Performances of anode-resistive Micromegas for HL-LHC

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ABSTRACT: Micromegas technology is a promising candidate to replace Atlas forward muon chambers -tracking and trigger- for future HL-LHC upgrade of the experiment. The LHC accelerator luminosity will be ten times the nominal one, increasing background and pile-up event probability in the same proportion. This requires detector performances which are currently under studies in intensive RD activities.

We studied performances of four different resistive Micromegas detectors and with different read-out strip pitches. These chambers were tested using $\sim 120$ GeV momentum pions with rates from 25 up to 250 kHz/cm$^2$, at H6 CERN-SPS beam line in autumn 2010. We found that the resolution is degraded, if the strip pitch is too wide with respect to the charge distribution at the readout plane. To reduce the systematic effects of the charge sharing we propose a cluster reconstruction algorithm. For narrow strip pitch 500$\mu$m we measure a resolution of $\sim 90$ $\mu$m and a efficiency of $\sim 98\%$. The track angle effect on the efficiency was also studied. Our results show that resistive techniques induce no degradation on the efficiency or resolution, with respect to the standard Micromegas. In some configuration the resistive coating is able to reduce the discharge currents at least by a factor of 100 and no HV breakdown was observed.

KEYWORDS: Performance of High Energy Physics Detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)

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1 Introduction

With the Large Hadron Collider (LHC) running and ramping in energy and luminosity, plans are already advancing for an upgrade. For the High Luminosity LHC (HL-LHC) project, the luminosity upgrade is expected to increase in two stages: 

i) by a factor of three in collision rate, \(3 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\), for phase-I and

ii) by a factor of ten in view of nominal HL-LHC phase-II [1].

The particularly harsh background environment in the detectors at the HL-LHC places a number of severe constraints on the performance of such detectors. Counting rates will grow up to 20 kHz/cm\(^2\) in the most unfavourable regions of the Atlas muon system [2].

To cope with the corresponding increase in background rates, Atlas experiment muon system will likely need major changes, at least in the highest rapidity region, see figure 1. Based on background estimations at HL-LHC, a list of requirements for these new detectors has been established:

- High counting rate capability, including dense ionization.
- High single plane detection efficiency, (\(\geq 98\%\)).
- Spatial resolution better than 100 \(\mu\)m, possibly up to large incident angles, 45\(^\circ\).
- Second coordinate measurement, with a few mm precision.
- Two-track discrimination at a distance of \(~1\text{-}2\) mm.
- Good time resolution, \(~5\) ns, to allow bunch crossing identification.
- Level-1 triggering capability, within 1.088 \(\mu\)sec.
- Good ageing properties.
Figure 1. Schematic view of a quarter of the Atlas detector with its different constituents parts [2]. Atlas will need an upgrade at least in the highest rapidity region.

The MAMMA\(^1\) collaboration is focused on the development of large-area muon detectors based on bulk-Micromegas\(^2\) technology as candidates for such an upgrade.

The Micromegas technology was introduced in 1996 [3] and have been successfully used in nuclear and high energy particle physics experiments during the past years [7, 8] when good spatial resolution at high rates was required. Micromegas were also successfully used as readout chambers of Time Projection Chambers [9, 10].

The bulk-Micromegas technology may also have a position resolution better than 100 \(\mu\)m at counting rates of up to several tens of kHz/cm\(^2\), along with trigger capabilities. These characteristics, combined with the detector’s robustness, makes them a promising candidate for the Atlas Muon Spectrometer upgrade. In this paper, after a short introduction to the resistive Micromegas detector, the analysis of the autumn 2010 test beam data is presented.

2 2010 test beam

2.1 Characteristics of the resistive detectors under study

The Micromegas are Micro Pattern Gaseous Particle Detectors (MPGD). They are made of three parallel planes as we can see in figure 2. The first one is a planar drift electrode, followed by a gas gap of a few millimeters thickness acting as conversion and drift region. Then a thin metallic mesh at 100\(\mu\)m typical distance from the PCB board, creates the amplification region. The PCB board is equipped with readout strips. The drift electrode and the amplification mesh are at high voltage potentials, and the readout electrode is at ground potential. The HV are chosen such that the electric field in the drift region is a few 100V/cm and in the amplification region a few tens of kV/cm [3].

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\(^1\)Muon Atlas MicroMegas Activity, ref. [4].

\(^2\)Micro-MEsh GASEous Detector.
When a charged particle passes through, it ionizes the gas volume in the drift space. The electrons released drift towards the mesh, where the high electric field lying between the mesh and the readout strips allows electron avalanche amplification. The mesh is almost fully transparent to electrons as long as the electric field in the amplification region is of the order of 100 times larger than the drift field [3].

