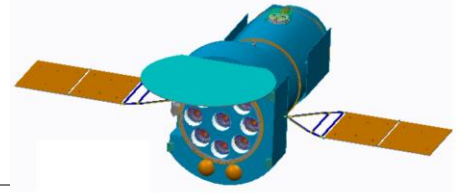
中国科学院高能物理研究所
INSTITUTE OF HIGH ENERGY PHYSICS



Development of X-ray Focusing Mirrors onboard the eXTP Mission

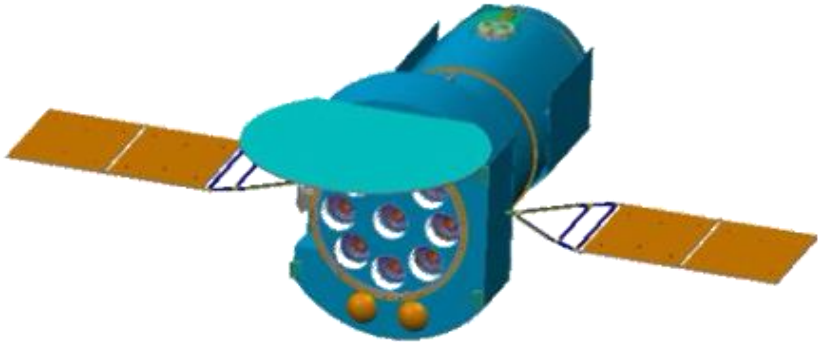
Yanji Yang

Behalf of eXTP Optics Collaborative Team

14th Nov. 2024

11-15 Nov. 2024, AXRO2024, Prague, Czech

eXTP: enhanced X-ray Timing and Polarimetry



Important Sciences

- Extreme density, gravity, magnetism
- Neutron stars, black holes, etc

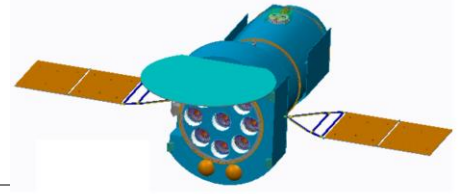
Cutting-edge technology

- Spectral, polarization, timing, imaging
- Large eff. Area (~2700 cm^2@6 keV)
- High spec. resol.(<180 eV@6 keV)

Payload	Configuration	Eff. area (m^2)	Timing res. (μs)
Spectroscopy Focusing Array (SFA)	6 telescopes	0.6 m^2@1-2 keV	10
Polarimetry Focusing Array (PFA)	3 telescopes	300 cm^2@3 keV	10

Consolidated in Phase B

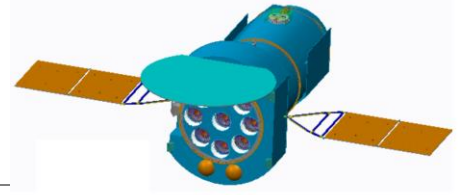
Phase B Progress



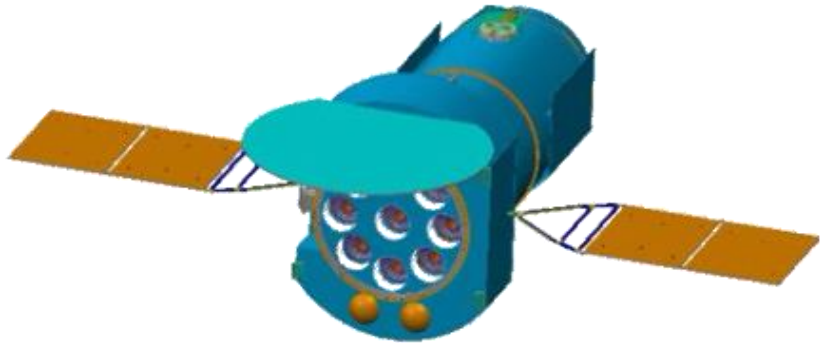
Supported through *eXTP Major Background Study project* by CAS.

- 2019.02 The 2nd eXTP Consortium meeting
  & Phase B technical kick-off in Beijing.
- 2022.01 Satellite/Chinese payloads conceptual design review.
- 2022.06 Selection for the China Space Science Plan (SPP-3) .
  - Organized by CAS with support of a international review team.
  - eXTP is highly recommended with perspective adoption around the end of 2023.
- 2023.03 - eXTP Major Background Study project under evaluation
  - Technical part successfully completed.
  - Budget/programmatic part completed.

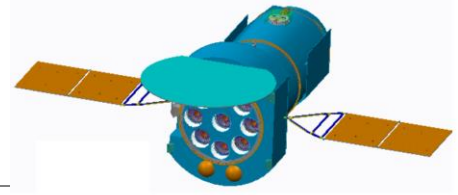
eXTP Mission Overview



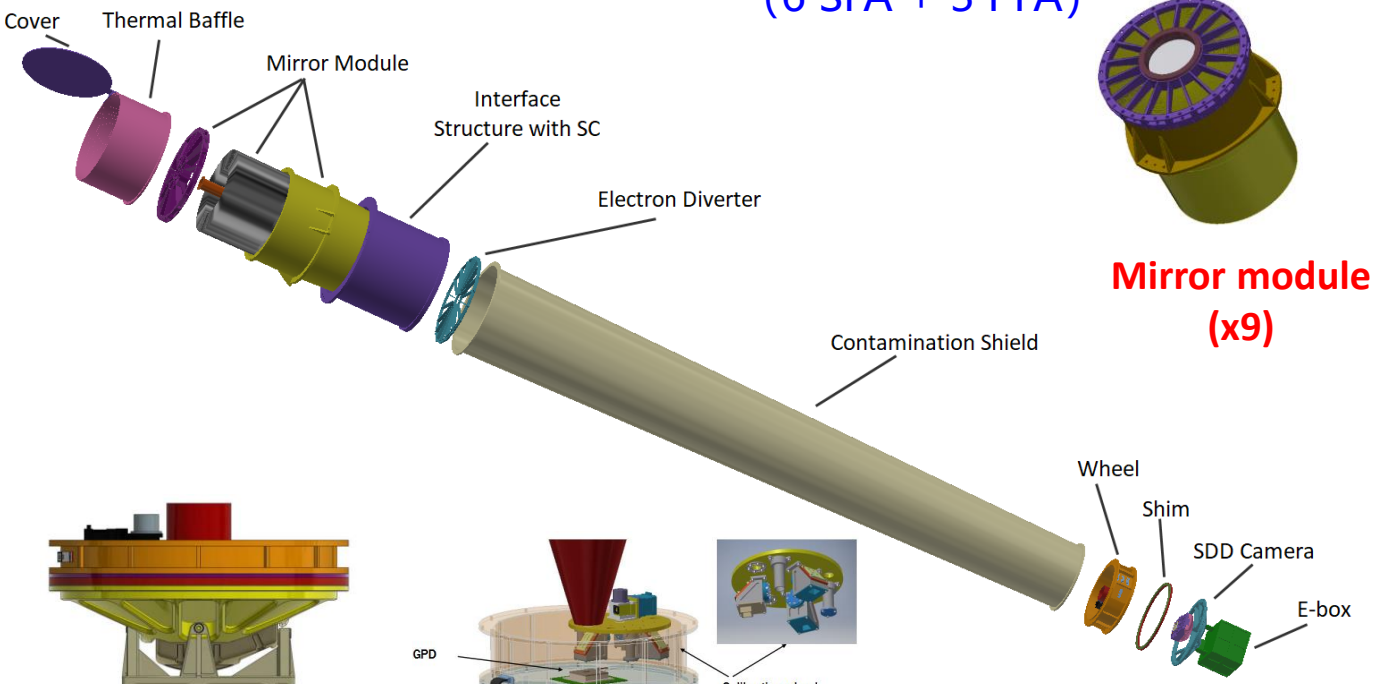
Parameter	Value
Orbit	Apogee>100000km, perigee 5000km, Earth's highly elliptical orbit.
inclination	28°
Pointing	3-axis stabilized, < 3" (3σ)
Launch	LM3B, from XiChang
Launch mass	~4000 kg
Telemetry	1.7 Tb/2 day (Ku-band)
Mission duration	5 years (goal 8 years)
Launch date	~ Jan. 2030



