*Advanced Telescope for High-Energy Astrophysics (ATHENA)*

*BEaTriX, the Beam Expander Testing X-ray facility*

# Test results of the BEaTriX paraboloidal mirror at PANTER

INAF/OAB technical report 03/2021

*Issued by the BEaTriX team and the PANTER team*


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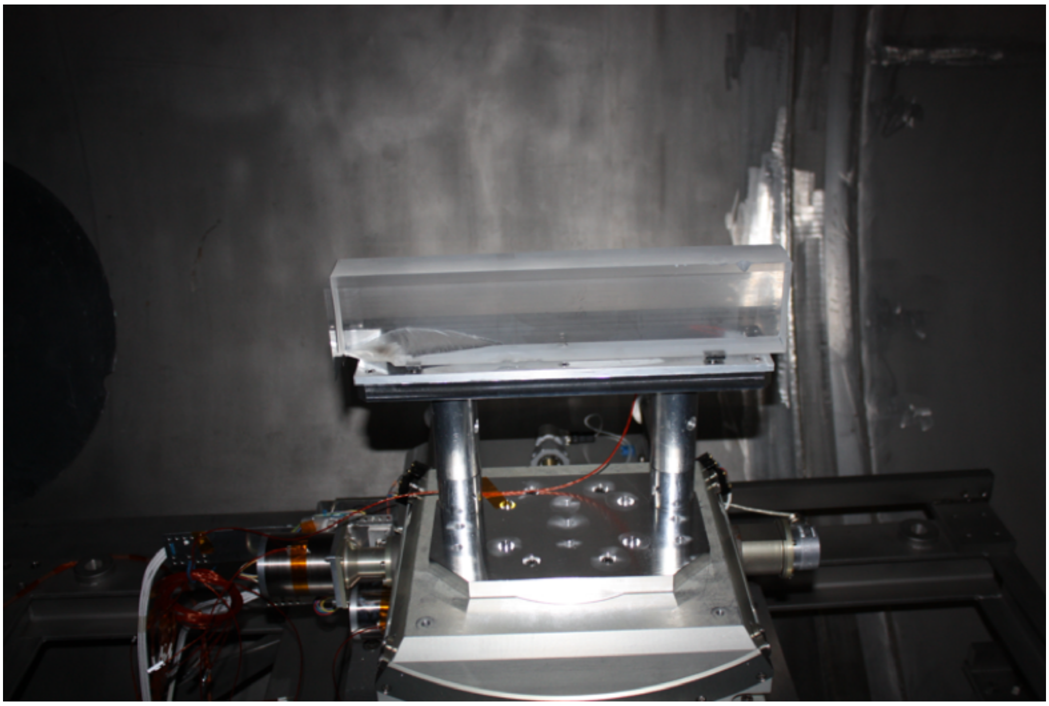

*The BEaTriX collimating mirror mounted on the manipulator at PANTER*


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# Contents



## Reference documents

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## Acronyms

| | |
|---|---|
| ATHENA | Advanced Telescope for High-Energy Astrophysics |
| BEaTriX | Beam Expander Testing X-ray facility |
| CCW | Counter-Clock-Wise |
| CW | Clock-Wise |
| DTU | Denmark Technical University |
| EA | Effective Area |
| ESA | European Space Agency |
| FWHM | Full Width Half Maximum |
| HEW | Half Energy Width |
| HPD | Half Power Diameter |
| INAF | Istituto Nazionale di Astrofisica |
| MPE | Max Planck Institut fur Extraterrestrische Physik |
| OAB | Osservatorio Astronomico di Brera |
| PSF | Point Spread Function |
| RoC | Radius of Curvature |
| ROI | Region of Interest |
| ZP | Zone Plate |

