Performance of the Gas Pixel Detector: an X-ray imaging polarimeter for upcoming missions of astrophysics

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ABSTRACT

X-ray polarimetry is a hot topic and, as a matter of fact, a number of missions dedicated to the measurement of the polarization in the ∼2-8 keV energy range with photoelectric devices are under advanced study by space agencies. The Gas Pixel Detector (GPD), developed and continuously improved in Italy by Pisa INFN in collaboration with INAF-IAPS, is the only instrument able to perform imaging polarimetry; moreover, it can measure photon energy and time of arrival. In this paper, we report on the performance of a GPD prototype assembled with flight-like materials and procedures. The remarkably uniform operation over a long period of time assures a straightforward operation in orbit and support the high readiness level claimed for this instrument.

Keywords: X-ray, Polarimetry, Gas detectors, Astronomy

1. INTRODUCTION

Polarimetry in the X-ray energy range is expected to provide a prime contribution to the understanding of the source emitting in this energy range. In fact, emission processes are typically non-thermal, and then distinctively polarized. Polarimetry can provide two observables - the degree and the angle of polarization - which complement and are completely independent from the spectral and temporal information currently available for discriminating competitive models. Notwithstanding, X-ray polarimetry is an observational window still to be opened, because technical hurdles which limited the sensitivity of instrumentations have in fact prevented the launch of further instruments after the first attempts in 1970s. Such a scenario has changed with the development of photoelectric polarimeters, which can provide both a good sensitivity to polarization and a good efficiency over a broad energy band. Currently, out of six missions under study by ESA and NASA in the context of the 4th call for a medium mission and of the small explorer program, respectively, three of them, XIPE (see Soffitta et al. in these proceedings), IXPE (see Weisskopf et al. in these proceedings) and PRAXyS (see Jahoda et al. in these proceedings), are dedicated to X-ray polarimetry with photoelectric polarimeters. Both XIPE and IXPE use the Gas Pixel Detector (GPD), which was the first device to be sensitive in the ∼2-8 keV energy range[1–3] and still the only to provide a real image of the source with a very good spatial resolution.[4]

For a recent review on the GPD design and characteristics, refer to Bellazzini et al.[5] and references therein; in this paper, we will present a measurement campaign which was dedicated to the characterization of a GPD prototype built with flight-like materials and procedures to validate its use on-board next satellite missions. We studied not only the scientific performance of the instrument, that is, the sensitivity to polarization, energy resolution, and uniformity of the response, but also the temporal stability of these characteristics over a period of time comparable with a space mission.

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2. GPD CONFIGURATION

The characteristics of the GPD under test are summarized in Table 1. The prototype has the same characteristics as the instruments proposed on-board XIPE and IXPE, and was manufactured with the same materials and procedures which would be exploited for the construction of flight models for these missions. The GPD is based on a gas cell for the absorption of X-rays, in which the photoelectron can leave a track long enough to be sampled. Secondary ionization is drifted with an electric field, on average orthogonal to the photoelectron emission plane, towards a multiplication stage (a Gas Electron Multiplier, GEM) and then towards the sampling anode, which is a finely segmented ASIC that includes the amplification chain. The GPD was filled and sealed at the moment of manufacturing with a mixture optimized for the operation in the ∼2-8 keV energy range, Helium 20% + DME 80% at 1 bar.

Table 1. Characteristics of the GPD under test.

Window	Beryllium, 50 μm thick
Gas filling	He 20% + DME 80% at 1 bar
Cell thickness	1 cm
GEM	50 μm pitch, 50 μm thick. Total area 88x88 mm^2, active area 18x18 mm^2
ASIC	105k pixels, 50 μm pitch sensitive area 15x15 mm^2 see Bellazzini et al.[2]

3. MODULATION FACTOR

Photoelectric polarimeters measure the polarization by imaging the track of the photoelectron emitted after a photoelectric absorption in a gas mixture and by reconstructing its emission direction, which is more probable along the photon electric field.[1] The sensitivity to polarization depends, in addition to quantum efficiency ϵ, on the capability of measuring accurately the initial direction of the photoelectrons; longer photoelectron tracks, produced by higher-energy photons, are easier to reconstruct before scatterings with atomic nuclei smear the information on the initial direction and, therefore, the response of the instrument to polarization at higher energy is larger. This is usually accounted for by introducing the energy dependent *modulation factor* μ, that is, the amplitude of the modulation in the instrument response in case of completely polarized radiation (see, e.g., Fabiani & Muleri[6]).

