IXPE Gas Pixel Detector characterization with the X-ray Calibration Facility

S. Tugliani

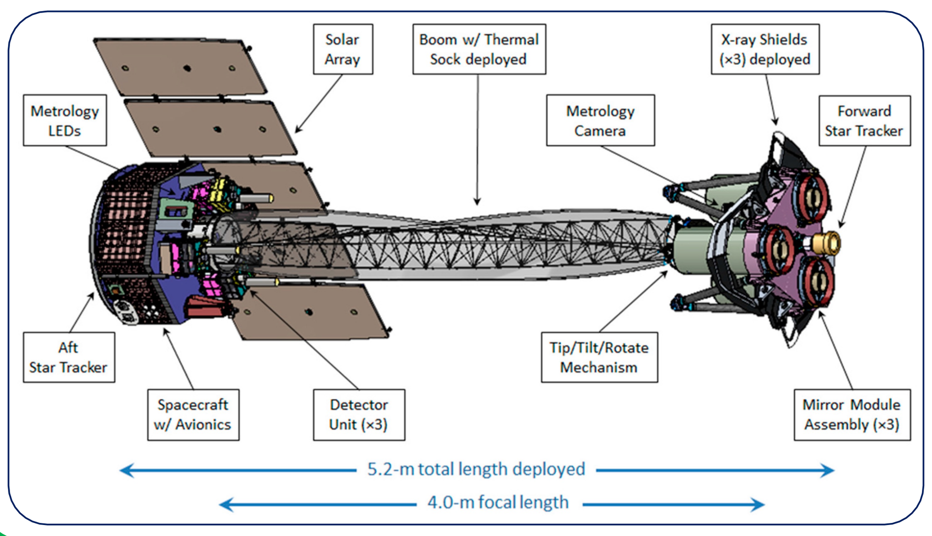
M. Aglietta, R. Bonino, N. Cibrario, A. Frassà, A. Gorgi, L. Latronico, S. Maldera, M. Marengo, L. Messina P.

Istituto Nazionale di Fisica Nucleare SEZIONE DI TORINO

Finanziato dall'Unione europea NextGenerationEU · Ministero dell'Università e della Ricerca · Italiadomani · NODES · Spoke1

The Imaging X-ray Polarimetry Explorer (IXPE) (collaboration NASA – ASI) represents the current state-of-the-art astrophysical X-ray polarimeter: it can measure the linear polarization of different astrophysical sources over the photon energy range 2-8 keV. The core of IXPE Detector Unit and future X-ray polarimetry missions is the Gas Pixel Detector (GPD).
It can be calibrated and characterized using the X-ray Calibration Facility (XCF), available at the Physics Department at the University of Turin. The XCF is a table-top, open-design irradiation setup for research: it offers beams of photons at different energies and with different spatial and polarization configurations. XCF can provide two beam-lines and one of them is linearly polarized through Bragg diffraction. Both beams can be monitored and characterized using a Silicon Drift Detector and a modified CMOS ASI ZWO Camera. Thanks to a handling system, the GPD can measure both the unpolarized and polarized beam.
Initially conceived as a calibration source to qualify GPDs, the XCF can satisfy evolving requirements to support R&D programs of innovative position-energy and polarization-sensitive X-ray detectors.