# 1. Scope of the document

Scope of this technical note is to report on the X-ray tests of the BEaTriX collimating mirror [RD1] that have been carried out at the PANTER X-ray facility, before (May 4th-17th 2021) and after the coating with a Cr+Pt reflective layer at DTU [RD2], in the framework of the joint activities on optics for the ATHENA X-ray telescope [RD3]. The tests planned before the deposition of the coating were aimed at confirming the mirror's imaging quality expectations from the metrology tests, performed along with the polishing and finishing processes [RD4]. Post-coating tests are oriented to the final qualification of the mirror and to ascertain that the mirror has maintained the focusing properties. Prior to coating, only tests at 1.49 keV are possible on the mirror. At this energy, PANTER can test the mirror in either diverging beam setup or making the beam parallel by means of a dedicated zone plate [RD5], canceling in this way the focus aberrations due to the finite distance of the source [RD6]. After coating, in addition to the same tests at 1.49 keV, a test in diverging beam will be performed at 4.51 keV. The ZP cannot be used to collimate the 4.51 keV beam, but a comparison of the best focus at 1.49 keV and 4.51 keV will allow us to estimate the X-ray scattering that can be expected in the operation of the BEaTriX parabolic mirror [RD7]. Simulations [RD4] carried out from metrology [RD8, RD9] on the uncoated mirror currently demonstrate a very low impact of the roughness on the mirror focusing performance.

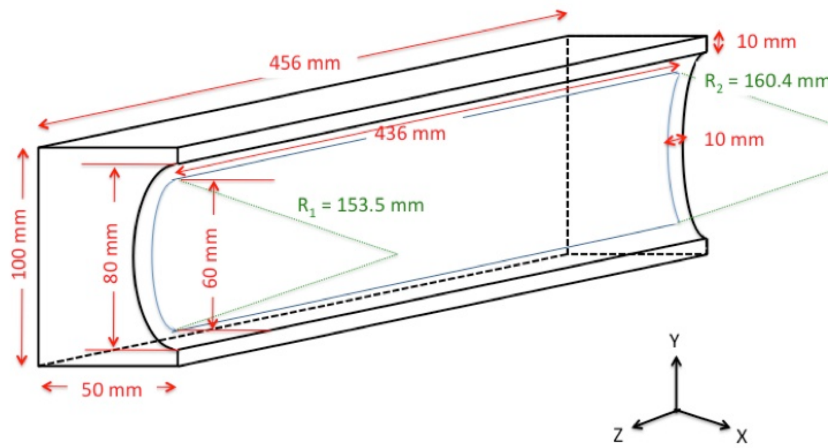


*Figure 1: geometric parameters of the BEaTriX paraboloidal mirror. In the BEaTriX setup, the microfocus source will be placed on the minimum diameter side, at approx. 4741 mm from the beginning of the optically-finished part, measured along the axis. In the PANTER setup, the full X-ray illumination comes from the max. diameter side, and will involve the central 400 mm × 60 mm area.*

A drawing of the mirror with characteristic dimensions is displayed in Figure 1. More information not reported in the picture is listed hereafter:

- *focal length along the axis*: 4959 mm from the mirror center
- *focal length along the rays*: 4961 mm from the mirror center
- *central RoC*: 156.94 mm
- *incidence angle at mirror center*: α = 0.91 deg
- *meridional sag*: 37 µm

Detailed information on mirror metrology, the mechanical setup, the results expected, and the alignment details can be retrieved from [RD4]. In the following sections we concentrate on the results obtained, in both diverging and parallel beam, using the TRoPIC and the PIXI detectors available at PANTER.

