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5 **Construction and Quality Assurance of Large Area** 6 **Resistive Strip Micromegas for the Upgrade of the ATLAS** 7 **Muon Spectrometer at LHC/CERN**

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11 **ABSTRACT:** Large area Micromegas detectors will be employed for the first time in high-energy
12 physics experiments. To cope with increasing background rates, associated with the steadily
13 increasing luminosity of LHC to 10 times design luminosity, the present detector technology in
14 the current innermost stations of the muon endcap system of the ATLAS experiment (the Small
15 Wheel), will be replaced in 2019/2020 by resistive strip Micromegas and small strip TGC detectors.
16 Both technologies will provide tracking and trigger information. In the “New Small Wheel” the
17 Micromegas will be arranged in eight detection layers built of trapezoidally shaped quadruplets of
18 four different sizes covering in total about 1200 m² of detection plane. In order to achieve 15 %
19 transverse momentum resolution for 1 TeV muons, a challenging mechanical precision is required
20 in the construction of each active plane, with an alignment of the readout strips at the level of 30 μm
21 RMS along the precision coordinate and 80 μm RMS perpendicular to the plane. Each individual
22 Micromegas plane must achieve a spatial resolution better than 100 μm at background rates up to
23 15 kHz/cm² while being operated in an inhomogeneous magnetic field ($B \leq 0.3$ T). The required
24 mechanical precision for the production of the components and their assembly, on such large area
25 detectors, is a key point and must be controlled during construction and integration. Particularly
26 the alignment of the readout strips within a quadruplet appears to be demanding. The readout
27 strips are etched on PCB boards using photolithographic processes. Depending on the type of the
28 module, 3 or 5 PCB boards need to be joined and precisely aligned to form a full readout plane.
29 The precision in the alignment is reached either by use of precision mechanical holes or by optical
30 masks, both referenced to the strip patterns. Assembly procedures have been developed to build the
31 single panels with the required mechanical precision and to assemble them in a module including
32 the four metallic micro-meshes. Methods to confirm the precision of components and assembly
33 are based on precise optical devices and X-ray or cosmic muon investigations. We will report on
34 the construction procedures for the Micromegas quadruplets, on the quality control procedures and
35 results, and on the assembly and calibration methods.

36 **KEYWORDS:** HL-LHC, ATLAS, NSW Upgrade, Micromegas, resistive strips

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48 1 The ATLAS NSW Upgrade Project

49 With the High Luminosity upgrade of the Large Hadron Collider (LHC) to up to $7.5 \times 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$,
50 about 10 times the design luminosity the background hit rate in the innermost end-cap region, the
51 so-called Small Wheel (SW), of the ATLAS [1] Muon Spectrometer (MS) will increase in such a
52 way that the currently used detector technology cannot cope with this [2]. For example the efficiency
53 of the precision tracker in the SW, the Monitored Drift Tube chambers (MDT), will decrease below
54 60 % at already 2 times the design luminosity (see figure 1 (right)). The rate of fake triggers in
55 the end-cap region ($|\eta| > 1$) is very large if only the middle wheel of the MS is included in the
56 trigger chain. This is illustrated in figure 1 (left) where the eta distribution of the muon trigger
57 is shown for Run1. A slight reduction of fake trigger rate has been obtained in Run2 adding the
58 Thin Gas Chambers (TGC) of the SW in the trigger. However this reduction is not enough for
59 operation at even higher luminosities. With the inclusion of the New Small Wheel (NSW) the muon
60 tracks can be unambiguously online reconstructed to the interaction point. Therefore fake tracks
61 from beam-pipe scattering or from the calorimeters can be neglected. The NSW will be a totally
62 redundant detector system consisting of eight layers of small-strip Thin Gap Chambers (sTGC) [4]
63 and MICRO-MESh Gaseous Structures (Micromegas) each [3].

