The Gas Pixel Detector on board the IXPE mission

Carmelo Sgrò for the IXPE team

Istituto Nazionale di Fisica Nucleare - Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

ABSTRACT

Polarimetry is universally recognized as one of the new frontiers in X-ray astrophysics. It is a powerful tool to investigate a variety of astrophysical processes, as well as a mean to study fundamental physics in space. The Imaging X-ray Polarimetry Explorer (IXPE) has been selected by NASA to be the next mission dedicated to X-ray polarimetry. It is based on a Gas Pixel Detector that is able to add polarization measurement to imaging and spectroscopy, and will be placed at the focus of a conventional X-ray optics. The detector exploits the photoelectric effect in gas and a finely segmented ASIC as a collecting anode. In this work I will describe in detail the experimental technique and the detector that will fly on the IXPE mission.

Keywords: X-ray, Micropattern gaseous detector, Polarimetry

1. INTRODUCTION

Polarimetry is the missing piece of X-ray astrophysics. While imaging, timing and spectroscopy evolved significantly in the past decades, leading to development of extremely successful X-ray observatories, the only positive detection of X-ray polarization was made on the Crab Nebula and was done almost 40 years ago.[1]

X-ray polarimetry allows a wealth of physical phenomena in astrophysics to be studied, in particular when coupled to spectroscopy and imaging. X-ray polarimetry investigates the acceleration process in many astrophysical sources like supernova remnants or jets from active galaxies, in the strong magnetic fields of neutron stars and white dwarfs. It detects scattering in asymmetric structures such as accretion disks and columns. In addition, it allows to study fundamental physics in regimes of gravity and of magnetic field intensity not accessible to experiments on the Earth. Finally, models that describe fundamental interactions (e.g. quantum gravity and the extension of the Standard Model) can be tested. For a more complete and detailed discussion of the several scientific topics related to X-ray polarimetry the reader can refer to several papers in the literature.[2]

In recent years, with the development of sensors based on the photoelectric effect,[3] polarimetry has been again considered as a realistic option, both for large telescopes and for dedicated small missions, in the energy band of a few keV, where X-ray optics are highly efficient. Because the emission direction of the photoelectron is correlated with the electric field vector of the photon, the degree of polarization of an incident beam can be measured via a modulation of the photoelectron emission angle. This technique has been exploited with the Gas Pixel Detectors (GPDs) that use an Application-Specific Integrated Circuit (ASIC) as a segmented collecting anode.

Thanks to this development, NASA has selected a mission entirely devoted to X-ray polarimetry in the latest round of the Small Explorers program: the Imaging X-ray Polarimetry Explorer (IXPE). Scheduled for launch in late 2020 in Low Earth Orbit, it is a small satellite with mass of approximately 300 kg, about 200 W of allocated power, and a nominal lifetime of 2+1 years. The payload is composed of three identical telescopes, operating in the 2–8 keV energy range, each with a GPD in the focal plane, built in Italy by INFN in collaboration with INAF-IAPS, and the grazing-incidence X-ray optics will be provided by the Marshall Space Flight Center.

In this contribution, the details of the GPD are discussed, while other aspects of the IXPE mission are covered by other contributions in this conference.

Further author information: E-mail: carmelo.sgro@pi.infn.it

2. PRINCIPLE OF OPERATION

The dominant interaction process for a few keV photons is the photoelectric effect, which is in principle a perfect analyzer for X-ray polarization measurements. In fact the direction of emission of the photoelectron for a K-shell absorption and 100% linearly polarized incident radiation, is 100% modulated around the polarization direction with a $\cos^2$ function of the azimuth angle. Therefore this process is well suited for the energy window below ~ 10 keV, where the source fluxes are relatively high and the grazing-incidence optics provide reasonable efficiency. The main difficulty inherent to this approach (that for a long time prevented any practical implementation of a photoelectric polarimeter) is the very small path length of the photoelectron, which even in a light gas can be of the order of few hundred μm, and the reconstruction of its direction of emission is a highly non-trivial problem.

