X-ray polarimetry on-board HXMT

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ABSTRACT

The development of micropixel gas detectors, capable to image tracks produced in a gas by photoelectrons, makes possible to perform polarimetry of X-ray celestial sources in the focus of grazing incidence X-ray telescopes. HXMT is a mission by the Chinese Space Agency aimed to survey the Hard X-ray Sky with Phoswich detectors, by exploitation of the direct demodulation technique. Since a fraction of the HXMT time will be spent on dedicated pointing of particular sources, it could host, with moderate additional resources a pair of X-ray telescopes, each with a photoelectric X-ray polarimeter (EXP$^2$, Efficient X-ray Photoelectric Polarimeter) in the focal plane. We present the design of the telescopes and the focal plane instrumentation and discuss the performance of this instrument to detect the degree and angle of linear polarization of some representative sources. Notwithstanding the limited resources, the proposed instrument can represent a breakthrough in X-ray Polarimetry.

Keywords: Astrophysics, X-ray Mission, Polarimetry

1. INTRODUCTION

Polarimetry is the sub-topic of X-Ray Astronomy for which we have the maximum gap between the expectations deriving from theoretical analysis and the achievements deriving from experiments. The main reasons for this are the limited sensitivities in terms of both statistics and control of systematics of the conventional techniques of Compton/Thomson scattering around 90$^\circ$ and Bragg diffraction at 45$^\circ$. The recent but impetuous development of the micropixel polarimeters, based on the visualization of photoelectron tracks in a gas, makes possible the design of experiments with much higher sensitivity and an excellent control of systematic effects. A sample of high luminosity and/or high expected degree of polarization could now be studied even with telescopes of modest area: this includes Crab Nebula/PSR, Accreting Binary, Pulsars, Black Hole Binaries and the brightest AGNs. But polarimetry should be a tool capable to solve crucial problems on several classes of X-ray emitting sources, provided that an adequate telescope is available. Models predicts polarizations of the order of a few percent in low luminosity sources, such as AGNs, or in sources showing a high luminosity in a short time interval, such as millisecond binary pulsars or Soft Gamma Repeaters. The detection of polarization in this range requires the detection of $10^5$ - $10^6$ photons, to be compared with a number of photons of the order of 10, required to detect a source in an image, and this can be achieved only with an adequate collecting area. The reverse of this limit is that polarimetry, when performed in the focus of a telescope with an imaging detector, is in any case performed

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on sources much brighter than the background in the image pixel. The polarimetric sensitivity is only a matter of number of photons, independently whether they are collected with a single telescope or with a cluster. This is not true for imaging, where the sources at the limit of sensitivity are by definition, comparable with background and the passage from one telescope to a cluster is never for free. This opens the possibility to build up adequate collecting areas by adding more than one telescope of shorter focal length to be harbored aboard a bus much less demanding in terms of launcher or to be included as piggy-back package on another mission.

Due to the room and weight limitations the inclusion of a focal plane polarimeter aboard HXMT can be only based on the design and manufacture of a dedicated telescope. With the proposed design and with a combined use of the polarimeters and of the Hard X-ray Telescope we set up a very performing mission, much more than a simple pathfinder.

In the following we describe the status of development of the Gas Pixel Detector (GPD) and its polarimetric capabilities, and propose a configuration of telescopes, that could be compliant from the point of view of volume and weight with the launcher bay. The derived sensitivities are very attractive.

In the paper we give for each subsystem the level of readiness of the technologies involved and the strategies assumed to arrive to a B1 phase design all under control or have very safe back-up solutions. None is based on items subject to export restrictions out of control of the involved authorities.

2. THE DETECTOR

The X-ray polarimeter is basically a gas detector with fine 2-D position resolution we developed (1) to exploit the photoelectric effect. Basically the polarimeter is made of a gas cell with an X-ray window, made of Beryllium, a gas electron multiplier (GEM) which amplifies the electron tracks generated in the drift gap and provides energy and time information and, below it, of a pixellated plane which collects the charge content in each pixel to be processed by the readout electronics.

