Performance of Large Area Micromegas Detectors for the ATLAS Muon Spectrometer Upgrade Project

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Abstract—32 high-rate capable SM2 Micromegas quadruplets are built, for the upgrade of the Small Wheels of the ATLAS muon spectrometer. The cathodes and strip-anodes of the 2 m^2 quadruplets consist of stable honeycomb sandwiches with a requested planarity better than $80\text{ }\mu\text{m}$.

The qualification of full-size SM2 quadruplets will be performed in the Munich Cosmic Ray Measurement Facility (CRF). Two fully working $4\text{ m} \times 2.2\text{ m}$ ATLAS drift-tube chambers provide muon tracking, a RD51 SRS based data acquisition system provides readout of all 12288 electronic channels using 96 APV25 front-end boards. The goal is to measure the homogeneity of pulse-height and efficiency and to determine the planarity of the sandwich planes and the positions of the readout-strips.

This has been pioneered by studying a $102 \times 92\text{ cm}^2$ Micromegas chamber with similar readout pitch in the CRF using the TPC-like analysis method. At trigger rates above 100 Hz data taking takes only a few days for sufficient statistics. Shifts of readout planes and bulging due to overpressure were resolved with an accuracy better than $50\text{ }\mu\text{m}$, single plane angular resolution with an accuracy of about 5° and spatial resolution of $300\text{ }\mu\text{m}$ in agreement with $83\text{ }\mu\text{m}$ for the same detector at high energy 120 GeV pion beams when taking into account the multiple scattering of the low energy cosmic muons.

Index Terms—ATLAS, Muon Spectrometer Upgrade, New Small Wheel, resistive strip Micromegas, SM2, Cosmic Ray Measurement Facility

I. INTRODUCTION

DUE to the high luminosity upgrade of the Large Hadron Collider (LHC) it will reach for Run 4 luminosities up to seven times above the design luminosity. To process the increased data volume the detectors of the inner end-cap region of the ATLAS Muon Spectrometer (Small Wheel) have to be upgraded as well [1]. The Monitored Drift Tube chambers (MDT) presently used in the outer radius of the Small Wheel will have an efficiency loss to below 90 % at design luminosity and below 60 % at two times the design luminosity (see Fig. 1)[4]. Additionally the New Small Wheel will be fully integrated in the muon trigger system to suppress fake triggers. Therefore the future detectors have to be trigger and high rate capable. Small-Strip Thin Gap Chambers (sTGC) [3] and MICROMESH Gaseous Structures (Micromegas) [2] were chosen.

The New Small Wheel will have a disk-like design with eight small and eight large sectors (see Fig. 2). Each sector is subdivided in two modules consisting of two Micromegas quadruplets with main emphasis on precision tracking sandwiched by two sTGC quadruplets with main emphasis on

Figure 1. Efficiency of Monitored Drift Tubes as function of the hit rate for one tube (red circles) and for a chamber with 2×4 tubes (dashed line). Efficiency decreases below 90 % for design luminosity of LHC and below 60 % for double design luminosity. Figure Taken from [4].

triggering. Both detector technologies are capable of tracking and triggering. Thus each module has in total 16 active layers [4].

Figure 2. Layout of the disk-like New Small Wheel. The large and small sectors are both subdivided in two modules. Figure Taken from [4].

II. CONSTRUCTION OF SM2 QUADRUPLETS

The Micromegas quadruplets of the outer part of the small sector are constructed by a consortium of four German University groups. We will focus on these Micromegas quadruplets (SM2), starting with a small introduction to the working principle of Micromegas.

A. Working Principle of Micromegas

Each Micromegas of the SM2 quadruplet consist of three planar structures a cathode, a grounded micro-mesh and a resistive micro-strip anode [5]. Thus it is divided in drift and amplification regions. A traversing muon ionizes the gas mixture (Ar:CO₂ 93:7 vol%) in the drift region. The produced electrons drift to the amplification region, undergo gas amplification and are collected on the resistive strips. There are two main position reconstruction methods, centroid and μ TPC. The centroid method is the charge weighted mean of the strips (indicated with the red dot in Fig. 3) and the μ TPC method is a Time-Projection-Chamber-like method using the drift time of the electrons to reconstruct the incident angle in a single plane. With the reconstructed angle the center of the track can be reconstructed and thus the position of the traversing muon. For this analysis only the centroid method was used.