The Gas Pixel Detector (GPD) proposes a solution based on the usage of an Application-Specific Integrated Circuit (ASIC) as a finely pixelized collecting anode of a proportional gas detector, and a Gas Electron Multiplier (GEM) as amplification stage. This concept is shown in Fig. 1: a photon is absorbed in a gas gap emitting a photoelectron (and, possibly, an Auger electron), the tracks ionize the gas and an electric field allows electron/ion pairs to drift respectively to the GEM and top plane. The differential voltage on the GEM induces electron multiplication and the pixelized anode allows a detailed imaging of the track. The ASIC and the GEM pixel pitch can be small enough to permit a good sampling of the short photoelectron tracks. In the current generation both the readout and amplification stage exploit a hexagonal pixel pattern with only 50μm pitch.

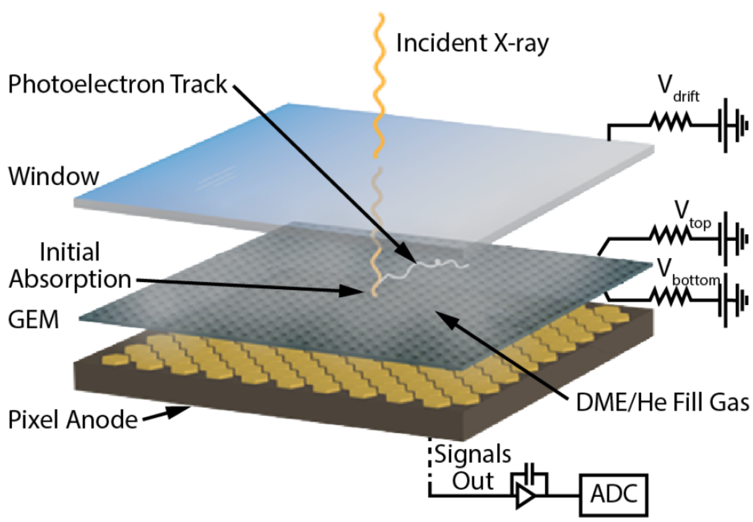

Figure 1. Schematic representation of the working principle of the Gas Pixel Detector. The photon enters in the sensitive gas volume from the top side and, after absorption, a photoelectron is emitted, which ionize the gas creating several electron-ion pairs. Electrons are drifted to the bottom with an electric field, multiplied with a Gas Electron Multiplier, and collected on a segmented anode. In this way a detailed image of the photoelectron track can be obtained for subsequent reconstruction of the impact point and emission direction.

Another key characteristic of this class of detectors is the gas mixture, since diffusion of the electron cloud during the drift in the absorption gap can smear out the information of the photoelectron information. Therefore it is mandatory to use a gas with a small diffusion coefficient (like Dimethyl ether, DME) and select the proper gas pressure and depth of the absorption gap, trading a bit of efficiency for best track reconstruction capability.

Off-line event reconstruction is another important ingredient for a good polarimeter, as we want to identify the initial part of the track and in particular the absorption point (for good imaging capabilities) and angle of emission of the photoelectron (for polarimetry). The latter shows the same $\cos^2$ behavior as the absorption cross section, but its modulation is not 100% and obviously depends on a combination of all the characteristics of the detector, pixel geometry and pitch, diffusion in gas, reconstruction algorithm etc.

For the current generation of GPD a two-step process has been implemented to take into account the effect of the Coulomb scattering and the smearing due to the transverse diffusion. Fig. 2 shows an example of one event, a 5.9 keV photon form a ^{55}Fe source, and the main steps of the reconstruction algorithm. In the first step the charge barycenter is found and the track main axis is identified via a moment analysis. The presence of the Bragg peak allows to distinguish the final part from the initial part of the track and refine the estimation of the absorption point. A second moment analysis is performed after weighting the pixel charge according to the distance from the absorption point and a better estimate of the track direction is found.

