Study of the performance of the Micromegas chambers for the ATLAS Muon Spectrometer Upgrade

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Abstract—Micromegas (MICRO MESH Gaseous Structure) chambers are Micro-Pattern Gaseous Detectors designed to provide a high spatial resolution in highly irradiated environments. In 2007 an ambitious long-term R&D activity was started in the context of the ATLAS experiment, at CERN: the Muon ATLAS Micromegas Activity (MAMMA). After years of tests on prototypes and technology breakthroughs, Micromegas chambers were chosen as tracking detectors for an upgrade of the ATLAS Muon Spectrometer. These novel detectors will be installed in 2018 and 2019 during the second long shutdown of the Large Hadron Collider, and will serve as precision detectors in the innermost part of the ATLAS Muon Spectrometer. Eight layers of Micromegas modules of unprecedented size, up to 3 m², will cover a surface of 150 m² for a total active area of about 1200 m². This upgrade will be crucial to ensure high quality performance for the ATLAS Muon Spectrometer in view of the third run of the Large Hadron Collider and of the High-Luminosity LHC, as the luminosity of the collider will significantly exceed the one the machine was originally designed for. To meet the demanding performance requirements of the ATLAS Muon Spectrometer, Micromegas chambers are required to achieve a single plane resolution of 100 μm with an efficiency better than 95% for tracks up to an inclination of 32° and in a magnetic field up to 0.3 T. A thorough test program on Micromegas prototypes has been performed during the past years and is still ongoing, with the goal of driving the design of the ATLAS Micromegas chambers and of fully characterising and certifying their performance. These tests produced excellent results, proving that the prototypes fully meet the performance requirements. The methodology and the results of this activity will be reviewed in this paper.

I. INTRODUCTION

Micromegas (MM), or MICRO MESH Gaseous Structure, is an innovative design concept for Micro-Pattern Gaseous Detectors, first introduced during the 1990s [1]. These high-resolution, radiation-hard detectors have been chosen for the upgrade of the Muon Spectrometer [2] of the ATLAS detector [3] which will take place in 2018 and 2019, during the second long shutdown of the Large Hadron Collider (LHC), in view of the third run of the LHC and of the High-Luminosity LHC, where the peak luminosity of the collider is foreseen to reach up to $7 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [4]. Such a high luminosity is a great opportunity for physics searches and measurements, but requires a huge upgrade effort for

the experiments working at the LHC in order to cope with the increase of the radiation background level. Among other upgrade activities, the complete replacement of the innermost part (the so-called Small Wheels) of the endcaps of the ATLAS Muon Spectrometer will become necessary. Two New Small Wheels (NSW) will be therefore installed in the endcaps of the ATLAS Muon Spectrometer, and will exploit MM and small-strip Thin Gap Chambers (sTGC) detectors [2].

A. The New Small Wheel

In Figure 1 the layout of the NSW is shown: it will be composed of 16 sectors, 8 large sectors and 8 small ones. Each sector will have modules of sTGC and of MM detectors, arranged in the order sTGC-MM-MM-sTGC, each module being a quadruplet of detector layers. Therefore, 16 points will be measured for each track in the NSW. MM will be mainly used for tracking, while sTGC will be mainly exploited for the trigger system. An overall active area of about 1200 m² will be provided by each one of the two technologies employed in the Muon Spectrometer. Both technologies will be used for tracking and for the trigger, therefore ensuring a redundant and flexible detector system.

Fig. 1. Layout of an assembled New Small Wheel. A large and a small Micromegas sector are highlighted in the figure, where in reality they would be placed between two sTGC quadruplets and will therefore not be visible.

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One of the aims of the NSW is to ensure high-quality operation for the muon spectrometer in a highly-irradiated background. The hit rate in the ATLAS muon detectors has been measured to linearly increase with the luminosity, as expected. In Figure 2 the degradation of the performance of the currently used precision detectors, Monitored Drift Tube (MDT) chambers, is shown: beyond the design luminosity of the LHC, the efficiency of the MDTs suffers a significant degradation.

