately and then together as 2D KB module.

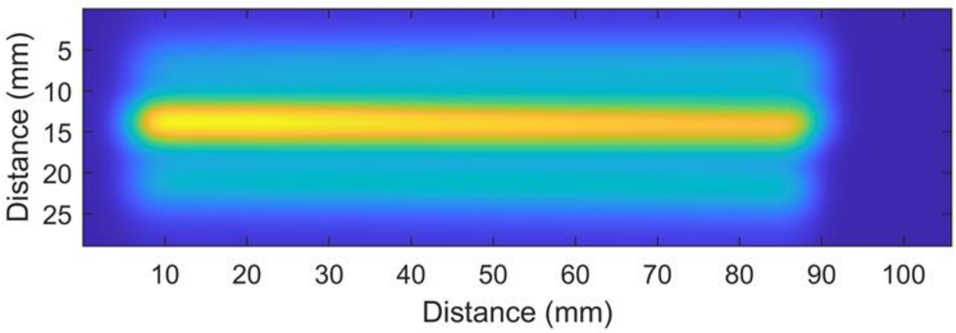

Figure 20 Example of 1D optical focus of the large KB module.

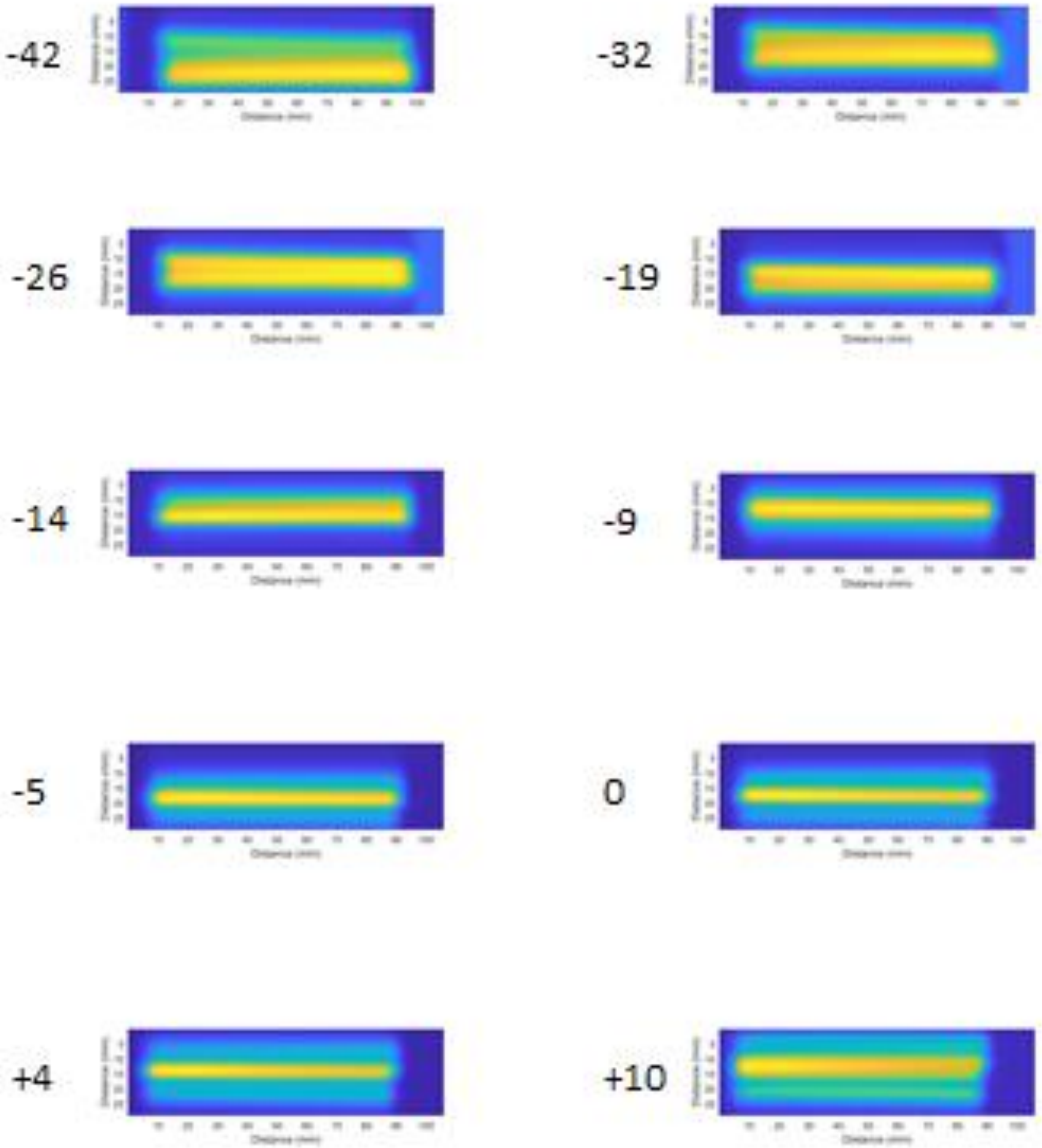

Figure 21 Linear focus behaviour along the optical axis, large KB module.

6.2 Tests in X-rays

Tests in X-rays were performed in Prague in collaboration with the VZLU Institute where a small X ray test facility was created and in the PANTER X-ray test facility of the Max Planck Institute for Extraterrestrial Physics near Munich in Germany in the collaboration with MPE team. The tests in Prague were important especially during the covid period when long distance international travel was limited.

6.2.1 X-ray tests in Prague

Several LE and KB test modules designed and developed within the project were tested at the X ray test facility in Prague VZLU (Figure 22) with some examples given below. The examples of results obtained for the LE f 400 mm module are presented in Figure 23, Figure 24, and Figure 25 The large KB test module developed within the project was tested there as well prior to the tests at the PANTER facility (Figure 26).

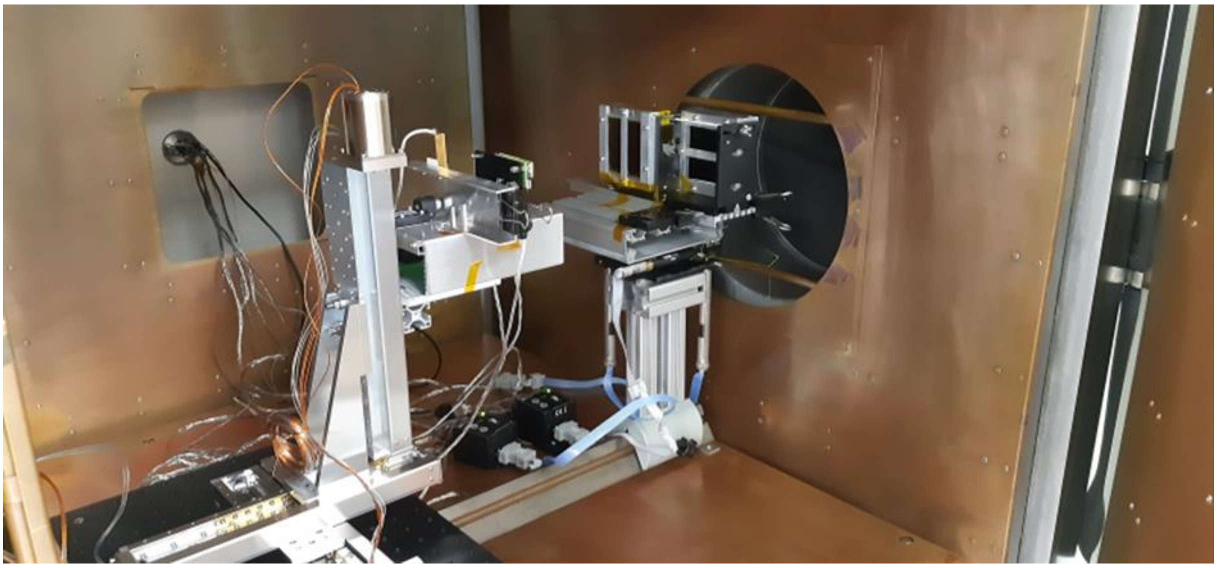

Figure 22 LE f 400 mm test module at the X ray test facility in Prague (VZLU).

Figure 22 illustrates the test arrangement of the f 400 mm LE test module within the vacuum chamber of the VZLU Prague test facility. The LU modules were tested both in the 1D arrangement as illustrated in the figure as well as in the full 2D arrangement.

The behaviour of the imaging quality as function of the distance between the detector and optical module is illustrated in Figure 23. While the designed LE focal distance was 400 mm, the measured focal spot quality remains excellent and stable within range 403-411 mm, i.e. slightly more than the calculated and designed f value. The sharpness of the focus is of the order of 10 mm.

In addition to that, the off-axis behaviour of the LE module was also exploited and measured. Figure 24 illustrates the off-axis performance of LE module f 400 mm: Image of the focus on the detector is shown for different position of the Ti source – off-axis imaging (±1.6 deg in the horizontal and ±1.2 deg in the vertical direction). The large FOV of order of min 3 degrees' diameter with nearly constant image quality within this FOV was clearly demonstrated by these measurements. We note that in specific space applications requiring larger FOV, several identical LE modules can be used in slightly tilted arrangement in order to cover larger FOV.

