Large Area Precision Cathode Boards for ATLAS Muon Upgrades

Dan Shaked Renous[1] & Damian Sheppard[2]
on behalf of the ATLAS collaboration

[1]Weizmann Institute of Science, Rehovot, Israel
[2]TRIUMF, Vancouver, British Columbia V6T 2A3, Canada

Small-strip Thin Gap Chambers for the ATLAS New Small Wheel

The largest phase-1 upgrade project for **the ATLAS Muon System** (Figure 1) is the replacement of the present first station in the forward regions with the so-called New Small Wheels (**NSWs**) during the long-LHC shutdown in 2019/20.

The NSWs (Figure 2, left) will be equipped with 8 small and 8 large sectors. Each sector contains eight layers of small-strip thin gap chambers (**sTGC**) arranged in two wedges, pivot and confirm, for a total active surface area of more than 2500 m^2. The small and large wedges (Figure 2, middle and right respectively) will consist of three quadruplets,.

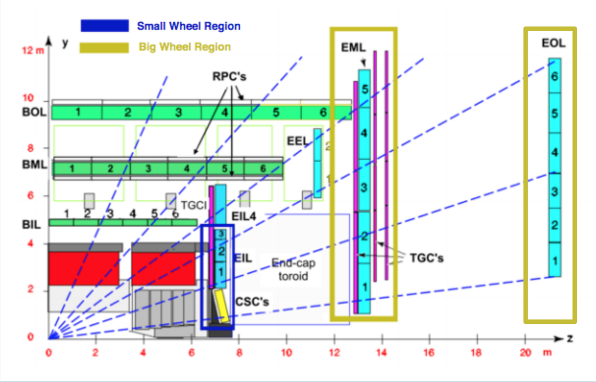

Figure 1: Cross section of one forth of the ATLAS Muon system. The Small Wheel region is marked in a blue frame

The sTGC detectors (Figure 3) consist of a grid of 50 µm gold plated tungsten wires at potential at the order of 2.9 kV, with a 1.8 mm pitch, sandwiched between two cathode planes at a distance of 1.4 mm from the wire plane. The cathode planes are made of a graphite-epoxy mixture with a typical surface resistivity of 100-200 kΩ/square sprayed on a 150-200 µm thick G-10 plane, behind which there are on one side precision strips (that run perpendicular to the wires and have 3.2 mm pitch) and on the other pads (covering large trapezoidal surfaces), on a 1.6 mm thick printed circuit board (PCB) with the shielding ground on the opposite side. **The sTGC cathode boards** have trapezoidal shapes with surface areas up to 2 m^2.

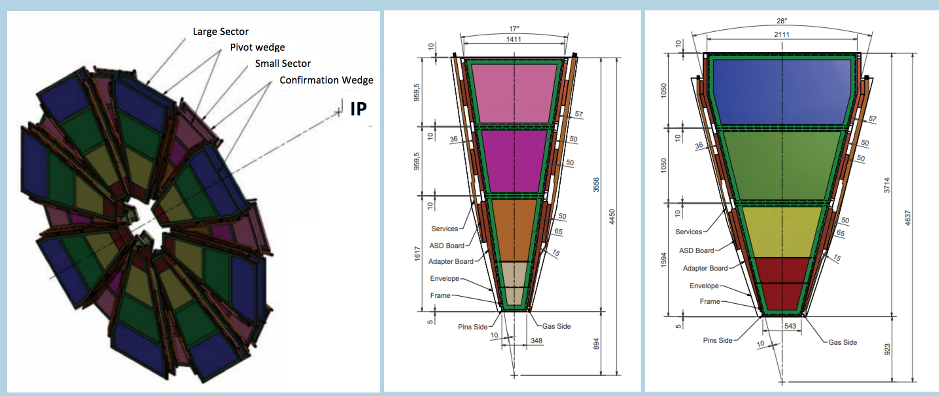

Figure 2: Left: The NSW layout. Middle: The layout of the small sTGC wedge. Right: The layout of the large sTGC wedge.

