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Multi-Foil X–ray optics tests at PANTER: Preliminary results

L. Pina[1], **R. Hudec**[2,3], **A. Inneman**[2], **O. Nentvich**[2], **M. Urban**[2], **V. Marsikova**[2], **V. Stehlíková**[2], **D. Doubravova**[4], **V. Burwitz**[5], **C. Pelliciari**[5], **G. Hartner**[5] **and V. Daniel**[6]

[1] *Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, Prague 115 19, Czech Republic*

[2] *Czech Technical University in Prague, Faculty of Electrical Engineering, Technicka 2, Prague 166 27, Czech Republic*
(E-mail: hudecren@fel.cvut.cz)

[3] *Engelhardt Astronomical observatory, Kazan Federal University, Kremlyovskaya street 18, 420008 Kazan, Russian Federation*

[4] *Advacam, U Pergamenky 12, 170 00 Praha 7, Czech Republic*

[5] *Max Planck Institute for Extraterrestrial Physics, Giessenbachstrasse, 85748 Garching, Germany*

[6] *Czech Aerospace Research Centre, Beranovych 130, Prague 199 05, Czech Republic*

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Abstract. We present and discuss preliminary test results performed with selected modules of Multi–Foil X–ray Optics in the MPE PANTER X–ray test facility. Three X–ray optics Multi–Foil modules were tested, namely 1D Kirkpatrick-Baez module, 2D Kirkpatrick-Baez module, both developed within the EU Horizon 2020 AHEAD Project, as well as the Lobster–Eye module REX for the rocket flight experiment.

Key words: X–ray optics – X–ray telescopes – X–ray test facilities – X–ray astrophysics

1. Introduction

In this short contribution, we present very preliminary results of tests of selected X–ray optics in Multi–Foil Optics (MFO) arrangements, namely Kirkpatrick-Baez (KB) and Lobster-Eye (LE) (Hudec, 2010; Inneman et al., 1999) test modules in the MPE PANTER X–ray test facility in Neuried, Germany (Burwitz et al., 2013, 2017; Freyberg et al., 2008). In these full aperture X–ray optical tests, two KB modules and one LE module were tested. The very preliminary results are briefly summarised below.

2. AHEAD WP on X–ray Optics

The work within the optics works package of EU AHEAD project (Piro et al., 2015) comprises studying, simulating and ray tracing the current optical design possibilities for three X-ray optics geometries, namely Wolter–I, Kirkpatrick-Baez, and Lobster-Eye. An assessment and modeling of inherent aberrations of the investigated technologies will be performed to determine a detailed error budget break-down of all the contributions which limit the angular resolution, size of the field of view and collecting area. A detailed simulation of instrument response for all cases will allow a prediction of the scientific performance. Also studies of different substrates Si vs. Glass for the KB modules will be carried out. For all the tests the setup geometry in PANTER will be optimised for each optic and the analysis software modified so that the consistency between measurement and simulations can be adequately checked.

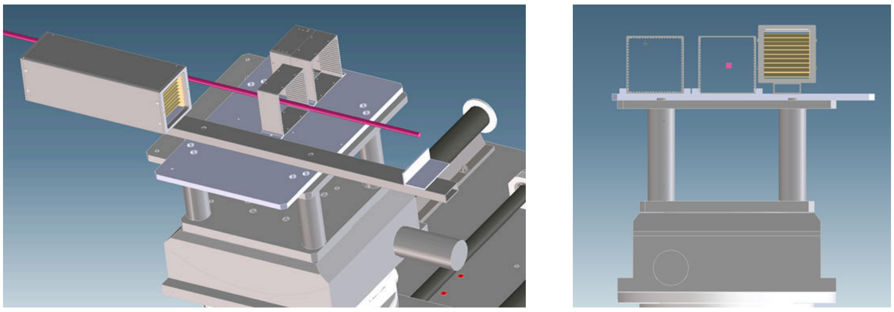

Figure 1.: A sketch of the setup of the MFO modules in the vacuum chamber of PANTER (in the left panel, from left to right REX optics, 1D KB optics, 2D KB optics). In the right panel the sequence is REX, 1D-KB, 2D-KB from right to left.

The AHEAD optics programme aims at simulating, producing and testing prototype X–ray optics using four key technologies as follows.

– Silicon Pore Optics (SPO) developed by ESA/Cosine for the Wolter-I geometry ATHENA telescope. SPO will also be studied for use in KB geometry.

