

CZECH CONTRIBUTION TO AHEAD2020: NOVEL/ALTERNATIVE X-RAY OPTICS

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ABSTRACT. We briefly present selected results in the field of X-ray optics obtained within the project at the CTU in Prague in collaboration with other Czech Institutes, mainly Rigaku Prague, where X-ray optics modules were assembled. These efforts covered the simulations and designs of LE (Lobster Eye) and KB (Kirkpatrick-Baez) optical Systems, a study of new and alternative simulation/ray tracing methods, studies of alternative/improved coatings, studies of improved substrates (Si and float glass), design and assembly of new test modules where both LE and KB test modules were based on Multi Foil Technology (glass and Si substrates < 1 mm) finished by tests in visible light and X-rays.

KEYWORDS: X-ray optics, X-ray telescopes, Kirkpatrick-Baez, ray-tracing, X-ray optical tests.

1. INTRODUCTION

In this report, we briefly describe the progress in the design and development of novel X-ray optics of LE and KB type within the AHEAD2020 (Integrated Activities For The High-Energy Astrophysics Domain) project. The Czech Technical University in Prague (CTU) contributes to this project 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.

The first grazing incidence system to form a real image was proposed by Kirkpatrick and Baez [1]. This system consists of a set of two orthogonal parabolas of translation as shown in Figure 1. The first reflection focuses to a line, which the second surface focuses to a point. This was necessary to avoid the extreme astigmatism of a single mirror, but it was still not free of geometric aberrations. The system is nevertheless attractive for the ease of constructing of the reflecting surfaces. These surfaces can be produced as flat plates and then mechanically bent to the required curvature. In order to increase the aperture, a number of mirrors can be nested together, but it should be noted that such nesting introduces additional aberrations. This configuration is used mostly in experiments not requiring a large collecting area (solar, laboratory). Recently, however, large modules of KB mirrors have also been suggested for stellar X-ray experiments.

The other investigated optics, the Lobster Eye, mimic the arrangements of eyes of lobsters (Figure 2) and were suggested in 70ies for very wide field X-ray

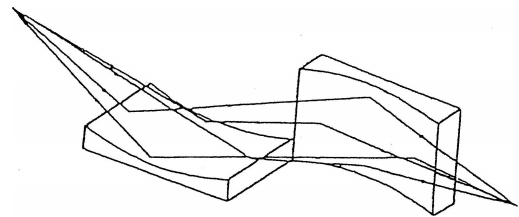


FIGURE 1. The arrangement of the Kirkpatrick-Baez X-ray objective (according to Kirkpatrick and Baez, 1948 [1]).

imaging but used in space only recently, mostly due to severe manufacturing problems. More recently, a number of test modules have become available for both the Schmidt [2] and alternative Angel configurations [3]. Images in the eye of a lobster are formed through reflections off the internal walls of a lattice of small square-sided tubes arranged over the surface of a sphere. This design can be used in the construction of a grazing incidence system to focus X-rays. The X-ray objective based on the lobster eye was proposed by Angel [3], following a similar design of a wide-field lens by Schmidt [2]. Each small channel is aligned along a radius of a sphere. A ray reflected twice off adjacent walls inside the channel is focused onto a spherical focal plane. Rays reflected only once are focused to a line, causing background images to appear as a tapered cross. Some rays go through the lens with no reflections, contributing to diffused background. The finite size of the tubes produces specific defocusing in the image, while the angle subtended by each tube at the focus limits the resolution of the system.

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 were 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 the advanced modules in the KB arrangement. These modules were based on stacked:

- (a) high-quality glass foils,
- (b) superior-quality silicon wafers.

The work included the selection and detailed analyses of the best substrates available. Such superior substrates may help to significantly increase the performance of the newly developed modules, with emphasis on improving the FWHM (Full width at half maximum, a statistical measure used to describe the width of a normal distribution or Gaussian distribution), the effective area, and extending the energy range.

(2.) Lobster Eye Optics in Schmidt arrangement. We have simulated, designed, assembled, and tested advanced modules in LE Schmidt arrangement. These modules were based on:

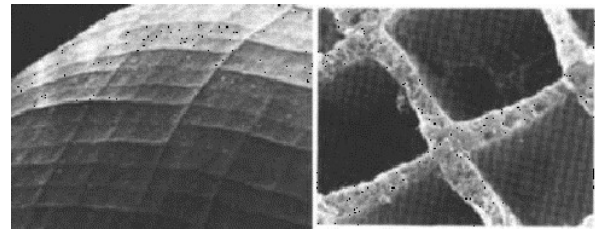
- (a) high-quality glass foils,
- (b) superior-quality silicon wafers.