Preliminary Design of eXTP Optics



9 Telescope
(6 SFA + 3 PFA)



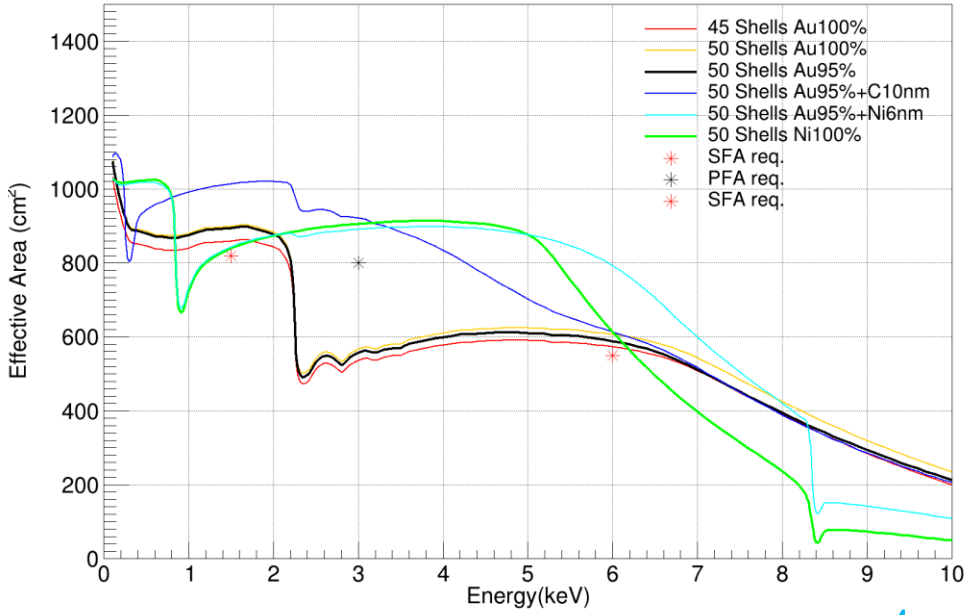
Mirror module (x9)

SFA camera (x6)

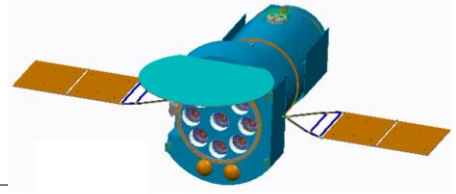
PFA camera (x3)

SFA Coating	Baseline: Gold Optimized: Au+Nickel
PFA Coating	Baseline: Nickel Optimized: Au+Nickel

eXTP MM Effective Area with Spider

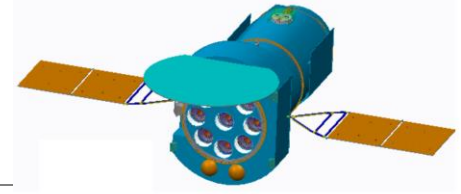


Collaborative group of X-ray Focusing Mirror



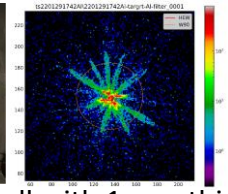
- IHEP
  - General technical unit
  - Structural and thermal design, testing and assembly of the mirror shells
- HIT
  - Development of the mandrels and mirror shells
- XIOPM
  - Optical design, vibration and thermal testing,
  - Development of X-ray baffle, rear spider and electronic deflector

Development Milestone of X-ray Focusing Mirror



Start the Phase A+ study of eXTP

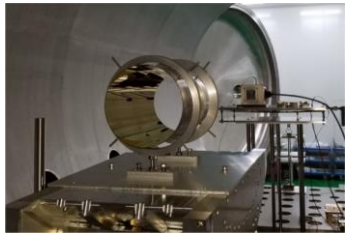
- Finish STM2 of the Einstein Probe mission in February.
- The development laboratory has been built in December.

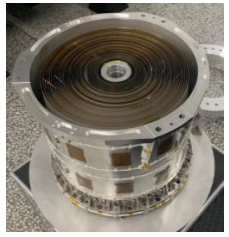


- The first eXTP mirror shell with 1 mm thickness has been test by X-ray, HPD = 20” in February.
- The eXTP mirror shell with 0.2 mm thickness has been test by X-ray, HPD = 33” in April.
- The DM1 has been finished, HPD = 64” in November.

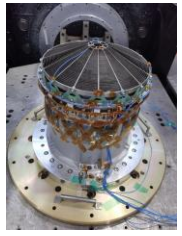
2018 2019 2020 2021 2022 2023

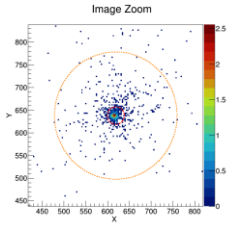
- Our first focusing mirror has been tested by X-ray in March.
- Finished the STM1 of the Einstein Probe mission in October.



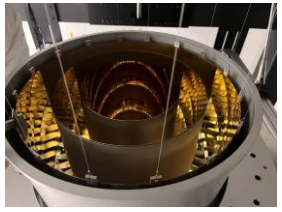


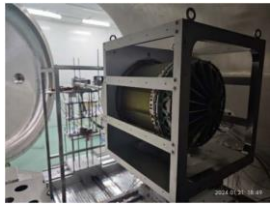
- Finish the QM of the Einstein Probe mission in July.





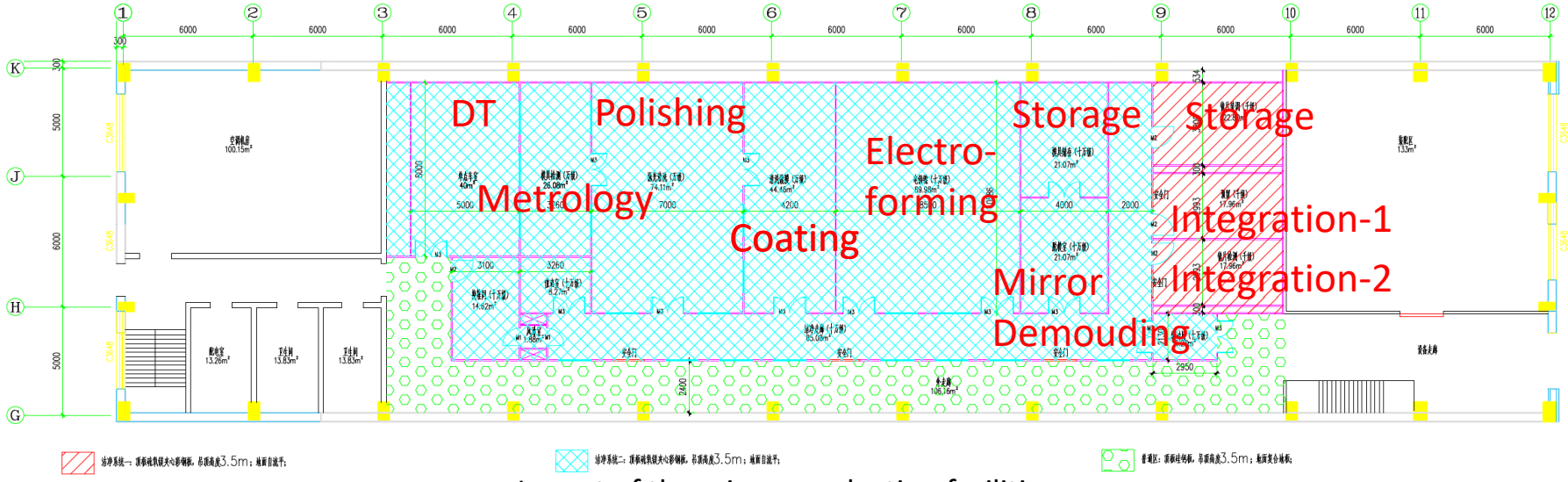
- The DM2 has been finished, which angular resolution is ab. 40” in June.
- The DM3 from MLS has been accepted in September, 24 ”.
- The flight spare of FXT has accepted in November, 57” 。





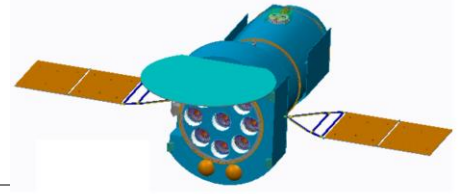
The Development Laboratory

- 1000m^2 clean room located at south of Harbin City with:
  - Diamond turning machine
  - Dedicated metrology room & instruments
  - Polishing (super polishing & figuring)
  - Gold coating chamber
  - Electro-forming bath
  - Mirror separation stand & mandrel storage room
  - Mirror inspection & integration



Layout of the mirror production facilities

Technical Approach



Optical Design → Manufacture of the Mirror shells → Inspection of the mirror shells → Precision Integration

Manufacture of the Mirror shells → Raw turning → Electroless plating → Precision Turning → Fine Polishing → Au Coating → Electro-forming → Shell release





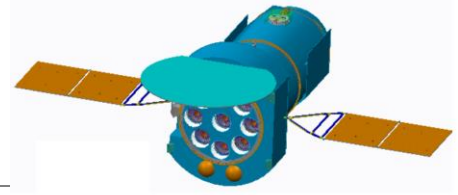


Electroless Plating

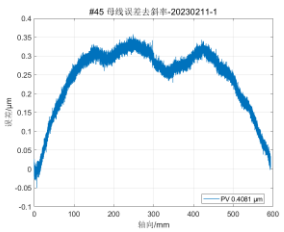
- The surface of the mandrel is plated electroless with nickel-phosphorus alloy.
- The thickness is controlled at ~130 μm, uniformly and without pitting.
- 15 pre-treatment steps before the plating
- 10-15μm/h

Mandrel after the electroless plating

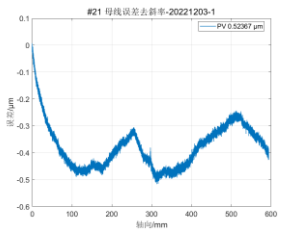
Precision Turning



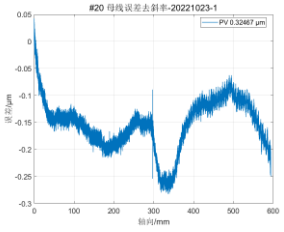
- Using natural diamond turning, the surface accuracy is better than 10″. The roughness is about 5nm RMS after turning.