Fig. 2. Efficiency of a single tube and of a complete chamber for the MDT technology which is currently used in the ATLAS Muon Spectrometer, as a function of the hit rate due to the environmental background.

Another crucial goal of the NSW is to improve the precision of the current muon trigger system in ATLAS. The increase of the radiation background expected for the 3rd and 4th LHC runs will inevitably lead to a higher rate of trigger signals produced by fake tracks. An increase of momentum threshold would ensure a reduction of the trigger rate to an acceptable level but would cause a loss of efficiency for physics events. To maintain the same efficiency with a trigger rate within the acceptable bandwidth, the NSW will provide a tighter selection of tracks pointing to the interaction vertex. This will significantly reduce the trigger rate produced by forward tracks in the muon spectrometer, as shown in Figure 3.

B. The Micromegas technology

The working principle of MM chambers, with the layout chosen for the ATLAS NSW, is shown in Figure 4. A thin metallic micro-mesh (stainless steel, 325 lines/inch) is placed between two planar electrodes (PCB boards), held by pillars with a pitch of a few millimeters. The detector is filled with a 93:7 Ar:CO₂ gas mixture. The *drift* electrode, with a -300 V voltage applied, and the mesh, which is grounded, define the so-called *drift region*, where the low electric field leads ionisation electrons produced by ionising particles towards the mesh. Following the field lines, the electrons enter in the very thin *amplification region* between the mesh and the *readout electrode*, where a 540-580 V voltage is applied. Due to the very high electric field in the amplification region the drifting electrons produce avalanches, with a gain of the order of 10⁴. The signal produced by these avalanches is then read with readout strips. The thin amplification region allows for a fast evacuation of ions, which occurs approximately in 100 ns: for

Fig. 3. Rate of the level-1 ATLAS muon trigger predicted for a luminosity of $3 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with the settings used during the Run-1 acquisition in 2012 (black line), with conditions and settings expected for late Run-2 (blue line), and with these conditions and settings with the addition of the New Small Wheel system (red line).

Fig. 4. Working principle of the ATLAS Micromegas chamber.

this reason MM can operate in highly irradiated environments. One of the most significant innovations introduced during the R&D of MM chambers for the ATLAS detector is the usage of resistive strips on the readout electrode, with the signal read by readout strips capacitively coupled to the resistive ones [5]. This configuration significantly reduces the performance degradation due to discharges in the detector. A very interesting feature of MM detectors is that, by measuring the time of arrival of the signal on the readout strips and knowing the drift velocity of electrons in the gas mixture, the position of the primary ionisation can be reconstructed for each strip, thus allowing for track reconstruction in a single detector plane. This working mode is described in detail in Section II-A.

C. Challenges for Micromegas chambers in the New Small Wheel

MM chambers for the NSW project will be modules composed of 4 MM layers with a very large area, up to 3 m². This unprecedented size represents an important challenge in the development of a new construction technique, with a required precision of about 30 μm on the positioning of detector elements for the precision coordinate measurement,

in order to achieve the requirements of muon reconstruction in the NSW. After installation in the NSW the alignment of the chambers will be guaranteed by an optical system [2] and, if needed, improved by dedicated data acquired with no magnetic field. The requirement for the ATLAS Muon Spectrometer is to achieve a relative momentum resolution of 15% for muons with a transverse momentum of 1 TeV and a reconstruction efficiency close to 100%. This requires a resolution on the precision coordinate at the level of $100 \mu\text{m}$ and an efficiency of at least 95% per MM plane, which will operate in a magnetic field up to 0.3 T and with tracks with an inclination between 8° and 32° with respect to the chamber plane. Furthermore, a resolution of $\approx 2.5 \text{ mm}$ is required for the position reconstruction in the second coordinate (i.e. the coordinate perpendicular to the precision one), in order to be able to correctly match reconstructed muon tracks with those reconstructed by the ATLAS muon trigger system. MM chambers in the NSW will have readout strips in one view only. The layout for a MM chamber providing also the measurement of the second coordinate is discussed in Section III.

