MicroPattern Gas Detectors with Pixel Read-Out

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Abstract

MicroPattern Gas Detectors with pixel read-out are position-sensitive proportional counters obtained by coupling a gas amplifying stage, provided by a GEM detector, to a charge collection plane patterned with pixel electrodes. Advanced PCB techniques, offering typical feature size of the order of a few microns, are used to construct both stages of these detectors, which show high detection efficiency, excellent spatial resolution and fast charge collection. In this paper it is shown how the design of the read-out system can maximize the intrinsic performance of these devices for two practical implementations, in the field of X-Ray Astronomy and Plasma Imaging.

Keywords: MicroPattern; Position-sentivive detector; Pixel read-out

1. Introduction

The evolution of gas detectors saw remarkable advances when new technologies were introduced for development of higher resolution devices. The birth of a whole new class of detectors took place with the introduction of photolithographic techniques from microelectronics industry, which allowed definition of the charge-collecting electrodes with sub-μm accuracy. Micro-Strip Gas Chambers were developed and studied for many years in the 90's, reaching performances very similar to silicon-strip tracking detectors, like a spatial resolution of ~30μm and a rate capability of a few MHz/mm^2. On the other hand this optimization required a complete control of the surface effects connected to the substrate, obtained with specific processing that added cost and complexity to the device [13]. Furthermore, applications to environments with high radiation density, like the tracking systems of high luminosity experiments, revealed a weakness of the electrodes, which could become subjected to destructive discharges if not properly protected by ad-hoc solutions ([11]).

The GEM was at first introduced as a pre-amplifier stage that could be coupled to an MSGC in order to reduce its gain and therefore the risk of sparking [1]. It was soon realized that the advanced PCB technology used for the development of the GEM offered enough precision (~μm) to build high definition structures, capable of sustaining high electric fields, thus combining high gas gains (up to 10^5) and high spatial resolution. The large flexibility in the electrodes patterning, based on processes far simpler and cheaper than micro-electronics photolithography, had the advantage that virtually any electrode configuration could be built with adequate resolution.

This technological development, together with the detailed knowledge of the behavior of complicated multi-electrode structures obtained during MSGC development [12], triggered the development of a new generation of detectors, called Micro-Pattern Gas Detectors (MPGD). Many examples of such detectors were invented, with many different electrode patterns, like the Micro-Groove [2], the CAT [3], the WELL [4] and many others.

A very attractive class of MPGD is the one where a GEM detector is used as a charge-amplifying stage, completely decoupled from the readout electrodes, allowing use of a pixel read-out pattern which can be optimized for the desired application.

Two examples of this approach are described in this paper, where we demonstrate how a careful design of the pixel geometry provides excellent resolving power and high rate capability that would be unavoidably lost by using a conventional projective read-out approach.

2. Detector overview and principle of operation

The detectors described in this paper were developed for X-ray detection, a typical application of gaseous detectors.

The principle of operation common to both applications is described in figure 1. X-ray convert inside a first gas gap, and the primary charge released is drifted to the GEM plane, a 50μm Kapton foil, metal-clad on both

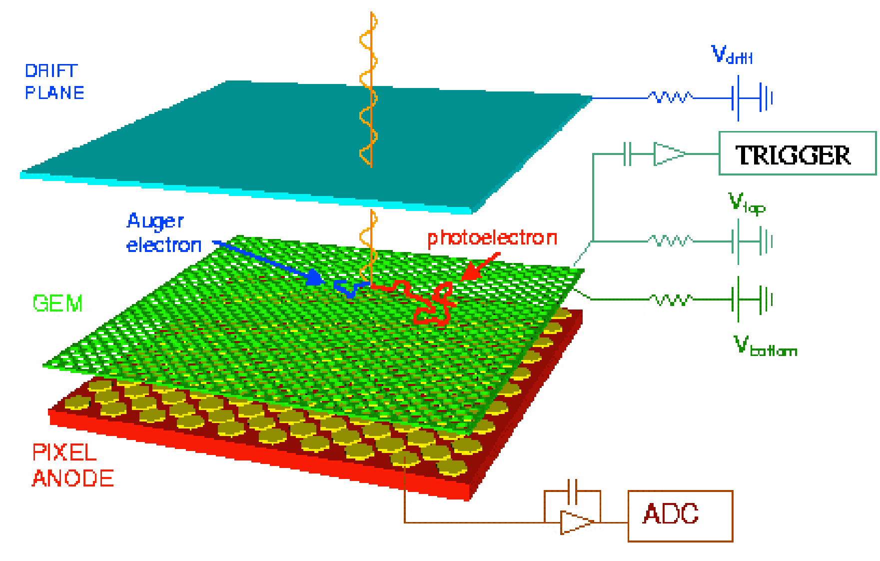

Fig.1: View of an MPGD with pixel read-out

sides and chemically pierced by a regular matrix of holes, tipically 60 μm in diameter and 90 μm pitch.

