Design and Construction of Large Size Micromegas Chambers for the ATLAS Upgrade of the Muon Spectrometer

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Abstract—Large area Micromegas detectors will be employed for the first time in high-energy physics experiments. A total surface area of about 150 m$^2$ of the forward regions (pseudo-rapidity coverage – 1.3 $< |\eta| < 2.7$) of the ATLAS detector at LHC will be equipped with 8-layer Micromegas modules. Each module extends over a surface from 2 to 3 m$^2$ for a total active area of 1200 m$^2$. Together with the small strip 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. In order to achieve a 15% transverse momentum resolution for 1 TeV muons, in addition to an excellent intrinsic position resolution, the mechanical precision of each plane of the assembled module must be $30 \mu m$ along the precision coordinate and $80 \mu m$ perpendicular to the chamber. All readout planes are segmented into strips with a pitch of $450 \mu m$ for a total of 8192 strips per plane and more than 2 million channels for the NSW. In two of the four planes the strips are inclined by $1.5^\circ$ and provide a measurement of the second coordinate. The design and construction procedure of the Micromegas modules are presented, as well as the design for the assembly of modules onto the New Small Wheel. Emphasis is given on the methods developed to achieve the challenging mechanical precision. Measurements of deformation on chamber prototypes as a function of thermal gradients, gas over-pressure and internal stress (mesh tension and module fixation on supports) are also shown and compared to simulation. These tests were essential in the development of the final design in order to minimize the effects of deformations. During installation and operation all deformations and relative misalignments will be monitored through an optical alignment system and compensated in the tracking software.

I. INTRODUCTION

With the increase of luminosity around $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ foreseen after the upgrade of the Large Hadron Collider (LHC) [1] in 2018/2019, the number of tracks and the background level will increase proportionally, especially in the forward regions. The expected rate in the innermost endcap region of the ATLAS [2] muon spectrometer (Small Wheel) is around 15 kHz/cm$^2$. In these conditions of background, the muon trigger is affected by fake triggers and the efficiency of current detectors drops significantly. For these reasons, the inner endcap regions of the muon spectrometer will be replaced by a combination of large Micromegas (MM) detectors [3] and small strip Thin Gap Chamber (sTGC) [4] detectors: the New Small Wheel (NSW) [5].

II. THE MICROMEGAS DETECTORS FOR THE NSW

The NSW will be equipped with multi-layers of two fully redundant types of technology:

- the sTGC, which are the primary trigger detectors, providing beam crossing identification with an adequate time resolution but also a good online spatial resolution and an angle resolution better than 1 mrad for NSW track vectors.
- the MM detectors, dedicated to precision tracking, with spatial resolution better than 100 $\mu m$, independent from the incident angle and good track separation (0.45 mm readout granularity).

Both these technologies will work with a common front-end ASIC, the VMM [6] (under development at BNL1). Detectors must be robust and redundant since the NSW will operate for more than 15 years starting from 2019.

Micromegas stands for MICRO-MEsh GAseous Structure. They are position sensitive gaseous detectors, working in proportional mode, with a parallel plates structure. The main part of these detectors is a thin metallic mesh supported by 128 $\mu m$ high pillars, dividing the gas volume in two asymmetric gaps (see figure 1):

![Fig. 1. Schematic view of a Micromegas detector](image)

- the conversion gap of 5 mm where the energy deposited by the incident muon releases primary electrons.

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• the amplification gap of 128 \( \mu \text{m} \) where an electronic avalanche occurs.