IXPE: Imaging X-ray Polarimetry

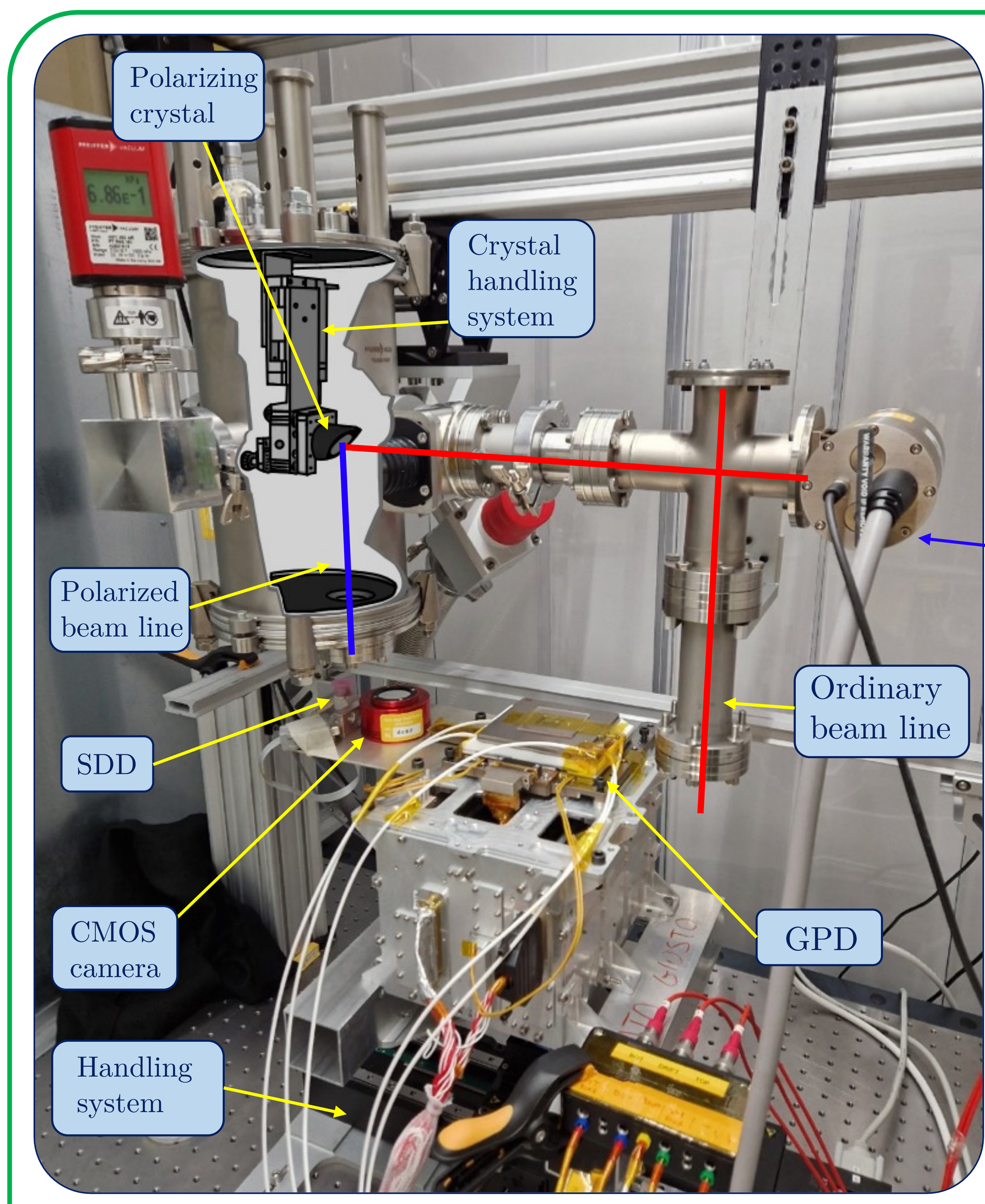


IXPE's aim is the study of the linear polarization of astrophysical X-ray sources in the 2-8 keV energy range.

- Launch: 9th December 2021.
- Orbit: 600 km, equatorial (inclination 0°).
- Detector: **3 Detector Units (DU)**, each of them equipped with a **Gas Pixel Detector.**

POLARIZATION: information about the geometry of the emitting matter and of magnetic and gravitational fields.

X-RAY CALIBRATION FACILITY



XCF is an irradiation setup at the University of Turin to test, characterize and qualify:

- IXPE Gas Pixel Detectors.
- Position- energy- and polarization-sensitive X-ray detectors.

