IL NUOVO CIMENTO **47 C** (2024) 141
DOI 10.1393/ncc/i2024-24141-9

Colloquia: IFAE 2023

IXPE Gas Pixel Detectors characterization using the X-ray Calibration Facility(*)

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received 13 February 2024

Summary. — The Imaging X-ray Polarimetry Explorer (*IXPE*) is a space mission launched on 9 December 2021 (collaboration NASA and ASI) to measure the linear polarization of different astrophysical sources over the photon energy range 2-8 keV. The heart of *IXPE* Detector Unit, and of future polarization-aimed missions, is the Gas Pixel Detector. These detectors can be calibrated and characterized using the X-ray Calibration Facility, *XCF*, available at the Physics Department of the University of Torino. The *XCF* allows us to study X-rays at different energies with different spatial and polarization configurations. Initially conceived as a calibration source to qualify Gas Pixel Detectors, the *XCF* will support R&D programs of innovative position- energy- and polarization-sensitive X-ray detectors.

1. – Introduction

The state-of-art of X-ray polarimetry is the Imaging X-ray Polarimetry Explorer (*IXPE*), launched on 9 December 2021 (collaboration NASA and ASI) [1]. It combines good imaging capabilities and unprecedented polarization sensitivities in the energy range 2-8 keV, adopting a Gas Pixel Detector (*GPD*).

IXPE studies and measures the linear polarization of X-rays from different astrophysical sources. The polarization properties provide information about the geometry both of the emitting matter and of magnetic and gravitational fields: the level and type of symmetry of the system influence the polarization degree, while its angle indicates its orientation.

1˙1. *The Gas Pixel Detectors.* – The heart of *IXPE* Detector Unit is the Gas Pixel Detector, *GPD* [2]. The X-ray photons enter the detector volume through a Beryllium window and are absorbed into the dimethyl-ether gas ($(CH_3)_2O$, 800 mbar), interacting via photoelectric effect. In the gas gap, an electric field orthogonal to the detector plane

(*) IFAE 2023 - "Poster" session
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drifts the primary ionization electrons towards the Gas Electron Multiplier, *i.e.*, the gain stage. Finally, the produced charge is collected on the readout ASIC, that acts as anode.

The photo-electron is ejected in a direction, which preferably lies on the oscillation plane of the electric field of the incoming X-ray (*i.e.*, the polarization direction). The polarization information is then recovered on a statistical basis from the azimuthal distribution of the photo-electron emission directions, that are reconstructed analyzing the projections of the tracks on the readout plane.

The polarimeter sensitivity depends on two parameters: the quantum efficiency ϵ and the modulation factor μ, that represents the response to a 100% linearly polarized radiation. The figure of merit of a polarimeter is called Minimum Detectable Polarization and it is the minimum polarization degree that can be detected within a specific confidence level:

$$MDP_{99\%} \simeq 4.29/(\mu\sqrt{N}) \propto 1/(\mu\sqrt{\epsilon}) \tag{1}$$

2. – The X-ray Calibration Facility

The X-ray Calibration Facility (*XCF*) is housed in the Physics Department of the University of Torino. It is a table-top, open-design irradiation setup offering photon beams of various energy, size and polarization properties, suitable for detector calibrations. It has been conceived to characterize and qualify the Gas Pixel Detectors of *IXPE*, but its employment can be extended also to other position- energy- and polarization-sensitive X-ray detectors.

Its scheme is presented in fig. 1 (*Left*) and its main components are: the X-ray source (sect. **2**·1), the vacuum system, that allows working at $\sim 2 \times 10^{-6} mbar$, an handling system and the polarizing crystals.

2·1. *The X-ray source.* – The *XCF* source is an X-ray tube (McPherson Mod. 642) with two orthogonal output beam lines. The tube is equipped with a multi-anode carousel that allows to select the desired anode as X-ray source: the different anodes produce their

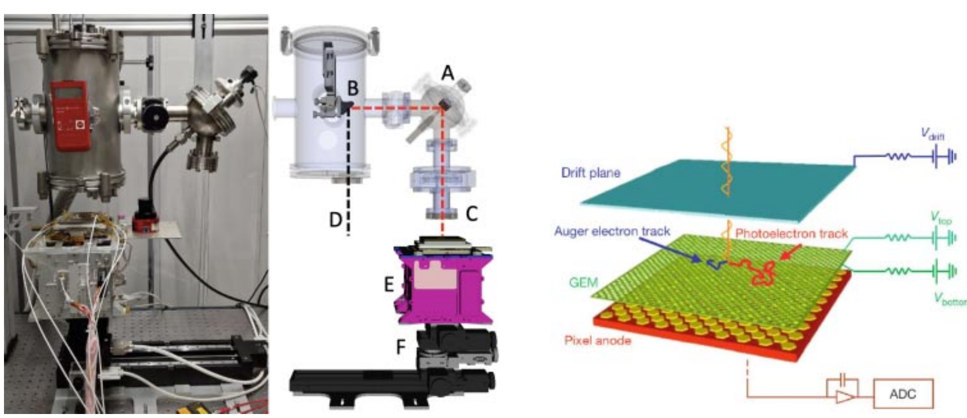

Fig. 1. – *Left*: the *XCF* scheme: A is the X-ray source, B is the polarizing crystal, C is the unpolarized beam, D is the polarized beam, E is the detector and F is the handling system. *Right*: the *GPD* working principle.