Figure 3. Scheme of the working principle of a Micromegas consisting of three planes, a cathode, a grounded stainless steel micro-mesh and an anode strip structure. A traversing muon (green) ionizes the gas in the drift region. The electrons produced by this process build avalanches in the amplification region and are read out on the strip structure.

B. Design of the Micromegas Quadruplet

Each Micromegas quadruplet consists of three drift and two readout panels (see Fig. 4). A panel is a stiffening structure of aluminum bars and honeycomb sandwiched by printed circuit boards (PCB). The surface of the PCBs is either used as drift cathode or as anode-strip structure and the gas volumes between the panels are the active Micromegas layers.

Figure 4. Cross section of three drift and two readout panels assembled to a Micromegas quadruplet.

C. Global and Relative Alignment of the PCBs

As industrially made PCBs are limited in size each plane of the panels have to be constructed of three PCBs. The alignment of these PCBs has to be very accurate within 20 μ m, at least for the readout panels. To achieve this accuracy the PCBs have to be aligned before the gluing process. This is done with a precision alignment frame shown in fig 5. One part of the alignment frame, the reference frame, is permanently installed on a granite table. It has two external precision pins for the global alignment which define the position of the panels on the granite table. The six 8 mm precision pins on the second part of the alignment frame provide alignment for the three readout boards. Precision markers on the readout boards are produced in the same lithographic step as the readout strip. Precision washers are glued on top of these markers with an accuracy of about 5 μ m by use of a telecentric camera. The precision pins fit exactly into the washer.

Figure 5. The alignment frame for the readout boards of the SM2 module. An external permanently installed reference frame with two precision pins (green) define the position of the readout panels on the granite table. Six 8 mm precision pins provide alignment for the three readout boards of the SM2 module. The pins fit exactly into precision washers (red) which are glued concentrically on top of precision markers. These markers are produced in the same lithographic step as the readout strips and reference with high accuracy the position of the strips. A relative alignment of the PCBs with an accuracy of better than 20 μ m is expected.

D. Panel Construction in a Two Step Gluing Process

Figure 6. Schematic drawing of the two step gluing process. In the first step the PCB is sucked to the granite table and the aluminum frames and honeycomb are glued on top. After curing in the second step a second PCB is sucked to the granite table. The half-panel produced in the first step is sucked on the stiffback and placed on top of the second PCB. Precision balls are used to define the distance between the PCBs.

The two steps of the gluing process are shown in Figure 6. After the alignment of the three PCBs they are sucked onto the granite table for the first gluing step. The precision of the surface of the granite table with a flatness better than $6\text{ }\mu\text{m}$ will be transferred to the sandwich panel. Glue is distributed on the PCBs and the aluminum bars and honeycomb are placed on top. After about 10 hours of curing the half-panel can be removed and a second set of PCBs is aligned and sucked to the granite table. Meanwhile the first half-panel is sucked to a stiffback, a planar rigid structure with a surface RMS of $14\text{ }\mu\text{m}$ which weighs only 30 kg. After the glue distribution on the second set of PCBs the half-panel mounted on the stiffback is placed on top. Precision balls are placed between granite table and stiffback to obtain an exact thickness of the panel. The panel is finished after a second 10 hours curing time. Drift and readout panels have a very similar production procedure, except for the precise relative alignment of the PCBs on the readout panel. This is not necessary for drift panels.

E. Planarity Measurement of a SM2 Drift Panel

After the gluing process the surface of the panels is measured with a triangulation distance laser sensor mounted on a Computer Measurement Machine (CMM). The result of one topology measurement is shown in Figure 7 with an RMS of $22\text{ }\mu\text{m}$ with respect to the best fit plane. This fulfills the ATLAS requirement of $30\text{ }\mu\text{m}$ RMS at a min-max value of $120\text{ }\mu\text{m}$.