A high dipole field (see fig2) inside the holes is created by application of a voltage gradient across the GEM, and when primary electrons cross the GEM an avalanche multiplication with proportional gains above 10^3 takes

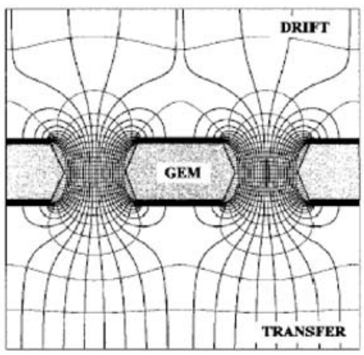

Fig.2 – Electric field lines inside a GEM.

place.

Ions generated in the avalanche are collected at the GEM electrodes, inducing a signal that can be used to trigger the read-out electronics. Secondary electrons are instead drifted away in the transfer gap towards the read-out electrodes on the collection plane. The electric field in the transfer gap is a uniform, plane-capacitor field, as the GEM alone provides the necessary amplification. The printed-circuit board collecting secondary electrons can therefore be freely structured in pixels, with shape and dimensions determined by the application, to get full bi-dimensional reconstruction capability.

The signal on the read-out electrodes is induced by the motion of electrons only, as no other ions are created in the second gap; as the transit time of electrons is ~20 ns (FWHM) in a 1mm transfer gap, the time development of the signal in these detectors is fast.

3. Applications: X--ray astrophysical polarimetry

Many astrophysical sources like neutron and binary stars, AGNs, Black Holes, are strongly believed to emit polarized photons in the X-ray band, as a consequence of asymmetries in the material surrounding the source and scattering primary radiation, or because of the existence of intense magnetic fields which are not randomly oriented [9].

The MPGD with pixel read-out plane described here is a powerful tool for X-ray polarization detection. The key measurement is the full reconstruction of the photoelectron tracks produced in the gas by incoming X-rays. The photoelectric effect is in fact very sensitive to photon polarization: the differential cross section for a linearly polarized photon has a maximum in the plane orthogonal to the direction of the incoming photon and varies with θ (the polar angle) and ϕ (the azimuth angle) in the following equation (1):

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

Photoelectrons from polarized X-rays are therefore preferentially ejected in the plane orthogonal to the photon, with $\cos^2\phi$ modulation.

Polarization of the incoming radiation can be then be measured by a detector that after converting X-rays into photoelectrons, is able to reconstruct their angular distribution.

The charge collection plane of our detector is structured in a finely segmented, hexagonal pixel array with 100-200 μm pitch.

The photoelectron tracks, of the order of few hundreds μm for the chosen gas mixture, can then be efficiently sampled and reconstructed in two dimensions with very good resolution.

Moreover, the signal collected by each pixel is proportional to the charge of the primary clusters released in the ionizing collisions along the track, so that full reconstruction of the photoelectron energy loss dynamics is possible.

A typical event is shown in figure (3), where full development of the track can be followed. At the beginning of

