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BEaTriX, the new facility to measure the modular X-ray optics of the ATHENA telescope with an expanded and parallel X-ray beam

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ABSTRACT

BEaTriX (Beam Expander Testing X-ray facility) is the new facility available at the INAF-Osservatorio Astronomico Brera (Merate, Italy) for the calibration of X-ray optics. Specifically designed to measure the point spread function (PSF) and the effective area (EA) of the mirror modules (MM) of the ATHENA X-ray telescope at their production rate, BEaTriX gives the unique possibility to test the optics with a source that approximate an astronomical source, i.e. with a large, parallel X-ray beam (170×60 mm^2) that fully covers the entrance pupil of the MM.
For a fast and precise testing, BEaTriX is a compact facility (9×18 m^2) with fast vacuum pump-down (to 10^{-6} mbar), and an optical setup able to create the X-ray beam with a residual divergence of about 2-3 arcsec, HEW, and with a flux of 60 photons/s/cm^2. The first beam line at the energy of 4.51 keV is now operative, and a second beam line, working at the energy of 1.49 keV, will be implemented in the coming future.
The unique characteristics of the BEaTriX X-ray beam are obtained with an X-ray microfocus source placed in the focus of a paraboloidal mirror, a monochromation stage with 4 symmetrically cut crystals, and an expansion stage where the beam is diffracted and expanded by an asymmetrically-cut crystal. The beam, reflected by the MMs, is then imaged at 12 m distance, where a directly-illuminated CCD camera is placed.
This paper presents the facility, the calibration of the beam and the latest results with the ATHENA MMs.

Keywords: BEaTriX, ATHENA, X-ray testing, X-ray microfocus source, beam expander, asymmetric diffraction, crystals

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1. INTRODUCTION

ATHENA is an ESA mission with the aim to improve the knowledge of the hot and energetic universe by measuring the X-rays emitted by extremely hot sources [1]. Currently under development, the mission is waiting for the adoption step, but many components are in advance phase of implementation. The telescope will have an effective area of 1.4 m^2 and an angular resolution of 5 arcsec Half Energy Width (HEW) at 1 keV[2]. The MMs are manufactured at cosine with the Silicon Pore Optic technology (SPO) [3]. BEaTriX is the facility at INAF – Osservatorio Astronomico di Brera[4] dedicated to the MMs calibration. It is now operative with the 4.51 keV line, and it demonstrates the possibility to characterize MMs in term of PSF and effective area with the desired testing rate of 2 MMs/day. This is possible with a combination of attendant factors, the big size of the parallel beam, the relative short exposure time and the fast time for the evacuation. The size of the beam is 170×60 mm^2 illuminating at once the entire footprint of the MM under test avoiding the necessity to combine and reconstruct the beam as, i.e. at the XPBF 2.0 beam line of the synchrotron radiation facility BESSY II [5]. The exposure time to characterize the MM is in the order of 30 minutes in order to collect the desired number of photons for angular resolution and effective area measurements, while shorter exposures are needed to perform the focal search (~100s). The time between the tests of two different MMs is about 2 hours for venting, MM installation, evacuation and preliminary alignment. This is extremely faster than other facility with large chambers (i.e. PANTER, MPE) [6]-[7].
A first ATHENA MM (MM-0042) has been tested at BEaTriX for the commissioning and it has been used to define procedures and to characterize the facility. This paper reports the result of this phase and describes in details the characterization of the X-ray beam by means of a Hartmann plate to check the divergence and the flux.

2. DESCRIPTION OF THE BEATRIX FACILITY

The working principle of BEaTriX is sketched in Figure 1 [8]-[23].
All the optical components are installed in vacuum chambers ($P<10^{-4}$ mbar) in order to propagate the X-rays from the source to the detector. The divergent beam, coming from the X-ray source, is collimated by a paraboloidal mirror and monochromated by two channel cut crystals (CCC1 and CCC2) in Si (220). The beam is then diffracted by another crystal in Si (220) named Beam Expander (BE): this last crystal is asymmetrically cut to horizontally expand the beam by about 50 times providing the final size of the parallel beam 170 mm × 60 mm [24]-[25]. By doing so, the BE bends the beam to about 90 degrees generating a flux of about 60 ph/s/cm^2.
The expanded and parallel beam is then propagated to a separated chamber (MM chamber), where the MM to be tested is installed, and, after being reflected, it is focused at 12m (the Athena focal length). A detailed description of the facility is in Ref. [26].

