Micromegas detectors for the Muon Spectrometer upgrade of the ATLAS experiment

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ABSTRACT: Through the years the Micromegas (MICRO MEsh GAseous Structure) devices have proven to be reliable detectors with excellent space resolution and high rate capability. Large area Micromegas will be employed for the first time in high-energy physics for the Muon Spectrometer upgrade of the ATLAS experiment at the CERN LHC. A total surface of about 150 m² of the forward regions of the Muon Spectrometer will be equipped with 8 layers of Micromegas modules. Each module covers a surface from 2 to 3 m² for a total active area of 1200 m². Together with the small-strips Thin Gap Chambers, they will compose the two New Small Wheels, which will replace the innermost stations of the ATLAS Endcap Muon tracking system in the 2018/19 shutdown. The breakthroughs and developments of this type of Micro Pattern Gas Detector will be reviewed, along with the path towards the construction of the modules, which will take place in several production sites starting in 2015. An overview of the detector performance obtained in the test beam campaigns in recent years at CERN will be also presented.

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

The Micromegas (MM) 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 [1] in view of the LHC luminosity increase. MM are micro-pattern gaseous detectors 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 2018/19 [2].

In figure 1 the present Small Wheels are shown together with the layout of the NSW, divided into eight small and eight large sectors. Similarly the MM and sTGC detectors will be arranged in the NSW in 16 sectors, in a sandwich configuration of four wedges sTGC-MM-MM-sTGC. Each module is a quadruplet, composed by four planes for position measurements in the radial (precision) and in the azimuthal coordinates. For the two wheels (one on each endcap side of the Spectrometer), the total number of MM quadruplets to be built is 128, for a total active area of 1200 m² detector planes.

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 endcap middle stations, thus exploiting trigger capabilities. In this way, the sTGC-MM combination forms a fully redundant detector system for triggering and tracking with both online and offline functions.
Figure 1: Left: photo of the present Small Wheels before entering the cavern. Despite the name, its size is about 9.3 meters in diameter. Centre: Layout of the New Small Wheel. In one sector the radial segmentation of the MM modules is visible. Right: View of one sector of the wheel. It is composed of a central spacer and a sandwich of MM and sTGC modules.

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 15% at $p_T \sim 1$ TeV with the Muon Spectrometer in ATLAS, each track segment in the NSW needs to be reconstructed with a position resolution in the bending plane to 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 $\mu$m is required for each of the MM and sTGC planes. Considering the 16 measurement planes (sTGC+MM) with a resolution of 100 $\mu$m per plane, the position of the read-out strips along the precision coordinate should be known with an accuracy better than 30 $\mu$m and the position of each plane on the coordinate perpendicular to the chamber surface (out-of-plane) should be known within 80 $\mu$m accuracy. Given the large surfaces of the individual detector elements, the mechanical precision requirements of the readout planes positioning represent a challenge in the design, construction, modeling and control of all possible deformations.

2 History and breakthroughs in the Micromegas technology

The concept of the Micromegas has been developed in the ‘90s [3] in the context of R&D on Micro Pattern Gaseous Detectors (MPGD). A sketch of the MM operating principle is shown in figure 2.

The anode is segmented in metallic strips with a pitch of a few hundreds microns. At a distance of about 100 $\mu$m, sustained by special pillars built on the strip plane, a stretched metallic mesh is positioned. This gap, as well as a few mm gap between the mesh and a cathode plane are filled with a gas mixture. The electric field between the mesh and the metallic strips (the so called amplification region) is held at a large value ($\sim$ 40–50 kV/cm), while the electric field between the mesh and the cathode (the so called drift region) is much lower (few hundreds V/cm).

Charged particles traversing the drift space ionize the gas. The electrons liberated by the ionization process drift towards the mesh. Due to the high ratio between the two electric fields, the metallic mesh is essentially transparent for the electrons so that they drift to the mesh, pass in
Figure 2: Principles of operations of Micromegas chambers. The sketch shows a MM with the reference operational parameters used during the first years of R&D at CERN in view of the ATLAS upgrade.

the amplification region, where the avalanche takes place, and finally the signal is collected by the metallic read-out strips.