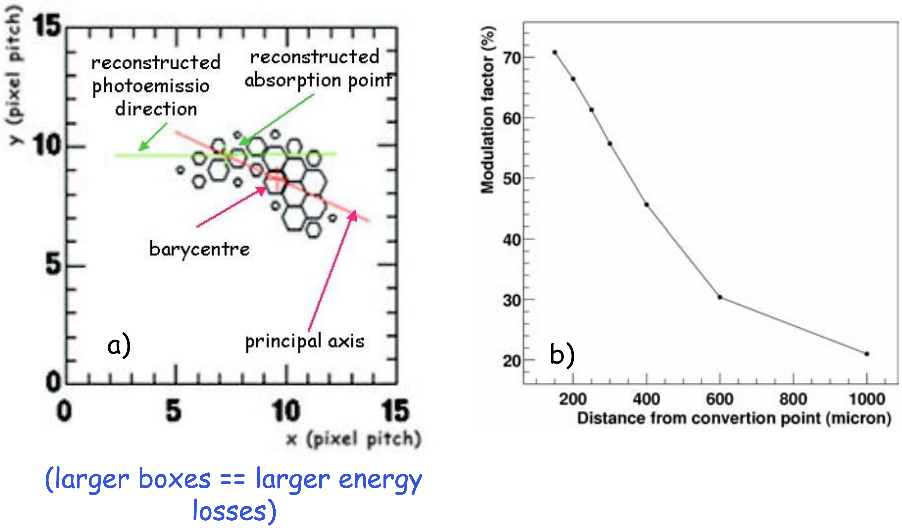

Figure 3: a) Real photoelectron track. Reconstruction of the photoemission direction is done with identification of the absorption point and the removal of the final part of the track, where directional infromation is lost due to track randomization after Coulomb scattering. b) Effect of the track length used for reconstruction on the modulation factor

the track an Auger electron is emitted in a random direction, then the photoelectron travel in the direction of the electric field orientation until all the energy is released along its path. In the last part of the track, the residual energy is deposited in few collisions (Bragg peak), ad large Coulomb scattering with nuclei can occur, which randomize the track.

It's clear that the choice of gas is critical not only to effectively produce photoelectrons, but mainly to be able to follow the development of their tracks. The gas amplifies photoelectrons tracks to ranges of ~mm, differently from solid state devices where ionization would be point-like. Pixels of typically ~100 μm, achievable with advanced PCB technology, have the required granularity to sample the development path of photoelectrons.

The ideal gas mixture is a trade-off between conflicting requirements, and needs to be optimized for different energy ranges. Low Z gases allow for longer ranges, easier to sample with reasonable size pixels, and an acceptable number of large angle scatterings that spoil the resolution. Higher Z, on the other hand, increases the detection efficiency. We have chosen a medium-low Z gas mixture, e.g. Ne(80%)-DME(20%) at atmosferic pressure, which besides having a high stopping-power/scattering ratio, also has the advantage of a very low energy K-edge from Neon. This reduces the fraction of energy that goes into the Auger electron, which is emitted in a random direction independently of the X-ray polarization, and is particularly important in the energy range 2-10KeV [10].

The track reconstruction algorithm that is used relies on the initial part of the track development, where the correlation between polarization and track direction has a maximum.

A first pass algorithm computes the barycenter of the charge distribution, its major axis and third momentum, which points in the direction of smaller charge release, i.e. the initial part of the track, for the asymmetric charge distributions detected here. The impact point is defined at a given distance from the barycenter, along the principal axis, in the direction of the third momentum. A new cluster of pixels is defined within a given range from the impact point, and the principal axis of this new distribution is the reconstructed photoemission [11]. This algorithm maximizes the resolution to polarization measurements (see fig.3b) as well as the imaging capability of the detector. Fig.4 shows the distributions of the barycentres and absorption points from unpolarized radiation collimated in a 50 μm hole: while absorption points are concentrated in a spot of ~70 μm , large charge releases at the end of the tracks make the distribution of barycentres much wider.

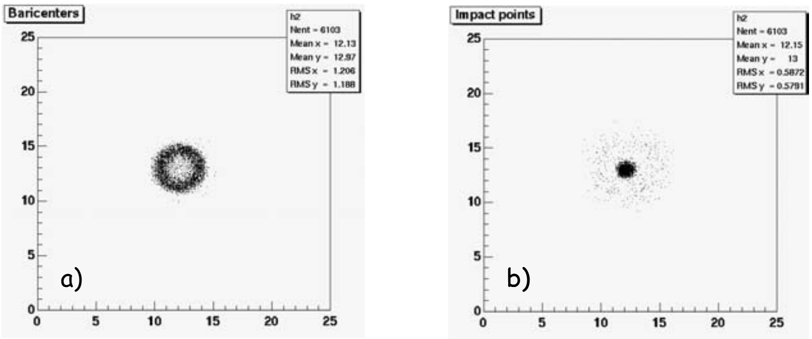

Figure 4: 5.4 KeV X-rays from a 50 μm collimated source: b) the distribution of absorption points well represents the source profile, while the barycentres distribution (a) is shifted away by the Bragg peak at the end of photoelectrons tracks

