Performance studies of MicroMegas for the ATLAS experiment

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ABSTRACT: The performance of MicroMegas (MM) has been extensively studied during several test beam campaigns with high energy particle beams at CERN up to the year 2012, and more recently (June 2013) with electron beams at DESY. Main objectives of the tests were to demonstrate that the requirements could be achieved for the upgrade of the ATLAS Muon Spectrometer, where the MicroMegas will be mounted (along with small-strip Thin Gap Chambers — sTGC) on the New Small Wheel for forward muon detection. The MM layout and operating settings have then been chosen to satisfy the ATLAS upgrade requirements and trigger timing constraints. Results for efficiencies, time resolution and spatial resolution for perpendicular and inclined tracks are presented. Moreover, in ATLAS the MM will operate in a non-uniform magnetic field up to 0.3 T. Dedicated test beam measurements have been carried out in a variable magnetic field between 0 and 1 T. The performance of MM in magnetic fields is also reported along with a comparison to simulations.

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

1On behalf of the Muon Atlas MicroMegas Activity (MAMMA) collaboration.
1 Introduction

The MicroMegas (MM) [1] is one of the detector technologies that has been chosen for precision tracking and trigger purposes for the upgrade of the forward muon detectors of the ATLAS experiment in view of the LHC luminosity increase. The MicroMegas is a micro-pattern gas detector with excellent high rate capability and good performance in terms of efficiency, spatial and time resolutions. Together with small-strips Thin Gap Chambers (sTGC), the MM will compose the New Small Wheel (NSW) that will replace the present Small Wheel of the ATLAS Muon Spectrometer in the LHC Long Shutdown in 2018 [2]. In the NSW, the sTGC are primarily devoted to the Level-1 trigger. However they also have the ability to measure offline muon tracks with good precision. The MM are primarily dedicated to precision tracking, but can, at the same time, confirm the existence of track segments found by the muon end-cap middle stations, thus exploiting trigger capabilities. In this way, the sTGC-MM combination forms a fully redundant detector system for triggering and tracking both for online and offline functions. The MM and sTGC detectors will be arranged in the NSW in a four module configuration sTGC-MM-MM-sTGC. Each module is composed by four planes for position measurements in the bending (precision) and in the azimuthal coordinates. This detector combination has been designed to be able to also provide excellent performance for the High Luminosity LHC upgrade. In order to ensure a momentum resolution better than 10% at $p_T \sim 1$ TeV with the muon spectrometer in ATLAS, each track segment in the NSW need to be reconstructed with a position resolution in the bending plane better than 50 $\mu$m. This performance should not degrade even if a considerable fraction of the detected hits are caused by
background particles or if some detector planes are not operational. Thus, a spatial resolution better than 100 µm is required for each single plane of MM. In order to fulfill trigger capabilities, both detectors are requested to have a time resolution better than approximately 10 ns, such that the exact bunch-crossing of the event can be identified, being the bunch-crossing separation 25 ns at LHC.

In figure 1, the MM layout and principle of operation are sketched.

The performance of MM has been extensively studied during the 2012 test beam campaigns with high energy particle beams at CERN. The main objectives of these tests were to demonstrate that the requirements for the New Small Wheel could be achieved, such as spatial resolution and tracking performance for inclined tracks; time resolution and trigger capability; effects of the magnetic field.

Most of the tests were performed at the H6 beam line of the Super Proton Synchrotron (SPS) at CERN. The tests with the MM in a magnetic field were carried out in the H2 SPS beamline. Different detector configurations, operating conditions, front-end electronics and DAQ were tested in the above mentioned test beam campaigns. In this paper we present in section 2 the results obtained with small size MM prototypes in the absence of a magnetic field, while in section 3 the performance of MM in magnetic field will be reported, along with measurements of basic quantities such as the Lorentz angles and the components of the drift velocity for different values of the magnetic field.

2 Performance of the MicroMegas with high energy particle beams

2.1 CERN H6 experimental hall — setup and operating conditions

The reported results are based on the test beam data collected in July 2012 at the SPS H6 beam line. The beam was composed of 120 GeV/c pions with a particle rate between 5 and 30 kHz and transverse dimensions of ∼ 2 cm² on the chambers.

