Caliste-MM: a spectro-polarimeter based on the micromegas concept for soft X-ray astrophysics

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ABSTRACT: Performing X-ray polarimetry of astrophysical sources is a topic of growing interest, with only a few flying experiments dedicated to it so far. For soft X-rays sources detection from 1 keV to a few tens of keV, the best technique certainly consists in using the photoelectric effect, which is the dominant phenomenon at those energies in gaseous detectors. One of the main issues is the gaseous detector’s reliability in space and the sensitivity to sparks of their associated front-end electronics caused by cosmic rays. To overcome this limitation, we investigate the opportunity of building a new spectro-polarimeter with outer and contactless radiation hard readout electronics, placed outside the gas chamber. In order to perform this, we use a Micromegas detector with a resistive anode spread on a ceramic plate. The signal is then transmitted by capacitive coupling to the outer electronics. The readout electronics in question, inherited from Caliste-HD, consists of a fine pitch 3D detector module developed at CEA initially designed for semi-conductor applications.

In this paper we present the different parts of our experimental setup as well as recent results obtained by illuminating our prototype with an $^{55}$Fe source. In addition to the optimization of the detector’s parameters, we also present the first spectrum of a soft X-ray gaseous detector with outer and contactless electronics and photo-electron tracks obtained with the detector making a step forward in the field of soft X-rays spectro-polarimeter.

KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Polarimeters; Spectrometers; X-ray detectors

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1 Introduction

X-ray astronomy allows the observation of the most violent phenomena in our universe. Spectroscopy, imaging and photometry in soft X-ray energies (1 keV – 15 keV) are well mastered sciences performed by famous missions (Chandra, RXTE, XMM-Newton). But X-ray polarimetry is still missing: only a few pioneer dedicated experiments have been flying on board of rockets or satellites [1–4]. Because of the low sensitivity of the instruments based on Bragg diffraction and Thomson scattering the only positive detection was the polarization of the Crab Nebula [5].

Thanks to the improvement of gaseous detectors in the late 90s and the possibility to use the photoelectric effect to perform soft X-ray polarimetry, the interest for this scientific domain has been renewed. In fact, because polarimetry gives significant information on the magnetic field of the emitting X-ray source, it would give information on a wide variety of X-ray sources and allow the validation of theoretical models. Consequently, various missions are currently under development such as the XIPE [6], IXPE [7] and PRAXyS missions. Such applications are for instance [6] the observation of accelerating phenomena in supernovae remnants or pulsar wind nebulae by measuring the variation of the magnetic field inside the nebulae.

Polarimetry can be performed in a gaseous detector thanks to the photoelectric effect, where an incoming photon is converted in the gas into a photo-electron. The differential cross-section for this effect is given by the Heitler formula [8]:

\[
\frac{d\sigma_{ph}}{d\Omega} = r_0^2 \alpha^4 Z^5 \left( \frac{m_e c^2}{E} \right)^2 \frac{4 \sqrt{2} \sin^2 \theta \cos^2 \phi}{(1 - \beta \cos \theta)^4} \]

(1.1)

where \( r_0 \) is the classical radius of the electron and \( \beta \) its velocity in units of the speed of light, \( \alpha \) the fine-structure constant, \( m_e \) the rest mass of the electron, \( E \) the energy of the incoming photon, \( Z \) the atomic number of the absorbing atom, \( c \) the speed of light and \( \theta \) and \( \phi \) are respectively the polar angle and azimuthal angle of ejection as defined in figure 1. The ejection direction is modulated by \( \cos^2 \phi \) and is then directly linked to the polarization direction of the incident photon. By looking at the angular distribution of the azimuthal ejection direction of the incoming photons of an X-ray source, it is possible to derive the polarization direction of the source and measure its polarized fraction.
2 The Caliste-MM system

Our new gaseous detector is based on the Micromegas concept presented in [9]. When considering a space-borne application, specific attention must be paid to the protection of the electronics from the sparks caused by cosmic radiation, which can easily damage the electronics, without sacrificing the performance. The classical solution is to use large protection cards: if the detector is to be used in orbit those protection cards would need to be space qualified and radiation hardened, which would inevitably bring a significant increase of the development costs and mass. A more original and convenient solution is to use a piggyback Micromegas [10]. Based on the bulk technology, the particularity of this detector is its anode, which is a resistive layer of sheet resistance of $100\,\mathrm{M}\Omega/\square$ spread on a $300\,\mu\mathrm{m}$ thick ceramic plate. Figure 2 (left) shows the detector chamber with the piggyback inside: one of its face is not inside the gas and is directly in contact with the outside, so there are no electronics inside the detector. Figure 2 (right) shows a scheme of the piggyback and represents its mesh, amplification gap, resistive layer and ceramic plate. It is this ceramic plate which is directly in contact with the outside. The readout electronics are to be placed outside the detector, facing the ceramic to read the signal through it by capacitive coupling. It is then possible to have easily interchangeable and possibly contactless electronics and should provide a natural protection from the sparks, as the electronics being outside the gaseous medium.

