PROCEEDINGS OF SCIENCE

Small-Strip Thin Gap Chambers for the Muon Spectrometer Upgrade of the ATLAS Experiment

Benoit Lefebvre[*a] **on behalf of the ATLAS Muon Collaboration**
[a]*TRIUMF*
4004 Wesbrook Mall
Vancouver, BC, V6T 2A3
Canada
E-mail: benoit.lefebvre@cern.ch

The instantaneous luminosity of the Large Hadron Collider at CERN will be increased by about a factor of five with respect to the design value by an extensive upgrade program over the coming decade. The largest Phase-1 upgrade project for the ATLAS Muon System is the replacement of the present inner station in the forward regions with the New Small Wheels (NSWs) during the long LHC shutdown in 2019/20. Along with Micromegas, the NSWs will be equipped with eight layers of small-strip Thin Gap Chambers (sTGC) arranged in multilayers of two quadruplets. To retain the good precision tracking and trigger capabilities in the high-background environment of the high luminosity LHC, each sTGC plane must achieve a spatial resolution better than 100 μm to allow the Level-1 trigger track segments to be reconstructed with an angular resolution of approximately 1 mrad. The sTGC design, performance, construction and integration status will be discussed, along with results from tests of the chambers with nearly final electronics with beams and high-intensity radiation sources.

XXIX International Symposium on Lepton Photon Interactions at High Energies - LeptonPhoton2019
August 5-10, 2019
Toronto, Canada

[*]Speaker.

PoS(LeptonPhoton2019)071

1. Introduction

The instantaneous luminosity of the Large Hadron Collider (LHC) at CERN will be gradually increased following major upgrades of the accelerator complex planned over the next decade. In particular, the LHC will reach its High-Luminosity (HL-LHC) configuration in 2026 after which a luminosity of at least $\mathscr{L} = 5 \times 10^{34}$ cm^{-2}s^{-1} will be achieved, a 5-fold increase compared to the nominal value.

Ambitious upgrade projects for ATLAS [1] are planned to fully benefit from the challenging high-luminosity data taking periods and maximise the discovery potential of the experiment. The Phase-1 upgrade of ATLAS will be carried out during the LHC Long Shutdown 2 of 2019/20. A major aspect of the Phase-1 upgrade consists of the replacement of the end-cap inner (EI) station of the ATLAS Muon Spectrometer in the forward regions by the New Small Wheels (NSWs) [2]. Half of the new muon detector modules installed during the upgrade are small-strip Thin Gap Chambers (sTGC).

2. Challenges of High-Luminosity Data Taking

The ATLAS Level-1 (L1) trigger rate is observed to increase linearly as a function of the instantaneous luminosity and is expected to surpass the available bandwidth during HL-LHC operations. In particular, extrapolations based on current ATLAS data have shown that the single-muon trigger rate for low transverse momentum (typically $p_T > 20$ GeV) will reach an unacceptable level. As shown in Fig. 1, a large fraction of the single-muon L1 triggers currently originate from the forward regions and approximately 90% of those triggers could not be matched to a $p_T > 10$ GeV muon after offline reconstruction. These spurious triggers are *fake muons* that consist of low energy particles generated in the material between the Inner and Middle stations where the end-cap toroid magnets are located.

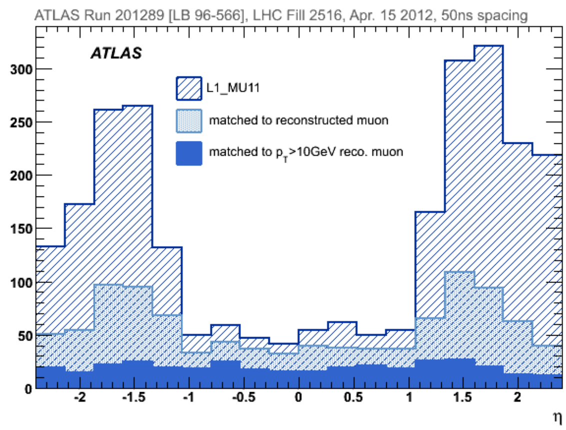


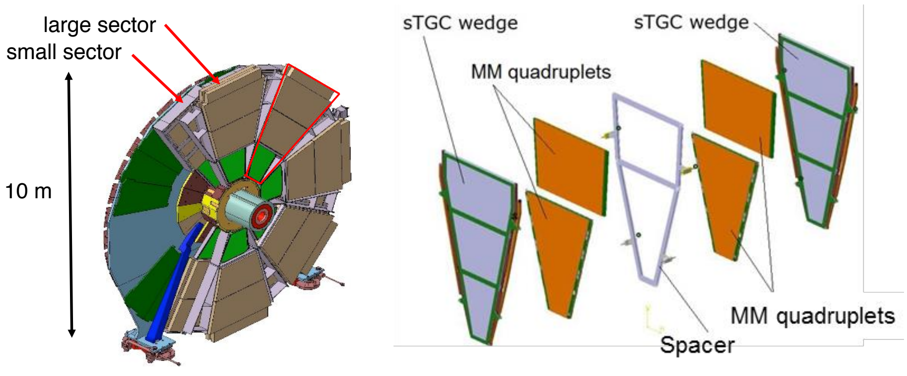
Figure 1: Distribution of the number of single-muon L1 triggers identified with $p_T > 10$ GeV as a function of pseudorapidity compared to the number of those triggers which are associated to a muon reconstructed offline. [2]

