
ELSEVIER
Nuclear Physics B (Proc. Suppl.) 166 (2007) April 2007
NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS
SpacePart 2006
Proceedings of the Third International Conference
on Particle and Fundamental Physics in Space
Beijing, China
19–21 April 2006
Edited by
R. Battiston
T. Li
P. Zuccon
www.elsevierphysics.com

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B (Proc. Suppl.) 166 (2007) 266–269
NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS
www.elsevierphysics.com

Gas Pixel Detectors for low energy X-ray polarimetry

Gloria Spandre[a]

[a]INFN sez.Pisa, Largo B. Pontecorvo, 3 I-56127 Pisa, Italy.

Gas Pixel Detectors are position-sensitive proportional counters in which a complete integration between the gas amplification structure and the read-out electronics has been reached. Various generation of Application-Specific Integrated Circuit (ASIC) have been designed in deep submicron CMOS technology to realize a monolithic device which is at the same time the charge collecting electrode and the analog amplifying and charge measuring front-end electronics. The experimental response of a detector with 22060 pixels at 80 μm pitch to polarized and un-polarized X-ray radiation is shown and the application of this device for Astronomical X-ray Polarimetry discussed.

1. Introduction

Astronomers believe that, by measuring the polarization of the radiation emitted in the X-ray energy range by celestial objects such as active galactic nuclei, spinning bodies or black holes, many fundamental informations about the geometry and the internal structure of these sources can be extracted thus allowing to uncover how matter behaves in extremely intense magnetic and gravitational fields. Unfortunately, up to now, the lack of sensitivity has prevented X-ray polarimetry of faint and weakly polarized sources. For this reason we have developed a new instrument ([1],[2]), belonging to the class of Gas Pixel Detectors (GPD), based on the photoelectric effect, a process very sensitive to photon polarization and with a large cross-section in the energy range, 2-10 keV, of great astronomical interest. Photoelectrons liberated by X-rays which convert into the gas chamber have their initial trajectories peaking around the polarization direction of the photons. The degree and angle of polarization can be then derived from the angular distribution of the tracks which are reconstructed by the finely structured collecting electrode.

2. The Gas Pixel Detector

The principle of operation of the GPD is shown schematically in fig. 1.

The few hundreds micron ionization track of the photoelectron, emitted in a low Z gas mixture (usually Neon 50% - DME 50%), is drifted by the applied electric field ($\sim$1 kV/cm) towards the amplification structure (Gas Electron Multiplication, GEM). Passing through the GEM holes, the ionization electrons are multiplied by the intense electric field (80$\div$100 kV/cm) and subsequently the charge is collected onto the pixelized top metal electrode of a custom read-out chip, realized in 0.35μm technology (1 mm collection gap, $\sim$3 kV/cm collection field). The fine pitch (80μm) and high granularity (22080 pixels in a honeycomb array of 11$\times$11 mm^2 active area) of the device allow to reconstruct the track with a high degree of detail. Each pix-

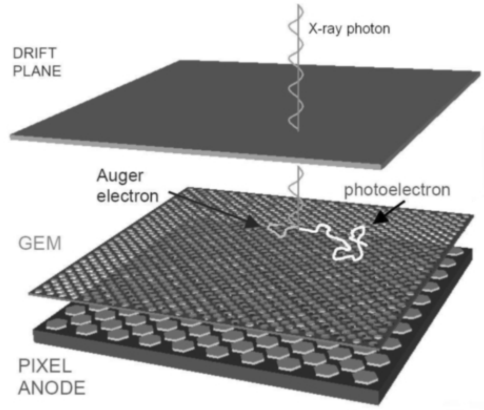

Figure 1. Schematics of the concept of the Gas Pixel Detector.

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2006.12.023

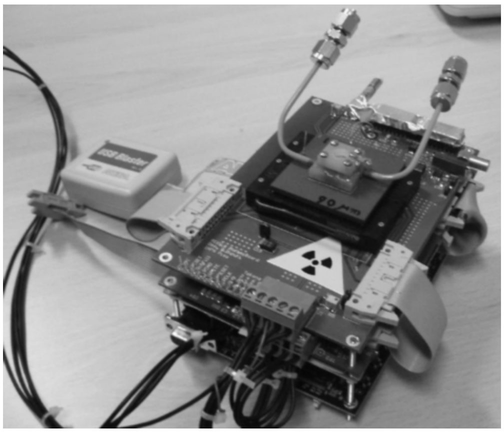

Figure 2. The Gas Pixel Detector mounted on the control motherboard. The gas-tight enclosure, on top of the ASIC, is built up from top to bottom by: a Mylar entrance window, an absorption gap spacer (6 mm thick), a GEM foil (90 μm pitch, 50 μm thick) and a collection gap spacer (1.6 mm).