# 2. Uncoated mirror under diverging X-ray beam (1.49 keV)

## 2.1. Mounting and alignment at PANTER

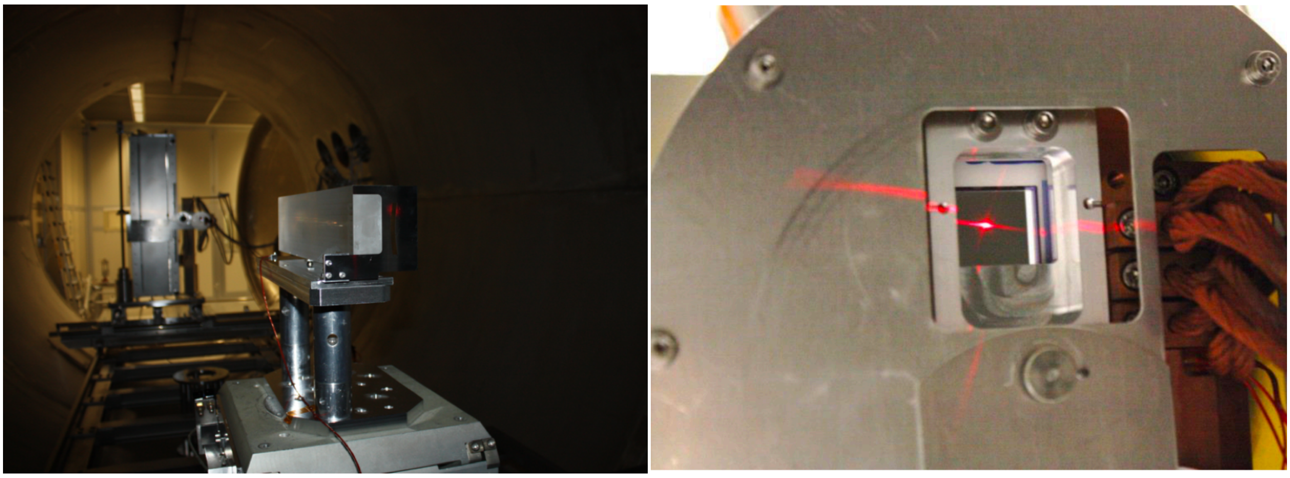

*Figure 2: left: the BEaTriX paraboloidal mirror mounted in the PANTER vacuum chamber, viewed from the beam entrance side. The laser used for pre-alignment can be seen shining on the slit that limits the beam to the optically-polished region. The TRoPIC and the PIXI detectors are visible in the background. Right: the laser beam focused by the parabolic mirror on the TRoPIC detector.*

The BEaTriX mirror, supported by a kinematic mount and interfaced to the PANTER manipulator, was mounted with the optical surface upright and facing the Pantolsky side, at a 126872 mm distance from the source to the physical phi-max mirror entrance (Figure 2, left). Therefore, the *mirror center sits at 127100 mm from the source*. This is the distance we will consider in the further assessments (the value assumed in [RD4] was 125 m, but the difference does not alter the conclusions substantially). A slit was mounted in front of the mirror entrance to avoid incidence of the X-ray beam on non-optically polished parts of the mirror. The illuminated part of the mirror (the central 400 mm × 60 mm) is the only one that is certified within the specification. The mirror region that will be used during the BEaTriX operation is inscribed within this rectangle.

The mirror was aligned in the chamber using the PANTER laser passing through the slit aperture and impinging on the beam. In order to set the correct incidence angle, the laser was initially aligned to the mirror front wall using a back-reflecting flat mirror. The mirror was subsequently rotated in the CW sense by the nominal angle of 0.91 deg (Sect. 1). The distance to the detector was then adjusted mid-way between the parallel (4731 mm from mirror edge) and the diverging focus (4932 mm from mirror edge), observing the laser sharp focus on the detector. This allowed us to start the focus search with the diverging beam as close as possible to the real focus. Due to the laser concentration in a very sharp focus (Figure 2, right), ***it is always recommended to use protective eyewear during the alignment with the laser***.

We report, for appropriate reference throughout the remainder of the text, the following information:
DETQK: detector distance, +1 mm = 800 steps away from the mirror
ODKKI: pitch angle, 0.9 arcsec = 1 step in CW sense. The laser alignment is at 40902 steps.

## 2.2. Alignment in X-rays at 1.49 keV (Al-Kα)

Unlike double reflection mirrors, in which the coma terms off-axis nearly cancel out, in a paraboloidal mirror changing the pitch angle affects the focusing and increases the best focal length by 94 mm for each arcmin decrease of the incidence angle on the mirror surface. The alignment procedure is thereby intrinsically complicated. However, the alignment in the yaw angle can be achieved simply orienting the defocused are in upright position. A typical pitch/focus scan is displayed in Figure 3. As expected from the simulations [RD4], the width of the defocused beam is mostly controlled by the pitch angle (left to right). The best align corresponds to the "skinniest" figure, which not necessarily the shortest one. The vertical extent of the arc is subsequently corrected by varying the mirror-to-detector distance.

