ATLAS NSW Micromegas readout boards: Industrialisation and Quality Control and Quality Assurance

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Abstract. Micromegas with a spark protection scheme were selected as instrumentation of the first forward muon station in the upgrade of the ATLAS detector for the operation of the Large Hadron Collider at high luminosity. The readout boards carrying the readout strips, the resistive anode strips for spark protection and the mesh distance holders (pillars) are industrially produced in Europe. A detailed quality control and quality assurance scheme has been developed and implemented at CERN to closely follow the industrial production. Up to today, about 2000 readout boards have been checked for their quality in a dedicated test facility at CERN. The detailed procedure, highlighting the crucial aspects leading to the rejection or acceptance of an anode board, as well as the statistical overview of the results will be presented.

1. Introduction to the project
One of the most relevant ATLAS Phase-I upgrades, to take place in the 2019-2021 LHC shutdown, is the New Small Wheels project [1]. It consists in the replacement of all detectors currently installed in the innermost forward muon station of the ATLAS experiment. New detectors have been designed to operate in the harsh high luminosity environment expected in future LHC runs: the small-strip Thin Gap Chambers (sTGC), mainly devoted to trigger purposes, and the resistive Micromegas [2], devoted, on the other hand, to high precision tracking.

Each of the two New Small Wheels consists of 16 sectors, 8 small and 8 large overlapping in azimuthal angle with each other. Each sector consists of 2 Micromegas and 2 sTGC wedges. A Micromegas wedge is divided radially into two modules (SM1, SM2 for the small sector and LM1, LM2 for the large sector); each module contains four layers of Micromegas detectors, grouped into two pairs (quadruplet). The location of the Small Wheels in the ATLAS muon spectrometer and a cutaway of the wheels, wedges and Micromegas quadruplet design described above are shown in Fig. 1.

To build a Micromegas quadruplet two readout panels and three drift panels are needed. Details on the construction technique can be found at Ref. [3]. The readout panel carries the most important part of the detector: the readout boards. The drift panel comprises the drift electrode, the micro-mesh and the gas distribution system. To equip two New Small Wheels 2048 readout boards are needed, of 32 different types from the smallest S1 (Eta/Stereo) to the largest L8 (Eta/Stereo). Eta and Stereo boards differ for the inclination of the readout strips:
Figure 1: In the top left the location of the Small Wheels in the ATLAS Muon spectrometer is indicated. Moving to the right, the New Small Wheel sector design and a wedge cutaway are shown. In the lower part, to the right, the segmentation of the Micromegas readout panels in three or five readout boards is reported, while the left image shows the structure of a Micromegas quadruplet.

in the Stereo boards they are tilted by ±1.5 degrees, to allow the measurement of both the $\eta$ and $\phi$ coordinate.

2. Readout boards production

The readout boards represent one of the biggest technological challenges of the project. They integrate the readout copper strips, and the resistive protection schema, composed of a Kapton® insulating layer on which resistive strips, the anode of the detector, are screen-printed. On the resistive strips $\sim$120 $\mu$m high pillars are laminated defining the anode-to-mesh distance, representing the amplification gap. The metallic mesh (cathode) is then coupled to the readout board at the detector assembly and sits on the pillars, pulled by electrostatic force when HV is applied. The structure of a readout board is shown in Fig. 2.

Resistive layers are produced in industry by Matsuda-Screen Inc. (Japan) and undergo a deep quality control at Kobe University. Readout boards are also manufactured in industry, ELTOS (IT) and ELVIA (FR), involving several non-standard procedures. Since most PCB industry is limited to 600 mm wide PCBs, the size of the PCBs has been kept in one dimension below 600 mm while the other dimension can be up to 2500 mm, as in the case of L8 boards. The production of the readout boards involves several steps as illustrated in Fig. 3:
• Starting from the base material (fiber glass epoxy (FR4) with a 17 µm copper layer), the copper is etched via photolithography in order to create the readout strips.

• The resistive protection layer (50 µm thick Kapton® foil with screen-printed resistive strips) is glued under high pressure and temperature on top of the readout strips with a 25 µm thick layer of glue.

• On top of the resistive strips, the pillars are created after lamination of a double layer of 64 µm thick photoimageable coverlay via a photo-lithographic process. Pillars have a rectangular shape of 1000 µm in length and 200 µm in width, placed perpendicularly to the strips. The average measured pillar height is 120 µm.

3. Readout boards QC

Readout board components, such as resistive foils, and bare material, are, at first, shipped to CERN and then dispatched to the two producers. Once ready, boards are then delivered to CERN where they undergo a deep Quality Control 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 Collaboration are used to build detectors.

Tests are organized in several stages, or desks, as the one shown in Fig 4; all the results are saved in a dedicated database through a web interface for later use. The most relevant QC tests performed are listed below:

• Visual inspection: board surface is checked for any kind of irregularities such as surface dents, bumps, enclosures, damages of the coverlay or its surface, scratches and blemishes in the resistive layer as well as structural damages of the FR4 board. Electrical tests, such as insulation and conductivity, are also performed at this step.