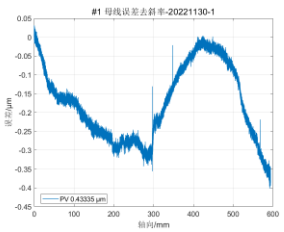
45# 0.43μm



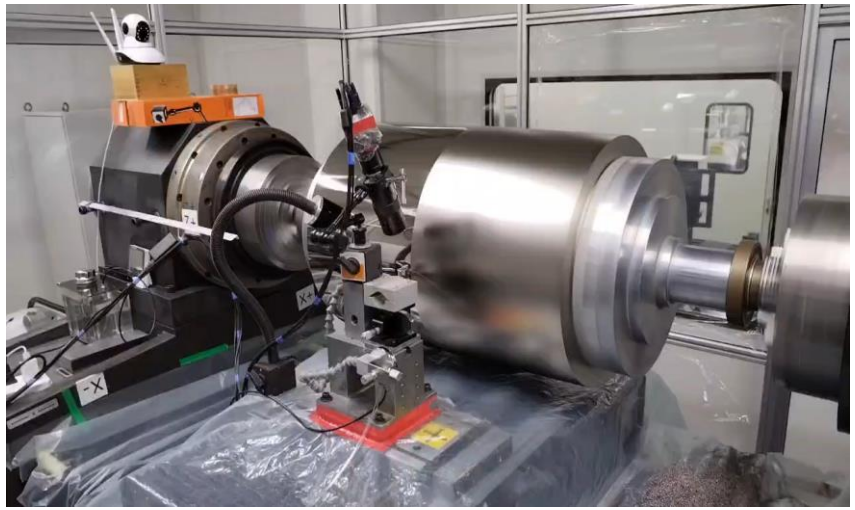
21# 0.52μm

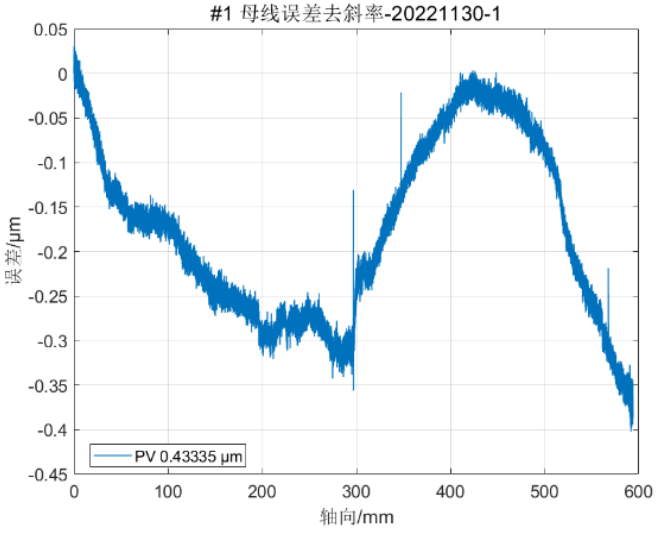


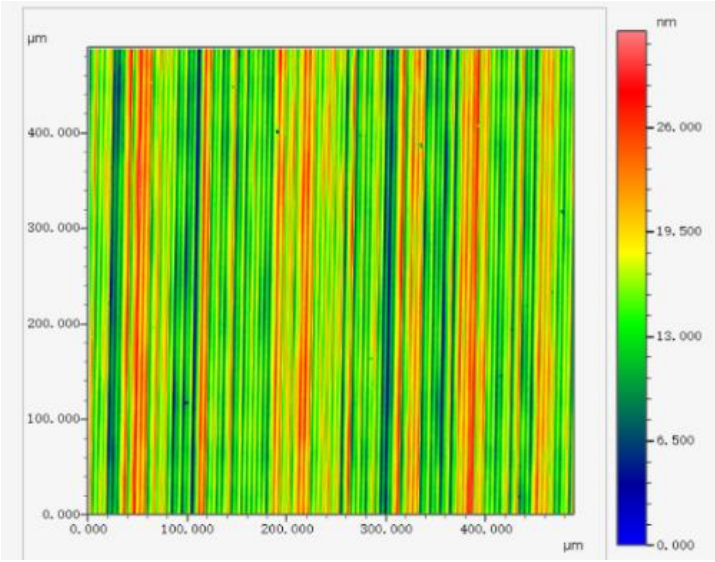
20# 0.32μm



1# 0.4μm

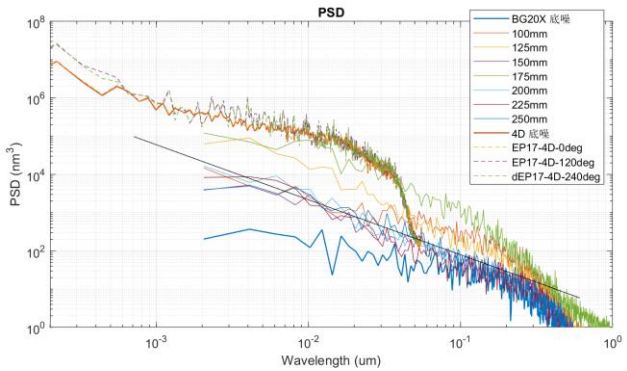


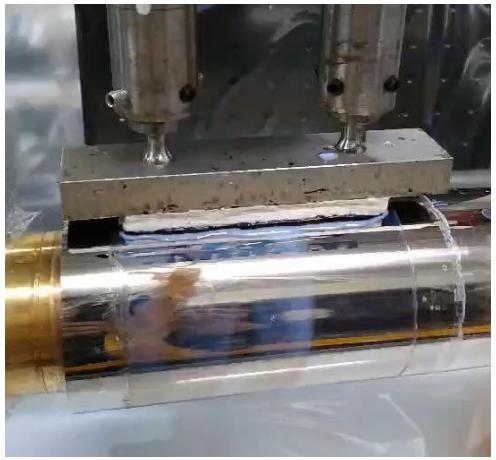


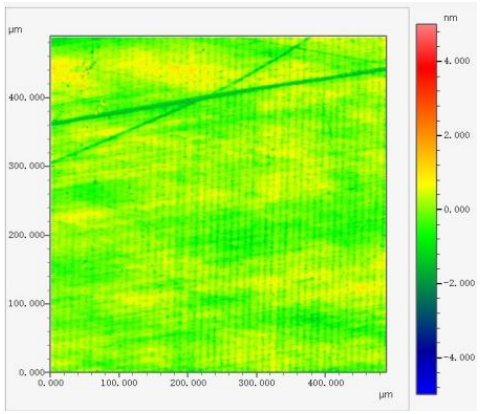


Fine Polishing

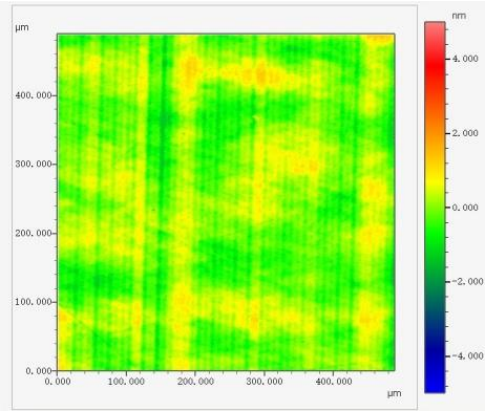
- Use asphalt of optical grade to suppress mid-frequency noise.
- use damping cloth to suppress high-frequency noise.