II. PERFORMANCE STUDIES FOR SMALL MICROMEGAS PROTOTYPES

In the context of the R&D effort of the MM chambers for the ATLAS detector, many performance studies have been carried out and are still ongoing. Several MM chamber prototypes have been studied at test-beam and irradiation facilities, in order to fully characterise their performance, to optimize the design of the detectors, to define their optimal working point and to develop reconstruction strategies and software. Prototypes used for tests presented in this section, which is mostly focused on test-beam studies, are resistive MM chambers with an active area of $10 \times 10 \text{ cm}^2$, constructed with the *bulk* technology [6], i.e. with the micro-mesh integrated in the structure of the readout PCB panel. Prototypes with different layouts have been tested: *T* (one-view readout strips with a pitch of 0.4 mm and pillars every 2.5 mm), *TQF* (one-view readout strips with a pitch of 0.4 mm and pillars every 5 mm) and *Tmm* (two-views readout, with strips in x and in y direction, with a pitch of 0.25 mm and pillars every 2.5 mm) chambers. Figure 5 shows the setup for a test beam study on 8 *T* chambers organised in 4 doublets. During the last year new prototypes, with a design close to the one that will be used for the MM chambers in the NSW, have been built and tested; this is reported in Section III.

A. Single-strip response and track reconstruction

For all tests presented in this report 128-channel APV25 front-end electronics cards [7] read by the Scalable Readout System [8] have been used to read signals from the readout strips. An example of a single-channel signal is shown in Figure 6: the signal is sampled in 25 ns bins. With a fit to an inverse Fermi-Dirac function defined as

$$FD(t) = \frac{A}{1 + e^{-(t-t_{FD})/B}} + C \quad (1)$$

Fig. 5. Test beam studies on 8 *T* chambers organised in 4 doublets with adjustable inclination with respect to the beam.

the time of arrival of the signal on the strip can be measured as the inflection point t_{FD} of the curve. The resolution on the time measurement obtained with this method has been measured on chambers equipped with APV25 electronics to be of the order of 12 ns for the earliest hit in a chamber for track with an inclination of 30 degrees [2]. Charge induced on the strip is measured as the maximum of the distribution, subtracted by the baseline level C .

Fig. 6. Example of a single-strip signal read by APV25 electronics. Fit to the rising part of the distribution is performed using equation 1.

For each strip i a measurement of charge q_i and time t_i is therefore performed. Clusters of neighbouring strips above the single-channel electronics threshold are then formed by dedicated clustering algorithms. The simplest hit reconstruction that can be performed is by using the *centroid* method, where the hit position is calculated as the average position of strips in a cluster weighted by their charge measurements:

$$x = \frac{\sum_i x_i q_i}{\sum_i q_i}, \quad (2)$$

x_i being the positions of the strips. This method performs well for tracks approximately perpendicular to the chamber. Another possibility is to exploit the time measurement from the strips to measure for each of them the position of the primary ionisation as $z_i = t_i \cdot v_{drift}$, where v_{drift} is the drift velocity of electrons in the gas mixture, which is approximately $50 \mu\text{m/ns}$ with the mixture and conditions used for

the tests presented in this report. In this way a proper track reconstruction can be performed: this is the so-called μ TPC *method*. The hit position on the detector can be defined as the x coordinate of the reconstructed track at half gap, which is called x_{half} . The angle of incidence $\theta_{\mu\text{TPC}}$ can also be measured with the track fit. An example of centroid and μ TPC reconstruction is shown in Figure 7.

Fig. 7. Example of hit reconstruction in a MM chamber with readout strips with a 400 μm pitch on a track inclined by 30°. Top, centroid and μ TPC reconstruction for a cluster of strips (see text). Bottom, charge read by strips in the same cluster as a function of their position on the readout plane x .

The performance of μ TPC reconstruction can be optimized with dedicated reconstruction techniques. For example, the Hough transform pattern recognition technique was applied with success during the analysis of test beam data to correctly reconstruct events with multiple tracks [2]. Furthermore, it was observed that, due to capacitive coupling between the strips, the first and last strips in a cluster may have a signal which is only coming from the coupling with their neighbours. It was determined in simulation that charge-sharing between neighbouring strips is at the 10% level. This effect may lead to a bias in μ TPC reconstruction. A dedicated filtering technique was thus developed to discard strips on the edge of a cluster with a low deposited charge when performing the μ TPC reconstruction.

