Imaging X-ray Polarimetry Explorer (IXPE) Mirror Module Assembly

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IXPE addresses key scientific objectives

• Opens a new window on the universe — imaging (30") X-ray polarimetry
  – The science driver that advances and impacts high-energy astrophysics
  – Increases information space and lifts modeling degeneracies

• Addresses key questions, providing new scientific results and constraints that trace back to the Astrophysics Roadmap and the Decadal Survey
  – What is the spin of a black hole?
  – What are the geometry and magnetic-field strength in magnetars?
  – Was our Galactic Center an Active Galactic Nucleus in the recent past?
  – What is the magnetic field structure in synchrotron X-ray sources?
  – What are the geometries and origins of X-rays from pulsars (isolated and accreting)?

• Provides powerful and unique capabilities
  – Reduces integration time by a factor of 100 over our OSO-8 experiment
  – Simultaneously provides imaging, energy, timing, and polarization data
  – Devoid of instrument systematic effects at less than a fraction of a percent
  – Meaningful polarization measurements for a large number of sources of different classes, as evidenced by our Design Reference Mission
Mission Design and Operations Concept are Straightforward

- NASA Explorer Mission, cost capped at $175M (FY15)
- Class D Mission managed by MSFC
- XL launch from Kwajalein
- 540-km circular orbit at 0° inclination
- 2 year baseline mission, 1 year SEO
- PI: Martin Weisskopf, MSFC
- Launch ready by end of 2021

Institutional Roles and Responsibilities are Clearly Defined

- NASA Marshall Space Flight Center
  - PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving
- LAPs
  - INAF
  - INFN
  - Polarization-sensitive imaging detector systems
- LASP
  - Mission operations
- ROMA
  - University
  - Scientific theory
- Stanford
- McGill
  - Science Working Group Co-Chair
- MIT
  - Student collaboration

Mission Timeline:
- Stage 1 Ignition: T = 60.05 (min sec), h = 12.2 km
- Stage 1 Burnout: T = 48.05 (min sec), h = 12.4 km
- Stage 2 Ignition: T = 97.56 (min sec), h = 512.4 km
- Stage 2 Burnout: T = 102.56 (min sec), h = 124.3 km
- Stage 3 Ignition: T = 110.23 (min sec), h = 439.8 km
- Payload Fairing Jettison: T = 110.56 (min sec), h = 110.3 km
- Stage 2/3 Variable Length Coax
- Stage 3 Burnout: T = 112.76 (min sec), h = 350.5 km
- Payload Deployment
- Orbital Plane
- IXPE Solar Array
- IXPE Payload
- IXPE Focal Plane
Measures spatial, spectral, timing, and polarization state of X-rays from a selection of known targets (~50)

- Set of three mirror module assemblies focus x rays on to three corresponding focal plane detector units.
- Mirror modules provide imaging and background reduction
- Detectors provide position, energy and polarization information, photon by photon, plus time stamp
**IXPE Deployment**

Mast Deployment – used successfully on multiple missions

**IXPE Boom Stowed and Deployed with thermal sock**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>4.9 kg</td>
</tr>
<tr>
<td>Length</td>
<td>3.64 m</td>
</tr>
<tr>
<td>Deployment repeatability</td>
<td>Length: 0.2 mm, Translation: 0.07 mm, Twist: 0.27°</td>
</tr>
</tbody>
</table>
MSFC will fabricate:

- **24 mandrels**
- **1 engineering unit** consisting of 6 shells, 3 mass simulators, 2 external thermal shields, 1 support spider /combs & 1 end capture spider
- **96-102 Nickel – Cobalt (not Ir coated) very thin shells**
- **4 flight units (3 + spare) with w/ 24 nested shells, 2 external thermal shields, spider /combs & end capture spider**

### MMA Optical Requirements

<table>
<thead>
<tr>
<th>MMA</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMA-7</td>
<td>The combined effective area of all three MMAs with their thermal shields shall be greater than 589 cm$^2$ at 2.3 keV, and greater than 686 cm$^2$ at 4.5 keV.</td>
</tr>
<tr>
<td>MMA-9</td>
<td>The focal length of each MMA shall be 4000 +/- 1 mm, measured from the node of the optical assembly.</td>
</tr>
<tr>
<td>MMA-8</td>
<td>The HPD of each mirror module assembly shall be no greater than 26 arcseconds at 2.3 keV and 4.5 keV on axis.</td>
</tr>
</tbody>
</table>
Replicated Optics Manufacturing at MSFC

1. CNC machine, mandrel formation from Al Bar
2. Chemical clean and activation & Electroless Nickel (EN) plate
3. Precision turn to sub-micron figure accuracy
4. Polish and superpolish to 3-4 Å finish
5. Metrology – repeat Step 4 until surface finish met
6. Ultrasonic clean & passivation to remove surface contaminants
7. Electroform nickel shell onto mandrel
8. Separate optic from mandrel – reuse mandrel for next shell
9. Test module

