

Advancing BEaTriX: a high-performance X-ray calibration facility for scientific and industrial applications

B. Salmaso^{*a}, S. Basso^a, D. Sisana^a, A. Chauhan^a, B. Dalla Barba^a, A. Rizkallah^{a,b}, M. Ghigo^a, G. Vecchi^a, G. Sironi^a, D. Spiga^a, G. Pareschi^a, G. Tagliaferri^a, M. Uslenghi^c, M. Fiorini^c, L. Lessio^d, S. Chinellato^d, C. Ferrari^e, E. Ferrari^e, V. Burwitz^f, T. Schmidt^f, B. Budau^f, M. Bavdaz^g, I. Ferreira^g

^aINAF Osservatorio Astronomico Brera, Via E. Bianchi 46, 23807 Merate, Lecco (Italy)

^bGerman University in Cairo, El-Tagamoa El-Khames, Cairo (Egypt)

^cINAF-IASF Milano, Via A. Corti 12, 20133 Milano (Italy)

^dINAF Osservatorio Astronomico Padova, Vicolo Osservatorio 5, 35122 Padova (Italy)

^eIMEM-CNR, Parco Area delle Scienze 37/A, 43124 Parma (Italy)

^fMax-Planck-Institut für extraterrestrische Physik, Giessenbachstr., 85748 Garching (Germany)

^gESTEC, European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk (The Netherlands)

ABSTRACT

The Beam Expander Testing X-ray facility (BEaTriX), operated by INAF at the Brera Astronomical Observatory (Merate, Italy), is a compact laboratory solution for X-ray characterizations requiring a parallel, highly monochromatic beam. It was designed and built to test Silicon Pore Optics Mirror Modules (SPO MMs) for ESA's NewAthena mission at a throughput of 3 MMs/day. Beyond this primary role, the facility is evolving into a multi-purpose X-ray platform. The 4.51 keV beamline has been operational since 2022 and was used in 2024 for the first X-ray characterization of a coated SPO MM across the full NewAthena acceptance temperature range of $20 \pm 20^\circ\text{C}$. The second beamline at 1.49 keV is progressing, with commissioning planned to start in early 2027. The BEaTriX+ upgrade enables a tunable focal length from 1.4 to 14 m, opening calibration capability to a broader class of X-ray optics. This paper describes the facility's status and highlights its potential as a versatile hub for X-ray metrology and calibration for scientific and industrial applications.

Keywords: *BEaTriX, X-ray calibration, NewAthena, Silicon Pore Optics, detectors, variable focal length*

1. INTRODUCTION

NewAthena is the ESA's next flagship X-ray space observatory; it will feature a 2.5 m diameter telescope based on Silicon Pore Optics (SPO) technology, designed to deliver an on-axis Half Energy Width (HEW) below 9 arcsec over a 0.2–12 keV energy range [1,2]. The telescope will integrate up to 600 Mirror Modules (MMs), manufactured by the Dutch company *cosine* [3]. Given the number of modules and the stringent performance requirements, the Assembly, Integration, and Test (AIT) phase demands dedicated calibration facilities capable of verifying each MM before integration into the final telescope assembly. To this goal, the Italian National Institute of Astrophysics (INAF) conceived and realized at the Brera Astronomical Observatory (OAB) a unique facility called BEaTriX, the Beam Expander Testing X-ray facility [4]. BEaTriX generates a wide ($170 \text{ mm} \times 60 \text{ mm}$), quasi-parallel ($\text{HEW} < 2.5 \text{ arcsec}$), and monochromatic X-ray beam within a laboratory-scale footprint of $8 \times 14 \text{ m}^2$, without a long vacuum tube required to reduce the divergence of conventional sources or the use of synchrotron light to produce a small parallel beam. Since its first light in 2022 [5], the facility has served as the acceptance-test infrastructure for NewAthena SPO MMs, alongside other important facilities dedicated to the MMs characterization, like PANTER-MPE (Garching, Germany) [6] and XPBF 2.0 at BESSY II (Berlin, Germany) [7].

Two major advancements define the current phase of BEaTriX: (i) progress on the second energy channel at 1.49 keV, scheduled for commissioning in the first half of 2027; (ii) the BEaTriX+ upgrade, which extends the operational focal length from the fixed 12 m of the NewAthena configuration to a tunable range of 1.4–14 m. Together, these developments transform BEaTriX into a versatile X-ray platform for scientific and industrial applications.

