Quality Control and Statistical Analysis of the MICROMEGAS Readout Boards

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Abstract

The construction of large area Micromegas detectors for the New Small Wheel (NSW) upgrade of the ATLAS experiment have started since 2018. The main detector components, the resistive anode boards, are produced in industry and undergo a thorough evaluation at CERN following a detailed Quality Assurance and Quality Control (QA/QC) procedure. Up to today, more than 2000 Micromegas anode boards have been produced and checked for their quality. For a better understanding of the detector behaviour, a statistical analysis of the measurements qualifying the anode boards was performed and the results are shown in this report.
1 Introduction

Micromegas is selected as instrumentation of the first forward muon stations, the so called New Small Wheels (NSW) in the upgrade of the ATLAS detector for the operation of the Large Hadron Collider (LHC) at high luminosity (HL-LHC), expected for 2026, at CERN.

This chapter describes the NSW Micromegas detectors and their operational principle as well as the layout of the NSW.

1.1 Micromegas for the New Small Wheels

For the ATLAS NSW Micromegas detectors the drift electrode is at negative high voltage (HV) potential, the resistive strips are at positive HV potential and the mesh is at ground potential.

Figure 1 shows the schematics of a resistive-strip Micromegas detector adopted for the ATLAS NSW. It consists of a drift electrode, a gas gap of a few mm thickness acting as a conversion and drift region, as well as a conductive mesh that is kept at a fixed distance of about 120 µm from the readout electrode by regularly spaced insulating pillars. The amplification takes place between the mesh and the readout electrode. The latter is made of a PCB with readout strips protected by a thin insulating layer on top of which resistive strips are screen-printed with the same pattern as the readout strips. The HV potentials are chosen such that the electric field in the drift region is a few 100 V/cm while in the amplification region it is 40–50 kV/cm. For the ATLAS NSW Micromegas detectors the drift electrode is at negative high voltage (HV) potential, the resistive strips are at positive HV potential and the mesh is at ground potential.

Figure 1: Schematics of a resistive-strip Micromegas detector

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1 The name CERN derives from the acronym Conseil Européen pour la Recherche Nucléaire. CERN was founded in 1954 and it is one of the largest scientific research centers worldwide focused mainly on fundamental particles

2 MICROMEGAS is the abbreviation of MICRO-MEsh GAseous Structure
Charged particles passing through the drift gap ionize the gas molecules, creating ion-electron pairs. The electrons drift towards the mesh while the ions drift towards the cathode. When the electrons approach the mesh, owing to the much stronger electric field in the amplification region, they are guided through the mesh openings to the readout electrode. In the amplification region, the electrons have sufficient energy to further ionize the gas and multiply. As the HV is applied to the resistive strips, the charge induced on them by the movement of the electrons is capacitively coupled to the readout strips.

1.2 Layout of the New Small Wheels

For the ATLAS NSW two detector technologies were chosen: Micromegas and the small-strip Thin Gap Chambers (sTGC). Both of them are able to operate efficiently in high rates for tracking and triggering. For the NSW, Micromegas will be the main tracking detectors while the sTGC will provide for the main trigger signal, but both detector technologies will complement each other.

Figure 2a shows the position of the old Small Wheels in the ATLAS detector. The NSW follows the design of the current one. It consists of 16 sectors; 8 large and 8 small (Figure 2b). One Micromegas sector consists of eight detector layers grouped into 2 wedges of 4 layers (quadruplets) as shown in Figure 2c. In each quadruplet, the 4 detection layers are separated into 2 pairs, where are mounted back-to-back to one readout panel (Figure 2d). On one readout panel the strips on both detectors are arranged perpendicular to the $\eta$-coordinate ($\eta$-panel). On the the other panel the strips are inclined by $\pm1.5^\circ$ with respect to the $\eta$ strips. By combining the information of the two stereo layers the precision and the second ($\phi$) coordinate can be measured.

Each Micromegas wedge is divided radially into 2 modules. Figure 3 shows the segmentation of the Micromegas wedges (small and large). For small wedges, the lower radius module is called Small Module 1 (SM1) while the upper radius module is called Small Module 2 (SM2). The same naming convention is applied for the large wedges (LM1 and LM2).