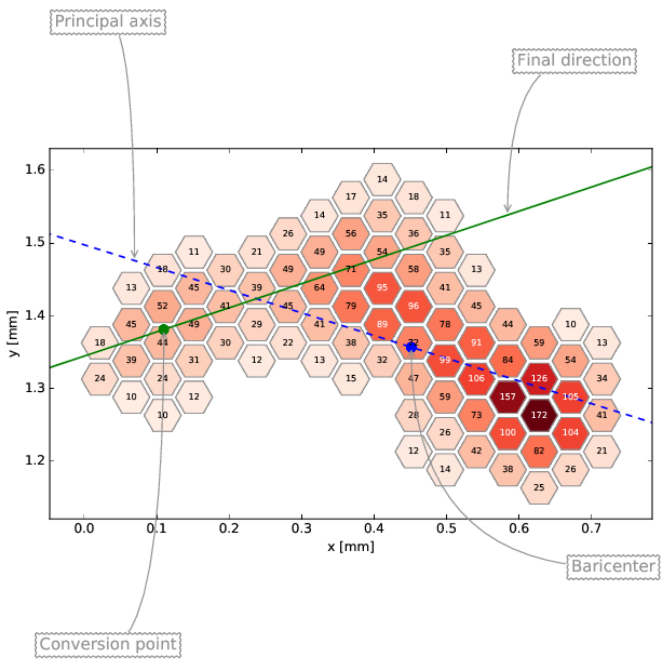

Figure 2. Example of a photoelectron track of a 5.9 keV photon as seen by the GPD. Color scale (and numbers) of each pixel show the collected charge. The main step of the current reconstruction algorithm are also shown: the principal axis of the charge distribution is the dashed blue line, while the solid green line is the emission direction. The reconstructed absorption point is also indicated.

It is important to keep in mind that this technique allows to measure, at the same time, all the 4 characteristics of the incident radiation: incoming direction, energy, time and polarization. This is one of the peculiarities of having the GPD in the focal plane of an X-ray telescope.

3. GPD ASSEMBLY

The implementation of the concept described in the previous section is shown in the schematic representation in Fig. 3. The central part of the detector, the ASIC, is contained in a standard ceramic package that is bonded to a custom PCB. This board is glued to a mechanical support structure that serves as a holding structure for the entire detector and interface (mechanical and thermal) with the detector housing on the satellite.

The GEM is placed on top of the PCB board and kept in the right position by a ceramic support frame. On top of the GEM a second ceramic frame define the gas absorption gap of 1 cm.

The cell is closed on the top side by a titanium frame that acts also as high-voltage electrode for the drift electric filed. An aperture in this frame allows the passage of X-ray radiation and a 50μm beryllium window guarantee gas sealing with adequate radiation transparency.

The gas cell has a copper filling tube and is completely sealed after filling with the gas mixture of He 20% and DME 80% at 1 bar, optimized for the 2–8 keV range of the IXPE mission. The detector is built in collaboration with the Oxford Instrument Technology Oy, in Finland, that has extensive experience in flight-grade sealed gas detectors.