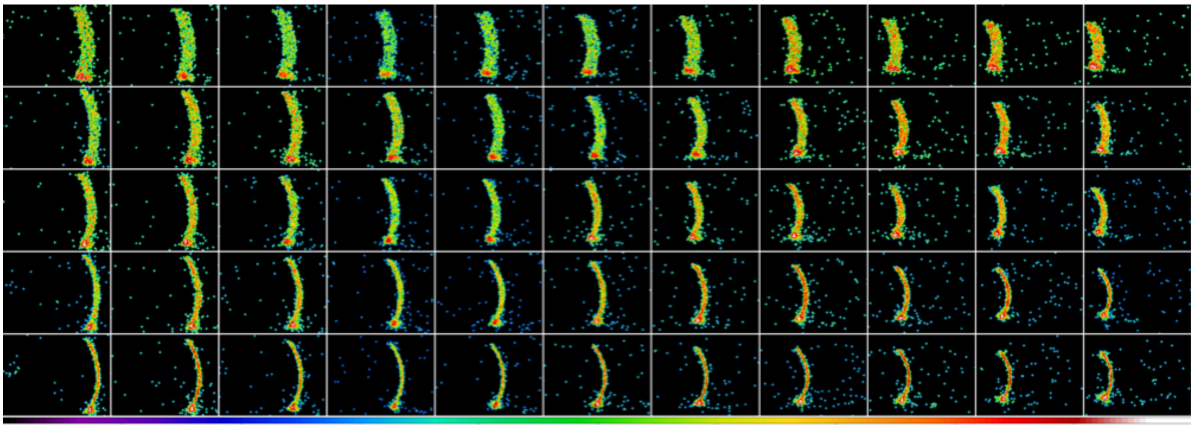

*Figure 3: focus searches at variable detector distance (left to right) and variable pitch angles (top to bottom).*

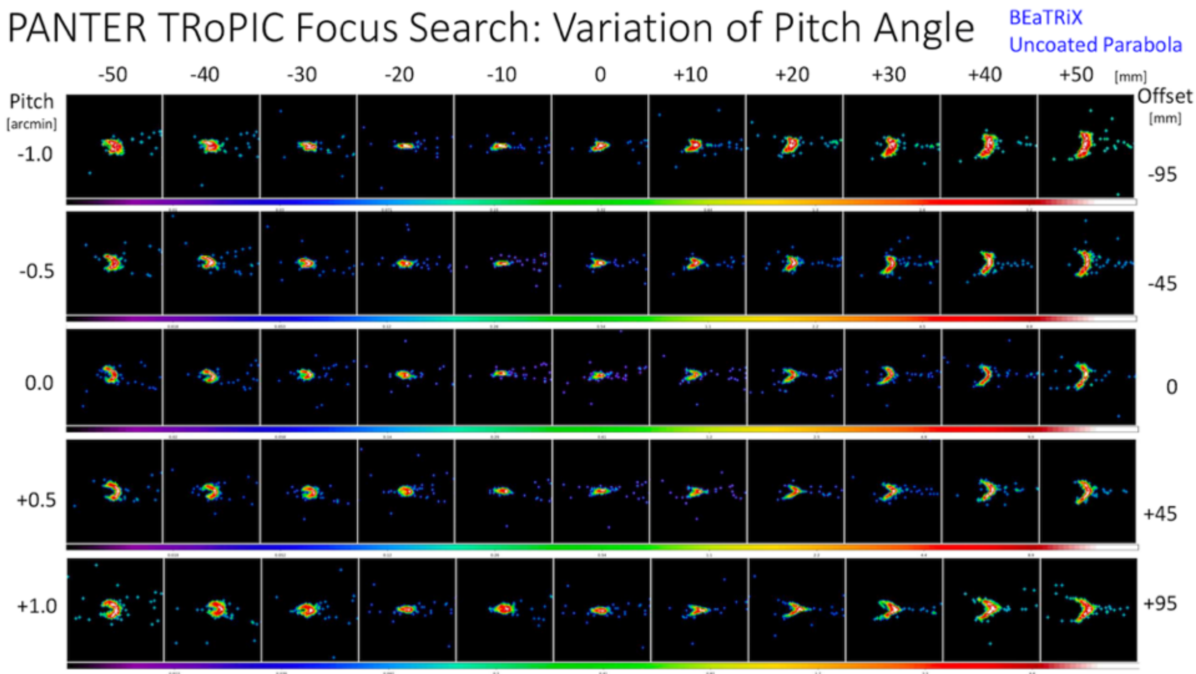


*Figure 4: fine focus search in proximity of the best focus, obtained varying the pitch and the detector distance from the mirror. The distance scans are not parallel in reality; they are shifted by the amount specified on the right, which depends on the pitch angle (on the left). As expected, the concavity keeps facing the Pantolsky side passing from intra- to extra-focal and vice-versa.*