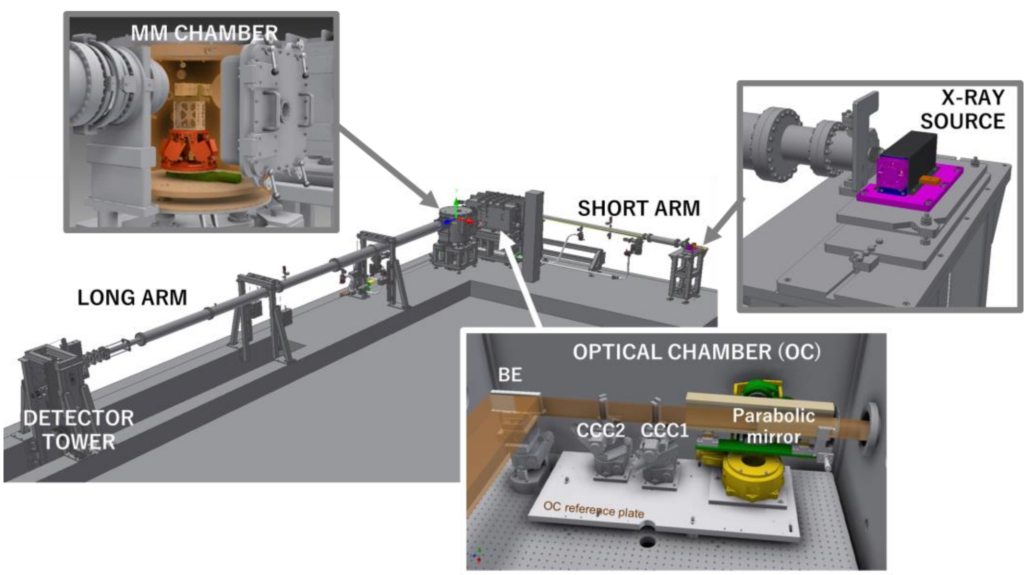

Figure 1. BEaTriX overall view and zoom on X-ray source, optical components inside the Optical Chamber and MM chamber. The RGB triad represents the BEaTriX coordinate system

The 4.51 keV beam line offers the possibility to choose a configuration with a better horizontal divergence but lower flux (3 arcsec and 10 ph/s/cm^2), or a second one with a worst horizontal divergence and a higher flux (4 arcsec and 60 ph/s/cm^2).

3. CHARACTERIZATION OF THE BEAM

The CCD used in the detector tower is equipped with a 27.6 × 27.6 mm^2 sensor. In order to cover the entire beam, a matrix of 21 images is recorded (3 rows and 7 columns). The characteristics of the beam to be checked are the divergence, the flux, the stability and the uniformity. These parameters can be derived from the analysis of the beam passing through a Hartmann Plate (HP) composed by a grid of squared holes (d=0.4 mm, 0.4 mm horizontal step and 2 mm vertical step). The HP is placed in the MM chamber and the long distance to the detector ensures a high sensitivity to wave-front deviation.

3.1 Divergence

Computing the deviation from the nominal position of the centroid of the holes projected into the CCD, it is possible to consider the component of the divergence due to the low frequency error (misalignment of the optical components or shape error at low frequency). The divergence contribution due to high frequency error (roughness of the parabolic mirror or dispersion of the beam expander) is computed analyzing the intensity profiles of the holes projected into the CCD (Figure 2). The edges of the image of the square holes are not sharp but spread to a Gaussian profile. In order to reach a high level of confidence the images of all the holes are overlapped in a single image.

