IXPE
Imaging X-Ray Polarimetry Explorer

Ground Calibration of the Imaging X-ray Polarimetry Explorer (IXPE)

Wayne Baumgartner
IXPE Calibration Scientist
NASA/MSFC

Fabio Muleri
IXPE Instrument Calibration Lead
INAF-IAPS

Brain Ramsey, Jeff Kolodziejczak, Nicholas Thomas, Martin Weisskopf, Steve Bongiorno, Allyn Tennant, Steve O'Dell
NASA/MSFC

Sergio Fabiani, Luca Baldini, Simone Castellano, Enrico Costa, Alessandro Di Marco, Fabio La Monaca, Simone Maldera, Alberto Manfreda, Fabio Muleri, John Rankin, Paolo Soffitta, Carmelo Sgrò, Fei Xie
Italian Instrument Team (I2T): IAPS/INFN

30 April 2021

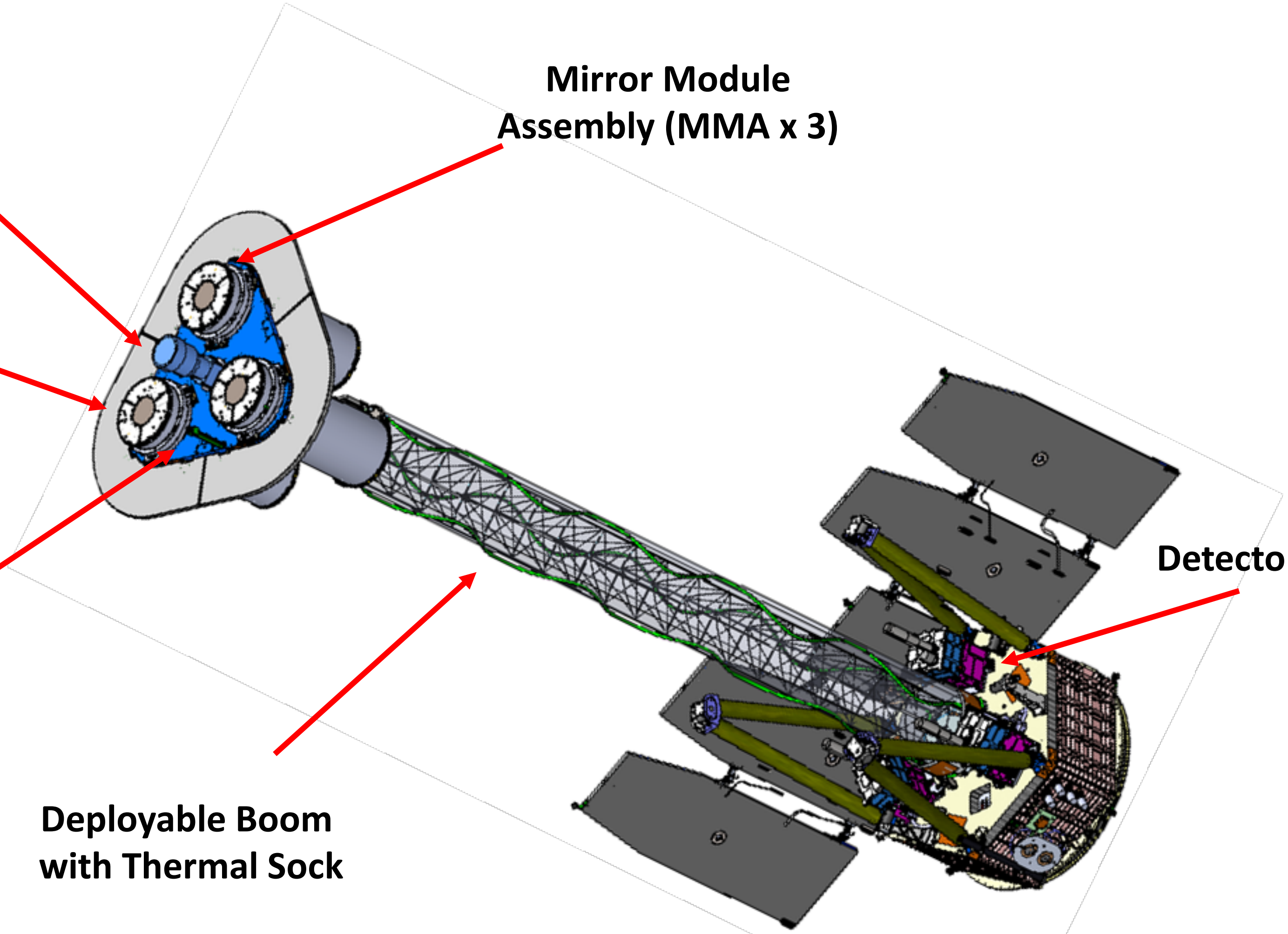
The IXPE Team

Institution	Role
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
ASI (agenzia spaziale italiana)	Detector system funding, ground station
Ball	Spacecraft, payload structure, payload, observatory I&T
IAPS, INAF (Istituto Nazionale di Astrofisica – National Institute for Astrophysics), INFN, OAC, OHB Italia	Polarization-sensitive imaging detector systems
CU / LASP	Mission operations
Roma Tre Università degli Studi, Stanford University	Scientific theory
Nagoya University	Thermal Shields
Massachusetts Institute of Technology	Co-Investigator

Science Advisory Team

SAT currently comprises > 90 scientists from 12 countries

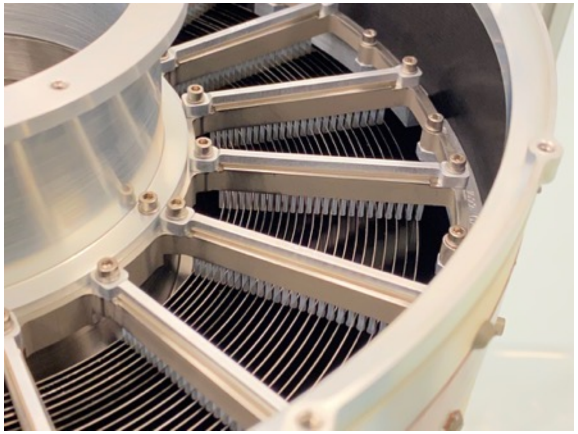
Deployed Configuration

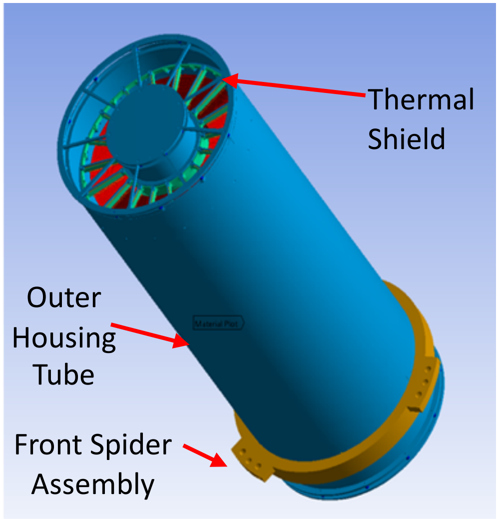


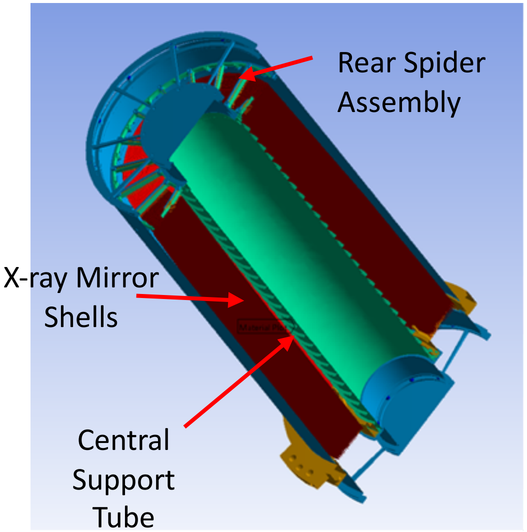
Launch date: Late November, 2021

The Mirror Module Assemblies (MMAs)

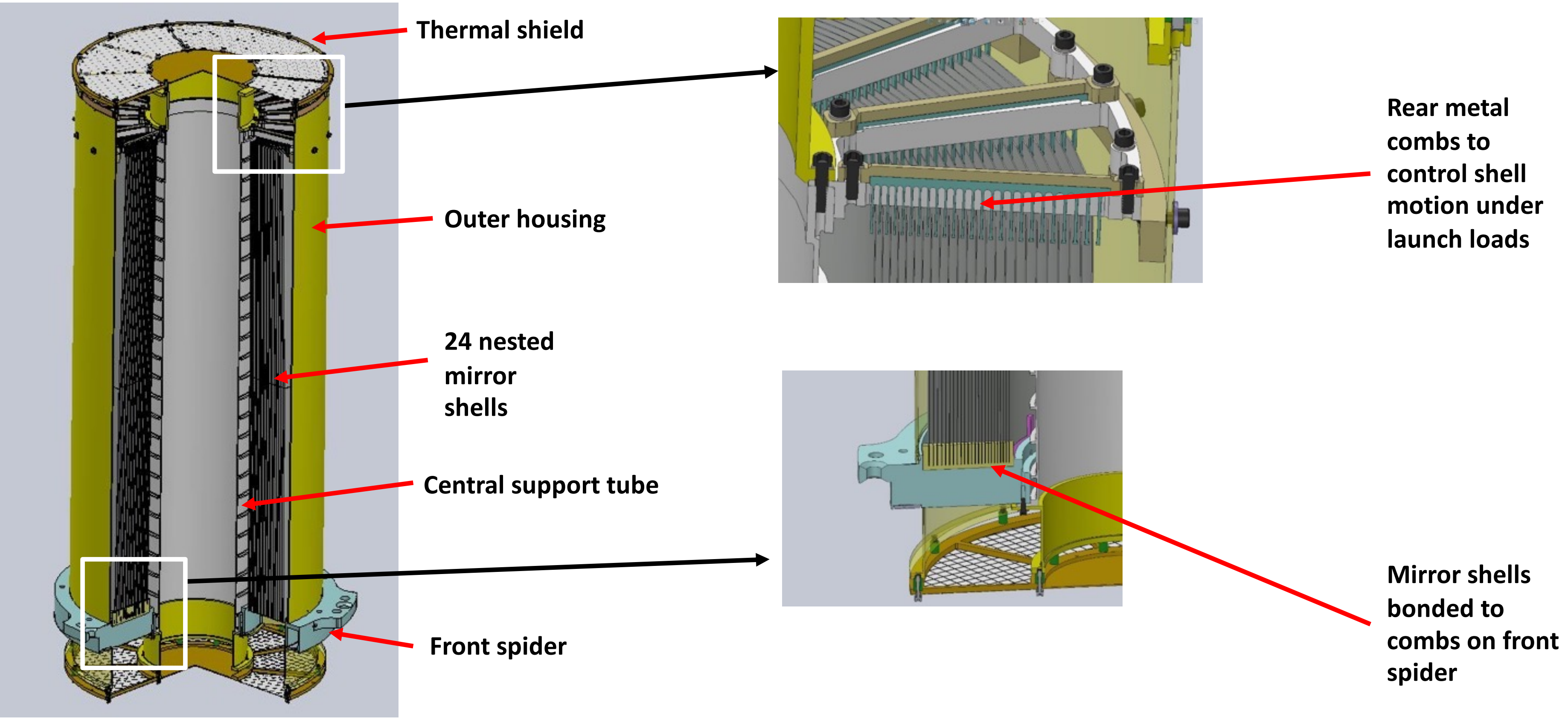
Parameter	Value
Number of mirror modules	3
Number of shells per mirror module	24
MMA Mass	93 kg (three together)
Focal length	4 m
Total shell length	600 mm
Range of shell diameters	162–272 mm
Range of shell thicknesses	0.16–0.25 mm
Shell material	Electroformed nickel–cobalt alloy
Effective area per mirror module	163 cm^2 (@ 2.3 keV); >192 cm^2 (3–6 keV)
Angular resolution (HPD)	~25 arcsec (MMA alone)
Field of view (detector limited)	12.9 arcmin square