Micromegas detectors specifications are summarized in table I. The highest rate in the inner regions of the NSW will be around 15 kHz/cm\(^2\) and so MM detectors must demonstrate a high rate capability. To avoid sparks at high rate and resulting dead time, a resistive anode plane deposited on a Kapton foil is glued and capacitively coupled to the detection plane of strips (figure 1). As shown in figure 2, voltage drops due to sparks, and thus inefficiency of the detector, disappear completely with a resistive MM [7].

\[
\text{TABLE I} \\
\begin{array}{|c|c|}
\hline
\text{Requirement} & \text{Specification} \\
\hline
\text{Total area: } 1200 \text{ m}^2 & \text{Large area detector} \\
\text{Rate up to } 15 \text{ kHz/cm}^2 & \text{High rate capability} \\
\text{n, \( \gamma \) and hadron background} & \text{No aging effect observed} \\
\text{Tracking precision independent} & \text{Position resolution } \leq 100 \mu\text{m} \\
\text{from incident angle} & \text{Angular resolution } (\sim 1 \text{ mrad for a multilayer}) \\
\text{Trigger capability} & \text{Angular resolution} \\
\hline
\end{array}
\]

The total MM area in the NSW is around 1200 m\(^2\) and for this reason, the capability to build large area MM detector has been studied in the past years by the MAMMA\(^2\) collaboration [8]. One of the main problems to solve was how to obtain a 128 microns gap on such large areas (2 to 3 m\(^2\) per module), which is crucial for the efficiency and the homogeneity of response of the detector. The solution that has finally been chosen is to separate the detector in two parts, on one hand the drift electrode with the mesh stretched and glued on it and on the other hand the plane of strips with the pillars. Then the detector is closed as described in the figure 3. Planarity and stiffness of the panels must be very good to keep the amplification gap at 128 microns. More details about the mechanics will be given in section IV.

Position resolution for resistive Micromegas has been studied thoroughly in several test beams and results obtained for different incident angles are presented in figure 4. Two different methods are used:

• centroid method – the position is given by the calculation of the strips centroid weighted by the signal amplitude of each strips.

• micro-Time Projection Chamber (\( \mu \)TPC) method – the constant drift velocity of the electrons in the drift gap for a given drift electric field is used, together with time information, to calculate the position of the primary electrons in the gas volume and then reconstruct a track-segment of the incident muon along the 5 mm (see figure 1).

\[\text{\textsuperscript{2}Muon ATLAS MicroMegas Activity}\]
The centroid calculation gives good results for small angles but the accuracy decreases rapidly for larger track angles. Position is calculated using the $\mu$TPC method for larger angles (up to $32^\circ$) since the performance of this method improves with increasing cluster size. $\mu$TPC method can be furthermore refined applying corrections for capacitive coupling between strips, fine tuning of the primary-electrons position, or implement pattern recognition techniques for track identification (Hough transform) – see ref. [9] for more details.

Fig. 4. Position resolution obtained in test beam for different incident angles (impact angle in NSW between 8 and $32^\circ$) using centroid and $\mu$TPC methods, with and without corrections.

The detectors will operate for several years and so aging is a major concern that has been studied in different radiation environments. No aging evidence has been observed in prototype detectors irradiated in high flux of thermal neutrons, gamma rays or in long term operation in X-ray beam [10].

III. DESIGN OF THE NSW

The NSW sub-detector is made of two wheels of 10 meters in diameter. Each wheel is made of 16 sectors, 8 large and 8 small, that are fixed on a circular mechanical structure. The large sectors cover an area from radius 92 to 465 cm and are located on the opposite side from the interaction point, while the small sectors cover an area from radius 90 to 445 cm and are facing the IP (see figure 5).

Each sector is in fact a multilayer made of 8 layers of MM and 8 layers of sTGC mounted on the two sides of a spacer frame (4 sTGC + 4 MM + spacer frame + 4MM + 4sTGC). Each Micromegas sector is divided into two stations, inner and outer, each made of 2 modules so that there are 4 module types: Small Module 1 and 2 (SM1 and SM2); Large Module 1 and 2 (LM1 and LM2) - see figure 6.

Each module is about $3 \text{ m}^2$ for the large and $2 \text{ m}^2$ for the small, and is a quadruplet made of four detection layers (figure 7).

Fig. 5. View of the two sides of the NSW where the feet of the mechanical structure are also visible.