The current limitation of Micromegas comes mainly from the generation of a large number of electron-ion pairs in the thin amplification region. When the total number of electrons in the avalanche reaches the Raether limit [11], it leads to a discharge (or spark) between the micro-mesh and the readout strips.

For a gain of the order of few thousand, such ionization levels could be reached in the most unfavorable regions of the Atlas muon system where less than 10% of this rate is expected to come from muons, approximately 20% from protons and pions, the rest, from photon and neutron interactions [2]. The latter are of concern since neutrons interacting in the chambers create slowly moving recoils from elastic scattering and low-energy hadronic debris from nuclear breakup. They both are heavily ionizing and lead to large energy deposits with the risk of sparking [6].

One of the suggested solutions for sparks that are currently being pursued is the use of resistive coating on top of the anode read-out strips. The micromegas structure is then built on top of the resistive strips or layer. The mesh is supported by small pillars (400 \( \mu \)m diameter) arranged in a regular matrix with a distance between neighboring pillars of 2.5 mm in x and y. During this test we studied three different resistive configuration:

- **Kapton 2 \( M\Omega/\square \) layer**: In a standard Micromegas the avalanche electrons induces a signal directly on the readout strips. In this case we have on top of the readout strips an insulating layer of 70\( \mu \)m thickness, followed by a 2 \( M\Omega/\square \) continuous Carbon-loaded Kapton resistive layer, (see figure 3 a), the charge movement in this layer results in an RC-type differentiation of the signal [13]. It also causes a spread of the signal to neighboring strips and this effect help to obtain good resolution with wider (fewer) strips.
2.2 The test beam setup

The resistive chambers described above, were subsequently exposed to pions with momentum of \( \sim 120 \text{ GeV} \), at CERN SPS H6 beam line, during two weeks in autumn of 2010. An external reference measurement, on the plane normal to the beam direction was given by a telescope consisting of 3 (X-Y) planes of standard Micromegas. Four resistive detectors were tested in a two (X-Y) configuration.

The goal of the test was to evaluate the influence of the resistive technology on the spatial resolution and efficiency of the prototypes. The experimental set-up is illustrated in figure 4. The beam entered from the right of the figure, passed through one scintillator, then the Micromegas and finally through two more scintillators. The trigger was defined by the coincidence of these three scintillators.

The standard telescope detectors were manufactured at Saclay, whereas the resistive detectors were manufactured at CERN. The main characteristics of the resistive detectors are summarized in table 1. During the test beam, two different gas mixtures were used: \( \text{Ar} + 2\% \text{C}_4\text{H}_{10} + 3\% \text{CF}_4 \) and
Figure 4. Picture and scheme of the test beam setup. The red arrow shows the beam direction. In black the 3 scintillators of the trigger and the five planes of chambers (X-Y direction) i.e 10 Micromegas chambers in total.

Table 1. Characteristics of the four resistive chambers tested.

| Chamber | Pitch | Strips | Circuit Type | Capacitance | Energy Resolution $^{55}$Fe | Gain max |
|---------|-------|--------|--------------|-------------|-----------------------------|----------|
| R10     | 2.0 mm| 48     | kapton layer 2MΩ/□ | 1.67 nF     | 22.1% (310V)                | 7829 (410v) |
| R17     | 1.0 mm| 96     | resistive strip to ground | 943 pF     | 29.8% (310V)                | 10236 (410v) |
| R14     | 1.0 mm| 96     | resistive strips 300 kΩ/□ | 943 pF     | 36.3% (350V)                | 10023 (410v) |
| R12     | 0.5 mm| 96     | resistive strips 300 kΩ/□ | 637 pF     | 24.4% (320V)                | 9835 (410v) |

Ar + 2%$^4$He$_{10}$ for the telescope. The resistive detectors were tested with different high voltage values and mounted on a rotating structure, in order to collect data with different beam angle.

2.3 Signal acquisition system

The three scintillators coincidence signal is used to trigger the acquisition of an event. For each trigger, the charge on the strips of all the Micromegas is read out with the help of electronic cards based on the gassiplex chip [14]. Each card have 6 gassiplex chips, for a total of 96 channels, a peaking time of 1.2μs and is controlled by a CAEN sequencer with four CRAM modules. The data acquisition, storage management and online monitoring system were achieved with LabView acquisition software developed by Demokritos.
3 Data analysis

In this section we will expose the selection used to study the performances of the different resistive Micromegas.

3.1 Common mode noise rejection

First of all the Gassiplex pedestals were aligned and the width calculated for each run, using data. In order to use data to do pedestal calculations, we remove event per event, the information of the fifteen strips with the highest signal. Doing that we are sure that we remove the beam signal and only keep the pedestals. Then we do a gaussian fit, strip by strip using the remaining data. We use the mean value for pedestal alignment and sigma as the pedestal widths ($\sigma_{ped}$).