Analogous results are also illustrated in Figure 25 confirming the large FOV of the LE f 400 mm 2D optics. Measurements with Ti target, with Timepix focal detector. This image provides also a demonstration of the large FOV of he LE module tested.

Also the large KB module developed within the project was in X ray first tested at the Prague VZLU vacuum chamber facility (Figure 26) just before transferring this module to Neuried in Germany for the PANTER facility full aperture X-ray measurements.

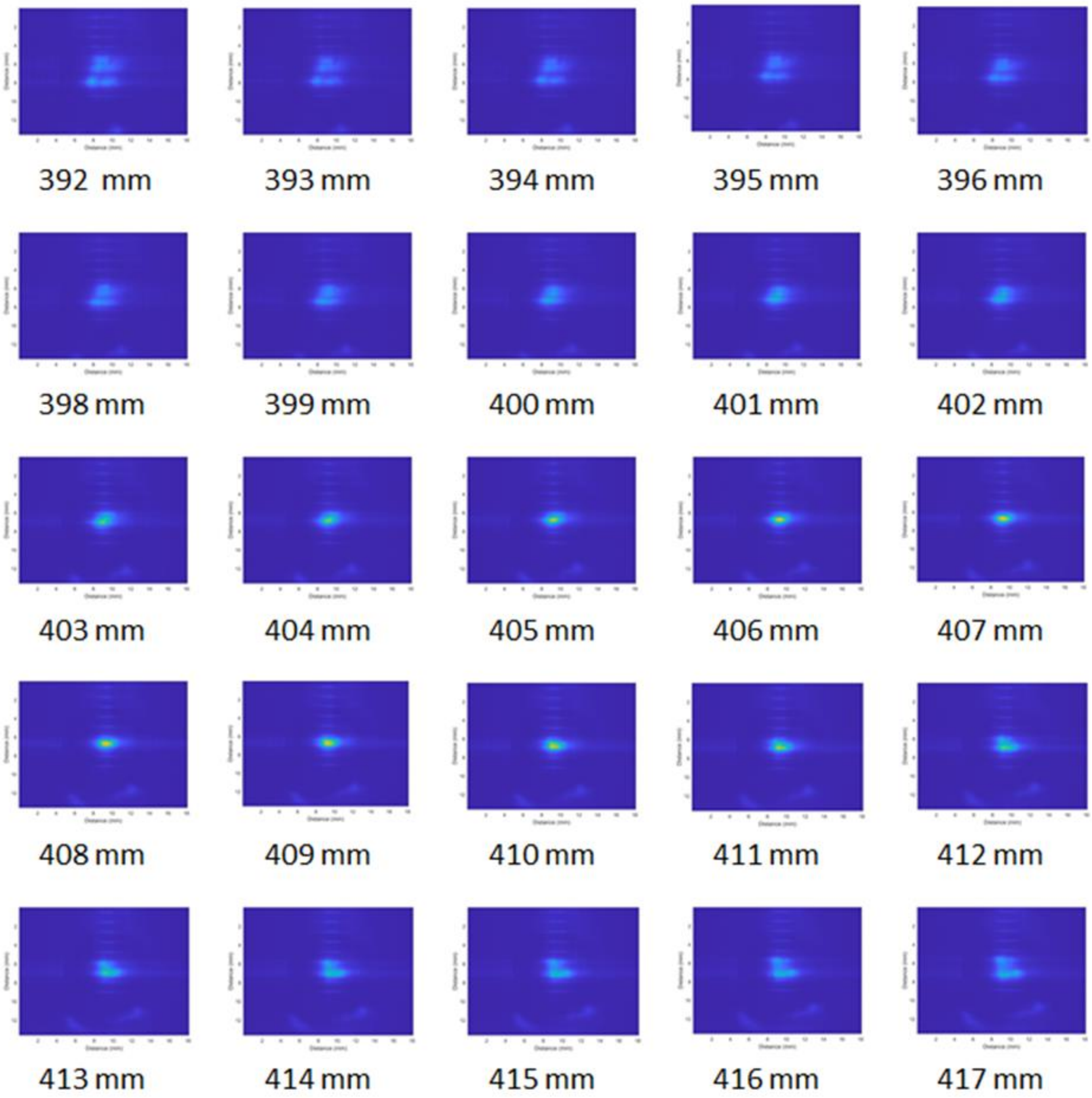

Figure 23 Lobster Eye f 400 mm behaviour of focal image at 4.5 keV in dependence on the position along the optical axis

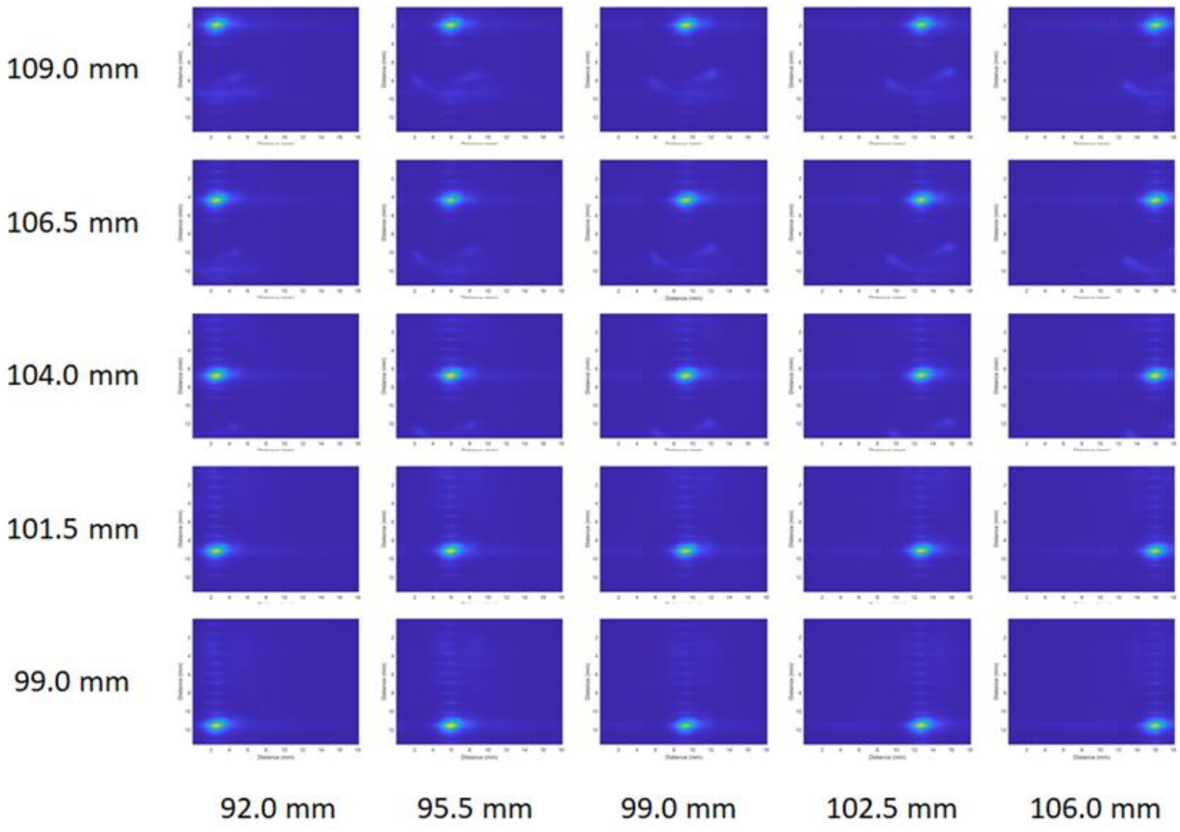

Figure 24 The off-axis performance of LE module f 400 mm: Image of the focus on the detector for different position of the Ti source – off-axis imaging (±1.6 deg in the horizontal and ±1.2 deg in the vertical direction).