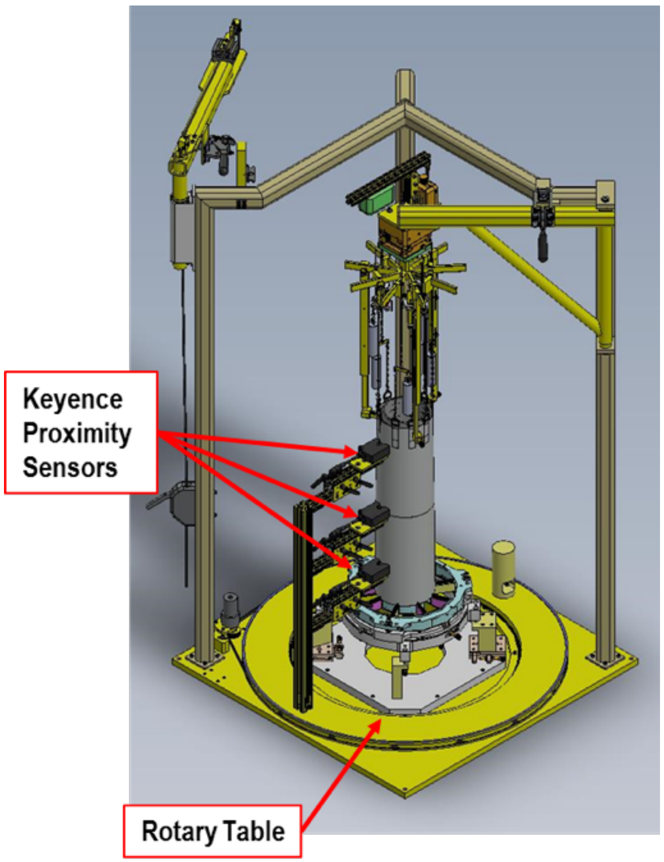




Mirror Module Design

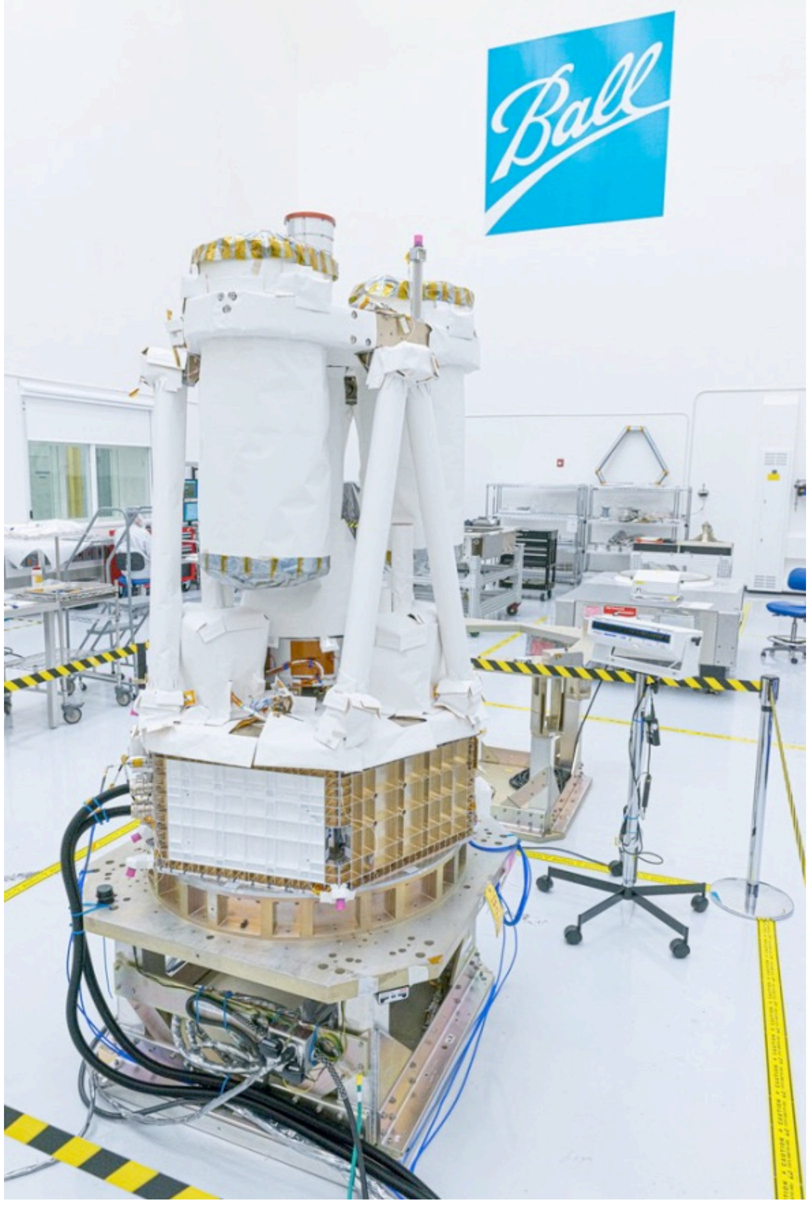


Mirror Module Assembly Process

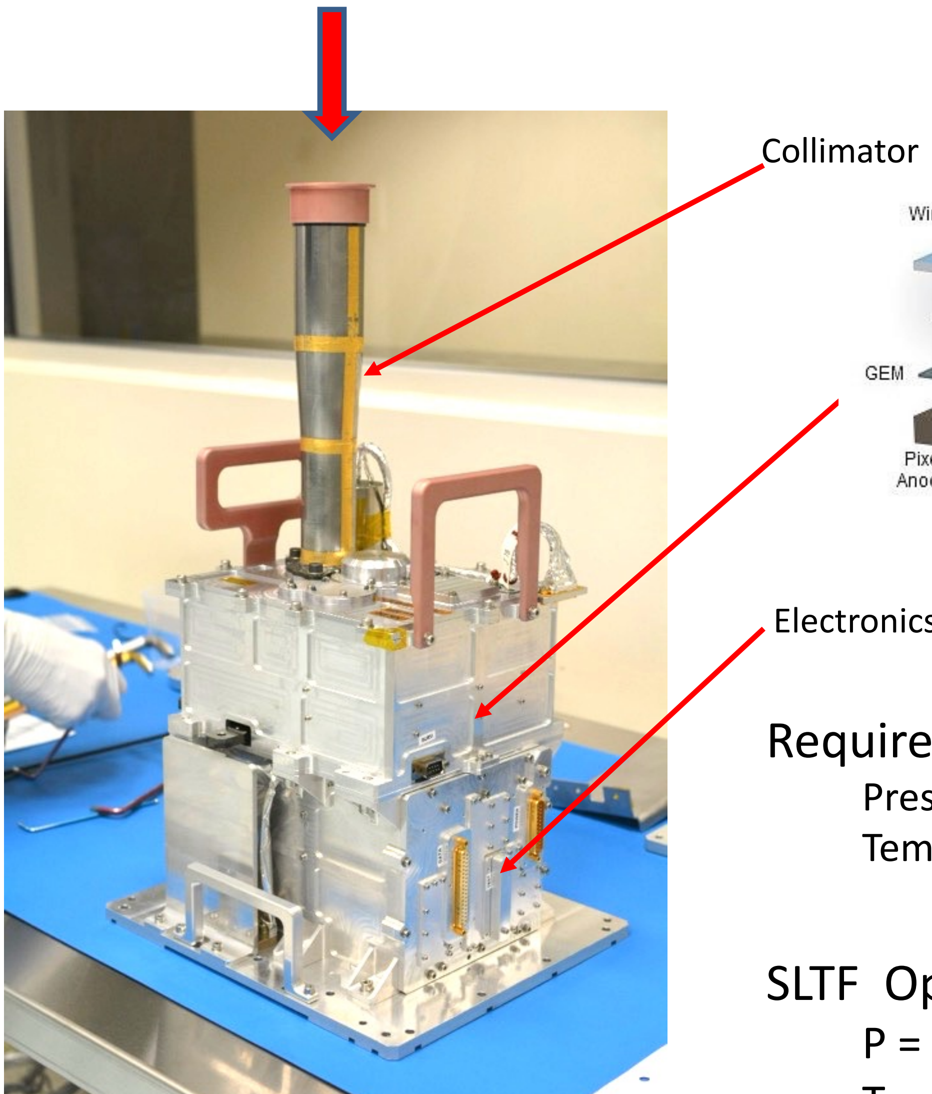


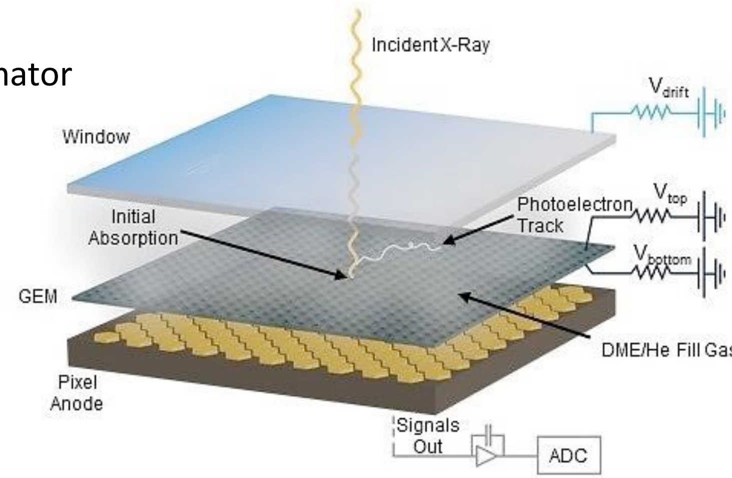
- The assembly system holds each successive shell by hanging via a set of three support wires, which then can be adjusted by piezo actuators, and six tuned mass off-loaders
- The rotary table and Keyence sensors rotate together, under computer control, and the sensors measure radial displacements of the mirror external surface
- Software takes the displacement data as a function of rotation angle and fits various curves (and calculate various performance parameters) to aid in the alignment process

MMAs Mounted in Observatory



Detector Unit (DU)





Gas Pixel Detector

Required DU Operating conditions:

Pressure: < $1x10^{-4}$ Torr

Temperature : 6 < T < 28 C

Baseplate temperature

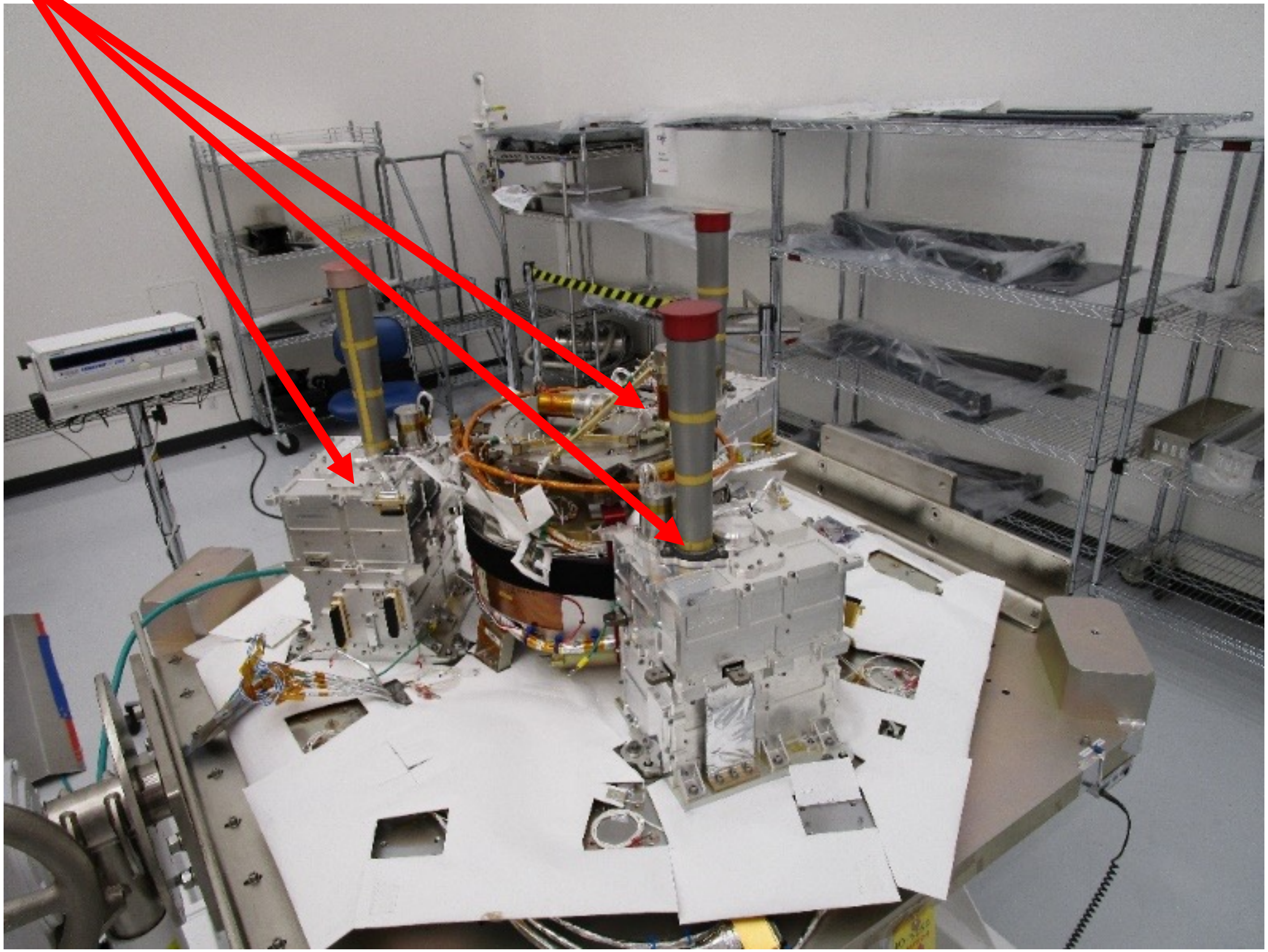
SLTF Operating Conditions:

P = $8x10^{-6}$ Torr

T = 12.5 C

The Detectors

- The Detectors mounted to the spacecraft top deck at Ball Aerospace

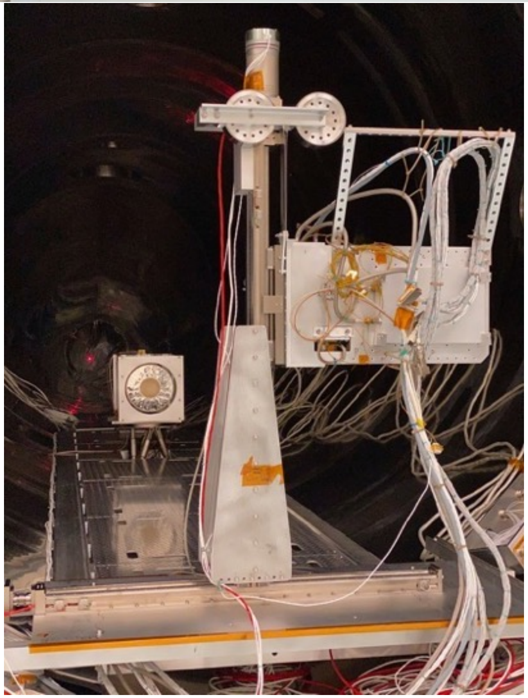


MSFC GROUND CALIBRATION OVERVIEW

- **X-ray Calibration for IXPE was in three parts:**
  1. Instrument (detectors) in Italy
  2. MMA (optics) at MSFC
  3. Telescope (Flight Optic + Flight Detector) at MSFC

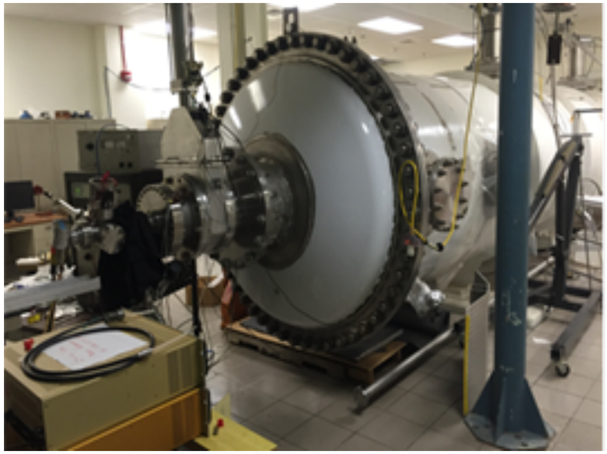
- **Calibration timeframe:**
  1. Instrument calibration in Italy [2020]
  2. Calibration checkout at MSFC (calibration of engineering units)
  3. MMA Optics calibration of MMA 1-3 [16 Jul – 28 Aug 2020]
  4. Telescope calibration (MMA 4 & DU-FM1) [30 Nov - 27 Jan, 2021]

- **Data Taken :**
- ~ 1000 measurements taken for 4 MMAs
- ~ 150 measurements for Telescope