The MPGD has been tested with unpolarized and polarized radiation; the angular distribution of the photoelectrons emitted in the two cases is shown in figure 5.
As expected, the electric field for unpolarized radiation is randomly oriented, while the distribution for polarized radiation is peaked around the polarization angle and modulated with the characteristic $\cos^2\phi$ term from the photoelectric effect cross section, plus a constant term due to the randomization induced by Coulomb scattering.
A fundamental parameter in polarimetry, which measures how well a polarimeter detect polarized radiation, is the so-called modulation factor, given by (see fig.5):

$$\mu = \frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}} \qquad (2)$$

For a perfect polarimeter where the constant term in the angular distribution is null, the modulation factor μ is equal to 1. The distribution of fig5b) has a modulation factor of ~50 \%.

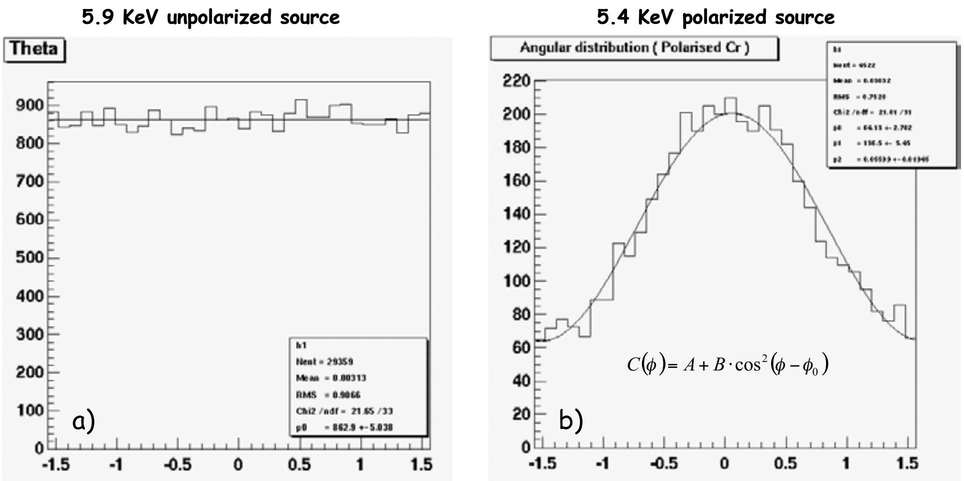

Figure 5: Cluster angular distribution for unpolarized (a) and polarized radiation (b)

The modulation factor, together with detector efficiency, is used to define the Minimum Detectable Polarization (MDP), which is the minimum modulated flux needed to exceed the background and the signal from the unpolarized fraction of the source, at a given confidence level.
The tested prototype at the focus of the XEUS-1 space mission could perform polarimetry at 1\% MDP, in the energy range 2÷10 keV, on many bright AGN with about 1 day observation.
The corresponding improvement in sensitivity is between one to two orders of magnitude with respect to conventional Thomson or Bragg polarimeters.
Such a good performance was considered as a breakthrough for astrophysical polarimetry measurements, and triggered enormous interest for developing a new generation of X-ray missions that would measure polarization of cosmic sources [12].
A high degree of polarization is in fact expected in many sources, but the available detection techniques limited new observations. As today, the only accepted measurement of a polarized source is an observation of the Crab Nebula with a Bragg crystal polarimeter flown on board of the satellite OSO-8 25 years ago.

4. Applications: time-resolved plasma diagnostic

As explained in section 2, MPGD with pixel read-out are fast detector that can be read-out at very high rate, and therefore used for applications where a high rate of photons must be detected. We have combined the imaging capability of these detectors with their high time resolution, and developed a system for monitoring the dynamics of nuclear fusion plasmas in space and time. We were able to obtain very high global counting rate (up to ~1GHz) by reading the many individual pixels of the read-out plane in parallel, and operating each one of these as an independent, free-running counter.