Radiation source:

- Multi-anode X-ray tube (Mc Pherson Mod. 642).
- Sealed Micro X-ray tube equipped with a Molybdenum anode with emission at 2.293 keV.
- ^{55}Fe source.

The X-ray tube can be mounted in two positions:

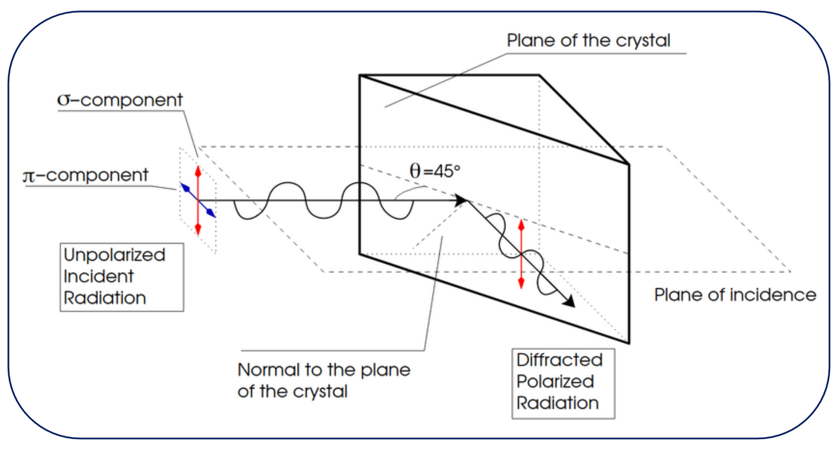
1) Vertical: X-ray photons follow the ordinary beam line.

2) Horizontal: X-ray photons are polarized via Bragg diffraction on polarizing crystal, thus obtaining the polarized beam line.

Bragg diffraction

$$E = \frac{nhc}{2d\sin\theta}$$

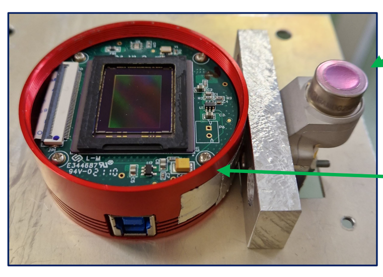
E: photon energy, *d*: grating constant, *n*: diffraction order, θ: incidence angle



The polarization degree of the diffracted radiation is $P = \frac{1-k}{1+k}$. $k = \frac{R_E^{\pi}}{R_E^{\sigma}}$ is the ratio between the integrated reflectivity of the parallel and orthogonal components with respect to the incidence.
For a totally polarized radiation: k=0 e θ=θ_{Bragg}=45°.

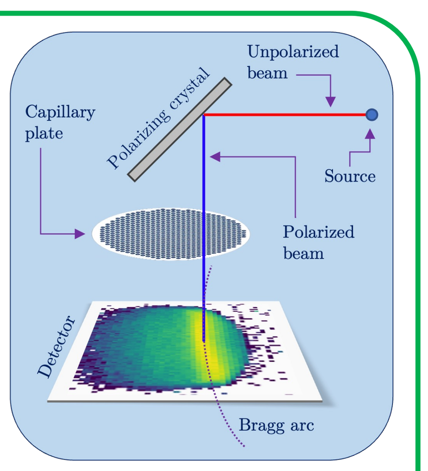
The Bragg diffraction polarizes the incoming radiation and selects only the energies that satisfy the Bragg law.