Test configuration: Optic & Detectors in SLTF chamber

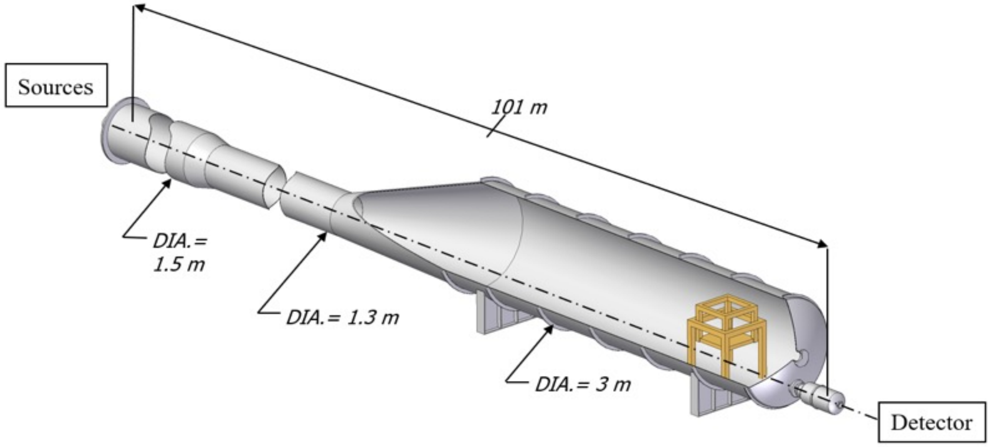
Stray Light Test Facility

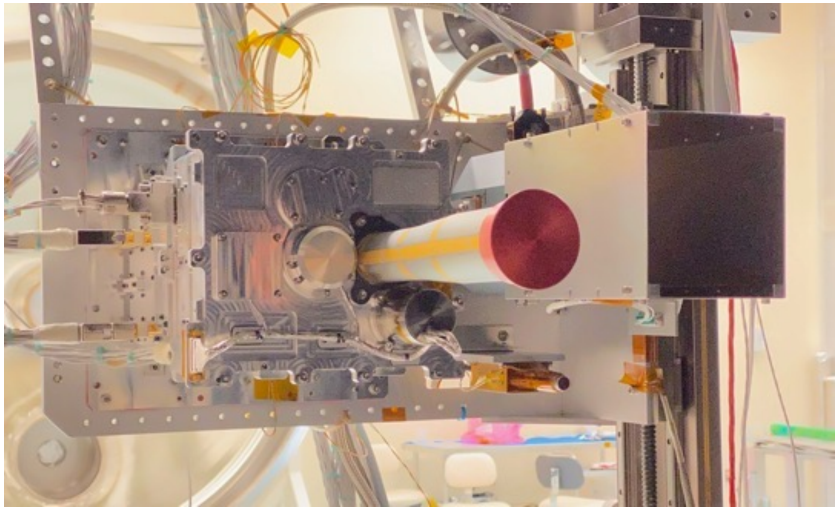


X-ray source end

Beam tube

Instrument Chamber

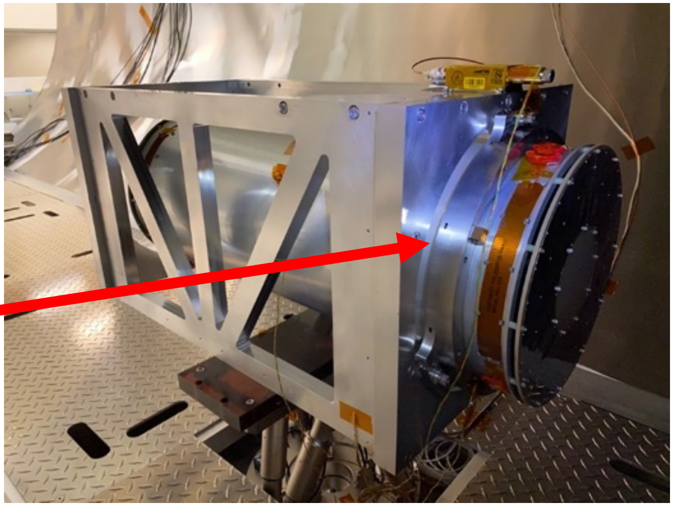


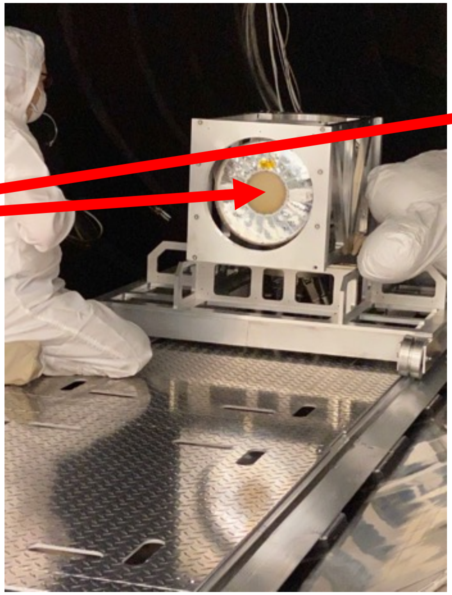


DU-EM on SLTF Detector Plate
with CCD & SDD detectors

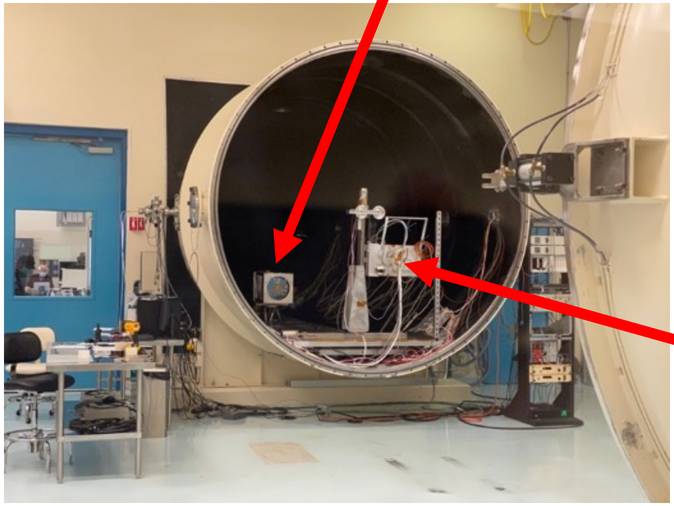
Stray Light Test Facility

• X-ray calibration of the optics took place at MSFC's 100-m X-ray test facility



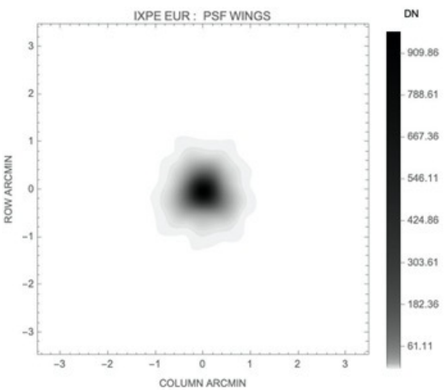


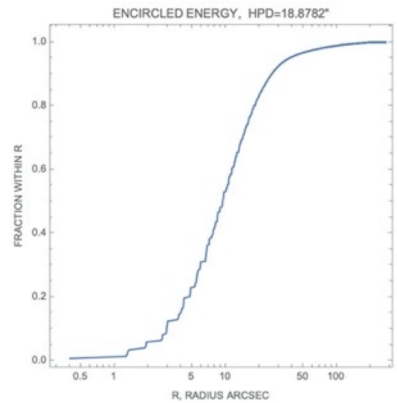
Mirror Module Assembly



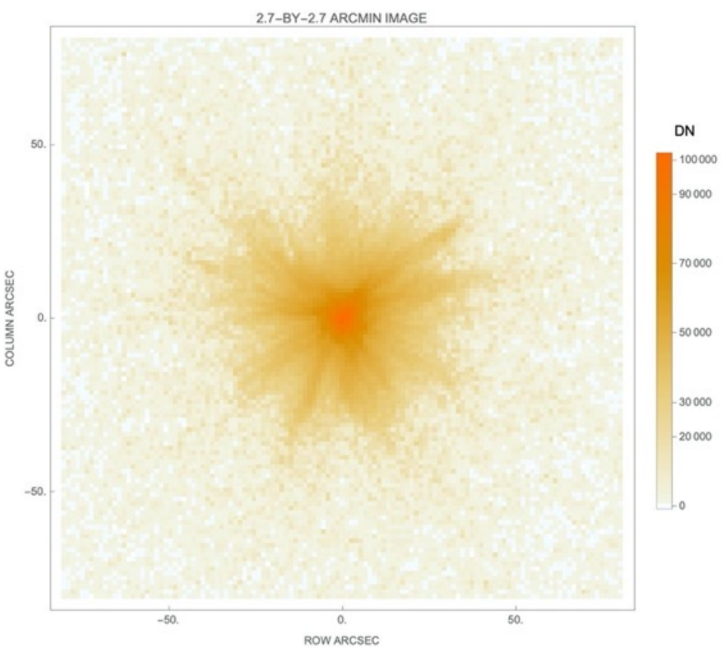
X-Y stage with detector mounting plate

MMA Angular Resolution

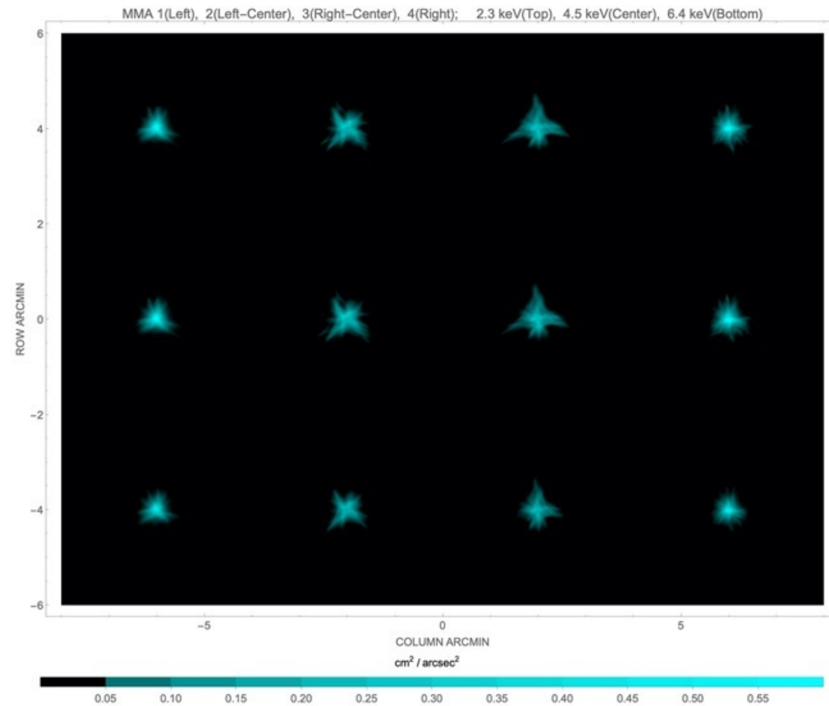




MMA1 PSF: HPD = 19.0”



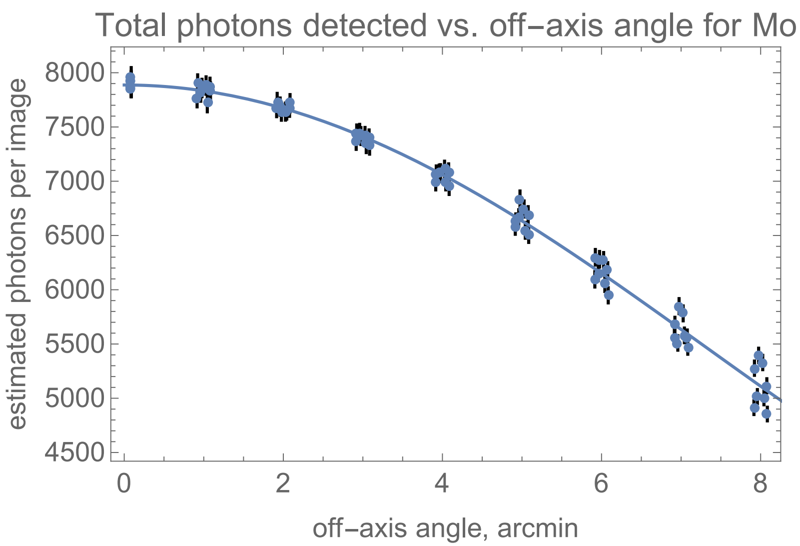
Composite Image of: 4 MMA PSFs at 3 energies



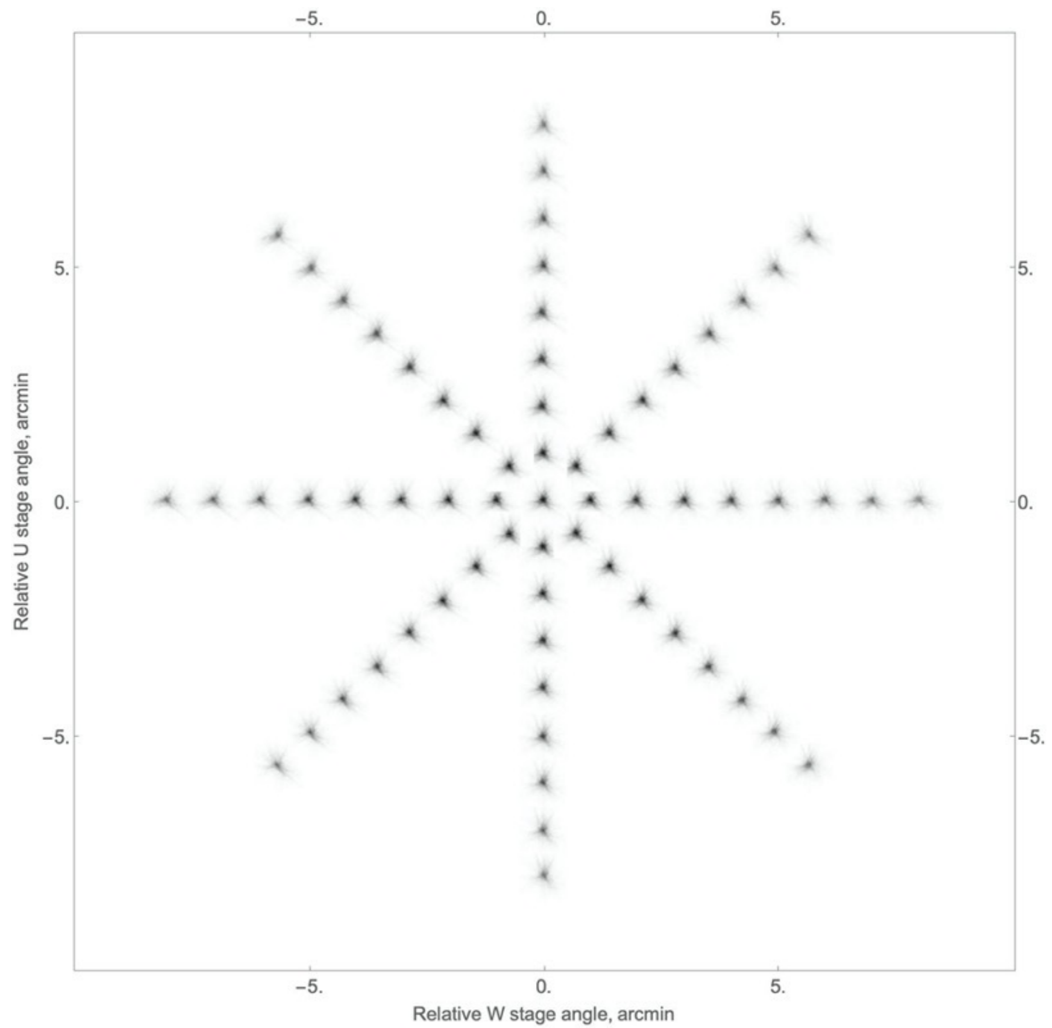
IXPE MMA Angular Resolutions: HPD [arcsec]

