Test Beam Results and Performance Studies of ATLAS Micromegas Production Modules

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Abstract. The LHC at CERN plans to have a series of upgrades to increase its instantaneous luminosity up to $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$. The ATLAS experiment will upgrade its inner end-cap muon chambers to cope with the increased collision rate expected from the High-Luminosity-LHC. This project, called New Small Wheel, includes resistive Micromegas chambers together with small-strip Thin Gap Chambers, forming a system of $\sim 2.4$ million readout channels in total. This is the first time that Micromegas detectors are built in such a large scale. In total, 128 Micromegas modules up to 3 m$^2$ in size, will be produced in different sites spread across Europe, targeting for an installation at the end of the Long Shutdown 2 of the LHC. One of the first series modules, equipped with a prototype of the final front-end electronics based on the VMM chip, was tested in a muon/pion beam at the H8 beam line of SPS at CERN during the summer of 2018. We present the test setup and performance results, namely efficiency and resolution, for perpendicular and inclined tracks. These studies were focused on determining the high voltage working point of the ATLAS Micromegas detectors. Studies with several gas mixtures were also carried out and will be presented.

1. The ATLAS NSW Upgrade
In the context of the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, its experiments also need to be upgraded to cope with the higher particle rates. One of the main upgrades of the ATLAS detector is the replacement of the innermost end cap of the muon spectrometer by the New Small Wheel (NSW). Its position within the ATLAS detector is shown in figure 1a. The NSW will contribute to the trigger system of the ATLAS detector, reducing the muon fake trigger rate in the end cap region, which is currently responsible for 90% of the bandwidth in that region. This will allow to maintain low trigger thresholds during the operation in the high rate environment of the HL-LHC. The second motivation for the NSW upgrade is to maintain a good spatial resolution and tracking efficiency at high rates, as these quantities deteriorate with higher rates at the current Small Wheel (SW). The NSW will use two detector technologies, namely the small-strip Thin Gap Chambers (sTGCs) and the Micro Mesh Gaseous Detectors (Micromegas, MM), where the sTGCs mainly focus on the trigger and the MMs on the precise tracking. The NSW has a wheel like structure segmented into eight small and eight large sectors. Each sector consists of a sandwich like structure shown in 1b, where two MM wedges are surrounded by two sTGC wedges. Each wedge consists of two or three quadruplets for the MM and sTGCs respectively. As both sTGC and MM quadruplets each have 4 detector layers, the system has 16 detection layers in total. This offers a great
2. Micromegas Detectors
The NSW will use large scale Micromegas detectors, covering an active area of 1280 m$^2$. An MM detector consists of three main components shown in figure 2a. The first one is the readout structure which also serves as the anode. Only 128 $\mu$m above the anode there is a stainless steel mesh, which separates the amplification gap from the drift gap. Due to this thin amplification gap a fast collection of ions is possible allowing to operate a MM detector at high particle rates. The third component of a MM detector is the drift cathode. Both the drift gap and the amplification gap are filled with gas. A mixture of 93 % argon and 7% carbon dioxide is used.

A charged primary particle travels through the 5 mm drift gap where it creates primary...
electrons through ionisation of the process gas. An electric field of around 600 V/cm is applied to the drift gap making the primary electrons drift towards the grounded mesh. Passing through the mesh, the electrons reach the thin amplification gap, where an electric field of around 40 kV/cm causes an avalanche of electrons due to the primary electron. The gain within this process is of the order of $10^4$. Finally, the charge from the avalanche gets collected at the readout anode. In the NSW configuration a resistive strip readout is used. The voltage is applied to the amplification gap through resistive strips. The copper readout strips are placed underneath the resistive ones, coupling to them capacitively. Between the resistive and the readout strips, there is an insulating kapton foil. This configuration makes the detector more stable against sparking. Both the resistive strips and the readout strips have a width of 300 µm. The pitch depends on the type of chamber in the NSW and is either 425 µm or 450 µm. This high granularity of the readout allows for a good spatial resolution of the detector. In the layout of the NSW, four layers of MM form a quadruplet, also referred to as a module. Two of the layers, the so called eta layers, have the strips configured to be perpendicular to the eta coordinate of the ATLAS experiment to allow a good spatial resolution in this precision coordinate. The strips of the other two layers, the so called stereo layers, are tilted by ±1.5° to obtain a measure of the second coordinate. Four types of quadruplets are build for the NSW, all having surfaces in the order of several m². Their dimensions are shown in figure 2b. Their naming follows the position in the wheel, where LM and SM defines if they are used in a large or a small sectors, while M1 and M2 specifies the radial position of the module in the sector. The production of the four types of quadruplets is distributed between institutes in different countries: France (LM1), Russia-Greece-CERN (LM2), Italy (SM1) and Germany (SM2).