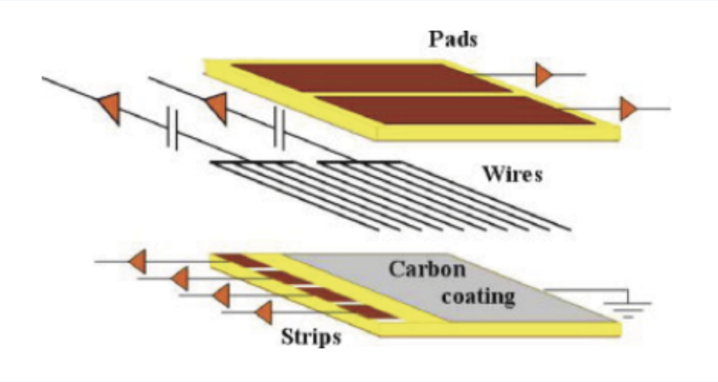

Figure 3: Schematic description of the sTGC detector

sTGC chambers – Precision requirements

The precision requirements imposed on the sTGC cathode boards are derived from the required muon momentum resolution at the trigger and tracking levels:

- Trigger level: track segments should be measured with an angular resolution of approximately 1 mrad.
- Tracking level: 15% p_T resolution for 1 TeV muons.

The muon spectrometer measures the momentum of muons through their sagitta in the toroidal magnetic field. The sagitta of a 1 TeV muon of 500 µm should be measured to 10% precision.

For three equidistant wheels, $i = 1,2,3$, the sagitta can be approximated as $S = (k_1 + k_3)/2 - k_2$, where k_i is the measured precision coordinate in each wheel. The error is dominated by the measurement accuracy in the middle station $\Delta S = \sqrt{\frac{1}{4}\Delta k_1^2 + \Delta k_2^2 + \frac{1}{4}\Delta k_3^2}$ allowing for somewhat poorer precision in the NSW (wheel 1) relative to the precision chambers in the two big wheels (wheels 2 and 3, see Figure 1).

The error in each wheel has three main contributions: the construction precision, the precision of each hit measurement and the relative alignment between the layers: $\Delta k_i = \sigma_{chamber} \oplus \sigma_{hit}/\sqrt{n} \oplus \sigma_{alignment}$.
Given the sTGC hit precision (better than 100 µm), and the alignment precision in ATLAS (about 40 µm), the needed precision can be achieved with an accuracy of **40 µm RMS along the precision coordinate** (strip position) **and 80 µm RMS along the beam direction**.

Cathode boards – Precision requirements

The precision to which the strips and pads patterns are positioned onto the boards has a key importance for enabling a precise measurement by the assembled quadruplet. The cathode boards are produced in industry by either CNC machining or chemical etching of copper plated FR4 boards. An insulating pre-preg layer is pressed on top of the copper readout elements. Material flow of the underlying FR4 boards during the cathode board mechanical and chemical manufacturing along with pressing have been found to have significant impact on the placement of the copper read-out elements. This production feature leads to different kinds of potential non-conformities, i.e. the difference between the design and the actual strip/pad patterns.
Production tolerances are defined for four non-conformities:

constant offset by which the entire strip pattern is moved up/down along the y-axis
pitch scale for which the distance between adjacent strips changes gradually while the new pattern stays parallel to the original one
non-parallelism for which the distance between adjacent strips changes gradually, e.g. at only one edge of the layer, braking the parallelism of the original pattern
rotation in the x y plane where the entire pattern is rotated around a certain axis during manufacturing of the layers, e.g. around the axis defined by brass insert

In addition, the position in the beam direction is controlled through the board thickness and flatness.

The tolerances specified for the production are based on the producers capabilities and are summarized in Table 1. They are insufficient for achieving the required tracking momentum resolutions. This depends on software correction. Thus, as part of the QA/QC procedure, each strip board is measured with CMM or FaroArm, the values of the non-conformities are stored in the data base to be in reconstruction.

Table 1: production tolerances checked as part of the cathode board QA/QC procedure

Parameter	Limit		Remark
	GS1, GL1 boards	GS2, GS3, GL2, GL3 boards	
Average thick-ness*	Within +- 75µm from nominal		For pad and strip boards
Flatness**	(Max – Min)/2 <= 35µm		For pad and strip board
Angle θ deviation from nominal	<= 0.01°	<= 0.005°	For strip boards
Offset Δ	<= +-300µm	<= +-300µm	For strip boards***
Scale s	<= +-400µm	<= +-400µm	For strip and pad boards***
Parallelism	<=+-400µm	<= +-400µm	