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 a wide field of view. Both large Kirkpatrick-Baez modules and lobster eye X-ray telescopes may serve as solutions as these can offer innovations, such as a wide field of view, low mass, and reduced costs.

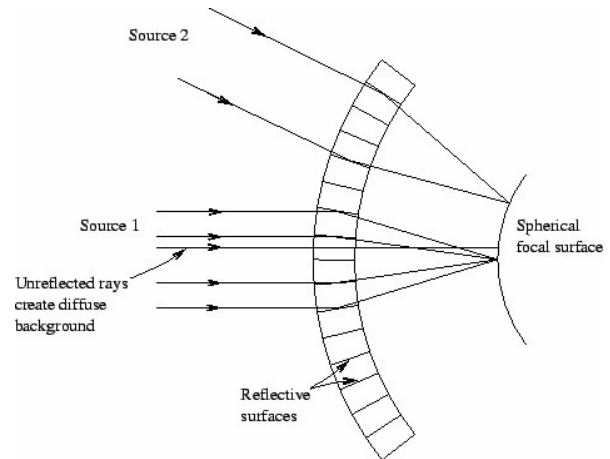
A few selected results obtained within the project are briefly presented below.

2. SIMULATIONS OF X-RAY OPTICS

Alternative simulation and ray tracing methods for LE optics were investigated and compared including the Zemax (OpticStudio) based, MATLAB (Optometrika toolbox) based, and Python code. They were compared with LESim RITE-owned 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 a coded rectangular mask [5]. Point sources are used as sources of beams for selected energy and material reflectivity based on the CXRO (Center for X-Ray Optics) database [6]. We have a newly developed novel ray-tracing simulator



(A). The real lobster eye.



(B). The schema.

FIGURE 2. The Lobster-eye wide field X-ray imaging system [4].

that 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 uses real ray-tracing principles and the mirrors' arrangements and their surface finish as input parameters to provide accurate results based on physical principles and thus allows for optimisation of the system. The goal of the software is to verify the properties and behaviour 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 [7]) and the Optometry toolbox from MATLAB. The developed software respects the dependence of the reflectivity of individual mirrors with regard to their coating and their 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 [5] are listed below:

- written in Python language,
- supports Lobster-eye optics with coded rectangular mask,

Arrangement	1D	2D horizontal	2D vertical
Focal length	250 mm	1 345 mm	1 079 mm
Mirror thickness	0.145 mm	0.35 mm	0.35 mm
Mirror spacing	0.300 mm	0.750 mm	0.750 mm
Number of mirrors	56	47	47
Reflective surface	Au	Au	Au
Field of view	2.75 deg	1.01 deg	1.29 deg
Angular resolution	6.12 arcmin	1.40 arcmin	1.59 arcmin

TABLE 1. Example parameters of LE Optics used for various ray tracing method tests and comparison illustrated in the Figure 3.