Tests have been performed on a piggyback detector filled with argon-isobutane mixture (95% - 5%). The detector has been illuminated with an $^{55}\mathrm{Fe}$ source, producing 5.9 keV photons. Figure 3 is obtained by reading the signal developed inside the piggyback: the mesh and drift voltages are independently powered by a CAEN N471A module and the signal is read on the mesh by an electronics chain consisting of an ORTEC charge pre-amplifier with its output fed into a CANBERRA 2022 Amplifier and a multichannel analyzer AMPTEK MCA-8000A for spectra acquisition. The number

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{photoelectric_effect.png}
\caption{Photoelectric effect. The light blue arrow represents the electric vector, the purple line is the ejection direction of the photo-electron and the black point is the ejected photo-electron. $\theta$ and $\phi$ are respectively the polar and azimuthal angles. The ejection direction is modulated by $\cos^2 \phi$.}
\end{figure}
Figure 2. Left: the gaseous detector’s chamber: there are no electronics inside the gaseous medium. Right: focus on the piggyback. Its resistivity is $R = 100 \text{ M}\Omega/\square$.

Figure 3. Gain and Energy resolution as a function of the amplification field. The performances are the expected ones for the bulk technology.

of charges collected is obtained from the ADC units of the MCA by calibrating the electronics chain. The absolute gain is determined by calculating the ratio between the charge collected at the mesh and the primary electrons’ charge created by the incoming 5.9 keV photon. These results show expected performances for the bulk technology with an 128 $\mu$m amplification gap in terms of gain and energy resolution reaching 18 % FWHM at 6 keV. This limit on the resolution is due to the use of a 35 $\mu$m standard stainless mesh which degrades the electric field lines between the holes. Resolutions of 11.5% FWHM at 6 keV can be attained with Micromegas microbulk detectors using 5 $\mu$m thick meshes [11]. In the near future we plan to use a flat mesh on a piggyback to improve the energy resolution.

The readout electronics must have some specific qualities. It must be low noise and sensitive enough to be able to read the signal through the ceramic plate of the piggyback. It should be position sensitive and be finely pixelated to be able to recover the ejection direction of the photo-electrons in order to perform polarimetry. It should also be able to perform spectroscopy with good energy resolution to reach at least the resolution of the piggyback detector. Caliste electronics [12, 13] (figure 4 left), initially used for semiconductors hard X-Ray spectroscopy, present all those characteristics.

Caliste has in fact several interesting properties to read the signal of the piggyback, summarized in table 1. The electronic noise is very low, which makes it a perfect candidate to read the signal of the piggyback through the ceramic. Each channel of the electronics is a self-triggered spectroscopic chain presented in figure 4 (right), and the 256 pixels are multiplexed by 8 IDeF-X ASICs [14].
Table 1. Caliste body main characteristics.

| Characteristic       | Value                                      |
|----------------------|--------------------------------------------|
| 3D block:            | $10 \times 10 \times 16.5 \text{ mm}^3$  |
| 16x16 pixels:        | 8 ASICs IDeF-X of 32 channels             |
| Pixel diameter:      | 450 $\mu$m                                 |
| Pixel Pitch:         | 625 $\mu$m                                 |
| Consumption:         | 850 $\mu$W/channel                         |
| Low Noise:           | ENC = 50 e$^-\text{rms}$                   |

Figure 4. Left: the Caliste electronics. The dimensions are 1 cm$^2$ by 1.65 cm high. The 256 pixels, organized in an array of 16x16, can be seen on top of the electronics. Right: spectroscopic chain block diagram of one channel.

An incident charge on a pixel is converted into a pulse and its pulseheight measured. The signal is read out if it is above the preset threshold that is tunable for every channel. With the IDeF-X ASICs, it is possible to tune several parameters to optimize the reading of a gaseous detector instead of a semiconductor. In particular it is possible to optimize the shaping time, the dynamic, the charge preamplifier bias current and the controller frequency. Another advantage of the Caliste is its radiation hardness and space-qualification, which gives a tremendous asset toward the use of the detector in space-borne applications.

