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ABSTRACT

IXPE (Imaging X-ray Polarimetry Explorer) is the next NASA Small Explorer mission foreseen for the launch in 2021. It is a partnership with the Italian Space Agency (ASI). IXPE is devoted to X-ray polarimetry in the 2-8 keV energy band. The IXPE telescope comprises three grazing incidence mirror modules coupled to three Detector Units (DUs) hosting each one a Gas Pixel Detector (GPD) polarimeter. The GPD, developed by the INFN and INAF-IAPS Italian research institutes, exploits the photoelectric effect to measure the linear polarization of the X-ray emission from astrophysical sources. Its spectroscopic (energy resolution $< 20\%$ at 6 keV), timing and imaging capabilities allow IXPE to perform unprecedented polarimetric measurements with high significance.

A wide and accurate on ground calibration was carried out on the IXPE detector units at INAF-IAPS in Rome. A dedicated facility was set-up to calibrate the DUs with polarized and unpolarized X-rays at different energies in the operating energy band.

In this proceeding we introduce this calibration set-up called Instrument Calibration Equipment (ICE) and the relevant outcomes from the calibration activity that confirms the capability of IXPE to open the window of high significance polarimetry in X-rays.

Keywords: IXPE, X-ray polarimetry, calibration, Gas Pixel Detector, GPD

1. INTRODUCTION

IXPE is a NASA SMEX mission in a partnership with ASI, scheduled to lunch in 2021.[1,2] It will measure the polarization of cosmic X-ray sources in the 2-8 keV energy band with high significance. The focal plane DUs and the Detector Service Unit (DSU) were developed by the Italian research Institutes INAF-IAPS and INFN and with contributions from OHB-I. Each DU is based on the same design and it employs a Gas Pixel Detector (GPD) photoelectric polarimeter.[3,4] The DU Flight Models (FM) underwent a full on ground calibration to determine the response to polarized and unpolarized radiation at different energies, the energy resolution, the spatial resolution and the quantum efficiency. Figure 1 shows the portioning of the amount of time spent to calibrate different parameters. The large fraction of calibration time (60%) was dedicated to the precise measurement of the spurious modulation with unpolarized X-ray sources and 17.5% of time was spent to calibrate the DU-FMs with polarized X-rays. The precise knowledge of the polarimeter behaviour to polarized and unpolarized

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radiaiton accross the energy band is needed to reach the required sensitivity. Beside to the calibration of other usual parameters such as energy and spatial resolutions and quantum efficiency, the response of the DU-FMs was characterized also with an inclined X-ray beam to anticipate the behaviour due to the coupling with grazing incidence optics.

The on ground calibration activity was performed by means of a dedicated facility (Instrument Calibration Equipment - ICE) specifically built at INAF-IAPS (see Figure 2). The calibration took place in a ISO7 (10,000 class) clean room and nominally lasted 40 days for each one of the 4 DU-FMs, 24 h a day, 7 days a week. To match the schedule constrains the ICE was partially duplicated in the AIV/T Calibration Equipment (ACE) facility to perform the calibration of two DU-FMs at the same time. After on ground calibration the DU-FM2, DU-FM3 and DU-FM4 were delivered to Ball Aerospace (Boulder, Colorado - USA) for the Instrument integration on the spacecraft. The DU-FM1 was delivered to the MSFC (Huntsville, Alabama - USA) for the telescope calibration with the spare X-ray optic module MMA4 at the Straylight Test Facility (SLTF).

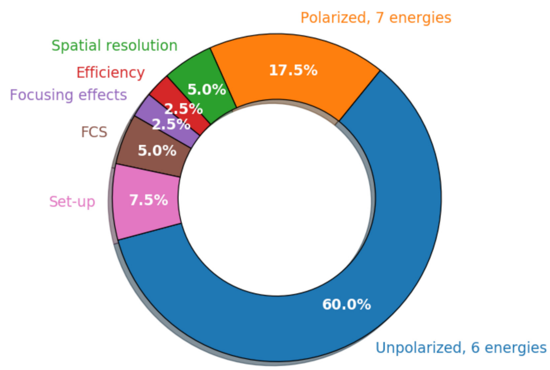

Figure 1. Time portioning of the calibration activities for the 4 DU-FMs: from set-up preparation to measurements.