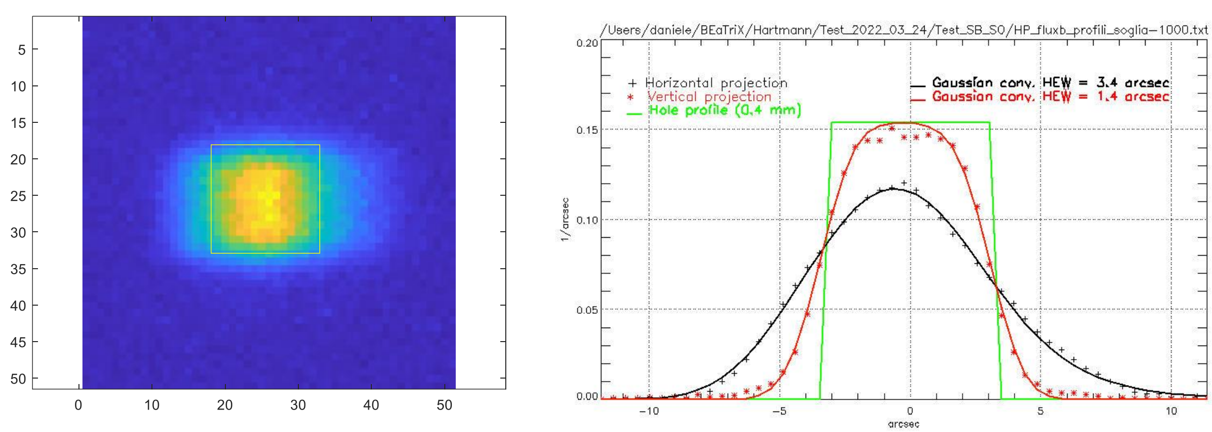

Figure 2. Overlapped image of holes (left, the yellow square is the hole size), and HEW computation from vertical or horizontal profiles (right) applying a convolution process between Gaussian curve and hole profile.

The divergence due to the low order is computed from the centroid of each hole. The behavior in the spatial range between 4 mm to 27 mm is mapped inside each image, while the divergence from 27 mm to 150 mm is obtained by a stitching procedure which needs to be very accurate, as every errors in mosaic stitching means an overestimation of the divergence. Different methods have been investigated; the best one adjusts the images in vertical direction (Y) reading the position from the encoders mounted on the Y motor stage of the CCD, and shifts the images in horizontal direction (X) to overlap two columns of holes between adjacent images.

Four mosaics have been acquired, and analyzed with the described procedure, between March 2022 and June 2022, three with the baseline configuration and one with an oscillation of the beam expander. This movement is needed to improve the uniformity in the high spatial frequencies, like described in section 3.2. Just before each mosaic the optical components have been accurately aligned in their critical rotations. The result is shown in Figure 3 where the divergence is computed on a size of 136 × 52 mm: apart some local artefacts due to cosmic rays, the general map is very similar. This proves the stability of the beam divergence and the fact that the oscillation of the beam expander does not degrade the beam collimation. Taking into account these considerations, the mean of the 4 mosaics has been analyzed and hereafter presented.

The acquired data refers to the high flux configuration, the sole configuration possible in a time frame of a day. Using the low flux configuration, the exposure of the mosaic would require more than a week, a time too long compared to the stability of the beam.
The total divergence of the beam is the quadratic sum of the two contributions according to the formula:

$$\mathrm{HEW}_{\mathrm{HOR\text{-}BEAM}} = \sqrt{(2 \cdot Div50_{HOR-CENTROID})^2 + (HEW_{HOR-HOLE})^2}$$

$$\mathrm{HEW}_{\mathrm{VER\text{-}BEAM}} = \sqrt{(2 \cdot Div50_{VER-CENTROID})^2 + (HEW_{VER-HOLE})^2}$$