We measured the modulation factor as a function of energy using the X-ray facility at INAF-IAPS.[7] Completely polarized radiation was produced by diffracting unpolarized X-ray photons on different crystals at 45° at 2.0, 2.6, 3.7, 4.5, 6.4 keV and 8.0 keV. A 400 μm diaphragm was used to produce a spot on the GPD which is representative of that expected in the focus of an X-ray telescope,[8] except for the measurements at 3.7 and 8.0 keV because of the low flux. A picture of the set-up is shown in Figure 1.

At the data analysis stage, an event selection was applied to maximize the quality factor $\mu\sqrt{\epsilon}$, which is proportional to the instrument sensitivity to polarization. The cut removes 20% of the less eccentric tracks, which contain a very limited information on the photoelectron initial direction and hence on the photon polarization.[9] The modulation curve at 3.7 keV and at 6.4 keV are reported in Figure 2(a) and Figure 2(b), respectively. A typical photoelectron track at 6.4 keV is shown in Figure 3(a), and the image of the source at 4.5 keV is in Figure 3(b).

The modulation factor measured in the current calibration campaign is reported in Figure 4 as the solid red line. The result is compared with the modulation factor measured at 4.5 keV and 6.4 keV with the same sealed prototype 26 months before the calibration campaign presented in this paper (green dashed line). Although a complete set of measurements over the entire energy range is not available, the comparison shows a remarkable stability of the GPD response to polarization, lower than the statistical errors of the measurements.

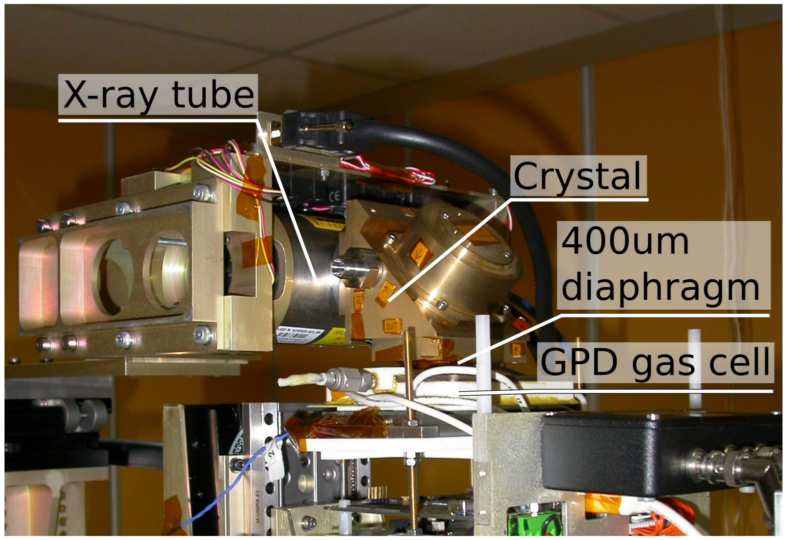
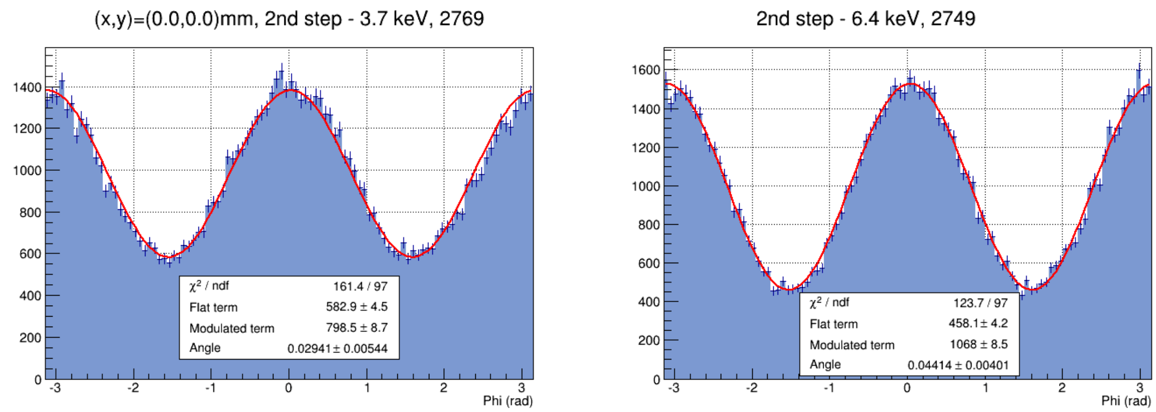