While the drift of the electrons in the conversion gap is a relatively slow process the amplification process happens in a fraction of a nanosecond [4], resulting in a fast pulse of electrons on the readout strip. Contrary to the electrons, the ions that are produced in the avalanche process are moving back to the amplification mesh. Most of the ions are produced in the last avalanche step and therefore close to the readout strip. Given the relatively low drift velocity of the ions, it takes $\mathcal{O}(100 \, \text{ns})$ for them to reach the mesh, which is the typical duration of the slower signal induced on the strips. Still very fast compared to other detectors. It is the fast evacuation of the positive ions which makes the MM particularly suited to operate at very high particle fluxes.

Micromegas detectors have been successfully used in a number of High Energy Particle Physics experiments. COMPASS was the first experiment, since the beginning of data taking in 2002, equipped with MM detectors [5] and has shown to operate in very high particle rate environment (up to $\sim 10 \, \text{kHz/mm}^2$) with excellent spatial resolution. However, MM chambers were not yet produced in large quantities and the dimensions were limited in COMPASS to an active area of $40 \times 40 \, \text{cm}^2$. Other medium-size MM were also produced for the T2K TPC readout [6] with dimensions $36 \times 34 \, \text{cm}^2$.

Despite the good performance of the MM in these experiments, it was soon realized that the greatest problem to solve for this technology was the discharges with high flux of highly ionizing particles (hadrons) leading to sparks between the mesh and the strips planes, thus to inefficiencies and aging issues. In COMPASS the discharge rate has been minimized by using a low density gas (Ne/C$_2$H$_6$/CF$_4$ – 80:10:10) and by operating the detectors at a moderate gain.

2.1 Bulk Micromegas

Due to the very narrow amplification gap MM are particularly vulnerable to sparking. Moreover, small variations in the gap, imply significant variations in the amplification, which in turn can result in a higher probability of sparks (narrower gaps) or in inefficiencies (larger gaps). The positioning
of the mesh in order to obtain a good flatness and parallelism with respect to the anode was a challenge in the construction. The introduction of the “bulk Micromegas” by Giomataris et al. [7] represented a new method of producing MM elements in one single process in which the mesh is embedded into the readout PCB structure. This allowed to make the mounting of the detector a much simpler procedure. The production of bulk MM based on the printed circuit board technology could be extended to medium size area detectors made by the industry, consequently with low cost of fabrication and robustness. Going to very large area, this method is limited by the industrial manufacturing of PCB boards, nowadays limited to a maximum width of 60 cm.

2.2 The resistive-strip spark protection scheme

In order to detect minimum ionizing particles with high efficiency, the MM operate at quite large gain, of the order of $10^4$. In case of highly ionizing particles (as for example, slowly-moving charged debris from a neutron - or other - interactions in the gas and/or detector materials), the Raether limit [8] of about $10^7$ electrons in the avalanche, where sparks start to occur, can easily be reached. This was immediately recognized to be a limiting factor to operate MM in ATLAS after the LHC luminosity upgrade.

In order to explore the potential of the MM technology to be adopted for the NSW upgrade, an R&D activity, called Muon ATLAS MicroMegas Activity (MAMMA) started in 2008 [9]. In the first years most of the R&D work at CERN was dedicated to address the spark issue. The discharge problem has been overcome with the implementation of a layer of resistive strips facing the amplification gap. This was a breakthrough in the technology development. The principle of the resistive-strip protection scheme is illustrated in figure 3 and described in more detail in ref. [10]. It consists of a thin layer (50–70 $\mu$m thick) of insulator (e.g. kapton foil) on top of which resistive strips are deposited. The resistivity of the strips should be of the order of few tens of M$\Omega$/cm. Geometrically, the resistive strips match the pattern of the readout strips and are electrically insulated from them. The signals are induced through capacitive coupling to the readout strips. In case of sparks, the resistive strips charge up and the electric field locally drops down hence damping the discharge.

The proof that the principle works was obtained operating a bulk MM chamber with resistive
Figure 4: The monitored HV and currents as a function of the mesh HV under neutron irradiation for a non-resistive MM (left) and the resistive MM (right) [10]. The continuous line shows the HV, the points the current.

protection with a 5.5 MeV neutron beam at the Demokritos National Laboratory in Athens [10]. The resistive MM and a MM without resistive strips were exposed to neutrons flux up to $1.5 \times 10^6$ n/cm$^2$/s, on the chambers. Both chambers were operated with the same electronics and the same Ar:CO$_2$ gas mixtures.