**Principle of operation** Polarized X-rays introduces a \( \cos^2 \) asymmetry with respect to the azimuthal angle \( \varphi \), the angle between the direction of emission of the photoelectron and the polarization vector (see for example(2)). The track produced by the photoelectron in a gas mixture brings memory of the polarization of the original polarization vector. Imaging the tracks with modern gas pixel detector permits to derive the absorption point and the initial direction of the photoelectron path. From the distribution of emission angles we derive the degree and polarization angle of the X-ray photon. The Auger electron instead is not modulated by the X-ray polarization therefore represent a disturbance, especially at low energy.

**The chip** The request of usage of the polarimeter in real astrophysical experiment, in particular toward the reach of an area matched with the PSF and Field of view of typical X-ray telescopes has pushed us to leave the first pioneeristic technology of a pixellated plane made with PCB multi-layer technology and the electronics on a side. This technology was in fact limited either in the number of pixel (~1000) and in the pixel pitch (~100 \( \mu \)m). We therefore decided to adopt the solution to bring the electronics inside the detector gas cell by designing and building a multilayer ASIC CMOS analog chip made with 0.18 \( \mu \)m VLSI technology. The top layer of the ASIC chip is pixellated and is the readout plane of the charge produced in the gas volume and amplified by the GEM. Two generations of chip are already behind us. The third generation chip is currently working (3) has the characteristics reported in Table 1.

Each pixel is made of a metal pad, is connected to an individual charge-sensitive amplifier and a shaping circuit. The chip usually operates in a Region of Interest mode (ROI) which downloads the charge content in each pixel within a rectangular area which surrounds the pixels that passed the threshold, in order to include all the photoelectron track plus a selectable margin of 10 or 20 pixels. The coordinates of the ROI are provided as soon as an internally triggered event has terminated. The characteristics of the chip are already suitable for an astrophysical experiment and we do not envisage great changes to be done but only customization if any. In case of HXMT the performances of the chip are suitable for the mission requirements and we are planning to use it as it is. In Figure 1(a) and in Figure 1(b) we show a sample of a track collected for a He-based mixture and a collection of 100 tracks imaged from the same chip.

**The gas mixture.** The gas mixture which fills the polarimeter determines the working energy band. To be effective, the energy of X-ray photons should be sensitively larger than Auger electrons energy and thence of the
Figure 1. Tracks from the Gas Pixel Detectors. (a) Single Photoelectron Track. (b) Collection of photoelectron tracks imaged by the GPD in few seconds of data

|          |                  |
|----------|------------------|
| Pixels   | 105600           |
| Pitch    | 50µm             |
| Pixel Density | 470 Pixel/mm²   |
| Area     | 15 mm x 15 mm    |
| Peaking time | 3-10 µs       |
| Read-out | Asynch, Synch    |
| Trigger  | Intern, extern, self |
| Clock    | 10 Mhz           |
| Access to pixel | Direct, Serial, Full Matrix, ROI |

Table 1. Main Characteristics of the 105600 Pixel ASIC chip

k-shell energy of the heaviest elements of the gas that dominate the absorption. Mixtures containing Ne or He or organic molecules are preferred. Mixtures filled with Ar can be effective only above 6 keV. Since the diffusion during the drift should be kept small DME is best suited as quencher over Carbon-Dioxide or Methane. When in combination with He, DME is the gas where most of the X-ray interaction occurs and He is used as ‘filler’. We studied different gas mixtures based with He and Ne and DME as quencher. At the moment the mixture which provides the better performances, as shown below, are the He based mixture in the 2-10 keV energy band. We usually worked at a gas pressure of 1-atm which is our baseline pressure. We use a mixture DME 80 % He 20 % as the baseline.