Currently contracted out
## Mandrel Error Budget Allocations

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SENSITIVITY</th>
<th>ALLOWANCE</th>
<th>HPD (ARCSEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIRCULARITY (OUT OF ROUNDNESS)</td>
<td>100 ARCSEC HPD / MM</td>
<td>0.0125 MM (0.0005&quot;)</td>
<td>1.2</td>
</tr>
<tr>
<td>P-H SLOPE ERROR</td>
<td>0.6 ARCSEC HPD / MRAD</td>
<td>10 MRAD</td>
<td>5.8</td>
</tr>
<tr>
<td>INTERSECTION SHIFT</td>
<td>2.5 ARCSEC HPD / MM</td>
<td>0.5 MM (0.020&quot;)</td>
<td>1.25</td>
</tr>
<tr>
<td>RADIUS ERROR</td>
<td>73 ARCSEC HPD / MM</td>
<td>0.025 MM (0.001&quot;)</td>
<td>1.8</td>
</tr>
<tr>
<td>AXIAL FIGURE PROFILE</td>
<td>1 ARCSEC / ARCSEC</td>
<td>10 ARCSEC</td>
<td>10.0</td>
</tr>
<tr>
<td>BOW (PARABOLA)</td>
<td>2 ARCSEC / MICRON (NOT LINEAR)</td>
<td>1.5 MICRON</td>
<td>3.0</td>
</tr>
<tr>
<td>TOTAL (RSS)</td>
<td></td>
<td></td>
<td>12.2</td>
</tr>
</tbody>
</table>

These specifications have been routinely achieved in previous programs.

Based on past experience with similar mandrels:

- **ART-XC** (25 arcsec HPD modules from 15 arcsec mandrels)
- **FOXSI** (20 arcsec modules from 10 arcsec mandrels)
- **HERO** (25 arcsec from 8 arcsec mandrels but with no alignment system)
IXPE EDU Status

Engineering Development Unit consist of the inner 3 (M1-M3) and outer 3 (M22-M24) shells and mass simulators for the 18 shells in between. This will be x-ray tested, vibrated at launch qualification levels and x-ray tested again to verify the shells remain bonded and aligned.

Currently M1-M3 and M22 are in the polishing cycle and M23 and M24 are in the diamond turning process.

Top panels show model of MMA structure and mirror shells. Bottom panels show a typical mode excited during launch (displacements magnified for clarity).
IXPE Alignment System

ART-XC shells supported from 3 points during the alignment and bonding process.

IXPE shells are thinner than ART and will be gravity off-loaded during the alignment and bonding process.
### MSFC X-ray Optics Heritage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FOXSI -1 (-2 &amp; 3)</th>
<th>ART-XC</th>
<th>IXPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mirror modules</td>
<td>7</td>
<td>7 (plus 1 spare)</td>
<td>3 (plus 1 spare)</td>
</tr>
<tr>
<td>Number of shells per mirror module</td>
<td>7 (10 for selected modules)</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>Focal length</td>
<td>2000 mm</td>
<td>2700 mm</td>
<td>4000 mm</td>
</tr>
<tr>
<td>Total shell length</td>
<td>600 mm</td>
<td>580 mm</td>
<td>600 mm</td>
</tr>
<tr>
<td>Range of shell diameters</td>
<td>76 – 104 mm</td>
<td>50 – 150 mm</td>
<td>162 – 272 mm</td>
</tr>
<tr>
<td>Range of shell thicknesses</td>
<td>0.25 mm</td>
<td>0.25 - 0.35 mm</td>
<td>0.18 – 0.26 mm</td>
</tr>
<tr>
<td>Shell material</td>
<td>Electroformed nickel–cobalt alloy Coating: &gt; 30 nm of iridium (&gt; 90% bulk density)</td>
<td>Electroformed nickel–cobalt alloy Coating: &gt; 10 nm of iridium (&gt; 90% bulk density)</td>
<td>Electroformed nickel–cobalt alloy</td>
</tr>
<tr>
<td>Effective area per mirror module</td>
<td>150 cm² (200) at 8 keV, 14 cm² (40) at 15 keV</td>
<td>≥ 65 cm² at 8 keV (on axis)</td>
<td>197 cm² (at 2.3 keV); &gt; 230 cm² (at 3–6 keV)</td>
</tr>
<tr>
<td>Angular resolution (HPD)</td>
<td>10 arcsec</td>
<td>25 arcsec HPD on axis (measured)</td>
<td>≤ 25 arcsec HPD on axis</td>
</tr>
</tbody>
</table>
FOXSI Free Flyer Science Objectives

- FOXSI Free Flyer currently in Phase A study
- FOXSI Free Flyer addresses the fundamental processes of impulsive energy release and particle acceleration in the solar corona.
- FOXSI will achieve this through focused hard X-ray imaging with **100 times better sensitivity and dynamic range** than previous instruments (e.g. RHESSI).
- FOXSI will observe emission from energetic electrons:
  - directly in the acceleration site in the corona such as near flare reconnection sites or CME shocks,
  - as they travel through the corona,
  - where they are stopped in the chromosphere, and
  - as they escape into interplanetary space.
• If selected MSFC will provide 2 flight modules + 1 spare module, fully calibrated, each with 15 or 20 shells
• X-ray optics is a Tier 1 for Scientific Research at MSFC
• FOXSI science requires high-resolution hard x-ray optics, niche area for MSFC – no domestic competitors
• Sub-Orbital Development (significant)
  • FOXSI rocket flights (Nov. 2012, Dec. 2014), FOXSI-3 on schedule
  • HERO(ES) balloon flight (May, 2001 and Sept. 2013)
• Orbital Development
  • ART-XC fabricated and delivered by MSFC
• IXPE SMEX under development