– Square pore micro-channel plates for Lobster Eye module development.

– Slumped glass optics applicable to the Wolter I geometry or KB.

– Silicon wafer optics for the construction of KB optics.

All the X–ray tests here presented were performed at the PANTER X-ray test facility (Burwitz et al., 2017), characterization tests of the industrial production will be performed with BEaTriX (Spiga et al., 2017). The PANTER

X–ray test facility has for over a period of 35 years been involved in the developing, testing and calibrating X–ray optics for most X-ray satellite observatories that have flown to date (especially for ROSAT and XMM–Newton). This wealth of experience will be used in the design, preparation, and implementation of the X–ray tests within the AHEAD project. In the last years, PANTER has been upgraded and optimized to measure X–ray optics with a large focal length (up to f = 20 m, e.g. ATHENA has f = 12 m) (Burwitz et al., 2013, 2017; Freyberg et al., 2008).

In the AHEAD project, the PANTER X-ray test facility is expected to perform the following tasks

- Optimisation (materials and geometry) of a collimated beam using a zone plate sector approach.
- Design and implementation of X–ray test setups.
- Perform the measurements of the different X-ray optics.
- Developing software for analysing the test specific data.
- Optical analysis of the results and comparison with simulation.
- Characterization of high resolution X–ray optics units (HEW $\leq$ 5 arcsec)

3. AHEAD KB test modules for PANTER tests

The first KB modules (see Fig. 2 and Tab. 1) designed and assembled within the AHEAD project (Piro et al., 2015) were tested (see test setup in Fig. 1 and Fig. 2) at the Max Planck Institute for extraterrestrial Physics at the PANTER facility in Neuried, Germany in 2017, with preliminary results discussed below.

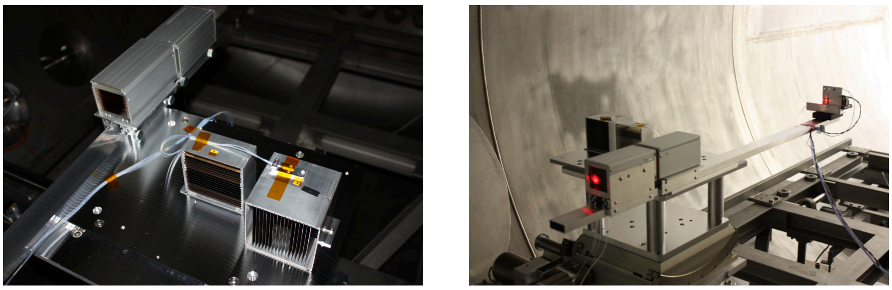

Figure 2.: The tested MFO modules inside PANTER facility (in the left picture from left to right REX optics, 1D KB optics, 2D KB optics). In the right panel REX optics with Timepix detector illuminated by laser beam.

Table 1.: Parameters of KB X-ray optics module for PANTER X ray tests. These parameters are for one 1D KB sub-module. Full 2D KB system is represented by 2 analogous modules (Hudec et al., 2018a).

Properties	Value
Aperture	$80 \times 80\,\mathrm{mm}^2$
FOV	$0.5{\times}0.5$ degrees
Focal length	6 500 mm
Dimensions of foils	$50 \times 100 \times 0.625\,\mathrm{mm}^3$
Number of foils in one sub–module	17
Spacing	4.5 mm
Reflective surface	Au
Detector	TRoPIC
Detector resolution	256×256 pixels
Pixel size	75 μm

Each module consists of 17 pieces of thin parabolic silicon foils (thickness 0.625 mm) which are arranged such that the focal length corresponds to around 6.5 meters (theoretical). The field of view (FOV) of this X–ray optics is 30 arcmin. The module housing was manufactured from aluminium alloy. External dimensions of 1D module are approximately $105 \times 105 \times 50\,\mathrm{mm}^3$. The sub-module A in 2D X-ray optics was more distant from the detector and foils were in the vertical arrangement. The sub-module B was closer to detector and foils were in the horizontal arrangement, as illustrated in Fig. 3. The Si substrates represent promising alternative to glass foils used in MFO nowadays (Hudec et al., 2006, 2008a,b, 2009).