The position assignment of the charge on the strips was also studied in simulated data. The resolution on the position of the charge deposited on the strips, which is assumed to be the position along the readout plane of the primary ionisation, is driven by the strip pitch. By default it is assumed during the reconstruction that the charge is deposited in the middle of a strip. This assumption was studied in simulation, and found to be correct only for strips in the middle of a cluster, while for strips at the edge of a cluster the assumption was observed to introduce a bias in the reconstruction. A dedicated

correction for this bias was therefore developed on simulated data and then tested with real data. The position assignment of hits at the edge of a cluster is corrected by taking into account the ratio of the charge of the nearby strips. Figure 8 shows the mean angle of tracks reconstructed with the μ TPC technique, as a function of the incident angle of the tracks, with the default reconstruction, and with the application of the filtering and correction techniques described above: a significant improvement can be observed.

Fig. 8. Mean angle of tracks reconstructed with the μ TPC technique as a function of the incident angle of the tracks, with the default reconstruction (red) and with the application of the filtering and correction techniques described in the text (blue). Data were acquired at the SPS/H4 test beam facility at CERN with a 150 GeV/c μ/π beam.

B. Efficiency

The reconstruction efficiency of Micromegas chambers has been measured using data collected at test-beam facilities. For this purpose several MM chambers are used as a telescope to reconstruct a track, which is then extrapolated to another chamber, to check whether a hit is reconstructed in that chamber or not. Results are shown for a T and a TQF chamber in Figure 9 for perpendicular tracks, and in Figure 10 for tracks with a 30° inclination. The data were acquired at the PS/T10 test beam facility at CERN with a 6 GeV/c π^+/p beam. In both cases efficiency is very high. For perpendicular tracks localised inefficiencies due to mesh pillars have a higher impact, as expected, but the overall efficiency is at 98% level. For inclined tracks the reconstruction efficiency is nearly 100%.

C. Resolution

The spatial resolution of the small prototypes has been measured using test beam data. The resolution can be measured from the width of the distribution of the position difference of the hits reconstructed in two chambers. To minimise the impact of the angular divergence of the beam, chambers included in a doublet in the test beam setup, separated by just few centimeters, are used for this measurement. Figure 11 shows such a distribution obtained with T chambers on perpendicular

Fig. 9. Efficiency measured for a *TQF* (left) and a *T* (right) chamber on a perpendicular π^+/p beam with a momentum of 6 GeV/c. The localised inefficiency due to mesh-pillars, which have a pitch of 5 mm for *TQF* and 2.5 mm for *T* chambers, are visible.

Fig. 10. Efficiency measured for a *TQF* (left) and a *T* (right) chamber on tracks inclined by 30° acquired using a π^+/p beam with a momentum of 6 GeV/c.

tracks: a fit to a double-Gaussian function, to take into account the tails of the distribution, is performed. The inner gaussian has a standard deviation of $68 \mu\text{m}$, while the weighted average of the standard deviations of the two Gaussian functions is $89 \mu\text{m}$. The tails described by the widest gaussian function belong to events where the μTPC reconstruction is affected by the presence of spurious hits in the cluster. These effects can be significantly reduced with optimized reconstruction techniques which are currently under study.

With this method the resolution has been measured for centroid and μTPC reconstruction for *T* prototypes as a function of the inclination of the tracks, as shown in Figure 12. As expected, the centroid method is best performing for perpendicular tracks, while the μTPC method can be used for inclined tracks. Positions reconstructed with the μTPC and centroid methods can be averaged. The average is weighted by a function of the number of hits in the cluster. This results in a flat resolution at the level of $100 \mu\text{m}$ can be obtained for tracks with all inclinations, and in particular for tracks between 8° and 32° , the relevant range for the NSW.