The Body. The detector body hosts the window, the electrodes, the feed-throughs and the readout chips with its package. The package brings-out 300 signals from the chip. The X-ray window provides, also, the drift field at -2000 V. The GEM is a thin kapton foil metalized on both sides, perforated by microscopic holes (50 µm pitch) with the top at -750 V and the bottom at -300 V. The chip is at ground. During the development phase we used detectors with flowing gas system. We have built later, a sealed detector capable to withstand a long term operation in space environment. It is manufactured with materials and components with low out-gassing rate. Ceramic component as Alumina for the spacers, kapton and ceramic feed-throughs are components of the body. The distance between the chip and the window (the absorption/drift gap) is 1-cm. Various prototypes of this sealed detector have been produced and extensively tested along more than one year. The prototype detector is shown in fig. [2]

Stability vs time. The detectors have shown no degradation of any performance during an extensive testing lasting months. One has undergone high radiation testing for two months and further serendipitous testing for more than one year. All time long it was irradiated with a rate higher than that foreseen for the brightest sources in the focus of HXMT telescope.

Disposition The detector is directly mounted on a board. This is part of a very compact Interface Electronics
that performs the A/D conversion, the suppression of zeros, the tagging of events with time and forwards a packet of data to a processor hosted within the Control Electronics. The detector and Interface electronics are included in a box (10 cm $\times$ 10 cm $\times$ 5 cm).

**Performance and survival in temperature.** Since the performance tests have shown a certain sensitivity of the gain to temperature (as any other detector based on gas multiplication) a Peltier cooler is included in the box to stabilize the temperature of the detector around 10°C. The detector and the Interface electronics were thermal cycled and thermal-vacuum cycled between -15°C and 45°C showing beside survival, no degradation in the performances.

**Radiation Hardness.** The detector was irradiated with a Fe$^{55}$ source to collect as much as radiation foreseen for the lifetime in orbit without loss of performance. We foresee further testing with ions to improve the confidence on the radiation hardness of the GEM.

### 2.1 The focal plane

In the figure we report a sketch of the focal plane of the polarimeter. It is composed by a box for the electronics (on the top left), where the interface electronics can be placed, a filter wheel (on the right) and high voltage power supplies to be located close to the detectors not shown in the figure.
We envisage to use a dedicated filter wheel. The use of the filter wheel procures many advantages. Other than the ‘Open’ position the inclusion of a ‘closed’ position permits to gather and monitor internal background rate along the orbit. Two positions for two different low-rate calibration sources permit to check the gain stability in-orbit and calibrate the gas-gain. One of the sources will emit (unpolarized) fluorescence photons. The other source will radiate the detector with photons polarized by means of a Bragg diffraction around 45° (shown in the fig. 3). A position with a diaphragm permits to eliminate a possible bright source on the edge of the field of view. The interface electronics will be located close to the detectors but connected via a flexi-cable to have more freedom in the distribution of weights and thermal inputs. To exploit at best the low energy optics bandpass, we envisage to use two detectors, filled with slightly different mixtures. These could be interchanged in the focal plane with a motorized linear stage, to optimized the measurements on the observed source. The development cost ad the resources needed for the alternate operation of the detectors are very limited, since the detectors are just filled with different mixtures and the control electronics could be shared. Moreover the functionality of the filter wheel and of the linear stage could be joined in an unique motorized stage, reducing the total weight of the focal plane. We are currently studying the scientific improvements achievable by means of the inclusion of a polarimeter softer than the current He-DME baseline.

3. THE INTERFACE ELECTRONICS AND THE CONTROL ELECTRONICS

The Interface Electronics (IE) resides close to the detector body eventually below it. Mainly consists of an ADC which converts the analog signals from the chip and stores them in the DPRAM. An FPGA handles and generates the signals for the chip and routes the data coming from a DPRAM to the control electronics. An actual board of interface electronics is currently working in laboratory. The Control Electronics (CE) contains the Data Processing Unit (21020 DSP as a baseline) a board which handles the telecommands and a board with DC-DC converters which provides the supply to the chip. The mass-memory shown in the figure is also included in the Control Electronics. We are open to discuss an onboard mass memory shared with HXMT payload or with the bus but as a baseline we prefer to assume that EXP has its own mass memory.