The fine focus search in the proximity of the best focus is displayed in Figure 4, varying the pitch angle and the mirror-detector distance in quite small steps. While the best focus is located near the initial alignment position (pitch = 0 arcmin) and near the expected distance, the uncertainty on the focus is ± 5 mm.

Figure 5 depicts two typical scans in focal distance and pitch angle. The metric to be used to assess the best focus is not totally apparent: while the FWHM in vertical direction returns a sharp minimum when the distance is changed, the same parameter in the horizontal direction stays nearly constant. The HEW (or HPD) exhibits, nevertheless, a minimum well defined to within the uncertainty mentioned above. We observe the same behavior in the pitch angle scan, but this time also the horizontal FWHM reaches a minimum. The minima of the FHMM in x and y and of the HEW coincide within 5 mm (i.e. astigmatism is minimized), only in the best align position.

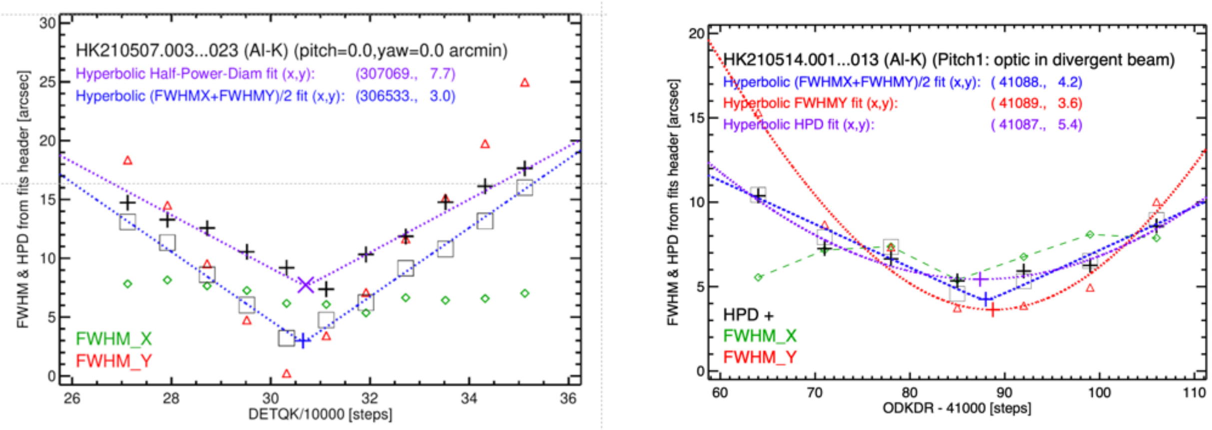


*Figure 5: focus search in the diverging beam varying (left) the distance mirror-detector and (right) the pitch angle.*

If one adopts the minimum HEW as the best metric to locate the focal length (the + signs in Figure 5), the best focus in diverging beam illumination is found at a 311200 DETQK steps, always to a 4000 steps uncertainty. In Sect. 3.2 we will see that the best focus in parallel beam setup, as measured by TRoPIC, occurs at 154400 DETQK steps, i.e., at $\Delta f_{TRO}$ = 196 mm vs. a $\Delta f_{exp}$ = 201 mm expectation value. However, the same measurement with PIXI (Sect. 3.3) locates the smallest HEW at 150341 DETQK steps, returning $\Delta f_{PIXI}$ = 201 mm, as per the expectations. The sensitive surfaces of PIXI and TRoPIC coincide to each other to within 1 mm. This confirms an uncertainty in 5 mm in all the focal length measurements.

Finally, a measurement done with the open PANTER tank, after leaving the detector stage in the best focus of PIXI, yielded $f_{par}$ = 4958 mm and $f_{div}$ = 5151 mm, yielding $\Delta f$ = 193 mm, denoting a few mm shorter focal length. The measurements therefore seem consistent with an average focal length ***f* = (4956 ± 5) mm**.