*corresponding author: bianca.salmaso@inaf.it; phone +39-02-72320-456; <https://brera.inaf.it/>

2. THE BEATRIX FACILITY

2.1 Optical principle and layout

BEaTriX generates a large ($170 \text{ mm} \times 60 \text{ mm}$), quasi-parallel ($\text{HEW} < 2.5 \text{ arcsec}$), monochromatic X-ray beam by combining four optical elements in an L-shaped vacuum system: (i) a microfocus X-ray source at the focus of (ii) a paraboloidal grazing-incidence mirror, which collimates and vertically expands the beam; (iii) a monochromatization stage using Bragg crystals; (iv) a horizontal beam expansion stage using asymmetrically cut Bragg crystals, which widens the beam by a factor $\times 40/\times 50$ while preserving angular collimation thanks to the upstream monochromatization [8,9].

This design avoids the two main limitations of conventional approaches. Unlike facilities approximating the infinite distance of stars with an X-ray source mounted at the end of vacuum tubes with hundreds of meters length, BEaTriX is a very compact facility. Unlike pencil-beam synchrotron sources where the PSF is reconstructed from scanned data, the full MM aperture is illuminated in a single exposure. The BEaTriX facility occupies $8 \times 14 \text{ m}^2$ and achieves a throughput of 3 MMs/day, fully compatible with the NewAthena production schedule.

BEaTriX was designed and built to host two energy channels at 4.51 keV and 1.49 keV. Together, they provide sufficient information to calibrate the NewAthena MMs by constraining the mirror models and validating the predicted effective area across the full 0.2–12 keV band.

2.2 The 4.51 keV beamline

The first BEaTriX channel operates at 4.51 keV, and it has been operational since 2022 [5]. The photons are produced by the Ti-K α line of a micro-focus X-ray source, and the beam is moderated by a paraboloidal mirror for vertical beam expansion, two symmetrically cut Si(220) channel-cut crystals acting as a monochromator, and one asymmetrically cut Si(220) crystal for horizontal beam expansion ($\times 50$). The system produces a beam expansion of $170 \times 60 \text{ mm}^2$. Two configurations are available: high-flux (HF: $\sim 60 \text{ ph s}^{-1} \text{ cm}^{-2}$, $\text{HEW-hor} \sim 4 \text{ arcsec}$) and high-collimation (HC: $\sim 10 \text{ ph s}^{-1} \text{ cm}^{-2}$, $\text{HEW-hor} \sim 2.5 \text{ arcsec}$), selectable by rotating one monochromator crystal [4]. Originally, the HF configuration was preferred for Effective Area Measurements, and the HC configuration for PSF and HEW measurements. In the HC configuration, the residual beam divergence is below 2.5 arcsec HEW, but the exposure time reaches ~ 30 minutes per MM (for a module with 10 cm^2 effective area). A deconvolution-based method using the Damped Richardson–Lucy algorithm was developed to recover the intrinsic MM PSF from HF images [10]. Applied to data obtained at BEaTriX with the first coated SPO MM, the method recovered the intrinsic PSF to within 0.5 arcsec, reducing per-MM exposure time from 30 to 5 minutes and enabling calibration entirely in the high-flux configuration.

Table 1. BEaTriX beam parameters for both energy channels. HF = high-flux; HC = high-collimation.

Parameter	4.51 keV	1.49 keV
X-ray source anode	Ti (K α)	Al (K α)
Flux	$\sim 60 \text{ ph/s/cm}^2$ (HF) / ~ 10 (HC)	$\sim 12 \text{ ph/s/cm}^2$
Beam collimation (HEW)	$< 2.5 \text{ arcsec}$ (HC) / $\sim 4 \text{ arcsec}$ (HF)	$< 3.5 \text{ arcsec}$
Beam footprint	$170 \times 60 \text{ mm}^2$	$152 \times 60 \text{ mm}^2$
Energy bandwidth (ΔE)	35 meV	23 meV
Focal length (BEaTriX+)	$1.4 \div 14 \text{ m}$ (tunable)	$1.4 \div 14 \text{ m}$ (tunable)
Status	Operational since 2022	Commissioning Q1 2027

