IXPE Instrument Calibration

Calibration of IXPE focal plane detectors

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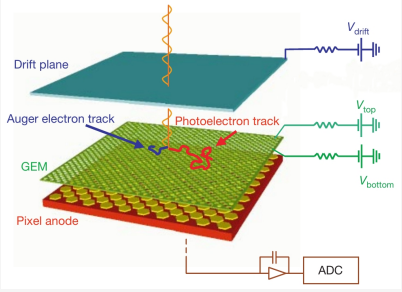
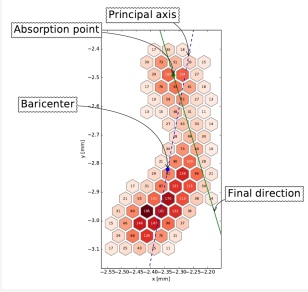
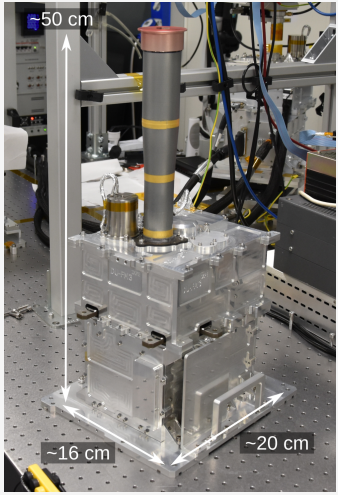
The IXPE focal plane polarimeters I

- 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

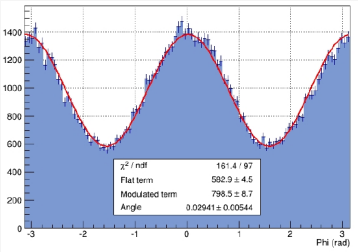




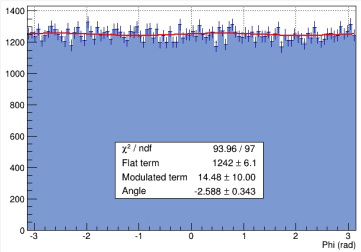


The IXPE focal plane polarimeters II

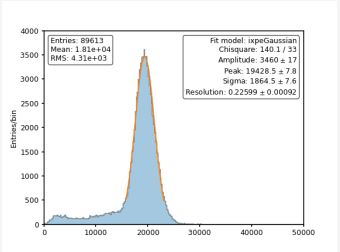
- Emission direction statistically related to the polarization of absorbed photons
- All the characteristics of the photons (direction, time of arrival, energy and polarization) are measured contemporaneously and photon by photon