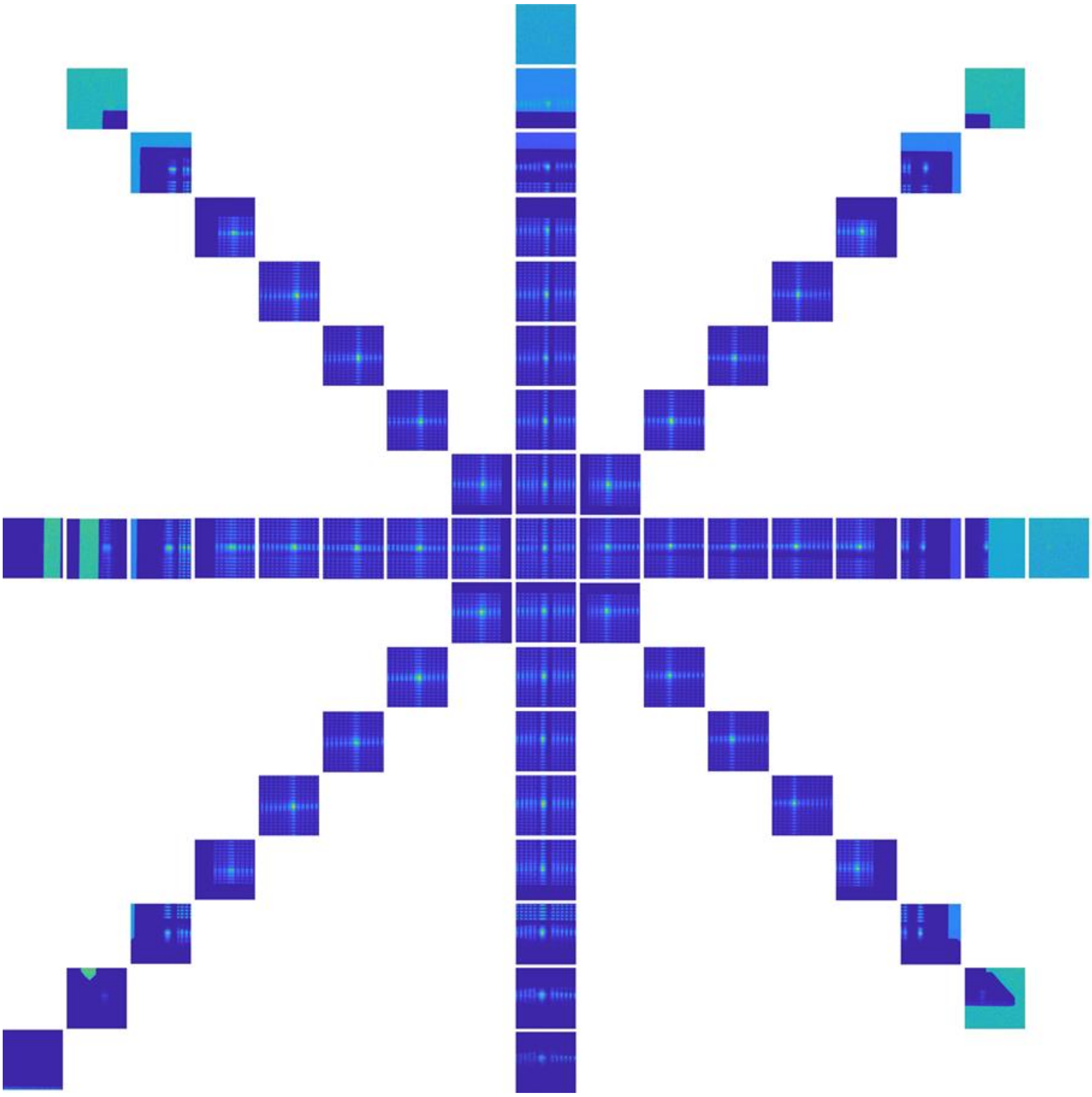

Figure 25 FOV of the LE f 400 mm 2D optics – Ti target, Timepix detector. Demonstration of the large FOV.

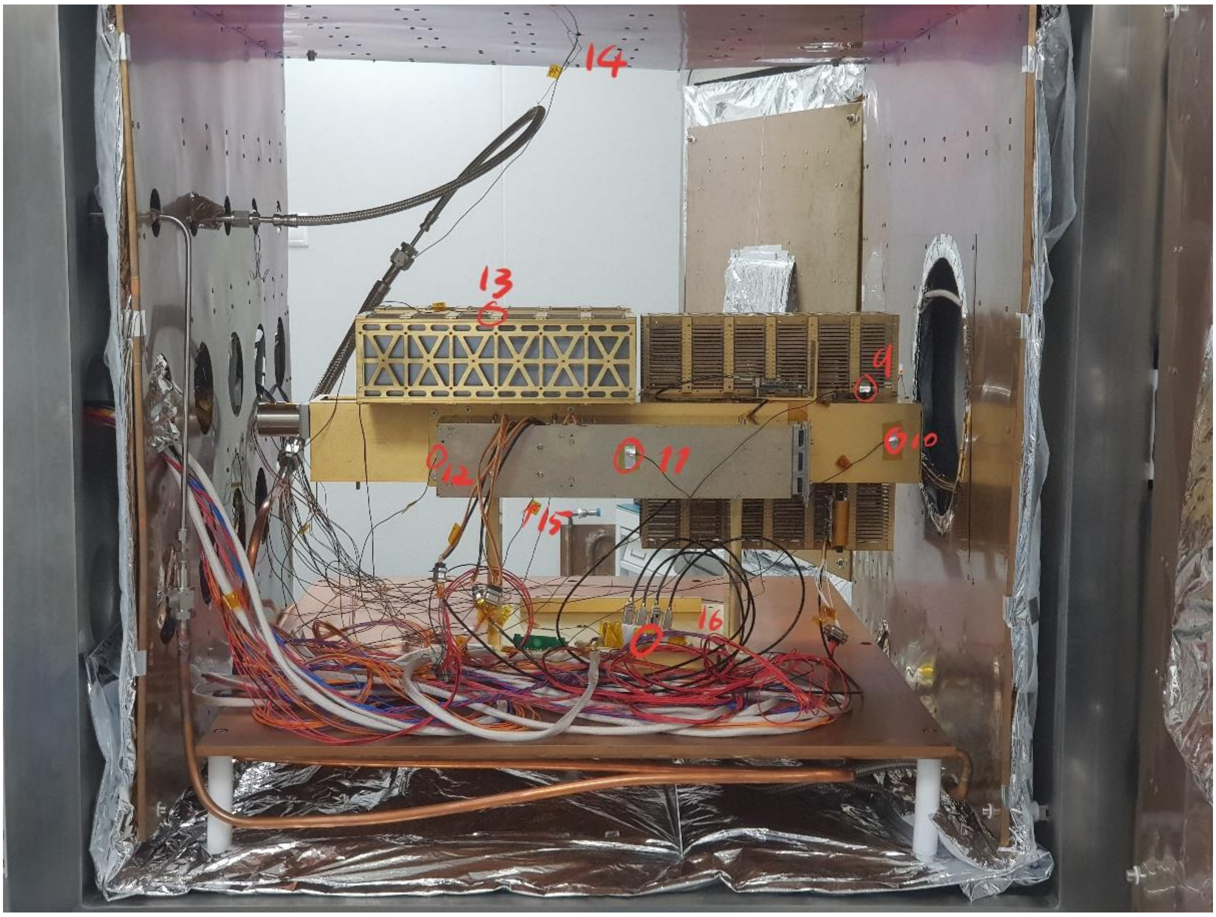

Figure 26 Large KB module at the Prague X ray facility (VZLU).

6.2.2 X ray tests at the PANTER facility

X ray full aperture tests at the PANTER facility in Neuried, Germany, were performed in two runs, one in April 2021 and second one in November/December 2022. Double LE HORUS test module was tested in the first run (Figure 27,Figure 28,Figure 29,Figure 30) and the large KB module together with the small f 400 mm LE module in the second test period (Figure 31 and Figure 32).

Examples of results gained are presented in Figure 27 -Figure 30 for the f 400 mm LE module and in Figure 33- Figure 38 for the large KB module.

HORUS

The Horus optics is a modified Lobster Eye X-ray optics. The Lobster Eye optics is a type of X-ray optics, which are designed to resemble the large reflecting superposition eye of a Lobster. The reflecting tubes are arranged on a spherical surface with their axis oriented to the centre of the eye [RD1]. The Horus optics combines a hybrid design between the Kirkpatrick-Baez design (K-B), which uses cambered mirrors, and the Lobster Eye optics. It consists of two separated mirror sets, turned for 90 degrees in Schmidt’s arrangement, which uses dual reflections to increase the collecting area of the telescope [16] .

The objective of the test at PANTER was to evaluate the performance of the two combined mirror modules in terms of the focus positions, PSF characteristics, and reflectivity via measuring the effective area of the combined module and selected single plates. See [14] and [15] for more details.