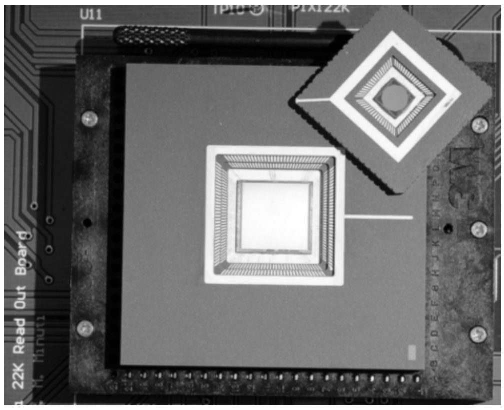

Figure 3. The large area ASIC (22080 pixels) compared with the first ASIC generation (2101 pixels).

els of the ASIC is connected to a full electronics chain (preamp, shaping amplifier, sample&hold, multiplexer) built immediately below it, in the five lower layers of the CMOS technology. A photo of the GPD mounted on the control motherboard and a close view of the large area ASIC die bonded to its ceramic package are shown in figs. 2 and 3. Due to the very low pixel capacitance, an average noise level of 100 electrons (rms) has been measured allowing to reach, at a gas gain of $\sim$ 1000 and with a 3 rms threshold, a good single primary electron sensitivity. Features and electrical characteristics of the chip are listed in Table 1 (for a general description of the large area ASIC, layout, architecture and functionality see ref. [4]).

To trace the initial part of the track by searching the photon conversion point, a sophisticated reconstruction algorithm has been developed (a description of the method can be found in ref.[3]). Fig. 4 shows and example of a real raw event (top panel) and the reconstructed 2D track (bottom panel). The principal parameters of the track, resulting from the reconstruction algorithm, i.e. total charge, cluster size, S/N ratio, shape, moments and emission angle, are also listed in the figure.

3. Polarimetric sensitivity

If photons are polarized, photoelectrons are emitted preferentially along the polarization direction, that means a characteristic cos^2 modulation term (from the photoelectric effect cross-section) peaking at the polarization angle φ_{pol} (and $\varphi_{pol}+180°$) is observed in the track angular distribution. A fit of the distribution with the function $N(\varphi) = C_1 + C_2 cos^2(\varphi - \varphi_{pol})$[1] allows to obtain a fundamental parameter in polarimetry, the modulation factor μ, defined, for 100% linearly polarized radiation, as (see fig. 5):

$$\mu = \frac{N_{max} - N_{min}}{N_{max} + N_{min}} = \frac{C_2}{2C_1 + C_2} \qquad (1)$$

To check the sensitivity to low energy polarized radiation, which sets the lower limit on the minimum detectable polarization (MDP), the residual modulation level of totally unpolarized photons has been measured. This value is essentially due to the presence of systematic effects affecting the data. With a ^{55}Fe source (5.9 keV X-rays)

[1] the constant term C_1 is due to the randomization induced by Coulomb scattering

Table 1
Main electrical and functional characteristics of the CMOS ASIC.

ENC:	100 e^-
Dynamic range:	0.2÷20 fC
Amplifier gain:	100 mV/fC
Shaping time:	∼3.5÷4 μs
Trigger:	external (from top GEM), asynchronous
Read-out layout:	8 serial analog buffer (8 clusters of 2760 pixels)
Read-out frequency:	5 MHz (up to 10 MHz)
Read-out time:	200 ns/pixel (serial)
Frame rate:	550 μs

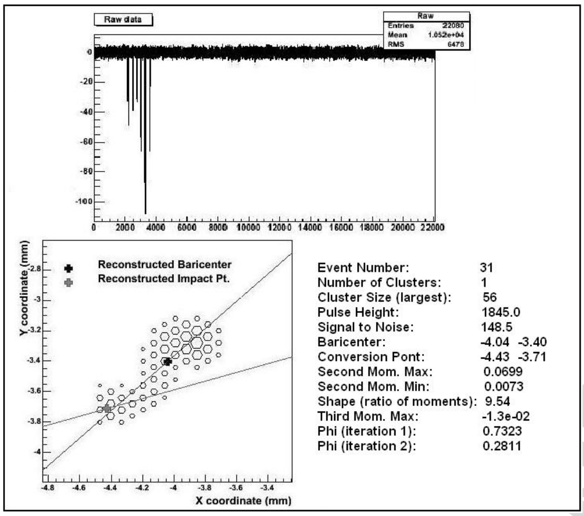

Figure 4. Raw data (top panel) and reconstructed track (bottom left panel) from 5.9 keV photons in Ne(50%)-DME(50%). The characteristics of the track are listed.