Each module type uses several readout boards (see Chapter 2.1) for each detection layer. The SM1 and LM1 detectors are made of 5 readout boards while the SM2 and LM2 of 3 readout boards.
Figure 2: (a) Position of the current Small Wheel in the ATLAS detector, shown in red circle. (b) One NSW: the large sectors are represented with green color, the small sectors with purple. (c) Drawing of one large NSW sector in assembled (left) and exploded (right) view showing the position of the Micromegas (MM) and the sTGC detectors. (d) A Micromegas quadruplet showing the arrangement of the detectors in assembled view. Not to scale.

Figure 3: Segmentation of small and large sectors
2 Micromegas Readout Boards

2.1 Readout Board Production

The production of the Micromegas readout boards is one of the biggest challenges in the NSW project. They are produced in two industry, ELTOS in Italy and ELVIA in France.

Figure 4a shows the construction process of a Micromegas readout board. With the base material (fiber glass epoxy (FR4) with a layer of 17 mm thick copper), the copper strips and other copper structures are etched via photolithography. The resistive layer is glued onto the readout strips with a layer of 25 µm thick glue under high temperature (170°C) and pressure (12 bar). The pillars are created on top of the resistive strips via photolithography after lamination of 2 layers of 64 µm photoimageable coverlay. A schematic structure of the Micromegas readout board can be seen in Figure 4b.

In each readout board the active area is split into two HV sectors by interrupting the resistive strips in the middle of the resistive layer. The HV is supplied from the two sides of the board (HV antenna) as shown in Figure 5.

Figure 4: (a) Construction process of the Micromegas readout board. (b) Structure of the Micromegas readout board
2.2 Quality Control Procedure and Statistical Analysis

The main components of the readout boards, the resistive foils and the bare material, are first shipped to CERN and then dispatched to the two companies. Once ready the readout boards are delivered to CERN where they undergo a deep Quality Control (QC) at a dedicated lab. Tests are devoted to fully qualify the functionalities of the boards and assure that only the ones satisfying all the requirements set by the ATLAS Muon NSW Collaboration are used to build detectors [7].

Figure 6 shows an overview of the readout boards that have been received at CERN until August 2019 from both companies (labeled as Received@CERN), the quantity of the boards that have been tested for their quality (labeled as Shifter QC done) and the quantity of the boards where the final decision was taken (labeled as Final decision taken) including the yield from both companies.

The quantity of the boards that have been received at CERN by both ELVIA and ELTOS are 2427 in total (96% including the yield and extra production; the nominal production to complete two NSW is 2176 boards). From those boards, 2340 boards have been checked for their quality (96%) and the final decision is taken on 2068 in total (85%).

In this section, a brief overview of the QC tests will be discussed as well as the statistical analysis for the
measurements performed. More detailed description on the QC tests can be found in Reference 8.

2.2.1 Visual Inspection

The visual inspection is devoted to investigate all the possible defects that could cause high voltage instabilities to the detectors. It is performed on a dedicated station with the help of microscopes as shown in Figure 7. Bump height on the anode surface caused by enclosures in the resistive material or trapped under the Kapton® foil are potential weakness for the HV stability of the detector, reducing the distance between the electrodes in the amplification gap as shown in Figure 8a. Bumps caused by enclosures below the Kapton® foil with a height lower than 10 µm can be tolerated; if higher, local passivation of the region can be performed by encapsulating the bump with a Pyralux disk as shown in Figure 8b. Bumps are measured with a length gauge tip having a precision of half µm [9] (Figure 9).

![Figure 7: Station for visual inspection](image)

![Figure 8: (a) Schematics of an enclosure under the Kapton® foil. (b) Passivation of a bump using a Pyralux disk.](image)

In this station also damages in the edges of the PCBs are checked, as well as any damage on the Kapton®
foil that can affect the insulation in between the resistive and the readout strips (such as deep scratches or holes). If the insulation is violated, no reparation can be performed and the board cannot be used.

2.2.2 Back-light Inspection

A retro-illuminated table (Figure 10), in jargon called back-light table, is used to check:

- The alignment between the resistive and the copper pattern (Figure 11). A sequence of lines and gaps, each of them with a width of 100 µm is designed on the PCB while a double square marker is printed with the resistive pattern. If the resistive strips and the copper strips are perfectly aligned, the sequence is covered by the 2 squares; in case of a misalignment the numbers of gaps and lines uncovered provides an estimate of the mismatch.