	MMA1	MMA2	MMA3	MMA4
2.3 keV	19.0	25.0	27.6	20.0
4.5 keV	19.9	26.0	28.0	20.8

MMA off-axis Angular Resolution



MMA3 vignetting function

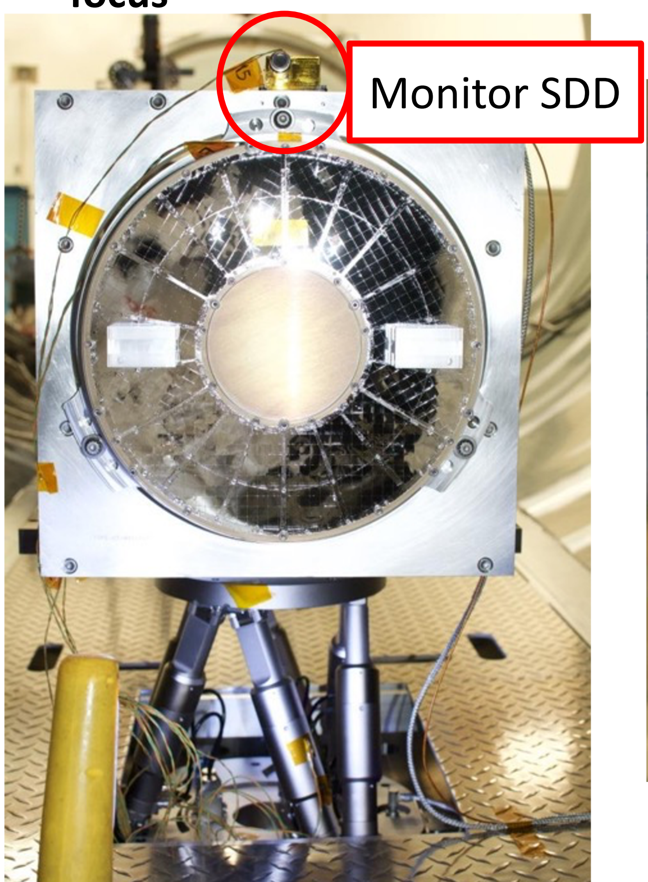


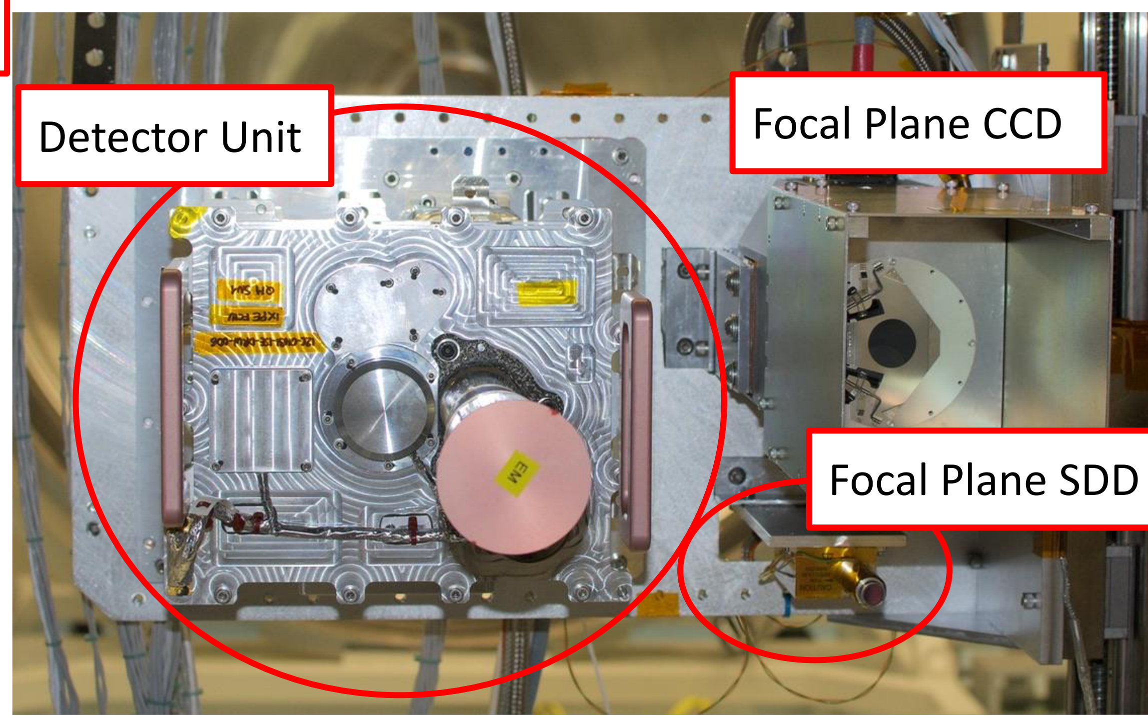
Composite image of MMA1 PSF at several off-axis angles

EFFECTIVE AREA

MMA EA measured by MSFC with two Silicon Drift Detectors, one in front of the MMA (monitor SDD) and one at the focus (focal plane SDD). SDD area = 50 mm2.

MMA EA measured with the monitor SDD beside the MMA and the Focal Plane SDD at the focus

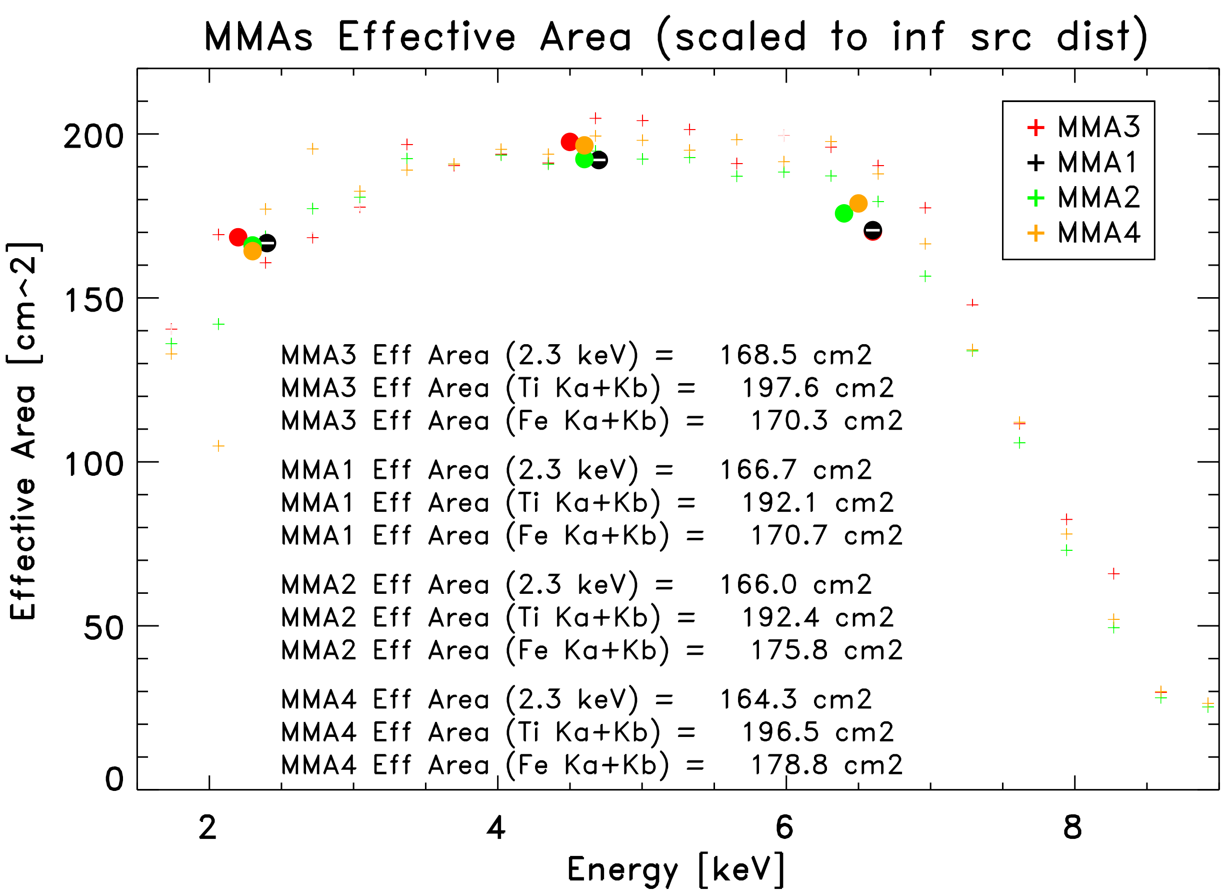




SLTF Focal Plane with DU and Facility Detectors

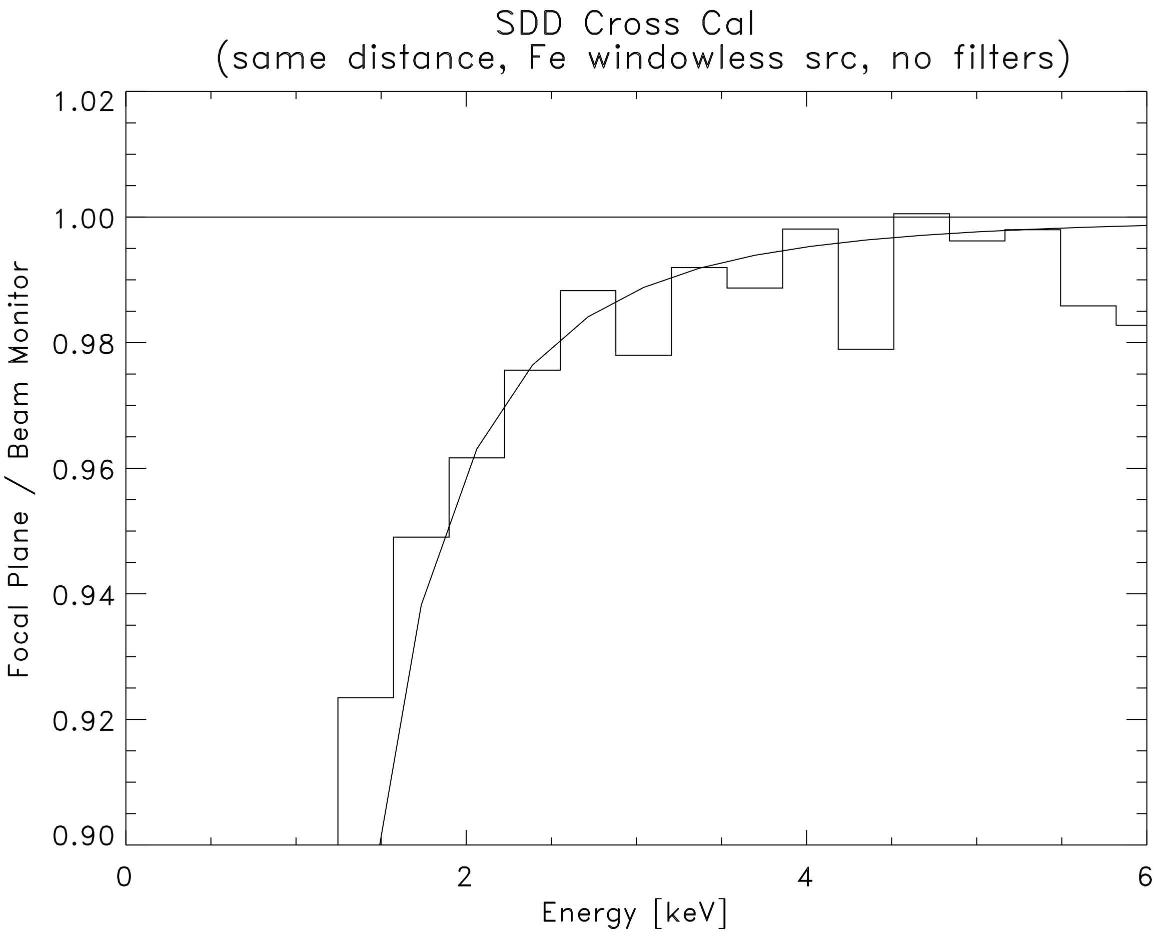
MMA EFFECTIVE AREA

- **Effective area measured at finite source distance (98m) and corrected to infinite source distance using ray trace**
  - Ray-trace calculation verified by observation of small mirror sector viewed normal to beam



SDD Detector Correction

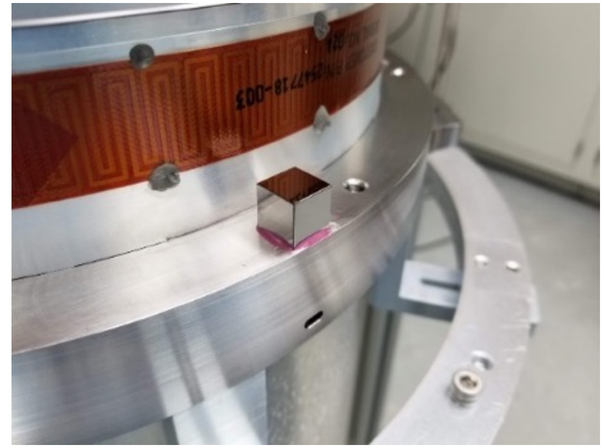
- **SDD Correction**
  - We test illuminated the Focal Plane SDD and Beam Monitor SDD simultaneously at the same distance
  - FP slightly lower count rate than BM
  - Looks like additional 3um Be absorption (SDD Be window is nominally 12.5um)
    - (smooth curve is transmission of 3um Be)
  - Correction is ~1.03 * EA (at Mo) , 1.01 * EA (at Ti)
  - SDD QEs otherwise assumed identical



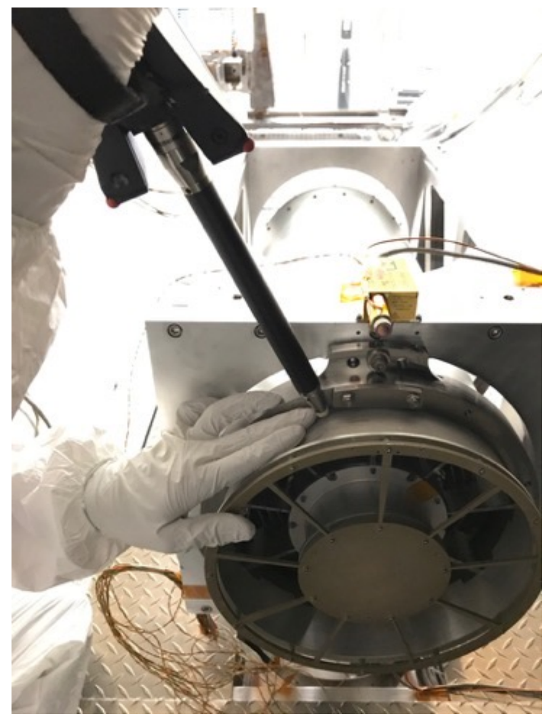
MMA Focal Length

- MMA focal lengths measured with Leica laser tracker system
- Finite distance focal length measured between MMA and CCD camera, then corrected to infinite source distance focal lengths using the thin lens equation and an X-ray source to optic distance of 98 meters

	Inf src dist Focal Length [mm]
MMA1	3997.2
MMA2	3997.8
MMA3	3997.5



Reference Optical Cube mounted to MMA front Spider



Measuring MMA position with T-probe and laser tracker

MMA Ghost Rays

- Ghost rays: Unwanted rays that reach the detector from off-axis angles through unfocused paths (single bounce, or straight through the optic instead of nominal double-bounce path)
- Ghost ray images made with source at 10 off-axis angles up to one degree; ghost ray intensity measured
- IXPE requires a reduction of 200x for ghost rays at off-axis angles up to 1 degree
  1. Measured in 11-arcmin diameter active detector area
  2. Compared to focused rays from same source
  3. Measured to 10% precision