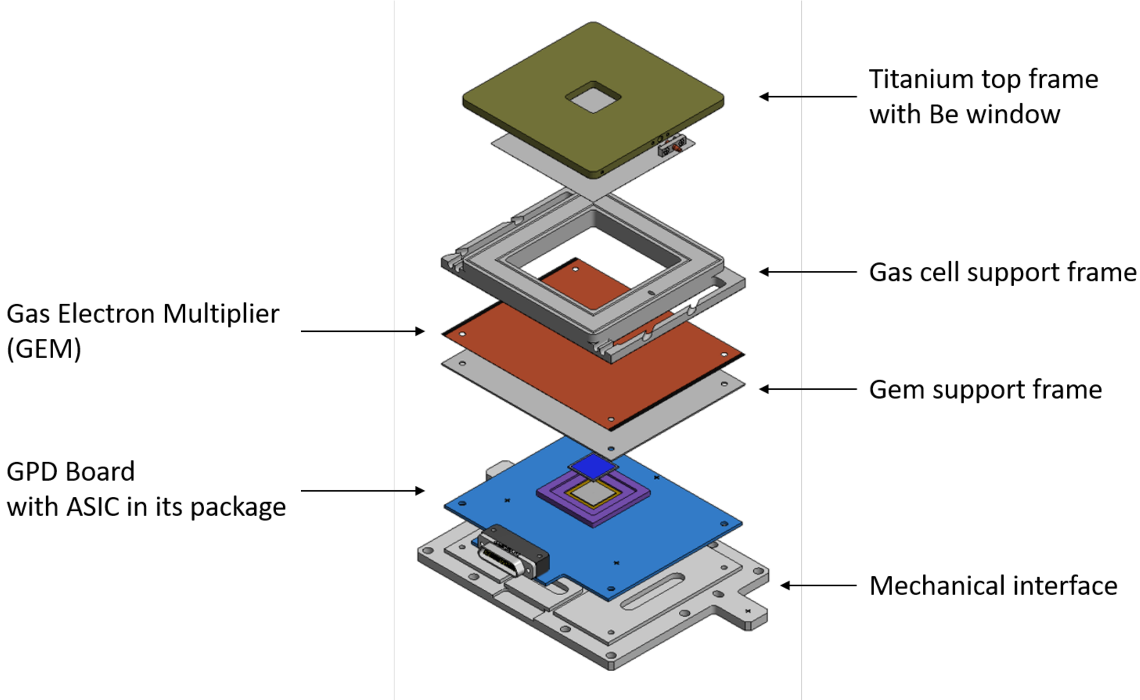

Figure 3. Exploded view of the GPD assembly showing all its components. A PCB board contains the ASIC and and is bonded on top of a mechanical interface. A ceramic support frame holds the GEM and is glued on the PCB, while another ceramic frame serves as a spacer for the absorption gap. The top of the detector is closed by a titanium frame with a thin beryllium window. The gas gap is filled with a DME-based mixture and sealed via a copper filling tube.

The full custom ASIC[4] features a matrix of 300×352 hexagonal pixels, with 50μm pitch, for an active area of 15×15 mm^2. Each pixel contains its signal amplification chain and has an electronic noise as low as 50 electrons ENC. Normal operation exploits the ASIC self trigger circuitry and its capability to select a region of interest around the triggering pixels: only the selected pixels are serially connected to an external ADC for analog signal conversion, and the readout time is much smaller than reading the entire matrix. Fig. 4 shows the ASIC in its board during the GPD assembly phase.

The GEM is another critical component of the detector, it is built on a 50μm thick LCP substrate with copper electrodes on both sides. Holes are arranged in an hexagonal array with 50μm pitch that covers the entire area of the ASIC with another external ring with larger holes. When a voltage difference of 400-500 V is applied on the two sides, the electric field is so strong inside the holes to result in an avalanche multiplication of the electrons crossing this device. This kind of GEMs are produced by SciEnergy, in Japan. A microphotograph of the latest generation of GEM is shown in Fig. 5.

4. GPD PERFORMANCE

The concept of the GPD polarimeter has been developed in the last decade with several prototypes and extensively tested to evaluate its performance, with the goal of studying its sensitivity in a realistic telescope configuration, i.e. when coupled to an optics with known effective area and point spread function (PSF). The final configuration, that will fly in the IXPE mission, has been studied with a lab-grade prototype for a few years and the results of this test campaign was used as baseline for the IXPE mission proposal.