In order to correct some common mode noise, like potential pedestals shifts, we also calculate the mean event value and bring to zero. Finally we identify the noisy or dead channels and we mask them for the rest of the analysis.

3.2 Cluster and track reconstruction

A Cluster is a group of fired strips with charge above a given threshold. The threshold is defined by 3.5 $\sigma_{ped}$ of electronics noise (usually $\sim$ 2-3 ADC counts). The particle position is reconstructed using a simple Center Of Gravity (COG):

$$x_{hit} = \frac{\sum w_i \cdot x_i}{\sum w_i}$$  \hspace{1cm} (3.1)

where $w_i$ is the charge on the strip, $x_i$ is the coordinate of the strip in cluster, and $x_{hit}$ is the coordinate of the cluster COG. Using this algorithm we estimate the impact point for each Micromegas. When we have all the reconstructed clusters we use the telescope hits to fit a track, which could be extrapolated to the resistive Micromegas.

Figure 5 (top left) shows the differences of the COG position ($x_{hit}$) given by a resistive Micromegas and its corresponding extrapolated value ($x_{track}$) form the telescope detectors. We can see that the residual distribution has not the expected gaussian shape.

In order to understand the bias origin, on figure 5 (bottom left), we traced the position of the COG with respect to the central strip ($x_{strip}$); a zero value means the beginning of a strip and 1 the end. The vertical line exactly at $x_{strip} = 0.5$ correspond to the one strip cluster signal, where the impact point is reconstructed on the strip middle. We can clearly see that there is bias that follows a S-shape. We traced this distributions for all detectors and found that this bias was present only for those with large strip pitch (i.e larger than 0.9 mm). So we concluded that the discretization of the signal created by large strip pitches with respect to the avalanche size, introduces this systematic error [15].

In order to correct this bias, we propose a new way of giving weight to the strips: the idea is to calculate the impact point like a center of gravity, but with logarithmic weights. So $w_i$ will be:

$$w_i = w_0 + \log \left( \frac{Q_i}{\sum_j Q_j} \right)$$ \hspace{1cm} (3.2)

$$w_0 = -\log \left( \frac{Q_{\min}}{Q_{\text{tot}}} \right) \rightarrow w_0 > 0$$ \hspace{1cm} (3.3)
$Q_i$ is the charge on the strip and $\Sigma_j Q_j$ is the total charge of the cluster. We constrain the weight $w_i$ to be positive (otherwise set to zero). We can interpret $w_0$ as a charge threshold to decide which strip will be taken into account for the center of gravity calculation. Using this technique we will increase the relative weights of the strips surrounding the central one. And on the calculation of the reconstructed position this will avoid giving all the weight to the central strip, which is one of the main effects of the discretization induced by large strip size.

This new technique result can be seen on the right plots of figure 5. The agreement of the gaussian fit is clearly better and the S-shape disappeared. Since this way of give weight to the strips seems to work well, we decided to use it for the resistive detectors with large strip pitch (R10, R17 and R14) and the normal COG’s for the rest.

3.3 Efficiency and resolution results

To avoid any possible bias on resistive Micromegas properties, events are selected using only telescope information. Specifically, we request events to have:

- A cluster in all telescope detectors.
- All cluster charges, to be below a maximum threshold.
- All telescope cluster size < 3mm.
- The track direction within the mean beam dispersion in x and y.

3.3.1 Spatial resolution

Misalignments of individual chambers have been corrected using tracks, with a final position precision below $< 10 \mu m$. The obtained resolutions are shown for one run on figure 6. The resolutions with the chamber of interest in the track fit (red fit) are overestimated, and those obtained by excluding it (blue fit) are underestimated. The compromise proposed by ref. [16] is a geometric-mean...
Figure 6. Residuals for the four resistive chambers under study. The red and blue right panels show the results for $\sigma_{in}$ and $\sigma_{ex}$, $\sigma_{Mm}$ is considered the resolution of the detector (see text).

Figure 7. On the left $\sigma_{Mm}$ vs the mesh HV. On the right efficiency at 5$\sigma_{Mm}$ vs high voltage of the micromesh for three of the technologies tested. The detection efficiency increases with the voltage set on the micromesh until a value close to 100% is reached.

recipe, to determine the resolution of the detector $\sigma_{Mm}$:

$$\sigma_{Mm} = \sqrt{\sigma_{in} \cdot \sigma_{ex}}$$

(3.4)

Where $\sigma_{in}$ and $\sigma_{ex}$ are obtained by computing the track resolution including, and respectively excluding the chamber of interest from the track fit.