## 2.3. In-focus measurements with TRoPIC

The best focus was finally located with TRoPIC (19.2 mm size, 75 μm pixel) at the end of a pitch angle scan (Figure 6). The expected values for the HEW in diverging beam setup were: **$\mathbf{HEW_{div\text{-}exp\text{-}PIXI}}$ = 5.3 arcsec** with the PIXI pixel and **$\mathbf{HEW_{div\text{-}exp\text{-}TRO}}$ = 5.9 arcsec** with the TRoPIC pixel.

In the best focus, the HEW is very difficult to calculate exactly, because it is sharply peaked on a single pixel (1 TRoPIC pixel, at this distance, covers 3 arcsec). Using a linear interpolation of the PSF, the HEW returns 5.4 arcsec; refining the interpolation with a 2$^{nd}$ order polynomial, the HEW in diverging beam setup becomes slightly better, **$\mathbf{HEW_{div\text{-}meas}}$ = 4.8 arcsec**. This is anyway better than the predicted value of 5.9 arcsec! The discrepancy is probably due to the initial assumption that the X-ray source profile is a gaussian with FWHM ≈ 1 mm, while it is smaller in reality (FWHM ≈ 0.4 mm). Repeating the simulation with the correct source size, the result comes very close to the measured result (**$\mathbf{HEW_{div\text{-}exp\text{-}TRO}}$ = 5.0 arcsec**). Comparing the images (Figure 7) shows that the amount of scattering is slightly overestimated, even if the photon counts in the simulated and the real exposures are not the same.