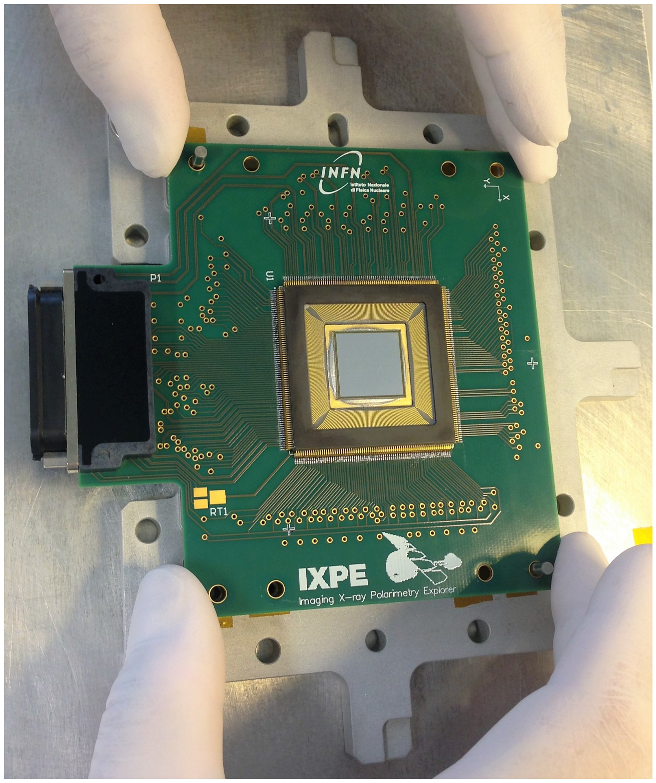

Figure 4. This picture shows one of the prototype of the IXPE GPD board during the detector assembly. The ASIC at the center of the board is clearly visible. The PCB contains also the passive components that need to be close to the chip. Other components like the ADC and the control system are placed in a separate board.

The main parameter for a polarimeter is the modulation factor: the response of the detector to a perfectly polarized beam. This quantity has to be maximized, since the sensitivity to polarization of celestial source scales linearly with this quantity. Moreover the knowledge of the modulation factor, as a function of other parameters like the photon energy, is important to reduce systematic uncertainties. Also the response to a non polarized beam is very important and allows to quantify any spurious effect that may result in systematic uncertainties. The plan for the calibration of the IXPE instrument will be discussed in a separate contribution to this conference.[5]

We can expect that it is easier to reconstruct tracks that have a longer projection on the detector plane. This is in general true, even if longer tracks have a higher chance to suffer from coulomb scattering. In fact the modulation factor increases with photon energy and goes from about 20% at 2 keV to about 70% at 8 keV. It has to be noted that the efficiency of X-ray absorption in the GPD gas cell decreases with energy. Therefore the final sensitivity has to take into account the exact scaling of these two parameters and peaks at about 3 keV (for bright sources). Quite close to the lower end of the energy range, which is determined by the beryllium window that, despite being as thin as possible, absorbs the majority of the radiation below 2 keV.

We stressed already the capability of the GPD to do imaging together with polarimetry. A test on the GPD PSF was performed in realistic conditions placing the detector on the focal plane of a JET-X x-ray optics, at the PANTER facility in Munich. Angular resolution was measured in the 3–8 keV energy range, both on- and off-axis,[6] proving that a telescope with angular resolution better that 30 arcsec is feasible.

A quick summary of the performance of the detector are shown in table 1.

5. CONCLUSIONS

After 40 years from the last X-ray polarimeter in orbit, we have a NASA mission fully dedicated to polarimetry. The IXPE satellite will explore the polarization of celestial sources in the 2-8 keV energy range. The central part