64 2 Construction of NSW Micromegas Quadruplets

65 The NSW has a disk-like design with eight small and eight large sectors (see figure 2 (left)). Each
66 sector consists of two Micromegas wedges sandwiched by two sTGC wedges (see figure 2 (right)).
67 The wedges are multi-layers with four active detector planes. Therefore the NSWs have in total
68 eight layers of sTGCs and eight layers of Micromegas. In this paper only Micromegas quadruplets

Figure 1. Left: Trigger rate as a function of the pseudorapidity of the ATLAS Muon Spectrometer. The trigger distribution shows a much higher rate for $|\eta| > 1$. When reconstructing muons with $p_T > 10$ GeV the distribution is almost homogeneous. Right: The red dots in the right figure indicate the measured efficiency for a single tube and the dotted line shows the extrapolated efficiency for a whole chamber. Figures taken from [2].

will be discussed. Micromegas are planar structure detectors consisting of three planes, the cathode, the woven micro-mesh and the anode-strip structure. A traversing muon ionizes the gas molecules along its path in the 5 mm drift region between cathode and mesh. The created electrons drift through the mesh into the amplification region and build avalanches. 128 μm high pillars support the mesh and assure the exact height of the amplification gap. The multiplied electrons are then detected on the readout strips of the anode structure located below additional high-resistive strips acting as discharge protection [5].

Figure 2. Design of the New Small Wheel with eight large and eight small sectors (left). Each sector consists of two Micromegas wedges of four active layers each sandwiched by two sTGC wedges of additional eight active layers (right). In total each New Small Wheel has sixteen active layers. Left figure taken from [2].

2.1 Design of the Micromegas Quadruplets

The Micromegas wedges are subdivided in two Micromegas quadruplets (see figure 2 (right)). Thus four types of Micromegas quadruplets with different dimensions exist. Each Micromegas quadruplet consists of three drift panels and two readout panels (see figure 3). A panel is a stiffening sandwich structure consisting of a 10 mm thick aluminum honeycomb core framed by aluminum bars and sandwiched by 0.5 mm FR4 printed circuit boards (PCB). Three or five PCBs are needed for one panel, depending on the quadruplet type. On the surface of the PCBs either the readout structure or the cathode is lithographically etched. After mounting a 5 mm thick aluminum mesh frame onto the drift panel the micro-mesh is glued onto the frame. Thus after the assembly of the quadruplet the four gas volumes between the panels are the active Micromegas layers. To maintain the current excellent momentum resolution of $\Delta p_T \approx 15\%$ for $p_T = 1$ TeV muons a spatial resolution better than $100\ \mu\text{m}$ in a single plane is required. This is very challenging over an area of 2 to $3\ \text{m}^2$. To achieve this excellent spatial resolution a very high mechanical precision is required in the construction of each active plane, with an alignment of the readout strips at the level of $30\ \mu\text{m}$ along the precision coordinate and $80\ \mu\text{m}$ perpendicular to the plane. Each quadruplet type is built at a different construction site, hence the procedures vary slightly.

Figure 3. Design of a NSW Micromegas quadruplet consisting of three drift panels and two readout panels. The four gas volumes between the panels are the active Micromegas layers. Zebra connectors are used to connect the MM-FE8 front-end boards to the readout strips. Dedicated pins and bushes are using to align the two readout panels perfectly during assembly.

2.2 Panel Construction

The construction of the drift and readout panels follow generalized procedures. Two construction procedures were chosen, either to glue a panel in only one step or in two steps. In the following the panel construction in two steps will be explained first (see figure 4). Here the first set of PCBs is placed and aligned on a granite table. Then they are sucked using vacuum to the granite table to transfer the very good planarity of the granite table of about to

the panels. Before placing the aluminum bars and honeycomb on the PCBs, glue is distributed homogeneously on the PCBs with a thickness of about 300 μm . This so-called halfpanel cures over night in a vacuum bag. On the following day it is removed from the granite table and sucked by vacuum to a so-called stiffback, a very stiff and planar aluminum sandwich structure. A second set of PCBs is placed and aligned on the granite table and again glue is distributed on top. The stiffback with the halfpanel is then lowered onto the granite table and placed on precision distance pieces, which define the thickness of the panel. This has to cure again over night. The only difference for the panel construction in one gluing step is to suck the second set of PCBs during the first gluing step to the stiffback with glue distributed on top. Then the stiffback is lowered onto the halfpanel.

Figure 4. Panel construction in two gluing steps. The upper figure shows the first gluing step before curing and the lower figure shows the second step with the half panel sucked to the stiffback and the distance pieces for the well defined panel thickness.