Figure 7. Measured topology of a SM2 drift panel with a laser distance sensor mounted on a CMM. This measurement shows the deviation from the plane with $22\text{ }\mu\text{m}$ RMS.

F. Interconnections in SM2 Quadruplets

Due to the large area of the quadruplets and 2 mbar overpressure in the gas volume the outer layers of the Micromegas quadruplets would have deformations of the drift region above 1 mm. To avoid this effect six interconnections are integrated in the quadruplets. Figure 8 shows the result of a deformation simulation with six interconnections. With a maximum deviation of only $51\text{ }\mu\text{m}$ from true planarity the deformation is well within the ATLAS requirements.

III. QUALITY CONTROL OF SM2 QUADRUPLETS WITH COSMIC MUONS

In the following section we will concentrate on the aspects which can be measured in the LMU Cosmic Ray Measurement Facility (CRF) using muon reference tracks.

Figure 8. ANSYS simulation [6] of blow up in the outer detector layers due to 2 mbar overpressure inside the chambers. This simulation shows a maximum deviation of $51\text{ }\mu\text{m}$ using six interconnections. Taken from Ref. [7].

A. Cosmic Ray Measurement Facility, LMU

The CRF is equipped with two $4 \times 2.2\text{ m}^2$ ATLAS MDT chambers for precision muon reference tracking sandwiched by two trigger hodoscopes with sub-ns time resolution (see Fig. 9). They provide additional position information along the wires of the MDTs. Due to the active area of about 9 m^2 and an angular acceptance between -30° and $+30^\circ$ track analysis provides not only information of strip positions within the readout plane but also information on the perpendicular dimension and the distance between active planes. Thus the CRF is well suited for the investigation of large area Micromegas.

Figure 9. Scheme of the LMU Cosmic Ray Measurement Facility (CRF) consisting of two ATLAS MDT chambers for precision tracking and two trigger hodoscopes for position information along the wires of the MDTs sandwiching the Micromegas under test.

In between the MDT reference chambers the Micromegas under test is placed. In this case this is a prototype detector with an active area of $102 \times 92\text{ cm}^2$ to establish the procedures for the quality control of the SM2 quadruplets. The prototype detector is very similar in construction as the SM2 quadruplets except being a single plane detector without interconnections to prevent the deformation of the drift region. Due to the large size it consists of two resistive strip readout boards with 1024 strips each and a strip pitch of $450\text{ }\mu\text{m}$. The readout consists of a Scalable Readout Unit and a Front-End Concentrator card

with 16 APV25 front-end boards [8][9]. These 16 APV25 boards, together with a segmentation along the strip with the information from the trigger hodoscopes in ten segments, are used to subdivide the detector in 160 identical partitions of about $60 \times 100 \text{ mm}^2$ to enable detector alignment, determine deformations and deviations of strip locations and to allow for information on homogeneity in efficiency and pulse height (see Fig. 10).

Figure 10. Scheme of the $102 \times 92 \text{ cm}^2$ Micromegas under test consisting of the readout boards with its subdivision in 160 partitions by 16 APV25 front-end boards and 10 positions along the strips obtained from the trigger hodoscope information.

B. Deformation of Drift Region

The muon reference tracks are used for the detector alignment relative to the MDTs as well as for calibration of the strip positions.

Using inclined muon tracks the position perpendicular to the detector can be determined. Figure 11 shows a scheme of the reconstruction of the z position obtained from the dependence on the track angle of the residual of reconstructed y position with respect to the MDT reference track. Due to the small overpressure of about 10 mbar (in ATLAS this will only be about 2 mbar) there is a blow-up of the detector. By construction the base plate is more stiff than the cathode and so the deformation occurs only in one direction. The reconstructed z position is always in the middle between base plate and cathode.

