Performance of large pixelised Micromegas detectors in the COMPASS environment

F. Thibaud, P. Abbon, V. Andrieux, M. Anfreville, Y. Bedfer, E. Burtin, L. Capozza, C. Coquelet, Q. Curiel, N. d’Hose, D. Desforge, K. Dupraz, R. Durand, A. Ferrero, A. Giganon, D. Jourde, F. Kunne, A. Magnon, N. Makke, C. Marchand, D. Neyret, B. Paul, S. Platchkov, M. Usseglio and M. Vandenbroucke

CEA Saclay DSM Irfu, 91191 Gif sur Yvette Cedex, France

E-mail: florian.thibaud@cea.fr

ABSTRACT: New large-size Micromegas detectors are being developed for the future physics program of the COMPASS experiment at CERN. These detectors will have a pixelised readout in their center to detect particles in the beam region, where the particle flux can reach several MHz/cm$^2$ in nominal conditions, and will have to handle high intensity hadron beams (up to a few $10^7$ hadrons/s) with a discharge rate lower than 0.01 to 0.001 discharge/s. Several prototypes with two different discharge rate reduction technologies (preamplification stage with a GEM foil and resistive readout with buried resistors) have been studied in the COMPASS beam since 2010. Four of them have been included in the spectrometer since 2012, and have been used for the track reconstruction. Their performance (detection efficiency, space and time resolutions, and discharge rates) for different beam intensities and magnetic fields environments are presented. These detectors play an important role in the track reconstruction at very small angle; their impact is presented, with a particular emphasis on the effect of the background reduction due to an improved cluster selection.

KEYWORDS: Gaseous detectors; Hybrid detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Gaseous imaging and tracking detectors

$^1$Corresponding author.
1 The COMPASS experiment and Micromegas detectors

The COMPASS experiment [1] is dedicated to study the spin structure of the nucleon and the spectroscopy of hadrons. It uses the secondary muon and hadron beams delivered on the M2 beamline of the SPS (Super Proton Synchrotron) accelerator at CERN. These beams have an energy range from 100 to above 200 GeV and their intensity can reach several $10^7$ particles per second. The experimental set-up consists of a fixed target and a two-stage spectrometer for the detection and identification of particles at a large momentum and angular range.

COMPASS was the first physics experiment equipped with Micromegas detectors [2]. Since the beginning of the data taking in 2002, 12 Micromegas detectors have been used to detect particles scattered at low angles. They were developed by CEA Saclay in order to fit the requirements of the experiment: handle a flux up to 500 kHz/cm², with a spatial resolution better than 100 µm and a low material budget. These detectors have an active area of $40 \times 40$ cm², with a blind disk of 5 cm diameter on the path of the beam. They have demonstrated very good performance since their installation: a detection efficiency between 96% and 98%, a spatial resolution between 90 µm and 110 µm, and a time resolution better than 10 ns. The discharge rate has been minimised by using a light gas (Ne/C₂H₆/CF₄ in proportions 80/10/10) and by operating the detectors at a moderate gain thanks to the low noise SFE16 electronics [3]. With a high flux muon beam ($4 \times 10^7$ muons/s...
on a 1.20 m LiD solid target), the discharge rate per detector is lower than 0.02 discharge/s. With a hadron beam the discharge rate reaches 0.04 to 0.1 discharge/s with a beam of $10^7$ hadrons/s [4]. This rather high discharge rate is tolerable but prevents from any future increase of the hadron beam flux, as higher rates would reduce the detection efficiency and might deteriorate the detectors and the electronics.

2 The Pixel Micromegas detector

The COMPASS collaboration completed in 2011 its initial physics program [5]. For the future (2012 and beyond), new physics objectives have been proposed [6] like the study of Generalised Parton Distributions via Deeply Virtual Compton Scattering and Transverse Momentum Distributions via polarised Drell-Yan.

The perspective to use Micromegas detectors during many more years and in higher beam intensities implies in the design and production of a new generation of detectors. Two major objectives have been defined: the new detectors must be active in their center to detect particles in the beam region in order to improve the track reconstruction at very small angle, and must handle hadron beam intensities up to $5 \times 10^7$ hadrons/s while maintaining the same performance as the first detector generation.