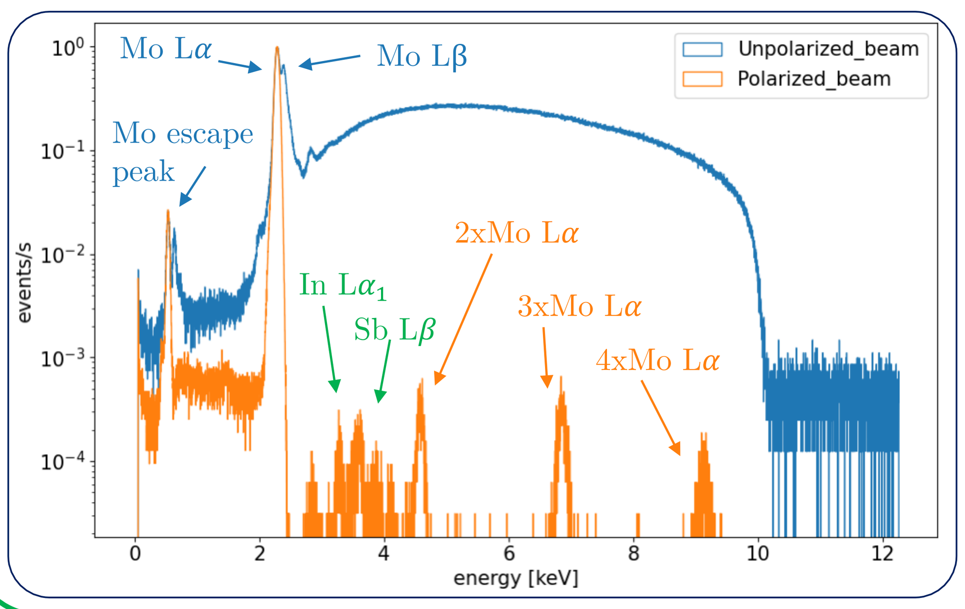
X-RAY BEAMS MONITORS



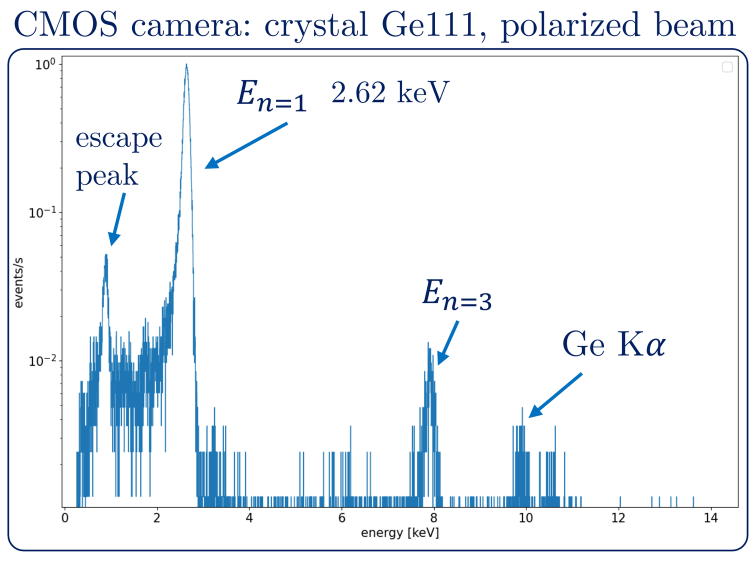
Silicon Drift Detector:
Resolution: 2% FWHM @ 5.9 keV ⟹ *Spectrum*

CMOS ASI ZWO camera: (originally conceived for astro-photography), 2822x4144 4 μm pixel array (modified removing the protective glass) ⟹ *Spectrum* and *charge map*