Figure 4 (from [10]) shows the monitored high-voltage (HV) and the currents for both chambers for the same neutron irradiation exposure for different mesh HV settings. In the non-resistive chamber the mesh HV broke down as soon as the neutron beam was switched on. For the detector with the resistive-strip protection no HV breakdown was observed and the current did not exceed $\sim200$ nA for a mesh HV of 590 V, corresponding to an effective gas gain of $\sim1.2 \times 10^4$. The few high current points in figure 4 (right panel) correspond to the currents during HV ramp up. Following these tests, all further developments for the ATLAS upgrade were done on MM with resistive strips.

3 Further improvements towards large area Micromegas for ATLAS

Whilst the problem of sparking has been resolved, a number of remaining issues had to be addressed to move towards the construction of the large area MM for the NSW ATLAS upgrade. Among them, the need to overcome the limitation in the dimensions imposed by the bulk technique of PCB manufacturing (see section 2.1). While in the bulk MM the metallic mesh is integrated into the readout PCB, in the proposed scheme of large area MM, the mesh is integrated in the panel containing the cathode plane. This forms the drift gap, which is separated from the readout PCB, thus not depending on its dimensions. In figure 5 the sketch of the MM assembly with the “floating mesh” technique, is shown. The figure is a schematic drawing of a single MM plane assembly with the drift and readout panels in open (left) and closed (right) position. On top of the resistive strips on the readout panels, the mesh support pillars are deposited. The pillars define the distance between the mesh and the resistive strips. Are produced by laminating two layers of 64 $\mu$m thick photo-imageable coverlay to the PCB, exposing, and developing the pattern of the pillars. The mesh is integrated in the drift panel. It is first stretched and then glued on the aluminum frame surrounding the drift stiffening panel. The coupling of the drift panel to the readout panel requires
very high mechanical accuracy to position the mesh on top of the pillars and in contact with them. As shown in figure 5, when closed, the mesh-frame should reach a position just below the top of the pillars. For ATLAS, the required precision in the machining of all the frames is at the level of $\sim 50 \mu m$ over lengths of meters.

In the process of optimizing the design and ease the construction, and following the results of tests on prototypes, the high–voltage (HV) scheme has also been revised and improved. Instead of applying negative HV on the mesh and keeping the resistive strips at ground potential (as usually adopted in MM), the mesh has been grounded and positive HV was applied to the resistive strips. Such a scheme has several advantages. It simplifies the detector construction (especially in the considered scheme of figure 5 where having an insulation between the mesh and the frame would be an issue) and allows for an easy implementation of a segmentation of the HV, if desired (through a segmentation on the readout boards). At the same time, it decouples the drift and the amplification voltage and allows for a lower voltage on the drift electrode for the same drift field (compare for example the HV distributions in figure 2 and figure 3). Most importantly, it was observed from tests that it provides a more stable detector performance allowing for operation of the detectors at a higher gas gain. This can be explained by the better electrostatic configuration between mesh and the resistive strips. All field lines end on the strips and not on the insulator between the strips, contrary to the configuration where the resistive strips are at the same ground potential as the insulator. In the event of a spark the mesh stays at ground potential and the field perturbation owing to the spark, is constrained locally.

4 Layout and construction of Micromegas for the New Small Wheel

The design and the construction procedures for the NSW Micromegas, are the result of detailed studies of panels construction with extensive prototyping and tests, and of a campaign of measurements of deformations in comparison with (and with the support of) mechanical simulations models. In each sector, the MM are arranged in two wedges (see figure 1) mounted on the two sides of a central support frame. Each wedge is radially segmented into two MM 4-layers modules (quadruplets). There are four types of MM quadruplets (basically different in dimensions)
arranged on the various sectors of the NSW: LM1 (lower radius) and LM2 (larger radius) for the large sectors, and SM1 and SM2 for the small sectors. All quadruplets have trapezoidal shapes with dimensions between 2 and 3 m$^2$.