- Edge cutting; to see if the board is cut too close to the first copper strip from the edge, a four-ladder marker is printed onto the PCB (see Figure 12). Each copper line and gap is 100 µm wide. The ladders
are shifted by $\pm 50 \mu m$ with each other.

- Precision of the mechanical hole drilling (Figure 13).

- Missing Pillars. The missing ones are replaced with new ones in the corresponding position in order to keep the mesh in a safety distance from the resistive layer.

Figure 11: (a) Design of the marker with copper lines and gaps of 100 $\mu$m. The dashed lines show the nominal position of the square boxes of the resistive foil in case of a perfect alignment. (b) An example of misalignment $+400 \mu m$ in vertical direction (y) and $-150 \mu m$ in horizontal direction (x).

Figure 12: (a) Design of the four-ladder pattern with copper lines and gaps of 100 $\mu$m. (b) An example of a board cut slightly inside with a deviation $\sim 50 \mu m$.

2.2.3 Dimensions and Accuracy

The PCB is well known to have a hygroscopic behaviour and tends to expand while accumulating water molecules. The size of the PCB, namely the copper images, have been rescaled by about $-0.4 \text{ mm/m}$\(^3\) to take into account the expansion due to the ambient humidity. The rescaling factor is based on measurements performed on a sample of pre-production boards, providing a benchmark of the expansion and are tuned depending on the company. At CERN the dimensions of the boards are measured with 9 CCD\(^3\) surveyors

\(^3\)Abbreviation for Charged Coupled Device.
Figure 13: Photo of the mechanical hole drilling. Ruler in the photo is to measure the displacement of holes between the PCB and the foil.

with 25 µm accuracy \[9\], which are placed in specific position on a granite table (Figure 14). A tighter (±30 µm/m) and a looser limit (±100 µm/m) with respect to the average elongation are set for the short dimension while a much looser requirement (±500 µm/m) is set for the long direction.

Figure 14: Schematics (a) and a photo (b) of the setup for the dimension measurement.

Figure 15 shows the average elongation in the short direction and in the long direction for each board type. Error bars refer to the standard deviation of the elongation distribution. For the short direction 22 out of 32 board types are within the ±30 µm/m limit (green box) and all of them are within the ±100 µm/m limit (yellow box), while in the long direction all the boards are within the limit.

A slight difference between the average elongation of the boards constructed by the two companies is observed. Figure 16 shows a distribution of the elongation in the short direction for all the boards made by the two companies. They are approximately a Gaussian distribution with a mean value being −36.0 ± 1.5 µm/m for ELTOS and −13.2 ± 1.9 µm/m for ELVIA.
2.2.4 Pillar Height Mapping

In a Micromegas detector it is important that the mesh is positioned at the same distance from the resistive strips to guarantee a uniform electric field. Any missing pillar or an inhomogeneous distribution of the pillars in the active area can reduce the distance between the anode and the mesh, creating a region with a stronger electric field. The height of the pillars is measured on a granite table (Figure 17) with a precision tool consisting of a stainless steel holder and four length gauges. Within one measurement, the surface of the holder sits on top of the pillars while the 4 length gauges with an accuracy of 0.5 μm touch the resistive layer (Figure 18).

A sampling of the height of the pillars in the active area is performed to create two-dimensional maps (Figure 19).

Figure 15: Average elongation as a function of the board type (a) in the short direction and (b) in the long direction. Boards made by the two companies are marked with different colors (blue for ELVIA and red for ELTOS). The limit box in (a) is centered at the average elongation in the short direction for all the boards, being $-23.4 \pm 1.2 \, \mu m/m$.

Figure 16: Distribution of elongation of the PCBs in the short direction. (a) for ELTOS and (b) for ELVIA.
Figure 17: Granite table to measure the height of the pillars

Figure 18: Tool with four length gauges to measure the pillar height. (a) schematic and (b) photo.