4. THE TELESCOPES

In our baseline we assume a coating for the outer surfaces of shells of Iridium with a thin over-coating of carbon. The Iridium, due to its higher density (resulting in larger critical angles), provides a better reflectivity than gold at higher energies. A thin carbon layer “fills” the reflectivity decrease around the M absorption edges, that for Au and Ir is around 3 keV where the polarimeter is particularly sensitive. The deposition of Iridium is different from that of Gold. It has been tested in several contexts and we do not foresee any major problem to introduce it in the process of manufacture of the mirrors. For soft X-ray telescopes based on the Ni replication technology operated so far (SAX, XMM, SWIFT) it was used an Au reflecting coating, because gold also acts as the release agent in the replication process due to its low adherence onto the superpolished mandrel surface and good adherence to the nickel. On the contrary, both Iridium and Carbon present a strong adherence to the mandrels and, then, have to be applied to the gold surface in a post-process coating deposition after having followed the usual replication method. The deposition of carbon is also a very well established operation. The application to HXMT mirrors could be difficult for the inner mirrors but should be feasible for outer mirrors where they give the dominant contribution at low energies. Anyway the adoption of this coating does not interfere with the manufacture of mandrels which is the most demanding part of the process. In case some unexpected obstacle is found the traditional coating with gold is a very safe back-up solution. In this worst case the effective areas given below must be scaled down by about a 20%.

Two identical telescopes with the same focal length of 2100 mm are foreseen. Each telescope is composed by 30 shell with diameter ranging from 90 to 270 mm. Iridium and Carbon coating is foreseen for the 22 outer shells.

The manufacture of the telescope HXMT has an ambitious time schedule, that discourages the application of technologies requiring a too long and uncertain development phase. The volume available for the X-ray telescope is filled with a reasonable efficiency and with an acceptable weight with telescopes manufactured with the technology of replicas of superpolished mandrels by Ni electroforming of the mirror shell walls. Moreover
this is completely under control of Italian institutes and industries, and a design/manufacture/test planning can be set up under the control of Italian and Chinese Space Agencies, without depending on third subjects. For this reason we propose here solutions based on this technology. The design we propose is therefore based on this technique. The thickness of the shells is fixed to 0.2 mm. The possibility to reduce this thickness to 0.1 mm at least for a number of shells is under study. This is not necessarily the best solution but allows for a very realistic evaluation of the weights of the shells and of the mechanical structure needed to keep them mounted and aligned. This means that the proposed designs are feasible with the declared weights with high level of confidence. This will result in an optical quality of the order of 30", Half Energy Width (HEW), that, combined with the effects of inclined penetration in the gas will guarantee the resolution less than arcminute, compliant with all the targets of the polarimeter for HXMT.

Figure 4. The telescope tube which holds the mirror for HXMT.

The design proposed is based on the well established technique of SAX, XMM and SWIFT. The capability of producing shells thinner with a controlled loss of angular resolution has been already tested by the production both of a thin shell from a mandrel of JET-X and of thin shells from mandrels developed as part of the Simbol-X project. All these thin shells have been tested at the Panter Facility providing HEW < 30". To avoid any uncertainty in the manufacture integration and testing of the flight units, two HXMT prototype shells will be
produced and tested in the connecting phase. Also the procedures for the Iridium and Carbon coating will be assessed during the connecting phase. In case a complete confidence is not achieved the Ir coating can be released and the C coating can be deposited via a collaboration with other institutions (USA) that have a good control of this technique and with which we have already a scientific collaboration in place (CfA) for other projects.

5. THE INTEGRATION OF THE POLARIMETER WITH HXMT

To fully employ the free space in the bay of the launcher, we envisage to use two identical "telescope units", each composed by a telescope and by the focal plane instrumentations with different power supplies, filter wheels and Interface Front End Electronics, enclosed in a thin carbon fiber tube. We assume that the mirrors are positioned with the so-called spiders within the tube structure which is then positioned on a bulk-head to be fixed to a side of HXMT see fig. 4. The tube is connected to the spacecraft through a flange. The tube itself is divided in two part, both mounted on the interface flange. A forward tube on which is mounted the mirror module and that carries also the closing door on top, and a tapered rear-tube that will hold the focal plane detector. The flange will divide the tube at the center of mass.