2. THE ICE CALIBRATION FACILITY

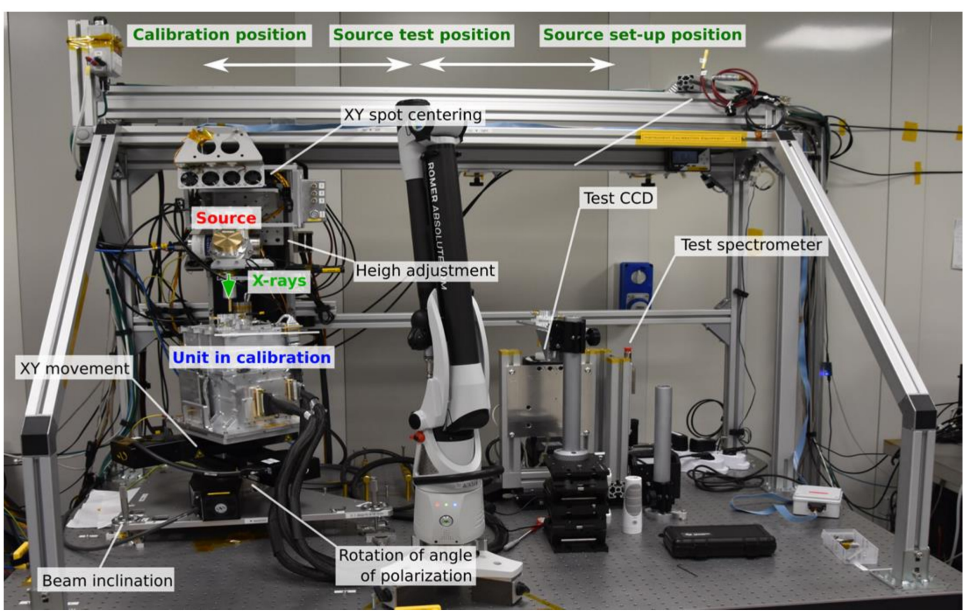

Figure 2. The Instrument Calibration Equipment (ICE).

The calibration facility ICE is the result of a long heritage in polarimetric test activity carried out at INAF-IAPS in the last 10 years. The ICE is equipped with polarized and unpolarized X-ray sources. The polarized sources exploit Bragg diffraction at 45° of different X-ray tube characteristic lines on different crystals matching the Bragg condition (see Table 1). The unpolarized sources comprises three different setups (see Table 2 and Figure 3). There are sources that exploits fluorescence emission from targets made of different materials, a sources based on the employment of an head-on X-ray tube (Ca Ka line at 3.69 keV) and an ^{55}Fe radionuclide source at 5.89 keV. Some of these sources show a detectable residual polarization that reaches the highest value for the 2.98 keV of the direct fluorescence emission form the X-ray tube with Ag anode. A filter made of Ag is added to cut the high energy part of the Bremsstrahlung energy spectrum. The residual Bremsstrahlung emission under the fluorescence line produces a certain level of polarization. Any residual polarization is removed from the data by summing, for all the X-ray sources, two measurements rotated by 90 degrees.

The precise alignment of the DU with the X-ray beam was achieved by means of micrometric stages that allow to translate in xy, to rotate and incline (tip/tilt) the DU-FM. The possibility to flow He in the polarizer, when present, and in the collimation path of the beam, allows to keep a high radiation flux also at low energy.

The ICE is equipped with two test detectors, an Andor iKon-M SY CCD and an Amptek FAST SDD 50 mm^2 spectrometer that allow to fully characterize the X-ray beam in terms of image and energy spectrum before to start the polarimetric calibration. A ROMER Absolute Arm was used to perform metrology at a level of few tens of micrometers.

The X-ray source is mounted on a mechanical support which allows to adjust its position and inclination with respect to the DU. It comprises both manual and micrometric motorized stages. We defined three different positions during the operations on the ICE: (1) calibration with DU; (2) source characterization with test detectors; (3) source set-up and mounting.