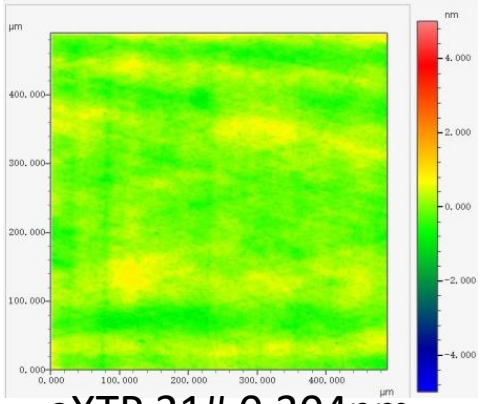




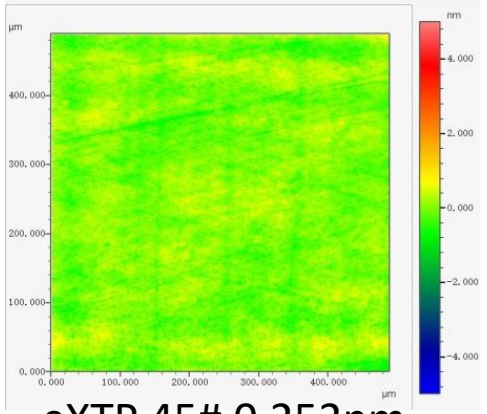
eXTP 1# 0.409nm



eXTP 20# 0.463nm



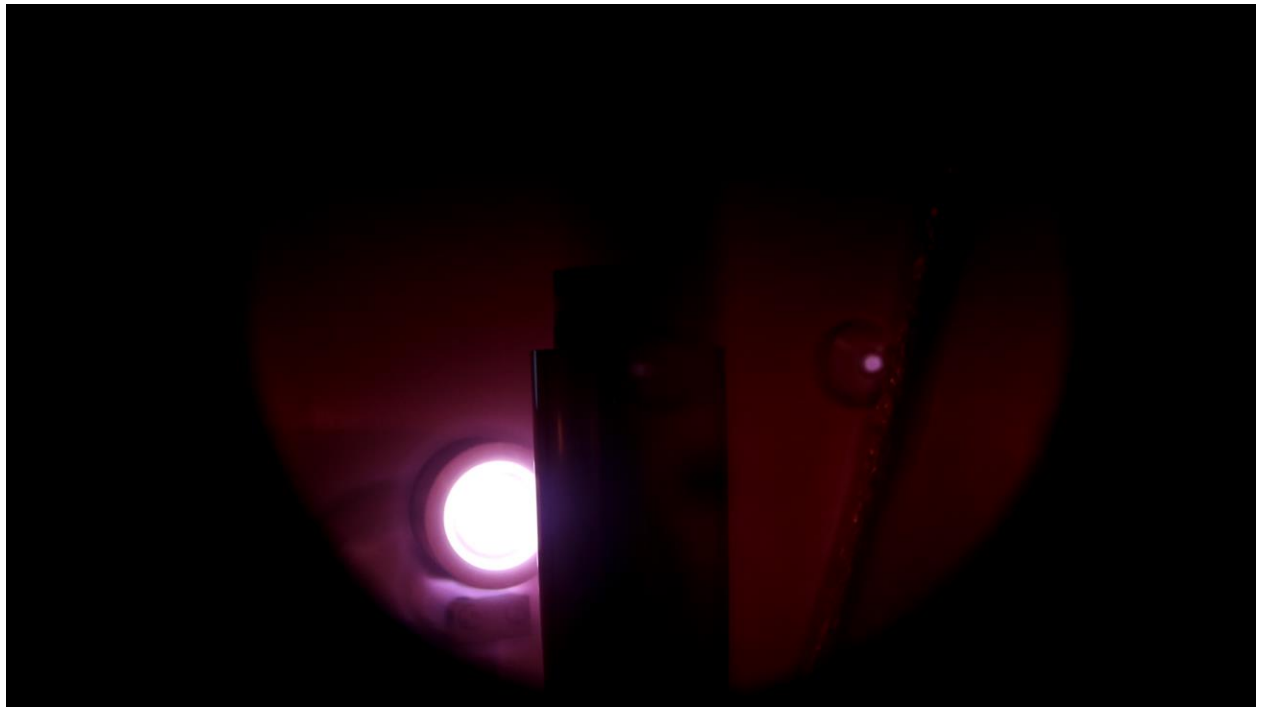
eXTP 21# 0.304nm



eXTP 45# 0.252nm

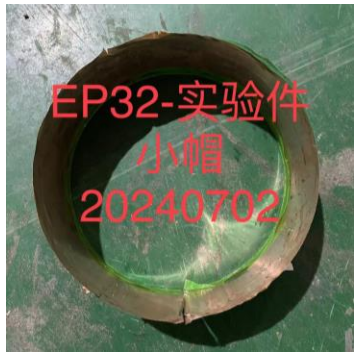
Au Coating with Magnetron Sputtering

100 nm Au coating as the reflective layer of X-ray



Electro-forming

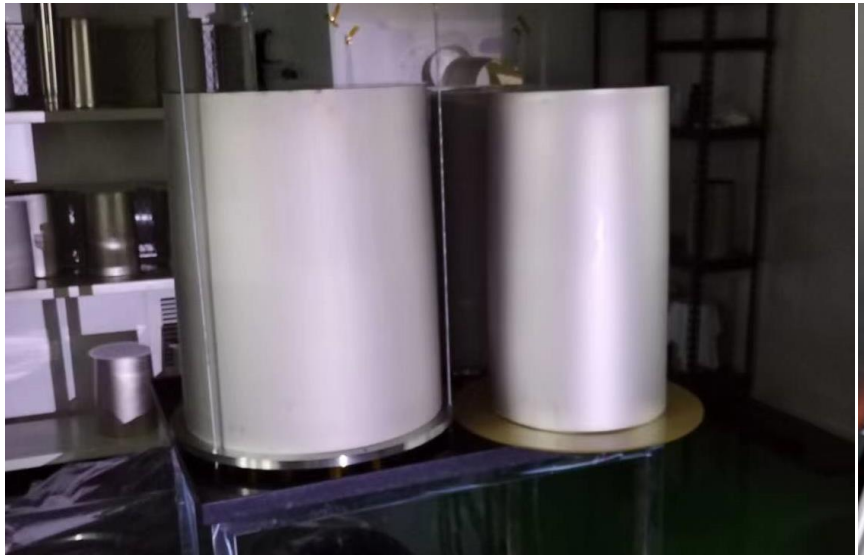
- The 100nm gold layer cannot keep itself from deformation, and a nickel layer needs to be electroformed on its surface.
- The thickness of electroformed nickel on mandrel with different radii is different, which is generally characterized by the thickness-to-radius ratio (t/R ratio).
- the t/R ratio is getting smaller and smaller during the development, which brings us a challenge to try to keep the angular resolution under 30 arcsecs.