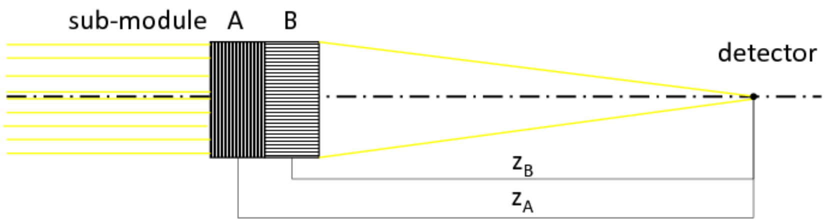

Figure 3.: Mounting configuration of the 2D-KB and LE optics during Panter tests.

4. Lobster Eye X–ray optics REX for PANTER tests

In addition to the AHEAD KB modules described above, LE flight module designed and manufactured for the REX rocket experiment was also tested in the same experiment (Hudec et al., 2018b). The Water Recovery X–ray Rocket (WRX–R) experiment is organized by the Pennsylvania State University (PSU), USA with a primary payload of a soft X-ray spectroscope. The Czech team developed the hard X-ray Lobster-eye telescope REX as a secondary payload. The basic optics parameters are listed in the Tab. 2, and preliminary measurement results are listed in the next sections. For more details on the rocket experiment see Dániel et al. (2017); Stehlikova et al. (2017).

Table 2.: Parameters of the LE optics for rocket experiment REX (Hudec et al., 2018b)

Properties	Value
Aperture	$54 \times 54\,\mathrm{mm}^2$
FOV	$1.3{\times}1.6$ degrees
Focal length	1 065 mm
Radius of convergence	2 130 mm
Dimensions of foils	$150 \times 75 \times 0.35\,\mathrm{mm}^3$
Number of foils in one sub–module	47
Spacing	0.75 mm
Reflective surface	Au
Effective area @ 8 keV and 80 % reflectivity	$\sim 1.4\,\mathrm{cm}^2$
Effective area @ 10 keV and 50 % reflectivity	$\sim 0.5\,\mathrm{cm}^2$
Angular resolution	1.1×1.4 arcmin
Detector	Timepix
Detection material	$300\,\mu$m Si detector
Detector resolution	256×256 pixels
Pixel size	$55\,\mu$m

The 2D LE X-ray optic REX is composed of two 1D sub-modules. The modules were assembled using MFO technology. Each module consists of 47 pieces of thin flat glass foils (thickness 0.35 mm) which are arranged such that the focal length is around 1.0 meter. The gold coating allows the material to reflect X–ray photons incoming under small incident angle of up to 0.5 deg. The field of view of X-ray optics is around 1.5 deg. The housing of the module is made of an aluminium alloy. The external dimensions of the 1D module are approximately $80 \times 80 \times 170\,\mathrm{mm}^3$. The sub-module A of 2D LE X–ray optics was more distant from detector and foils were in the vertical arrangement. The sub-module B was closer to detector and foils were in the horizontal arrangement.

5. X–ray tests of MFO at PANTER

The full illumination X–ray tests of the KB and LE modules designed and assembled for the AHEAD project and for the REX rocket experiment were performed at the vacuum beamline of the MPE PANTER facility in Neuried (Germany) in 2017, with preliminary results briefly presented below.

5.1. KB AHEAD Optics tests

The AHEAD KB X-ray optics was tested at 3 different energies, namely Al–Kα (1.49 keV), Ti–Kα (4.51 keV)/ Ti–Kβ (4.93 keV) and Cu–Kα (8.04 keV). The TRoPIC CCD detector (PANTER) with 256×256 px (75 μm pixel size, area of 19.2 mm $\times$ 19.2 mm) was used. The exposure time was 15 min.

The optimal focus was investigated at energy of 1.49 keV with aluminium (Al–Kα) anode and 10 μm thick Al filter, the high voltage (HV) power supply was set to 2.9 kV anode voltage. The optimal focus in the X-axis direction was measured as 1.1 mm (vertical 1D module A), then in the y-axis direction was measured as 2.1 mm (horizontal 1D module B) which can be seen the Fig. 4. The best focus for the whole KB 2D X–ray optics was looked for which is presented in (Hudec et al., 2018a). Because of different focal lengths of each sub-module the best focal length for 2D optics was found as their compromise. The 2D focus is in the Fig. 5, its FWHM was measured as 3.2 mm in vertical and 2.8 mm in horizontal direction. see Fig. 6.

5.2. LE REX Optics tests

The X–ray optics was tested at 3 different energies: Ag – Lα (2.89 keV), Ti–Kα (4.51 keV)/ Ti–Kβ (4.93 keV) and Cu–Kα (8.04 keV). The Timepix detector with 256×256 px (55 μm pixel size, 14.1 mm $\times$ 14.1 mm area) was used during tests (Jakubek et al., 2014). The exposure time was 15 min.