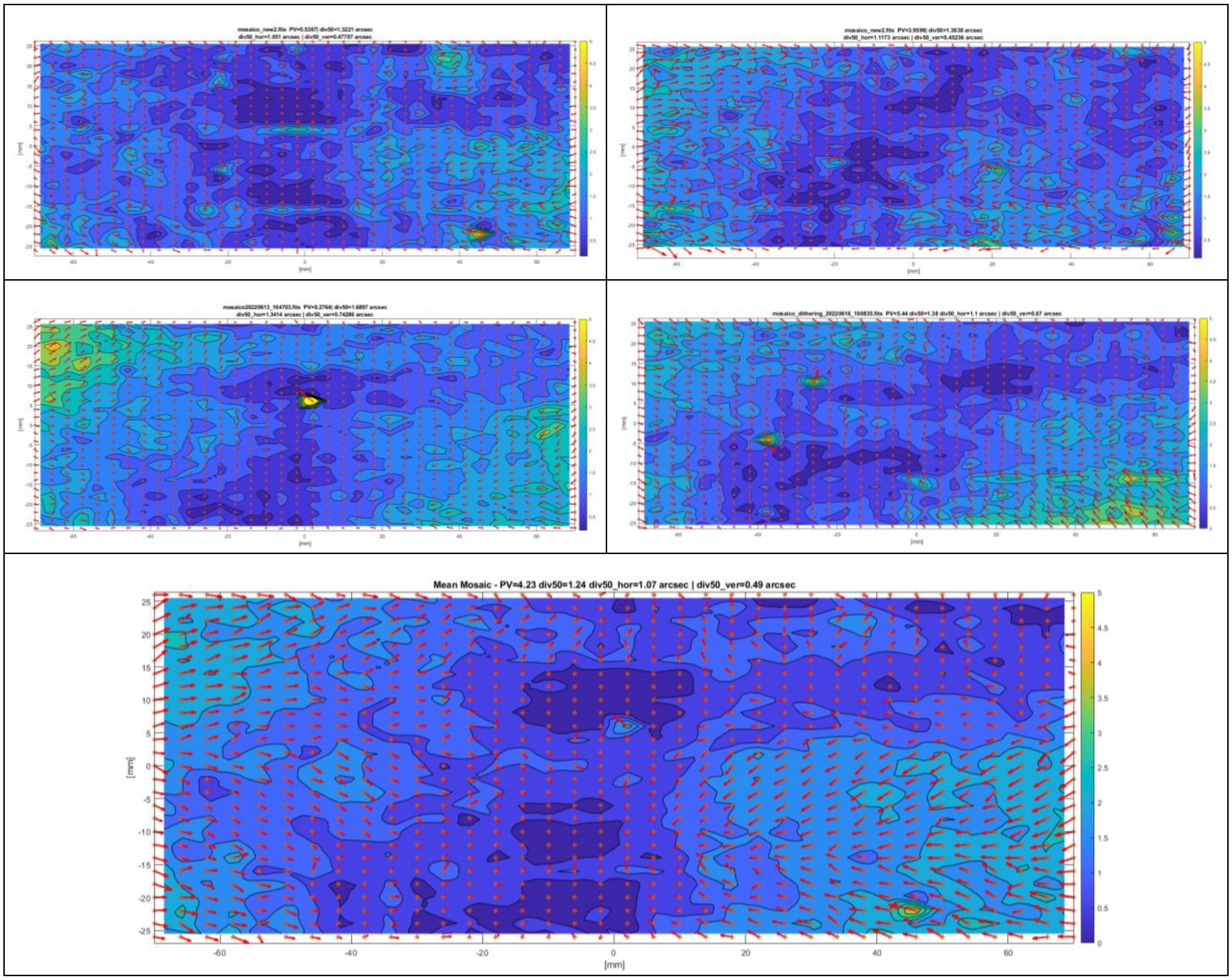

Figure 3. Divergence computed with the holes centroid method. The red arrows show the direction of the wave-front and the color map represents the amplitude in arcsec. The first 4 images are different mosaic acquisitions, the forth being the one taken with the oscillation of the Beam expander. The image at the bottom shows the mean result of the four mosaics.

The results are summarized in the table.
Considering that the MMs have a narrower width than the beam, we have computed the total divergence limiting the width of the beam (Figure 5). This affects essentially the horizontal divergence due to the centroid method, as can be seen in Figure 4.

Table 1 – Summery of the divergence computed at different date

	24-mar	06-apr	11-giu	14-giu (BE oscillation)
$Div50_{HOR\text{-}CENTROID}$ [arcsec]	1.05	1.12	1.34	1.1
$Div50_{VER\text{-}CENTROID}$ [arcsec]	0.48	0.45	0.74	0.67
$HEW_{HOR\text{-}HOLE}$ [arcsec]	3.4	3.48	3.57	3.28
$HEW_{VERT\text{-}HOLE}$ [arcsec]	1.38	1.5	1.25	1.59
$HEW_{HOR\text{-}BEAM}$ [arcsec]	4.00	4.14	4.46	3.95
$HEW_{VERT\text{-}BEAM}$ [arcsec]	1.68	1.75	1.94	2.08

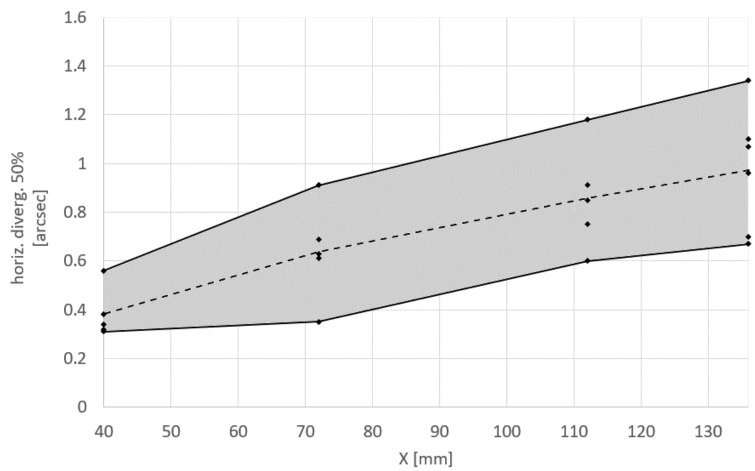

Figure 4. Horizontal divergence with the centroid method computed considering portion of the beam with different width.