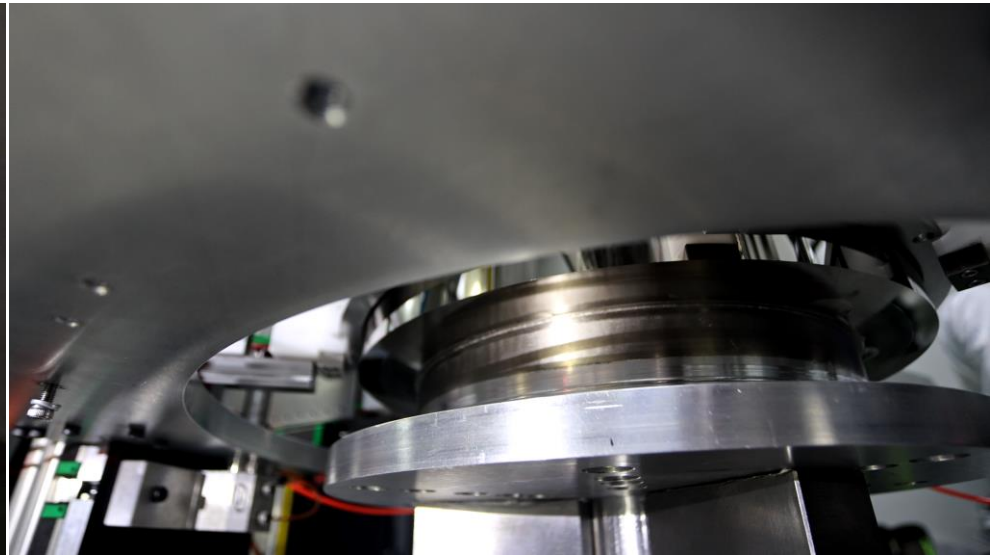


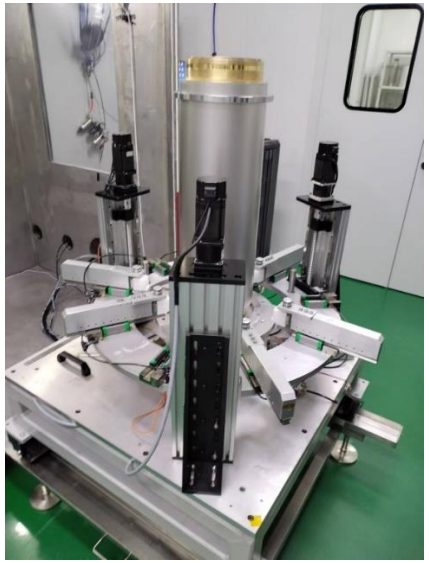
圆形陪片（≈ 0.21 MPa）

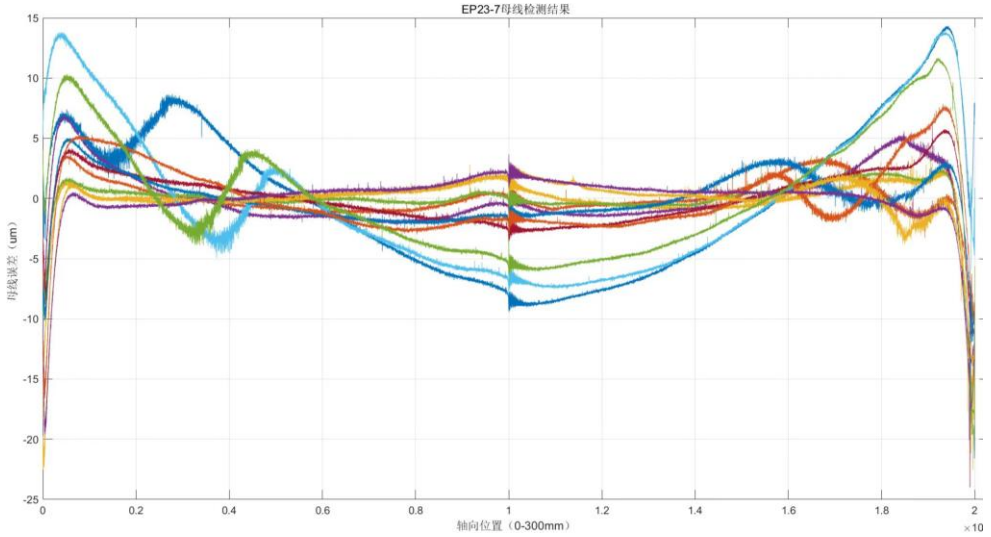
Releasing from the mandrel

- The difference in thermal expansion coefficient between the nickel mirror shell and the aluminum mandrel is used to separate the mirror shell from the mandrel.
- The entire releasing process is carried out in the chamber, and It needs to remain a low humidity environment during the process, by using the high-purity nitrogen.

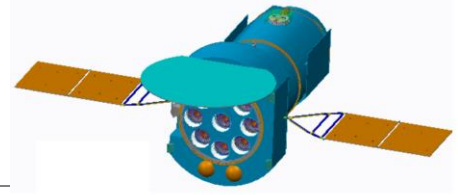




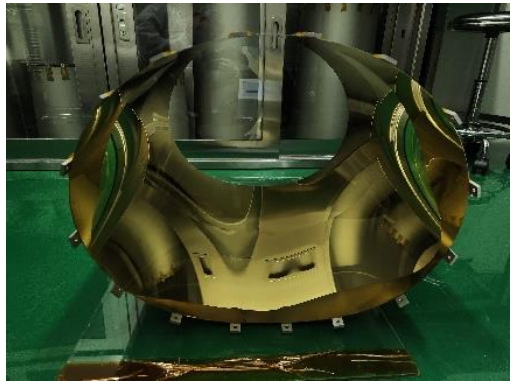


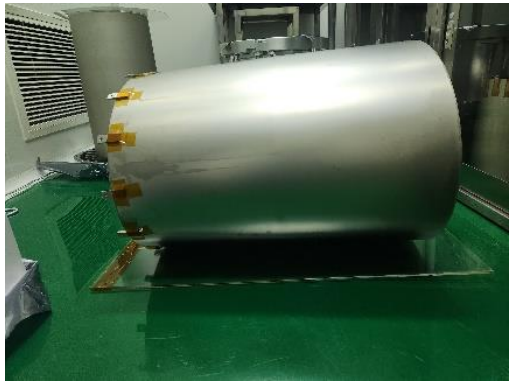


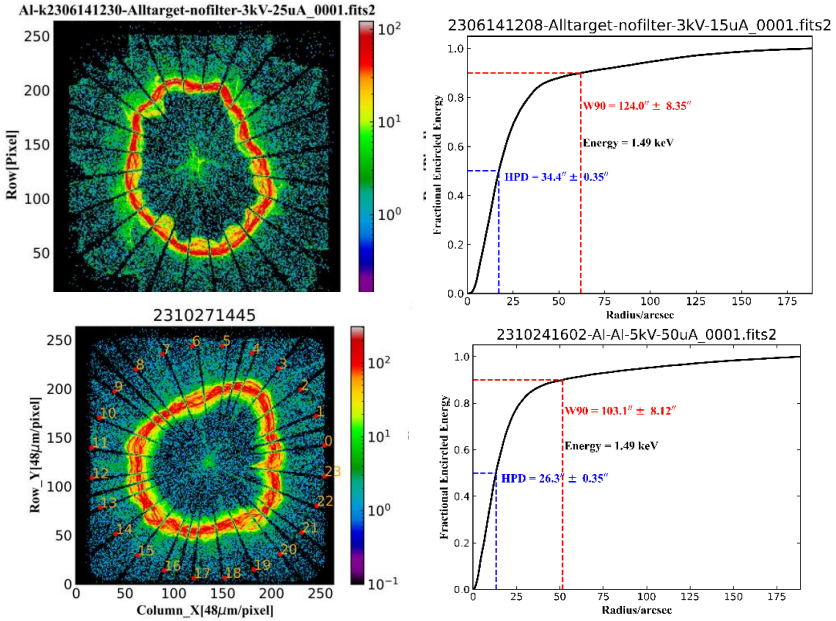
Comparison with Media Lario



- The eXTP focusing mirror has the smallest t/R ratio among all Wolter I-type gold-coated nicel focusing mirror, which is 1.75×10^{-3}, about half smaller than XMM and eROSITA (3×10^{-3}), and smaller than IXPE (2×10^{-3}).
- The eXTP1# shell is the largest layer, with an aperture of 480mm, a height of 600mm, and a wall thickness of 0.41mm (5 sheets of 70g A4 paper). It is the most easily deformed of all eXTP focusing mirror shells.