Figure 20a shows the average pillar height as a function of the board type \( \text{#} \) while Figure 20b shows the distributions of pillar height for boards made by ELTOS and ELVIA, with an average of \( 121.10 \pm 0.06 \mu m \) and \( 119.10 \pm 0.04 \mu m \) respectively.\[4\]

4 Error bars refer to the standard deviation of the pillar height distribution.
2.2.5 Resistivity Mapping

During the production, good performance under high irradiation and quick charge evacuation put an upper limit on the resistivity of the resistive strips. For this reason, the resistivity is first measured after the screen-printing procedure. The foils are classified according to their resistivity. A second measurement is performed after the production of the boards. Both measurements are done with the same tool as shown in Figure 21. It consists of 99 probes

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5 Resistivity means the resistance between two probes in our measurement tool. The probes are of 2 cm length and are placed in a distance of 5 cm from each other. The unit for resistivity is defined to be MΩ/sq.

6 At Kobe University.

7 The average resistivity should be within the range of [0.28, 2.0] MΩ/sq for all the foils; foils with 99% of the measured points within the range [0.28, 2.6] MΩ/sq are Grade A; foils with 95% of the measured points within the range [0.28, 2.6] MΩ/sq are Grade B; foils with 95% of the measured points within the range [0.21, 3.4] MΩ/sq are Grade B−; the rest are Grade C.

8 At CERN
used to map the resistivity at different positions along the board. An example of a resistivity mapping is shown in Figure 22.

![Figure 21: Resistivity tool placed on top of a readout board.](image1)

Figure 22: Resistivity mapping for one type of board in MΩ/sq.

Figure 23a and Figure 23b show the distribution and average value, the latter with an associated error equal to the standard deviation of the resistivity average for each board type, before and after foil gluing respectively. After the gluing procedure, foils with high initial resistivity (LE6, LE7, LS6, LS7 and SE6–8) tend to end up with even higher resistivity. In some cases the change was 5 times higher than the initial values (Figure 23c). For foils with an initial resistivity lower than 0.8 MΩ/sq, no significant increase was observed after the gluing procedure for both companies (Figure 24).

The difference in resistivity among the boards has also an impact in the measurement of the resistance between the HV supply line and the edge of the active area or the end of each HV sector (Figure 25). The operation of the detectors is affected by the low resistance as the intensity of a discharge is inverse proportional to it. As shown in Figure 26, readout boards showing HV stability problems are those who have very low resistance near the edge of the active area.

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Figure 23: Average resistivity (a) before and (b) after Kapton® gluing as a function of the board type. (c) Average ratio of the measured resistivity before and after gluing as a function of the board type. In all plots, the z-axis shows the occupancy per board type.

Figure 24: (a) Correlation plot between the average resistivity before Kapton® gluing and after Kapton® gluing. (b) Correlation plot between the average resistivity before Kapton® gluing and the ratio of the two measurements.
Figure 25: (a) mean and one sigma of minimum resistance as a function of board type measured at the left and right edge of active area; (b) mean and one sigma of minimum resistance as a function of board type measured at the center for left and right HV sector.

Figure 26: (a) Distribution of the minimum resistance measured close the coverlay rim on the right HV sector. (b) Zoom of the distribution in the range 0.2–0.4 $\Omega$. 
2.2.6 Strip Capacitance Measurement

Figure 27 shows the drawing of the smallest readout board for SM1 module. Each PCB accommodates up to 1022 readout strips. The strips are split into 2 groups. The upper 511 strips are routed out of the active area to the up-right side while the lower 511 strips are routed to the down-left side. A strip capacitance measurement is performed to detect unconnected readout strips with the tool shown in Figure 28.

Figure 27: (a) Drawing of the copper structure of Micromegas readout board (red). The green rectangle accommodates the readout electronic devices (b) Zoom of the purple rectangle area in (a). The copper structure routing strips out of the active area is visible.

Figure 29 shows an example of the capacitance measured for each single readout strip of one LE1 board. Strips on the left connectors that show a capacitance lower than 20 pF are not connected to the active area by design. The periodical fluctuations in the measurement are due to the fact that the probes of the tool are partially touching the copper strips and the PCB. Strips with a measured capacitance lower than 20 pF are removed from this analysis.

Figure 30 shows the average of the capacitance mean value of each board with an associated error equal to the standard deviation of the distribution as a function of the board type. As it can be seen the capacitance does not increase linearly with
Figure 28: Capacitance measurement tool. This tool carries two probes touching the readout strips. (a) Schematics and (b) photo.

![Figure 28](image_url)

Figure 29: Strip capacitance for one type of board. (a) for left connector and (b) for right connector. Some strips in the left connector are not connected by design.