2.3 Alignment of the Readout Boards

Simultaneously to the etching of the readout structure, precision markers were etched on the readout PCBs as well. These precise markers are used for the alignment of the readout boards for the panel construction. Again two methods are used for the alignment. One is to drill precision holes at the positions of the markers. With precision pins mounted on well aligned plates on the granite table the PCBs are aligned to each other (see figure 5).

The second method is to glue metallic stable precision washers concentrically onto the positions of the markers. The coarsely aligned PCBs are then aligned using an accurate alignment frame. It is globally aligned on the granite table. Pins are used for the relative alignment of the PCBs. These pins are guided by precision bushes in the alignment frame.

Figure 5. Granite table with five precision aluminum plates. On the aluminum plates pins are mounted for the alignment of the readout PCBs.

2.4 Precision Assembly using Dedicated Pins

After the construction of the panels and the installation of the woven micro-mesh the Micromegas quadruplets can be assembled. Therefore pins and bushes are precisely glued into the readout panels for a perfect alignment of both readout boards against each other (see figure 3). For the position of the drift panels an accuracy of a millimeter is sufficient. During the assembly pressure sensor and micrometer adjustment units are used for an assembly free of forces. Hence the pins can move freely in the bushes.

3 Quality Assurance of NSW Micromegas Quadruplets

In the following some examples for the quality assurance of the NSW Micromegas quadruplets will be given.

3.1 Planarity Measurement of the Panels

All produced panels undergo a planarity measurement. This is done using a laser triangulation head mounted on a coordinate measurement machine (CMM). Figure 6 (left) shows all expected details and the excellent planarity of a readout panel consisting of 3 PCBs. The green area is the active detector plane with an RMS of about $15\text{ }\mu\text{m}$ (see figure 6 (right)), which is well within the requirement. The red dots within this area is an interplay between measurement and the $128\text{ }\mu\text{m}$ high coverlay pillars. At the edge of the active area a $128\text{ }\mu\text{m}$ coverlay line can be seen. The blue areas left and right is for the electronics region, which is per construction about $100\text{ }\mu\text{m}$ lower than the active area.

3.2 Verification of Strip Alignment

Simultaneous to the etching of the readout structure and precision markers eight coded masks were etched on the readout PCBs as well. These masks with an chessboard-like pattern can be used for the verification of the strip alignment.

Figure 6. Left: Planarity measurement of a readout panel consisting of three PCBs performed with a laser triangulation head mounted on a CMM showing the active area (green), the interplay between measurement and pillars (red) and the electronics region (blue). Right: The residual distribution for this measurement with an RMS of the active area of about 15 μm (right).

141 Additionally the quadruplet can be calibrated after assembly using cosmic muons as in the Munich
 142 cosmic ray facility. With two precise external tracking references (MDTs) the position of the muons
 143 traversing the Micromegas is predicted. This was performed as a study of principle using a 1 m²
 144 prototype detector with two readout boards. At this detector no alignment tool has been used for the
 145 alignment of the anode structure. With the difference between predicted and measured hit position
 146 the variation of gap size between PCBs during gluing can be determined (see figure 7). This results
 147 into a shift between the PCBs of about 100 μm and a rotation of about 350 $\mu\text{m}/\text{m}$ measured with an
 148 accuracy of 20 μm . This effect is eliminated for NSW quadruplets using the precise tooling. For
 149 more details see [7].

Figure 7. Shift and rotation of the two PCBs of a 1 m² prototype detector. The results of a measurement with two external reference trackers is shown left and a resulting deformation scheme right. Figures taken from [7].

150 4 Summary

151 It was shown that the challenging mechanical requirements for the NSW Micromegas quadruplets
 152 can be fulfilled. A precise alignment of readout boards is done using precision templates. The very
 153 good planarity from a granite table is transferred to the panels using vacuum technique.

154 Dedicated tests for the quadruplets were developed to assure their quality. The planarity of each
 155 panel will be measured using optical precise instruments. Coded masks on the readout panels are
 156 used to verify the strip and surface alignment. Each Micromegas will be calibrated using cosmic
 157 muons or x-rays. High rate irradiation tests will be performed for each quadruplet in the GIF++
 158 [6]. Finally, high energy testbeam campaigns will confirm spatial resolution, efficiency, etc. of a
 159 certain fraction of the assembled quadruplets.

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