PANTER measurements with REX optics and Timepix detector allowed the spectrum of reflected radiation to be analysed in the detection plane. Spectral plots show the spectrum of individual sources used for the experiment and con-

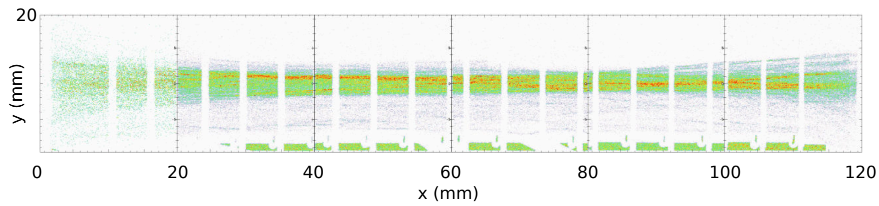

Figure 4.: The KB 2D X–ray optics – image of whole 1D focus in y direction (horizontal) at 1.49 keV.

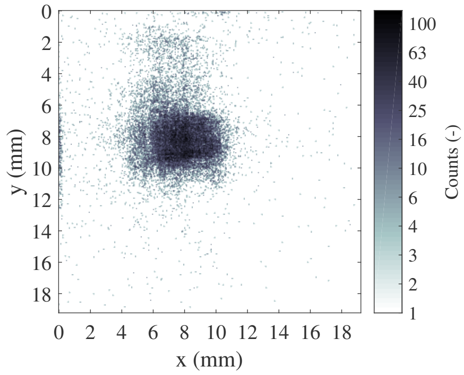

Figure 5.: AHEAD KB 2D X–ray optics – the best 2D focus at 1.49 keV, 33 arcsec FWHM (Hudec et al., 2018a).

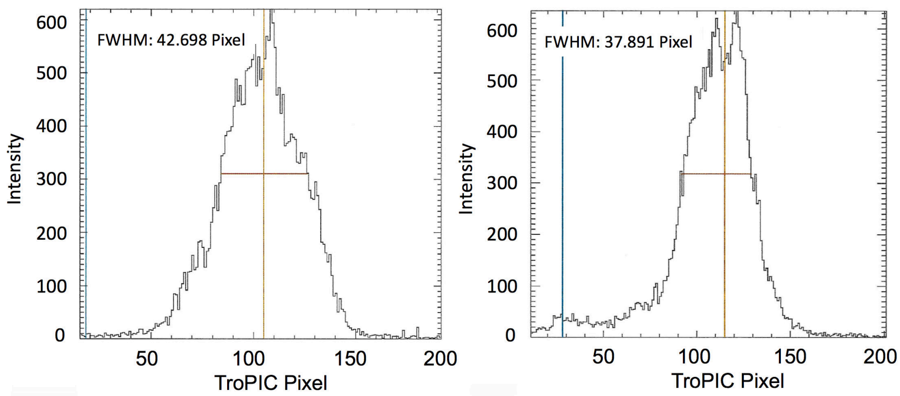

Figure 6.: The KB 2D X–ray optics – left FWHM of focus in vertical direction (3.2 mm), right FWHM of focus in horizontal direction (2.8 mm) at 1.49 keV.

firm that the REX optics operates in the energy range of 3 keV to 8 keV (higher energy could not be measured at this time due to experimental constraints).

The optimal focus was searched for an energy of 8.04 keV with copper anode (Cu-Kα) and 10 μm thick Al filter, the HV power supply was set to 15 kV anode voltage. The 1D modules and detector were tightly connected, so that 1D focus could not be investigated and only 2D focus was measured, see Fig. 7 and Fig. 8.