The sketch of the main components of a quadruplet is shown in figure 6. The readout (r/o) planes are disposed in a “back-to-back” configuration$^1$ onto two stiffening panels with an aluminum honeycomb internal structure (r/o panels). One of them is equipped with strips parallel to the bases of the trapezoid (eta strips or X planes) for the measurement of the precision coordinate (pseudorapidity $\eta$) while the two r/o planes of the second panel are tilted by $\pm 1.5^\circ$ (stereo strips or UV planes) for the measurement of the second coordinate (azimuthal). The pitch of the strips is 450 (425) $\mu$m for the panels in the large (small) sectors. One central double sided panel and two external panels sustaining the stainless steel mesh, (also referred to as drift panels) are then coupled to the two r/o panels to form the four gas gaps. In the assembly the panels are screwed and the relative alignment between the readout planes must be controlled with high precision (better than 30 $\mu$m). In each gas gap the mesh separates the drift and amplification gaps, of 5 mm and 128 $\mu$m, respectively.

At the time of this paper, the complete design and technical drawings are being finalized for the construction of the final full-size prototypes of each module type (Modules-0) before entering into series production in mid-2015. In figure 7 a preliminary technical drawing (3D model) of one of the modules (LM1) is shown. The drawing on the left shows an overview of the 5 panels. It also shows the segmentation of the PCB boards (per plane). The segmentation is imposed by the standard industrial PCB processing (<600 mm), and the segmentation was chosen with boards about 450 mm wide. The active area of one detection plane will be composed by 5 readout PCBs for the innermost modules (SM1 and LM1) and by 3 PCB for the outermost modules (SM2 and LM2). On the contrary the mesh, connected to the drift panels (not visible in the figure) is not segmented, it is a single piece with chamber dimensions, so that the module has essentially no

$^1$The strips are on either sides of the stiff panel resulting in opposite field configuration.
dead area in the junction between two PCBs (only one missing strip). The drawing on the right of figure 7 shows a detail of the assembled module along with some of the services. In particular, cooling (light brown) and gas (dark brown) distribution pipes are visible as well as the envelopes of the front end boards (green rectangles).

4.1 Construction of the first four plane Micromegas prototype

Before starting the construction of the Modules-0 several large size single plane MM prototypes (up to $1 \times 2 \, \text{m}^2$) have been built at CERN [9]. A step forward in the prototyping towards the final configuration was done in the summer 2014 with the construction of the first quadruplet, with dimensions $1.2 \times 0.5 \, \text{m}^2$, basically with the same structure as foreseen for the NSW upgrade. This is the first example of a multilayer MM chamber ever built. The construction of this medium-size prototype also provided input for the design of the final modules just reported in the previous section, and is essential to establish the procedures for the construction and assembly. The MMSW prototype (MicroMegas for the Small Wheel) was designed to fit the dimension of half a Cathode Strip Chamber (CSC) detector installed in the present Small Wheel in ATLAS (copper colored chambers in left of figure 1). The goal is to install the MMSW into the ATLAS experiment in 2014, facing a CSC chamber, hence in the location where the NSW will eventually replace the current Small Wheel. This will allow the integration of a new detector into the ATLAS Muon Spectrometer, and to evaluate the detector response under realistic conditions during the 2015–2016 LHC run.\(^2\)

In figure 8 a picture of the detector is shown together with some of its components. The detector has been realized using the resistive-strip technology and decoupling the amplification mesh from the readout structure. The four readout planes are segmented into strips with a pitch of 415 $\mu\text{m}$ and comprise a total of 4096 strips. In two of the four planes the strips are inclined by $\pm 1.5^\circ$ and provide the second coordinate. In the central panel of the figure, a photo of the readout PCB is shown where the layer of resistive strips is visible. The resistive strips are deposited on a polyimide film (Kapton) that is then press-glued to the readout PCB. A magnified picture and a microscopic picture of the resistive pattern are also shown in the figure (right bottom and right top, respectively). As can be seen from these pictures the pattern is designed with resistive strips

\(^2\)At the time this paper is published, the schedule is such that the MMSW is foreseen to be installed (in Summer 2015) first in a different position in the Endcap part of the Muon Spectrometer and eventually moved in the Small Wheel during the first shutdown when accessibility allows.
Figure 8: The Micromegas prototype for the Small Wheel (MMSW). Left: the first MM quadruplet built so far. Center: The readout board. Right: magnified views of the resistive pattern.

