Combined readout of a triple-GEM detector

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ABSTRACT: Optical readout of GEM based devices by means of high granularity and low noise CMOS sensors allows to obtain very interesting tracking performance. Space resolution of the order of tens of µm were measured on the GEM plane along with an energy resolution of 20%−30%. The main limitation of CMOS sensors is represented by their poor information about time structure of the event. In this paper, the use of a concurrent light readout by means of a suitable photomultiplier and the acquisition of the electric signal induced on the GEM electrode are exploited to provide the necessary timing informations. The analysis of the PMT waveform allows a 3D reconstruction of each single clusters with a resolution on z of 100 µm. Moreover, from the PMT signals it is possible to obtain a fast reconstruction of the energy released within the detector with a resolution of the order of 25% even in the tens of keV range useful, for example, for triggering purpose.

KEYWORDS: Time projection chambers; dE/dx detectors; Particle tracking detectors (Gaseous detectors)

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1 Introduction

Time Projection Chambers based on a Micro Pattern Gaseous Detector optical readout represent ideal candidates for high resolution particle tracking. MPGD are a simple solution for equipping large surfaces, ensuring very good spatial and timing resolution. In particular Gas Electron Multipliers [1] are very easy to assemble and their structure is able to suppress the Ion Back Flow inside the sensitive volume. In these devices, during the multiplication processes, photons are produced along with electrons by the gas through atomic and molecular de-excitation. Optical readout of gas detectors offers several advantages:

- optical sensors are able to provide high granularities along with very low noise levels and high sensitivities;
- optical coupling allows to keep sensors out of the sensitive volume (no interference with HV operation and lower gas contamination);
- suitable lens allow to acquire large surfaces with small sensors.

This approach was already studied in the past ([2, 3]). In last years, the developments of large granularity and low noise CMOS sensors made it possible to obtain very interesting results with detectors based on optically readout GEM ([4, 5]). Very good tracking performance were obtained with a space resolution (on the GEM plane) of 35 \( \mu \text{m} \) even for minimum ionising particles. Moreover, they allow the measurement not only of the total released energy but also of the energy release density along the tracks that can be very useful for particle identification ([6]). To overcome the poor timing information provided by the CMOS, a combined light readout with a fast PMT is proposed. In this paper, the performance obtained by reading out the light provided by a triple-GEM structure with a CMOS sensor together with a fast PMT, are described.
2 Experimental set-up

A sketch of the setup used to test ORANGE (Optically ReAdout GEm) prototype (described in more details in [6]) is shown in figure 1.

Measurements were taken with 450 MeV electrons at the “Beam Test Facility” [7] of INFN Laboratori Nazionali di Frascati.

Three standard 10 x 10 cm\(^2\) GEM were used with 2 millimetre transfer gaps between the GEM and a drift gap of 1 cm. The sensitive volume was, therefore, 0.1 litre. The device was flushed with an He/CF\(_4\) 60/40 mixture and the gas volume was closed by means of a transparent PMMA window. The detector was operated with a drift field of 1.5 kV/cm and two transfer fields of 2.0 kV/cm. In this configuration an electron velocity in the drift gap of of about 74 \(\mu\)m/ns was estimated with Garfield [8].

2.1 Detector readout

The light emitted by gas mixture in the third GEM channels was readout by an Orca Flash 4 CMOS-based camera\(^1\) equipped with a large aperture (\(f/0.95\)) lens. Very clear images of high energy electrons from the beam as the one shown in figure 2, were acquired by this device.

\(^{1}\)For more details visit the site www.hamamatsu.com.
The image in figure 2 represents a single electron traveling in the drift gap, parallel to the GEM foils. In order to acquire the time structure of the signals, light was concurrently readout by a 25-mm diameter PMT\(^2\) placed close to the camera lens. Moreover, the electric signal induced by the motion of the electrons on the third GEM bottom electrode (G3D) was acquired by means of a 10 GS/s sampling oscilloscope.\(^3\) These two signals are able to provide two independent measurements of time structure of the event. The acquired waveform of the PMT output and of the electrical signal in the event of in figure 2 are shown respectively on the left and on the right of figure 3.

![Figure 2](image)

**Figure 2.** Examples of acquired image of a 450 MeV electron.

![Figure 3](image)

**Figure 3.** Example of an acquired waveform of the PMT output and the electric signal induced on the bottom electrode of the third GEM (G3D).

In both cases clear and narrow (less than 10 ns FWHM) waveforms are visible. The relative noise level in the electric signal is considerably larger, most likely due to jitter on the high voltage supply line. From a gaussian fit of the PMT output, a sigma of 5.5 ns was measured. By measuring the distribution of the differences of the time of arrival of the two signals, the time resolution of the detector for tracks parallel to the GEM plane could be evaluated (figure 4, left).