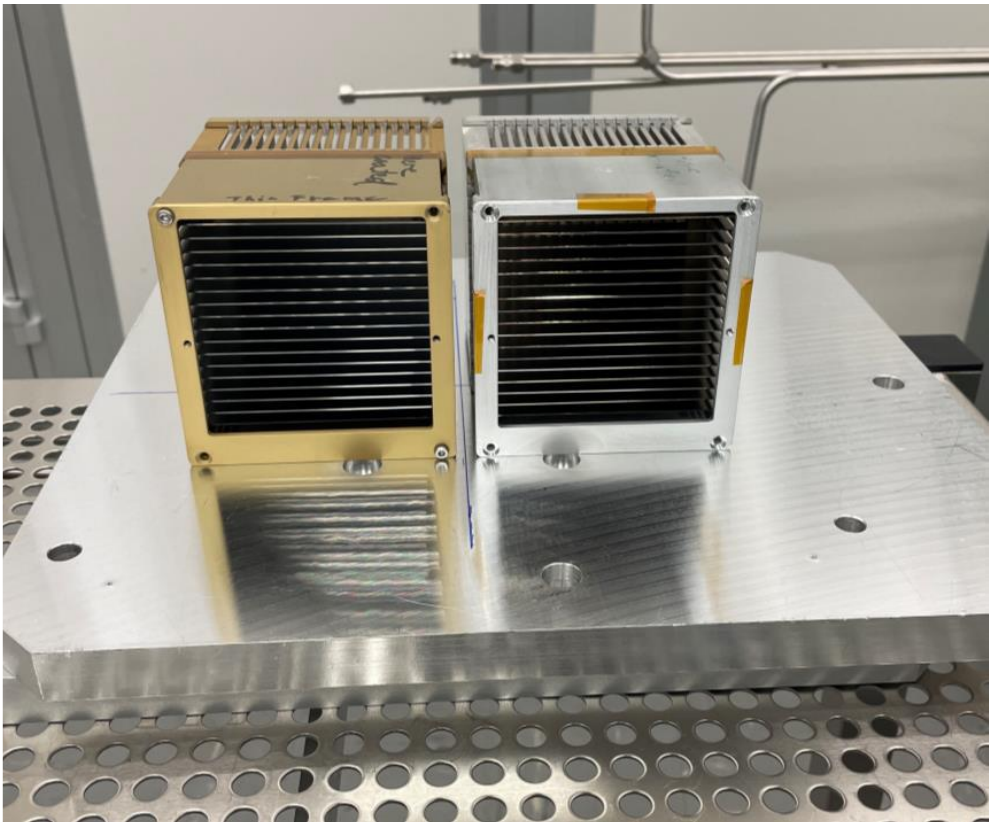

Figure 27 The double LE HORUS test module at the PANTER X ray test facility , March 2021

The Horus optic (assembly II) was tested at PANTER at high energy Al-K, low energy continuum band (lEbc) where one can see both Ti-L and W-M, and mid energy band (mEbc), with has the Ti-K line embedded. A focus search of the optical module was carried out at Al-K where each module is set at 1º pitch and yaw. A map of the focal plane of the Horus optic II was created at Al-K and lEbc at 0.6º,1.2 º and 1.8º. The effective area measurements were carried out at lEbc at various angles from 0.7º to 2.4º focusing on the double reflection spots. A map of single layer reflectivity measurement was created at plate #9 at 0.6º and 0.9º both horizontal and vertical direction.

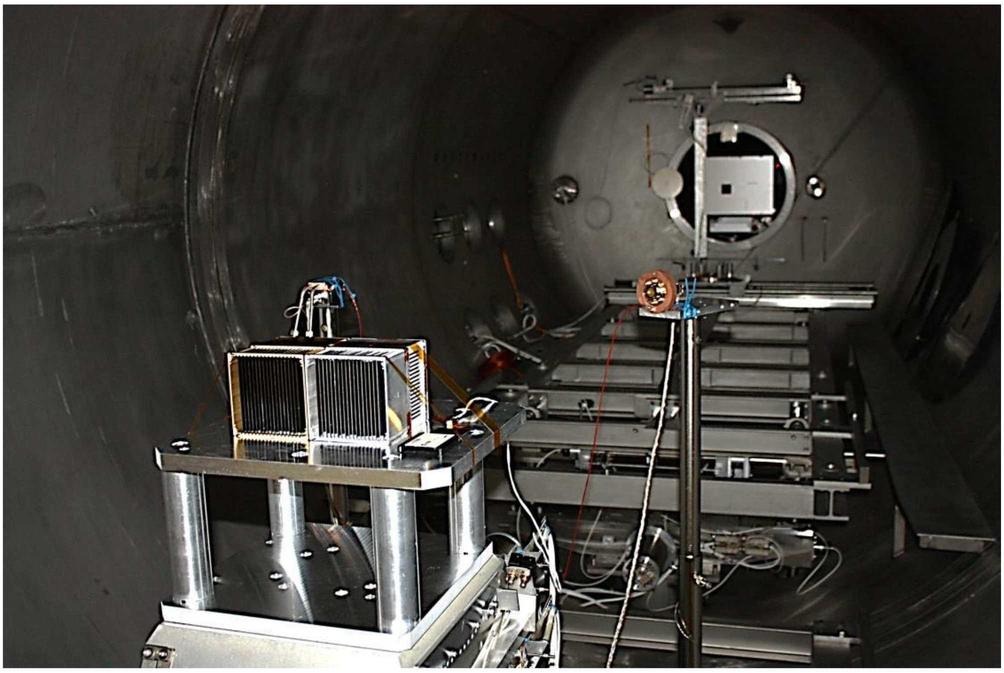

Figure 28 The double LE HORUS module inside the PANTER vacuum chamber.

At mEbc, the effective area of double reflection spots was measured at 0.7º, 0.8º, 1.0º, 1.2º and 1.4º. The single layer reflectivity measurement was carried out at 0.6 º. A moveable mask was used for the whole campaign. The measurement of the full optical module was done through the big opening of the mask while the single layers were measured through the thin horizontal or vertical mask.

In a first campaign, we characterized two independent modules, one Ir-coated and one Au-coated module, which were placed next to each other in the test chamber. In the second campaign, we combined both modules in a row, with the Au-coated one placed closer to the x-ray source and the Ir-coated one closer to the detector.

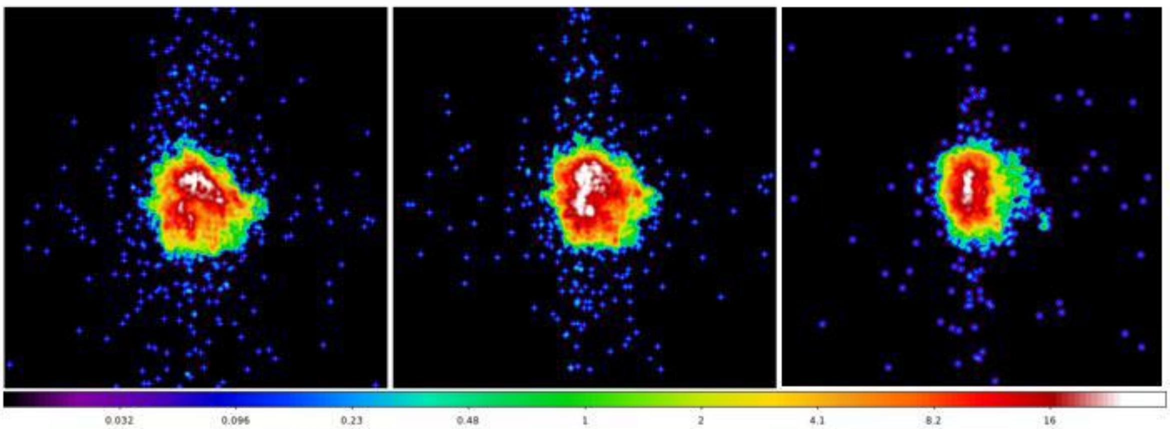

Figure 29 The Double LE HORUS module. The double reflection spots of the GCM at Al-K. From left to right: measurement at 1º, 1.6º and 2.2º.

The focal length of the combined optical modules was approximately 2000 mm. Originally the design was planned to assemble four modules after each other: two modules with horizontal arrangement and two modules with vertical arrangement (rotate 90º respected to the horizontal ones). Each module has different focal length starting from 2050 mm for the first submodule and decreased by 65 mm, the size of one housing and frame, for the adjacent module.

The alignment of the combined optic was carried out under x-rays at Al-K, using the TRoPIC detector. The 4 mm mask diameter located 1650 mm from the x-ray source is used. This limits the beam diameter to approximately 315 mm diameter beam at the optic. The alignment under X-rays starts from the position of the laser alignment at pitch 1º and yaw 1º where the observer can observe the single and double reflections on the TRoPIC camera. For the measurements at different angles, the detector position is adjusted accordingly.