CMOS camera: crystal Ge111, polarized beam

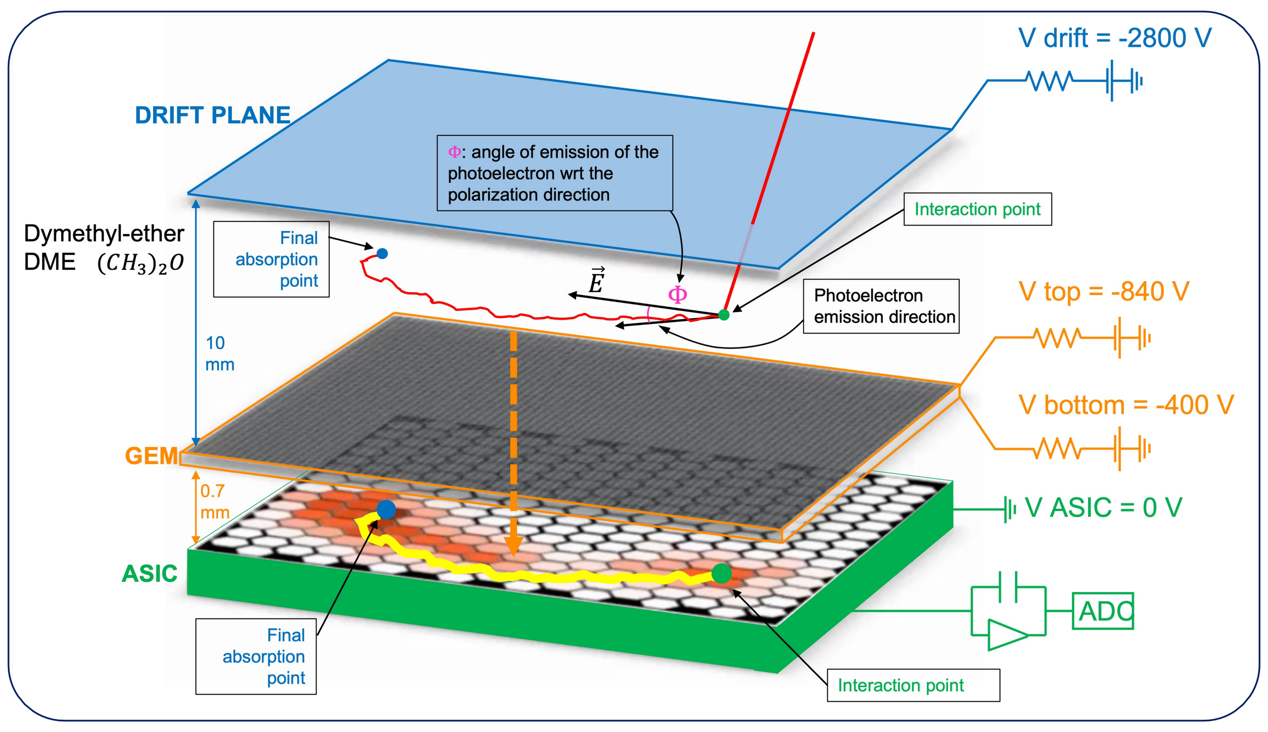


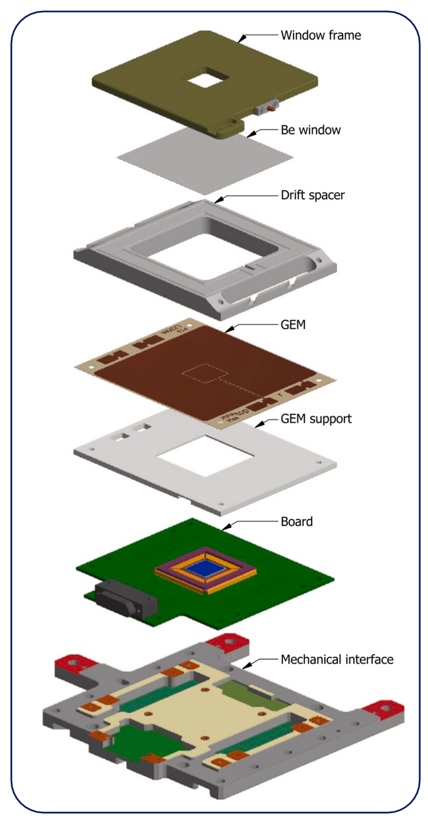
GAS PIXEL DETECTOR

1) X-ray photons enter the detector through a Beryllium window and they are absorbed in the Dymethil-Ether (DME, $(CH_3)_2O$, 800 mbar), interacting via photoelectric effect;

2) Into the gas gap, an electric field (orthogonal to the detector plane) drifts the primary ionization electrons towards the gain stage: the Gas Electron Multiplier GEM;

3) The charge is then readout by the ASIC, that acts as a pixel array anode.