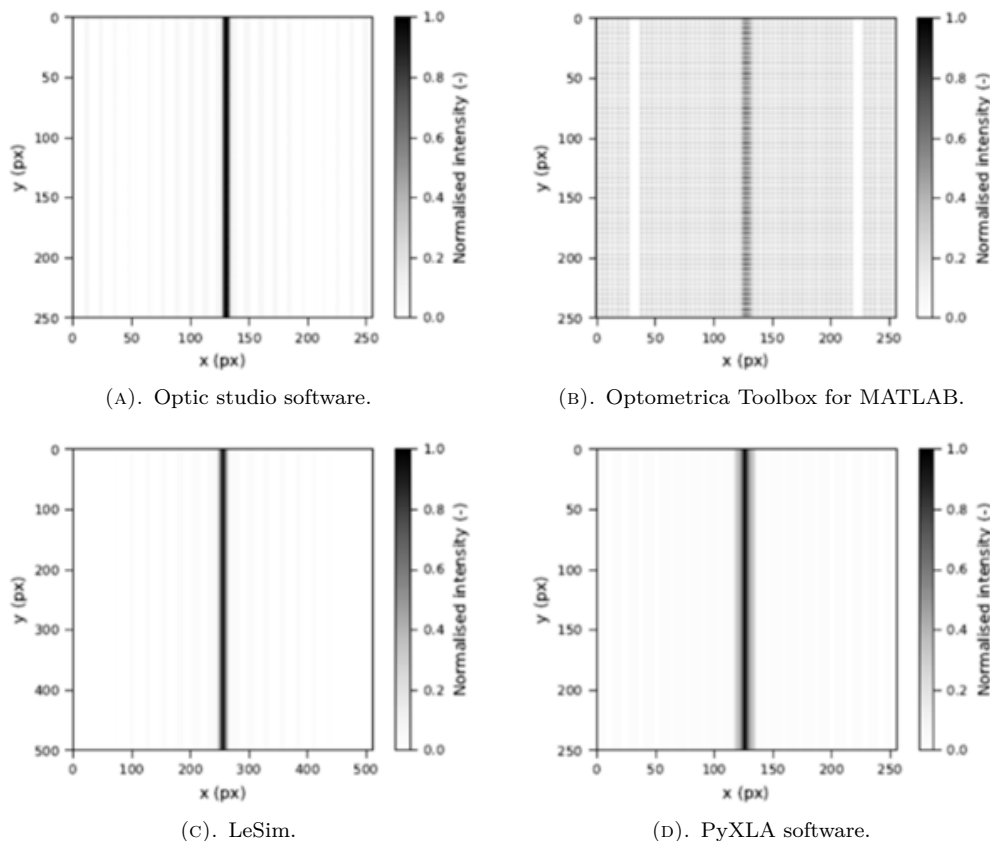


FIGURE 3. Results of simulations/ray tracing of the LE module described in Table 1 obtained by different methods. This approach does not take the angular dependence of the reflectivity into account. The figures show the simulated focal image of the 1D LE module, where values on x and y are in detector pixels and the right scale shows the normalised intensity.

- 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 a PyXLA – simulated image for LE optics with parameters from Table 1, along with images provided by alternative methods, is presented in Figure 3.

The 1D and 2D LE systems designed and assembled within the AHEAD2020 project were primarily simulated by LeSIM code [7].

3. NOVEL SUBSTRATES AND REFLECTING LAYERS

3.1. SELECTION OF REFLECTING SUBSTRATES

The possibility of using of newly developed high quality Si wafers with TTV of order of 0.2 microns or better, developed by an external collaborator, was investigated. The optimized methods for substrates cutting were explored too. Selected substrates were measured with the AFM machine. In collaboration with ON Semiconductor Czech Republic, the improved Si wafers with TTV better than 0.5 micron were studied (Figure 4). The use of such high-quality substrates is expected to help to improve the angular resolution of future modules.