2.3 The 1.49 keV beamline

The second BEaTriX channel operates at 1.49 keV, and it is now under implementation. This line shares the Optical Chamber and overall architecture with the 4.51 keV beamline, but it has an independent optical path and optical components. The photons are generated by the Al-K α line of an independent micro-focus X-ray source, at the focus of a second paraboloidal mirror. The monochromatization stage uses two asymmetrically cut Quartz (10-10) crystals. The horizontal beam expansion stage uses two ADP (Ammonium Dihydrogen Phosphate) crystals asymmetrically cut with

respect to the (101) planes, providing a beam expansion of $\times 40$ [7]. The challenges of the crystals used for this low-energy channel are described in [9]. All 1.49 keV optical components (parabolic mirror, Quartz monochromator towers, and ADP beam expander) have been procured, characterized, and installed in the BEaTriX Optical Chamber [8,9].

The Al-K α source is in its final development phase. It requires simultaneously a focal spot ≤ 35 μm FWHM and a brilliance $\geq 5 \times 10^{11}$ ph s $^{-1}$ sterad $^{-1}$, competing demands made harder by aluminum's low melting point. Auxilia Technology (Kraków, Poland) is developing the source in collaboration with rtw GmbH (Berlin, Germany). Recent tests were carried out at PANTER-MPE (near Munich, Germany), a versatile X-ray test facility where a long tube enables source to detector distances of about 130 m. The best measured focal spot was FWHM-X ~ 25 μm and FWHM-Y ~ 30 μm , well within the ≤ 35 μm requirements; the estimated brilliance was 4.1×10^{11} ph s $^{-1}$ sr $^{-1}$, almost meeting the flux specification.

We used two complementary methods to measure the source size at the PANTER facility. In the *pinhole-imaging method* (Figure 1), a pinhole is placed in front of the source and the penumbra region projected onto an imaging detector is analyzed. The source FWHM is derived from the first derivative of the penumbra intensity profile at the edges, corrected for diffraction effects via ray-tracing simulations. In the *blade-scan method* (Figure 2), a motorized blade is placed near the source to progressively occlude the beam; an integrating detector records the transmitted flux as a function of blade position, producing an erf-shaped curve whose first derivative gives a Gaussian with FWHM equal to the source size, corrected for the finite detector solid angle via a ray-by-ray simulation. Since only the blade scan will be available at BEaTriX, cross-calibrating the two methods at PANTER was a primary objective of this campaign, with the two tests performed sequentially. A residual $\sim 20\%$ discrepancy between the FWHM values returned by the two methods is attributed to a thermally driven variation of the source spot size between acquisitions: thermal effects in the cathode region were identified as a potential instability driver during the campaign, and a dedicated cathode cooling system is accordingly under development. Final source optimizations are now ongoing, as a follow-up of the PANTER campaign. After the final test at PANTER planned in fall 2026, the source will be installed at BEaTriX in Q1 2027. Both BEaTriX energy lines are foreseen to be fully operational by Q2 2027.

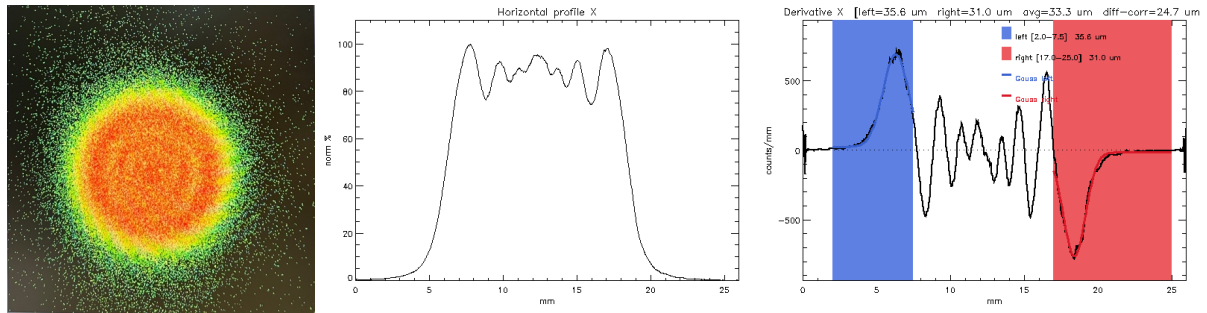


Figure 1. Pinhole-imaging method. Left: image of the 1.49 keV source through a 250 μm pinhole. Right: data analysis in the horizontal direction gives a source size of 24.7 μm .