3. Test Beam Setup
The first SM2 production module from the German construction sites has been tested in over four weeks of beam time at the H8 beam line of the SPS accelerator at CERN. The module has a size of 1.7 m in width and 1.4 m in height. It consists of four layers of MM detectors and has about 6000 readout channels. Since the beam diameter is only in the order of several centimeters, 512 channels per layer on the long base of the module have been equipped with readout electronics covering the full beam diameter. A beam of 180 GeV pions with a rate of several kHz was used. A picture of the setup is shown in figure 3. The setup included three other MM detectors with a size of $(10 \times 10)$ cm² providing an external track reference. Two $(10 \times 10)$ cm² scintillators mounted on the tracking chambers were used for the trigger. For the first time, the readout of a MM chamber of the final size has been realized using the VMM front end ASIC [6, 7] developed within the NSW project. Specifically the pre-final version VMM3 has been used for the readout of the SM2 module as well as of the tracking chambers. The VMM provides a digitized measurement of the pulse height and time for 64 channels, each connecting to one strip of the MM. Eight VMM3s are housed on a front-end card called MMFE8. In addition to the VMMs it also holds an FPGA which concentrates the VMM data and sends it out to the DAQ PC via UDP packages. Furthermore the FPGA is used to calibrate as well as to configure the VMMs. In total the setup consisted of 2048 readout channels on the SM2 module and another 1536 readout channels on the tracking detectors. During the test beam campaign, a total of 990 runs have been taken focussing on different inclinations of the SM2 module, different gas mixtures, as well as different configurations of the VMM ASIC.

4. Results for Perpendicular Tracks & Gas Studies
As this was the first beam time with a full scale MM module and the VMM read out chip, the module first was put perpendicular to the beam to validate the combination of the module and the readout in terms of spacial resolution and reconstruction efficiency. The position was reconstructed using the charge weighted mean strip position. A spatial resolution in the order
of 70 µm was determined which agrees very well with the results obtained with the smaller prototype chambers in earlier test beams [8]. Figure 4a shows the reconstruction efficiency with respect to the voltage applied to the amplification gap, where the detector is called efficient when a cluster of at least two strips is present around the extrapolated position of the track within a window of 10 times the spatial resolution of the detector. A gas mixture of Ar:CO₂ in the mixing ratio of 93:7 has been used which is the foreseen mixture for the NSW. At the nominal working point of 570 V applied to the amplification gap, the SM2 module has an efficiency greater than 90%. The same study has been carried out for different ratios of CO₂ in the operation gas at a voltage of 590 V for the 93:7 mixture and corresponding voltages for the other mixtures. The spatial resolutions were proven to be constant over all mixtures. The results in terms of efficiency are summarised in figure 4b. Efficiencies greater than 95% have been achieved for all the tested mixtures.

5. Reconstruction of Inclined Tracks
The NSW will cover a pseudorapidity range of 1.3 < |η| < 2.7. This translates into the requirement for the MM detectors to reconstruct tracks under an inclination angle of 8° < α < 31°. In this case a reconstruction with a simple charge centroid is not anymore precise since it is spoiled by the fluctuations of the position of the primary ionisations in the drift gap. Therefore, a more sophisticated reconstruction method which uses the information on the drift time for each strip needs to be applied. With that information, the position of the primary ionisation in the drift gap of the MM detector can be reconstructed like in a time projection chamber (TPC). As the 5 mm drift gap is small with respect to the regular TPCs, the method is called the µTPC method.

5.1. VMM Time Calibration
The VMM measures the time of charge arrival for each strip. Its time measurement is composed of two components, the bunch crossing clock (CKBC) serving as coarse timing as well as a time to amplitude (TAC) converter which measures the time of the pulse with respect to the next falling edge of the CKBC. While the frequency of the CKBC is given by an external reference,
Figure 4. Efficiency studies carried out for perpendicular tracks. The shown VMM parameters are: PT: peak time, NL: Neighbor logic of the VMM, G: Gain of the VMM, Thr: Threshold applied to the VMM in multiples of the measured noise RMS of 5000 ENCs. **Left**: Efficiency versus the voltage applied on the amplification gap. At the working point of the NSW at 570 V all four layers have efficiencies higher then 90%. **Right**: Efficiency as a function of the CO₂ content in the operating gas. For all three investigated mixtures, efficiencies above 95% were achieved. The voltages applied to the drift and the amplification gap are indicated with HV₃ and HV₅ respectively. © 2019 CERN for the benefit of the ATLAS Collaboration. Reproduction of these figures is allowed as specified in the CC-BY-4.0 license.