Up to eight resistive MicroMegas (MM) test chambers (T1–T8) were aligned along the beam line. All chambers had an active area of 10 × 10 cm², a strip plane with 0.4 mm pitch and drift gap
of 5 mm. In figure 2 the layout of the setup is reported. The eight chambers were oriented in a back-to-back configuration forming four doublets of MicroMegas with a total lever arm of 600 mm. The chambers were operated with standard Ar:CO\textsubscript{2} gas mixture (93:7) with different configurations of the drift and amplification electrical fields. Reference operating settings were 600 V/cm electrical drift field, with a drift velocity of 47 µm/ns, and an amplification voltage of HV = 500 V. These conditions were selected for the results reported in this paper.

### 2.2 Signal processing and time resolution

The data acquisition system was based on the Scalable Readout System (SRS) [3] developed by the RD51 Collaboration [4]. The front-end electronics were based on the 128 channel APV25 ASIC [5] in which detector signals are shaped with a CR-RC circuit and sampled at 40 MHz. In our setup the trigger was provided by the coincidence of three scintillators plus a veto. For each event, zero-suppressed data were acquired, for each strip by sampling the APV25 integrated charge signal shape. The adopted configuration allowed to record 27 samples for a total time window of 675 ns. It should be mentioned that the APVs were operated at a frequency of 40 MHz, completely unrelated to the particle beam. Since the APV25 only accepts clock-synchronous triggers, a jitter of ±12.5 ns, corresponding to the width of one clock cycle, is introduced by the synchronization of the scintillator/photomultiplier trigger signal. For this reason most of the results obtained by time measurements will be reported from differences between chambers where the contribution of a global time jitter vanishes.

From signal shaping analysis both time and charge information were obtained. In figure 3 a typical sampled signal from one channel is shown with a Fermi-Dirac fit function to the leading edge. Time at half height is taken as the strip time-hit, while maximum height is taken as strip-charge. The time resolution was estimated from the distribution of the differences of first hit arrival time of two chambers traversed by the same particle track. In figure 4 the gaussian fit to the distribution of the time difference of two chambers in back to back configuration, T1 and T2, has a width of 14.6±0.3 ns. Assuming the same resolution for the two chambers the single chamber time resolution is 1/√2 of the reported difference width, resulting in $\sigma_t = 10.3\pm0.2$ ns. From primary
Figure 3. A typical pulse shape from one channel (one strip) of the APV25 operated at 40 MHz with 27 samples. A fit with a Fermi-Dirac function with an additional baseline is performed to determine the strip-hit-time and collected charge.

Figure 4. Distribution of the differences of first time hits between two MM chambers in back to back configuration. The single chamber time resolution is $1/\sqrt{2}$ times the width of the fitted gaussian, assuming same resolution for the two chambers.

In order to estimate the spatial resolution, ionization spatial spread, a time resolution in the order of 5–6 ns is expected. The measured single chamber time resolution of about 10 ns in the present set-up is dominated by the contributions of the electronics read-out chain, front-end and DAQ, and by the hit-time extraction method.

2.3 Spatial resolution for perpendicular tracks and efficiencies

In case of perpendicular tracks, a good estimate of the spatial resolution can be obtained from the charge-weighted positions of the detector hit clusters. As in the case of time resolution studies, the spatial resolution for perpendicular tracks was estimated by the difference of cluster centroid measurements of pairs of MM chambers. An example of such a distribution is reported in figure 5.
Figure 5. Distribution of the difference between charge weighted cluster centroids reconstructed in the test chambers T3 and T4. The single chamber spatial resolution is $1/\sqrt{2}$ times the width of the fitted gaussian, assuming same resolution for the two chambers.

A spatial resolution of about 73 $\mu$m was obtained with an average cluster size of 3.2 strips. It should be mentioned that a prerequisite for the method considering differences on pair of chambers is that the particle trajectories in the beam have a limited divergence, so that the spatial spread on one chamber, for a fixed position on the other chamber, is well below the spatial resolution. This was indeed the case for the CERN test beam setup. The beam angular spread was estimated to be about 120 $\mu$rad, from the width of the difference of reconstructed track positions between chambers as a function of their relative distance. The impact of such an angular spread on the spatial resolution is $< 10 \mu$m considering differences between chambers with a relative distance of about 5 cm.