Results presented in this section are relative to the MM prototypes described above equipped with APV25 electronics and for the working point (voltages applied to the chamber, gas mixture, etc.) aforementioned. Chambers in the NSW will be equipped with VMM ASIC front-end chips [2], currently

Fig. 11. Distribution of the difference of the hit position reconstructed with the centroid method with two *T* chambers divided by $\sqrt{2}$ as obtained on test beam data. The data were acquired at the SPS/H4 test beam facility with a 150 GeV/c μ/π beam. A fit with a double Gaussian function is performed.

Fig. 12. Resolution measured for *T* chambers on test beam data for the centroid and the μTPC reconstruction methods as a function of the angle of inclination of the tracks. The data were acquired at the SPS/H4 test beam facility with a 150 GeV/c μ/π beam.

under development, and the faster electronics will be beneficial for the MM performance. Furthermore, the design and working points for chambers in the NSW are severely constrained by the working conditions, e.g. by the 25 ns LHC bunch crossing. Significant improvements on the resolution can be expected for other applications of the MM technology, when going to different working points, e.g. with modifications to the gap size, the drift and amplification electric fields and to the gas mixture.

D. Performance inside a magnetic field

MM chambers will operate immersed in a magnetic field up to 0.3 T in the NSW. The impact of the magnetic field on track reconstruction strongly depends on the inclination of the incident tracks. This is shown in Figure 13: given an external magnetic field, for a “critical” angle of inclination the

ionisation electrons are subject to a *focusing* effect due to the Lorentz angle, thus resulting in clusters with fewer strips. In the opposite case, electrons are subject to a *defocusing* effect.

Fig. 13. Focusing (left) and defocusing (right) effects for a MM chamber inside a magnetic field, as described in the text.

This effect has been studied and verified on real data, as reported in [2]. The degradation of the performance of the μ TPC reconstruction due to the focusing effect can be compensated by the improvement of the resolution of the centroid reconstruction in that case. A proper combination of the two reconstruction techniques allows to have a good spatial reconstruction at all angles.

Performance tests for chambers inside a magnetic field currently are one of the most active topics in the MM R&D activity. Measurements of the drift velocity of the gas and of the Lorentz angle for these chambers are being performed and compared with simulations. Preliminary results show good agreement for these measurements. Furthermore, the reconstruction techniques and software available for the MM chambers are being developed and optimized on test beam data for chambers in a magnetic field.

E. Radiation hardness studies

Radiation hardness studies have been performed at irradiation facilities with α particles, neutrons, x-rays and γ -rays on the small prototypes, with irradiation levels corresponding to many years of running at the high luminosity LHC. Figure 14 shows the mesh current measured on a MM chambers exposed to x-rays for a total dose of 230 mC/cm^2 , where a value of 32 mC/cm^2 is estimated for 5 years at the high luminosity LHC. No significant discrepancy is found with respect to a non-irradiated reference detector.

Fig. 14. Mesh current measured in a $10 \times 10 \text{ cm}^2$ MM prototype irradiated with x-rays and compared with that measured in a reference, non-irradiated detector. The total irradiation dose is 230 mC/cm^2 , corresponding to 5 years of operations at the high luminosity LHC with a safety factor above 7.

Figure 15 shows a similar measurement performed on a detector irradiated by thermal neutrons with a flux of $3 \cdot 10^{12} \text{ n/hour} \cdot \text{cm}^2$, showing also in this case extremely stable performance.

Fig. 15. Mesh current measured in a $10 \times 10 \text{ cm}^2$ MM prototype irradiated by a $3 \cdot 10^{12} \text{ n/hour} \cdot \text{cm}^2$ flux of thermal neutrons. The total exposure is equivalent to 5 years of operations at the high luminosity LHC with a safety factor above 10.

All studies performed confirmed the extremely high radiation tolerance of MM chambers and showed no hints of detector ageing for doses expected at the high luminosity LHC.

III. FIRST 4-LAYERS MICROMEGAS PROTOTYPES

In 2014 two large-size resistive MM prototypes, consisting of 4 MM-layers each, were constructed and studied on test beam data. These chambers, named *MMSW*, have a layout which is very close to that of MM chambers that will be installed in the NSW, and a full characterisation of their performance on real data is therefore a crucial step in the R&D process for the upgrade of the ATLAS Muon Spectrometer. In this section the layout of the chambers and the performance studies performed with them will be described. One of these chambers has been installed in the ATLAS cavern and will acquire data during the second run of the LHC, allowing for a test in working conditions.