The ICE, the ACE and the Electrical Ground Support Equipment (EGSE) which power and control the DU-FM during calibration run on an Uninterruptible Power Supply (UPS) system which preserves the equipment from primary-power failures, automatically switching off critical items, that are, GPD high voltages, within minutes since the power outage. This allows to run calibration without the continuous presence of an operator.

Table 1. Set-ups and energies of the polarized sources available on the ICE. In black color the set-ups used for IXPE DU-FMs calibration.

Crystal	X-ray tube	Energy (keV)	2d	Diffraction angle (deg)	Rp/Rs	Polarization (%)
PET(002)	Continuum	2.01	8.742	45.000	0.0000	∼ 100.0
ADP(200)	Mo Lα	2.29	7.500	46.209	0.0027	99.46
InSb(111)	Mo Lα	2.29	7.481	46.361	0.0034	99.32
Graphite(0002)	Continuum	2.61	6.708	45.000	0.0000	∼ 1000.0
Ge(111)	Rh Lα	2.70	6.532	44.877	0.0024	99.53
Si(111)	Ag Lα	2.98	6.271	41.562	0.0252	95.08
Al(111)	Ca Kα	3.69	4.678	45.909	0.0031	99.38
CaF_2(220)	Ti Kα	4.51	3.840	45.716	0.0023	99.54
Si(220)	Ti Kα	4.51	3.840	45.716	0.0023	99.54
LiF(220)	Fe Kα	6.40	2.848	42.859	0.0529	∼ 89.95
Si(400)	Fe Kα	6.40	2.716	45.511		∼ 100.0

3. THE CALIBRATION AND RESULTS

Calibration of flight units started with DU-FM2 on September 6 th 2019, continued with DU-FM3 ended with DU-FM4 on February 3rd 2020. Calibration of DU-FM1 was split in two periods: unpolarized flat field measurements

Table 2. Residual polarization of the ICE "Unpolarized" X-ray sources.

Nominal Energy (keV)	Source Set-Up	Measured Polarization (%)
2.04	Fluorescence of Zn target illuminated by Rh X-ray tube	1.02 ± 0.19
2.29	Fluorescence of Mo target illuminated by Ag X-ray tube	0.73 ± 0.12
2.70	Direct X-ray tube with Rh anode with a PVC filter	6.29 ± 0.10
2.98	Direct X-ray tube with Ag anode with an Ag filter	13.02 ± 0.09
3.69	Direct X-ray tube with Ca anode	Undetected MDP(99%)=0.23%
5.89	^{55}Fe nuclide, 4mCi	Undetected MDP(99%)=0.22%

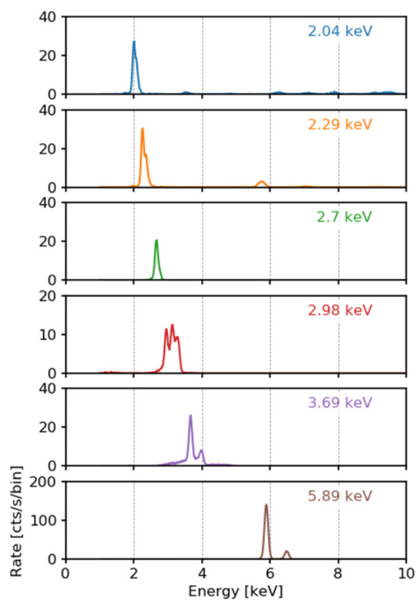

Figure 3. Energy spectra of the ICE "Unpolarized" X-ray sources.

were carried out between 27th July 2019 and 9th August 2019, whereas all other measurements were carried out from 15th July 2020 to 14th September 2020. 530 measurements were performed, for a total of 4052.3 hr of measurements and 2.250 billion counts collected.