Response to **polarized** radiation



Response to **unpolarized** radiation

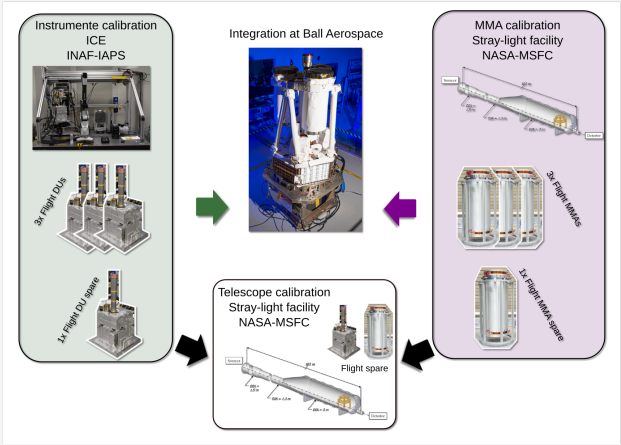


Spectrum at 5.9 keV

Instrument Calibration

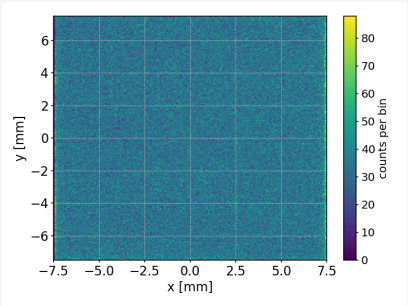
Overview of IXPE Instrument calibration

- 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

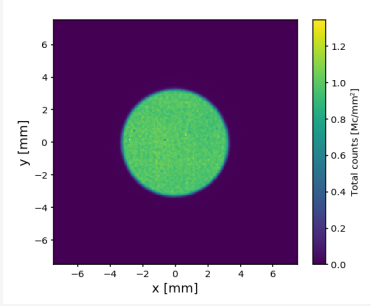


The IXPE Instrument calibration I

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



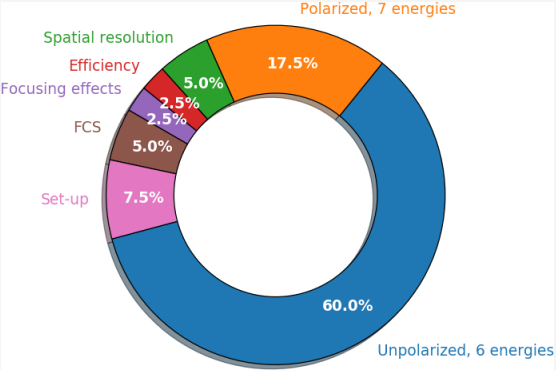
Full illumination



Deeper illumination in the center

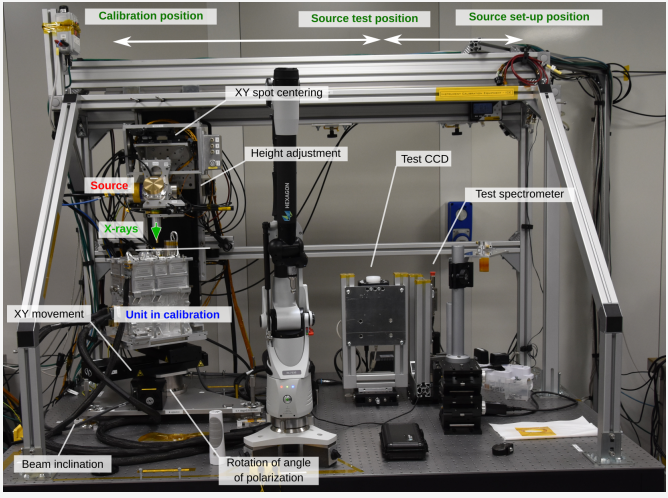
The IXPE Instrument calibration II

- 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

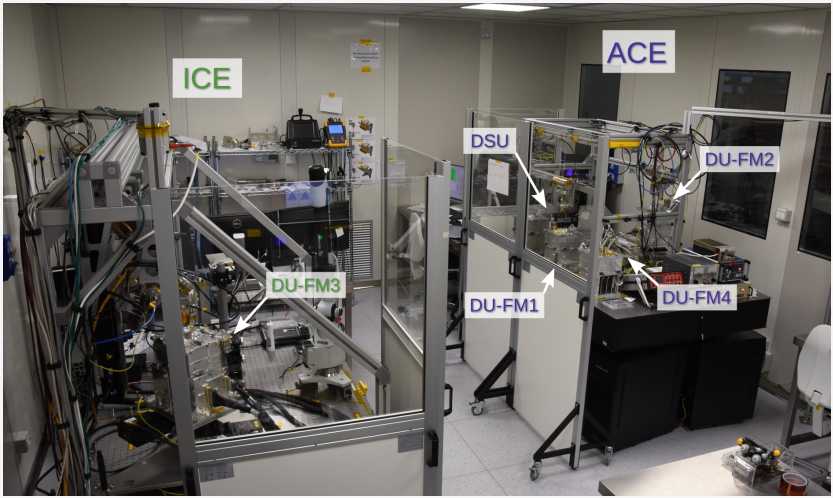


The Instrument Calibration Equipment I

- 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 $\simeq 10$ μm
  - ➥ Inclination $\simeq 1$ arcmin
- Spots from ~ 25 μm
- Commercial SDD spectrometer and CDD for source testing