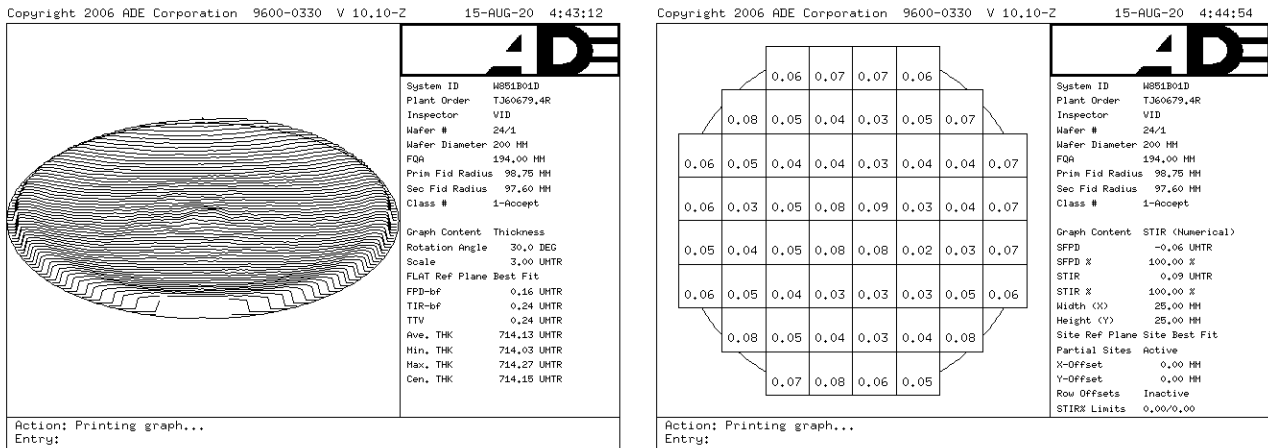


FIGURE 4. Advanced Si wafers type: W805B00 (diameter 200 mm, dopant bor, orientation <100>), with improved TTV better than 0.5 μm, by ON Semiconductor Czech Republic. Result of scientific collaboration with ON Semiconductor Czech Republic research department, Dr J. Sik. The parameters on the right side of the figures describes the in situ measurements of the particular wafer, for the application in the X-ray optics is the parameter TTV – total thickness variation – the most important.

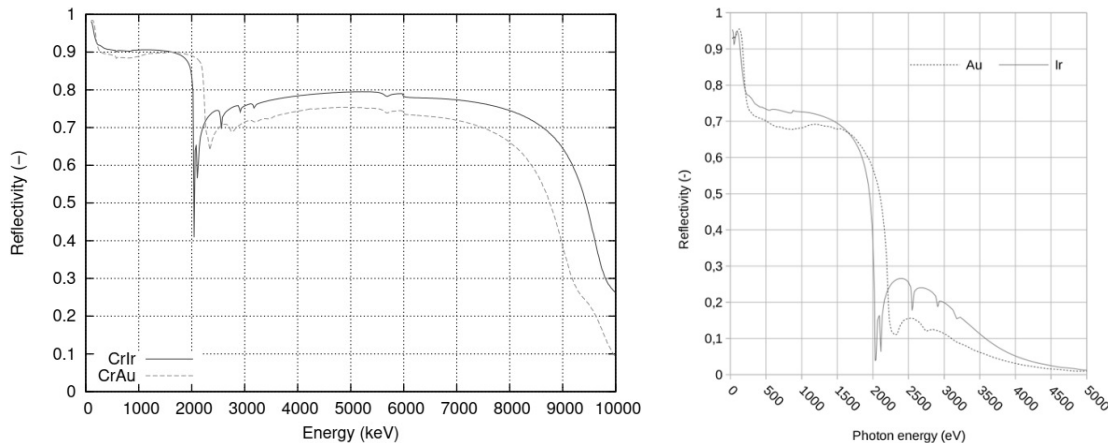


FIGURE 5. Study of alternative coatings. Multiple layers system – a sandwich of two metals. Result of scientific collaboration with Aschaffenburg University, prof. Doehring, dr. Stieglitz.

3.2. STUDIES OF ALTERNATIVE/IMPROVED COATINGS

In collaboration with Aschaffenburg University, RITE Rigaku Prague, and MPE, alternative and improved coatings were developed, applied, and tested (Figure 5). This includes the assembly of a double hybrid LE test module with Ir and Au reflecting surfaces, deposited on identical substrates namely silicon wafers [8, 9]. These studies are important for future advanced X-ray telescopes because of performance improvements (effective area, reflectivity, energy range).

4. NOVEL ARRANGEMENTS OF MFO MULTI FOIL OPTICS

The traditional concept of Lobster eye grazing incidence optics offers a wide field of view that makes these optics convenient for space X-ray sky monitors [4, 4, 10–16]. The Schmidt lobster eye [2] addressed in this contribution is composed of flat rectangular mirrors while Angel lobster eye [3] is formed by rectangular channels.

The modules of both the LE with Schmidt design and KB optics described in this contribution are assembled from a large number of thin (less than 1 mm), either Float glass and/or Silicon wafers. For LE – glass or Si polished on both sides was used, and for KB – a glass or a single side polished Si was used.

The following modules were designed, assembled, and tested within the project:

- LE optics module $f = 0.9$ m,
- LE optics module $f = 0.4$ m,
- KB optics double test module HORUS with Ir/Au coatings,
- large KB module $f = 6.5$ m,
- in preparation: KB with superior angular resolution.

These modules were developed in close collaboration with RITE Rigaku Prague, and Aschaffenburg University.