The distribution of local inefficiencies has also been studied using missing hits in one chamber, as revealed by the extrapolation of reconstructed particle tracks with all other test chambers. As shown in figure 6 inefficiencies are localized in positions corresponding to the pillars sustaining the mesh. A global inefficiency in the range 1 to 2% was measured, consistent with the partially dead area due to the presence of 300 $\mu$m diameter pillars, with pitch spacing of 2.5 mm.

2.4 Spatial resolution for inclined tracks. The micro-TPC method

For impact angles greater than 10° the cluster charge-centroid method cannot be applied anymore to guarantee the desired resolution. One possibility is to exploit single strip time information to operate the MM in the micro-Time-Projection-Chamber ($\mu$TPC) mode [6] which allows to perform a local track reconstruction in the few-mm wide drift gap. This is possible with strip time measurement and a highly segmented read-out electrodes: the position of each strip gives a $x$ coordinate, while the $z$ coordinate (perpendicular to the strip plane) can be reconstructed from the time measurement using the electron drift velocity as extracted from Garfield simulations in the conditions of operations: $z = v_{\text{drift}} \times t$ ($v_{\text{drift}} = 47 \mu$m/ns in our case).

In figure 7 the $\mu$TPC concept as well as a track reconstruction within the drift gap of a test chamber, are reported. Once a cluster is found, $(x_i, z_i)$ coordinates and $(\delta x_i, \delta z_i)$ errors are assigned
Figure 6. Distribution of inefficiencies from missing hits with full tracking reconstruction.

Figure 7. Left: illustration of the micro-Time Projection Chamber concept ($\mu$TPC) applied in the MM drift gap. Right: reconstruction of a $\mu$TPC track from data.

to each strip and fit with a straight line. Errors $\delta x$ basically account for the uncertainty of the hit in the finite strip pitch plus a weight depending on the charge on the strip (errors are increased for small charges possibly associated to charge induction); and $\delta z$ being the error as propagated from the time measurement error. The latter, extracted by the signal fit function, was checked to have a dependence from the maximum charge on the strip: the higher the charge, the smaller the error on the measured time. The track-fit $\chi^2$ probability was checked to be flat, thus supporting a correct determination of the errors.

Track angles are reconstructed with about 70 mrad resolution. The best position measurement is “$x_{\text{half}}$” corresponding to the track fit at half-gap, where the interpolated position estimate minimizes the error.

We recorded data with the chambers under various angles, 10°, 20°, 30°, and 40°. The $\mu$TPC spatial resolution has been measured by the difference of $x_{\text{half}}$ in two chambers with same orientation ($\Delta x_{\text{half}}$). The time jitter is equal in the two chambers introducing the same spatial offset, canceling-out in the difference. In figure 8 the distributions of $x_{\text{half}}$ differences for data taken at 30°,
Figure 8. Distributions of $\Delta x_{\text{half}}$ for particle impact angle of 30°. The distribution is fitted with a double Gaussian (red line) accounting for a core distribution (green line) plus tails (blue line). The spatial resolutions obtained from the inner (core) gaussian and from a weighted average of the two gaussians are reported.

The distribution can be fitted with a double-gaussian function accounting for a core distribution plus tails.\(^1\) Assuming the same resolution for the two chambers the single chamber resolution is $1/\sqrt{2}$ of its width.

The resolutions computed from the core gaussian and from the weighted average of the narrow and large gaussians widths are 87 µm and 120 µm, respectively. The resolution in $\mu$TPC mode depends on several parameters, among these the time resolution plays an important role. It is expected that the $\mu$TPC spatial resolution determination will improve even further by fully exploiting the MM intrinsic time resolution (of the order of 5–6 ns).