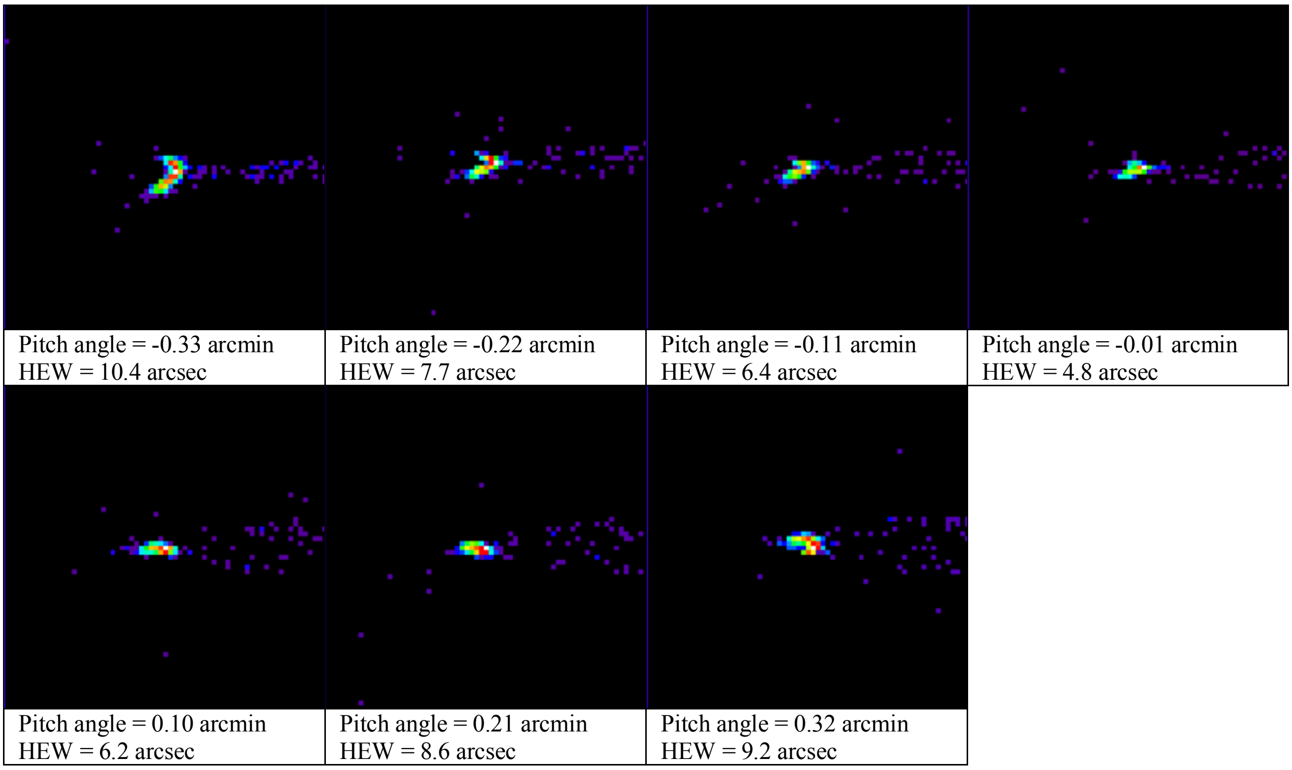


*Figure 6: final pitch scan of the BEaTriX mirror focus at 1.49 keV with the diverging beam, seen by TRoPIC. The images are zoomed to a 5 mm × 5 mm area. The best align is located near 0 arcmin, i.e., the position found at the alignment with the laser.*

As for the effective area at 1.49 keV, it was measured intra-focus and returned (3.01 ± 0.07) cm$^2$, in good agreement with the expected value (2.93 cm$^2$) and *excluding significant scattering out of the detector area* (due to roughness at high spatial frequencies).

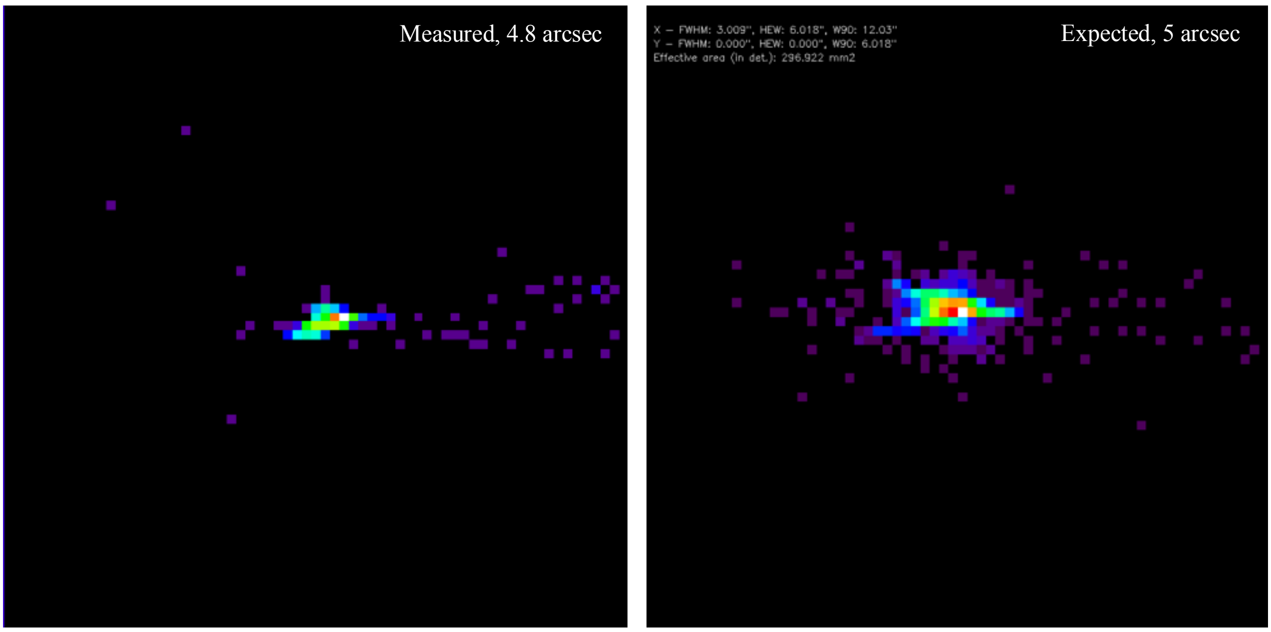


*Figure 7: (left) best focus measured with TRoPIC at 1.49 keV in diverging beam setup, HEW = 4.8 arcsec vs. (right) the theoretically predicted focus (HEW = 5.0 arcsec). Logarithmic color scale. The images have a 5 mm size.*