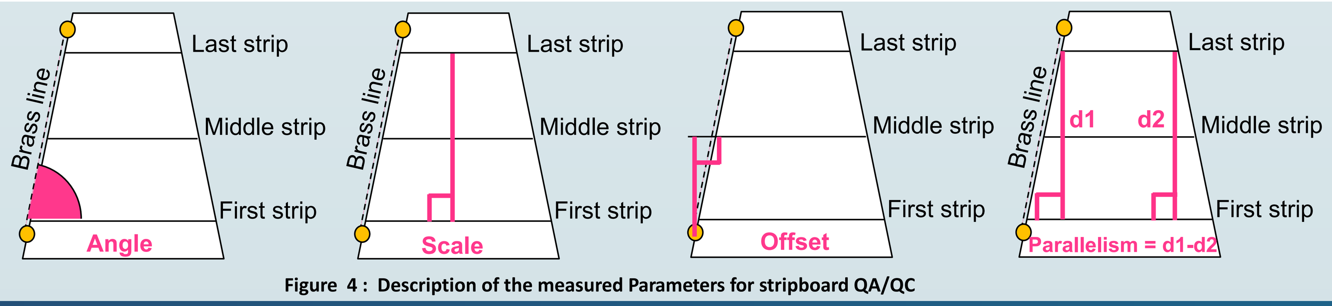

Figure 4: Description of the measured Parameters for stripboard QA/QC

Cathode board production

Two production lines: one based on chemical etching and the other on CNC milling. QA/QC assurance tests are performed all along the production. They include visual inspections, electrical tests and dimension measurements (see QA/QC Tests).

CNC production line @ MDT/DAGESH or MDT/Nuova Saltini*
Step 1: Production of raw material @ MDT Italy;
Testing @ Weizmann Israel: classification and type of board are decided (strip/pad).
Step 2: CNC milling @ Dagesh Israel; Testing @ Weizmann Israel.
Step 3: Pre-preg pressing @ MDT Italy;
Testing and @ Weizmann Israel: repeat set of tests and repair.
Step 4: Packaging and shipping to the production sites.

* Boards produced by MDT/Nuova Saltini are only tested after step 3

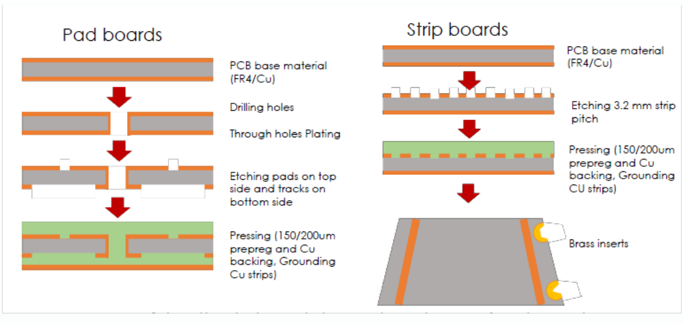

Figure 5: Production Steps for pad and strip boards

Etching production line @ Triangle Labs USA: (Figures 5-8)
Step 1: Precision tooling reference holes are drilled for pre-preg and cores
Step 2: Vias are added though drilled plated through holes (PTH) and electro copper plating (Figure 6)
Step 3: Board cores are laminated in blue dry film
Step 4: A laser direct imaging machine (LDI) activates the laminate where the copper is desired (Figure 7 and Figure 8)
Step 5: Developer removes laminate not activated by the LDI (Figure 8)
Step 6: An etcher removes the copper chemically (Figure 8)
Step 7: Stripping machine removes the remaining dry film (Figure 8)
Step 7: Core used in pre-preg pressing of boards in specific layup configuration
Step 8: After pressing boards are mounted using the references holes and brass inserts and board perimeter are cut using a precision drilling machine (Figure 8)