Our R&D project, started in 2008, has opted for a pixelised readout in the beam area and has set itself the target of a reduction of the discharge rate by a factor 10 at least with respect to the first generation detectors. The latter value applies to the discharge rate integrated over the entire detector, including the contribution of the highly illuminated central region. An compact integrated readout electronics using APV25-S1 chips [7] was adopted, and the “bulk” Micromegas technology [8] was chosen to build those detectors, since it produces more robust structures.

2.1 Discharge reduction technologies

Two solutions have been investigated to reduce the impact of the discharges. These solutions are either based on the addition of a GEM foil or on resistive layers.

The insertion of a GEM foil in a Micromegas detector (see figure 1(a)) has two effects. First, it acts as a preamplification stage, which allows to reduce the gain of the amplification gap. Second, due to the field configuration at the exit of the GEM holes, the electron cloud spreads in the transfer gap between the GEM foil and the micromesh. Thanks to these two effects, the space charge in the amplification gap is reduced for the same total gain compared to a standard Micromegas detector, and so is the discharge probability. Small hybrid Micromegas + GEM prototypes ($6 \times 10^2$ cm$^2$ active area) were tested in 2009 and 2010 at CERN SPS (150 GeV muon and hadron beams) and PS (0.4 to 3 GeV hadron beam). Discharge probability was reduced by 10 up to 100 compared to standard detectors at the same gain [9, 10]. Efficiencies and resolutions measured with muon beam were very similar to standard bulk Micromegas detectors [11].

The other solution, based on a resistive layer, aims at minimising the impact of the discharges by limiting the current to the strips and thus the amplitude and duration of discharges. The capacitance involved in the discharge process would also be limited by the resistive layer. Several kinds of coating were considered: resistive foil on insulating layer, resistive coating in contact with the strips, segmented resistive coating, etc. The need for a compatibility with a pixelised readout led
to choose a technology proposed by de Oliveira et al. in 2010 [12]. According to this scheme (see figure 1(b)), the anode strips are overlaid by an insulating layer and resistive pads connected to the strips by intermediate resistors. The signal is transmitted to the strips by capacitive coupling, while the charges are evacuated through the intermediate resistor. When a discharge occurs, the electric potential of the pad rises quickly to reach the mesh potential value, quenching the discharge. The internal resistor of this scheme is long enough to prevent electrical breakdown, leaving it unharmed after a discharge. This solution was also tested on a small prototype in 2010 at the same time as the hybrid Micromegas + GEM detectors. Discharge amplitudes were low enough not to be detected with the spark tagging system, and this detector showed very promising performance in terms of efficiency and resolution [11].

2.2  Design of the large size pixelised detector

At nominal beam intensity, the particle flux in the center of the COMPASS Micromegas detector is very high, approximately 2 MHz/cm$^2$, since the incoming beam goes through the detectors in this area. A readout with strips would lead to hit rates up to 500 kHz/channel, generating an inefficiency due to the electronics occupancy larger than 10%. A pixelised readout with a pixel area of about 1 mm$^2$ in the central area was thus chosen, in order to limit the hit rate to a maximal value of 200 kHz/channel. To optimise the spatial resolution, these pixels are rectangular and parallel to the strips, with a size of $0.4 \times 2.5$ mm$^2$ in the center and $0.4 \times 6.25$ mm$^2$ at larger angles. The remaining of the $40 \times 40$ cm$^2$ active area is subdivided in three slices, the central one ($\pm 7.68$ cm) being equipped with 20 cm long and 400 $\mu$m pitch strips, and the two lateral ones being equipped with 40 cm long and 480 $\mu$m pitch strips. The total number of channels is 2560, equally divided between strips and pixels (see figure 2). The material budget of these detectors is similar to the one of the first generation COMPASS Micromegas detectors (0.32% of $X_0$ instead of 0.287% of $X_0$). Detectors based on this design were produced by the CERN TE-MPE-EM group in 2011 and 2012. They were tested and integrated in the COMPASS spectrometer; their performance are presented in section 3.
2.3 Front-end electronics based on the APV25 chip

A compact electronics front-end based on APV25-S1 chips was adopted. It was developed by the E18 group of the Technische Universität München (TUM) and is already used in COMPASS for the GEM [13], PixelGEM [14] and Silicon detectors [15]. A common project with CEA Saclay has also permitted to develop a fast APV25 readout for the MWPC of the RICH detector [16].