Figure 11. Schematic drawing of the deformation of the drift region due to a small overpressure and the reconstructed detector layer using inclined tracks.

Figure 12 shows the measured deformation of 0.8 mm in maximum. This leads to a total blow-up of about 1.6 mm at

the cathode. The interconnections will avoid this blow-up in the SM2 quadruplets.

Figure 12. Measured deformation of the drift region with a maximum deviation of 0.8 mm in the reconstructed plane, which leads to a total blow-up of 1.6 mm.

C. Calibration of Strip Positions

Using perpendicular muon tracks the strip positions can be calibrated. As mentioned before the prototype detector consists of two readout boards the gluing of which did not use alignment tools different to the SM2 construction. The position of the readout strips is measured with an accuracy of 10-15 μm . Figure 13 shows this measurement. A shift from 100 μm to 450 μm between the readout boards can be seen. This is schematically displayed in Figure 14. The rotation between the PCBs is about 0.1° .

Figure 13. Measured shift and rotation between the two readout boards of the Micromegas under test with perpendicular tracks.

Figure 14. Scheme of the measured deviation between the two readout boards from 100 μm to 450 μm .

D. Efficiency and Charge Distribution

For each of the 160 partitions the 3σ tracking efficiency and the most probable value of the pulse height distribution is determined separately. The prototype detector shows a good uniformity of both.

Figure 15 shows the 3σ tracking efficiency variation which is over the whole active area within only 1 %. The absolute value of the efficiency is limited by multiple scattering of the low-energy muons. At the edges the efficiency is a little bit lower due to the frame on which the detector is mounted. Its additional matter increases the multiple scattering.

Figure 15. Homogeneity in efficiency determined separately for all 160 detector partitions with a mean of $(92 \pm 1)\%$. Regions with lower efficiency are due to edge effects of the detector.

The prototype detector shows a homogeneous pulse height distribution as well. It varies only within 20 %. Due to the readout in master/slave APV25 pairs a systematically larger pulse height for the slave APV25s can be seen. Additionally a gas circulation effect in the upper right corner can be seen. The gas inlet is in the upper left corner, the gas outlet in the lower right corner, so the circulation in the upper right corner is not good enough and the pulse height decreases. For the SM2 modules a homogeneous gas distribution is foreseen.

Figure 16. Homogeneity in pulse height determined separately for all 160 partitions of the detector shows a variation within 20 %. Due to the readout with master/slave pairs of APV25s the slaves show systematically larger pulse height. A gas effect in the upper right corner can be seen.

IV. CONCLUSION

We presented the principle of the construction of SM2 quadruplets for the ATLAS NSW Upgrade Project. The two step gluing process on a granite table with a flatness better than $6\mu\text{m}$ fulfills the accurate mechanical requirement. Each panel surface consists of 3 printed circuit boards which are aligned better than $20\mu\text{m}$ in precision direction using a precise alignment frame. To avoid a deformation of the drift region due to 2 mbar overpressure six interconnects are included in the SM2 quadruplets. The first manufactured drift panels fulfill the strict mechanical requirements with a planarity of $22\mu\text{m}$.

The quality control of the SM2 quadruplets in the Cosmic Ray Measurement Facility (CRF) using reference muon tracks includes measurements of the homogeneity of efficiency and pulse height, deformation of the drift region and calibration of the strip positions. A 1m^2 prototype Micromegas consisting of two readout boards was installed in the CRF to establish a procedure for the quality control. The measurement has shown a deformation of the drift region with a maximum deviation of 1.6 mm at the cathode due to about 10 mbar overpressure. The calibration of the strip position is feasible with an accuracy of 10-15 μm . A shift and rotation between the two readout boards due to the insufficient alignment during the gluing process was observed. The prototype detector shows a good uniformity of the efficiency within 1 % and of the pulse height within 20 %.

The LMU CRF is well suited to perform quality control of assembled SM2 quadruplets. A full set of electronics based on APV25 chips for the readout of all 12288 channels of a SM2 module is available.

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