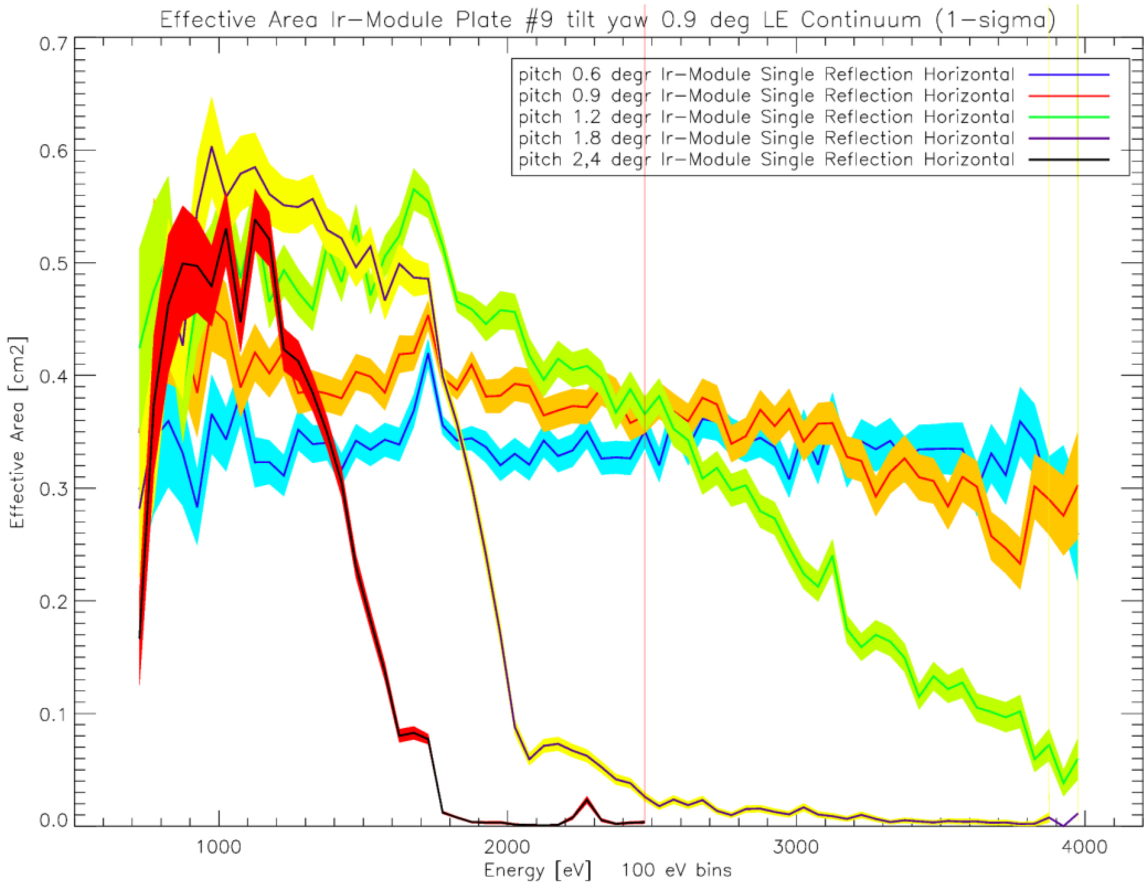

Figure 30 The effective area measurement, double LE module HORUS, PANTER measurements.

A focus search was made at Al-K. The optic was aligned at 1º. Then it was moved in Quelle-Küche by ±100 mm in 20 mm steps. The rough focus search was made within a range -200 to +250 mm in 50 mm step size. We made a fit for the minimum of the search range. Then the fine focus was performed around the minimum point of the rough focus search, range from - 100 to +100 in 20 mm step size. The count rate was recorded for each position. The first flat field was made at the beginning of the measurement set. The second flat field was made at the end of measurement set. For this campaign, the FWHM was used as the focus search metric, and was calculated by fitting a Gaussian to the PSF images. The minimum of the best fit (FWHM and relative position) was taken as the best focus position.

We note that similar procedures were applied also for X-ray tests at PANTER of additional X-ray test modules namely large KB system and small f 400 mm LE system.

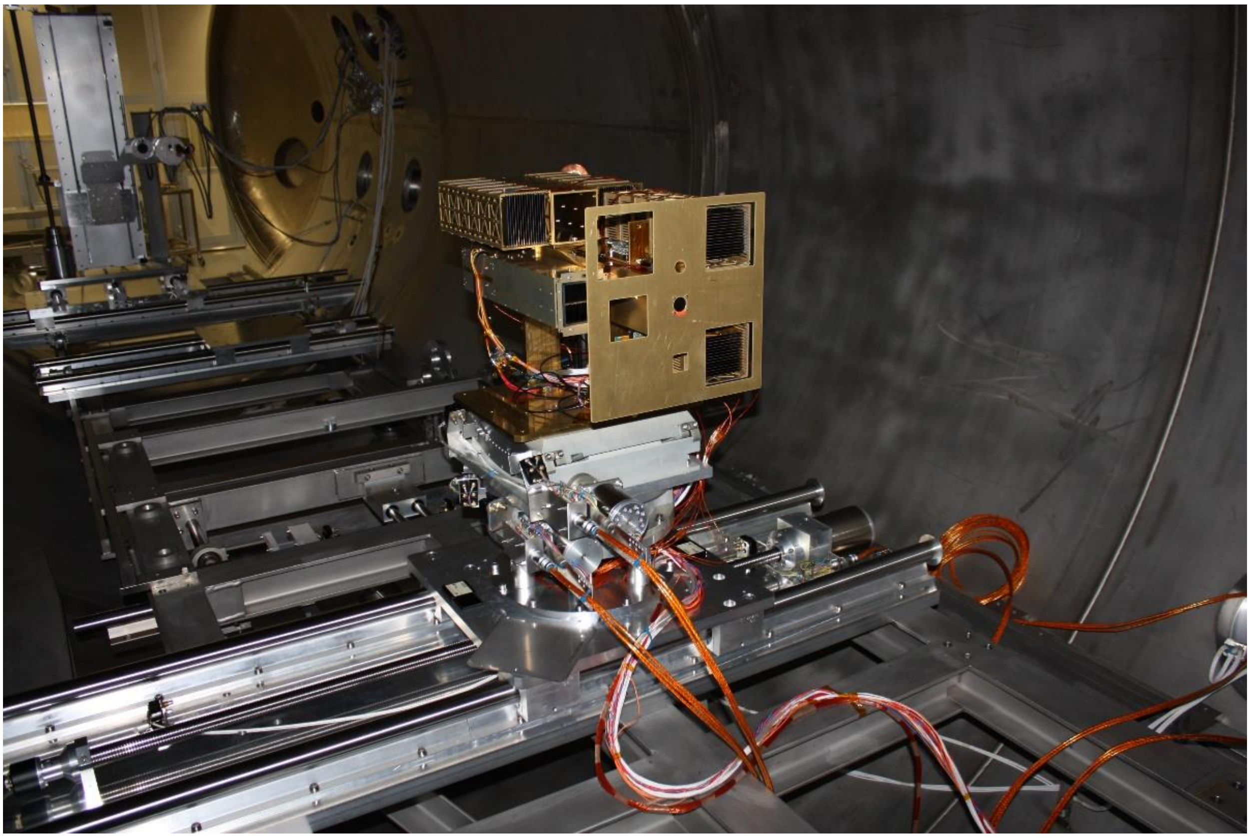

Figure 31 The array of large KB and small f 400 mm LE at the PANTER X ray test facility. The front view.

Large KB system

The optical X-ray vacuum test at the PANTER facility verified the geometrical properties of the optics (FWHM, focal length). Optical tests were performed for each of the 1D sub-module separately and then for the whole 2D optical system. Two detectors were used, namely Tropic a PIXI. The X-ray source with filter were used, so the KB optics was tested from 1 keV to 8 keV.

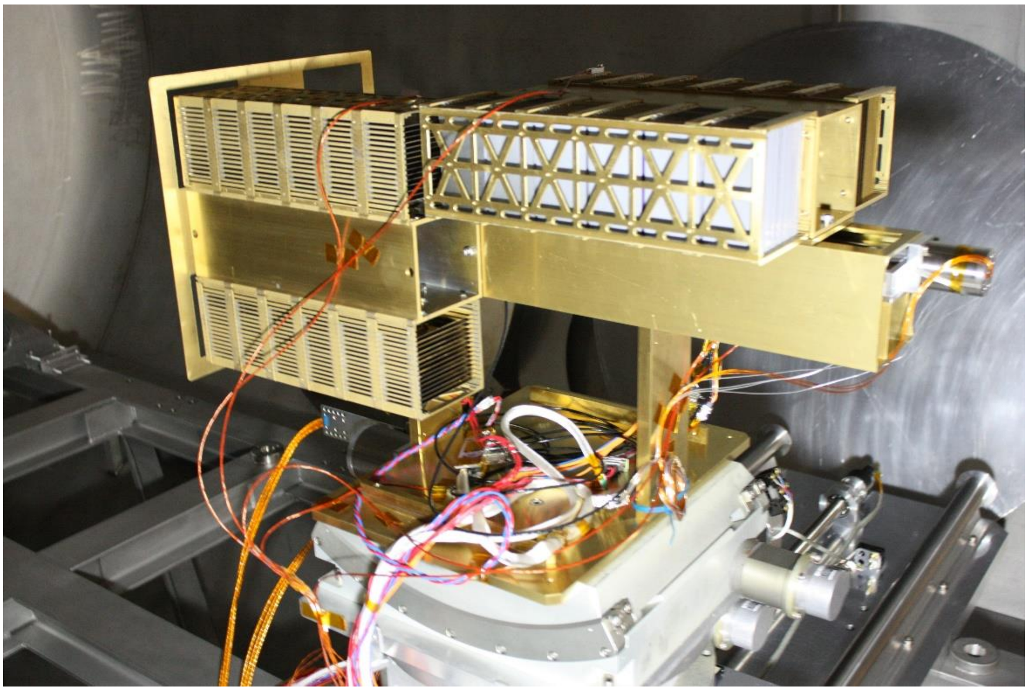

Figure 32 Large KB module at the PANTER facility. The side view.