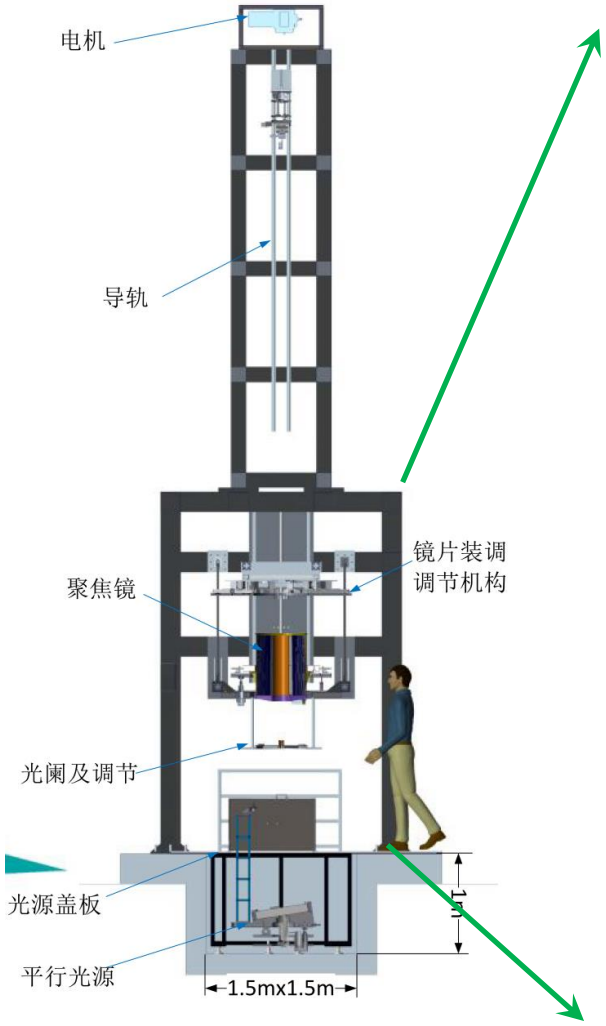


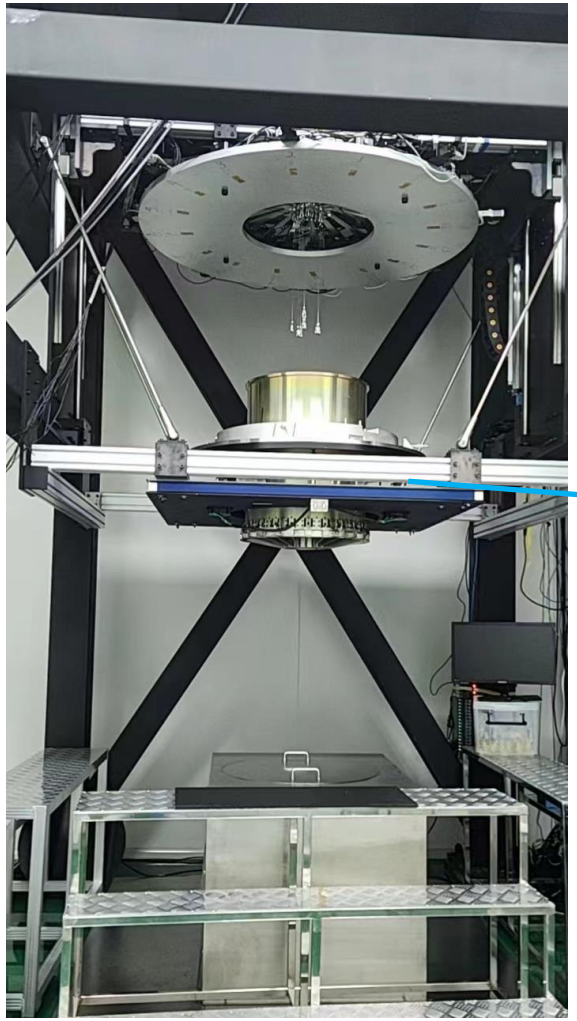


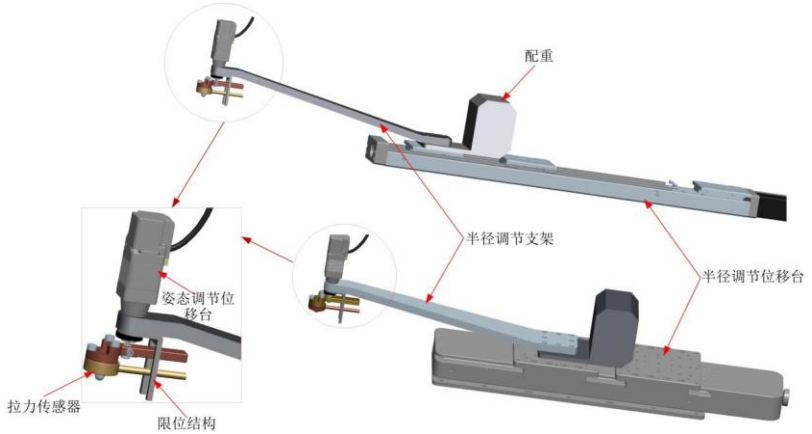
IHEP

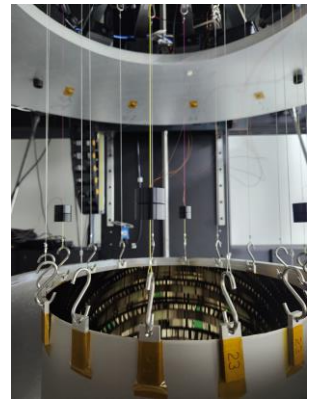
MLS

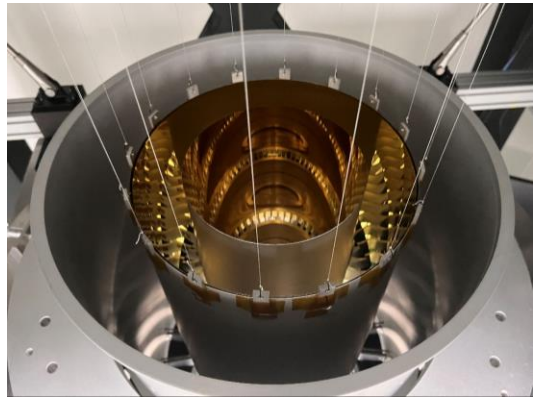
Integration Facility

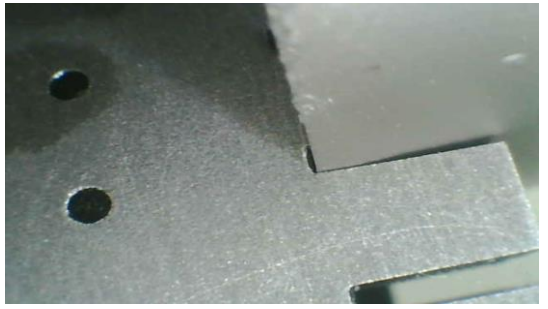






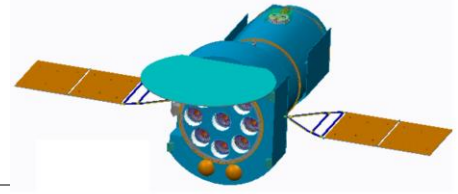






16

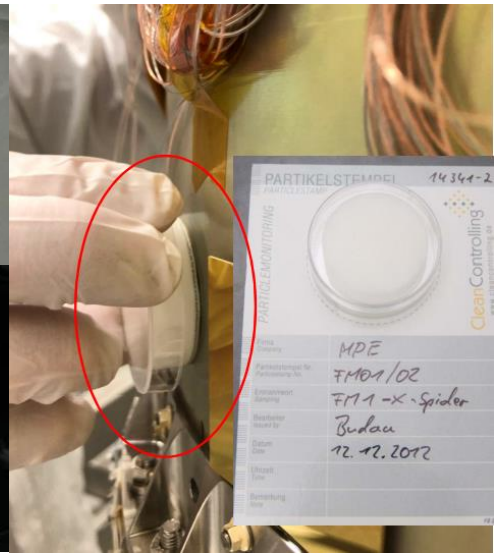
Contamination Control



- Wolter I X-ray focusing mirrors are very sensitive to particulate contamination (complete failure at 10,000 ppm).
- The particulate contamination was about 29.5 ppm from the time the EP satellite replaced the FXT focusing mirror to before the satellite transport to the launch site;
- The particulate contamination during the development of the flight spare focusing mirror for the EP satellite was about 70.9 ppm (FXT-QM from Media Lario was 40.1 ppm);
- During the in-orbit calibration of the EP satellite, the effective area did not decay (0.96~1.01), proving that the contamination controll is effective.

- Particulate Contamination （＜300ppm）

PFO



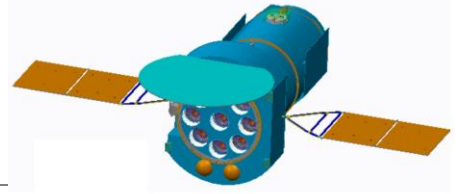
PAC

- Molecular Contamination （＜1×10^{-7} g/cm^2）

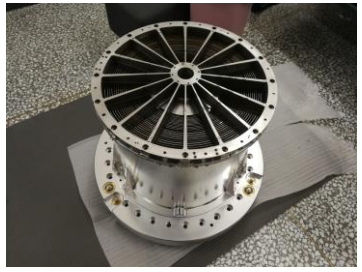
QCM

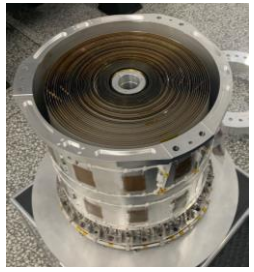
MoC

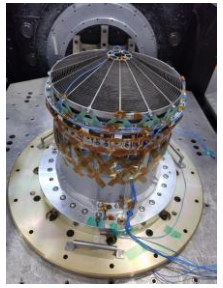
Development of FXT Mirror Module

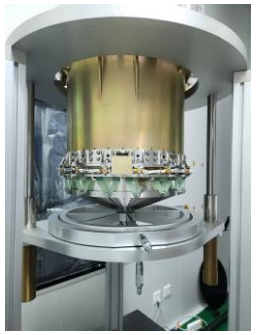


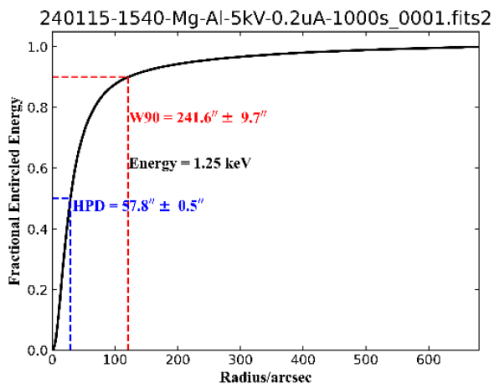
- Structural model (23 mirror shells), get the situation of the vibration test on the SC platform.
- Thermal model (32 mirror shells and 22 dummy), verify the thermal control of the mirror module.
- Qualification model (6 X-ray shells and 48 shells)，the angular resolution is 114 arcsecs in X-ray test.
- Flight spare model (54 X-ray shells), the angular resolution is 58 arcsecs.

