Study of the performance of the Micromegas chambers for the ATLAS muon spectrometer upgrade

C. Bini

Sapienza Università di Roma and INFN,
P.le A.Moro 5, 00185 Roma, Italy

E-mail: cesare.bini@roma1.infn.it

ABSTRACT: Micromegas (Micro Mesh Gaseous Structures) chambers and sTGC (small-strip Thin Gap Chambers) have been chosen for the upgrade of the forward muon detectors of the ATLAS experiment to provide precision tracking and trigger capabilities. The Micromegas chambers for ATLAS have been designed to allow operation in a high rate environment, to guarantee a resolution below 100 µm per point on a large area and to provide a fast trigger signal. In the last months several tests have been done on small area prototypes in order to verify that the requirements on resolution and rate capabilities are well matched. The results of the performance studies done on beams at CERN and of the ageing studies done at CEA Saclay are presented.

KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Muon spectrometers; Gaseous detectors

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1On behalf of the ATLAS-Muon collaboration and of the MAMMA (Muon Atlas Micromegas Activity) collaboration.
1 Introduction

Starting from 2019, the Large Hadron Collider (LHC) [1] will provide proton-proton collisions at the center of mass energy of 14 TeV with a luminosity that, in two separate steps (phase-I and phase-II), will reach $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, a value exceeding the project luminosity by a factor 5. A total integrated luminosity of 3000 fb$^{-1}$ should be collected in a time of the order of 10 years. Such an upgrade scenario is particularly demanding for the detector regions where a large flux of particles is expected, in particular the forward regions. For these regions a detector upgrade program is in progress.

The most relevant phase-I upgrade concerning the ATLAS muon spectrometer is the realization of the so called “New Small Wheels” (NSW) [2]. These completely new detectors will replace the present two Small Wheels, and will be installed in the forward region at a distance of about $\pm 7$ meters along the beams from the interaction region, covering the pseudo-rapidity region $1.3 < |\eta| < 2.7$. The NSWs will provide both tracking and triggering capabilities.

In the following, after a description of the motivations and the main features of the NSW project, the Micromegas chambers (MM) that will be used in this project are described, and the main test-beam and irradiation tests results are presented.

2 The New Small Wheel project

The need of a NSW is based on two independent motivations, one related to tracking efficiency, the other one related to the trigger rate.

The main precision tracking detectors of the Muon Spectrometer [3] are the MDT (Monitored Drift Tubes) chambers. MDT tubes have a diameter of 3 cm and a maximum drift time of about 700 ns. At a rate exceeding $\sim 300 \text{kHz/tube}$ a sizeable efficiency loss is observed, affecting the
overall chamber reconstruction capability. Such a rate corresponds to the maximum expected rate at the LHC design luminosity ($1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$).

The present forward muon trigger scheme is based on the coincidence of different layers of the TGC (Thin Gap Chambers) in the so called Big Wheel, standing 6 m behind the Small Wheel. Due to the lack of a pointing criterium, this trigger is strongly affected by background particles, like beam halo particles, or punch-through muons. 95% of muon triggers collected in this region in standard ATLAS operation are indeed fake triggers. A trigger station in the position of the Small Wheel, able to point to the interaction region with a resolution of $\mathcal{O}(\text{mrad})$, will reduce the overall trigger rate by a factor of at least 3. This will allow to trigger events on the basis of single muons with a $p_T$ threshold of 20 GeV. This is required in order to avoid efficiency losses in the main physics analyses.

Based on these two motivations, two different detector technologies have been chosen for the NSW: the sTGC (small-strip Thin Gap Chambers) will give the main trigger signal profiting from an improved spatial resolution, resulting in a $\mathcal{O}(\text{mrad})$ angular resolution at trigger level; the MMM will give the precision points to determine the trajectory of the muon before the Endcap Toroid entrance without significant efficiency loss due to the high rate. A single hit resolution below 100 $\mu$m is requested for the MM chambers. For each wheel the detectors will be arranged in 16 sectors for a total diameter of about 10 m. MM will consists of 2 independent “quadruplets” with 2 doublets each, for a total of 8 active layers crossed by the muon tracks.

### 3 The Micromegas chambers for the New Small Wheel upgrade project

The concept of the MM has been developed in the '90s [4] in the context of the so called MPGD, Micro Pattern Gaseous Detectors. The principle of operation of this detector is shown in figure 1. A few millimeters gap between two parallel electrodes is filled with a gas mixture. The anode is segmented in metallic strips with a pitch of few hundred microns, and above it, at a distance of about 100 $\mu$m determined by special pillars built on the strip plane, a metallic mesh is deposited and tensioned. The electric field between the mesh and the metallic strips (the so called amplification region) is held at a large value (of order of $40 \div 50 \text{kV/cm}$), while the electric field between the mesh and the cathode (the so called drift region) is much lower (of order of 600 V/cm).