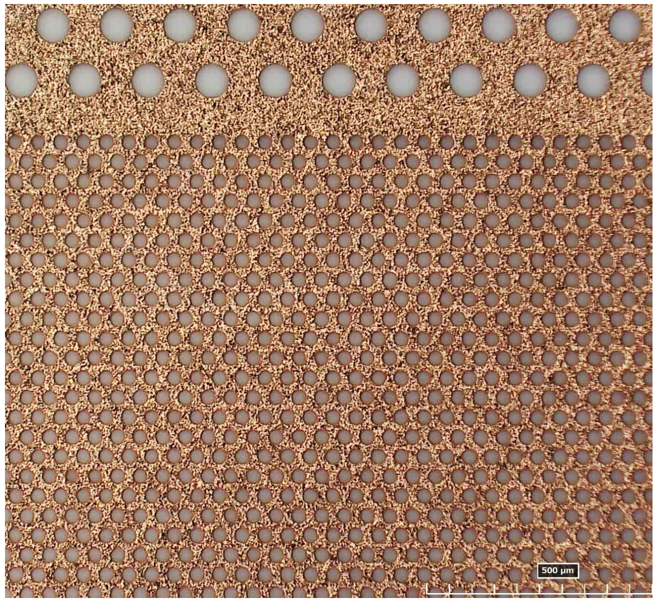

Figure 5. Microphotograph of a detail of one of the latest generation of GEM for the GPD in the IXPE mission. The scale on the bottom left highlights the small pitch of the holes that represents the state-of-the-art for this technology.

Table 1. Basic performance of the IXPE detector

Modulation factor	20% (70%) at 2 (8) keV
Residual modulation	<0.5%
Spatial resolution	90μm at 5.9 keV
Energy resolution	<20% at 5.9 keV
Timing resolution	$\sim 10mus$

of this mission is the Gas Pixel Detector in the focal plane of a grazing-incidence optics that allows space-resolved polarimetry for the first time in this band.

The characteristics of the GPD are well studied in the last years of activity with the lab-grade prototypes and will continue with next prototypes and flight models. Activity on event reconstruction and data analysis software will also continue, in parallel with the payload construction, with the aim of exploiting the maximum potential of the detector, including the highest modulation factor as possible and a good event quality estimation for scientific data analysis.

The design of the flight-grade detector is well advanced. The general architecture of the detector is basically frozen. A few prototypes are under construction or under test to define the few remaining details of flight models, like the mechanical and thermal interfaces or the integration and alignment procedure.

We expect to complete the design phase by the end of this year and begin the detector construction for the mission next year, to be on schedule for new IXPE discoveries in a few years.

REFERENCES

[1] Weisskopf, M. C., Silver, E. H., Kestenbaum, H. L., Long, K. S., and Novick, R., "A precision measurement of the X-ray polarization of the Crab Nebula without pulsar contamination," *Astrophysical Journal, Letters* **220**, L117–L121 (Mar. 1978).

[2] Bellazzini, R., Costa, E., Matt, G., and Tagliaferri, G., [*X-ray Polarimetry: A New Window in Astrophysics*] (July 2010).

[3] Costa, E., Soffitta, P., Bellazzini, R., Brez, A., Lumb, N., and Spandre, G., "An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars," *Nature* **411**, 662–665 (June 2001).

[4] Bellazzini, R., Spandre, G., Minuti, M., Baldini, L., Brez, A., Cavalca, F., Latronico, L., Omodei, N., Massai, M. M., Sgro', C., Costa, E., Soffitta, P., Krummenacher, F., and de Oliveira, R., "Direct reading of charge multipliers with a self-triggering CMOS analog chip with 105 k pixels at 50 μm pitch," *Nuclear Instruments and Methods in Physics Research A* **566**, 552–562 (Oct. 2006).

[5] Muleri F. for the IXPE team, "Calibrating IXPE from ground to space," *this conference* (2017).

[6] Fabiani, S., Costa, E., Del Monte, E., Muleri, F., Soffitta, P., Rubini, A., Bellazzini, R., Brez, A., de Ruvo, L., Minuti, M., Pinchera, M., Sgró, C., Spandre, G., Spiga, D., Tagliaferri, G., Pareschi, G., Basso, S., Citterio, O., Burwitz, V., Burkert, W., Menz, B., and Hartner, G., "The Imaging Properties of the Gas Pixel Detector as a Focal Plane Polarimeter," *Astrophysical Journal, Supplement* **212**, 25 (June 2014).