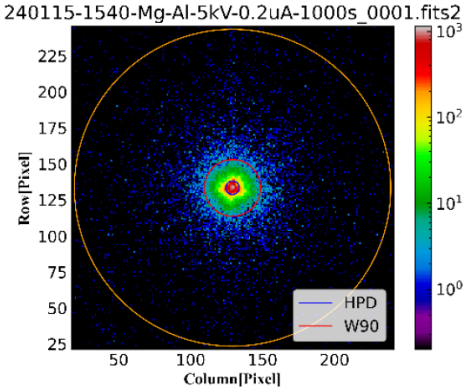




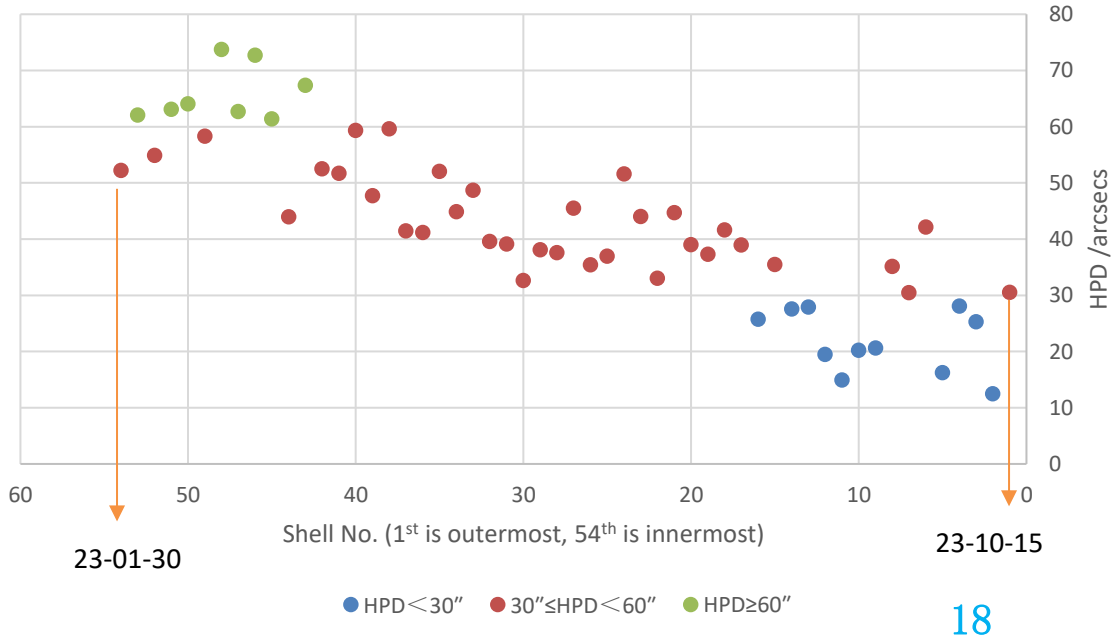






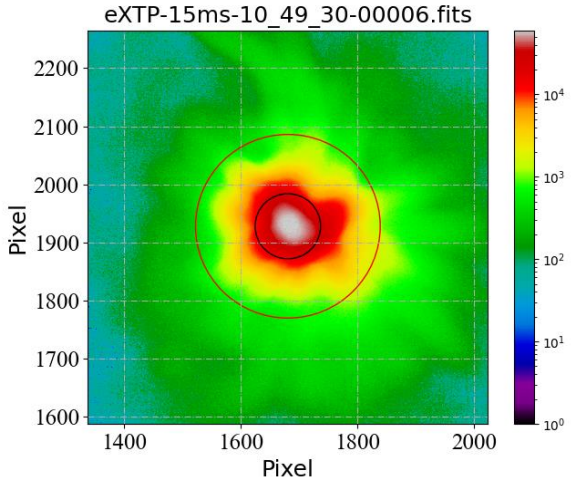


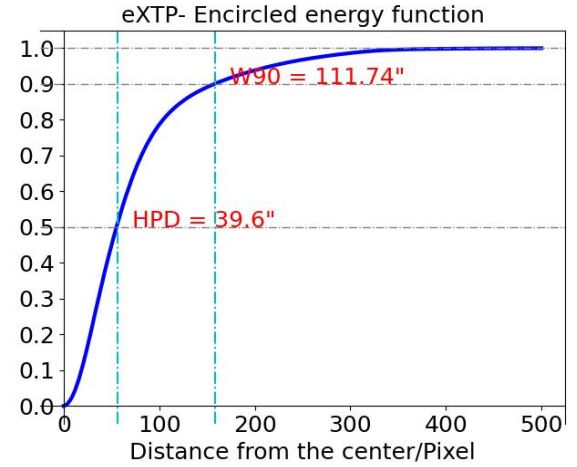
Predicted HPD of FXT Flight Spare MM

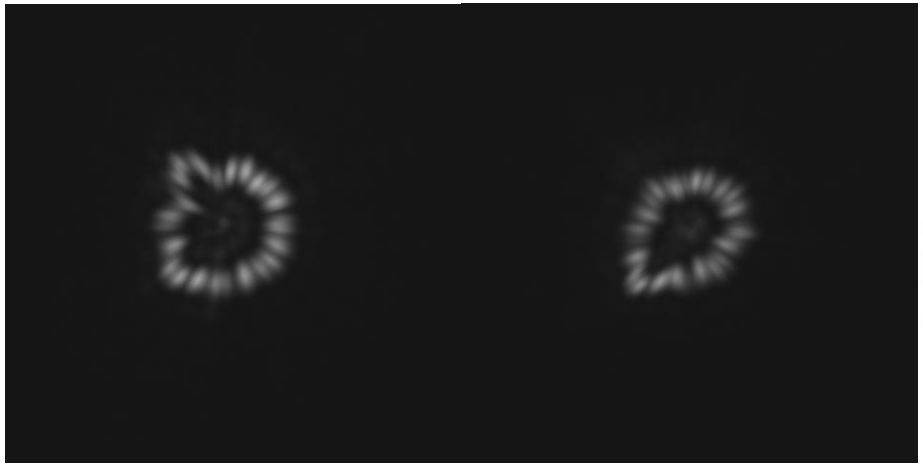


Development of the eXTP Prototype

473nm parallel visible light

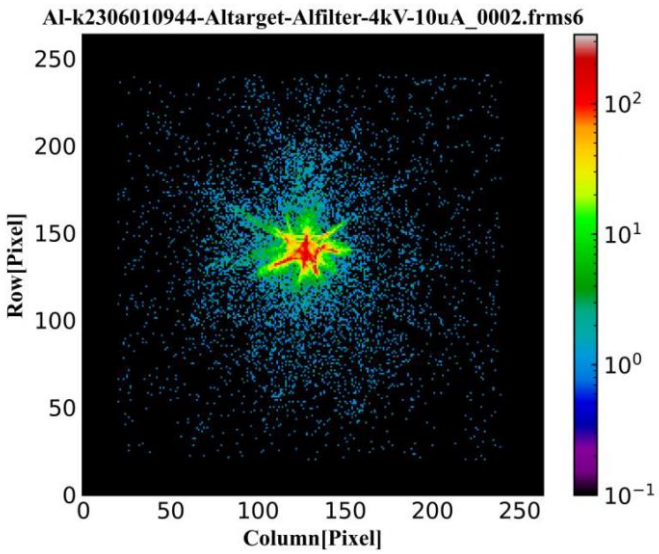


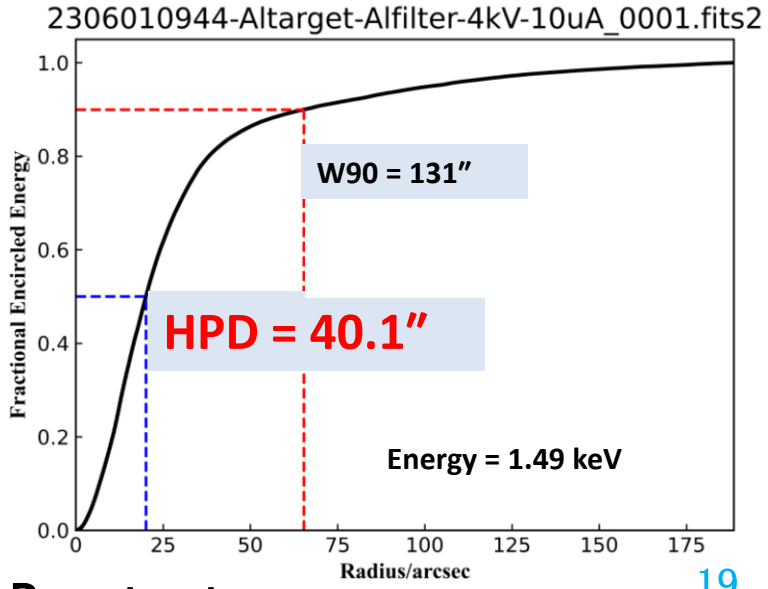




In-focal of shell No.21

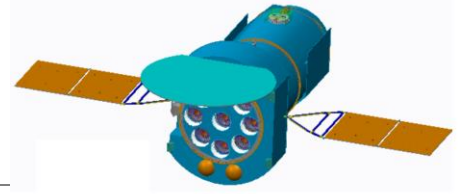
In-focal of shell No.20





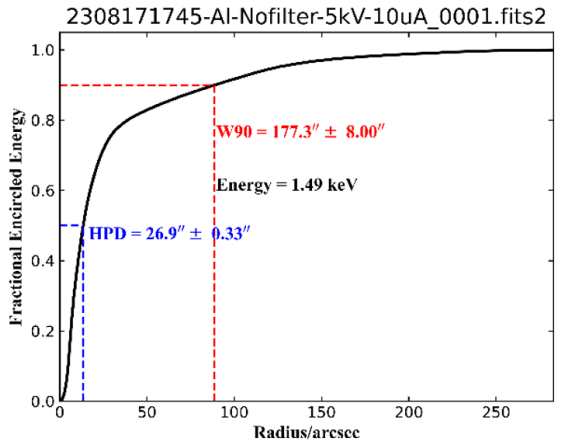
X-Ran test

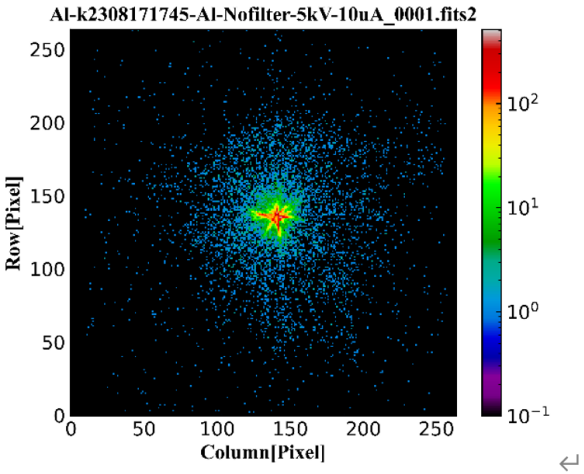
Mirror Shell with Gold free (for PFA)



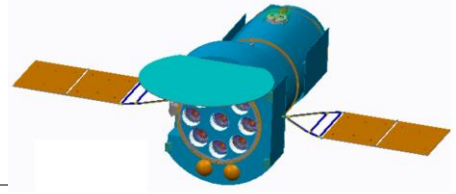
- $HPD_{\mathrm{X-ray}} = \sqrt{HPD_{\mathrm{opt}}^2 - HPD_{\mathrm{dif}}^2}$
- eXTP mirror shell No.21-7，Testing result in visible lights is 33.95″，HPD affected by diffraction is 21.6″， HPD in X-ray test is 26.9″（Predicted value is 26.2″）

Energy/keV	HPD/″	W90/″	Scattering ratio%
C-K：0.28	25.7±0.3	166.1±5.7	4.3
Al-K：1.49	26.9±0.3	177.3±8.0	6.1
Ag-L：2.98	26.9±0.5	185.6±11.6	8.1
Ti-K：4.51	28.8±0.6	204.1±8.3	9.4
Cr-K: 5.4	28.9±0.7	204.8±14.0	8.9
Fe-K：6.04	26.4±0.8	226.1±21.6	13.3