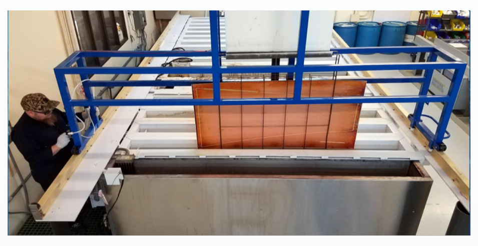
Figure 6 : Plated through holes

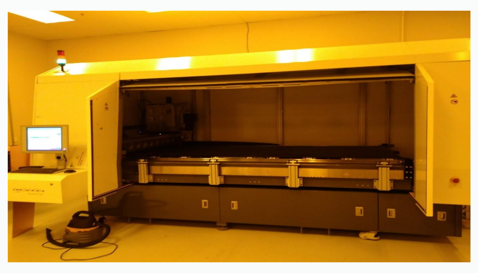
Figure 7: LDI machine

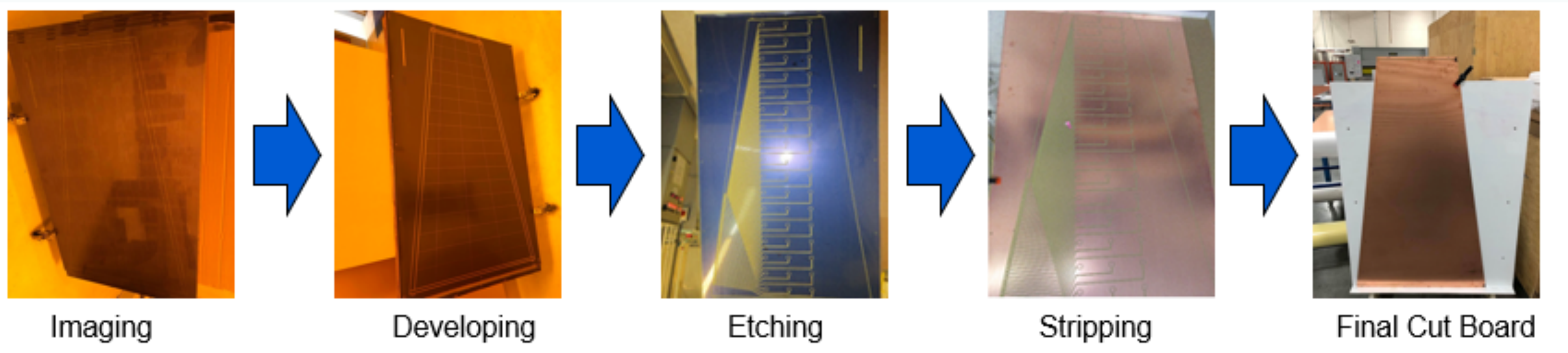

Figure 8: Production Steps at Triangle Labs

QA/QC Tests

Common QA/QC procedures :
- Visual Inspection
- Thickness Measurements (Figure 9)
- Electrical Testing (Figure 9)
  - High Voltage Shorts
  - Capacitance
  - Conductivity

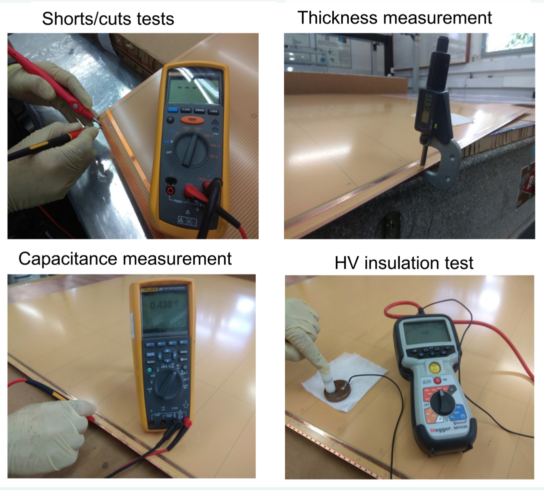

Figure 9: Cathode boards production QA/QC tests.

Other QA/QC procedures at Triangle Labs
- Dimensional Measurements with Coordinate Measurement Machine (CMM) (Figure 10)

Other QA/QC procedures at Weizmann
- Dimensional Measurements with Faro Arm (Figure 11)

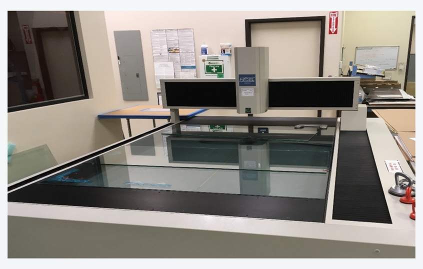
Figure 10: Coordinate Measurement Machine.