Table I. – *The anodes with their characteristic energies and the matched crystals.*

Anode	Energy [keV]	Crystal	θ_{Bragg}
Molybdenum [Mo]	2.293	InSb 111	46.28°
Rhodium [Rh]	2.697	Ge 111	44.87°
Palladium [Pd]	2.839	Si 111	44.12°
Titanium [Ti]	4.511	Si 200	45.71°
Iron [Fe]	6.40	Si 400	45.6°
Nickel [Ni]	7.478	Ge 422	45.86°

characteristic lines with energies in the range 70 eV - 10 keV (as well as the Bremmstrahlung component, up to 10 keV).

The polarized beam is obtained via Bragg diffraction on crystals appropriately coupled to the anodes (table I), *i.e.*, to the energy of the incoming X-ray, according to the Bragg diffraction law $E = \frac{nhc}{2d\sin(\theta)}$, where E is the energy of the photon, d is the crystal lattice step, n is the order and θ is the incidence angle. The polarization degree of the diffracted radiation is $P = \frac{1-k}{1+k}$, where $k = R^{\pi}_{E}/R^{\sigma}_{E}$ is the ratio of the integrated reflectivity of the parallel and perpendicular component, with respect to the incidence plane. For a full polarized radiation the condition to be satisfied is: $k = 0$ and $\theta = \theta_{Bragg} = 45°$ [4].

Since the *XCF* provides two output beams, it is equipped with a handling system that allows us to place the detector under the desired beam.

3. – The X-ray beam studies

The first operation performed with the *XCF* has been the study and characterization of the unpolarized beam, analyzing its spectral and spatial properties. A Silicon Drift Detector (*SDD*) and a CMOS ASI ZWO Camera have been used to monitor the beams.

3˙1. *The X-ray beam monitoring.* – The *SDD* has an energy resolution of 122 eV Full Width Half Maximum at 5.9 keV and the results for the spectra of the six anodes are plotted in fig. 2 (*Left*). The CMOS ASI ZWO Camera has been originally conceived for astrophotography, with $4\mu m$ sized pixel arranged in an array of 2822×4144. By removing a protective glass, it is possible both to acquire the energy spectrum and to display the X-ray beam. As an example, fig. 2 (*Left*) shows the polarized beam image acquired with the CMOS camera: the Bragg arc can be seen in the center.

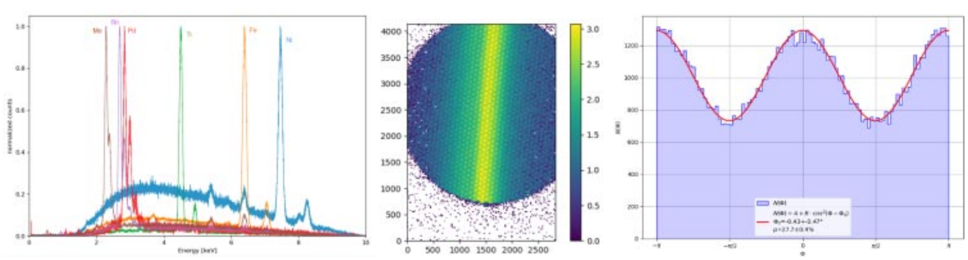

Fig. 2. – *Left*: *SDD* spectra of the anodes and the CMOS image of the Bragg arc. *Right*: the modulated distribution of the events with its fit, measured with the *GPD*.

3·2. *The polarized beam study with the GPD*. – Thanks to the handling system, the *GPD* has been used to analyze both the unpolarized and polarized beam. In the first case the results are compatible with those obtained with other detectors, mentioned in the previous section, while the study of the polarized beam allowed us to measure the modulation factor μ of the *GPD*.

A Rhodium anode (E=2.697 keV) coupled with the Ge 111 crystal has been employed for these first studies. The photo-electric effect differential cross section for a polarized radiation depends on the $\cos^2$ of the azimuthal angle ϕ, which identifies the photo-electron emission direction with respect to the polarization [5]. The integrated number of events is thus modulated according to

$$N(\phi) = A + B\cos^2(\phi - \phi_0), \tag{2}$$

where ϕ_0 is the polarization angle. The modulation factor μ can be evaluated both using the parameters A and B and from the Stokes parameters(1) [3]:

$$\mu = \sqrt{Q^2 + U^2}/I^2 = B/(2A + B) \sim 28\% \qquad \text{at 2.7keV} \tag{3}$$

The result is compatible with the expected value obtained during the tests performed for the acceptance campaign of the *GPD* flight models.

4. – Conclusions

We presented the *XCF*, a complete multi-functional experimental setup, to be used as calibration and test facility for different X-ray detectors. We described its main components, the monitoring of the beams and the first result achieved measuring the modulation factor of a *GPD*. In the future, the *XCF* will be employed for R&D programs of innovative position- energy- and polarization-sensitive X-ray detectors.

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The *XCF* is funded through contributions of the University of Turin (Bando CSP/Ateneo 2020, "Piccole e medie attrezzature di ricerca"), ASI (Agreement IXPE-2017.13-H.0, ADAM-2018.11-HH.0, eXTP-2020-3.HH.0) and INFN. This publication is part of the project NODES which has received funding from the MUR – M4C2 1.5 of PNRR with grant agreement no. ECS00000036.

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(1) The Stokes parameters allow to describe the polarization: calling ψ_k the azimuthal angle, $I = N$, $Q = \sum_{k=1}^{N} \cos(2\psi_k)$ and $U = \sum_{k=1}^{N} \sin(2\psi_k)$.