Fig. 6. Exploded view of a NSW sector.

Fig. 7. Dimensions of large and small sectors divided in inner and outer modules. Readout planes are made of 8 PCB in total, with a width of 430 mm for small sectors and 450 mm for large sectors.
The readout planes are made of 3 or 5 printed circuit boards (PCB), respectively for the inner and outer modules, assembled together back-to-back on a light mechanical structure (aluminum frames and honeycomb) to form a readout panel. The same design is used for the drift panels and one module is made of 5 panels (2 readout, 2 drift and 1 central drift, as shown in figure 8. All readout planes are segmented into strips with a pitch of 400 microns for a total of 5120 and 3072 strips respectively for inner and outer readout planes (resulting in more than 2 million channels for the entire NSW).

Finally each quadruplet is made with one ‘η’ readout panel (2 η-detector planes), used to measure two pseudorapidity (η) coordinates, and one ‘stereo’ panel (2 stereo detection planes, where strips have an angle of ±1.5°) to measure two η coordinates but also reconstruct the second coordinate with few mm resolution (see figure 9).

The 32 modules of 4 different types will be constructed in four different laboratory consortia:
- SM1: INFN, Italy
- SM2: Germany
- LM1: Saclay, France
- LM2: Dubna, Russia - Thessaloniki, Greece - CERN

![Fig. 9. Description of the four different readout planes](image)

Fig. 9. Description of the four different readout planes

**IV. MICROMEGAS MODULE CONSTRUCTION**

The mechanical requirements to be able to reconstruct a muon momentum with a resolution of 15% at 1 TeV in ATLAS are the following:
- precision of 30 microns r.m.s. for the strip position in η (precision coordinate)
- precision of 80 microns r.m.s. for the strip position in Z (perpendicular to the detection plane)

These requirements determine the mechanical constraints that must be taken into account for the module design and the construction methods.

To achieve the precision in η:
- The readout PCB must be precisely manufactured and positioned on one side of a readout panel with a tolerance of ±35μm
- The 2 sides of a readout panel must be aligned with a tolerance of ±35μm
- Each pair of modules must be precisely aligned on the spacer frame

To achieve the precision in Z:
- The thickness and planarity of the panel must be controlled (±110μm w.r.t. nominal plane)
- The thickness of assembly frames must be precisely machined (±45μm)
- The gas gap (drift) height must be precise on the area of a module (±110μm)

In the end modules must be stiff enough with controlled thermo-mechanical deformations in order to be able to monitor and correct these deformations with the alignment system (see section V) in operation.

**A. Readout boards**

The readout boards are the most sensitive parts of the detector since they carry the precision strips, the resistive protection and the pillars that will sustain the mesh. These PCBs will be manufactured in industry with special care, on the layout, the etching process and precision holes drilling in order to obtain the required precision. Figure 10 shows the process for readout PCBs manufacturing. The raw material is copper cladded FR4 epoxy sheets on which precision strips are etched. Resistive strips are deposited on a 50 microns thick kapton foil by screen-printing industrial process and glued at high temperature onto the plane of strips. Finally coverlay material is laminated on the resistive strips and etched to make the pillars.

The typical resistivity of the resistive strips is 10 to 20 MΩ (~300-600 kΩ/□) and the pattern is similar to the one of precision strips. The ladder structure (see Figure 11) improves the charge flow and avoids dead areas in case of
C. Module assembly

Once panels are built, a module is assembled by stacking 2 readout panels and 3 drift panels following the scheme presented in figures 8 and 9. The relative alignment of 2 readout panels in a module is obtained using precise pin and insert that are glued in the panel after panel construction (see figure 14).

In order to minimize the deformation of the outer drift panels due to gas pressure, the various panels must be interconnected by a thread at several points in the active area (see figure 15). These interconnections define precisely the height...
Fig. 13. Description of panel construction with stiffback method in 2 steps.