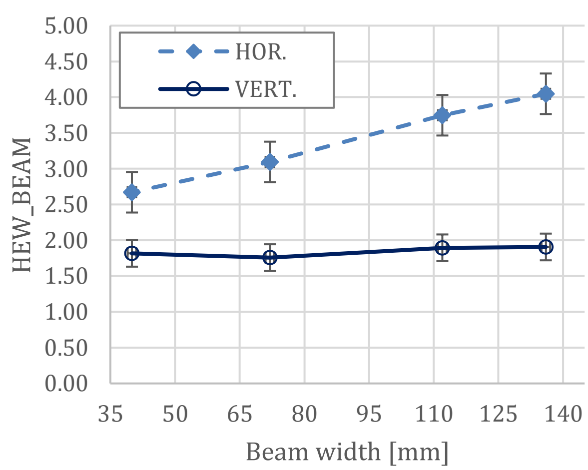

Figure 5. Total divergence as function of the width of the considered beam.

3.2 Photons flux

The X-ray flux depends on several factors, the intensity of the X-ray source, the reflectivity of the mirror, the absorption of the crystals and the alignment. The simulations foresee a flux of 60 photons/s/cm^2 and this is comparable with the measured values. The variation of the flux is due to change in the X-ray source intensity, misalignment along time due to mechanical assessment or temperature variation. In order to monitor the flux, a beam monitor is used to check the flux after the optical components.

A stability test has been performed along a week without any re-alignment of the beam (Figure 6). Even if the temperature is controlled and maintained within 1°C and the resolution of the encoders for the critical rotations is very accurate (0.5 arcsec) the intensity of the flux drifts along time. The flux was found stable for few days before it began to decrease (Fig. 6 left). Concerning the stability of the beam position, a correlation between the horizontal position of the HP holes images and the temperature of the parabolic mirror was observed (Fig. 6 right). The displacement of the beam in the vertical direction was found instead lower than a pixel. The temperature of the parabolic mirror, as the one of the other optical components, was observed to drift with the room temperature: a room temperature control better than 1°C is needed if higher stability is required.

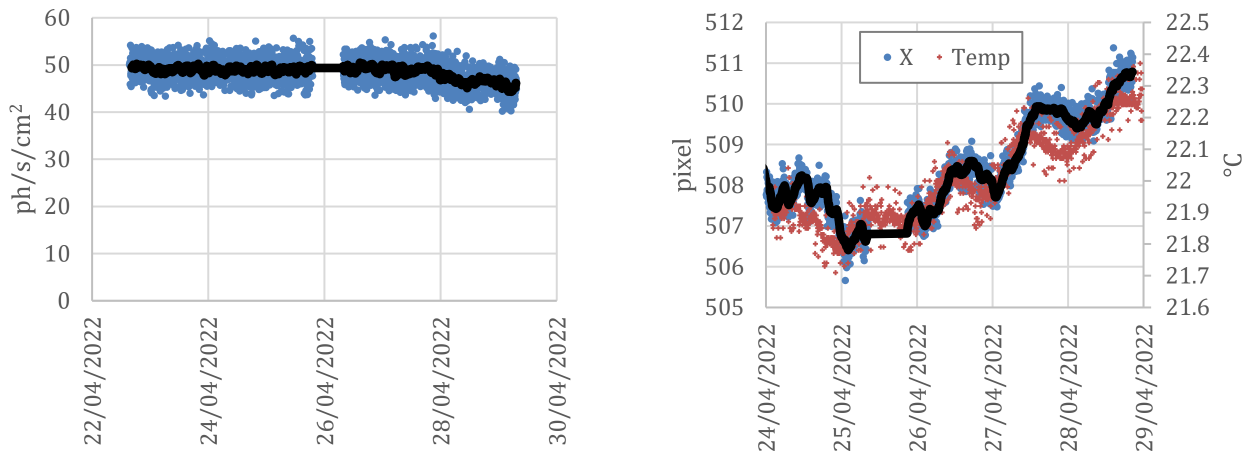

Figure 6. Stability test: photons flux (left). Center beam position along horizontal direction (right): the pixel size is 27 μm (the image was acquired with binning 2). The black lines are the mobile mean along 30 minutes.