In figure 9 the results of the core resolutions obtained with the $\mu$TPC method are summarized (solid red data point). Spatial resolutions have been also measured using the cluster centroid method. Results are reported with blue symbols in the figure. As expected, the cluster centroid behave better at small angles (small cluster size) while the $\mu$TPC method reaches best performance for larger angles. A combination of the two methods can be envisaged to improve the spatial resolution determination for all track angles. Moreover, due to the fact that the position determination with the two methods are systematically anti-correlated, a weighted average can improve the resolution further. The result of a simple combination method with weighted average of cluster centroid and $\mu$TPC position measurement is also reported in the figure (open black data points) demonstrating that spatial resolutions below 100 µm is attainable for all impact angles up to 40°. The impact angle range for muons in the NSW is approximately between 8° and 30°.

\(^1\)The origin of the tails is understood to be related to the finite pitch of the strips: the $x$-position of a hit is assumed to be the center of the corresponding strip, leading to a positive tail in the distribution of reconstructed angle. By taking the difference of $x_{\text{half}}$ in two chambers this effect generates symmetric tails in the $\Delta x_{\text{half}}$ distribution.
Figure 9. MicroMegas spatial resolution summary as a function of the track angle.

Figure 10. Garfield simulations [7] for the total drift velocity (left) and the expected Lorentz angle (right) in Ar:CO\textsubscript{2} 93:7 gas mixture for a magnetic field up to 2 T as a function of the drift electric field, with the electric and magnetic field vectors being perpendicular.

3 Performance of the MicroMegas in magnetic field

The MM chambers of the NSW will operate in a magnetic field with large variations and values up to about 0.3 T, with different orientations with respect to the chamber planes and a sizeable component orthogonal to the MM electric field.

The effect of the magnetic field on the detector operation has been studied with test beam data and simulations. Figure 10 shows the Garfield simulations [7] for the drift velocity and the Lorentz angle as a function of the drift electric field for several values of the magnetic field (perpendicular to electric field) and for an Ar:CO\textsubscript{2} 93:7 gas mixture. Figure 11 illustrates the effect of the magnetic...
Figure 11. Illustration of the effect of the magnetic field on the drift in a MM chamber. The electrons drift along the Lorentz angle direction. A “defocusing” (left) or “focusing” (right) configuration can be distinguished, depending on the track angle and the Lorentz angle having opposite or same sign.

Figure 12. Setup of the MicroMegas test chambers in the SPS CERN H2 experimental area in June 2012. Also shown is the superconducting solenoid generating a magnetic field up to 2 Tesla.

field on a MM chamber. The drift direction of the ionization electrons is tilted with respect to the electric field direction by the Lorentz angle. Depending on the relative signs of the track angle $\theta_{\text{track}}$ and the Lorentz angle $\theta_L$, a “focusing” or “defocusing” configuration is expected, where the ionization cluster is spread over a larger (smaller) number of strips when $\theta_{\text{track}}$ and $\theta_L$ have different (same) sign. A “singular” configuration is reached when the particle track inclination is equal to the Lorentz angle $\theta_{\text{track}} = \theta_L$. From the point of view of track reconstruction, this condition is equivalent to a perpendicular track in absence of magnetic field, where the clusters have minimal spread (minimal size) and the charge weighted cluster centroid provides best spatial resolution.

3.1 CERN H2 experimental hall — setup and operating conditions

The results reported here refer to data taken in June 2012 when four MM prototypes, of $10 \times 10$ cm$^2$ active area, have been exposed to the H2 beam at CERN. The four chambers were assembled in two back-to-back doublets, T1–T2 and T3–T4, respectively. T1 and T2 had a drift gap of 5 mm, while for T3 and T4 a larger drift gap, 10 mm, was chosen in order to magnify the effect of the magnetic field and compare with the T1, T2. The doublets were positioned on a frame at a relative distance of 20 cm, together with other reference chambers.

The detectors were positioned in a superconducting solenoid which can provide a magnetic field up to $B = 2$ T orthogonal to the beam line and to the MM electric field. In figure 12 the setup of the MM chambers in the H2 experimental area is reported, where, in addition to the T1–T4 test chambers, the other reference chambers are also visible. Also shown is the superconducting
solenoid. Different operating conditions were tested, but here, results will be shown for chambers operated in conditions similar to those described in section 2 (in absence of magnetic field), taken as reference. The setup was exposed to a 150 GeV $\pi^-$ beam.