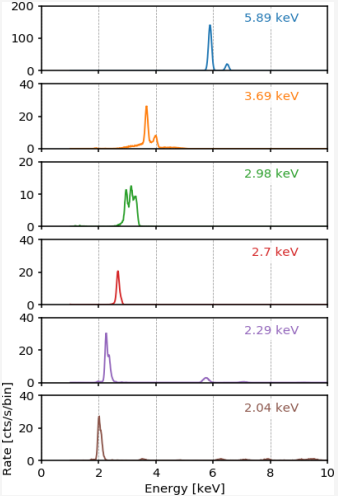
The Instrument Calibration Equipment II



IXPE clean room @ INAF-IAPS in November 2019

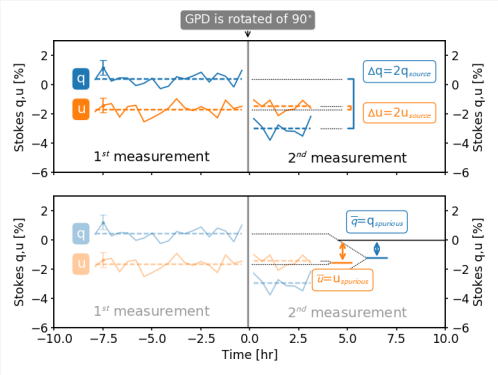
Response to unpolarized radiation I

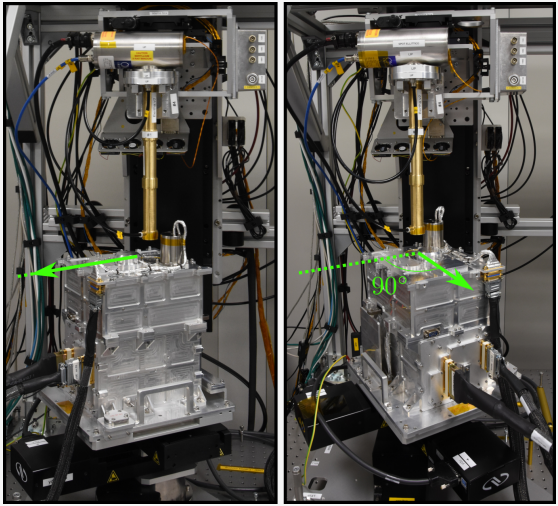
- Most time-consuming measurement
  - 10^5 cts/mm^2 over the entire field of view of $\sim$225 mm^2
    10^6 cts/mm^2 on the central $\sim$33 mm^2 region
  - 6 energies
- Unpolarized sources were based on commercial X-ray tubes or ^{55}Fe
  - Either direct or fluorescence
  - Filters to have a spectrum 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



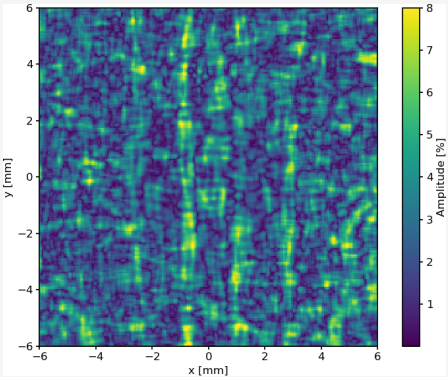
Response to unpolarized radiation II

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

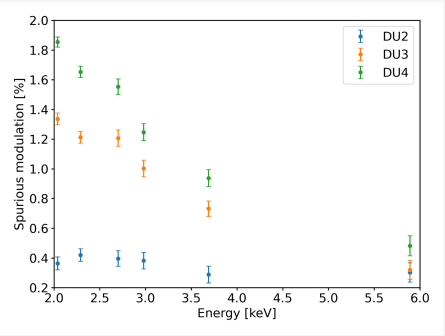




Response to unpolarized radiation III



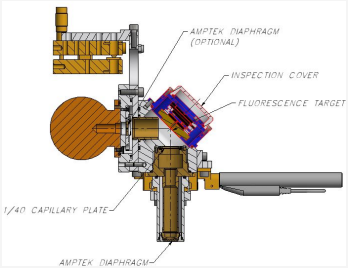
Map of spurious modulation at 2.7 keV for DU-FM2

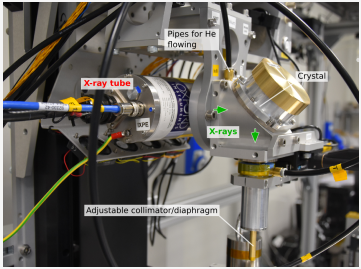


Spurious modulation as a function of energy on a spot with 3 mm diameter

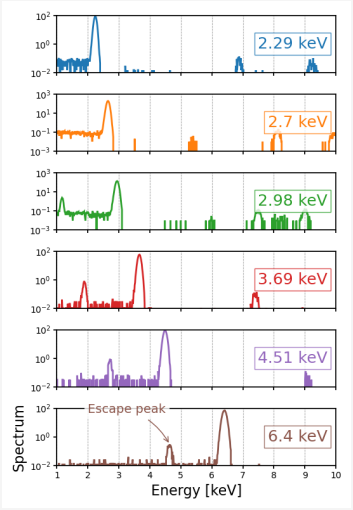
➥ Calibration will be applied in the pipeline running at SOC