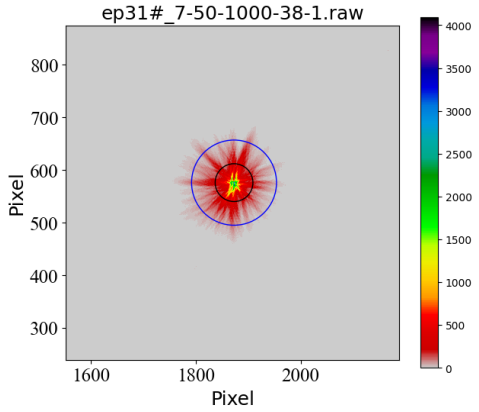


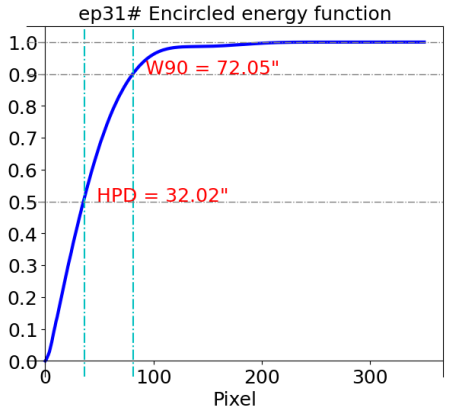


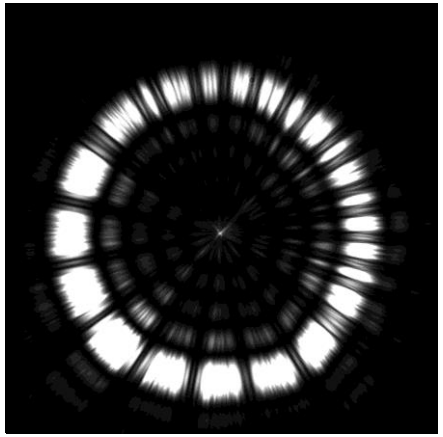
Mirror Shells Produced Recently

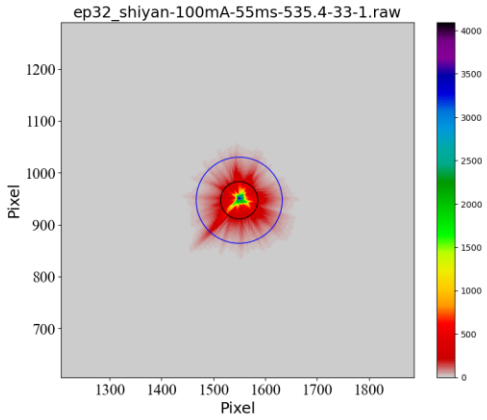


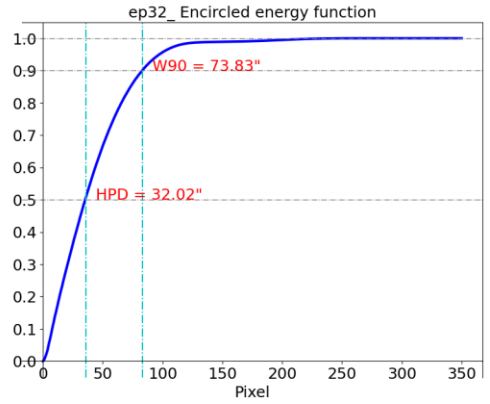
- EP mirror shell No.31, Testing result in visible lights is 32.02”, HPD affected by diffraction is 29.4”, Predicted value is ab. 10”.
- EP mirror shell No.32, Testing result in visible lights is 32.02”, HPD affected by diffraction is 30.2”, Predicted value is ab. 10”.

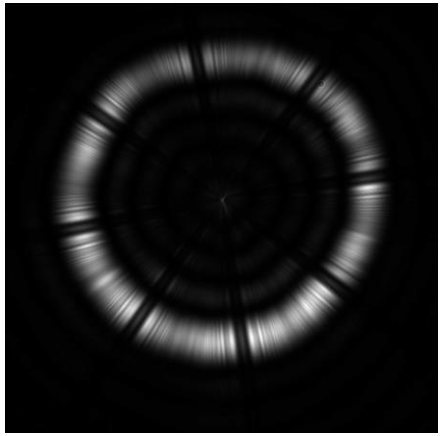




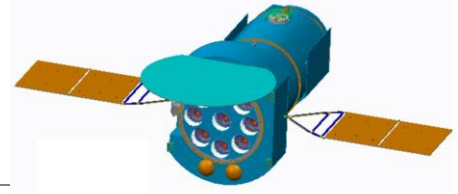








Conclusion and Outlook



- With the support of eXTP major background study and the development of EP-FXT, a clean laboratory for focusing mirrors has been established, with a total of more than 20 sets of facilities and testing equipment.
- The task of achieving an angular resolution of focusing mirror shells better than 30″ and the mirror module better than 60″ has been completed successfully.
- We will continue to explore how to reduce the weight of focusing mirrors while improving angular resolution, for related topics such as CATCH and millisecond pulsars detection.