IXPE will dither during the observations to reduce further more the effect of any residual spurious modulation after corrections of hardware effects and calibration. IXPE will observe point sources as well as extended sources, being the former the larger fraction of the observing plan. The precise calibration of the field of view is mandatory to reach the required sensitivity and it is particularly relevant for the central part of the field of view, where a deeper calibration was performed in a region of about 3 mm of radius. This region allows the observation of extended sources such as the Crab Pulsar Wind Nebula or the Super Nova Remnant Cas-A in a single pointing with a high level of sensitivity.

Therefore, the calibration was performed on all the field of view (Flat Field) and with increased sensitivity in the centre (Deep Flat Field) as shown in Figure 4. When calibrating polarized sources the source spot was moved to generate a nearly flat illumination (dithering). The analysis was carried out with respect to two regions in the image: SAT (1.5 mm radius, representative of the calibration quality over a region corresponding to the baseline satellite dithering area) and DFF (largest region common to all measurements, with 3 mm radius).

The detector and each source are aligned before any measurement with a Romer measurement arm. References on the mechanical frame of the GPD are used to derive the position of the GPD inside the DU. Beam direction, xy position and polarization direction of the incident beam are measured taking as a reference specific points identified on the source. Beam direction is aligned to GPD plane to better than 0.1 deg for unpolarized sources and 0.05 deg for polarized sources before starting calibration.

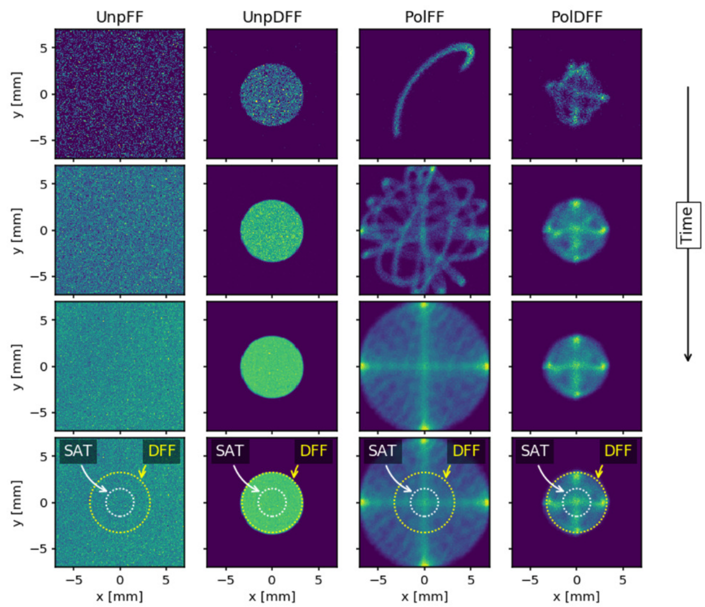

Figure 4. Dithering patterns and analysis regions.

4. RESULTS

The analysis of the calibration data reported in this proceeding is performed by means of the standard tools. The modulation of photoelectrons and the points of interactions are computed on the basis of the analysis of the statistical moments of the charge distribution. The modulation factor analysis is carried out by applying standard cuts as defined in the GPD acceptance tests. These removes 20% of the data with respect to the number of physical events, which are defined as the number of tracks that have at least one cluster of 6 pixels and occurs after more than 15 μs from the trigger enable signal. Standard cuts are applied in two steps:

- Spectrum of physical events is fitted with a Gaussian and events outside $\pm 3\sigma$ from the line peak are removed;
- Tracks are ordered as a function of their eccentricity. Lower-eccentricity tracks are remove up to a threshold which remove 20% of the original physical events (including the events removed at the first step).

Track images are corrected for known ASIC effects due to the read out of the Region Of Onterest (ROI).