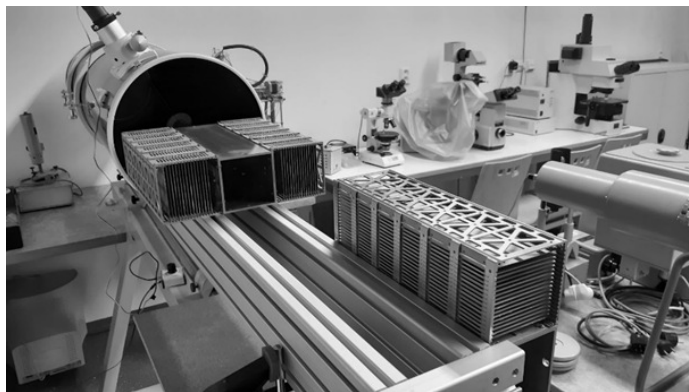


FIGURE 6. Large Kirpatrick Baez Array assembled in Rigaku Prague laboratory during optical tests at the Prague CTU laboratory.

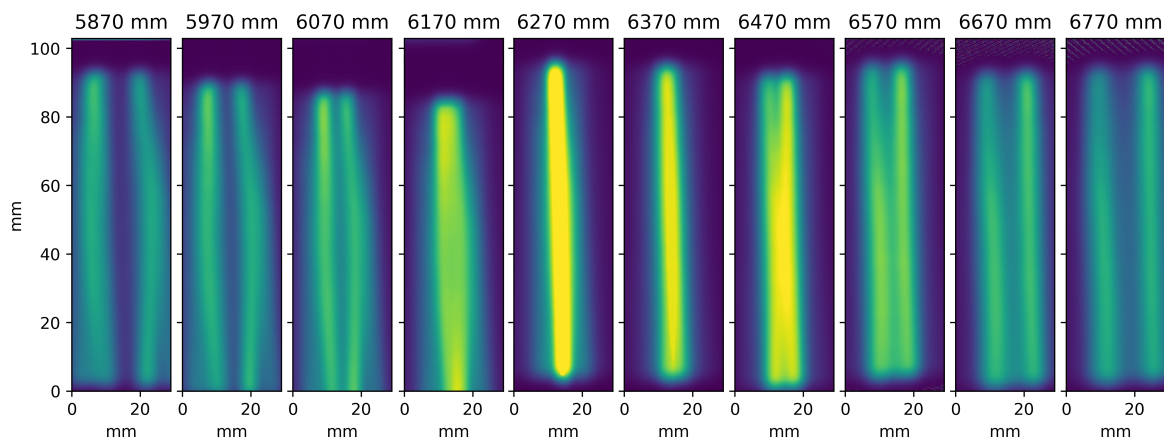


FIGURE 7. Linear focus behavior along the optical axis, large KB module.

5. TESTS OF KIRKPATRICK BAEZ (KB) AND LOBSTER EYE (LE) MODULES

5.1. TESTS IN VISIBLE LIGHT

Tests in visible light (and in addition to that in UV light) were performed on the optical bench in the optical laboratory of CTU in Prague, using a large aperture optical lens/collimator (Figure 6). Examples of obtained focal images for the 1D arrangement are presented in Figure 7. A more extended report is available at the CTU. CTU students were involved in these measurements. The measurement setup is illustrated in Figure 6. 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.

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

5.2. X-RAY TESTS

Tests in X-rays were performed in Prague in collaboration with the VZLU Institute (VZLU AEROSPACE [17]) where a small X-ray test facility was constructed and in the PANTER X-ray test facility of the Max Planck Institute for Extraterrestrial

Physics near Munich in Germany in the collaboration with the MPE team. The tests in Prague were important, especially during the covid period when long-distance international travel was limited.

5.2.1. 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 8) with some examples given below. The examples of results obtained for the LE $f = 400$ mm module are presented in Figure 9. The best image of the focus in Figure 9 has a focal length of 405 mm and FWHM was 1.9 mm (15.7 arcmin) in the horizontal direction and 0.9 mm (7.7 arcmin) in the vertical direction. The image size is approximately 18.0×13.5 mm (2473 \times 3297 pixels, pixel size of 5.4 μ m). The field of view (FOV) of the camera used was 2473 \times 3297 pixels (17.96 \times 13.52 mm), the pixel size was 5.4 μ m, and the dynamic range was 1 to 5 keV. The large KB test module developed within the project was tested there as well prior to the tests at the PANTER facility.