Ghost Ray Measured Attenuation Factors

MMA1

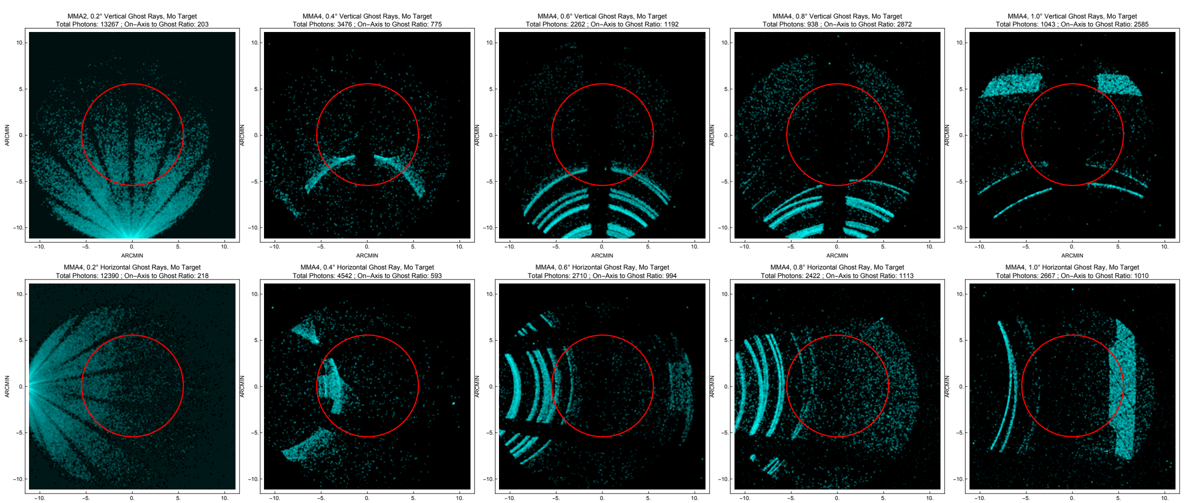
Angle	0.2°	0.4°	0.6°	0.8°	1.0°
Azimuth = 0°	280	735	872	1381	1780
Azimuth = 90°	241	595	858	897	650

MMA2

Angle	0.2°	0.4°	0.6°	0.8°	1.0°
Azimuth = 0°	229	712	890	1160	1517
Azimuth = 90°	237	508	818	834	529

MMA3

Angle	0.2°	0.4°	0.6°	0.8°	1.0°
Azimuth = 0°	262	776	770	1533	1543
Azimuth = 90°	221	510	981	796	681



Angle	0.2°	0.4°	0.6°	0.8°	1.0°
0°	203	775	1192	2872	2585
90°	218	593	994	1113	1010

MMA4

- **Instrument Calibration**

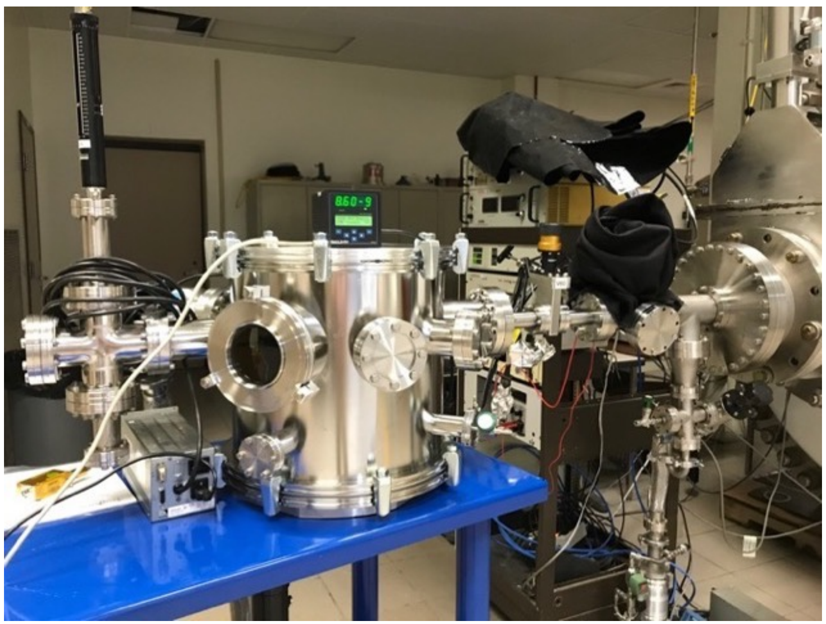
- **Telescope Calibration**

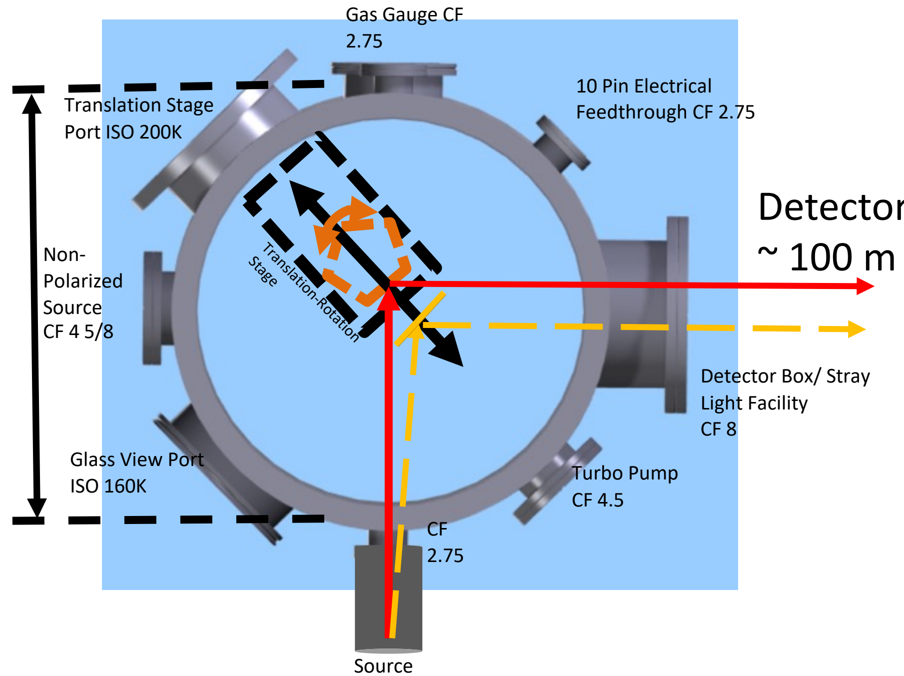
TELESCOPE CALIBRATION OVERVIEW

1. **Telescope calibration = end-to-end measurement**
   - Optic + Detector
   - Flight Spares: MMA4 + DU_FM1 used
2. **Telescope Effective Area**
   - Three energies: Mo, Ti, Fe; on and off-axis
3. **Telescope Angular Resolution**
   - Simultaneous with measurement #2 above
4. **Telescope Modulation Factor**
   - Response to 100% polarized X-rays
   - Three energies (2.7, 4.5, 6.4 keV) with polarized source
5. **Spurious Modulation**
   - Telescope response to unpolarized source; three energies

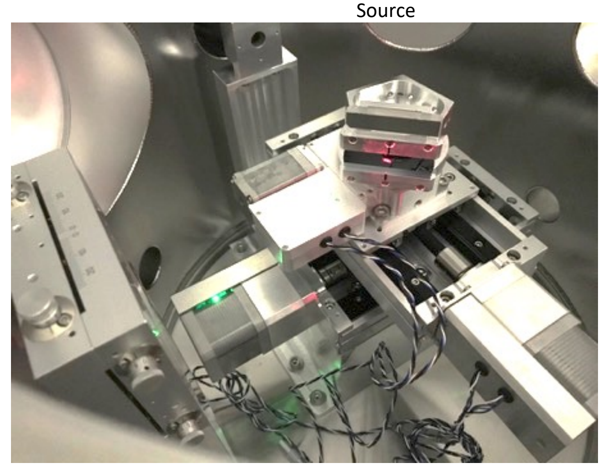
Polarized Sources for Telescope X-ray Polarization Measurements

- **3 Polarized Sources**
  - **Crystal Box**
    - Holds all X-ray sources
    - Holds crystals -- integral for polarized source





Energy	X-ray Tube	Crystal
2.7 keV	Rh	Ge(111)
4.5 keV	Ti	Si(220)
6.4 keV	Fe	aSi(400)



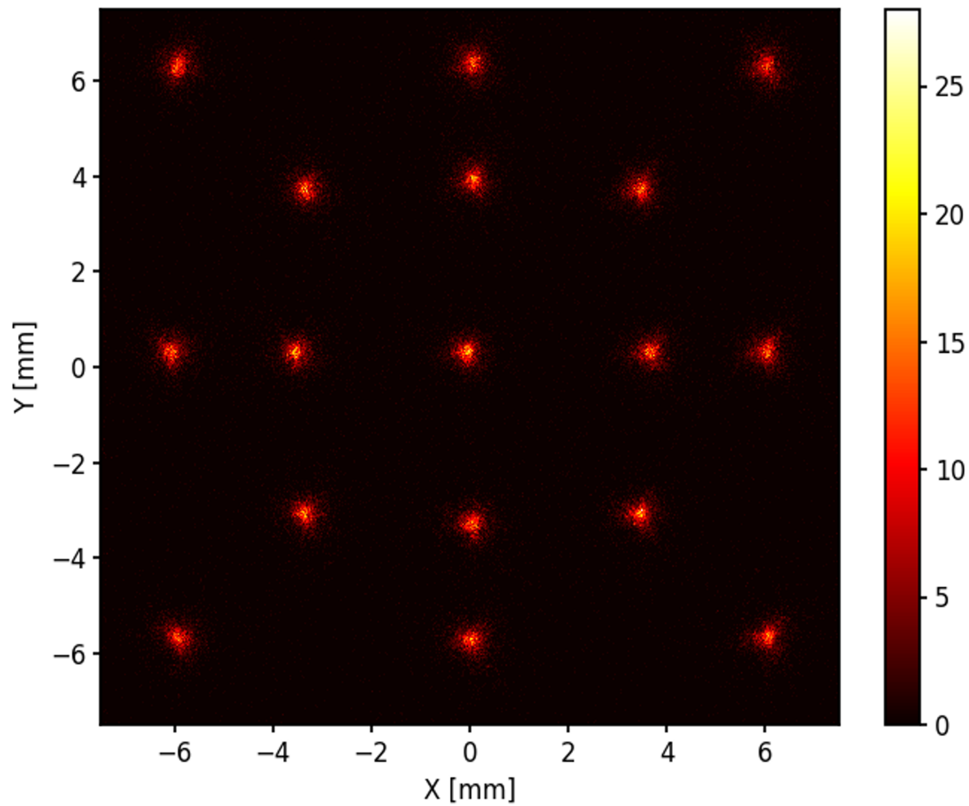
Interior of Crystal Box, showing stages and crystal being aligned

TELESCOPE ANGULAR RESOLUTION

- **PSF of flight spare MMA4 (HPD =20”) measured with facility CCD camera and flight spare DU-FM1**

- **On-axis PSF:**
  - Essentially convolves MMA PSF with DU spatial resolution

Energy [keV]	PSF on DU [HPD, um]	MMA4 + DU-FM1 HPD [arcsec]
2.3	474.6	22.1
4.5	513.2	23.8
6.4	528.0	24.1

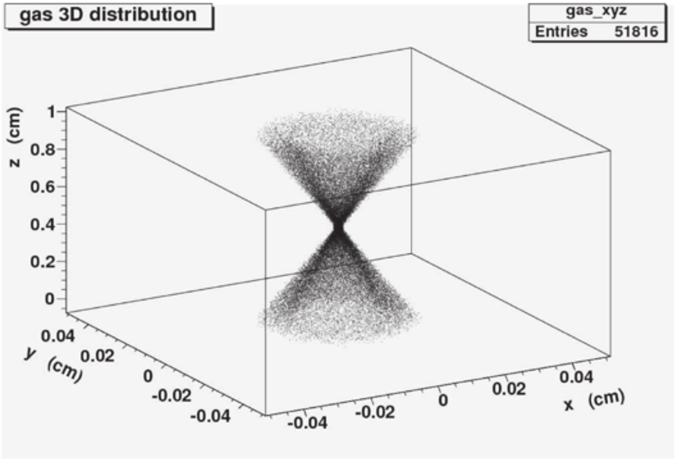


Composite image of on- and off-axis telescope PSF measurements across detector plane

TELESCOPE ANGULAR RESOLUTION
HALF POWER DIAMETER

GPD angular resolution

- intrinsic spatial resolution (pixels, blurring due to diffusion, algorithm)
- inclined penetration
- MMA PSF (only MMA)

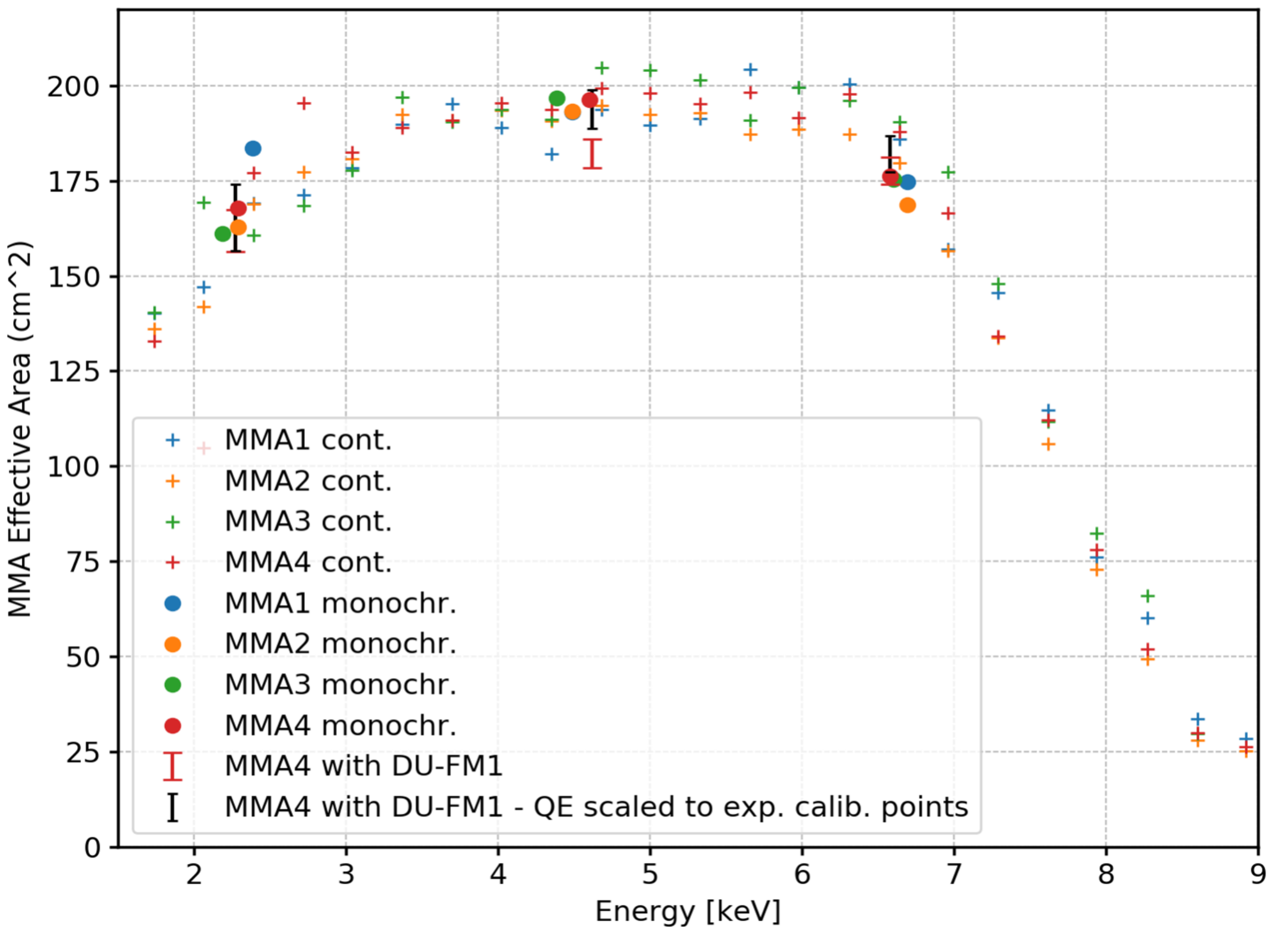


HPD On Axis

- **Refined analysis within 8mm of diameter and PSF fit**

Source	Mo	Ti	Fe
Only MMA4 (arcsec)	20.0	20.8	20.1
MMA4 + DU-FM1 (arcsec)	22.050 +/- 0.081	23.849 +/- 0.073	24.051 +/- 0.072
MMA4 + DU-FM1 (arcsec) misalignment effect subtracted in quadrature	22.006 +/- 0.083	23.787 +/- 0.076	24.005 +/- 0.077