The system is based on a pinhole camera coupled to an MPGD with a GEM as amplifying stage [13]. A sketch of the set-up with the detector positioned to get a tangential view of the hottest region of the plasma (1-10 keV) is shown in fig.6.
The read-out plane (2.5 cm^2) is equipped with a 2-D read-out PCB with 144 pixels of 2mm^2. In this application the dimension of pixels has to be large enough to contain each single photoelectron track and avoid charge

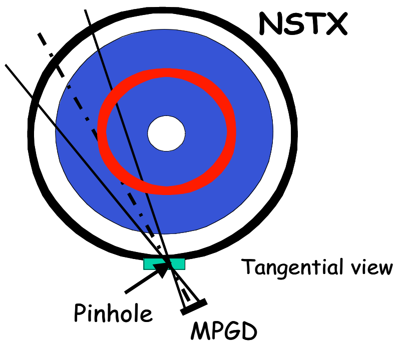

Fig. 6 - Sketched view of the National Spherical Tokamak EXperiment set-up

sharing over several pixels, which would produce a double counting. With this detector and the pinhole camera system we were able to image and area of roughly 80 cm^2 of the plasma.
All the photons along the line of sight hit the detector, but it is possible to isolate the contribution of the central core (the red circle in fig. 6), where the critical core of the plasma is confined. X-rays from the central region

have in fact higher energy than those coming from the surrounding area, so these latter can be rejected by setting a threshold on the pixels signal. All pixels were calibrated to within 2% accuracy and equalized. Energy discrimination is done by changing either the GEM voltage, or the discriminator threshold. Proportional gas gains over a large range are necessary for energy discrimination, as well as a favourable S/N ratio. The pixel noise is about 2000 e^-, and the high gain provided by the GEM accounts for S/N ratios of about 1000 at the highest emissivity. In this configuration the system can take images of the plasma at very high frame rate (up to 100KHz), with a maximum counting rate before saturation of $10^7\gamma$ / (s * pixel), for a global rate over the detector surface of more than 10^9 Hz (dead time ~170 ns). The dynamic range of the system is ~300.

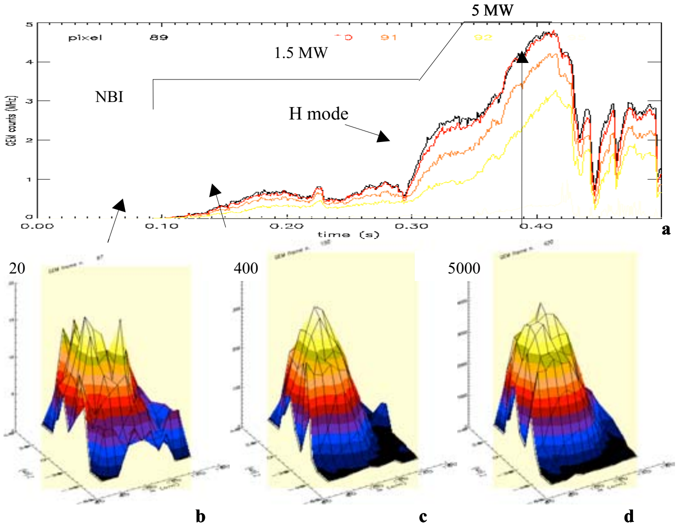

Fig. 7 - Time history of some central pixels (frame rate 1KHz)

The capability of the system to follow rapid changes inside the plasma is shown in fig.7, where the time history of a few central pixels as power is injected into the system is plotted. Instabilities in the last part of the injection generated large and fast saw-tooth oscillations that the system could entirely follow.

Fig.8 shows images of the time evolution of the plasma core for a critical injection, and compares data to the simulated expected behavior. The detector revealed a disagreement in the shape of the core that becomes elongated with time, and for the first time suggested reviews of current models.

Conclusions and prospects

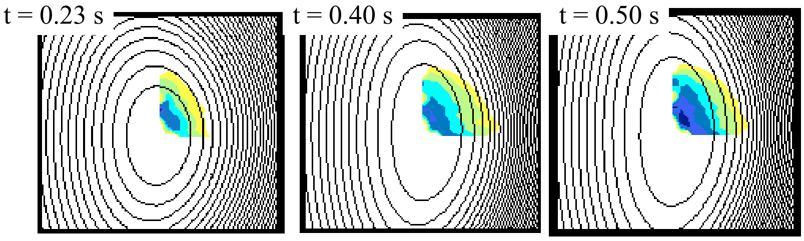

Figure 8:Time development of the plasma core in critical conditions (5MW, βp = 1.2 injection): measurements and current models (isolines) do not match