• Backlight inspection: boards are checked for lack of pillars (detached pillars are replaced with new ones glued in their place), hole drilling precisions and accuracy in the PCB edge cutting.

• Dimension test: size of the board is measured via CCD surveyors and dedicated masks.

• Pillar height measurement: board pillar height is measured by sampling homogeneously on the board surface with a gauge tool.

• Resistivity tests: strip resistivity is measured and compared with reference values.

• Capacitance test: a capacitance measurement between neighbouring readout strips is performed with a dedicated tool to identify cut strips as well as strips with a direct connection to one of their neighbours.

Figure 4: Visual inspection desk equipped with stereo microscope.
3.1. **Visual inspection**

Visual inspection is devoted to investigate all the possible defects that could cause HV instabilities. Bumps on the anode surface caused by enclosures in the resistive material or trapped under the Kapton® are a potential weakness for HV stability, reducing the distance between electrodes in the amplification gap as shown in Fig. 5a. Bumps are measured with a gauge tool having a resolution of few µm. Bumps up to 10 µm can be tolerated; if higher, local passivation of the region can be performed by encapsulating the bump in a coverlay disk as shown in Fig. 5b. Visual tests consist also in detecting PCB edge damages, or any damage of the resistive foil affecting the insulating Kapton® layer that would compromise the insulation between resistive and readout strips. If the insulation is broken, no reparation can be performed and the board cannot be used. The insulation between resistive and readout strip is also tested with a Megger® insulation tester.

3.2. **Pillars tests**

The amplification gap is defined by the height of the pillars, one of which is shown, as seen at the stereo microscope, in Fig. 6. The detector amplification can be affected, as already described, by bumps on the active area, but also by missing pillars, or even by the non-homogeneity of the pillar height. In this latter case the anode-to-mesh distance is not homogeneous, leading to region at higher amplification than others. This effect introduces a possible weakness for detector operation. Height inhomogeneities or smaller values than the nominal have been found to be mainly due to insufficient curing of the coverlay material. Then, by means of a tool composed of a stainless steel holder (resting on top of the pillars) and four precision length gauges (touching the anode and thus measuring the relative distance to the planes), the board surface is scanned aiming to produce a map of the pillars height as shown in Fig. 7a.

Figure 7b shows the average pillar height as a function of the board type: the mean value is within ±1 µm with a maximum fluctuation of ±8 µm observed with respect to the nominal value.

3.3. **Dimension test**

The FR4 PCB base material 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
Figure 7: (a) Bi-dimensional map of the pillar height as a function of the position. (b) Average pillar height as a function of the board type. Error bars refer to the minimum and maximum value of the average pillar height per board.

rescaled by about -0.4 mm/m to account for this effect. The rescaling factors are 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 board dimensions are measured with CCD surveyors with 25 µm accuracy. An elongation with respect to the design reference of 100 µm on the short dimension is accepted. Looser requirements are set for the long dimension. Figures 8a and 8b show the elongation of the short (precise) and long dimensions respectively, obtained on the boards measured so far as a function of the board type. Error bars refer to the RMS of the elongation distribution.

Figure 8: Elongation as a function of the board type for the short dimension (a) and long dimension (b). Error bars refer to the RMS of the elongation distribution.

3.4. Resistivity measurement

The resistivity of the screen-printed resistive foil has been tuned to balance particle rate capability, lower voltage drop at high current and resolution performance. At the companies, the glueing of the resistive foils on the FR4 is performed at very high temperature and pressure conditions. A large change in the resistivity can occur due to a problem in the production: pressing and polishing issues, resistive paste not fully cured, mechanical stress. The full mapping of the anodes surface resistivity, as the one shown in Fig 9a, is performed directly after the resistive foil production and again during the acceptance QC at CERN.
The surface resistivity is obtained measuring the resistance between two well-defined probes connected to the anode surface taking into account the geometry of the probes and the size of the board. The typical measured resistivity ranges from 0.3 to 2.5 MΩ/cm², but large increases (a factor of 3 or more), as in the case shown in Fig. 9b, have been also observed in some boards. Depending on the value of the resistance and on the size of the PCB, boards can be discarded.

Figure 9: Bi-dimensional distribution of the resistivity as a function of the board position (a). An example of large resistivity changes in a resistive foil before and after the glueing of the PCB (b).

3.5. Capacitance test
Copper readout strips are not visible by eye and not accessible by electric probes, being hidden below the resistive pattern and the Kapton® layer. Their integrity is checked by measuring the capacitance between each readout strip and the resistive line. The expected capacitance depends on the length of the readout strips (about 100-150 pF), so on the board type, but for cut strips it shows a very low value (close to 20 pF).

4. Conclusions and acknowledgements
More than 2000 boards have been produced and tested in the context of the New Small Wheels project so far since April 2017, keeping a steady rate since beginning 2018, as shown in Fig. 10. More than 1000 boards have been already delivered to the chamber construction sites, enough to fulfil the requirement to build the first complete wheel. The yield of accepted board is about 75%.

The quality control of readout boards has been, and still is, a crucial task for the success of the whole New Small Wheel project. A major acknowledgement goes to the CERN Muon group for the huge effort put in these years to cope with all the difficulties that have been encountered.

References
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