Front-end electronics cards have been adapted to the Micromegas detectors, in particular the protection and decoupling circuit between the readout electrodes and the APV25 chip. An important feature of this electronics is its high density: an APV card reads 128 channels, and an ADC board, connected to 16 APV cards, reads 2048 channels. Only 20 APV cards and 2 ADC boards are needed to read all the channels of a Pixel Micromegas.

3 Performance of Pixel Micromegas detectors in the COMPASS spectrometer

In 2012, two physics runs were carried out at COMPASS. A hadron beam (4 × 10^6 hadrons/s) was used from June to September, and a muon beam (5 × 10^7 muons/s with a μ^+ beam and 2 × 10^7 muons/s with a μ^- beam) was used from October to December. Four large size detectors were installed in the spectrometer during these periods of data taking. Three of them were hybrid detectors, and were successively installed in place of two standard Micromegas. The fourth one was a resistive detector which was installed during the hadron run, at an additional position, set between two standard Micromegas groups close to a dipole (see table 1). The hybrid detectors were operated with the following voltage settings: \( V_{\text{mesh}} = 320 \text{ V}, V_{\text{GEMbottom}} = 620 \text{ V}, V_{\text{GEMtop}} = 920 \text{ V}, \)
\( V_{\text{drift}} = 1420 \text{ V}, \) where GEMbottom and GEMtop are respectively the electrode of the GEM foil clos-
Table 1. Pixel Micromegas used in the COMPASS spectrometer in 2012.

| Detector   | Type      | Spec.                                   | Period in beam                        |
|------------|-----------|-----------------------------------------|---------------------------------------|
| PMM_2011.1 | Hybrid    | GEM foil w/ 2 μm copper layers          | 2012/10/16–2012/12/5 (muon beam)      |
| PMM_2011.2 | Hybrid    | GEM foil w/ 5 μm copper layers          | 2012/06/26–2012/11/15 (hadron and muon beams) |
| PMM_2012.1 | Hybrid    | GEM foil w/ 5 μm copper layers          | 2012/06/26–2012/10/16 and 2012/11/15–2012/12/5 (hadron and muon beams) |
| PMM_2011.3 | Resistive | Resistive structure w/ buried resistors  | 2012/06/26–2012/10/05 (hadron beam)   |

east to the micromesh and the one closest to the drift electrode. The voltage settings of the resistive detector were: $V_{\text{mesh}} = 450$ V, $V_{\text{drift}} = 700$ V. The gain for these settings is around 5000–6000.

All detectors were integrated in the physics data taking of the experiment and were used for the track reconstruction.

### 3.1 Discharge rate

The discharge rate of the detectors was monitored online by reading the current through the micromesh from the HV power-supplies. Due to the spill structure of the beam (one 10 s spill every 40 s), this current is not constant; its maximal value is of the order of a few 10–100 nA, depending on the beam flux. When a discharge occurs, it can be easily detected as the current through the micromesh can reach a few hundred nA. In the figure 3(a), the current through the micromesh versus time for a standard COMPASS Micromegas detector with a reduced gain is shown for a hadron beam ($4 \times 10^6$ hadrons/s). The high peaks of currents are due to discharges. On the contrary, the plots for Pixel Micromegas (figures 3(b), 3(c) and 3(d)) show no discharge at all. The higher mean value of the current than for a standard detector is due to the fact that they are operated at a higher gain and that the center of the detector, where the beam crosses, is active. As no discharge was observed during several hours long monitoring periods on Pixel Micromegas, one can estimate a maximal value for the discharge probability of the hybrid detectors of 0.001 discharge/s in a $4 \times 10^6$ h/s hadron beam, 100 times lower than for a standard COMPASS Micromegas detector. Concerning the resistive detector, this observation shows that the discharge amplitudes are negligible.