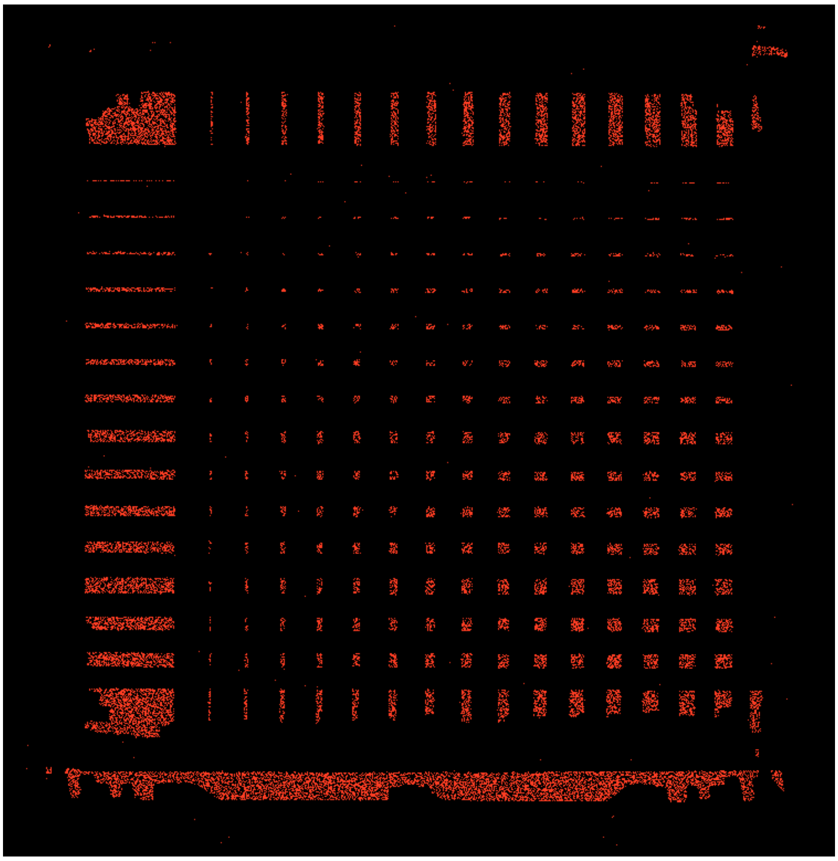

Figure 33 The direct beam mapping. Large KB module, PANTER X ray test facility.

The mosaic scan for the optimal focal distance was performed. The scans compare 2 energies (1.5 keV and 8.0 keV). This mapping confirms that the optics were correctly aligned with the system axis (source - optics - detector in one axis). The KB module was designed for 1-2 keV, with the optics still operating at 8 keV (experimental), while the critical angle is not exceeded, because the transmittances (in the upper left corner) are visible.

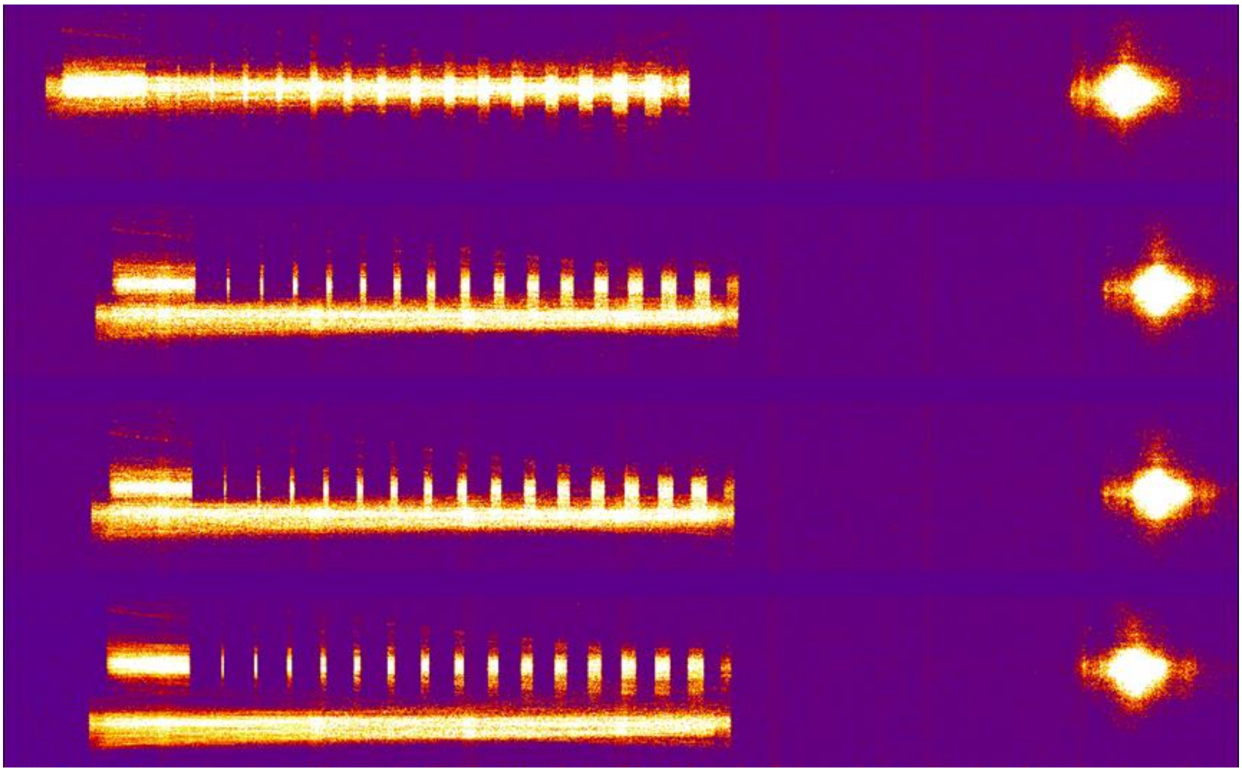

Figure 34 The horizontal mapping of the large KB module at PANTER – from top to bottom – (a) F = 5948 mm; (b) F = 5915.5 mm; (c) F = 6039 mm; (d) F = 5889 mm.

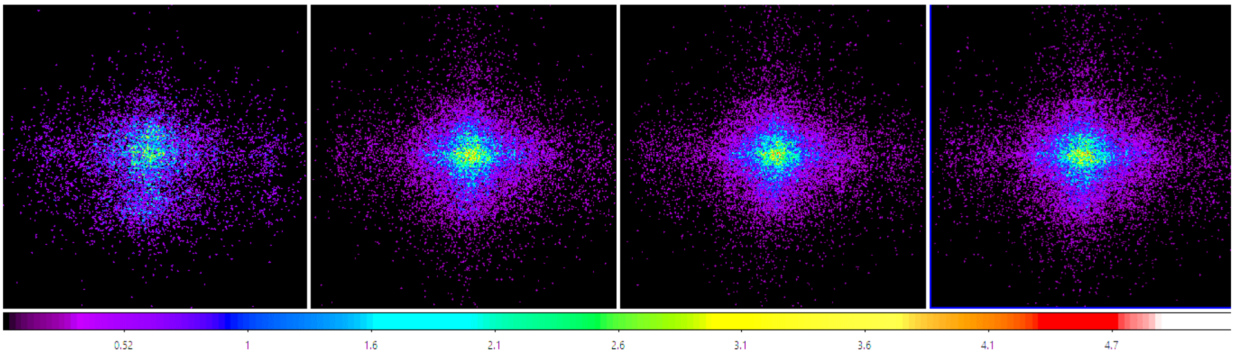

Figure 35 The double reflection deep PSF spots of the Large KB module on axis at different energies (left to right): Cu-K, Ti, Al-K, Ag-L. Measured at the PANTER facility.

The effect of off-axis imaging (i.e. the diagonal tilt of the optics) was monitored using 2D focus (with a step of 0.1 deg from -0.2 deg to 0.7 deg) for 4 different energies - 1.5, 3.0, 4.5 and 8.0 keV was also studies. The results show that the horizontal and vertical results are different, which was caused by the one sub-module. The individual energies were limited by the critical reflection angle on the reflective layer (the critical angle decreases with increasing energy). The results experimentally confirmed that a smaller angle of incidence (negative rotation) creates less focus because the smaller area of reflective layer is illuminated.