Since the baseline configuration of the detector is effective above 2 keV, we can afford a thin thermal blank in front of the mirrors and we do not foresee a long baffle as in the case of JET-X. The thermal stabilization of the mirrors is much less demanding (of the order of 15 W for both telescopes). We foresee a protective cover in front of each telescope to be opened when in orbit. A design of a possible interface of the telescopes with the bus can be seen in fig. 4 in practice we expect to fix the flange to the bus with a three points connection.

6. EXPECTED PERFORMANCES

Space/angular Resolution The reconstruction of the impact point of the photon can be performed with a resolution (FWHM) of 150 $\mu$m for an orthogonal beam. In the focus of a telescope the photons are impinging with a certain inclination and will be absorbed at an unknown depth in the gas. This introduces a further, and prevailing, uncertainty in determining the position where the photon has crossed the focal plane. This uncertainty is of the order of 400 $\mu$m. The angular resolution is the combination of the position resolution, divided by the focal length, and the resolution of the optics. Assuming that the errors combine with a quadratic law we find that our system will have a point spread function of one arcminute diameter.

Energy Resolution The MPGD has an energy resolution of the order of that of a Proportional Counter. We can assume: \((DE/E)_{FWHM} = 0.2 \ (6/E(kev))^{1/2}\) The detector could, in principle, perform better than this but it must be verified that this is consistent (e.g. in terms of gain) with the optimal use as a polarimeter.

Timing Capability Events can be tagged with the arrival time with a resolution of few $\mu$s. We fix a resolution to 8 $\mu$s on the basis of astrophysical considerations.

Polarimetric capability Polarimetric capability depends on the filling gas mixture that is to be tuned to the optics band-pass and to a trade-off of different astrophysical targets. In the case of a multi-detector design the filling gas would be different for each detector. We use as a reference a filling with 1 atmosphere of a mixture 20 % He 80 % DME (Dimethyl Ether), which is presently giving very interesting results, confirmed by recent measurements, but is not necessarily the final choice. For instance a larger fraction of He (e.g. 30 %) provides better results at low energies. Since the sensitivity of a polarimeter is proportional to $\epsilon^{1/2} \times \mu$, where $\epsilon$ is the efficiency and $\mu$ is the modulation factor, we use this quantity for the above mentioned mixture. In practical cases this has to be convolved with the effective area of the optics and with the spectrum of the source, and integrated in finite intervals of energy. This quantity gives an idea of the energy at which the device is performing better. The best sensitivity is reached at about 3 keV.

7. ASTROPHYSICAL PERFORMANCES

By combining the effective area of the telescopes with the polarimetric capabilities of EXP2, we can evaluate the astrophysical performances of the experiment. The Minimum Detectable Polarization with a 3$\sigma$ confident level for the current baseline configuration is reported in fig. 5 in the energy range 2 - 10 keV and for a selected sample of sources.
The background is evaluated considering both the internal background from low Z (neon or methane) proportional counter flown on board of OSO-8 and the diffuse X-ray background. The internal background is $1.5 \times 10^{-4}$ counts/s/cm$^2$/keV (1.6-3 keV ) and $1.0 \times 10^{-4}$ counts/s/keV/cm$^2$ (3-10 keV). We expect a total internal background of $(c/s) = 1.0 \times 10^{-5}$ and a total diffuse background of $(c/s) = 1.0 \times 10^{-8}$. The first of these two figures could be underestimated, but in any case our system will be source-dominated for orders of magnitude. This assures that the assumption of adding the two telescopes efficiencies to determine the total sensitivity is correct. X-ray polarimetry will be performed on all the class of sources of X-ray astronomy except, may be, for cluster of galaxies. A goal well within the reach is the observation of High Mass X-ray binaries. For the data of X-ray pulsators we can assume that even performing the polarimetry on selected phases (namely splitting the observing time) we are still sensitive to a few % level. Therefore EXP² can measure the swing of the polarization angle with phase, discriminate between fan beam and pencil beam and fix all the geometry of the system (6).