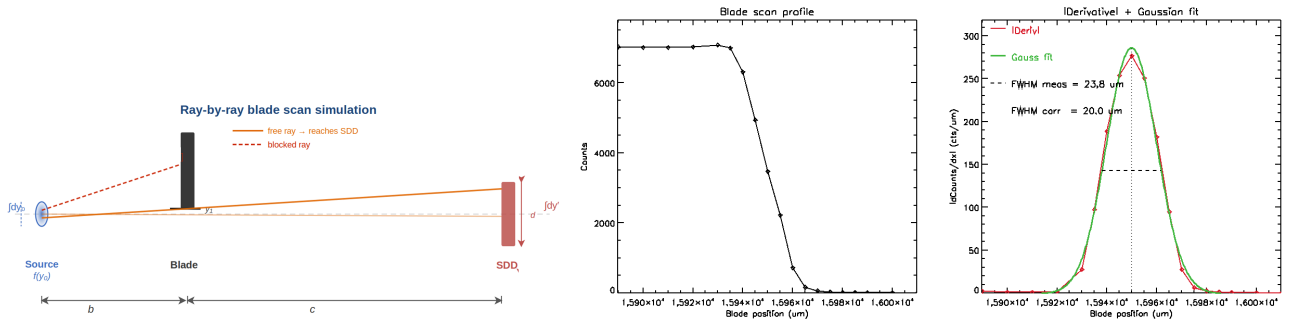


Figure 2. Blade-scan method. Left: sketch of the blade test. Right: data analysis in the horizontal direction gives a source size of 20 μm .

2.4 Upgrade in facility for variable focal length: BEaTriX+

The original BEaTriX long arm was configured for the fixed NewAthena focal length of 12 m. The BEaTriX+ upgrade, funded by INAF, replaces it with 21 modular vacuum sectors of constant diameter, enabling detector positioning at any focal length between 1.41 and 13.7 m in steps of ~ 300 mm. A stand-alone module hosts the focal-plane detector and a high-precision Z-stage motor for fine-focusing scans. Vacuum tightness, motor linearity, and beam stability have been verified at multiple configurations; BEaTriX+ is now fully operational [8].

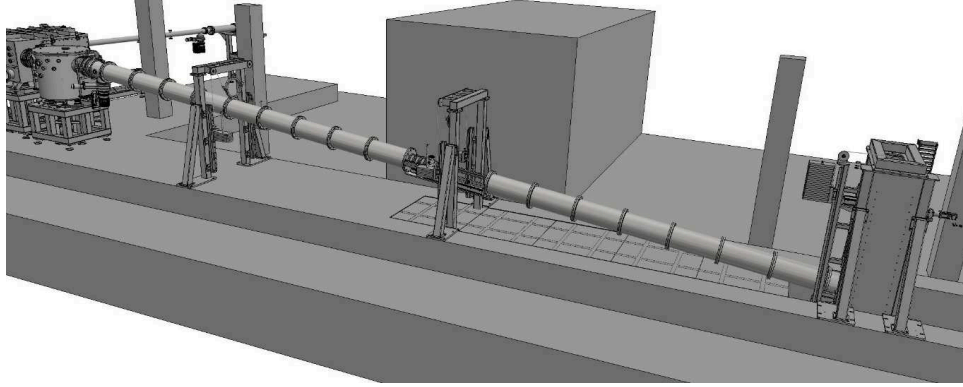


Figure 3. The upgraded design of BEaTriX+ showing the long tube with the 21 sectors, and the stand-alone module with the detector mounted at the middle of the long tube

3. BEATRIX FOR THE NEWATHENA CALIBRATION

In 2024, within the AHEAD2020 European programme, BEaTriX performed the first X-ray characterization of a fully coated SPO Mirror Module: MM-0058. The campaigns on MM-0058 have validated BEaTriX's capability to measure all key MM calibration parameters (PSF, effective area, and thermal stability) at the accuracy and throughput required by the NewAthena programme.