5.2.2. X-RAY TESTS AT THE PANTER FACILITY

Full aperture X-ray tests at the PANTER facility in Neuried, Germany, were performed in two runs, one in April 2021 and the second one in November/December 2022. The double LE HORUS test

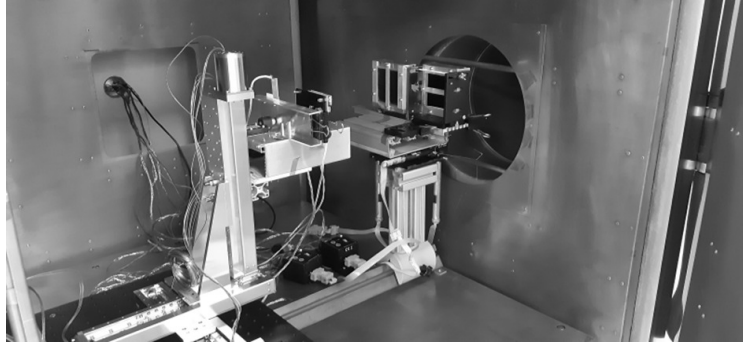


FIGURE 8. LE $f = 400$ mm test module at the X-ray test facility in Prague (VZLU).

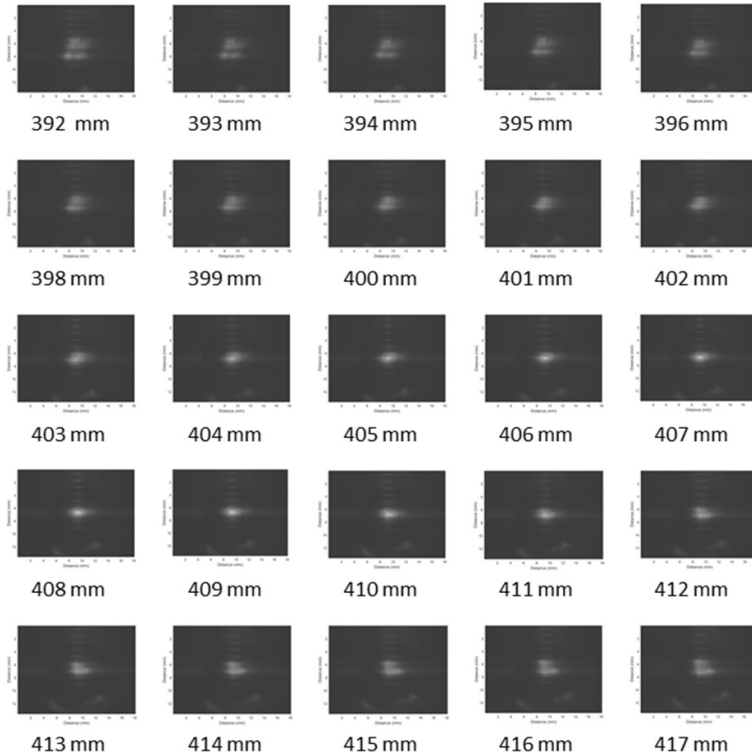


FIGURE 9. Lobster Eye $f = 400$ mm behavior of focal image at 4.5 keV in dependence on the position along the optical axis. See the Section 5.2.1 for a detailed explanation.

module was tested in the first run and the large KB module together with the small $f = 400$ mm LE module in the second (Figure 10). Examples of results obtained are presented in Figures 11 and 12 for the large KB module.

6. CONCLUSION

Innovative modules of X-ray optics with Lobster Eye and in Kirkpatrick Baez arrangements were calculated, designed, assembled, and tested. One of the LE modules was doubled 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 in both visible light at the CTU Prague optical laboratory and in X-rays at the X-ray test facility in Prague and at the large X-ray test facility PANTER in Neuried in Germany.

The data and results obtained are very extensive and are still being analysed in detail with a potential of other aspects of the results to be in detail presented and discussed in separate scientific papers, e.g. X-ray tests at the Prague and PANTER facilities and optical tests at the Prague CTU optical laboratory, novel measurement evaluation tools and software, etc. CTU students and research associates participated in these activities. In addition, there was both national (ON Semiconductor, Rigaku, etc) as well as international (MPE Garching, University Aschaffenburg etc) collaboration established in order to obtain the best results in this complex and interdisciplinary research. Future plans focus on further increasing the performance of the newly developed advanced LE and KB modules, with emphasis on further improving the FWHM, achieving large FOVs, effective area, and energy coverage.