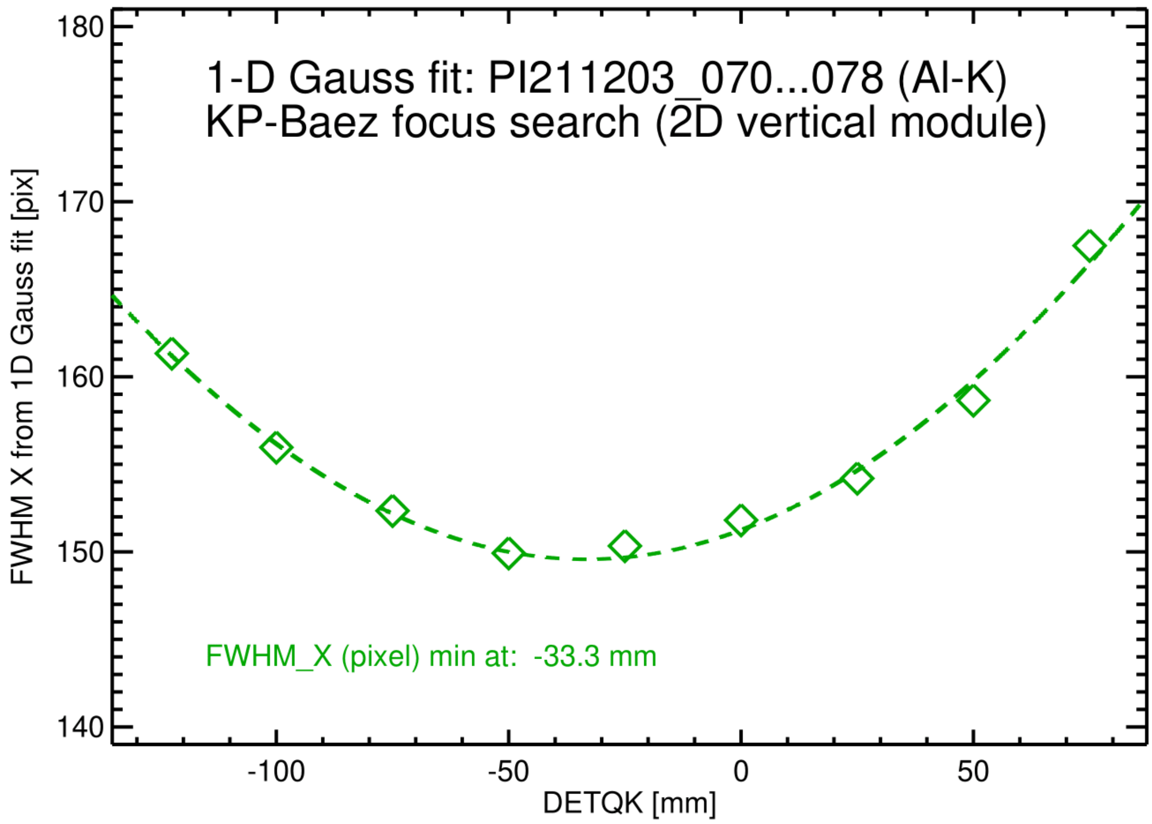

Figure 36 The fitted plot for the focus search of the 2D vertical module. Large KB module, PANTER.

The main monitored parameters were FWHM (full width at half maximum), HEW (Half Energy Width) and PSF (point spread functions). The half-energy width (HEW) is the angular diameter of the image of a point source, which contains half the flux (50% of the reflected photons at a given energy) focused by the X-ray optics.

The one of the key parameters of the KB optics is FWHM (full width at half maximum) respective the angular resolution. The shape of the focus is complicated that is why the FWHM was calculated from diagonal lines. The FWHM was calculated at 1.5 keV (Al target) and 3 keV (Ag target).

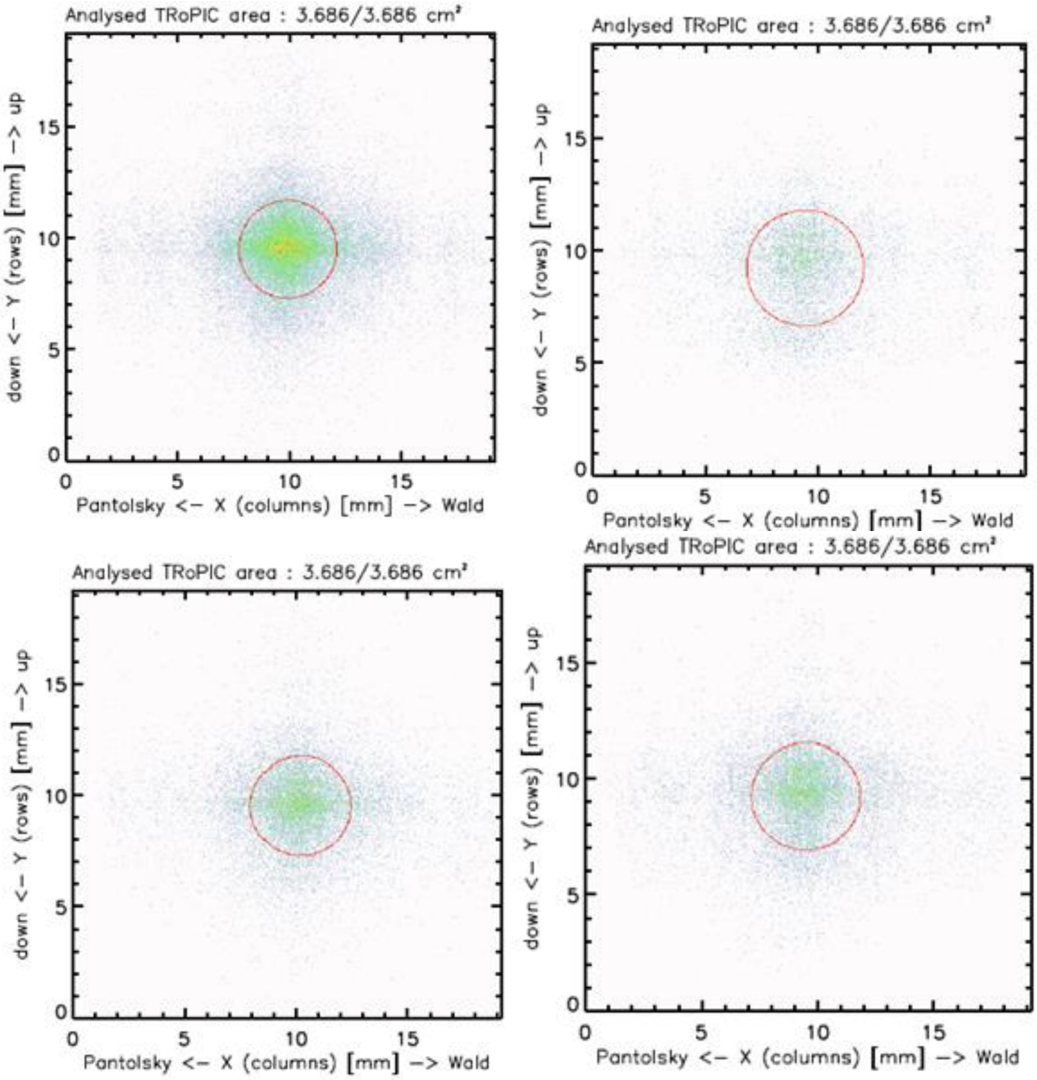

Figure 37 Focal images of large KB module at PANTER: Comparison of the 2D focus image for energy (a) 1.5 keV, (b) 3.0 keV, (c) 4.5 keV and (d) 8.0 keV.

In these tests, the Multi-foil technology for assembly of novel X ray optics (MFT) in large array arrangement has been verified. The MFO (360 pcs of Si foil) was assembled and tested in an X-ray tunnel. Tests confirmed that the edge effect at 1D focus is minimal. The 2D focus has the shape of a cross, which differs from the focus of rotationally symmetric optics (Wolter I). Experiments confirmed that the change in FWHM in off-axis imaging for 2D KB optic is around 25-30% and the shape of the focus at rotation (pitch and yaw 0.8 deg) is the same with compared to axis image (pitch and yaw 0 deg) @ 1.5 keV, i.e the 2D MFO X-ray KB optics imaging 125 mm from optical axis in the focal plane.

The FWHM in the vertical and horizontal direction were calculated from recorded images. Optimal focal length for SR-CT 2D X-ray KB optics was 6 078 mm (center of the 2D KB optics to detector) in the PANTER facility for X-ray source 125 844 mm. The focal length converted to source at infinity was 6 386.5mm. Difference between theoretical and real focal length is 231.5 mm.

The FOV (Field of view) of the 2D KB optical system was measured with Tropic detector. FOV for energy 1.5 – 3.0 keV (Ag) was better than 0.8 deg x 0.8 deg. FOV for energy 4.5 keV (Ti) was better than 0.7 deg x 0.7 deg.

The angular resolution for 2D X-ray KB optics was 40 arcsec in the diagonal direction @ 1.5 keV.