Analyzing the data of each of the 21 images of the mosaics described in section 3.1, it is possible to see how the flux change along the beam. An example of this behavior is shown in Figure 7 for the mosaic of 11 June 2022. The result is shown in *Table 2* where the CCD efficiency at 4.51 keV (ε=0.6) is taken into account.

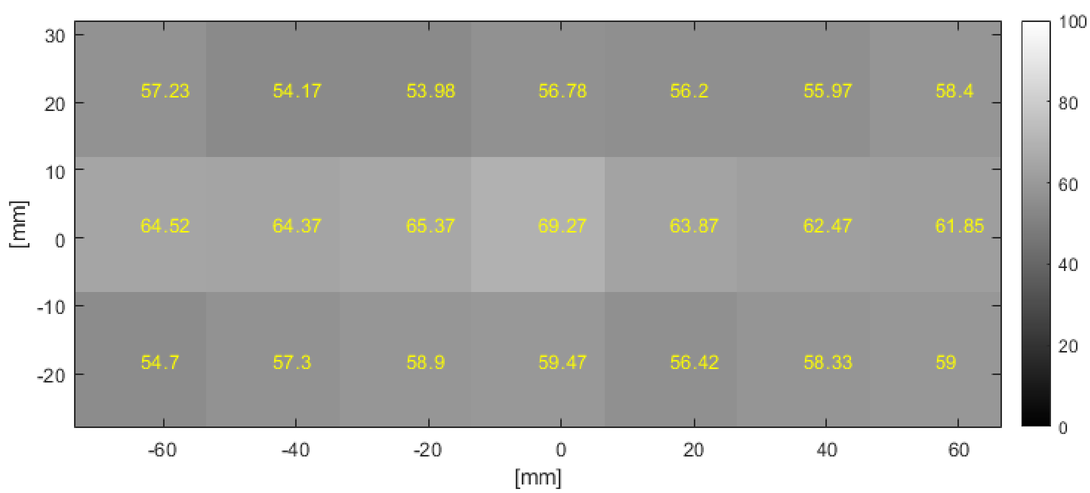

Figure 7. Flux uniformity of the beam with Hartmann plate [photons/s/cm^2]

The general behavior is that the central line (Y=0) has a flux slightly higher than the upper or lower row: this is due to small error on the yaw (rotation along Z) of the paraboloidal mirror, of the order of few arcsec. The error on the pitch angle (rotation along Y) of the CCCs moves this brighter band upward or downward.

Table 2 – Photon flux of the beam. The higher flux in the data of Jun is the effect of an improved beam alignment

	24-Mar-2022	06-Apr-2022	11-Jun-2022	14-Jun-2022 (BE oscillation)
Mean flux [ph/s/cm^2]	42.62	42.14	59.45	56.30
Flux min [ph/s/cm^2]	36.45	35.52	53.98	43.30
Flux max [ph/s/cm^2]	48.57	46.10	69.27	62.55
σ_{PERC}	10.5%	6.8%	7.0%	10.4%

Concerning the uniformity in a spatial range of 0.1 – 10 mm, some considerations can be done only looking to the direct beam without the Hartmann plate. High frequency inhomogeneities are present in the beam (Fig. 8 left): simulations have proven that the pattern is due to the residual shape errors on the parabolic mirror. The effect of this non-uniformity on the PSF is complex to be evaluated with simulations, but it will be easily measured by testing different portions of the beam with a MM representative in term of ATHENA optical quality. Nevertheless, this non-uniformity can be completely removed with the dithering of the BE (Figure 8).

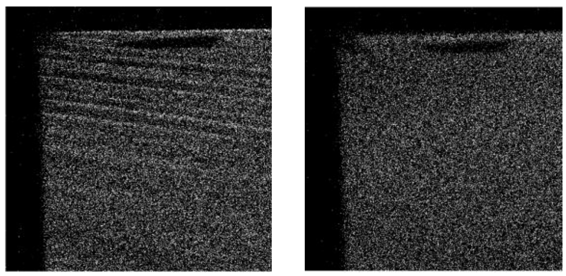

Figure 8. Improvement in the uniformity by dithering of the BE: no oscillation (left), oscillation with range = 0.5 mm and period = 20 s (right). The images are taken with exposure of 30min.