Due to the high ratio between the two electric fields, the metallic mesh is essentially transparent to the ionization electrons produced in the drift region, so that they drift to the mesh, pass in the amplification region, where the avalanche takes place, and finally the signal is collected by the metallic read-out strips. Moreover, due to the field configuration, the large amount of positive ions produced in the amplification region during an avalanche, are almost entirely collected by the mesh and evacuated in a short time (of order of 100 ns) thus reducing possible spatial charge effects affecting the dead time of the detector.

The design of the MM chambers for the NSW has to take into account the following specific conditions of operation.

- Muons in the NSW are expected to come at angles with respect to the direction perpendicular to the chambers, in the range $8 \div 35^\circ$. This implies that the $\mu$TPC operation mode (see below) has to be used.
Figure 1. (Left) Exploded view of a MM chamber including read-out electrodes with strips, pillars, mesh and drift cathode. (Right) Principle of operation of a MM chamber. Resistive strips running above the read-out strips are also shown. The dimensions given refer to the MM chambers used in the NSW.

• High fluxes of heavily ionizing particles, each releasing more than $10^3$ ionization electrons ($N_e$) in the drift gap are expected at LHC. Given the required amplification gain $G$ of at least $10^4$, in the region between the mesh and the readout strips sparks are expected to happen (since $N_e \times G > 10^7$). To overcome this problem by making inoffensive the possible sparks, resistive strips above the read-out strips are posed according to the scheme shown in figure 1 and described in ref. [5].

• A magnetic field of up to 0.3 T is present in the NSW region with different orientations. Corrections on the reconstructed positions have to be applied to account for the corresponding Lorentz angle effects.

• Strip positions must be known with precision of better than 50 µm, therefore the construction procedure has to guarantee such a precision and, at the same time, alignment tools have to be foreseen for the detector.

All these points have been addressed in the last years with a vast campaign of tests. In the following some of these tests are reported and discussed.

The NSW MM will be operated according to the following parameters: drift gap = 5 mm, amplification gap = 128 µm, strip pitch = 400 ÷ 450 µm, strip width = 300 µm; gas mixture Ar-CO$_2$ (93-7), $HV_{\text{drift}}$ = 300 V, $HV_{\text{ampl}}$ = 550 V. With these operating conditions, the drift velocity is about 5 cm/µs resulting in a maximum drift time of 100 ns.

4 Test results

Small size prototypes of MM chambers have been exposed to beams with two main objectives: determine efficiency and spatial resolution for tracks in the angular range expected at LHC, and study the effects of the magnetic field on the chamber operation. Moreover irradiation campaigns simulating the typical exposures of several LHC years have been done aiming to see if ageing effects are significant.
Figure 2. Schematic diagram of the H6 test-beam setup in July 2012. The twelve MM chambers indicated are mounted in a common frame that allow operation at different angles. The results reported here are given for the chambers named T1, T2, . . . T8, all characterized by a strip pitch of 400 µm, operated at the standard ATLAS working point described in the text.

Figure 2 shows the typical setup of the test-beam at the H6 line of SPS at CERN, providing 120 GeV pions. The prototypes used are 10 × 10 cm² chambers with either 400 or 250 µm pitch with resistive strips operated in the gas and HV conditions given above. Typically eight of such chambers are used, to provide full tracking. The chambers can be rotated in such a way to provide runs with the beam at angles \( \theta \) with respect to the chamber between 0 and 40° (\( \theta = 0 \) corresponding to orthogonal beam).

The chambers have a double strip read-out. However the results shown below concern the “precision coordinate”, namely the coordinate orthogonal to the strips running below and parallel to the resistive strips.

4.1 Efficiency and spatial resolution

The chamber detection efficiency is determined by reconstructing particle tracks using all chambers apart from one and looking for hits in the remaining chamber. Global 1 ± 2% inefficiencies are observed for runs with tracks at \( \theta = 0 \). Figure 3 shows the distribution of the position of the inefficiencies. This plot illustrates that inefficiencies are mostly due to the pillars where the mesh is held tensioned (see above), that are “towers” with 300 µm diameter and 2.5 mm pitch. The expected dead area due to pillars is \( \pi(0.3/2)^2/2.5^2 = 1.1\% \) of the total surface, in agreement with measurement. Apart from pillars the detector is fully efficient.

The precision coordinate \( x \) can be obtained in two ways: either making the charge centroid of the fired strips (that is the best algorithm for almost orthogonal tracks) or using the so called “µTPC mode” [6] for tracks at larger values of \( \theta \). The µTPC concept is described in figure 4. It requires: the measurement of the ionization electrons drift time on each strip; the determination through a linear fit of the “tracklet” parameters, as shown in figure 4; finally the evaluation of the \( x \) coordinate of the track at half gap \( x_{\text{half}} \).

The spatial resolution is determined as a function of \( \theta \) using both algorithms, by taking the distribution of the differences between the reconstructed positions in two adjacent chambers and dividing the width by \( \sqrt{2} \), the effect of the beam angular spread being negligible. The results,
Events

Figure 3. Distribution of the positions of the tracks impinging on a chamber when no hits are observed in the chamber in a run with $\approx 4 \times 10^4$ tracks. The peaks are clearly due to the pillars as discussed in the text.