Photoelectric cross section for a polarized radiation:

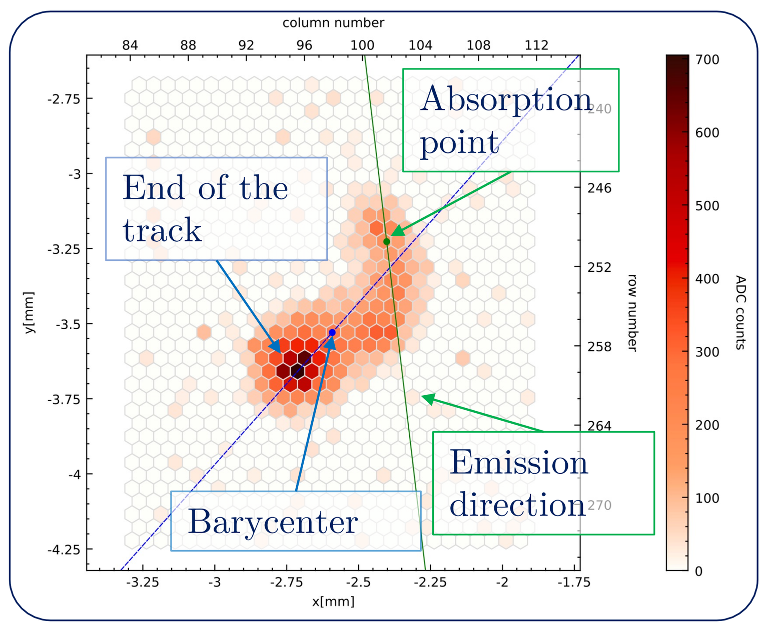
$$\frac{d\sigma}{d\Omega} = r_0^2\alpha^4 Z^5 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta\cos^2\phi}{(1-\beta\cos\theta)^4}$$

The azimuthal angle ϕ identifies the photoelectron emission direction with respect to the polarization one.

The integrated number of events are modulated by the law

$$N(\phi) = A + B\cos^2(\phi - \phi_0)$$ ϕ_0 Polarization angle

The polarization information is recovered on a statistical basis from the distribution $N(\phi)$.



Polarimeter sensitivity:
Minimum Detectable Polarization: minimum polarization degree that can be measured within a given confidence level:

$$MDP \propto \frac{1}{\mu\sqrt{\varepsilon}} \qquad MDP_{99\%} \simeq \frac{4.29}{\mu\sqrt{N}}$$

ε: quantum efficiency, μ: modulation factor

MODULATION FACTOR μ: response of the detector to a 100% linearly polarized radiation

- From the fit of $N(\phi)$ $\quad \mu = \frac{N_{max} - N_{min}}{N_{max} + N_{min}} = \frac{B}{2A + B}$
- From the Stokes parameters *I*, *Q* and *U* $\quad \mu = \frac{\sqrt{Q^2 + U^2}}{I}$

GPD MEASUREMENTS OF THE POLARIZED BEAM

XCF is equipped with a set of 6 crystals which are matched with specific energies so that the Bragg condition is satisfied.