MMA4 Effective Area derived from Telescope Measurement



Derivation of MMA Effective Area in Telescope configuration (using Detector QE) matches direct measurement of MMA with facility detectors

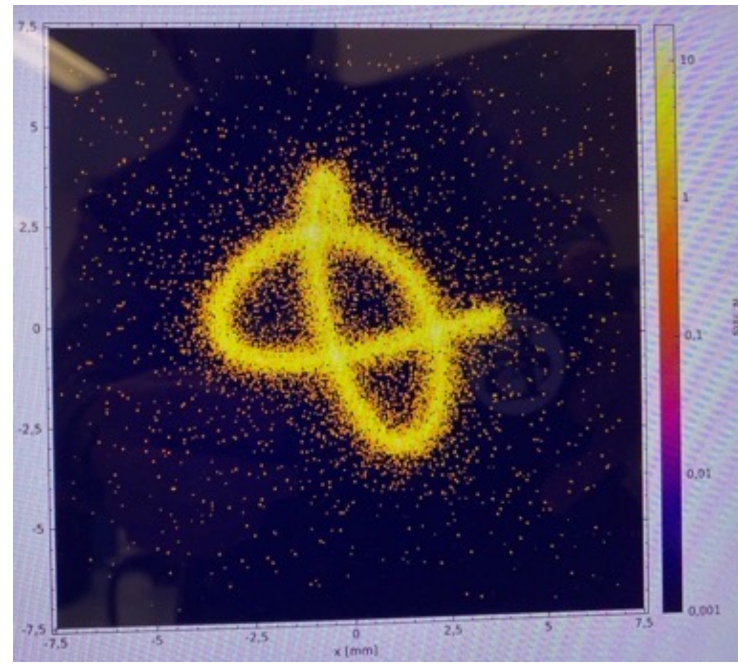
TELESCOPE MODULATION FACTORS

- **Definition: The telescope modulation factor is the modulation measured with a 100% polarized source**

- **Standard cuts:**
  1. Energy cuts isolate line emission from source
  2. Take highest 80% of moments ratio distribution
  3. Subtract spurious modulation (response to unpolarized source)

- **With and w/o optics measurement**
  - Done to test whether presence of optics causes systematic

- **Dithering adopted for flight and used to reduce calibration time**
  - Fewer measurements needed
  - Two dither radii measured to match anticipated flight pattern and
  - Deep field (and wider) detector calibration taken in Italy



Dither pattern in progress on DU

- **Measured with polarized source**

a Telescope Modulation Factor at one energy

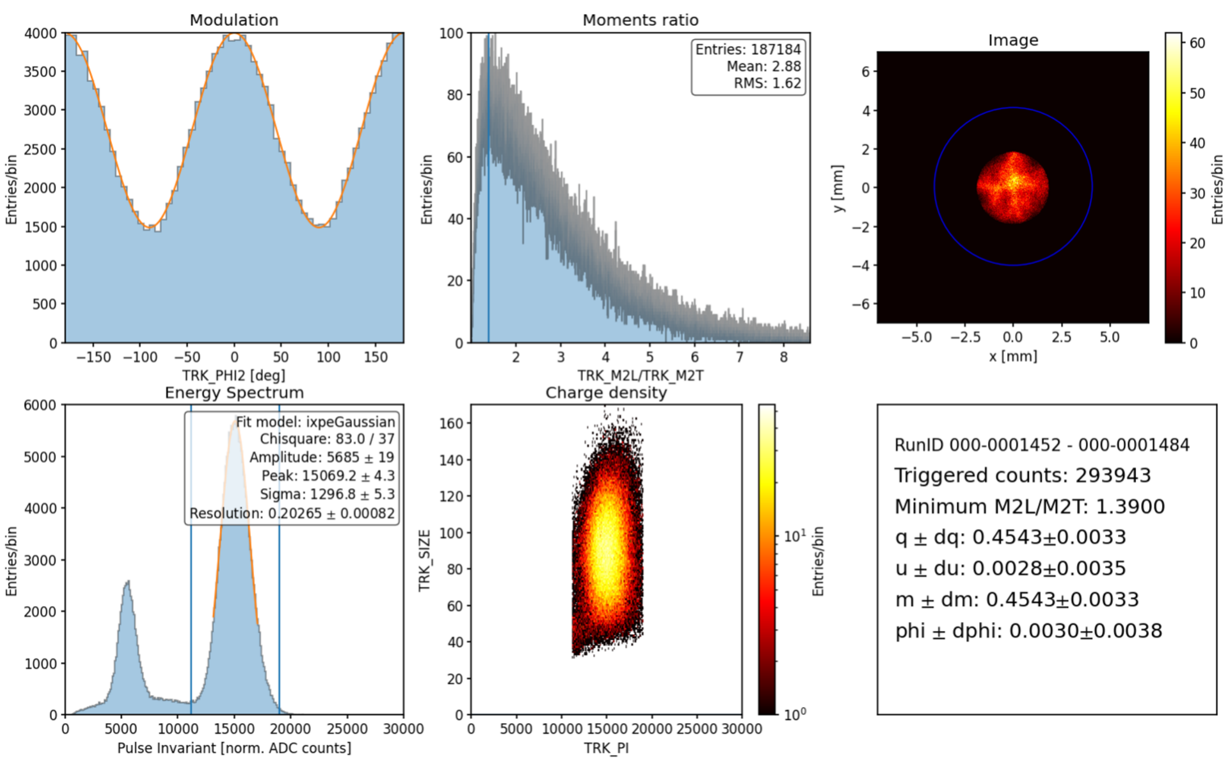
Ti X-ray tube (4.5 keV) + Si(220) - dithering radius 1.86 mm

Spurious modulation subtracted

Standard cuts applied

DU-FM1 calibration mod. factor (46.04 +/- 0.14) %

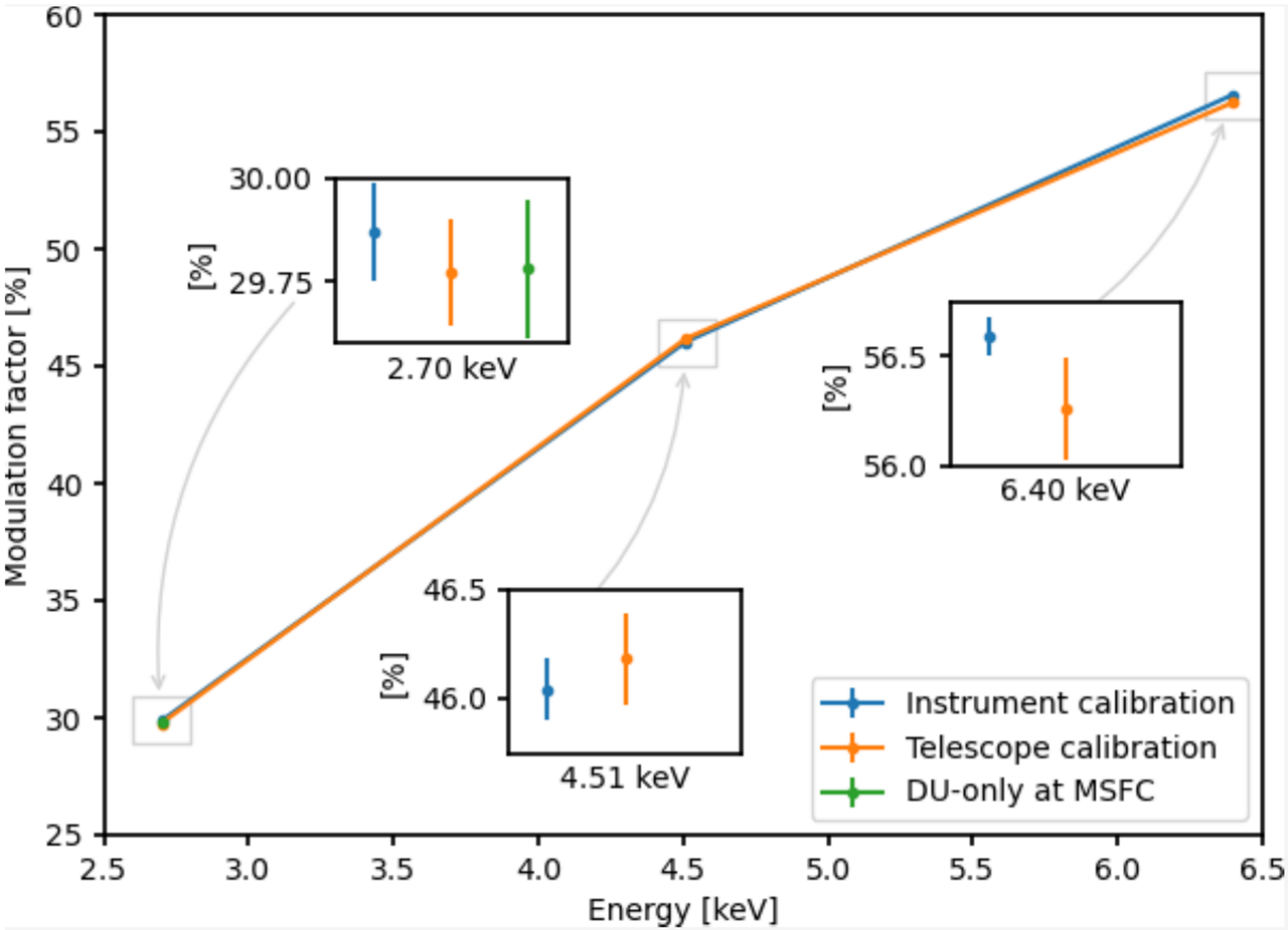
DU-FM1+MM4 mod. factor (45.43 +/- 0.33) %



Run ID
1452
1454
1456
1458
1460
1462
1464
1466
1468
1470
1472
1474
1476
1478
1480
1482
1484

A succession of 17 positions was taken to scan the non-uniform polarized beam across the optic

MODULATION FACTOR COMPARISON



Summary of Telescope Modulation Factors

	DU-FM1 alone modulation factor	Telescope (MMA4 + DU-FM1) Modulation Factor (r = 1.86mm)	Telescope (MMA4 + DU-FM1) Modulation Factor (r = 3.72mm)
2.7 keV	(29.87 +/- 0.12) %	(29.69+/- 0.20) %	(29.77 +/- 0.13) %
4.5 keV	(46.04 +/- 0.14) %	(45.43 +/- 0.33) %	(46.18 +/- 0.21) %
6.4 keV	(56.59 +/- 0.09) %	(57.08 +/- 0.42) %	(56.26 +/- 0.23) %

- **Modulation factors with and w/o optics agree**

- **Presence of MMA optics does not affect Polarization performance of detector**

SPURIOUS MODULATION

Spurious Modulation = Telescope response to unpolarized X-rays

Energies and X-ray sources

- Al X-ray tube (1.5 keV) + Al filter [additional if time available]
- Mo X-ray tube (2.3 keV) + Nb filter
- Ti X-ray tube (4.5 keV) + Ti Filter
- Fe X-ray tube (6.4 keV) + Fe filter

Two measurements rotated by 90 deg at each energy

- (separates residual source polarization from detector spurious modulation)

Spurious modulation measured with dithering of the telescope

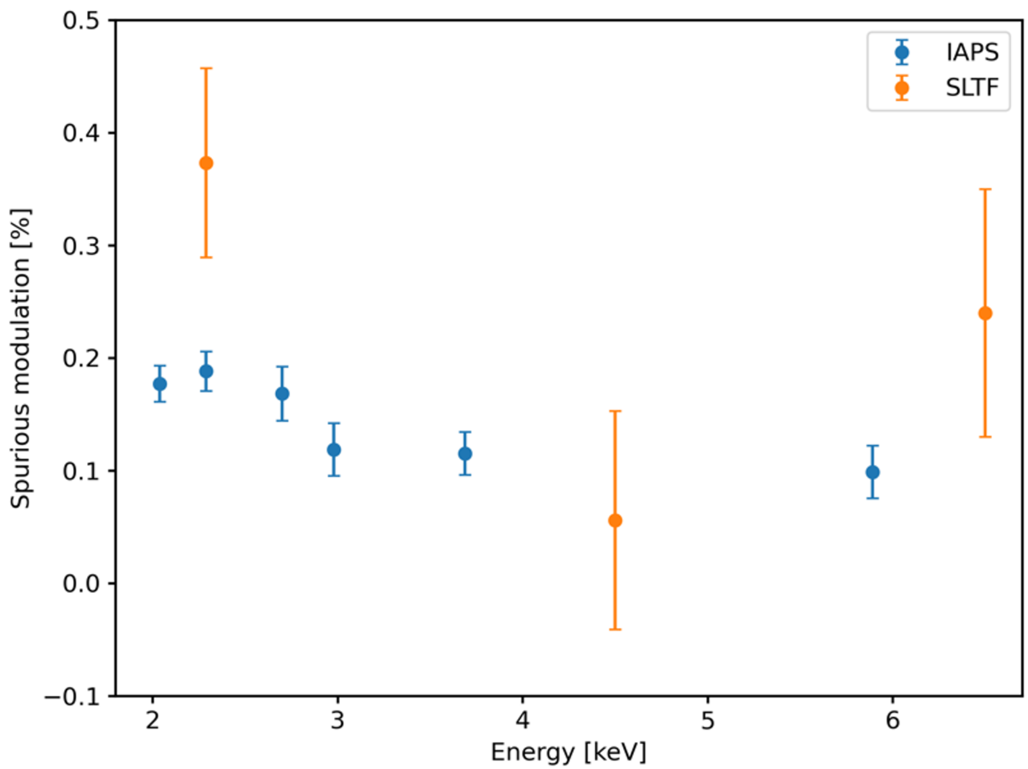
- Moved the MMA to simulate observations on orbit
- Dithering radius 3.72 mm to cover all the Deep Flat Field region (deeper calibration in the central region)

A single measurement with DU only (no MMA) at 2.3 keV

- no effect of the MMA on the polarization. Spurious modulation is consistent with and without the MMA

SPURIOUS MODULATION

Analysis in a 3.7 mm of radius to verify the Telescope calibration requirement of 0.1% absolute uncertainty on SM
SLTF measurement are with dithering
IAPS measurements are the sum of the Deep Flat Field and Flat Field Measurements to use the measurements with the highest statistics