A. Layout of the MMSW chambers

Figure 16 shows the layout and a picture of a MMSW chamber. A MMSW is composed of 5 panels, which constitute 4 MM detector layers, organised in two doublets of two back-to-back layers. Layers in the first doublet have readout strips perpendicular to the precision coordinate (*eta strips*), while layers in the second doublet have *stereo strips*, inclined by $+1.5^\circ$ (-1.5°) in the first (second) layer with respect to that of the first doublet. With this configuration hit reconstruction is possible in the second coordinate, with a $\approx 2.5 \text{ mm}$ resolution, as required by the ATLAS trigger system.

Fig. 16. (Left) layout and (right) picture of a MMSW chamber.

The two chambers, which have an active area of $1.2 \times 0.5 \text{ m}^2$, couldn't be built using the bulk technology as

for the small prototypes, because this technique is limited by PCB manufacturing to lengths up to approximately 60 cm. The so-called *floating mesh* technique was therefore used, with the mesh integrated in the drift panel, as shown in Figure 17.

Fig. 17. Sketch of the floating mesh construction technique, with the mesh first integrated in the drift panel (left) and then positioned on top of the mesh pillars (right) during the assembly procedure.

B. Performance of the MMSW chambers

The resolution and efficiency of the MMSW chambers have been studied with a dedicated test beam at CERN, using a beam of protons and pions with a momentum of 6-9 GeV/c. The methods used for the reconstruction and the analysis are the same as already described in Section II for the small prototypes. A reconstruction efficiency of approximately 98% was measured for each MM-layer of the chamber, well within the specifications. Figure 18 shows a measurement of perpendicular tracks of the per-layer resolution of the precision coordinate measured with the first two layers of a MMSW chamber, and of the second coordinate measured with the two stereo-layers of a MMSW chambers. In both cases the measured resolutions satisfy the requirements of the ATLAS NSW.

Fig. 18. (Left) difference between hit positions measured in the first and second layers (eta-layers) of a MMSW chamber. (Right) difference, divided by $\sqrt{2}$, between the second coordinate hit reconstructed in the MMSW chamber using the stereo-layers and the second coordinate hit reconstructed in one reference chamber at a distance of 20 cm from the first plane of the MMSW. Both measurements have been performed on perpendicular tracks with a beam of protons and pions with a momentum of 6-9 GeV/c at the test beam facility PS/T9 at CERN.

IV. CONCLUSION

The R&D activity for detectors with a novel design based on the Micromegas technology for the New Small Wheel upgrade project of the ATLAS Muon spectrometer started in 2007. The development of the construction technique of Micromegas chambers with an unprecedented size of up to 3 m² and the demanding requirements for the detector performance, in

order to cope with the outstanding physics objectives of the ATLAS experiment, represent great challenges. Micromegas chambers are required to provide a reconstruction with a per-layer resolution of 100 μm and a per-layer efficiency of at least 95%, for incident tracks with an inclination angle between 8° and 32° and inside a magnetic field up to 0.3 T.

The performance of the Micromegas chambers has been studied at test beam and irradiation facilities on small prototypes, with a 10×10 cm² active area. These detectors showed a resolution and a reconstruction efficiency well within specifications, and no significant radiation damage or ageing effects in conditions corresponding to many years of running at the high luminosity LHC. Furthermore, optimized reconstruction techniques developed in the context of the test beam studies allowed for a significant improvement of the performance of the Micromegas chambers.

In 2014 two new large-area prototypes have been built and tested. These chambers, named MMSW, have an active area of 1.2×0.5 m² and are composed of 4 Micromegas layers. The reconstruction efficiency and the resolution for the precision and the second coordinate have been measured on test beam data and found to fully satisfy the performance requirements for the detector. One MMSW chamber has been installed in the cavern of the ATLAS detector in view of the second run at the LHC, and will provide crucial data on the performance of a chamber in working conditions at the LHC.

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