0.3 mm wide with staggered interconnections every 10 mm. Such a configuration is the result of an optimization from the simple pattern with parallel strips, which guarantees a homogeneous resistivity, independent of the distance along the strips. Moreover it is essentially insensitive to broken lines.

Currently two techniques of resistive foils production are under evaluation: i) screen printing which is a standard technique to deposit resistive paste, used for small prototypes and in the recent years tested on large surfaces; ii) carbon sputtering and liftoff method, a new technique, developed in the context of MM detectors for the ATLAS upgrade, to produce MPGD resistive electrodes [12]. The resistive foils for the MMSW have been produced with the sputtering technique. The carbon layer (sub-micrometer thickness) is deposited on a 50 μm insulating Kapton foil by sputtering, resulting in a good uniformity (< 30%) of the resistivity. The foils produced so far with this technique, are extremely robust with respect to mechanical and chemical damage.

5 Performance of the Micromegas with high energy particle beams

The performance of MM have been extensively studied since the beginning of the MAMMA activity in 2009. First results have demonstrated a spatial resolution as good as 40 μm on a small MM prototype with a strip pitch of 250 μm operated with a Ar:CF₄:iC₄H₁₀ (88:10:2) gas mixture [13]. A result by far exceeding the requirements of the ATLAS upgrade.

Nevertheless a few points must be considered: i) a too fine granularity (small pitch size) would result in a huge number of electronic channels in ATLAS, with associated cost issues; ii) the gas mixture must be safe from the point of view of ageing (as a general rule eco-gases must be used). The reuse of an existing gas mixture in the Muon Spectrometer is also highly desirable in order to minimize the costs. After having tried several of the most popular gas mixtures, the choice of the Ar:CO₂ (93:7) mixture, already available in ATLAS to operate the MDT chambers, was demonstrated to fulfill the requirements of the NSW. Concerning the readout strips, the choice of a ~ 400 μm strip-pitch has been adopted, resulting in about 2M channels for the full NSW system, a large, but still reasonable, number.

Results presented in the following sections are mostly based on tests performed in the summer of 2012 at the H6 beam line at the Super Proton Synchrotron (SPS) at CERN on small size (10 × 10
cm$^2$) prototypes. The results presented here summarize and update previous studies [14], as a result of improved tuning of algorithms and a re-analysis of the data.

The SPS H6 beam line provides a 120 GeV/c pions beam, with a particle rate between 5 and 30 kHz and transverse dimensions of $\sim$2 cm$^2$ on the chambers. Up to eight resistive MM test chambers (T1–T8) were aligned along the beam line. All chambers had an active area of 10x10 cm$^2$, a readout plane with 0.4 mm strip pitch, and a drift gap of 5 mm. The chambers were operated with Ar:CO$_2$ gas mixture (93:7) with different values of the drift and amplification electrical fields. Results are reported for chambers operated at 600 V/cm electrical drift field, with a drift velocity of 47 $\mu$m/ns, and an amplification voltage HV=500 V.

The data acquisition system was based on the Scalable Readout System (SRS) [15] developed by the RD51 Collaboration [16]. The front-end electronics was based on the 128 channel APV25 ASIC [17]. The APV25 will not be employed in the NSW. The front-end ASIC providing the trigger and tracking primitives for both the MM and sTGC will be the VMM [18], currently being produced in its second prototype version.

5.1 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. The spatial resolution for perpendicular tracks was estimated by the difference of the cluster centroid measurements of pairs of MM chambers. The standard deviation from the gaussian fit is divided by $\sqrt{2}$ assuming the same resolution for the two chambers.

An example of such a distribution is shown in figure 9–left panel. A spatial resolution of about 73 $\mu$m was obtained with an average cluster size of 3.2 strips.