Figure 4. (Left) Concept of $\mu$TPC mode. The measurement of the strip signal times, once the drift velocity is known, allows to reconstruct the so called “tracklet”. (Right) Example of a tracklet in test-beam data. The error-bars on the points depend on the charge collected by each strip. The definition of the $x_{\text{half}}$ is also shown.

shown in figure 5, indicate clearly the opposite behaviours of the two methods as a function of the angle $\theta$. Moreover, for each event the two algorithms are combined giving an x value having a resolution that is well below 100 $\mu$m in the full angular range. Such a combination profits from the observed anti-correlation in the position reconstruction between the two methods.

4.2 Behaviour in magnetic field

A magnetic field component orthogonal to the electric field directly affects the drift motion of the ionization electrons, and systematically biases the measurement of the precision coordinate x. The typical displacements expected in the working conditions of the ATLAS MM are of the order of
Figure 5. MM spatial resolution as a function of the beam incidence angle. Resolutions obtained using the charge centroid and the $\mu$TPC mode are compared, together with the one obtained by combining the two methods. In the NSW the typical angles of incidence are expected to be between 8 and 35°.

Figure 6. At a given angle $\theta$ of the track on the MM chamber, a focusing or defocusing effect of the Lorentz angle is expected, depending on the sign of the magnetic field.

2.5 mm $\times$ B(T), so that systematics of the order of hundred microns are expected in the NSW region for both centroid and $\mu$TPC reconstruction. “Singular” configurations are expected when $\theta$ is close to the Lorentz angle due to the magnetic field. In these focusing configurations the ionization cluster is confined to a very small number of strips. On the other hand, when the Lorentz angle has different sign with respect to $\theta$ the ionization cluster is spread over a larger number of strips (defocusing configuration). The effect is schematically described in figure 6.

A dedicated test-beam has been carried out at the CERN H2 beam, with the MM chambers inside a magnet providing a field of variable intensity orthogonal to the electric field of the chambers. The Lorentz angle has been measured at different values of the magnetic field and has been compared to simulations based on Garfield [7]. A good agreement is found, as shown in figure 7.

Spatial resolutions for two different values of $\theta$ ($\pm 10^\circ$) and magnetic field values up to 1 T are shown in figure 8 for both charge centroid and $\mu$TPC method. As can be seen the resolution is at the same level of the B=0 measurement. In the “singular” configuration (B=0.2 T at $\theta = -10^\circ$) the centroid method allows to recover the resolution worsening of the $\mu$TPC method.
Figure 7. Measured values of the Lorentz angle compared to the Garfield predictions. The results are in good agreement. The measurement shows that at fields of 0.3 T, as present at the location of the NSW, we expect Lorentz angles of up to 20°.

Figure 8. Spatial resolutions as a function of the magnetic field for two angular configurations, namely ±10°. Note that the resolution is slightly worse with respect to the one shown in figure 5, since in this test, the HV_{drift} was held at a lower value.

Particular care is needed to avoid biases in the measurement. MM chambers mounted in doublets with the back-to-back read-out electrodes allow a self-correction, since the effect of the Lorentz angle in the two gaps is equal and opposite, provided that the magnetic field is uniform among the two gaps, as shown in figure 9. For this reason all chambers will be mounted in this configuration.

4.3 Ageing tests

An extensive program of ageing tests of small MM prototypes (10 × 10 cm²) has been carried out at CEA Saclay in 2012 [8]. The general concept is to expose one chamber to a full irradiation with X-rays, neutrons, γ rays and α particles, simulating a charge deposit equivalent of 5 ÷ 10 years at
Figure 9. Schematic view of the effect of a magnetic field on a MM doublet. The Lorentz force in the two gaps acts in opposite directions, so that the mean of the coordinates measured in the two chambers provides a bias-free estimator of the precision coordinate.

Figure 10. (Upper) Chamber efficiency as a function of the absolute gain for the irradiated (R17a) and unirradiated chamber (R17b). (Lower) Comparison of spatial resolution (charge centroid for $\theta = 0$ tracks) for R17a and R17b chambers as a function of HV$_{ampl}$. Note that HV$_{ampl} = 550$ V (the optimal resolution) corresponds to a gain of about 20000. In both cases no significant deterioration is observed.

the high luminosity LHC, and compare its performances to the ones of another chamber that has not been irradiated. In the end both chambers are tested with a muon beam to measure efficiency and spatial resolution. The results, shown in figure 10 show no significant effect.
5 Summary and outlook

The Micromegas chambers have been chosen as one of the detector technologies for the upgrade of the ATLAS muon spectrometer in the forward region. The tests done on small size prototypes show that these detectors provide the required performance in terms of efficiency, spatial resolution and operation in the expected magnetic field. Moreover, no significant ageing effects from irradiation similar to those expected at High luminosity LHC have been observed. In the next months the collaboration will build the first large size detectors and will have to prove that the required mechanical accuracy and the required performance can be maintained over large dimensions. Subsequently serial production will be started to allow an installation in ATLAS by 2018.

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