The behaviour of the time difference as a function of the voltage applied to the three GEM foils (figure 4, right) shows that a sigma of less than 2 ns can be achieved. Assuming that the time jitter of the signal is almost the same, a time resolution of \(2/\sqrt{2}\) ns can be evaluated for both of them. By using the calculated drift velocity, it is thus possible to conclude that the absolute track \(z\) position can be reconstructed with a resolution of about 100 \(\mu\)m.

\(^2\)Hamamatsu H10580.

\(^3\)Lecroy Waverunner 7300.
Figure 4. Distribution of the differences of the arrival time of the PMT and G3D signals with a superimposed gaussian fit (left) and of the behaviour of the time resolution as a function of the GEM voltage supply (right).

2.2 Exploiting the time information: combined readout

In figure 5, the PMT signal is shown for an inclined electron crossing the 1 cm drift gap at an angle of 0.1 rad (almost 6°) with respect to the GEM foils.

Figure 5. PMT waveform for a track crossing the drift gap inclined with respect to the GEM plane.

The arrival time of the main clusters is clearly visible, allowing an independent reconstruction of their absolute position in $z$. Taking into account the gap width (1 cm) and the width of the signal (about 135 ns), an electron drift velocity of 72 $\mu$m/ns is found in agreement with the value evaluated with Garfield.

Figure 6 shows an example of the lateral profile of the detected light as seen by the CMOS camera for a track together with the corresponding PMT waveform.

In both cases, with a simple peak finding algorithm, the position of the main peaks was evaluated. The tracks in the ten analysed events have an average length of almost 60 mm and 54 peaks were found in total. Therefore, the algorithm is able to individuate one peak per track centimetre on average.
Figure 6. Lateral profile of the light detected by the CMOS sensor along with the waveform of the PMT signal for the same event. The cluster structure is clearly visible in both cases. Peaks found by the finding algorithm are shown.

By assuming these peaks as due to ionization clusters along the tracks, their $x$ and $z$ coordinates can be evaluated. Their correlation is shown on the left of figure 7 while the distribution of the reconstructed $z$ residuals to a linear fit for a set of ten tracks is shown on the right.

Figure 7. Left: correlation with a superimposed linear fit of the $x$ and $z$ coordinates of the clusters found in a single track. Right: distribution of the residuals of the reconstructed to the linear fit $z$ for ten tracks with a superimposed gaussian fit.

From the superimposed fit, it is possible to evaluate a resolution on the reconstructed $z$ coordinate of about 100 $\mu$m.
3 Measurement of the released energy

The light collected by the PMT is expected to be proportional to the energy released by the 450 MeV electrons of the beam in the gas (i.e. 2.3 keV/cm in an He/CF$_4$ 60/40 mixture [6]). Before reaching the sensitive volume, electrons from the beam lose energy in the material present on the beam line as the black box containing the GEM structure or the frame used to have a gas-tight volume.

The distribution of the integral of the PMT signals for 100 events is shown on the left of figure 8. Separate peaks due to different numbers of particles per event are clearly visible. The distribution of the number of particles per event is compatible with a Poisson distribution with an expected value of 1.4.

![Figure 8](image_url)

**Figure 8.** Left: distribution of the integral of the PMT waveforms in a run of 100 events. For the single-track events a superimposed gaussian fit is also shown. Right: average PMT response as a function of the number of reconstructed particles with a superimposed linear fit.

For the events with a single particle, the jitter in the light detected by the PMT was studied as a reliable indicator of the resolution achievable in the measurement of the released energy.

From the gaussian fit on the distribution for single particle event, it is possible to evaluate that, by reading out the light produced by means of a PMT, an energy resolution of about 26% can be easily achieved for an energy release of the order of 20 keV.

The average PMT response is shown on the right of figure 8 as a function of the number of particles. A very good linearity was found. These last plots demonstrate that a simple light readout with a PMT allows a fast evaluation of the number of particles crossing the sensitive volume and the total energy released that can be exploited, for example, for triggering purpose.

4 Conclusion

With the aim of constructing a high resolution GEM-based Time Projection Chamber, several R&D activities are being carried on. In particular, the performance of a combined optical readout (CMOS sensor and PMT) was studied in detail. The photomultiplier signals showed a time resolution better than 2 ns and demonstrated of being able to provide detailed information on the time structure of the events, very useful for a 3D reconstruction. A resolution of 100 $\mu$m on the coordinate orthogonal to the GEM plane was measured. Moreover the analysis of the PMT waveform allows a fast measurement of the total released energy with an accuracy of 25%.
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