Figure 1. Picture of the set-up at the INAF-IAPS X-ray facility for measuring the modulation factor and the energy resolution as a function of energy.



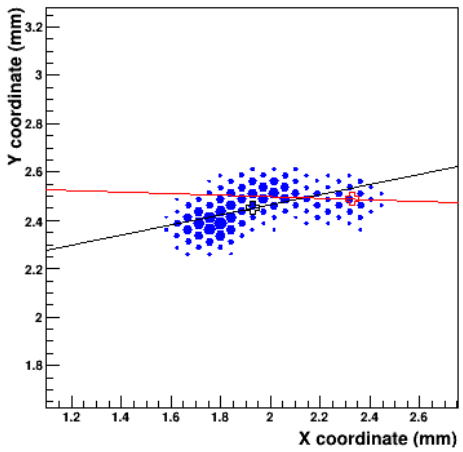
(a) (b)

Figure 2. Modulation curve at 3.7 keV (**a**) and at 6.4 keV (**b**).

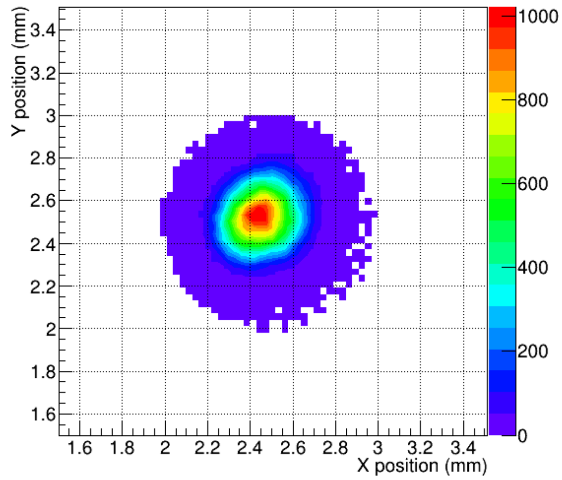
4. ENERGY RESOLUTION

Polarized photons generated at the X-ray facility at INAF-IAPS through Bragg diffraction at 45° are also nearly monochromatic. The intrinsic FWHM of the diffracted line depends on the crystal and on the details of the setup used for generating the beam, and ranges from a few eV to a few tens of eV; to all extents and purposes, photons of this kind can be treated as monochromatic when detected with the GPD. Therefore, the energy resolution of the instrument as a function of energy can be determined from the data as well; the result is shown in Figure 5, together with the values derived by the measurements carried out 26 months before the present campaign. The perfect consistency of the measured values supports the fact that the operation of the GPD is extremely stable over a period of several tens of months.

To further consolidate these results, we included in our analysis data samples obtained in the past over a period of about three years, i.e. since the GPD filling, in different setup. We included measurements with both monochromatic (and polarized) radiation and sources which show prominent but not spectrally resolved X-ray lines. In the former case, we simply fitted the spectrum with a Gaussian line to derive the energy resolution at that energy; in case unresolved lines are present, we fitted the spectrum with a function which is the sum of each contribution, with the proper weight fixed at the expected value. We focused on three energies, 3.7 keV, 4.5 keV



(a)



(b)

Figure 3. (**a**) Example of a track at 6.4 keV. The size of the blue markers represents the amount of charge in each pixel, and the red cross and line are the reconstructed absorption point and photoelectron emission direction. (**b**) Image of the calibration beam at 4.5 keV.