![Figure 29](image_url)

the length of the readout strips. Boards having higher resistivity (LE6, LE7, LS6, LS7, SE6–8) show a lower capacitance (see Figure 31b). To take into account this effect, a correlation was applied to the measurement as shown in Figure 32, where $E$ represents the power of the tool, $R$ is the average between the minimum and the maximum resistance measured at the end of the HV sector, $R_0$ stands for the internal resistance of the tool and $C$ for the capacitance of the circuit. The capacitance ($C$) can be expressed as

$$C = \frac{C'(R + R_0)}{R_0} \tag{1}$$

where $C'$ is the measured capacitance. Since $R_0 \ll R$, Equation 1 is simplified as

$$C \sim C'R \tag{2}$$

9 The average is divided by 47 which is the ratio between the size of the boards and the size of the probe and takes into account that all the strips are in parallel during the capacitance measurement.
Figure 30: Capacitance average for all the readout boards.

Figure 31: Average capacitance (a) and resistance (b) as a function of the board type. The y axis errors corresponds to the standard deviation of each distribution for each specific board type.

Figure 33a shows the values of $C$ as a function of the board type, while Figure 33b shows the value of $C$ as a function of the board length. Even with the large fluctuations a linear trend of the capacitance can be observed.
Figure 32: Equivalent circuit of capacitance measurement

Figure 33: Capacitance ($C$) as a function of the board type (a) and the board length (b). The y axis errors corresponds to the standard deviation of each distribution for each specific board type.
Appendix A  Test to Increase Low Resistivity Foils

The gluing of the Kapton® foil on top of a readout PCB is done under high temperature (170°C) and pressure (12 bars) using pads\(^{10}\) which helps in equalizing the pressure on the surface of the foil (Figure 34). During the last production of the Kapton® foils (in Matsuda), a resistive paste of about 0.3 MΩ/sq\(^{11}\) was used. Most of the foils that were produced have an average resistivity of about the same value but many of them (about 200) have a minimum resistivity of about 0.18 MΩ/sq which is out of the specifications. Due to time constrain in the NSW Micromegas project several tests were performed in order to increase the resistivity of these foils.

![Gluing procedure of a Kapton® foil on top of a readout PCB](image)

Figure 34: Gluing procedure of a Kapton® foil on top of a readout PCB

The test that was performed in ELVIA was to glue some foils with low resistivity (Grade C) and some foils with higher resistivity (Grade A/B) for comparison at higher temperature using another pressing release film\(^{12}\) (see Table 1).

Figures 35 shows the average and the minimum resistivity of the foils respectively at different temperatures. The average and minimum resistivity increased evidently for both grade A/B and C foils from 175°C to 180°C, such that the grade C foils can be classified as A/B.

What is also important is the uniformity of the resistivity along each HV sector. Figure 36 shows the resistivity averaged over the short direction as a function of the position along the long direction for the test at 175°C and 180°C. The non-uniformity between the two different HV sectors at 180°C can be due to a difference of the temperature inside the autoclave. In any case the inhomogeneity is less than 50% and can be tolerated for the operation of the Micromegas detectors.

\(^{10}\)Pacopads\(^{\text{TM}}\)

\(^{11}\)This resistivity value is rather low but still inside the specifications to build NSW Micromegas detectors

\(^{12}\)Pacothane\(^{\text{TM}}\) instead of Pacopads\(^{\text{TM}}\)
Table 1: Type of boards with different grade of foils glued at different temperature.

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<th>Gluing Temperature(°C)</th>
<th>Grade of foil</th>
<th>Board ID</th>
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<td>170</td>
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<tr>
<td></td>
<td></td>
<td>LE6090</td>
</tr>
<tr>
<td>175</td>
<td>A/B</td>
<td>SE8138</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SE8139</td>
</tr>
<tr>
<td>180</td>
<td>C</td>
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<tr>
<td></td>
<td></td>
<td>LE6086</td>
</tr>
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</table>

Figure 35: (a) average and (b) minimum resistivity as a function of the pressing temperature.
Figure 36: Resistivity averaged over the short direction as a function of the position along the long direction. (a) grade C foils tested at 170°C. (b) grade A/B foils tested at 175°C. (c) grade C foils tested at 175°C. (d) grade A/B foils tested at 180°C. (e) grade C foils tested at 180°C. The measurement on each board was repeated 5 times as shown in the legend.
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References