The most promising aspect of MPGD combined with a GEM is the complete separation of the charge amplification stage, confined to the GEM, from the read-out plane, that can be patterned in any desired configuration. Two novel systems for X-ray polarimetry and plasma diagnostic have been developed by coupling a Micro Pattern Gas Detector with pixel read-out to a GEM used as amplifying stage. For both applications tailoring of the read-out pattern was crucial to exploit the high resolution offered by these devices in view of the specific application. In the first application the high granularity of a low pitch (~100μm), full coverage hexagonal pixel array allowed to efficiently reconstruct photoelectron tracks as short as ~400-800 μm. In the second application, the extremely fast framte rate (up to 100 kHz) obtained with a matrix of independent macro-pixels ($2mm^2$) allowed following the time evolution of hot fusion plasmas.
Both prototypes described here demonstrated powerful possibilities in their application fields, and raised much interest in the respective communities. There are certainly margins for improvement which involve optimization of the gas mixture, dimensions of the gas gaps, read-out electronics, but the main limitation is the construction technology of the read-out plane. The number of channels in these prototypes is already close the maximum attainable with advanced PCB technology, since the routing of the pixel signal to the external read-out electronics can only be done using complex multiple layers architecture.
This is not only limited in the number of layers that can be patterned and superimposed, but it also causes large cross-talks and asymmetries in the path of the electrodes to their read-out amplifiers, with undesirable effects on signal and noise. This is an intrinsic limitation that cannot be overcome by advances in the technology.

We are currently developing an alternative, highly innovative approach that is based on a custom VLSI read-out chip used directly as the charge collecting anode of the GEM. Each pixel of the chip, equipped with a preamplifier, a shaper and a multiplexer will have a metallic pad directly exposed in the gas for collection of the electrons. This new concept will push the performances of gas pixel detectors, with their distinctive advantages described here, to the level of solid state devices.

References

[1] R. Bellazzini et al**., Operation of MSGCs with gold strips built on surface-treated glasses**, *Nuclear Instruments and Methods*, A382 (1996) 461

[2] F. Sauli, *Nucl. Instr. And Meth*. A386 (1997) 531

[3] R. Bellazzini et al., **The CMS micro-strip gas chamber project - development of a high resolution tracking detector for harsh radiation environments**, *Nuclear Instruments and Methods*, A457 (2001) 22

[4] R. Bellazzini, M.A. Spezziga, **Electic field, avalanche growth and signal development in Micro-strip gas chambers and micro-gap chambers**, *Riv. Nuovo Cimento* 17 (12), 1994

[5] R. Bellazzini et al., **What is the real gas gain of a standard GEM?**, Presented at the 8th Wire Chamber Conference, Vienna, 1998, *Nuclear Instruments and Methods*, A419 (1998) 429

[6] R. Bellazzini et al., *Nucl. Instr. And Meth*. A424 (1999) 444

[7] G. Chaplier et al., *Nucl. Instr. And Meth*. A426 (1999)

[8] R. Bellazzini et al., *Nucl. Instr. And Meth*. A423 (1999) 125

[9] M.J.Rees, **Expected polarization properties of binary X-ray sources**, *Mon. Nat. R. Astron. Soc*. 171 (1975) 457,

R.A.Sunyaev, L.G.Titarchuck , **Comptoniza-tion of low-frequency radiations in accretion disks: angular distribution and polarization of hard radiation**, *Astron. Astrophys*. , vol 143 (1985) 374

Yu.N.Gnedin, G.G.Pavlov, Yu.A.Shibanov ,**The effect of vacuum birefringence in a magnetic field on the polarization and beaming of X-ray pulsars**, *Sov. Astron. Lett*.,4 (1978) 117

[10] L. Pacciani et al., **The sensitivity of a photo-eletric X-ray polarimeter for Astronomy: the impact of gas mixture and pressure**, Proceeding of SPIE Vol. 4843 (2002) 394

[11] R.Bellazzini et al., **A novel gaseus X-ray polarimeter: data analysis and simulation**, Proceeding of SPIE Vol. 4843 (2002) 383

[12] E.Costa et al., P.Soffitta, R.Bellazzini, A.Brez, N.Lumb, G.Spandre, **An efficient photo-electric X-ray polarimeter for the sudy of black holes and neutron stars**, *Nature*, vol. 411 (2001) 662

[13]D. Pacella et al., **A X-VUV imaging system for fusion plasmas based on a Micro Pattern Gas Detector**, in publication on *Nucl. Instr. And Meth*. (Proceedings of the SAMBA Conference, Trieste 2002)