### 3.2 Data reconstruction

The electronics are configured to record three samples of the signal amplitude ($a_0$, $a_1$ and $a_2$) separated by 75 ns at each trigger. The latency is tuned to synchronise the acquisition by the APV25 and the signal so that the three amplitude samples are located on the rising edge of the shaped signal (see figure 4). The third sample ($a_2$) is used for the position reconstruction. The hits are gathered into clusters; their position is defined as the mean of the hits positions, weighted by the values of the amplitude samples ($a_2$). The hits with a value of $a_2$ lower than a threshold depending on the electronic noise of each channel are not kept for the reconstruction. The ratio of the last two samples $\frac{a_1}{a_2}$ is used for the time reconstruction. The evolution of this ratio versus a
Figure 3. Micromesh current vs. time for a 1 h time period during hadron beam data taking (4 × 10^6 hadrons/s). Discharge are only visible for standard Micromegas detectors (a). The accuracy of the power supplies is 10 nA.

Figure 4. Illustration of the sampling on an APV25 output signal.

variable called “TCS phase”, which is the difference between the time of the trigger signal and the time it is synchronised with the Trigger Control System (TCS) clock, allows to compute the time of the hits. The cluster time is defined as the time of the hit with the highest value of a_2.

3.3 Efficiency

The raw efficiency $e_{\text{raw}}$ of a detector is defined as the ratio of the amount of detected tracks over the amount of tracks crossing the detector. A track is detected if a cluster is found within a certain distance from the interaction point of the track, called the road width. In this analysis the road width is defined as four times the width of the residual distribution (see section 3.4). However a cluster may be present within the road width but not correlated with the track. To evaluate the
background level, the interaction points of the tracks are also compared to the positions of clusters from another event. The background probability \( \text{bg} \) is then defined as the number of tracks close to these uncorrelated clusters over the number of tracks crossing the detector. This allows to compute an efficiency corrected from the background \( \varepsilon_{\text{corr}} \) (see eq. (3.1)), which is a more reliable estimation of the detector efficiency, especially at high flux.

\[
\varepsilon_{\text{corr}} = \frac{\varepsilon_{\text{raw}} - \text{bg}}{1 - \text{bg}} \tag{3.1}
\]

Figure 5 shows the efficiency values versus the track position for one of the hybrid detectors, at low intensity. The values of the efficiency in muon beam for all the detectors at different flux are shown in table 2.

The results are very satisfying, as efficiency reaches more than 95% in the active area for every detector, even at the highest beam intensity, which generates a flux up to 2 MHz/cm\(^2\) on the pixelised area. A drop of efficiency around 1% at high flux, due to the electronics occupancy, is observed on the strips, which is comparable to the results observed on the standard COMPASS Micromegas detectors. For the pixelised area this drop is more important, around 1.5%, due to a higher occupancy.

### 3.4 Spatial resolution

The spatial resolution \( \sigma_{\text{detector}} \) is computed from the width of the residual distribution \( \sigma_{\text{residual}} \), which is the distance between the clusters and the interaction points of the tracks, using the following formula:

\[
\sigma_{\text{detector}} = \sqrt{\sigma_{\text{residual}}^2 - \sigma_{\text{tracking}}^2} \tag{3.2}
\]

where \( \sigma_{\text{tracking}} \) is the error on the track position computed by the COMPASS reconstruction software.
Table 2. Efficiency of Pixel Micromegas during the 2012 muon run for different flux (muon beam). The values marked with a * were taken while an APV card connected to a group of short strips was disconnected.