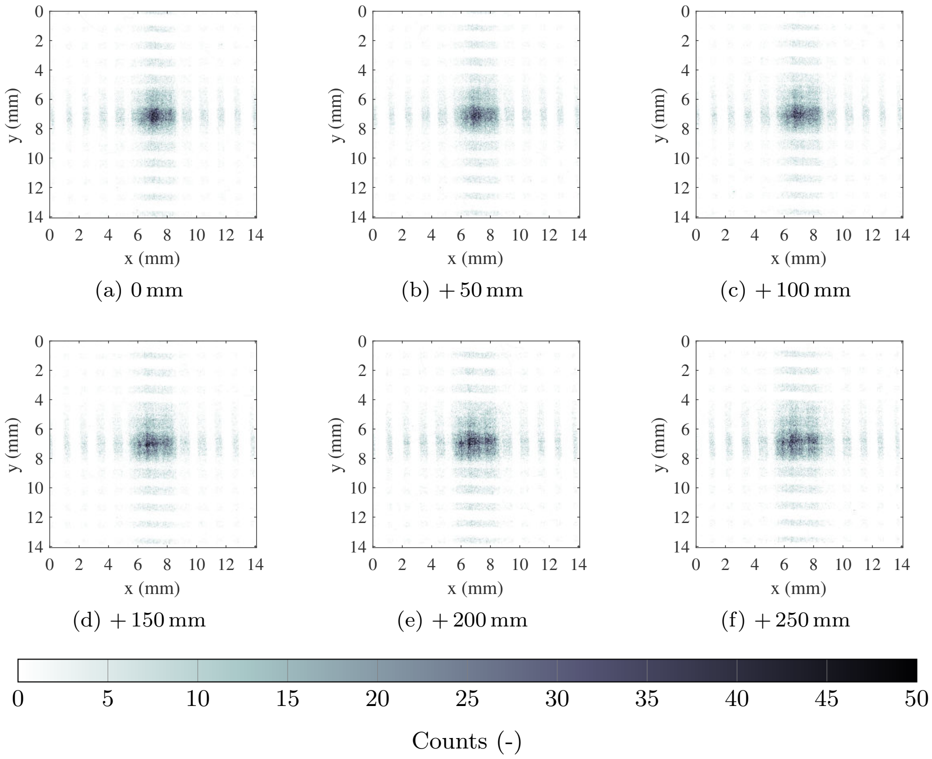

Figure 7.: The LE X–ray optics (REX) – image of the 2D focus at 8.04 keV for different focal distances - relative shift is shown in sub-figures (a) to (f).

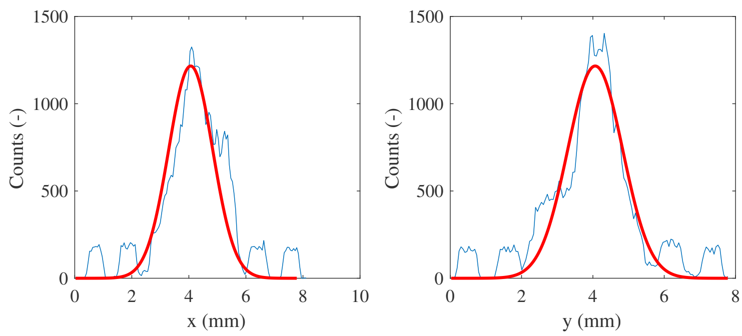

Figure 8.: The REX LE X–ray optics, the best focus – left FWHM of focus in horizontal direction (1.82 mm), right FWHM of focus in vertical direction (2.05 mm) at 8.04 keV at relative position + 0 mm.

6. Conclusions

The two types of X-ray optics were tested at the PANTER X–ray test facility – Kirkpatrick-Baez 1D and 2D modules with silicon foils and theoretical focal length of 6.5 m and Lobster Eye 2D module with glass foils and theoretical focal length of 1 m.

For the 2D X–ray KB optics, the best focus for the vertical sub-module was found to be 1.1 mm (18 arcsec) and for horizontal sub-module was 2.1 mm FWHM (33 arcsec). The combination of both sub-modules was not optimal thus the best 2D focus was $3.2 \times 2.8\,\mathrm{mm}^2$.

The X–ray measurements indicate that for the KB modules, the focal length is shorter than the theoretical assumption perhaps due to the x-ray test beam divergence.Unfortunately, the experimental setup did not allow to move the detector closer to the optics that is why the best focus was not achieved. Consequently, the real FWHM of the modules is very probably better than the measured value.

For the 2D X-ray LE optics (REX), the best focus in the vertical direction was found 2.05 mm FWHM and in horizontal direction FWHM 1.82 mm. Nowadays is this optical system (2D optic + Timepix detector) installed in Water Recovery X-ray Rocket and prepared for launch (Spring 2018).

The preliminary results of the full aperture X–ray optical tests of the MFO modules at the MPE PANTER facility confirm the expectations. It should be taken into account that the tested modules were based on standard commercially available substrates, namely silicon wafers for KB modules, and glass foils for LE module. Application of superior quality substrates, especially Si, considered for future modules, is expected to result in even better imaging performance.

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