3.2 Measurement of the Lorentz angle and drift velocity

In presence of magnetic field, the drift direction of the ionization electrons is tilted with respect to the electric field direction by the Lorentz angle $\theta_L$. The tilt of the drift direction gives a sizable shift ($\delta x$) of the reconstructed hit position with an average value of:

$$\delta x = 0.5 \times \text{gap} \times \tan(\theta_L)$$  \hspace{1cm} (3.1)

This shift affects both the centroid and the $\mu$TPC reconstruction. In figure 13 the shift induced by a magnetic field $B = 0.5$ T is shown. The measurement of the Lorentz angle from eq. (3.1) using the shift of the cluster centroid position with respect to the $B = 0$ case, was validated with simulations and used to determine the Lorentz angles from data in case of perpendicular tracks for different values of the magnetic field. The results are reported in figure 14 showing a good agreement with Garfield simulations. A systematic deviation of about $1^\circ$–$2^\circ$ is observed which needs further investigation.

Having measured the Lorentz angle (or from its knowledge), and measuring the electrons drift time, $t_{\text{tot}}$, along the drift gap, the drift velocity in the presence of a magnetic field can be derived:

$$v_{\text{Drift}} = \frac{\text{gap}}{\cos(\theta_L)}/t_{\text{tot}}$$

where gap = 5 mm is the MM drift gap. The total drift time was measured
Figure 15. Drift time distribution (in ns) in magnetic field for $B = 0.5\,\text{T}$ (left) and $B = 1.0\,\text{T}$ (right). A composition of a rising and a falling Fermi-Dirac function is used to fit the data to estimate the total drift time along the gap. Results are shown for the T2 chamber with 5 mm drift gap.

Figure 16. Drift velocity measurement as a function of the magnetic field from data and comparison with Garfield simulations. Left: drift velocity component along the drift electric field. Right: total drift velocity.

from the distribution of hit-time for all strips and the fit to the leading and trailing edges. An example is reported in figure 15 where a combination of rising and falling Fermi-Dirac functions were used in the fit and the total drift time is computed as the difference of times at half height of the rising and falling functions. In figure 16 the measured total drift velocity and its component along the electric field are reported and compared with Garfield simulation. A good agreement between data and simulation is obtained.

### 3.3 Track reconstruction with the micro-TPC method

As seen for inclined tracks in the absence of a magnetic field, the $\mu$TPC method was essential to improve the spatial resolution measurements (for angle larger than about $10^\circ$). In the presence of
a magnetic field the same approach should be applied for track angles different from the Lorentz angle (far from the “singular” configuration). In case we have no information about the local magnetic field components in the chamber, one possibility is to ignore the magnetic field effects and apply the \( \mu \)TPC method from hit time measurements, assuming the drift velocity along the electric field with its value at \( B = 0 \). As sketched in figure 17 this method introduces a distortion of the measured track angle, hence a systematic bias in the track position reconstruction. In the simple case of negligible differences in the absolute values of the drift velocities with and without magnetic field (or in the case the drift velocity is known and used in the method) the reconstructed “effective angle” \( \theta' \) has a simple dependence from the true track angle \( \theta_{\text{track}} \), and the Lorentz angle \( \theta_L \):

\[
\tan(\theta') = \cos \theta_L (\tan \theta_{\text{track}} + \tan \theta_L)
\]  

(3.2)

The \( \mu \)TPC technique has been applied both in simulation and test beam data always using the drift velocity corresponding to the current magnetic field. The results for the effective angle calculation are summarized in figure 18. The different colors correspond to 2 different incident track angles, red and green for 10° and 20° respectively. The empty squares represent the simulation and the filled circles show the angles reconstructed from the test beam data. The curves correspond to the effective angle function eq. (3.2) for 10° and 20° incident angle. The calculated angles follow the Garfield simulation with a small deviation for the 1 T case, where the small difference between data and simulation can be due to the magnetic field value uncertainty (\( \sim 5\% \)).