Fig. 14. Cross section of one module corner. Alignment pin (green) and insert (purple) are used to fix the relative alignment of the 2 readout panels in the module. The extension of the PCB (red) is where the electronics will be connected. The cooling channels will be glued in between the two FR4 sheets.

of the drift gap and increase the module stiffness. They are also used, together with the alignment platform (see section V) to control and monitor the global deformations of the modules.

D. Mechanical prototype

The global deformation of a full size mechanical prototype for a temperature gradient of 2°C has been measured and simulated. A prototype was divided in 4 modules instead of 2 as it is in the current design, and built with the same material: aluminum frames, FR4 sheets, honeycomb. The modules were mounted on an aluminum spacer frame, heated, and their deformations measured with a coordinate measuring machine (CMM). Thermo-mechanical simulations shown in figure 16 are in good agreement with the measurements made on the prototype and summarized in table II.

<table>
<thead>
<tr>
<th>Module</th>
<th>Maximum deformation</th>
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<tbody>
<tr>
<td>M1</td>
<td>55 µm</td>
</tr>
<tr>
<td>M2</td>
<td>59 µm</td>
</tr>
<tr>
<td>M3</td>
<td>38 µm</td>
</tr>
<tr>
<td>M4</td>
<td>37 µm</td>
</tr>
</tbody>
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Fig. 15. Left – Drawing of an interconnection: reinforcement nuts (beige and green) and endcaps (red) are necessary to tighten the panels together. Drift spacer (purple) defines precisely the drift height and allow gas circulation in the 4 gas gaps of the module. Right – Simulation of a half-panel deformation: for the LM2 size, with 7 interconnections, the maximum deformation is around 100 microns for 2 mbar of gas overpressure.

Fig. 16. Picture of the mechanical prototype with the 4 modules built in different laboratories involved in the construction of the NSW (top). Result of the thermo-mechanical simulations with a maximum deformation of 36 µm for a temperature increase of 2°C.

V. ALIGNMENT SYSTEM

All sectors will be monitored by the global alignment system of the NSW. Reference alignment bars are fixed and precisely positioned on the NSW structure taking into account the other bars on the NSW together with the Big Wheel and the Outer Wheel structures. Cameras and lenses are then fixed on these bars in order to define precise alignment lines (see figure 17).

Light source platforms, pointing in both directions with optical fibers, are glued on external drift panels (close to the
frame or interconnection) using a precise jig and alignment pin (figure 14) for reference position. The displacement of these sources is monitored to reconstruct the position and global deformations of the modules.

VI. OPERATIONAL PROTOTYPES

Several large-size (1x2 m²) operational prototypes of one single plane have already been built at CERN [8]. Recently, a first quadruplet, the MMSW (figure 18), has been built at CERN, with a structure very close to the design described in section IV. The goal is to install this detector in the existing ATLAS Muon Spectrometer and evaluate its response under real conditions.

Another quadruplet prototype is under construction in Saclay with the aim to test the alignment procedure with coded masks, for the 2 sides of a panel and for the 2 readout panels. Figure 19 shows one detector panel under test in clean room and in detail the coded masks used to position the alignment insert.

VII. CONCLUSION

It is the first time Micromegas detectors will be used on a very large scale to built large area chambers in a particle physics experiment. The ATLAS NSW upgrade will enable the Muon Spectrometer to retain its excellent performance after long shutdown 2. After few years of intense R&D program on Micromegas detector, design and construction methods have been refined and tested to achieve the ATLAS Muon Spectrometer requirements. The position of strips must be known with a precision of 30 \( \mu \text{m} \) in the plane (\( \eta \) direction) and 80 \( \mu \text{m} \) out of the plane (Z direction).

The construction of the two pre-series modules is about to start, with a first module completed in July 2015 and the second at the end of the year. The series production will start at the beginning of 2016 and is foreseen to run until the middle of 2017. Production intervals foresee completion of two modules per month per site to comply with the envisioned timescale.

REFERENCES