The Caliste is coupled to the piggyback detector in the setup shown in figure 5, called Caliste-MM. The Piggyback is placed on top of the Caliste and the system can be put in a contactless configuration where the electronics do not touch the ceramic. Preliminary characterization has been done by Attié et al. [15] in 2014. First tests have been done with a gaseous mixture of argon-isobutane (95%-5%) at atmospheric pressure, with a contactless configuration (Caliste at 500 $\mu$m from the ceramic) and an $^{55}$Fe source. Figure 6 shows some events read on the Caliste after the conversion of a photon inside the detector: the image represents the 2D pixels array of the Caliste, and the deposited energy is represented by the colormap. The events are round and their typical diameter is 6 mm. The large size of the events is mostly due to the diffusion inside the resistive layer of the piggyback. It is the first time that a gaseous detector has been readout by contactless electronics. The detector has been continuously tested for 4 months, experiencing frequent sparks but resulting in no observable damage to the detector, proving the merits of Caliste-MM and the resistive layer for electronics protection.
Figure 5. Left: setup with Caliste and Piggyback separated. Right: Caliste-MM setup. 1: 500 $\mu$m spacer. 2: piggyback’s ceramic. 3: piggyback’s chamber. 4: acquisition electronics. 5: entrance window. 6: gas tubes.

Figure 6. Photon conversion in argon-isobutane (95% - 5%) as read on the Caliste. The horizontal and vertical axes represent the pixel coordinates.

3 Results of the first prototype

The gain of the system as a function of amplification field is shown in figure 7 and compared to the gain of the isolated piggyback (already presented in figure 3). The voltages on the piggyback are provided independently by a CAEN N1471 module and the signal is read directly by the Caliste through the ceramic and the 500 $\mu$m air layer, this particular distance being chosen because of the higher precision of the 500 $\mu$m spacers. The absolute gain is determined by calculating the ratio between the charge collected on the Caliste and the primary electrons’ charge created by the incoming 5.9 keV photon. The general behaviour of the piggyback is preserved. Reading the signal through the ceramic coupled to a layer of air decreases the gain. But it is still of the order of magnitude of $10^3$ which is large enough for soft X-ray applications when using a low noise and highly sensitive electronics such as Caliste. Another interesting parameter for the Caliste-MM
detector is the distance between the Caliste and the ceramic, as it plays an important role on the induced signal on the detector. Figure 8 shows the variation of the gain of the detector versus this distance for an amplification field of 35 kV.cm\(^{-1}\). When closer to the ceramic, the gain is up to 4 times more important which seems natural because of the narrowing of the air layer. The variations of the gain are more important for closer distances. These phenomena are currently under study with the development of an analytic model of the detector, but already indicate that they influence the gain of the system. If a greater gain is needed (to detect lower energies for instance) the Caliste can be placed closer to the ceramic, while keeping the amplification field at the value that optimizes the energy resolution. However, decreasing the distance too much can create some problems. A contact between the ceramic and the Caliste can mechanically damage the pixels of the electronics. The pixels do not all have exactly the same size and their height can vary by ±25 µm. This variation degrades the energy resolution of the system for distances closer than 400 µm. Finally, the quality of the used spacers is not equivalent. The 500 µm spacers are more trustworthy and easier to use, explaining why they have been used for most of our characterizations.

Figure 9 shows a spectrum of the events presented in figure 6 after a calibration of each pixel of the Caliste. Each event is fitted with a 2D gaussian function. Several methods have been tested to build a spectrum: histogram of the maximum deposited on a pixel for each event, of the maximum of a 2D gaussian fit, or of the total energy deposited by each event on the Caliste. But the best results are obtained by integrating the value of the fit within 1σ from its centroid. The spectrum is built from the resulting value. Performing a 1σ integral, instead of a 2σ or other, ensures that the main peak of the spectrum is at around twice the energy of the escaping peak, as it should be (main peak at 5.9 keV, escape peak at 2.8 keV). Any other method moves the two peaks away from one another, thus distorting the energy calibration. We strongly suspect that the 1σ integral limits the influence of the diffusion inside the resistive layer by taking only the created charges deposited on the detector. This is still a preliminary result and a full modelization of the detector has to be carried out to confirm this. The spectrum exhibits a good energy resolution of 17.7 % FWHM at 6 keV. Having external and contactless electronics does not degrade the energy resolution, as we are able to recover the minimum resolution of the piggyback alone (shown in figure 3).