The polarimeter on-board HXMT will be able to perform signficative measurements on board the most luminous AGNs. From the sensitivity to Blazar we can be confident that EXP² can confirm the role of synchrotron on the emission process. For blazar with comptonized spectrum it will be possible to discriminate whether the seed photons come from the Broad Line Regions or from the Disk or are due to Self Synchrotron from the jet. Even looking to the galactic center EXP² will disentangle the origin of the emission of molecular clouds. A long pointing of Sgr B2 will allow for an MDP of 16 %. This can (and must) be expected in the reflection model. Moreover the angle should “point” to SgrA* demonstrating that a few centuries ago our Galaxy was a low luminosity AGN. Coming to galactic Black Holes and in particular micro-quasars polarimetry of soft-state when the emission is derived mainly from the disk can be decisive in detecting General Relativity effects. From the sensitivity of GRS1915+105 we have simulated $10^6$s of observing time (see fig. 6(a) and 6(b)) splitting polarimetry on selected phases (namely splitting the observing time). We are still sensitive to % level and we can discriminate between Kerr and Schwartschild black hole (7). The quoted errors are at $3\sigma$. This shows that the polarimeter aboard HXMT will be a breakthrough for many topics of High Energy Astrophysics.

To these ”guaranteed” results we can add a large space for discovery in particular for the polarization
Figure 6. Polarization properties simulated from GRS1915+105. (a) Expected rotation of the polarization angle with energy. (b) Expected variation of the degree of polarization with energy.

Figure 7. 1Ms observation of the blazar 1E 1101-232 (z=0.186) allows to reach an upper limit in the vacuum birifrangence in the Quantum Loop Gravity with unprecedent sensibility.
by shocks in shell-like Supernova Remnants, moderately space resolved polarimetry of the Crab Nebula (the prototype accelerator), polarimetry of magnetars in outburst (a test of QED effects of vacuum birefringence and/or proton cyclotron), polarimetry of quasars by scattering on the disc, polarimetry of GRB afterglows. A further very attractive possibility is the test of Loop Quantum Gravity models by searching (see fig. 7) for the rotation of the polarization angle with energy and distance in Blazars. We simulated the effect of Quantum Gravity on a fairly distant blazar to show at which level the linear term can be excluded.

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REFERENCES

[1] 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).

[2] Compton, A.H and Allison, S.K., [X–ray in Theory and Experiment], D. Van Nostrand Company (1935).

[3] 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).

[4] Muleri, F., Soffitta, P., Bellazzini, R., Brez, A., Costa, E., Fabiani, S., Frutti, M., Minuti, M., Negri, M. B., Pascale, P., Rubini, A., Sindoni, G., and Spandre, G., “A very compact polarizer for an X-ray polarimeter calibration,” in [UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XV, Oswald H.Siegmund, Editors, 668610], 6686 (2007).

[5] Muleri, F., Soffitta, P., Baldini, L., Bellazzini, R., Bregeon, J., Brez, A., Costa, E., Frutti, M., Latronico, L., Minuti, M., Negri, M. B., Omodei, N., Pesce-Rollins, M., Pinchera, M., Razzano, M., Rubini, A., Sgró, C., and Spandre, G., “Low energy polarization sensitivity of the Gas Pixel Detector,” Nuclear Instruments and Methods in Physics Research A 584, 149–159 (Jan. 2008).

[6] Meszaros, P., Novick, R., Szentgyorgyi, A., Chanan, G. A., and Weisskopf, M. C., “Astrophysical implications and observational prospects of X-ray polarimetry,” ApJ 324, 1056–1067 (Jan. 1988).

[7] Dovciak, M., Muleri, F., Goosmann, R., Karas, V., and Matt, G., “In preparation,” MNRAS (2008).

[8] Gambini, R. and Pullin, J., “Nonstandard optics from quantum space-time,” Phys. Rev. D 59, 124021 (June 1999).