The distribution of local inefficiencies has also been studied from the extrapolation of reconstructed particle tracks to the chamber under study. As shown in figure 9–right panel, inefficiencies occur at regular intervals, clearly corresponding to the pillars (300 $\mu$m in diameter, with pitch spacing of 2.5 mm) sustaining the mesh. Three different definitions of efficiencies have been considered: i) hardware inefficiency, accounting for a total of 0.2%, in case no hits at all are found in the chamber (red histogram); ii) cluster inefficiency (1.3%), if no clusters (with minimum 2 hits) are reconstructed in the chamber (blue histogram); iii) software inefficiency (1.9%), in case no clusters are found within 5$\sigma$ from the expected impact point (black histogram). A global inefficiency in the range 1 to 2% is consistent with the partially dead area due to the presence of the pillars. It also must be noted that in case of inclined tracks the inefficiencies are reduced since the signals spread over more strips.

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

For impact angles greater than 10° the cluster charge-centroid method cannot 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 [19]. Measuring the arrival time of the ionized electrons with a time resolution of a few nanoseconds allows reconstructing the position of the ionization process. With the Ar:CO$_2$ (93:7) gas mixture and an electrical drift field of 600 V/cm the drift velocity is 47 $\mu$m/ns and converting the measured time to the position from which the drift
**Figure 9:** Left: Distribution of the difference between charge weighted cluster centroids reconstructed in the test chambers T3 and T4; Right: Inefficiencies from full tracking reconstruction. The peak structure is clearly due to the pillars as discussed in the text. The text also describes the three definitions of the inefficiencies.

**Figure 10:** 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.

electrons originate, it is possible to reconstruct the segment of the track inside the drift gap. In figure 10 the $\mu$TPC concept as well as an example of a track reconstruction within the drift gap of a test chamber, are shown. The best position measurement is at “$x_{\text{half}}$” corresponding to the segment fit at half-gap, where the interpolated position estimate minimizes the error.

The $\mu$TPC method has been successfully applied in many test-beam data. However, a sizable angular bias is observed in the reconstructed values of the segment angles. This systematic effect can be seen in figure 11. In the left panel the angular distribution of the reconstructed $\mu$TPC segments, for a beam angle of 20° with respect to (the normal to) the MM chamber is shown. The peak of the distribution is at about 23°. The effect has been understood to be due to the capacitive induction of the signal on neighboring strips (the first and last strips in the cluster playing the major role) and it is well reproduced by simulations (LTSpice, ANSOFT Maxwell). In the central panel of figure 11 the measured and simulated reconstructed angles are reported for different inclinations of the beam, up to 40°. The simulations are in very good agreement with the data.
Figure 11: The left plot shows the reconstruction of the track angle for an incident beam at 20°. A systematic bias in the reconstruction of the angle with the \( \mu \)TPC method is observed. The bias to larger angles decreases with the track angle (central panel). The effect, understood to be mainly due to the capacitive induction on the first and last strips, is well reproduced by simulations. The sketch on the right explains the mechanism as reported in the text.

A sketch of the mechanism assumed to be responsible of the bias, is shown in the right panel of figure 11. Induced signals in the first and last strips of a cluster have same arrival times of their neighbors, and in the \( \mu \)TPC reconstruction the effect is a tilt of the original track towards larger angles. Recent developments of the algorithms have improved the performance of the \( \mu \)TPC segment reconstruction. A correction procedure, based on the identification of the strip signals by induced charge (based on the charge ratios) and subsequent weighting or suppression of the first and/or last strips in the cluster has been implemented. After correction, a significant reduction of the angle bias and an improvement in the \( \mu \)TPC spatial resolution is observed.

In figure 12 the results of the resolutions obtained with the \( \mu \)TPC method without and with correction are summarized (open red and full red data points, respectively). As expected the correction has larger effects at small angles. With such a correction, the use of the \( \mu \)TPC method alone guarantees a resolution of 100 \( \mu \)m or better in the full angular interval of the NSW (8°–32°). The spatial resolutions have also been measured using the cluster centroid method. Results are reported with blue symbols in the figure. As expected, the cluster centroid behaves better at small angles (small cluster size) while the \( \mu \)TPC method reaches best performance for larger angles. Combination of the cluster centroid and \( \mu \)TPC methods can be adopted to further improve the resolution (as shown in [2, 14])