Response to polarized radiation I



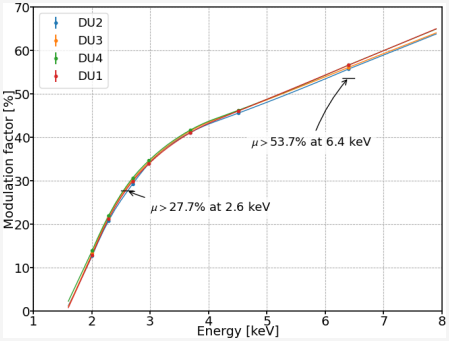


- Requirement is to collect 10^4 cts/mm^2 over the entire field of view
- Polarized sources based on Bragg diffraction at nearly 45°
  - Truly monochromatic photons
  - Degree of polarization derived by Bragg angle
  - Different crystals to diffract photons at different energies
- Up to five polarization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

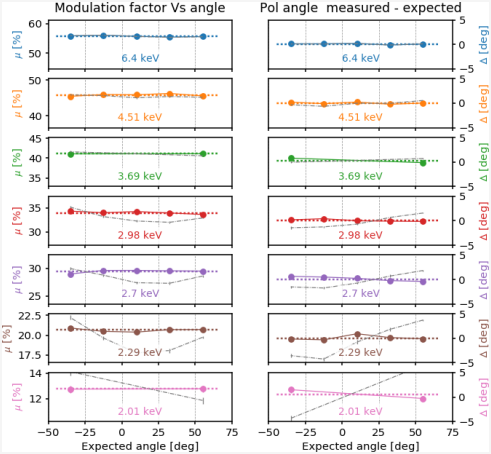


Spectrum with ICE test spectrometer

Response to polarized radiation II



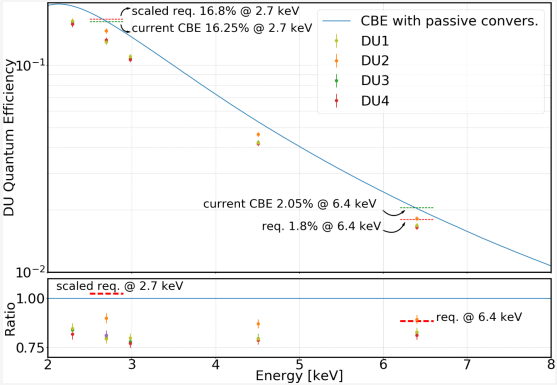
Modulation factor as a function of energy, constant over the field of view



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

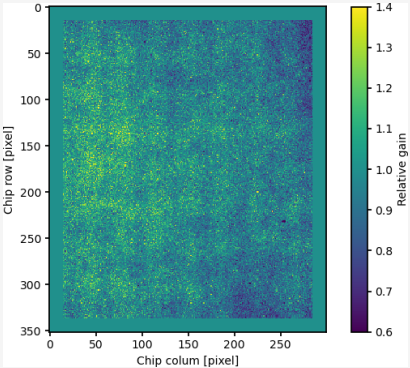
Quantum efficiency

- Comparison with flux measured with a reference detector
  - ➥ Measured with monochromatic sources at 5 energies
  - ➥ Globally, absolute uncertainty $\sim$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