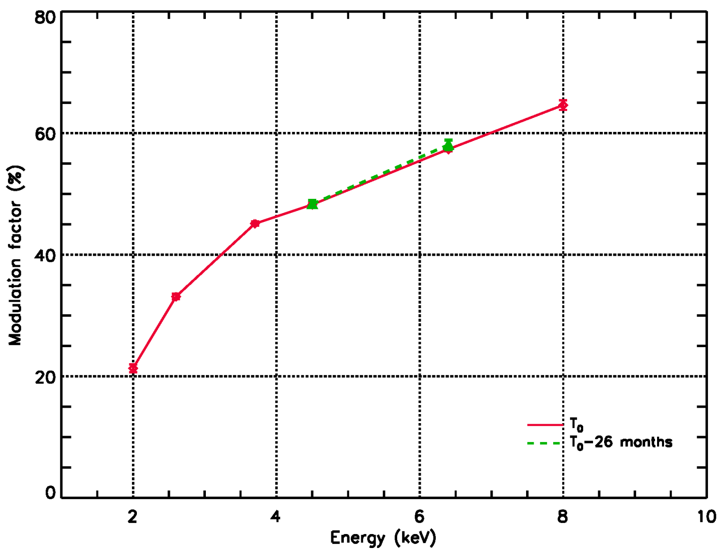


Figure 4. Modulation factor measured in the current calibration campaign (red solid line) compared with the value measured at selected energies 26 months before on the same sealed prototype (green dashed line).

and 5.9 keV. Measurements with photons at 5.9 keV were carried out with ^{55}Fe radioactive source; radiation at 3.7 keV and 4.5 keV was generated with X-ray tubes with calcium and titanium anodes, respectively, either directly or by diffraction on suitable crystals.

The result of our analysis is reported in Figure 6. Although the measurements are not consistent within the statistical errors reported in the figure, there is not any evidence of worsening of the energy resolution over a period of almost 3 years. Fitting the 4.5 keV points with a line, the trend is an increase of 0.1% (in absolute value) per year. This is particularly remarkable because it excludes any contamination of the gas mixture over a period of time comparable or longer than the operative lifetime of instrumentations on-board XIPE or IXPE. The scattering of data can be explained - at least partially - from the heterogeneity of measurement set-ups in our sample; residual variations, if any, will be monitored every $\sim$1 month in flight thanks to calibration sources included in both XIPE and IXPE payloads.

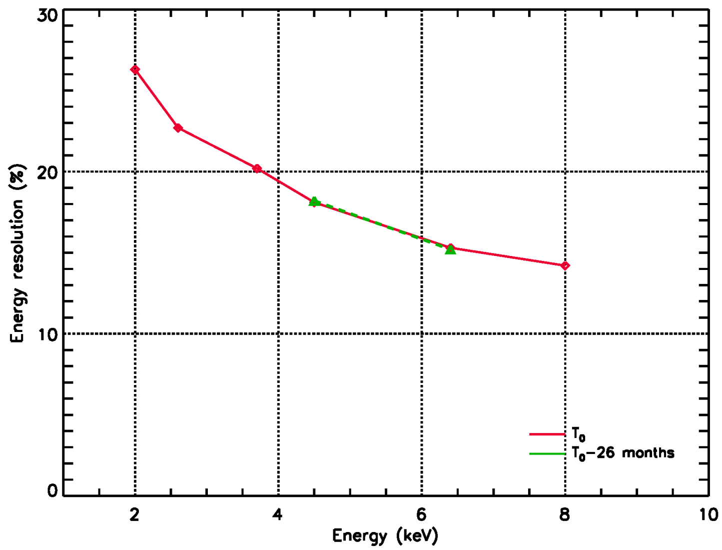


Figure 5. Energy resolution in FWHM as a function of energy measured in the current calibration campaign (red solid line) compared with the value measured at selected energies 26 months before on the same sealed prototype (green dashed line).