3.1 PSF

The first BEaTriX campaign on MM-0058 (February 2024) served as a cross-calibration with the PANTER facility, yielding $\text{HEW} = 11.9 \pm 0.1$ arcsec at BEaTriX and 11.8 ± 0.1 arcsec at PANTER for the full module aperture [8,11]. In addition to on-axis measurements, off-axis PSF dependence on yaw and pitch, stray-light from secondary sectors, and support remounting repeatability were also characterized.

3.2 Effective Area

The effective area (EA) of MM-0058 was measured at BEaTriX in the high-flux configuration for both the inner and outer X-ray Optical Units (iXOU and oXOU). BEaTriX yielded $\text{EA} = 2.42 \pm 0.2$ cm² for the iXOU and 2.72 ± 0.2 cm² for the oXOU, with uncertainties evaluated through measurement repetition. The PANTER facility measured $\text{EA} = 2.17 \pm 0.1$ cm² (iXOU) and 2.26 ± 0.1 cm² (oXOU) [11]. This difference will be clarified with systematic inter-facility comparison within the NewAthena calibration framework.

With the 1.49 keV beamline nearing completion, BEaTriX will provide Effective Area measurements at both reference energies in the NewAthena calibration plan. This dual-energy characterization is essential to constrain the coating reflectivity model and predict the MM effective area across the full 0.2–12 keV band.

3.3 Thermal characterization

A dedicated thermal box, designed and assembled by INAF–OAB, allows the MM temperature to be varied between -5°C and $+45^\circ\text{C}$ while X-ray measurements are performed in situ.

A second campaign on MM-0058 (fall 2024) characterized the module over the full NewAthena acceptance temperature range ($20 \pm 20^\circ\text{C}$), including five temperature cycles between 0°C and 40°C [8], simulating the environmental conditions it will experience between launch and commissioning. The campaign showed the HEW to have a minimal temperature dependence of ~ 0.1 arcsec per 10°C , with no significant variation in effective area and focal length. These were the first

thermal X-ray measurements of a coated SPO MM, indicating that the module can withstand such temperature excursions and that BEaTriX supports the thermal acceptance tests required by the NewAthena program.

3.4 MM pre-alignment

To improve the reproducibility and efficiency of the MM acceptance test, we integrated an inclinometer-based pre-alignment into the BEaTriX measurement workflow. A dual-axis inclinometer by *Fredericks* (0729-1765-99) was mounted on a dedicated reference plate that was interfaced to the MM. Before any X-ray measurement, the system records the MM roll and pitch orientation and drives the hexapod in closed loop to bring the module to a defined reference position, with a target accuracy of 0.002 deg. The pre-alignment routine is integrated into the main BEaTriX LabVIEW control software. In the production phase, this system will reduce per-module setup time and ensure repeatable illumination geometry across the full NewAthena testing campaign.

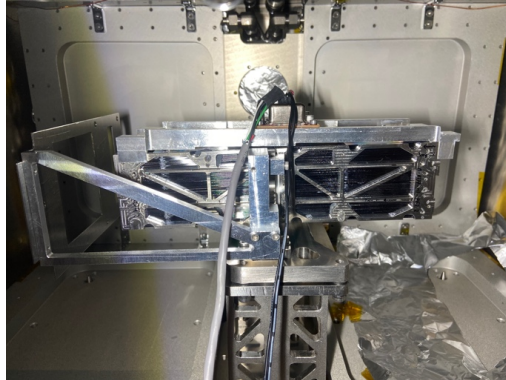


Figure 4. The inclinometer mounted on the interface of a MM in the BEaTriX experimental chamber.

4. BEATRIX AS A VERSATILE X-RAY PLATFORM

4.1 Unique capabilities in a laboratory environment

Beyond its primary mission as a NewAthena acceptance test facility, BEaTriX offers a combination of X-ray beam properties that is unique at laboratory scale and directly relevant to a broader class of scientific and industrial applications:

- Wide beam (up to $170 \times 60 \text{ mm}^2$): full-aperture illumination of X-ray optics in a single exposure, from compact CubeSat mirrors to medium-aperture telescope prototypes;
- High collimation (HEW 2–4 arcsec): equivalent to illumination by a point source at infinite distance, ideal for PSF characterization of the optic under test;
- High monochromaticity ($\Delta E \sim 23\text{--}35 \text{ meV}$): reflectivity and coating characterization without adjacent spectral contamination;
- Two calibrated energies (1.49 and 4.51 keV);
- High linear polarization ($>90\%$) in the vertical plane of the 4.51 keV beam, owing to the incidence at 45° on the Si (220) crystalline planes near the Brewster angle;
- Tunable focal length (1.4–14 m with BEaTriX+): accommodates optics across a wide range of current and planned X-ray missions;
- Stable calibrated flux ($10\text{--}60 \text{ ph s}^{-1} \text{ cm}^{-2}$): quantitative photometric measurements with traceable uncertainty;
- Temperature variation of the optics under test in the range $20 \pm 25^\circ\text{C}$, with possible gradients.