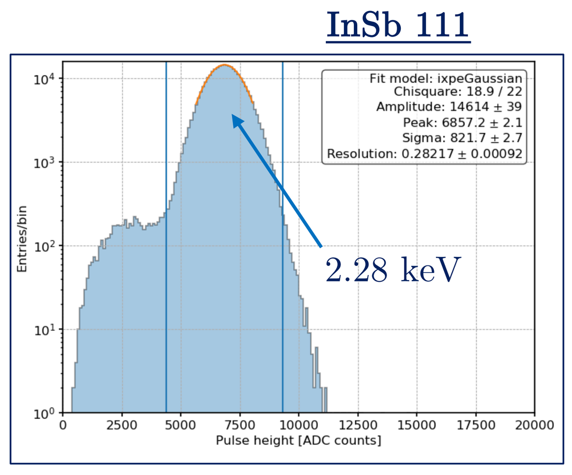
Crystal	Energy [keV]	Sigma [keV]	θ Bragg	P [%]
InSb 111	2.28	0.04	46.6 °	~99
Ge 111	2.62	0.04	46.5 °	~99
Si 111	2.82	0.04	44.4 °	~99
Si 220	4.45	0.05	46.6 °	~98
Si 400	6.32	0.06	46.3 °	~99
Ge 422	7.43	0.06	46.2 °	~99

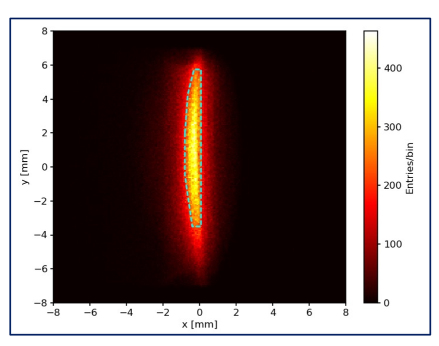
Data obtained using the SDD

Strategy: mounting the crystal at the Bragg angle, a totally polarized beam (~99%) at the corresponding energy is obtained.

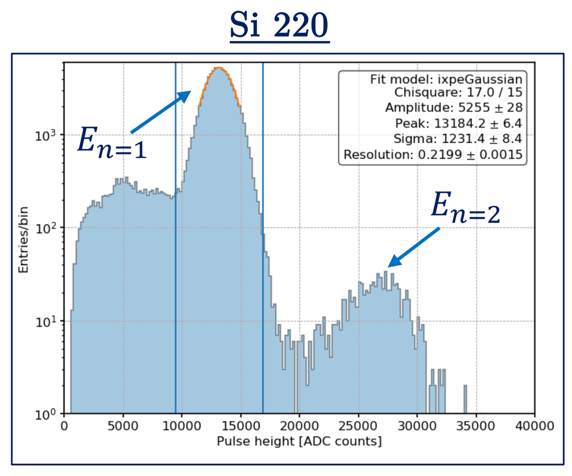
- InSb 111: the selected energy is the same of the anode of the MXR tube;
- With the other crystals, higher energies can be achieved, but with lower rates (Bremsstrahlung component of the tube spectrum).

InSb 111





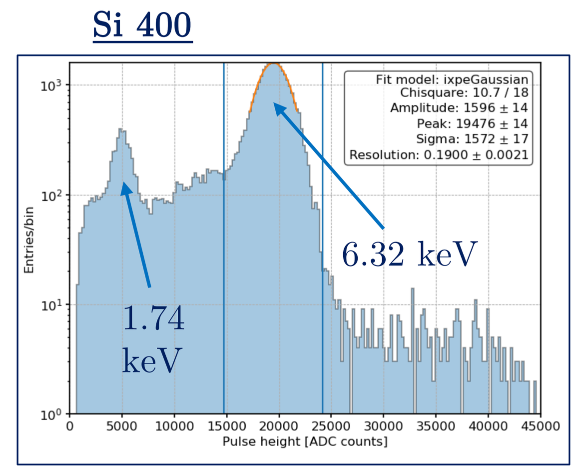
Si 220



It is possible to observe also the energy correspondent to the second diffraction order: the obtained μ is coherent with the one expected at that energy:

$E_{n=1}$=4.45 keV ⟹ $E_{n=2}$=8.90 keV ⟹ $\mu(E_{n=2}) \simeq 55\%$

Si 400



In addiction to the diffracted polarized X-ray, the spectra show features at the fluorescence energy of the crystal: these photons are not polarized.