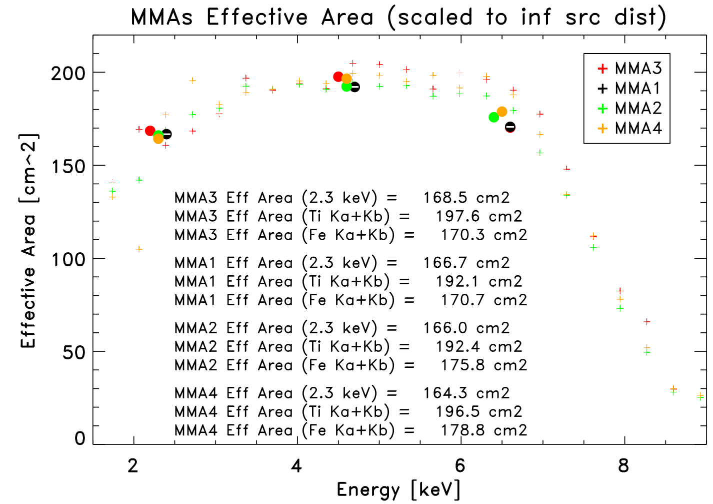
IXPE MSFC Ground calibration Summary

- **We have calibrated the 3 flight optics (MMA 1-3) and the flight spare (MMA4) at the NASA SLTF**
- **Angular resolutions of the optics are:**

	MMA 1	MMA 2	MMA3	MMA 4
2.3 keV	19.0	25.0	27.6	20.0
4.5 keV	19.9	26.0	28.0	20.8
6.4 keV	20.2	25.0	25.8	20.1

Average HPD = 22.9”

MMA EA > 192 cm2 at 4.5 keV



- **Telescope Modulation Factors (MMA + DU) are measured:**

	DU-FM1 alone modulation factor	Telescope (MMA4 + DU-FM1) Modulation Factor (r = 3.72mm)
2.7 keV	(29.87 +/- 0.12) %	(29.77 +/- 0.13) %
4.5 keV	(46.04 +/- 0.14) %	(46.18 +/- 0.21) %
6.4 keV	(56.59 +/- 0.09) %	(56.26 +/- 0.23) %

SUMMARY

- **We have calibrated 4 flight-like MMAs at SLTF**
  - MMA Average Angular resolution = 22.9" HPD
  - MMA Effective area > 192 cm2 at 4.5 keV
- **Four flight-like Detector Units have been calibrated in Italy**
  - Extensive characterization, including
    - Modulation Factor
    - Quantum Efficiency
    - Spurious Modulation
    - In-flight calibration sources characterized
    - Several energies and spatial areas on detector
- **End-to-end telescope calibration with the flight spare units has been performed at NASA/MSFC SLTF:**
  - Expected performance of the telescope verified in all areas
    - Effective Area
    - Angular resolution
    - Telescope Modulation Factor
    - Spurious Modulation

IXPE Instrument Calibration

Calibration of IXPE focal plane detectors

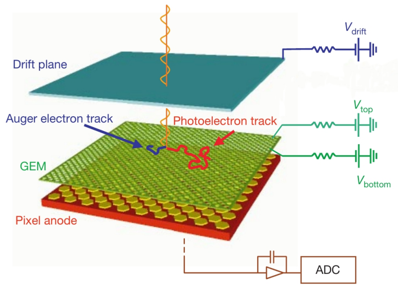
Fabio Muleri on behalf of IXPE Italian Team
fabio.muleri@inaf.it
INAF-IAPS

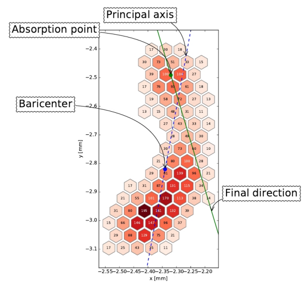
IACHEC April 2021 Plenary Sessions

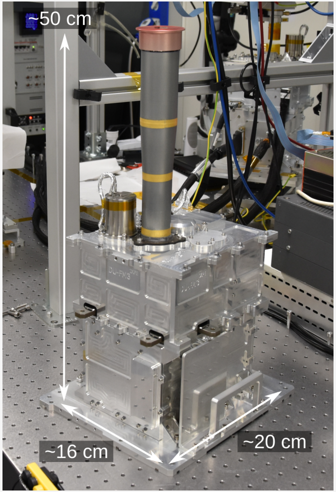
2021 April 30

The IXPE focal plane polarimeters I

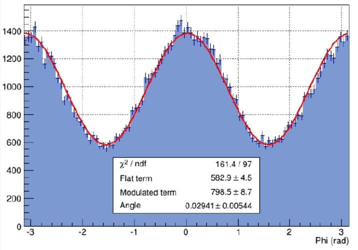
- IXPE Detector Unit (DU) are based on the Gas Pixel Detector (GPD)
  - ➥ Developed by INFN-Pisa and INAF-IAPS since 2001
  - ➥ Main Italian hardware contribution to the mission
- Response is the image of the path of the photoelectron in the gas



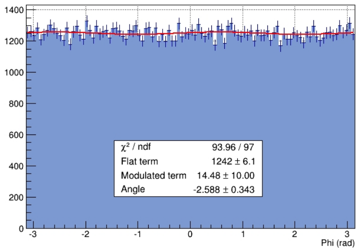




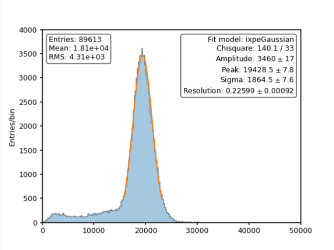
- Emission direction statistically related to the polarization of absorbed photons
- All the characteristics of the photons (direction, time of arrival, energy and polarization) are measured contemporaneously and photon by photon



Response to **polarized** radiation



Response to **unpolarized** radiation

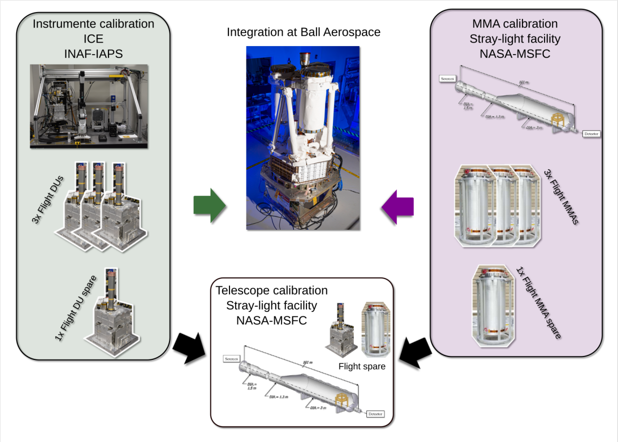


Spectrum at 5.9 keV

Instrument Calibration

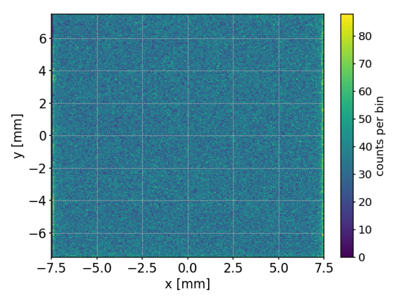
Overview of IXPE Instrument calibration

- DUs are calibrated at INAF-IAPS in Rome (Italy)
  - ➥ 3x Flight Models are delivered directly to Ball for integration
  - ➥ Spare DU (and spare MMA) are calibrated jointly at NASA-MSFC
- DU calibration possible also with on-board calibration sources

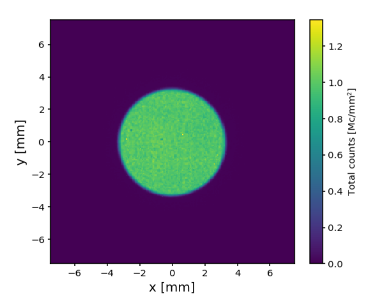


The IXPE Instrument calibration I

- Nominally, 40 days for each of the 4 DUs
- ∼80% of time dedicated to polarized and unpolarized response
  - ➥ Requirement on knowledge of the response <0.1%
  - ➥ Required custom sources and procedures
- Following satellite dithering strategy, deeper calibration at the center of the field of view



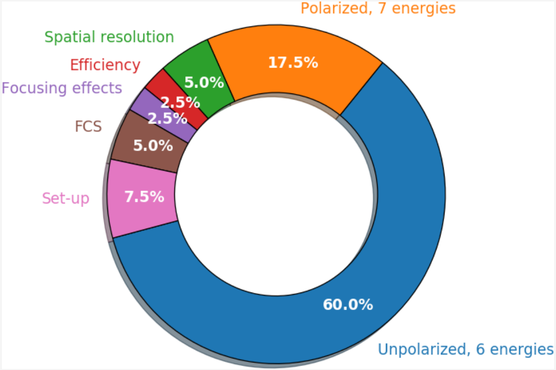
Full illumination



Deeper illumination in the center

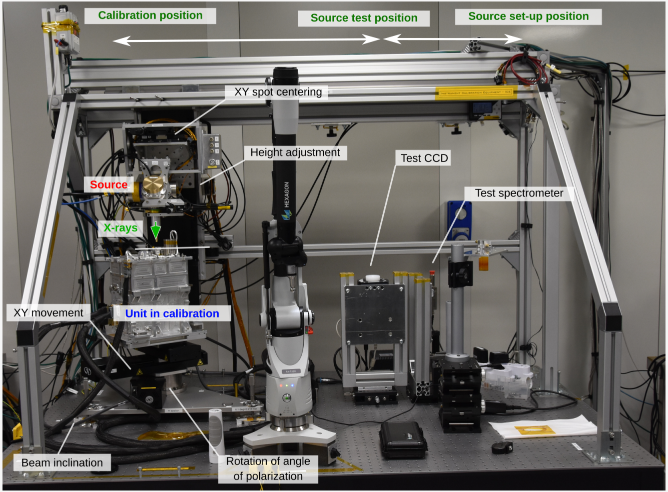
The IXPE Instrument calibration II

- Other calibrations:
  - ➥ Absolute quantum efficiency
  - ➥ Pixel-to-pixel equalization
  - ➥ Gain disuniformities
  - ➥ Energy resolution
  - ➥ Dead time
  - ➥ Spatial resolution
  - ➥ Response to inclined beam
- Started on 26th July 2019, last measurement on the spare on 14th September 2020
  - ➥ Source set-up and alignment during working hours, 7 days per week
  - ➥ Data acquisition round the clock with remote monitoring
  - ➥ 530 measurements, 4052.3 hr acquisition and 2.250 billion counts collect

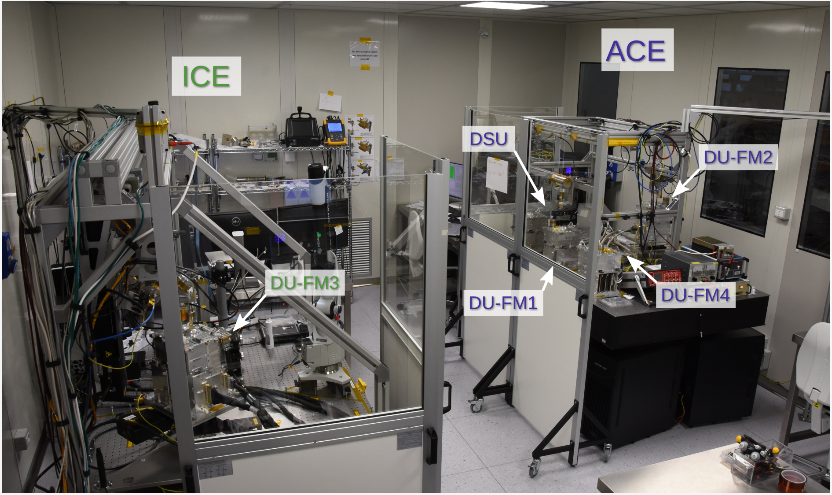


The Instrument Calibration Equipment I

- Small facility (yet versatile and **dedicated** to IXPE)
- Operating in air
  - Air absorption reduced with helium flowing along photon path
- Motorized and manual stages for source and beam-to-detector alignment
- Alignment with a measurement arm
  - Positioning $\simeq 10\ \mu$m
  - Inclination $\simeq 1$ arcmin
- Spots from $\sim 25\ \mu$m
- Commercial SDD spectrometer and CDD for source testing



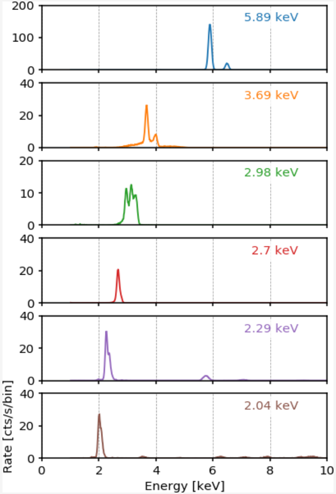
The Instrument Calibration Equipment II



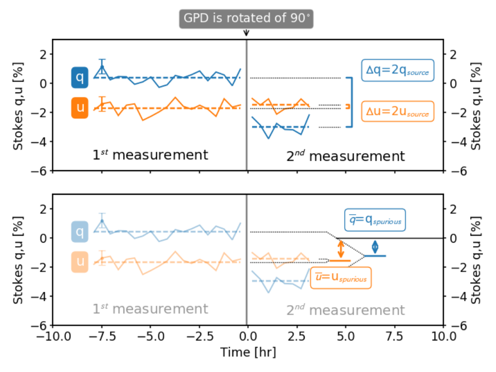
IXPE clean room @ INAF-IAPS in November 2019

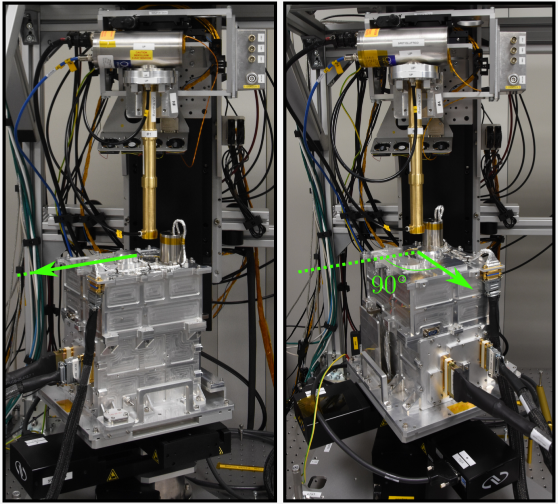
Response to unpolarized radiation I

- Most time-consuming measurement
  - 10^5 cts/mm^2 over the entire field of view of $\sim$225 mm^2
    10^6 cts/mm^2 on the central $\sim$33 mm^2 region
  - 6 energies
- Unpolarized sources were based on commercial X-ray tubes or ^{55}Fe
  - Either direct or fluorescence
  - Filters to have a spectrum largely dominated by photons at the same energy
- Often a genuine source polarization is still present depending on
  - bremsstrahlung continuum
  - X-ray tube geometry
  - Diffraction on fluorescence target

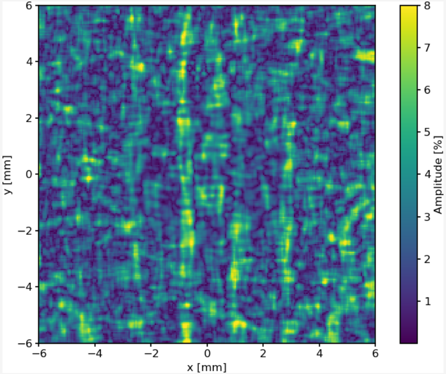


- Two measurements to separate it from the detector response to unpolarized radiation
- Source and spurious contribution sum differently for the two measurements