4.2 Testing of X-ray optics for small and future missions

The BEaTriX+ variable focal length directly expands the range of X-ray telescopes that can be characterized. At short focal lengths ($\sim 1.4\text{--}2 \text{ m}$), compact optics for CubeSat platforms and nanosatellite missions can be tested in full-aperture illumination at two reference energies, providing PSF and effective area data needed for in-flight performance prediction. At intermediate focal lengths (2–6 m), the facility is suited for prototype optics qualification for medium-class future missions (survey telescopes, soft X-ray spectrometers). At the longest configurations ($\sim 14 \text{ m}$), it can accommodate optics

for future large observatories. In all cases, the BEaTriX beam delivers calibration quality comparable to that demonstrated for the NewAthena programme.

4.3 X-ray detector and sensor qualification

The stable, monochromatic BEaTriX beam is a well-characterized reference source for the performance qualification of X-ray detectors and sensors. Operating at 4.51 keV and soon at 1.49 keV, the facility can deliver uniform flat-field illumination over areas up to $170 \times 60 \text{ mm}^2$. Relevant tests include: energy resolution and charge transfer efficiency at known photon energies; pixel-by-pixel gain uniformity; detector threshold and linearity over the available flux range. Furthermore, the thermal box infrastructure can also be adapted for detector environmental qualification (e.g. thermal cycling and gradient testing) during X-ray exposure in vacuum, a configuration difficult to achieve with conventional radioactive or fluorescence sources.

4.4 Mirror coating and materials characterization

The narrow energy bandwidth ($\Delta E \sim 23\text{--}35 \text{ meV}$) makes BEaTriX well suited for X-ray reflectometry of mirror coatings, multilayer structures, and diffraction gratings. By scanning the grazing incidence angle (rocking curve), the critical angle and reflectivity profile can be precisely determined at the two reference energies. This is directly relevant to the space optics supply chain: coating vendors, mirror manufacturers, and grating developers require a traceable, laboratory-scale reflectivity reference to complement synchrotron data and support routine quality control in production workflows, without requiring synchrotron access.

4.5 Compatibility with industrial AIT workflows

BEaTriX has been designed from the outset for industrial throughput. The modular vacuum architecture, with an isolated Experimental Chamber, enables sample exchange with minimal downtime while keeping the rest of the system under vacuum. The LabVIEW-based control software supports automated measurement sequences, data logging, and real-time safety monitoring. The hexapod alignment system provides six degrees of freedom for sample positioning to better than 1 arcsec. Measurement data are processed in standardized formats compatible with scientific data pipelines, making the measurement workflow straightforward for external users to operate and compatible with integration into industrial calibration and qualification supply chains.

5. CONCLUSIONS

BEaTriX, operated at the INAF Brera Astronomical Observatory, was designed and built to test the SPO MMs for ESA's NewAthena mission. The 4.51 keV beamline, operational since 2022, has demonstrated its capability to perform PSF and effective area measurements with the required accuracy, and to conduct thermal characterization across the full NewAthena acceptance temperature range. The deconvolution-based PSF reconstruction method enables routine testing entirely in the high-flux configuration.

The 1.49 keV beamline is in its final integration phase. With all optical components installed and the X-ray source under finalization, vacuum installation is scheduled for fall 2026 and commissioning for early 2027. The complete dual-energy facility required by the NewAthena calibration plan will be operational by Q2 2027.

The BEaTriX+ upgrade, now fully operational, extends the facility's reach to a broad class of X-ray optics: from CubeSat-scale instruments to future large observatories, testable at two reference energies and at any focal length between 1.4 and 14 m. Extended applications, such as thermal testing under X-ray illumination, coating characterization, and detector qualification, position BEaTriX as a versatile hub directly relevant to the space optics industrial community.

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