Figure 5 and Table 3 report the modulation factor integrated over the DFF region. There are small differences among the 4 DU-FMs. Only DU-FM2 is slightly below the requirement that is however defined at Instrument level (integrated performance of DU-FM2, DU-FM3 and DU-FM4 as reported in Table 4). The Instrument is compliant with the requirement at 2.6 keV and 6.4 keV. The left panel of Figure 6 shows the position resolution of the DU-FMs as a function of energy for polarized and unpolarized radiation. The position resolution is well

Table 3. Modulation factor as a function of energy measured with the 4 DU-FMs. These values are plotted in Figure 5

DU-FM	Energy	μ (%)	σ_μ (%)
DU-FM1	2.01	12.93	0.16
	2.29	21.24	0.11
	2.70	29.87	0.12
	2.98	33.92	0.13
	3.69	41.07	0.17
	4.51	46.04	0.14
	6.40	56.59	0.09
DU-FM2	2.01	12.77	0.19
	2.29	20.82	0.15
	2.70	29.23	0.15
	2.98	33.96	0.15
	3.69	41.09	0.16
	4.51	45.55	0.14
	6.40	55.71	0.13
DU-FM3	2.01	13.30	0.20
	2.29	21.72	0.15
	2.70	30.23	0.15
	2.98	34.27	0.13
	3.69	41.44	0.17
	4.51	46.10	0.13
	6.40	56.10	0.10
DU-FM4	2.01	13.97	0.20
	2.29	21.99	0.13
	2.70	30.62	0.12
	2.98	34.65	0.11
	3.69	41.67	0.16
	4.51	46.21	0.13
	6.40	56.64	0.09

within the requirement defined at 2.3 keV. This is the intrinsic position resolution of the detector that will contribute to the total spatial (and angular) resolution that includes the quality of the optics first and then also the inclined penetration of the X-ray optic and the effect of blurring due to the diffusion of tracks in the gas cell.[5] The right panel of Figure 6 shows the energy resolution as a function of energy for the DU-FMs. The values reported in the plot are the average over 100 spots with 500 um of radius (representative of the optics PSF dimension). The energy resolution is well below the requirement defined at 5.9 keV.

The IXPE DU-FMs are equipped with calibration sources to carry out in-flight calibration of the Instrument and monitor the health status of each DU and changes in performance during the IXPE lifetime. These calibration sources are four and they are mounted on a Filter and Calibration Wheel (FCW). All of them are based on the employment of an ^{55}Fe radionuclide to produce X-ray photons:

- Cal-A: this is a polarized calibration sources that exploits Bragg diffraction of 5.98 keV photons and 3 keV fluorescence photons from an Ag foil on a graphite crystal. This source will be employed to monitor the modulation factor and the energy resolution.
- Cal-B: this is an unpolarized X-ray source based on the direct emission of an ^{55}Fe radionuclide producing a spot of about 3mm of radius in the image. This source will allow to monitor energy resolution and spurious modulation and the quantum efficiency.

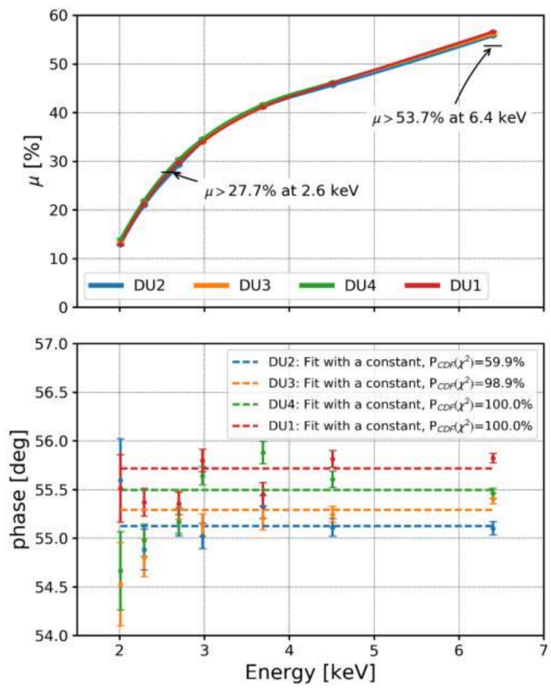

Figure 5. Modulation factor.