### 3.4 Spatial resolution of MM in the presence of a magnetic field

MM spatial resolutions were obtained for the charge centroid \( x_{\text{cent}} \) and the \( \mu \)TPC estimate \( x_{\text{half}} \) following the procedures described in section 3.3.
Figure 18. Effective angle measurements as a function of the magnetic field: data and simulation vs. expectations from eq. (3.2).

(a) \(B = 0\)  
(b) \(B = 0.2\) T

Figure 19. Comparison of space resolutions obtained in the H2 test-beam using the centroid (red) and the \(\mu\)TPC (blue) methods.

The widths of the core Gaussians of the \(\Delta x_{\text{half}}\) distributions for the T1-T3 pair are obtained and divided by \(\sqrt{3/2}\) to estimate the resolution for the chamber T1 (5 mm gap) accounting for the different drift gaps of T1 and T3 (5 and 10 mm, respectively), hence different resolutions for the two chambers. Figure 19 shows the spatial resolutions obtained using the centroid method and the \(\mu\)TPC method at five inclination angle configurations for data at \(B = 0\) and \(B = 0.2\) T. Notice that the absolute values of the resolutions here obtained at \(B = 0\) are systematically larger than those reported in section 2.4. This is due to the fact that in this case (June 2012 test-beam setup) the detector gain was lower and this affects directly the resolution. The results of the comparison
Figure 20. Illustration of systematic bias compensation making use of a MM doublet in back-to-back configuration for $\mu$TPC track reconstruction in magnetic field whose value is unknown. Due to the back-to-back configuration the same systematic shift is introduced with opposite sign and is thus canceled in the average.

between the $B = 0$ and $B = 0.2$ T cases, can be easily understood considering that at $B = 0.2$ T the Lorentz angle $\theta_L$ is very close to 10°, so that the resolution profiles as a function of track angle, are shifted by this amount with respect to the profile in absence of magnetic field. Accounting for this shift in angle, the spatial resolution is not degraded in presence of magnetic field. At the singular configuration, the bad performance of the $\mu$TPC method is compensated by the good performance of the cluster centroid method, due to the very small cluster size. A combination algorithm can be applied to have a constant resolution through all configurations. The systematic shifts of the reconstructed position due to the magnetic field can be corrected in two ways: i) by using the average point measured in a doublet in back-to-back configuration, as shown in figure 20, which is systematic-free as demonstrated with simulations; ii) by measuring accurately the magnetic field on the NSW with an adequate number of magnetic field sensors and using the knowledge of the drift velocity and Lorentz angle to correct the $\mu$TPC reconstruction. Both methods are subjects of studies for future programs.

4 Conclusions

In the past few years the MAMMA collaboration has performed several test beam campaigns, primarily with high energy particle beams at the Super Proton Synchrotron (SPS) beam lines at CERN, using MM detector prototypes of dimensions $10 \times 10$ cm$^2$. The aim of these tests was to evaluate the performance of the detectors under operational conditions similar to those expected for the ATLAS NSW.

A selected set of the test-beam results have been reported, which constitute a small part of the huge effort of the collaboration in performance studies. The data analysis reported here, has shown that a time resolution of about 10 ns was obtained. A spatial resolution of 100 $\mu$m was easily obtained, in absence of magnetic field, in the full angular range these detectors will operate in ATLAS: between $\sim 8^\circ$ and $\sim 30^\circ$.

The performance of MM inside a magnetic field has been evaluated. The values of Lorentz angles and the components of the drift velocity along and perpendicular to the electric field were
measured and found in good agreement with Garfield simulations. Moreover, a good agreement was found with simulations for the “effective track angle” reconstruction, that can be taken as a validation of the simulation. The measured spatial resolution has been shown to be not degraded in a magnetic field. The measured hit position, depending on the reconstruction analysis method, can be affected by systematic biases. However, exploiting a detector back-to-back configuration, it was demonstrated from simulations that the offsets introduced due to the magnetic field effect can be canceled out. The confirmation of this statement will be the next step in test-beam data analyses.

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