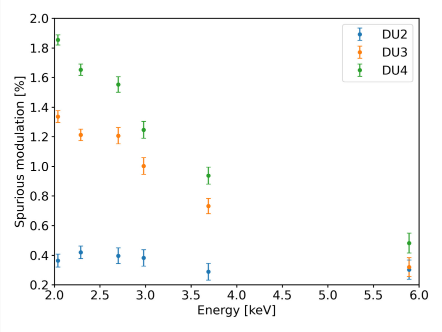




Response to unpolarized radiation III

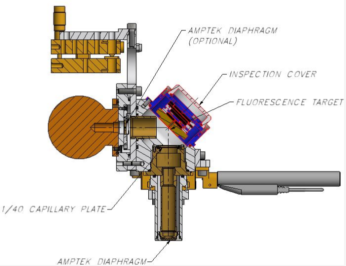


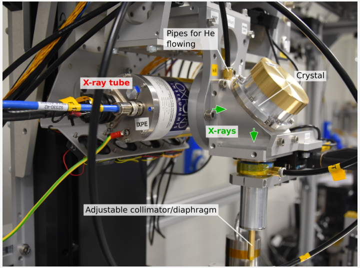
Map of spurious modulation at 2.7 keV for DU-FM2



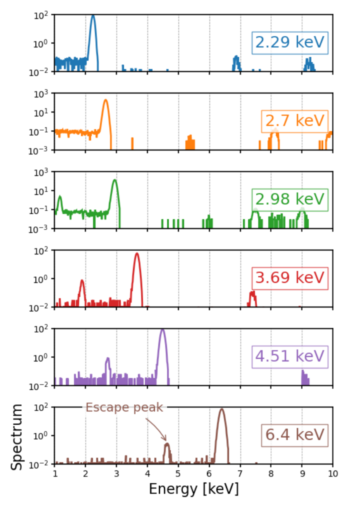
Spurious modulation as a function of energy on a spot with 3 mm diameter

➥ Calibration will be applied in the pipeline running at SOC

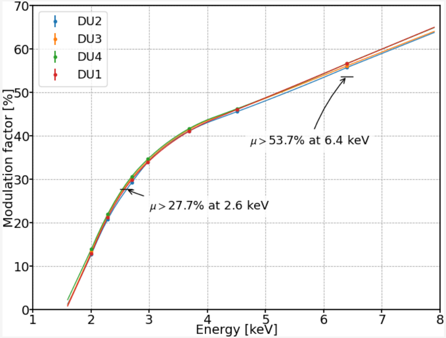




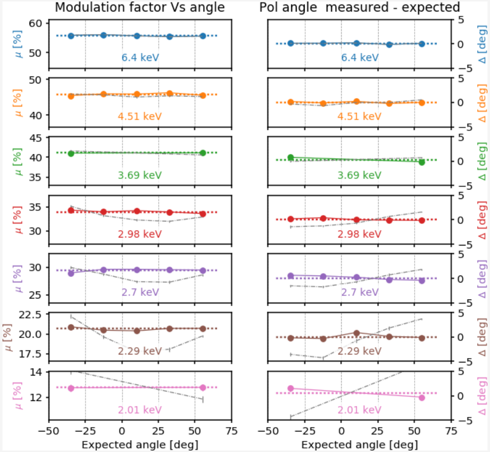
- Requirement is to collect 10^4 cts/mm^2 over the entire field of view
- Polarized sources based on Bragg diffraction at nearly 45°
  - Truly monochromatic photons
  - Degree of polarization derived by Bragg angle
  - Different crystals to diffract photons at different energies
- Up to five polarization angles for each energy



Spectrum with ICE test spectrometer



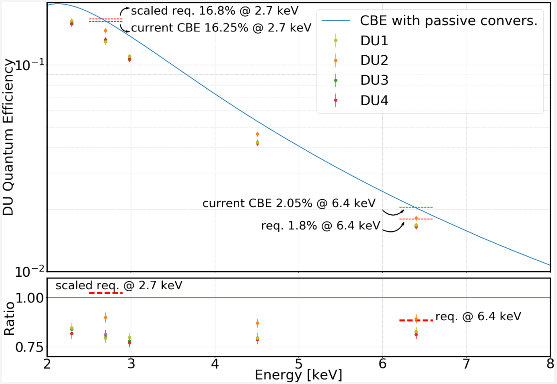
Modulation factor as a function of energy, constant over the field of view



Modulation factor as a function of polarization angle, before and after calibration for the spurious modulation

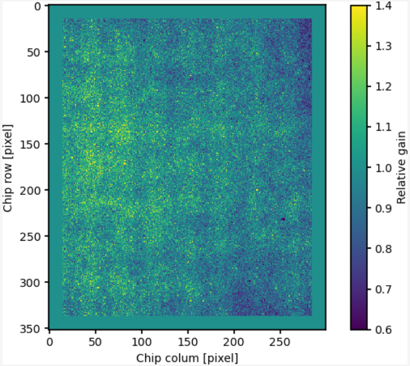
Quantum efficiency

- Comparison with flux measured with a reference detector
  - ➥ Measured with monochromatic sources at 5 energies
  - ➥ Globally, absolute uncertainty ∼1%
- Independent estimates with other techniques
  - ➥ Beam incident at known angle and imaging capabilities of the GPD
  - ➥ Relative quantum efficiency measurement with a reference source
- Measured value lower than expected
  - ➥ Now understood to be an effect of adsorption in the GPD gas cell
  - ➥ Internal pressure decreasing with time
  - ➥ Asymptotic value achieved by the launch
- Little impact on overall sensitivity

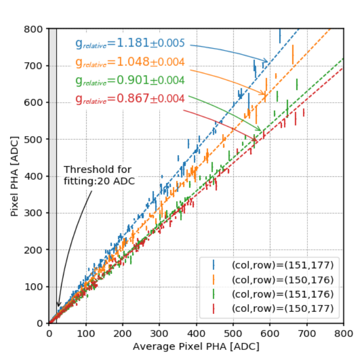


Pixel equalization

- By-product of polarimetric response calibration
- Gain of each of the 300×352 pixels equalized with respect to others
- Rely on the peculiar read-out scheme of the GPD

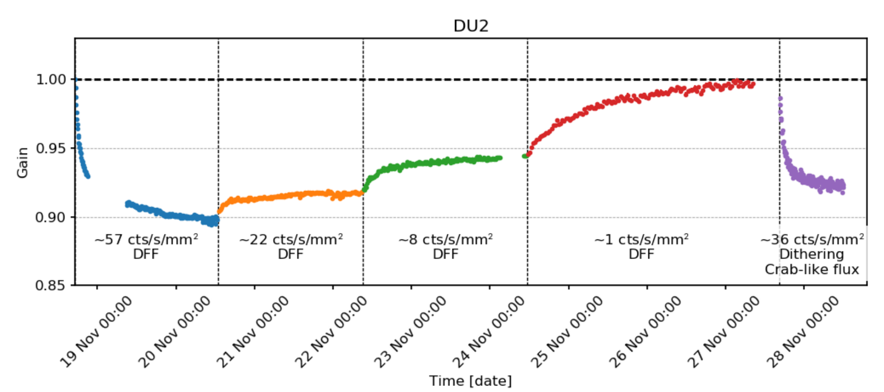


Pixel-by-pixel equalization map

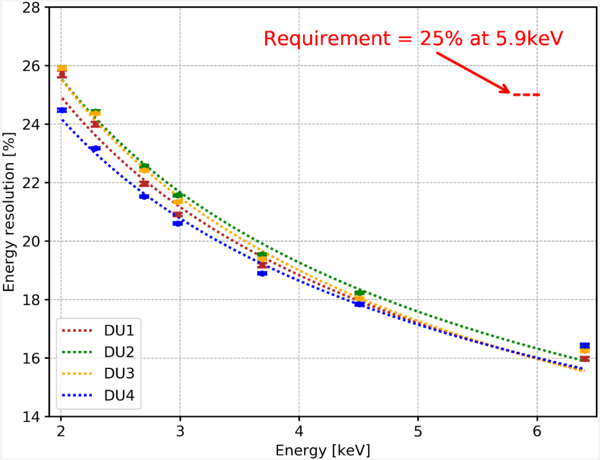


Relative equalization of single pixels

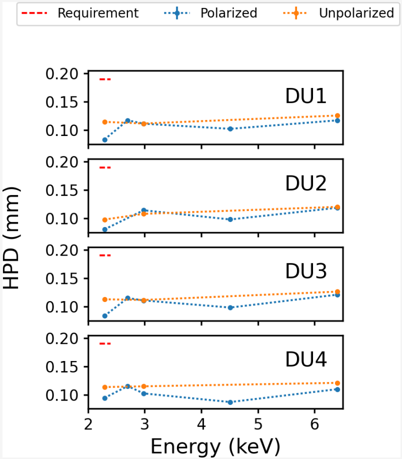
Gain calibration



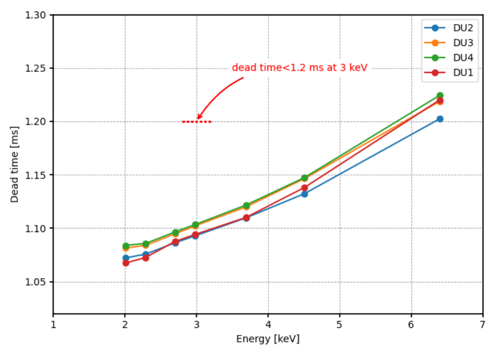
- Gain changes with illumination (Charging effect)
- Effect has been modelled
- Removed in the pipeline



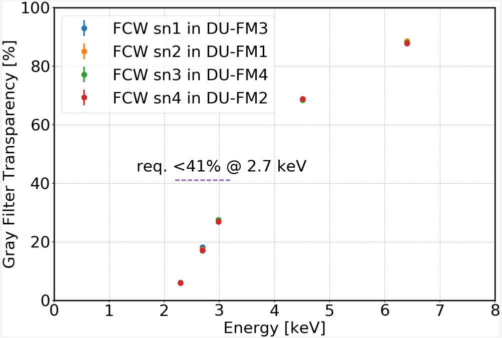
Energy resolution as a function of energy



Spatial resolution at different energies, polarized and unpolarized



Dead time as a function of energy

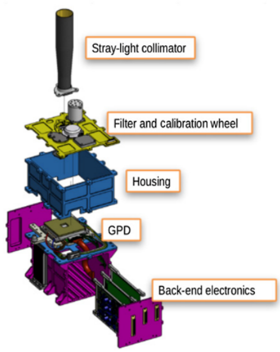


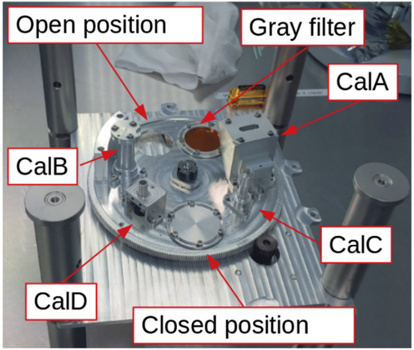
- Transparency of gray filter included in DU's FCW
- Provide flux calibration for exceptionally bright sources

On-board calibration sources

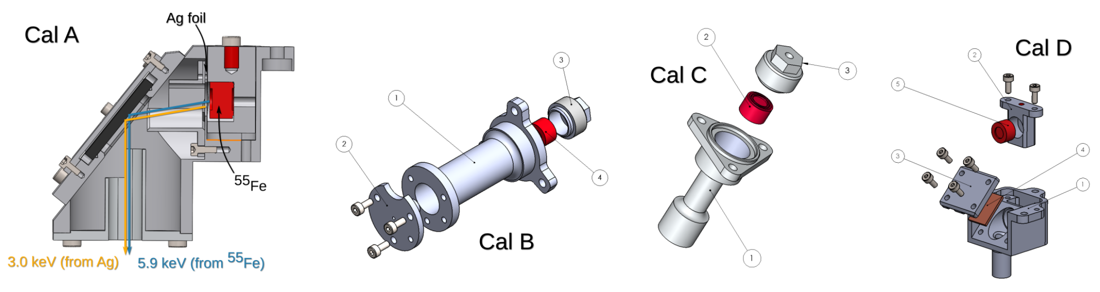
DU Filter and Calibration Wheel

- open position for normal observations
- 1 "gray" filter for observation of exceptionally bright sources
- closed position for background measurements
- 4x sources included in each DU
  - ➥ Used for monitoring performance, on-ground and in-flight



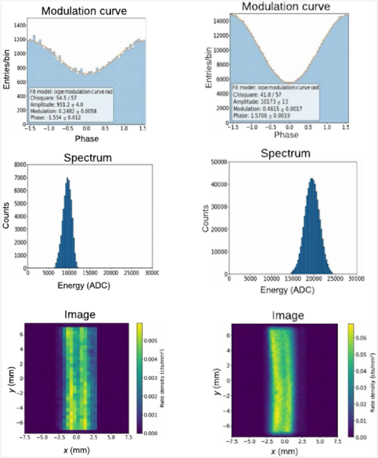


On-board calibration sources I

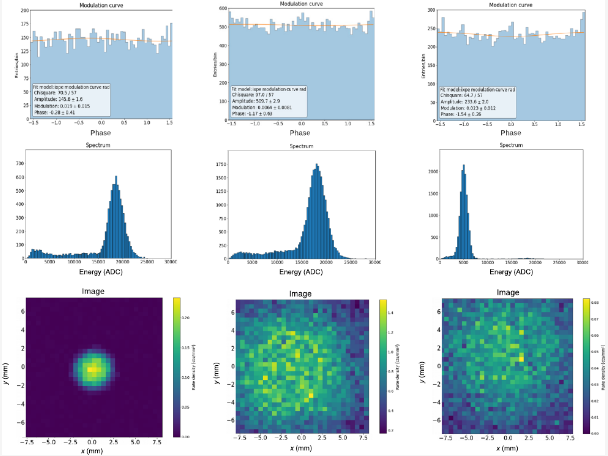


	Emission	^{55}Fe activity [mCi]	Notes
Cal A	polarized X-rays at 3.0 and 5.9 keV	100	Diffraction at $\sim 38^{\circ}$
Cal B	unpolarized spot at 5.9 keV	20	Response to unpolarized radiation
Cal C	unpolarized flat field at 5.9 keV	0.5	Gain calibration
Cal D	unpolarized flat field at 1.7 keV	100	Gain calibration Response to unpolarized radiation

On-board calibration sources II



Cal A at 3.0 and 5.9 keV



Cal B, C and D

Conclusions

- IXPE Instrument underwent an extensive on-ground calibration
  - ➥ $\sim$80% of time dedicated to measurements specific to IXPE
- Calibration will be monitored in-flight with on-board sources

Lessons learned:

- Calibration in-house was instrumental for successfully accomplishing the task
- Versatility allowed for adapting measurements to the peculiar needs of the detector
- The use of the second facility (ACE) allowed to recover delays in the schedule

Conclusions

- IXPE Instrument underwent an extensive on-ground calibration
  - ➥ ~80% of time dedicated to measurements specific to IXPE
- Calibration will be monitored in-flight with on-board sources

Lessons learned:

- Calibration in-house was instrumental for successfully accomplishing the task
- Versatility allowed for adapting measurements to the peculiar needs of the detector
- The use of the second facility (ACE) allowed to recover delays in the schedule

IXPE Instrument calibration team at INAF-IAPS

Thank you for your attention!