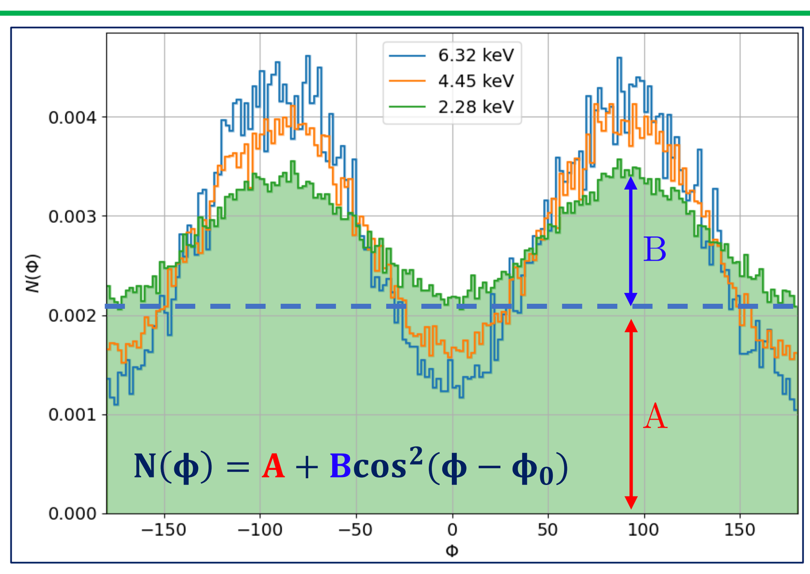
PRELIMINARY RESULTS

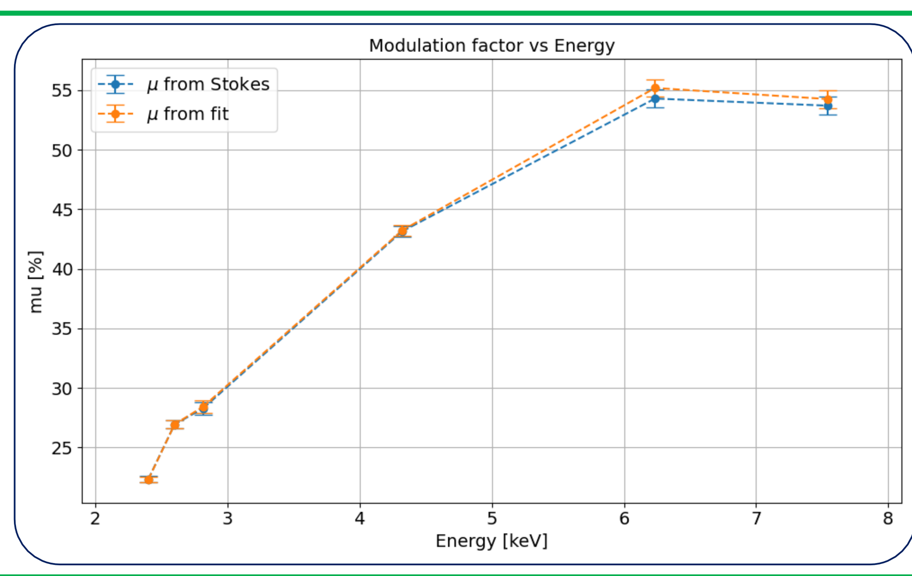
As the energy of the incoming X-ray photon increases, the track into the GPD is longer and the photoelectron emission direction is better reconstructed

⬇

The modulation factor increases with energy

N.B.: for the moment, these results are not yet corrected for the systematics of the detector.





Other applications of XCF:

- GPD long term studies: monitoring of a set of control detectors, identical to those currently operating in space, to study the secular pressure variations.*
- Study of the transparence of different windows for future X-ray detectors.
- Tests on other X-ray detectors sensitive to energy, position and polarization.

* Tomaiuolo, C. et al, poster 66 Pisa meeting 2024, Time-dependent instrumental effects in IXPE: pressure variation and GEM charging inside GPDs.

Bibliography