it has been obtained (fig. 6) a best fit modulation of 0.59%±0.81%, fully compatible with the absence of any modulation effect within the statistical error. Conversely, with 99% polarized radiation, obtained with a pencil beam from a Cr X-ray tube (5.4 keV, 20kV, 35 mA) scattered at 90° Thompson through a Li target, a modulation factor of ∼45% (fig. 5) has been measured. Even better results are expected with the new third ASIC generation, ∼ 100000 pixels at 50 μm pitch, able to push further forward the track reconstruction capability of the device, in particular at very low photon energies, 1÷2 keV (hence very small track lengths), where the photon flux from astronomical sources is much higher and the mirror effective area is wider. A complete simulation ruling the operation of the device here described has been performed. All the physics process, photoelectric interaction, scattering and slowing down of primary electrons in the gas, drift and diffusion, gas multiplication and final charge collection on the read-out plane, have been taken into account. Modulation factor and detection efficiency together with various mirror effective areas, observation time and source fluxes, which determine the sensitivity of the polarimeter, have been obtained for a wide energy range (from 1 keV to few tens of keV) and different gas mixtures. Fig. 7 shows the Minimum Detectable Polarization as a function of the photon flux (in mCrab units) that could be obtained with the polarimeter at the focus of XEUS optics, the ESA permanent spaceborne X-ray observatory planned to be launched around 2015. One day observations allow to measure the polarization of several AGNs at few % level.

4. Conclusions

The possibility to reconstruct photoelectron tracks with the degree of detail shown by the device presented in this paper represents a significant step forward in the development of high sensitivity polarimeters if compared with the traditional ones. Besides to be good imagers, this new class of Gas Pixel Detectors can perform simultaneously timing and spectral measurements

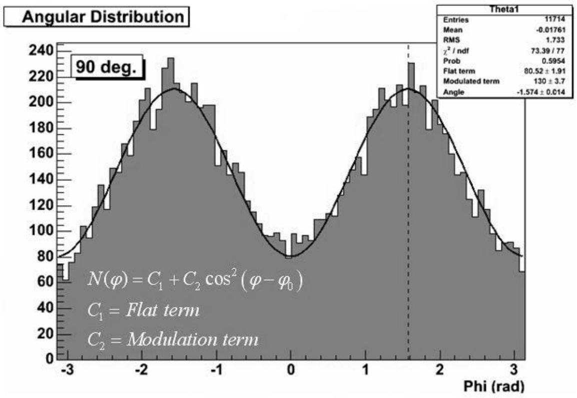

Figure 5. Angular distribution of the reconstructed photoelectron tracks. The polarization angle is 90°±1°. The modulation factor obtained is ∼45%.

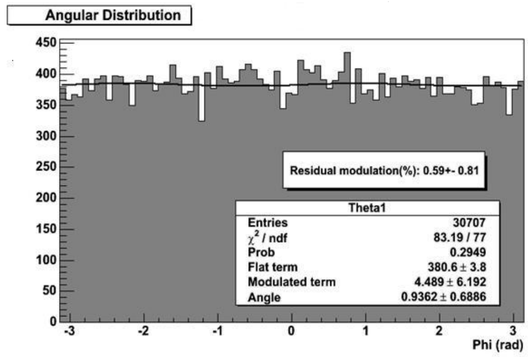

Figure 6. Polarimetric response to an unpolarized radiation.

and allow energy resolved polarimetry. In the final design with 100k pixels anf 50μm pitch, the device will reach a sensitivity that will likely allow polarimetry at level of % on thousands of galactic and extragalactic sources: a real breakthrough in X-ray astronomy.

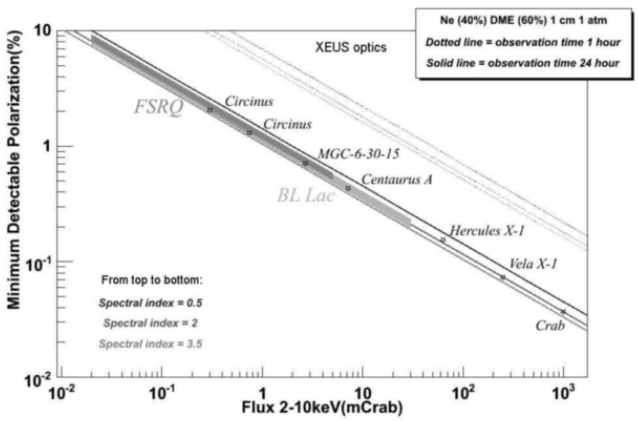

Figure 7. Minimum Detectable Polarization for the proposed Polarimeter at the focus of XEUS optics as a function of the flux, for a few representative sources.

REFERENCES

1. E. Costa et al., Nature, Vol. 411, 7 June 2001.
2. P. Soffitta et al., Nuclear Instruments and Methods in Physics Research A 469 (2001), 164184.
3. R. Bellazzini et al., Nuclear Instruments and Methods in Physics Research A 535 (2004), 477484.
4. R. Bellazzini et al., Nuclear Instruments and Methods in Physics Research A 560 (2006), 425434.