Argon has however two disadvantages: its K-edge energy is high (3.2 keV) so a soft X-ray photon will create a low energy photo-electron, and it is a high Z gas so the photo-electron’s track will be short. This makes an argon mixture at atmospheric pressure not well adapted to perform polarimetry as a photo-electron does not propagate far enough to leave a good track and allow the recovery of the ejection direction. It can be seen in figure 6 that recovering the ejection direction of the photons in argon is impossible as the events appear round. The gas has been replaced by helium - CO\(_2\) (90 % – 10 %) at atmospheric pressure. Helium has the advantages of being a low K-edge and low Z gas. The results for 8 keV photons are presented in figure 10. This figure proves that helium is well suited for polarimetry, as photo-electrons can propagate far enough to leave a visible track. The blue pixels are due to the diffusion of the signal inside the resistive layer of the piggyback and the pink and white pixels correspond to the photo-electron’s track: the fact that this track is visible makes polarimetry possible with the Caliste-MM. The maximum of the deposited energy in the conversion, represented by the white pixels in the picture, corresponds to the Bragg peak and is the end of the track. The ejection direction of the photo-electron can be recovered using the pixels at the beginning of the track. Without any data treatment, the ejection direction can be roughly estimated
Figure 7. Comparison of gains as a function of amplification field for Caliste-MM and piggyback alone. The distance between Caliste and the ceramic is 500 µm. The behaviour is comparable, but due to the coupling through the ceramic plate and a layer of air, the gain of Caliste-MM is attenuated.

Figure 8. Absolute gain versus the distance between the electronics and the ceramic for an amplification field of 35 kV.cm\(^{-1}\). When the distance is greater than 1 mm, the gain stabilises.

and seems to be horizontal going from the left to the right of the image. Data analysis will obviously give a better precision, but the fact that the track and the ejection direction can be estimated directly foresees good potential for the track reconstruction and polarimetry measurement.

4 Discussion

Caliste-MM can perform spectrometry or polarimetry using different gases, but its main objective is to perform both goals at the same time. For this using a neon or argon mixture at low pressure appears to be a good solution although the parameters of the detector will have to be optimized for spectro-polarimetry. To perform spectrometry it is important to use a specific amplification field
Figure 9. The $^{55}$Fe spectrum using Argon-Isobutane mixture. The energy resolution is 17.7% FWHM at 5.9 keV.

Figure 10. 8 keV photon conversion in helium: the photo-electron’s track is visible and its ejection direction can be recovered.
which gives the best energy resolution as shown by figure 3 (right). However, if the photo-electron leaves a track, as is expected for polarimetry, it is necessary to have a high gain in the detector in order to recover the entire length of it and especially the beginning. This can be done by decreasing the distance between the Caliste and the piggyback’s ceramic as shown in figure 8, without changing the amplification field. Both amplification field and distance play a role in the size of the events and we need to ensure that the entirety of each event is recovered by the Caliste in order to treat the event for spectrometry. This influence is presented in figure 11. On the left is the variation of the mean radius of the events expressed in number of pixels versus the distance between the Caliste and the ceramic for an amplification field of 35 kV.cm$^{-1}$. On the right is the same variation versus the amplification field. These figures show that increasing the amplification field increases the size of the events, following what seems to be a linear relation. If a high amplification field is needed for energy resolution purposes at other energies than 6 keV a part of the event will not be detected by the electronics and the data treatment will be degraded. However, figure 11 left shows that increasing the distance between the Caliste and the ceramic reduces the event’s size slightly. It may be a solution to compensate the influence of the amplification field when trying to keep events of various energy completely inside the Caliste for a better fit and analysis. This will, however, make the gain of the Caliste-MM lower and we might not be able to recover the beginning of the track and perform polarimetry. Spectro-polarimetry finally needs optimization of the different parameters such as gain, distance between the Caliste and the ceramic or gas mixture, and construction of an analytical model of Caliste-MM to help in this optimization. It must be noted that the figures presented in figure 11 will be very valuable in the validation of the analytical model.

5 Summary

Caliste-MM is a new detector developed to perform spectro-polarimetry in soft X-ray energies. It uses a Micromegas technology, called Piggyback, consisting of a resistive anode spread on a ceramic plate. The readout electronics, called Caliste, is placed outside the gaseous medium and the signal is read through the ceramic by capacitive effect, being then naturally protected from sparks. Several parameters of Caliste-MM have been characterized, such as its gain behaviour or the influence of the distance between the Caliste and the ceramic, which shows interesting properties that need to be studied in details. In Argon, the system also shows a good energy resolution of less than 18 % FWHM at 6 keV when using a specific 1σ cut, which is the minimum resolution of the piggyback alone. Having outer and contactless electronics does not degrade the resolution of the detector.
The $1\sigma$ cut limits the influence of the diffusion inside the resistive layer and is the method which does not distort the energy calibration by giving the best energy resolution. When using helium the photo-electrons' tracks are visible as well as their ejection direction, making a measurement of polarimetry possible. Different parameters need to be optimized and further work will include an analytic modelization of Caliste-MM to help this optimization, tests with Neon based mixtures in low pressure condition to perform spectro-polarimetry, and tests in a 100% polarized beam in order to make a measurement of the modulation factor of our promising polarimeter.

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