6 Conclusions

After six years of intensive R&D on ATLAS Micromegas, major breakthroughs and many improvements have been achieved. These efforts made it possible for the Micromegas to be approved as one of the technologies for the NSW. Further developments and optimizations on several aspects (layout, design, construction, operations, and analysis) have made the MM a mature technology. This will allow for a safe operation of ATLAS with high performance after their planned installation in 2018/19 and beyond for the high luminosity era of the LHC following the 2023/24 upgrades.
In the last two years the efforts have been aimed at the definition and finalization of the layout and design of large MM quadruplets ($\sim 2–3 \text{ m}^2$), as well as at the definition of the procedures for the construction and the design of the necessary tooling. This activity has always run in parallel with activities of construction and tests of a series of prototypes (mechanical and operational). Such a huge effort has made the project, started more than six years ago, to be ready now to enter in the production phase with the next milestone being the construction in 2015 of the Modules-0, final full size prototypes.

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References

[1] The ATLAS collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, 2008 JINST 3 S08003.
[2] ATLAS collaboration, New Small Wheel Technical Design Report, CERN-LHCC-2013-006 (2013).
[3] Y. Giomataris, P. Rebougeard, J.P. Robert and G. Charpak, Micromegas: A High granularity position sensitive gaseous detector for high particle flux environments, Nucl. Instrum. Meth. A 376 (1996) 29.
[4] G. Iakovidis, Research and Development in Micromegas Detector for the ATLAS Upgrade, CERN-THESIS-2014-148 (2014).
[5] C. Bernet et al., The 40 cm × 40 cm gaseous microstrip detector Micromegas for the high-luminosity COMPASS experiment at CERN, Nucl. Instrum. Meth. A 536 (2005) 61.

[6] T2K ND280 TPC collaboration, N. Abgrall et al., Time Projection Chambers for the T2K Near Detectors, Nucl. Instrum. Meth. A 637 (2011) 25 [arXiv:1012.0865].

[7] I. Giomataris et al., Micromegas in a bulk, Nucl. Instrum. Meth. A 560 (2006) 405 [physics/0501003].

[8] H. Raether, Entwicklung der Elektronen in den Funkenkanal, Z. Phys. 112 (1939) 464; H. Raether, Electron Avalanches and Breakdown in Gases, Butterworths London (1964).

[9] J. Wotschack et al., The development of large-area micromegas detectors for the ATLAS upgrade, Mod. Phys. Lett. A 28 (2013) 1340020.

[10] T. Alexopoulos et al., A spark-resistant bulk-Micromegas chamber for high-rate applications, Nucl. Instrum. Meth. A 640 (2011) 110.

[11] M. Bianco et al., Construction of a large-size four plane micromegas detector, to be published in Proceedings of Technology and Instrumentation in Particle Physics ‘14 - TIPP ’14.

[12] A. Ochi et al., Carbon Sputtering Technology for MPGD Detectors, to be published in Proceedings of Technology and Instrumentation in Particle Physics ‘14 - TIPP ’14.

[13] K. Nikolopoulos, Discovery Potential for the Standard Model Higgs → ZZ(*) → 4l and Contributions to Muon Detection in ATLAS, CERN-THESIS-2010-113 (2010).

[14] MAMMA collaboration, M. Iodice, Performance studies of Micromegas for the ATLAS experiment, 2014 JINST 9 C01017; ATLAS collaboration, C. Bini, Study of the performance of the Micromegas chambers for the ATLAS muon spectrometer upgrade, 2014 JINST 9 C02032.

[15] S. Martoiu, H. Muller and J. Toledo, Front-end electronics for the Scalable Readout System of RD51, IEEE Nucl. Sci. Symp. Med. Imag. Conf. (2011) 2036.

[16] The RD51 collaboration, R&D Proposal Development of Micro-Pattern Gas Detector Technologies, CERN-LHCC-2008-011 (2008).

[17] M.J. French et al., Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker, Nucl. Instrum. Meth. A 466 (2001) 359.

[18] G. De Geronimo et al., VMM1 - An ASIC for Micropattern Detectors, IEEE Trans. Nucl. Sci. 60 (2013) 2314.

[19] T. Alexopoulos et al., Development of large size Micromegas detector for the upgrade of the ATLAS muon system, Nucl. Instrum. Meth. A 617 (2010) 161.