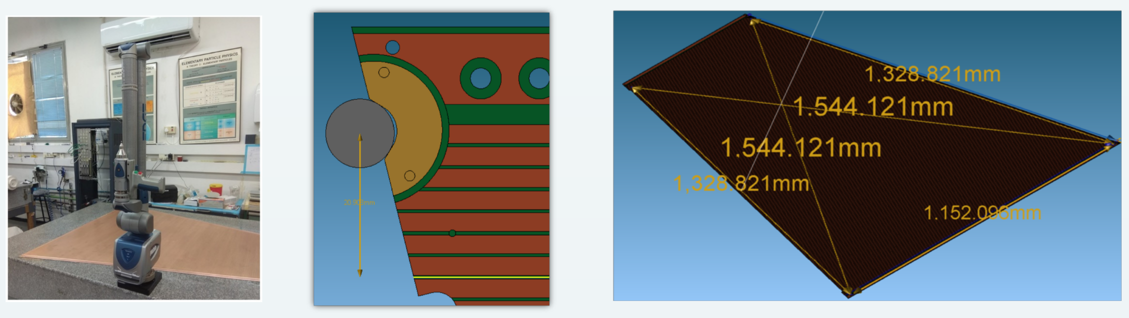

Figure 11: Dimension measurements. Left: the FaroArm 3D measurement instrument. Middle: measurement of the scale parameter. Right: measurement of the boards dimensions.

sTGC – from precise cathode boards to precise system

To achieve precision resolution the strip boards are referenced to the outside using brass features (Figure 12). These are used along all the assembly steps.

Cathode boards:
The misalignment is measured with respect to the brass features.
Quadruplet assembly:
The four layers are pushed against a single alignment pin, thus aligned with respect to the brass feature.
Relative misalignment between the layers are measured either using a microscope or a FaroArm (Figure 13) and stored in data base for offline analysis
Wedge assembly:
The three quadruplets are pushed against alignment pins using the same brass features (Figure 14).

Incorporating into the ATLAS coordinate system:
Local wedge alignment transferred to ATLAS alignment system based on precision measurements relative to the brass features (Figure 15).

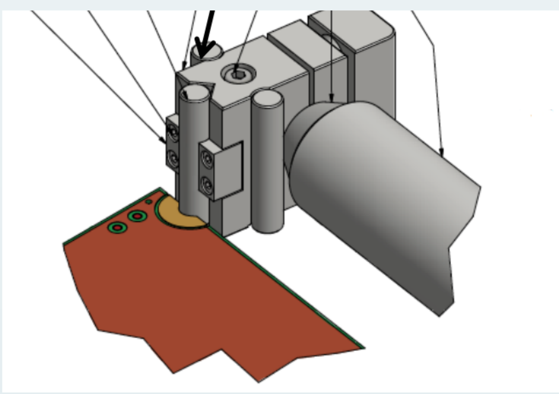
Figure 12: Brass features pressed against the alignment pins.

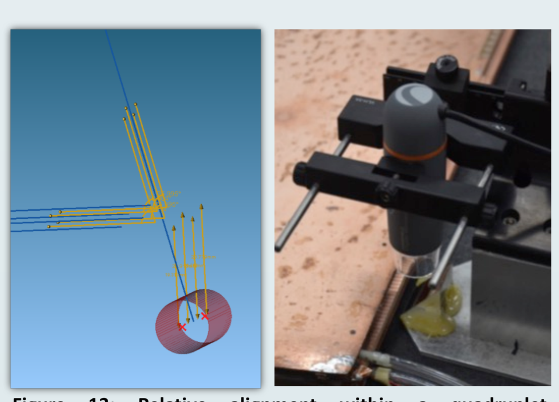
Figure 13: Relative alignment within a quadruplet. Measurement conducted with a FaroArm (Left) and Microscope (Right).


Figure 14: Wedge assembly. The brass features pushed against the alignment pins are marked in red circles

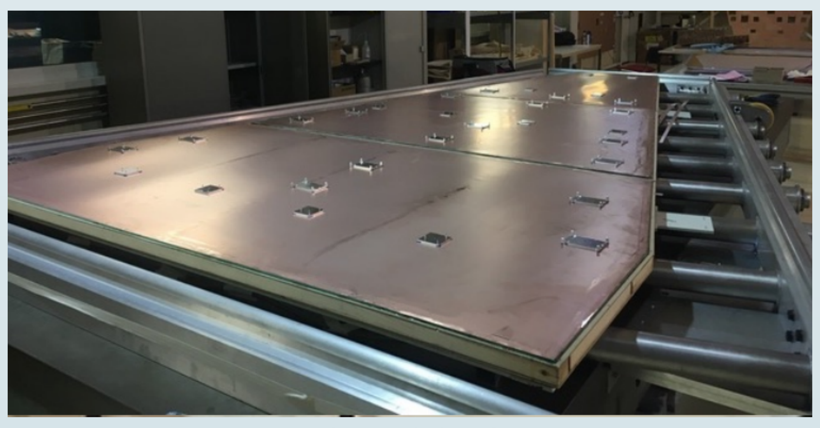
Figure 15: precision measurements relative to the brass features