4. OPTIC TEST

In March 2022, the first light with an ATHENA MM was measured at BEaTriX, measuring the MM-0042 provided by cosine. It was the only MM available so far for measurements at 4.51 keV and it is a not coated MM corresponding to the innermost ring of the ATHENA optic. The Half Energy Width (HEW) measured for all the module is 25 arcsec[27]. BEaTriX is able to measure MMs with a PSF better than a factor 10 w.r.t. MM-0042 and in order to obtain a better PSF the module has been masked to illuminate only the best optical part of the module itself (Figure 9). The HEW was found decreased to 18.5 arcsec, with unchanged focal length (f=11925mm).

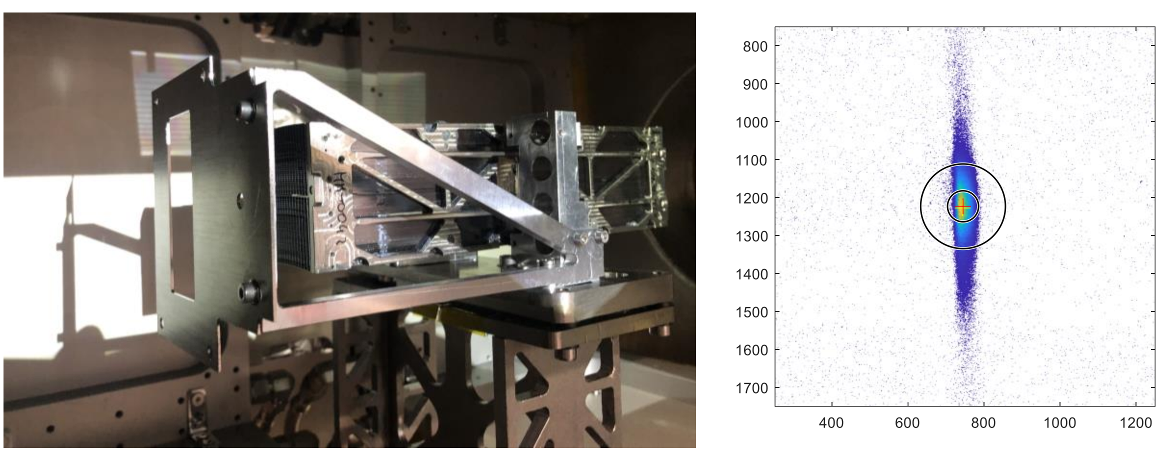

Figure 9. Left: MM-0042 mounted inside the MM chamber with the mask obscuring the external lateral wings. Right: PSF of the entire MM: pixel size is 13.5 μm. The two circles correspond to HEW and the W90 (the diameter enclosing 90% of the collected photons)

With this setup, an assessment of the installing procedure has been done, confirming the time needed to change the MM inside the MM chamber. In the next months, a MM with a better PSF will be provided to INAF-OAB: a comparison of calibration results at PANTER and XPBF 2.0 with the ones obtained with BEaTriX will conclude the commissioning of the facility.

5. CONCLUSION

BEaTriX has been built for testing X-ray optics with a parallel beam of 170 mm × 60 mm size, with a focal length in the range of 7.8-12.2 m. The BEaTriX facility is currently operative and it is in an optimization phase. Several scans of the beam have been acquired with a Hartmann plate showing a flux and a collimation according to the expectations. It is working with a flux of 60 photons/s/cm^2 at 4.51 keV and the vertical divergence is 1.9 ± 0.2 arcsec. The first measurements on a MM demonstrated the capabilities to test ATHENA MMs with the foreseen rate (2 MMs/day). The second line implementation at 1.49 keV will start in the next months further wading the capability of this unique facility.