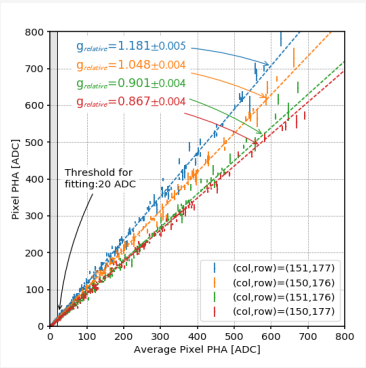


Pixel equalization

- 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

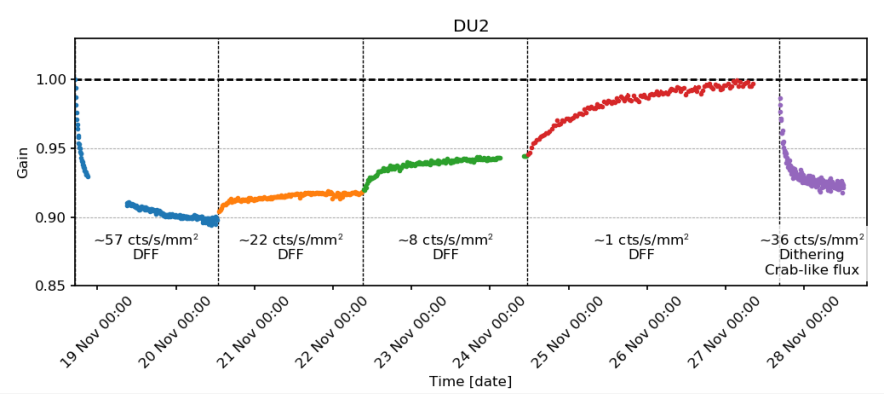


Pixel-by-pixel equalization map



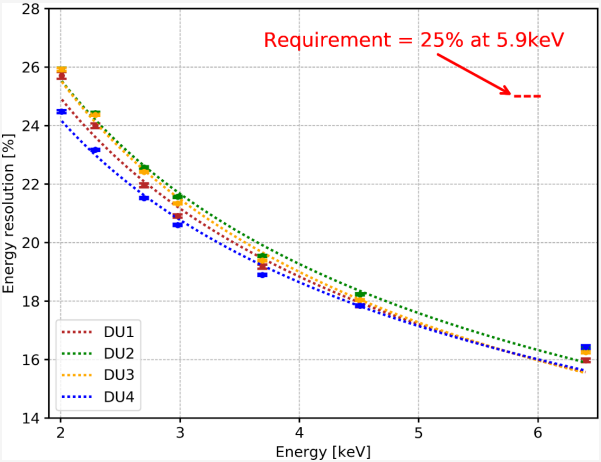
Relative equalization of single pixels

Gain calibration

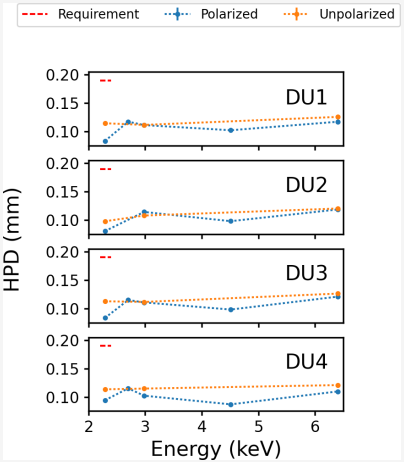


- Gain changes with illumination (Charging effect)
- Effect has been modelled
- Removed in the pipeline