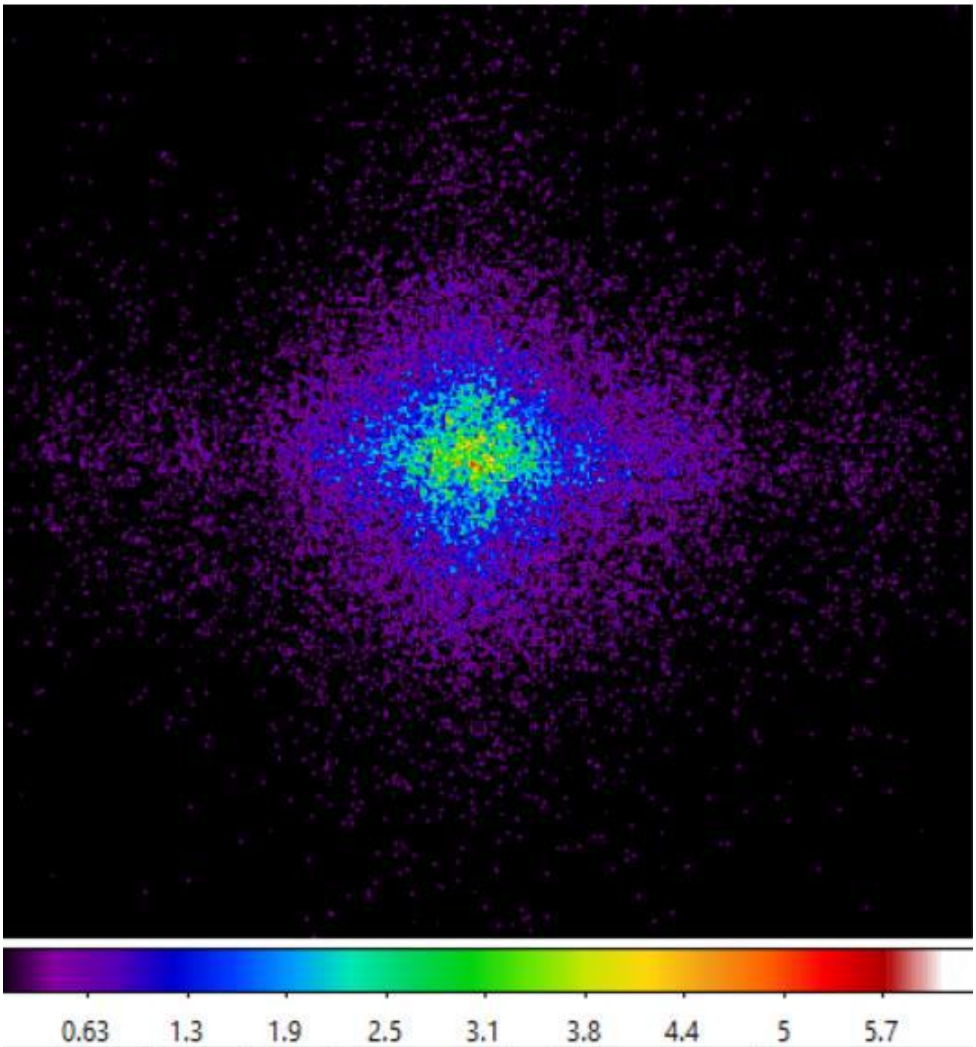

Figure 38 The PSF image at the best focus search position with TRoPIC. Large KB module, PANTER X ray test facility.

Small LE f 400 mm

Optical tests for LE f 400 mm test module were also performed in the PANTER facility in conjunction with KB module tests. The distance between source and optical module was 125 m. The tested LE module was placed on the hexapod. The source was in a fixed position. The X-ray source with and without filer was used, so the module was tested from 1keV to 8 keV

The X-ray source with Ti target (+ 20 μm Ti filter) was used in the fixed position. The FOV (Field of view) was scanned from -2.5 deg to +2.5 deg in the vertical, horizontal, and diagonal direction with step 0.5 deg

FWHM in the vertical and horizontal direction was calculated from images. Optimal focal length for 2D X-ray LE optics was 403 mm (start of the optic – detector), respectively 370.5 mm (center of the 2D optics to detector).

The FOV (Field of view) of the 2D LE optic was measured with a Rigaku, Timepix and Quad detectors in the VZLU tunnel. FOV for energy 3 keV (Ag) was better than 8 deg x 8 deg . FOV for energy 4.5 keV (Ti) was better than 6 deg x 6 deg. The FOV (Field of view) of the demonstrator was measured with a Quad detector in the PANTER facility. FOV for energy 4.5 keV (Ti) was better than 5 deg x 5 deg .

The angular resolution for 2D X-ray LE optics was 15.7 arcmin in the horizontal direction, respectively 7.7 arcmin in the vertical direction @ 2 keV and 15.7 arcmin in the horizontal direction, respectively 7.7 arcmin in the vertical direction @ 3 keV and 14.5 arcmin in the horizontal direction, respectively 7.5 arcmin in the vertical direction and 9.7 arcmin in the diagonal direction @ 4.5 keV. The average angular resolution for 2D X-ray LE optics was 9.2 arcmin in the diagonal direction @ 4.5 keV (Ti target) in the PANTER facility.

The advantage of MFO LE is that for off-axis points, the angular resolution is maintained throughout the FOV. Relative changes (in the % range) of the FWHM in the vertical, respective in the horizontal direction compared to center focus. Relative changes were 3.5% in the vertical direction and 4.5% in the horizontal direction.

The effective area was calculated for polychromatic rays from NiP target (0.85 keV, 2.00 keV 7.50 keV), Ag target (3 keV) and Ti target (4.5 keV). The effective area was approx. 11.5 cm^2 for 2-3 keV and approx. 10.3 cm^2 for 4.5 keV. The effect of focal length changes in the range of 5 mm was negligible.

7 Summary

Innovative modules of X-ray optics in Lobster Eye and in Kirkpatrick Baez arrangements were calculated, designed, assembled and tested. One of the LE modules was double with analogous silicon substrates but different coatings (gold-based multilayers versus Iridium) in order to compare these two alternative reflecting layers. The modules were tested both in visible light at the CTU Prague optical laboratory and in X-rays at the X ray test facility in Prague as well as at the large X ray test facility PANTER in Neuried in Germany. Based on these results, several scientific publications are in preparation. In addition to that, these results are planned to be presented in more detail at the 13th AXRO International workshop on astronomical X ray optics conference in Prague in December 2022.

The obtained data and results are very extended and are still in detailed evaluation with relevant scientific papers in preparation. There was participation in CTU students and young research fellows at the CTU in these activities. In addition to that, there was both national (ON Semiconductor, Rigaku, etc) as well as international (MPE Garching, University Aschaffenburg etc) collaboration established for the best results in these complex and interdisciplinary developments.

The future plans focus on further increase of the performance of the newly developed advanced LE and KB modules, with emphasis on further improvement of FWHM, achieving large FOVs, effective area, and energy coverage.

References

[1] Nentvich O. et al. PyXLA: Python X-ray-tracing for Lobster-Eye Application, submitted, in refereeing process

[2] Florian Gilles et al., Sensitivity of X-ray scientific payloads for cubesats and rocket experiments, Semestral work, CTU in Prague, 2021

[3] Stieglitz V. et al., Design and testing of a Kirkpatrick-Baez optics variation, Optical Conference Porto Portugal Proceedings, 2022

[4] Hudec R., Kirkpatrick-Baez (KB) and Lobster Eye (LE) Optics for Astronomical and Laboratory Applications, X-Ray Focusing: Techniques and Applications, Volume 2010 | Article ID 139148 | https://doi.org/10.1155/2010/139148, 2010

[5] Hudec R and Feldman C. Lobster Eye X-ray Optics, 2022, https://arxiv.org/abs/2208.07149.

[6] R. Hudec, L. Sveda, A. Inneman, L. Pina, Astronomical lobster eye telescopes, Proceedings of the SPIE, Volume 5488, pp. 449-459, 2004.

[7] Inneman, L. Pina, R. Hudec, H. Ticha, V. Brozek, Innovative x-ray optics for astrophysics, Design and Microfabrication of Novel X-Ray Optics. Edited by Mancini, Derrick C. Proceedings of the SPIE, Volume 4783, pp. 156-164, 2002.

[8] Marsikova, V. et al., AXRO2009 Online Proceedings, http://axro.cz, 2009

[9] P. Kirkpatrick, A. V. Baez, Formation of optical images by x-rays, Journal of the Optical Society of America, vol. 38, issue 9, p.766, 1948.

[10] Tichý, V.; Švéda, L.; Maršík, J.; Jakubek, J.; Maršíková, V.; Pína, L.; Hudec, R.; Hromčík, M., Tests of Imaging with Lobster-Eye X-Ray Optics and MEDIPIX2 Detector, Baltic Astronomy, Vol. 18, p. 369-373, 2010a

[11] J. R. P. Angel, Astroph. J. 233, 364, 1979.

[12] W. H. K. Schmidt, Nucl. Instr. And Methods 127, 285, 1975.

[13] L. Sveda, R. Hudec, L. Pina, A. Inneman, Lobster all-sky monitor, X-Ray Sources and Optics. Edited by MacDonald, Carolyn A.; Macrander, Albert T.; Ishikawa, Tetsuya; Morawe, Christian; Wood, James L. Proceedings of the SPIE, Volume 5539, pp. 116-125, 2004.

[14] PANTER X-Ray Test Facility Test Report – Horus Kirkpatrick-Baez Optic II, PAN-TR-MPE-0004, 2021.

[15] PANTER X-Ray Test Facility Test Report – Horus Kirkpatrick-Baez Optic PAN-TR-MPE-0003, 2021.

[16] Thorsten Döhring[1], Veronika Stieglitz[2,3], Vadim Burwitz[2], Gisela Hartner[2], Thomas Müller[2], Thomas Schmidt[2], Surangkhana Rukdee[2], Peter Friedrich[2], Fatih Sahin[1], Rene Hudec[3] Charakterisierung von Weitwinkel-Röntgenteleskopen in der Testanlage PANTER DGaO-Proceedings 2021 – http://www.dgao-proceedings.de – ISSN: 1614-8436

[17] Matej Skvor, Integrace merícího retezce s detektorem Timepix pro termovakuovou komoru, in Czech, Diploma Dissertation, CTU Prague 2021