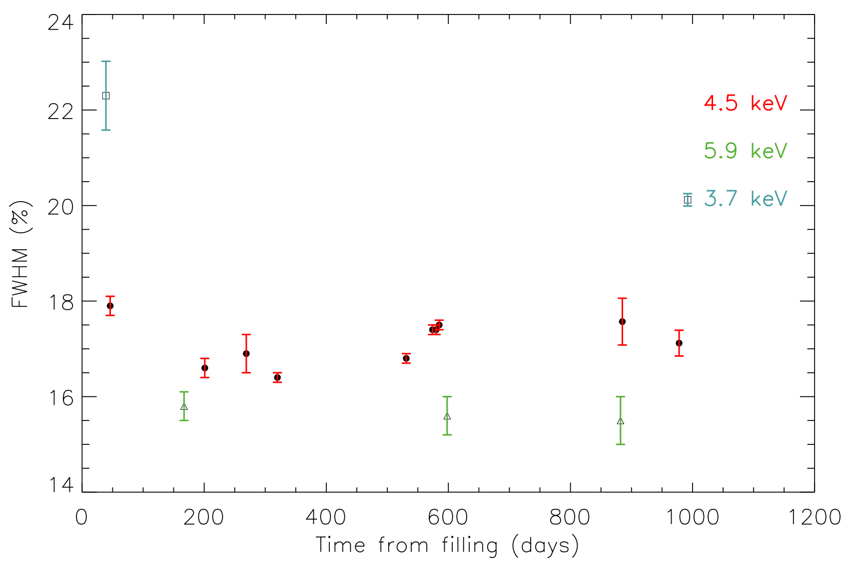
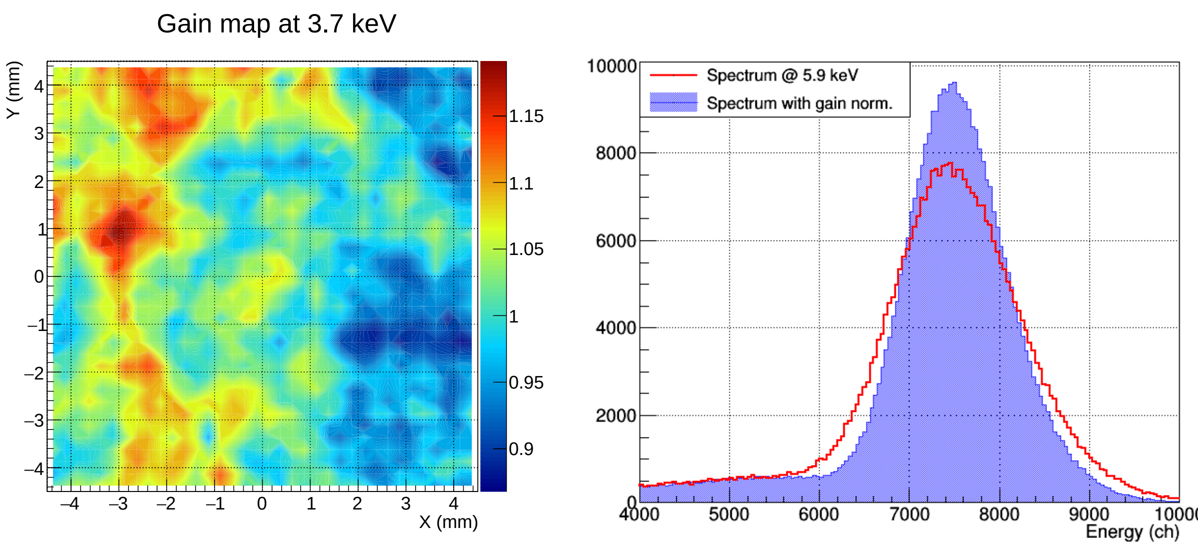


Figure 6. Energy resolution as a function of time since the GPD prototype mixture filling and sealing for three energies, 3.7, 4.5 keV and 5.9 keV. Only statistical uncertainties are show. At least part of the point variation can be attributed to measurements not taken in the same conditions. Measurements were carried out on the same point of the detector with a pencil beam, and gain correction was not applied.