| Detector         | $\Phi = 9 \times 10^5$ s$^{-1}$ | $\Phi = 2 \times 10^7$ s$^{-1}$ | $\Phi = 5 \times 10^7$ s$^{-1}$ |
|------------------|---------------------------------|---------------------------------|---------------------------------|
| PMM_2011.1 (hybrid) |                                 |                                 |                                 |
| Pixels           | 97.9%                           | 97.1%                           | 95.7%                           |
| Strips           | 97.8%                           | 97.4%                           | 97.0%                           |
| Global           | 97.8%                           | 97.2%                           | 96.3%                           |
| PMM_2011.2 (hybrid) |                                 |                                 |                                 |
| Pixels           | 97.7%                           |                                 | 96.9%                           |
| Strips           | 98.4%                           | 88.7% *                         | 86.7% *                         |
| Global           | 97.8%                           | 93.8% *                         | 92.3% *                         |
| PMM_2012.1 (hybrid) |                                 |                                 |                                 |
| Pixels           | 98.4%                           | 98.0%                           | 96.8%                           |
| Strips           | 97.8%                           | 97.0%                           | 97.0%                           |
| Global           | 98.2%                           | 97.6%                           | 96.9%                           |
| PMM_2011.3 (resistive) |                                 |                                 |                                 |
| Pixels           | 97.9%                           | not tested                       | not tested                       |
| Strips           | 98.1%                           | not tested                       | not tested                       |
| Global           | 98.0%                           | not tested                       | not tested                       |

Figure 6 shows the residual distribution for a hybrid detector for the strips and pixels at low intensity and with the dipole field turned OFF. The same plots for the resistive detector are shown in figure 7. The distributions are fitted by the sum of two gaussians and a flat background. The widths are determined as the mean of the sigmas of the two components, weighted by their integrals:

$$\sigma_{\text{residual}} = \frac{A_1 \times \sigma_1^2 + A_2 \times \sigma_2^2}{A_1 \times \sigma_1 + A_2 \times \sigma_2}$$

(3.3)

The spatial resolution achieved for the hybrid detectors in these conditions are below 60 $\mu$m for both strips and pixels, which is better than a standard COMPASS Micromegas detector, for which the resolution in these conditions is around 70 $\mu$m. The resolution obtained for the resistive detector is comparable to the one of a standard COMPASS Micromegas detector, with a value slightly above 70 $\mu$m. The difference observed between the two kinds of Pixel Micromegas can be explained by the cluster size, which is 50% higher for the hybrid detectors due to the spread of the electrons after the preamplification.

3.4.1 Impact of the dipole fringe field

The resistive detector was located next to the first dipole of the spectrometer, and its response is affected by the fringe field, because of the Lorentz angle effect. The value of the fringe field is between 100 and 150 mT at the detector level. When the dipole field is turned ON, a 50% degradation of the resolution is observed, which is similar on a standard COMPASS Micromegas detector in the same area. The hybrid detectors were too far from the dipole to be affected by its fringe field.
Figure 6. Residual distribution for a hybrid detector (PMM,2011.2).

Figure 7. Residual distribution for the resistive detector.

Table 3. Spatial resolutions of a hybrid Pixel Micromegas and a standard Micromegas for different flux (muon beam). All values are in $\mu$m.

| Detector          | $\Phi = 9 \times 10^5$ s$^{-1}$ | $\Phi = 2 \times 10^7$ s$^{-1}$ | $\Phi = 5 \times 10^7$ s$^{-1}$ |
|-------------------|---------------------------------|---------------------------------|---------------------------------|
| MM01U (standard Micromegas) |                                 |                                 |                                 |
| Strips            | 65                              | 71                              | 74                              |
| PMM,2011.2 (hybrid) |                                 |                                 |                                 |
| Pixels            | 56                              | 79                              | 87                              |
| Strips            | 57                              | 68                              | 72                              |

3.4.2 Impact of the beam intensity

Table 3 shows the results for one hybrid detector for different flux. The results for a standard COMPASS Micromegas detector are also shown for comparison. For the strips, a degradation of the resolution, which is mainly due to the pile-up of off-time tracks, is seen when the flux increases. It reaches 10–15% for the highest flux, which is comparable to the degradation observed on a stan-
3.5 Time resolution

Figure 8 shows the distribution of the clusters time for a hybrid detector with the gas mixture used for a muon run, i.e. Ne/C$_2$H$_6$/CF$_4$ in proportions 80/10/10. Only the clusters close to a track are selected in order to reduce background. Fitting by the sum of two gaussians and a flat background if needed, a resolution below 9 ns can be achieved, which is comparable to what is obtained with a standard Micromegas detector. With the gas mixture used for hadron run, i.e. Ne/C$_2$H$_6$/CF$_4$ in proportions 85/10/5, the resolution is larger, around 13 ns, which is also observed for standards Micromegas detectors [2, 11].