Other results I

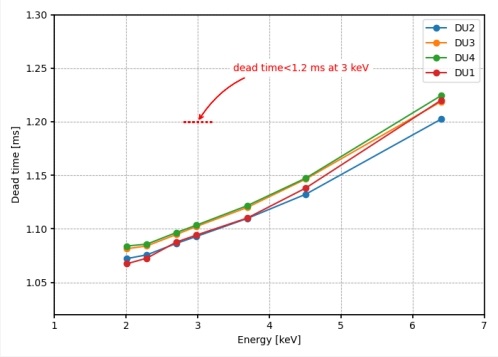


Energy resolution as a function of energy

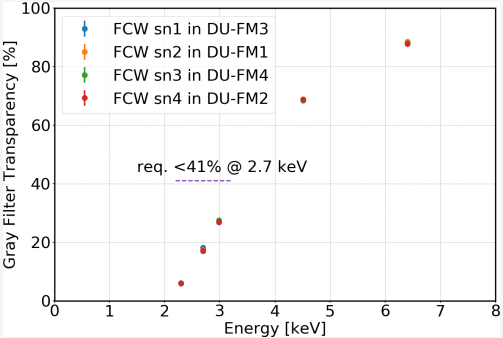


Spatial resolution at different energies, polarized and unpolarized

Other results II



Dead time as a function of energy

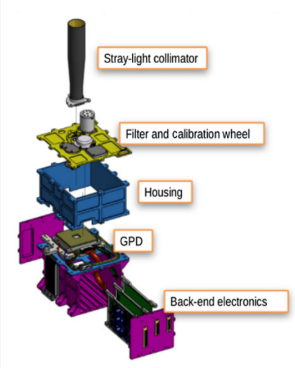


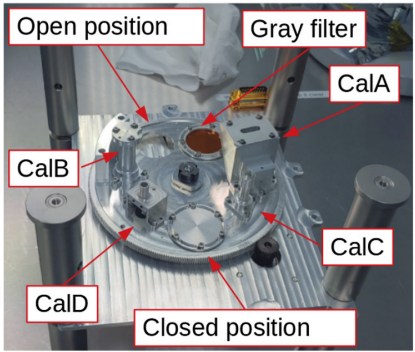
- Transparency of gray filter included in DU's FCW
- Provide flux calibration for exceptionally bright sources

On-board calibration sources

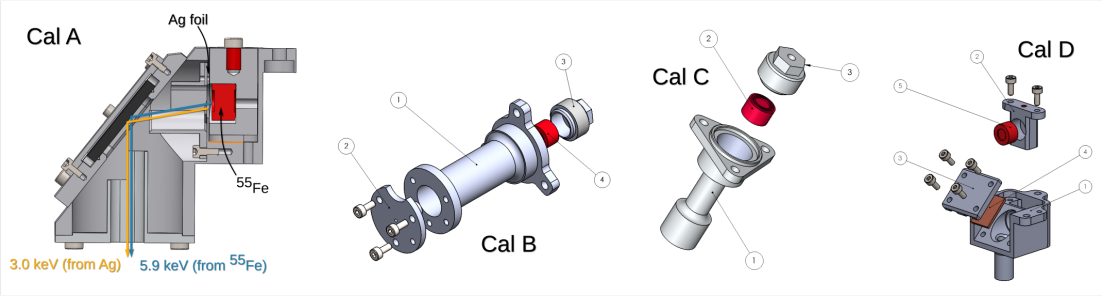
DU Filter and Calibration Wheel

- 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



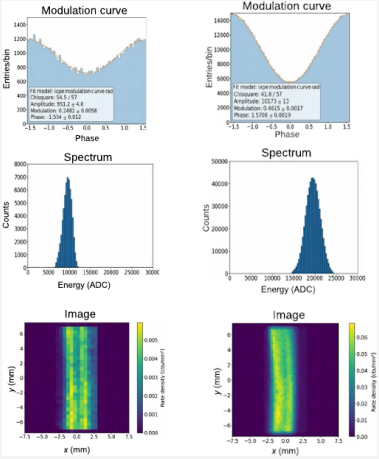


On-board calibration sources I

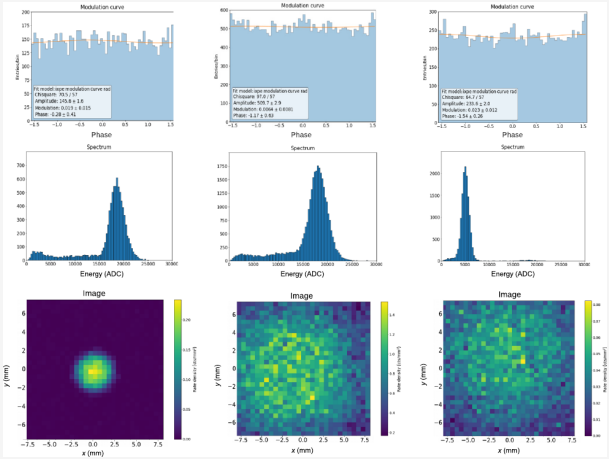


	Emission	^{55}Fe activity [mCi]	Notes
Cal A	polarized X-rays at 3.0 and 5.9 keV	100	Diffraction at $\sim 38^{\circ}$
Cal B	unpolarized spot at 5.9 keV	20	Response to unpolarized radiation
Cal C	unpolarized flat field at 5.9 keV	0.5	Gain calibration
Cal D	unpolarized flat field at 1.7 keV	100	Gain calibration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

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IXPE Instrument calibration team at INAF-IAPS

Thank you for your attention!