It is worth stressing that the energy resolution obtained for this GPD prototype is significantly better than previously reported. For example, Muleri et al.[10] reported an energy resolution of 19.8% at 4.5 keV, whereas here we obtained $\sim$18%. The main difference with respect to previous results is the use of pencil beams, which hit a smaller region of the detector. It was reported by Tamagawa et al.[11] that the gain of the GEM may show significant spatial disuniformities. Differences of $\pm$10-15% were reported by Takeuchi et al., and they were related to few-μm variations in the GEM thickness.[12] These may spoil the energy resolution in case the size of the beam spot is larger than disuniformities spatial scale. The unique imaging capability of the GPD among photoelectric polarimeters allows to easily map the gain and correct for dishomogeneities with a simple procedure. The first step is to illuminate all the sensitive area with a monochromatic source (like ^{55}Fe) or with an X-ray tube emitting a continuum spectrum with prominent fluorescence lines. Then, the sensitive area is divided in bins, and for each bin a spectrum is created and filled with the measured energy of the photons absorbed in that bin. Each spectrum is eventually fitted with a Gaussian line, so that the position of the peak is proportional to the gain of the instrument in that particular bin.

We show in Figure 7(a) the gain map obtained by illuminating the central part of the GPD prototype with the direct emission of a low-power X-ray tube with calcium anode, emitting fluorescence Kα line at 3.7 keV. The bin size is 0.25×0.25 mm^2, and the gain is averaged to the mean value measured over all the surface. Disuniformities of the order of $\pm 15\%$ are detected on a spatial scale of less than 1 mm; these are compatible with those reported by Takeuchi et al.,[12] and so we ascribe them to the GEM rather than to the electronic chain which processes the collected charge pixel by pixel.



(a) (b)

Figure 7. (**a**) Gain map obtained with a full illumination of the GPD with 3.7 keV photons. (**b**) Spectrum of a ^{55}Fe source with or without taking into account of the gain disuniformities.

The gain map can be used to normalize the energy measured for each photon on the basis of the point of absorption. We show in Figure 7(b) the spectrum of photons produced by a ^{55}Fe source which are absorbed uniformly over a circle centered on the center of the GPD and with radius 4 mm. For missions like XIPE and IXPE, this would roughly correspond to a source of about 4 arcmin radius, similar to, e.g., Tycho SNR. We fitted the spectrum with the sum of two Gaussian lines, representing the ^{55}Fe Kα and Kβ lines at 5.9 keV and 6.5 keV, respectively, and fixed the peak position, area and σ of the latter at the expected values. The spectrum without gain normalization is the red solid line and the energy resolution is 20.0%. The filled curve is the spectrum obtained by normalizing for the gain map; the energy resolution is 15.7%, so increased of more than 20% in relative value, proving the effectiveness of our procedure. For this reason, the possibility to periodically map the gain in orbit one-two times per year is forseen in missions like XIPE and IXPE.

5. CONCLUSION

We presented a number of measurements carried out on a GPD prototype manufactured with flight-like materials and procedures, spanning over almost 3 years. We measured both the modulation factor of the instrument and the energy resolution at different energies. The modulation factor is very stable, and there is no evidence of worsening of the energy resolution which would point to mixture contamination. The stability of measured performance supports the fact that the GPD in its current form has already a very high technology readiness level, which is one of the main requirement for launching new instrumentation with a well-defined schedule and cost.

Notwithstanding the reported performance stability, a polarized and monochromatic calibration source based on Bragg diffraction is currently in the baseline design of missions like XIPE and IXPE, to allow for monitoring the response to polarization and the energy resolution during the instrument lifetime. During the campaign, we also established that the unique imaging capabilities of the GPD provide a simple and convenient way to measure the GEM gain and normalize for its disuniformities, which are of the order of $\pm 15\%$. Applying our normalization procedure, the energy resolution increases of more than 20% (in relative value) when the collected photons are spread on a GEM area of a few tens of mm^2. On the basis of this result, we included the possibility of mapping the GEM gain in orbit with two monochromatic sources on-board mission like XIPE and IXPE.

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