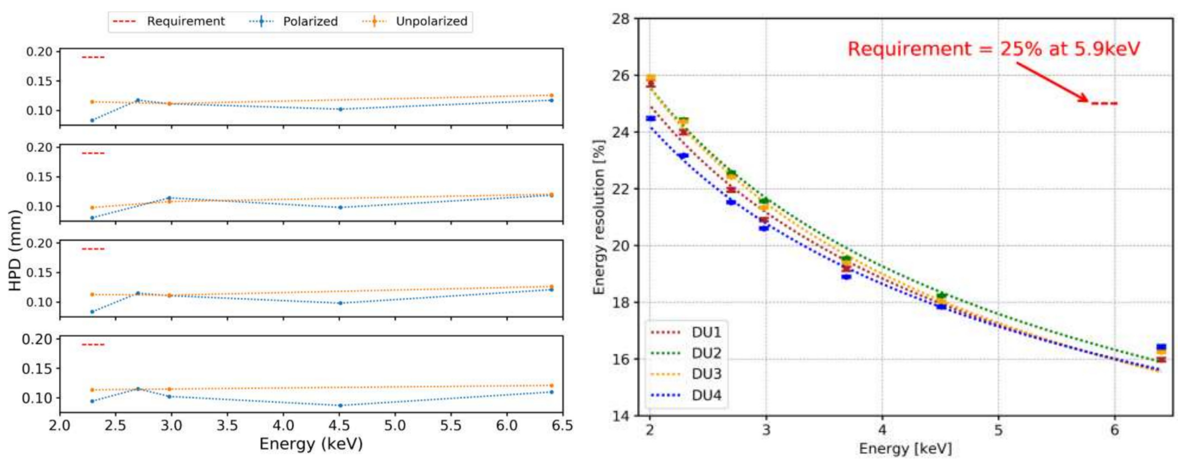

Figure 6. On the left: Half Power Diameter for the 4 DU-FMs (from DU-FM1 to DU-FM4) from top to bottom. On the right: energy resolution for the 4 DU-FMs as written in the figure legend.

- Cal-C: this is an unpolarized X-ray source based on the direct emission of an ^{55}Fe radionuclide that illuminates all the detector image to monitor the energy resolution, the gain and the quantum efficiency.
- Cal-D: this is an unpolarized X-ray source that produces fluorescence photons from a Si target to monitor the energy resolution and the spurious modulation at 1.7 keV.

These calibration sources where characterized during thermovacuum tests on the DU-FMs at INAF-IAPS.[6] The ^{55}Fe radionuclides that will actually fly on board the DU-FMs were installed at Ball Aerospace before the integration on the spacecraft. The calibration sources are currently employed to perform functional and performance test during the integration phase and environmental tests.

Table 4. Calibration parameters at instrument level (DU-FM2, DU-FM3 and DU-FM4)

Parameters	Requirements	Measured Instrument Performance
Modulation Factor (@2.6 keV; @6.4 keV)	(> 27.7%; > 53.7%)	(28.2%; 56.1%)
Quantum Efficiency (@2.7 keV; @6.4 keV)	(> 16.8%; > 1.8%)	(13.6%; 1.72%)
Gray Filter Transparency @2.7 keV	< 41%	17.4%
Energy Resolution @5.89 keV	< 1.5 keV (< 25%)	1.1 keV (18.1%)
Position Resolution @2.3 keV	< 190 μm	97 μm
Dead Time @3 keV	< 1.2 ms	1.1 ms
Amplitude of spurious modulation @5.89 keV	< 0.27%	0.25%
Systenatic error on polarization angle determination @6.4 keV	< 0.4 deg	0.2 deg

5. CONCLUSIONS

The DU-FMs of IXPE were fully calibrated on ground at INAF-IAPS in Italy before shipping them in USA to Ball Aerospace for the integration on the spacecraft and the environmental test campagn (DU-FM2, DU-FM3 and DU-FM4). The spare unit (DU-FM1) was shipped to MSFC for the telescope calibration with the spare unit of the optics modules (MMA4).

Table 4 reports the summary of the calibration parameters at Instrument level (all the DU-FMs except the spare DU-FM1). All the parameters are compliant with the requirements except for the quantum efficiency. The origin for this not compliance is known and does not affect the correct detector operation. The corresponding reduction in sensitivity can be mitigated with an improved analysis that increases the modulation factor and in any case by means of an increment of the observation time.

ACKNOWLEDGMENTS

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