Figure 9 shows the same plots for the resistive detector with the gas mixture used for hadron run. In this case the distribution cannot be fitted by gaussians and has a RMS around 30 ns. Further investigations are needed to understand this result.

Table 4 summarizes the results for muon and hadron runs.

4 Track reconstruction

During the muon run, only three planes of scintillating fibers detectors and two hybrid Pixel Micromegas were used to reconstruct tracks at small angle between the target and the first dipole. This lack of redundancy, combined with the high intensity of the beam (up to $5 \times 10^7$ muons/s), made the track reconstruction difficult. As Pixel Micromegas represent 40% of the tracking detectors in this area, precise time cuts have to be applied on them to reduce as much as possible the combinatorial background. Selecting only the clusters whose time is between $-30$ ns and 40 ns reduces the amount of clusters in the pixelised area by 70%, with a limited loss of efficiency and an important reduction of the background probability (see table 5).
Figure 9. Cluster time distribution for the resistive detector in Ne/C$_2$H$_6$/CF$_4$ in proportions 85/10/5. $\Phi = 4 \times 10^6$ s$^{-1}$ (hadrons).

Table 4. Time resolutions for Pixel Micromegas and a standard Micromegas detector. All values are in ns.

| Detector            | $\Phi = 5 \times 10^7$ s$^{-1}$ (muons) Ne/C$_2$H$_6$/CF$_4$ 80/10/10 | $\Phi = 4 \times 10^6$ s$^{-1}$ (hadrons) Ne/C$_2$H$_6$/CF$_4$ 85/10/5 |
|---------------------|-------------------------------------------------|-------------------------------------------------|
| Standard Micromegas | 9.3                                             | 12.6                                            |
| PMM_2011.2 (hybrid) | Pixels                                          | Strips                                          |
|                     | 9.1                                             | 13.2                                            |
|                     | Strips                                          | 8.7                                             |
|                     |                                                 | 13.3                                            |
| PMM_2011.3 (resistive) | Pixels                                        | Strips                                          |
|                     | not tested                                      | not tested                                      |
|                     |                                                 | 32.1                                            |
|                     |                                                 | 29.9                                            |

These cuts have a very positive impact on the track reconstruction. The amount of events with too many tracks or combinations generated by the COMPASS reconstruction software in the zone between the target and the first dipole is reduced by 90% when applying these cuts (see table 6), which is a good indication of the reduction of the combinatorial background.

5 Conclusions and perspectives

All the produced Pixel Micromegas fulfill the design requirements in terms of performance and discharge reduction, except the resistive detector, for which further studies about the time resolution are ongoing. In particular, the hybrid detectors keep an efficiency around 96% and a spatial resolution better than 90 $\mu$m at flux reaching 2 MHz/cm$^2$. The production and installation of twelve Pixel Micromegas to replace all the standard Micromegas in the COMPASS spectrometer is planned for early 2015. The choice of the discharge-reduction technology for the final series of detectors has not been made yet; however it appears that the hybrid detectors have better performance and are easier to produce.
Table 5. Effect of time cuts on the amount of clusters, efficiency and background probability (pixelised area of PMM\_2011.2, $5 \times 10^7$ muons/s beam).

| Time Cut                                      | Amount of clusters | Efficiency | Background probability |
|-----------------------------------------------|--------------------|------------|------------------------|
| No cuts                                       | 2145513            | 95.7%      | 11%                    |
| Cut on cluster time ($-30 \text{ns} < t < 40 \text{ns}$) | 634167            | 93.6%      | 2.9%                   |

Table 6. Events with too many tracks or combinations generated by the COMPASS reconstruction software ($5 \times 10^7$ muons/s beam).

| Time Cut                                      | Amount of tracks $>1000$ | Amount of combinations $>20000$ |
|-----------------------------------------------|--------------------------|---------------------------------|
| No cuts                                       | 29.8%                    | 0.5%                            |
| Cut on cluster time ($-30 \text{ns} < t < 40 \text{ns}$) | 3.1%                     | 0.1%                            |

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