Using this technique we estimated $\sigma_{Mm}$ for all detectors and for different HV values. Left plot of figure 7 shows $\sigma_{Mm}$ vs mesh HV. We found that the resolution degrades if the strip pitch is too wide with respect to the avalanche size due to insufficient charge sharing between readout strips. And also that for higher HV$_{mesh}$ the resolution is better because of higher gain. We were able to achieve a resolution of 88.1 $\mu$m for 500 $\mu$m strip pitch (R12).
3.3.2 Efficiency

The efficiency is defined as the fraction of tracks for which the residual between the extrapolated impact point and the closest cluster position is less than $5\sigma_{MM}$. For what concern the efficiency studies, tracks are reconstructed using only telescope chambers. When the extrapolated track intercept the studied detector near a dead or noisy region, the event is abandoned.

We calculate the efficiencies for different run conditions, and the results are shown on the right plot of figure 7. The detection efficiency increases with the mesh voltage until a value close to $\sim98\%$ is reached. The detector with resistive strips connected to the ground present the best efficiency results. In all the detectors we saw that the efficiency depends on the operating conditions, i.e. the mesh voltage (Even at high gain it depends on the track position with respect to the pillars).

For some runs we also rotated the detectors in order to get tracks with different incidence angles. With inclined tracks, the charge is spread over a larger number of strips, corresponding to the projection of the track onto the readout plane. The total number of strips contributing to a track signal depends on the track, strip pitch, and thickness of the drift gap, (see figure 2).

On figure 8, we see for the detector "R-strip to ground" R17, the efficiency for different HV$_{mesh}$ values and incidence track angle. For perpendicular tracks (0° angle) the efficiency is of the order of $\sim98\%$, the inefficiency mainly resulting from dead area coming from pillars supporting the mesh. For inclined tracks (the usual case in Atlas) the efficiency has been measured to be also around $\sim98\%$. So the efficiency for inclined tracks measured remains almost the same and can be even better for some HV values. Since the detector "R- to ground" (R17) has the best efficiency, it has been chosen to be proposed for the Atlas upgrade.

3.4 Sparks behavior

What we call sparks are electric arcs between the mesh and the anode at ground potential, be it resistive strips or metallic readout strips. The purpose of the spark resistive protection layer is to limit...
the spark discharge currents, to a level such that the drops of the mesh HV becomes insignificant.

The HV and the currents were monitored and recorded whenever a HV or current value changed. The resistive chambers worked correctly up to the highest gas gains, while the non-resistive chambers show very often HV breakdowns. Figure 9. shows the monitored HV and currents for one standard chamber on the left, and for the resistive chamber with strips connected to the ground (R17) on the right, both chambers with same beam exposure for different mesh HV settings (both with a gain $\sim 10^4$). For the standard Micromegas we see that a discharge induce HV drops (as current leakage) and for the resistive detector, we had no HV drops neither current leakage. We can associate the highest values of the current with the moment of the HV setting.

All four resistive chambers produced clean data, had no HV breakdowns, and the spark currents did not exceed a few 100 nA [17].

4 Conclusion

The performance of fourth resistive bulk-Micromegas detectors has been studied using a $\sim 120$ GeV pion beam from CERN SPS. The data was collected during the autumn of 2010, with the main objective of study the spatial resolution and efficiency of the detectors.

Four different strip pitch detectors have been tested, see table 1. We found that the resolution degrades if the strip pitch is too wide with respect to the avalanche size due to insufficient charge sharing between readout strips. In order to reduce the systematic errors we implemented a cluster reconstruction algorithm that take in account this problem. Therefore for the 500$\mu$m strip pitch, we don’t see this kind of systematic errors and we achieve a resolution of 88.1$\mu$m, with a $\sim 98\%$ of efficiency.

Three different resistive techniques were tested, inducing no degradation on the efficiency neither on the resolution with respect to the standard Micromegas. From the three technologies the "R-strip to ground" detector has the best efficiency results ($\sim 98\%$ at $5\sigma_{mM}$), and it has being proposed for Atlas upgrade.
During the test beam the HV and currents were monitored. All four resistive chambers produced clean data, had no HV breakdowns, and the spark currents did not exceed a few 100 nA. This proof that the resistive coating is able to contain or even suppress the spark signal.

In view of the final Atlas upgrade proposition with Micromegas, we still need to optimize the following points:

- the strip pitch with respect to the electron diffusion in drift region, i.e. make an adequate choice of the gas mixture and also the electric field;
- charge spreading among resistive strips, in particular if we propose a readout lecture on 2 or 3 directions;
- if needed, the impact point reconstruction algorithm can be optimized (depend also on gas and strip pitch choice);
- the integration of Micromegas in Atlas in view of the track resolution improvement (involving several Micromegas layers);

Some of this aspects have already been partially studied by the MAMMA collaboration [12, 18].

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