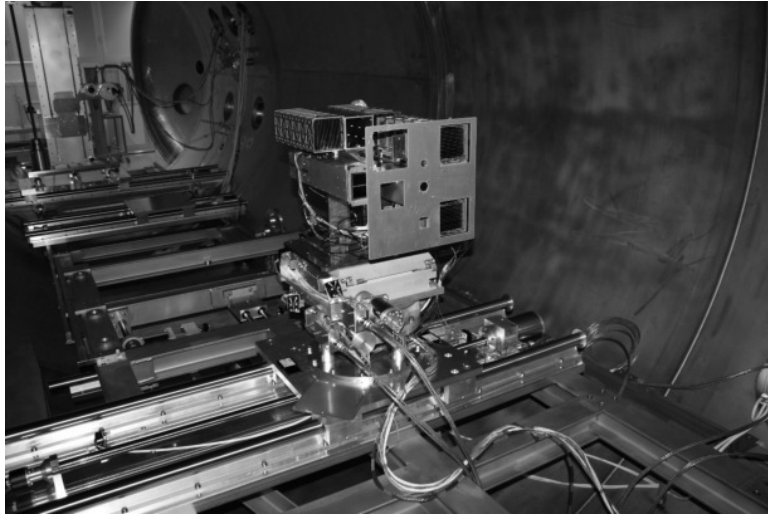


FIGURE 10. The array of large KB and small $f = 400$ mm LE assembled at RITE Rigaku Prague at the PANTER X-ray test facility. The front view.

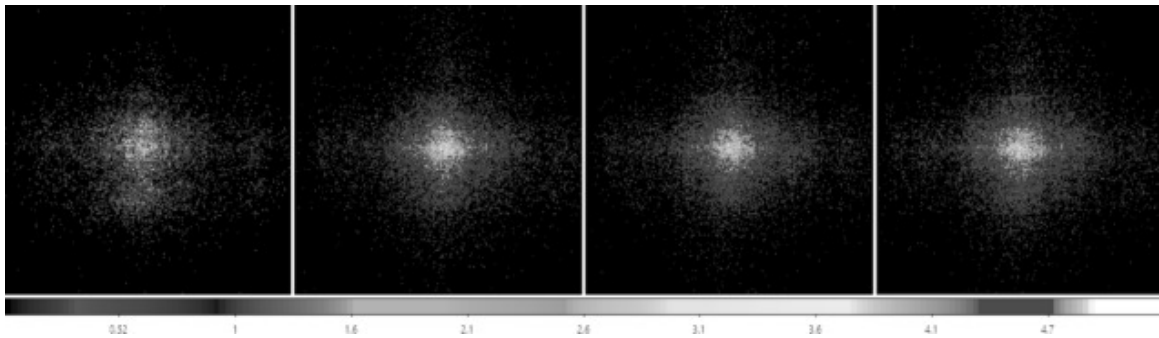


FIGURE 11. The double reflection deep PSF (Point Spread Function) spots of the Large KB module on axis at different energies (left to right): Cu-K, Ti, Al-K, Ag-L. Measured at the PANTER facility.

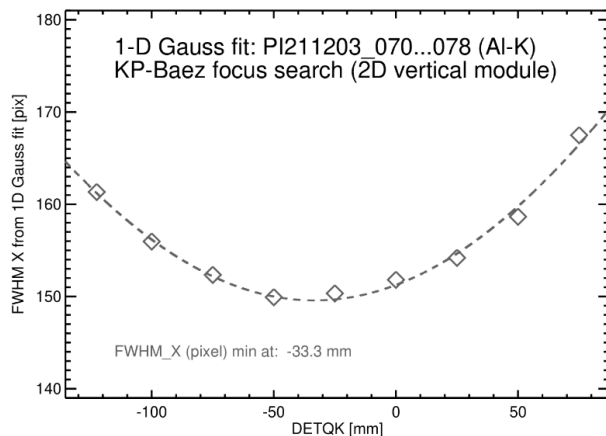


FIGURE 12. The fitted plot for the focus search of the 2D vertical module. Large KB module, PANTER.

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