5.2. The µTPC Method
The µTPC reconstruction method uses the drift time associated with each strip to reconstruct the track of the primary particle through the drift gap. A Hough transform is applied to the position and time data of the strips, to identify particles belonging to a line, rejecting outliers. Second, a straight line fit is performed on the filtered data. Finally the cluster position gets reconstructed at the lines position at the center of the drift gap. The method has been introduced in Refs. [8, 9].

5.3. Noise Levels during the Test Beam
The µTPC methods aims to reconstruct the position of single primary electrons in the drift gap. Therefore the charge collected at the readout strips is generated by the avalanche from a single electron and is in the order of the detector gain of $10^4$ electrons. During the test beam noise levels with an RMS of around 5000 equivalent noise charge (ENC) were observed. In order to get
5.4. Quantities of a Typical Run

Figure 6 shows the drift time and the number of strips in a \( \mu \text{TPC} \) cluster after the Hough transform has been applied for a run where the chamber was inclined by 28° with respect to the beam. The distribution of the number of strips per cluster shows a peak at six. This is in agreement with the results from smaller MM prototypes as well as simulations. Furthermore the distribution shows a shoulder at three to four strips. This is explained by a loss of strips due to the threshold as discussed above. The width of the time distribution shown in figure 6b is about 110 ns, extracted from the fit with a double Fermi function. This agrees with the predictions from the prototypes. The washed out edges can be explained by the signal loss.

Figure 7 shows the reconstructed angle extracted from the slope of the \( \mu \text{TPC} \) line fit. The peak is in agreement with the actual inclination of the chamber 28°. The large tails towards high angles can be explained by clusters with a low strip multiplicity caused by the signal loss discussed above.

5.5. Performance of the \( \mu \text{TPC} \) Reconstruction Method

Figure 8 shows the residuals with respect to the external track for the \( \mu \text{TPC} \) reconstruction method. Two runs with VMM peak times of 100 ns and 200 ns are presented. The residuals have been fitted with the sum of two Gaussian functions to account for the tails in the distributions. For the narrow Gaussian, resolutions between 211 µm and 275 µm have been achieved depending on the peak time. The combination of both Gaussians yields resolutions of 318 µm to 374 µm. In comparison with the precision of the centroid clustering which is in the order of 550 µm using a single Gaussian, this result shows a clear improvement of the resolution. The fraction of hits passing the cuts is between 62 % and 74 %, also depending on the peak time. The reason for these relatively low numbers is the loss of strips not passing the threshold, as discussed above. The fraction of events passing the cuts improves with higher peak time as more charge is collected. Just as the time resolution of the peak detection of the VMM gets worse for higher peak times,
so does the spatial resolution. As discussed above, the noise level was meanwhile reduced to its theoretical minimum. Furthermore, studies on combining the result from the $\mu$TPC cluster and the centroid reconstruction to reach higher efficiencies while maintaining good resolutions are ongoing.

6. Summary

For the New Small Wheel Upgrade project of the ATLAS detector, large scale resistive Micromegas detectors have been chosen due to their ability to perform precise tracking at high rates along with the sTGC detectors. The first SM2 module from the series production has been tested in 4 weeks of beam time at the SPS accelerator at CERN. For the first time, a penultimate version of the VMM ASIC, which was developed for the NSW detectors, has been used to read out a full size MM module. Runs with the SM2 module positioned perpendicular to the beam were used to validate the system. Spatial resolutions in the order of 70 $\mu$m at reconstruction efficiencies of greater than 95% have been achieved for different CO$_2$ ratios in the Ar:CO$_2$ operation gas. Furthermore it was shown that at the working point of the NSW
modules of 570 V, the reconstruction efficiency is above 90 %. In the ATLAS detector, the NSW needs to reconstruct tracks with angles between $8^\circ < \alpha < 31^\circ$. Therefore the module was also tested under an angle of 28° with respect to the beam. For the reconstruction the time of each strip has been used to turn the drift gap of the MM into a $\mu$TPC. Core resolutions between 211 $\mu$m and 275 $\mu$m have been achieved, depending on the peak time of the VMM. The fraction of events passing the cuts was between 62 % and 74 %. Both the resolutions and the number of events passing the cuts are suffering from a high noise level during the beam time. After the beam time, the noise level was intensively studied and got reduced to its theoretical limit.

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Figure 8. Track residuals and number of events passing the cuts using the $\mu$TPC reconstruction method. The measurements have been taken with a peak time of 100 ns (left) and 200 ns (right) at a gain of the VMM of 9 mV/fC. A VMM threshold of six times the noise RMS of 5000 ENCs has been used for both runs. The neighbor logic of the VMM was disabled in both runs. © 2019 CERN for the benefit of the ATLAS Collaboration. Reproduction of these figures is allowed as specified in the CC-BY-4.0 license.