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REFERENCES

[1] Nandra, K., Barret, D., Barcons, X., et al., "The Hot and Energetic Universe: A White Paper presenting the science theme motivating the Athena mission," http://arxiv.org/abs/1306.2307 (2013).
[2] Bavdaz, M., Wille, E., Ayre, M., et al., "The ATHENA X-ray optics development and accomodation", Proc. SPIE 11852, 1185220 (2021)
[3] Collon, M. J., Babic, L., Barrière, N. M., et al. 2021, "X-ray mirror development and production for the ATHENA telescope", Proc. SPIE 11852, 118521Z (2021)
[4] http://www.brera.inaf.it/beatrix-facility/
[5] Handick, E., Cibik, L. Krumrey, M., "Upgrade of the X-ray parallel beam facility XPBF 2.0 for characterization of silicon pore optics", Proc. SPIE 11444, 114444G (2020)
[6] Bradshaw, M., Burwitz, V, Hartner, G., et al., "Testing ATHENA optics: a new measurement standard at the PANTER x-ray test facility", Proc. SPIE 11852, 1185223 (2021)
[7] Menz, B., Braig, C., Brauninger, H., et al., "Large area x-ray collimator—the zone plate approach", Applied Optics Vol. 54, Issue 26, pp. 7851-7858 (2015)
[8] Spiga, D., Pareschi, G., Pelliciari, C., et al., "Functional tests of modular elements of segmented optics for x-ray telescopes via an expanded beam facility," Proc. SPIE 8443, 84435F (2012)
[9] Spiga, D., Pelliciari, C., Bonnini, E., et al., "An expanded x-ray beam facility (BEaTriX) to test the modular elements of the ATHENA optics," Proc. SPIE 9144, 91445I (2014)
[10] Pelliciari, C., Spiga, D., Bonnini, E., et al., "BEaTriX, expanded soft x-ray beam facility for test of focusing optics, an update," Proc. SPIE 9603, 96031P (2015)
[11] Spiga, D., Pelliciari, C., Salmaso, B., et al. "Design and advancement status of the Beam Expander Testing Xray facility (BEaTriX)," Proc. SPIE 9963, 996304 (2016)
[12] Salmaso, B., Spiga, D., Basso. S., et al., "Progress in the realization of the beam expander testing x-ray facility (BEaTriX) for testing ATHENA's SPO modules," Proc. SPIE 10699, 1069931 (2018)
[13] Spiga, D., Salmaso, B., Basso, S., et al, "Optical simulations for the laboratory-based expanded and collimated x-ray beam facility BEaTriX," Proc. SPIE 11110, 111100E (2019)
[14] Basso, B., et al. Thermal simulations for characterization of ATHENA Mirror Modules with a radiating box in the BEaTriX facility, Proc. SPIE 111191, 111191I (2019)

[15] Salmaso, B., Spiga, D., Basso. S., et al., "BEaTriX (Beam Expander Testing X-ray facility) for testing ATHENA's SPO modules: advancement status," Proc. SPIE International Conference on Space Optics 2018, Vol. 11180, 1118026 (2019)
[16] Salmaso, B., et al. BEaTriX, the Beam Expander Testing X-ray facility for testing ATHENAs SPO modules: progress in the realisation, Proc. SPIE 11119, 111190N (2019)
[17] Ferrari, C., Beretta, S., Salmaso, B.,et al., "Characterization of ADP crystals for soft x-ray optics of the Beam Expander Testing X-ray facility (BEaTriX)," Journal of Applied Crystallography, 52, 599-604 (2019)
[18] Spiga D., Salmaso, B., Basso, S., et al., "Performance simulations for the ground-based, expanded-beam X-ray source BEaTriX", Proc. SPIE 11837, 118370O (2021)
[19] Vecchi, G., Cotroneo, V., Ghigo, M., et al., Manufacturing and testing of the X-ray collimating mirror for the BEaTriX facility, Proc. SPIE 11822, 118220N (2021)
[20] Salmaso, B., Basso, S, Cotroneo, V. et al. "Building the BEaTriX facility for the ATHENA mirror modules X-ray testing", Proc. SPIE 11822, 118220M (2021)
[21] Basso, S., Salmaso, B., Ghigo, M., et al.,"The expanded, parallel and monochromatic X-ray beam of BEaTriX: alignment and characterization", Proc. SPIE, 12181 (2022)
[22] Ghigo, M., Salmaso, B., Basso, S., et al., "The control software of the BEaTriX X-ray beam calibration facility: problems and solutions" , Proc. SPIE, 12189 (2022)
[23] Spiga, D., Salmaso, B., Basso, S., et al., "Optical design and performance simulations for the 1.49 keV beamline of the BEaTriX X-ray facility", Proc. SPIE ICSO (2022)
[24] Christensen, F., Hornstrup, A., Frederiksen, P., et al., "Expanded beam x-ray optics calibration facility at the Daresbury Synchrotron," Proc. SPIE 2011, 540 (1994)
[25] Sanchez del Rio, M., Cerrina, F., "Asymmetrically cut crystals for synchrotron radiation monochromators", Review of Scientific Instruments 63, 936 (1992)
[26] Salmaso, B., et al., "X-ray tests of the ATHENA mirror modules in BEaTriX: from design to reality", Proc. SPIE 12181 (2022)
[27] Basso, S., Salmaso, B., Spiga, D., et al., "First light of BEaTriX, the new testing facility for the modular X-ray optics of the ATHENA mission", Astronomy & Astrophysics, Sect 13, arXiv:2206.15468 [astro-ph.IM]