The proposed solution for moderating the L1 trigger rate without raising the associated p_T thresholds is by improving the online muon identification in the end-cap regions. The present end-cap muon trigger algorithm uses hits from the middle station only. After the Phase-1 upgrade and onwards, the trigger algorithm will use, in addition, hits from the EI station. Candidate-muon track segments will be reconstructed online by the EI station. Only reconstructed track segments that point to the interaction point and match the middle station measurements will result in a L1 trigger. This enhanced trigger algorithm was shown by simulation studies to significantly reduce the single-muon L1 trigger rate while keeping the muon efficiency the same using the present p_{T} thresholds.

The new trigger algorithm requires a muon EI station to deliver candidate-muon track segments with an angular resolution better than 1 mrad. The time jitter of detector hits must be better than 25 ns for accurate bunch crossing identification. The spatial resolution of the muon-trajectory space points must be sufficient to maintain the current transverse momentum resolution of the Muon Spectrometer in the end-caps, currently 15% for 1 TeV muons. This requirement translates to a radial spatial resolution better than 100 µm per detector plane for multiplets of 8 layers. These performance specifications must hold up to the maximum expected background rates during HL-LHC operations. The current EI-station detector modules cannot fulfil those specifications and therefore will be replaced by the NSWs as part of the Phase-1 upgrade.

3. The New Small Wheel

The NSW, shown in Fig. 2(a), is a disk-shaped arrangement of detector modules made up of 8 large and 8 small pie-shaped sectors. The sectors combine the sTGC and Micromegas technologies. As shown in Fig. 2(b), each sector has 2 sTGC wedges on the outside with Micromegas wedges in between. Each sTGC wedge has 3 sTGC modules that are quadruplets made up of 4 independent detector planes.



(a) (b)

Figure 2: (a) The NSW layout with the perimeter of a large sector shown with a red line and (b) one sector made up of 2 Micromegas wedges between 2 sTGC wedges.

An sTGC is a multiwire chamber that operates with a gas mixture of n-pentane vapour and CO_2, a highly quenching gas mixture for operations at high gas amplification. The gas volume is contained between 2 resistive cathode planes that consist of FR4 covered with a copper clad laminate, a capacitive pre-preg, and a graphite resistive coating. Gold-plated tungsten anode wires are stretched with a pitch of 1.8 mm in the gas volume, larger than the anode-to-cathode spacing which is 1.4 mm. The high voltage applied to the anode wires is typically 2.8 kV. The copper on cathode boards is engraved with thin 3.2 mm readout strips on one side of the gas volume and readout pads of area varying between 10 and 500 cm^2 on the opposite side. Cathode strips are used for the precise radial measurements of the muon trajectory and pads for strip readout trigger [3]. The sTGC anode wires are ganged in groups of 20 and are read out for coarse azimuthal measurements of the muon trajectory. The sTGC technology features excellent tracking capabilities [4] and very small time jitter. A good hit efficiency is expected up to the radiation levels foreseen during HL-LHC operations.

4. sTGC Construction

The manufacturing of sTGC modules takes place in 5 independent production lines located in Canada, Chile, China, Israel and Russia, each responsible for different module types. The assembly of sTGC modules into wedges is carried out at CERN.

Manufactured modules are large, with surface areas varying between 0.7 and 2.3 m^2, while requiring very precise positioning of readout elements. Therefore, every step of the assembly must follow a stringent quality control procedure whereby parts with unacceptable non-conformities in planarity, thickness or positioning of readout elements are rejected. A precise dimensional control of readout elements is also performed such that deviations of detector features with respect to nominal are known within 40 µm in the radial coordinate and 80 µm along the beam pipe. As part of the dimensional control, non-conformities of the cathode strip pattern are measured with coordinate-measuring machines. The precision positioning of individual gas volumes during gluing is achieved using reference brass inserts attached to the side of the strip cathode boards.

As part of the quality control procedure, gas volumes are scanned with X-rays to check the uniformity of the gas amplification. The connectivity of the signal lines is checked with a pulser test which consists of injecting pulses in the module high-voltage line while reading out the signal induced at the level of the signal lines. Finished modules are tested with cosmic rays to check for the uniform response of all readout channels and to measure the relative alignment of detector planes. Upon reception at CERN, modules are tested at the GIF++ [5] irradiation facility to identify possible issues under a high-background environment. Finished wedges are tested for at least 2 months with high voltage to check if stable long-term operations can be achieved. The quality control tests provide a good characterization of the sTGC modules and wedges which will be an asset during ATLAS running and event reconstruction.

The position of sTGC wedges in the ATLAS coordinate system is measured with an optical system that combines reference platforms holding light fibres and CCD cameras attached to the NSW frame. The position of cathode strips with respect to the alignment platforms is obtained from an X-ray scan performed after wedge assembly.

5. sTGC Readout Electronics

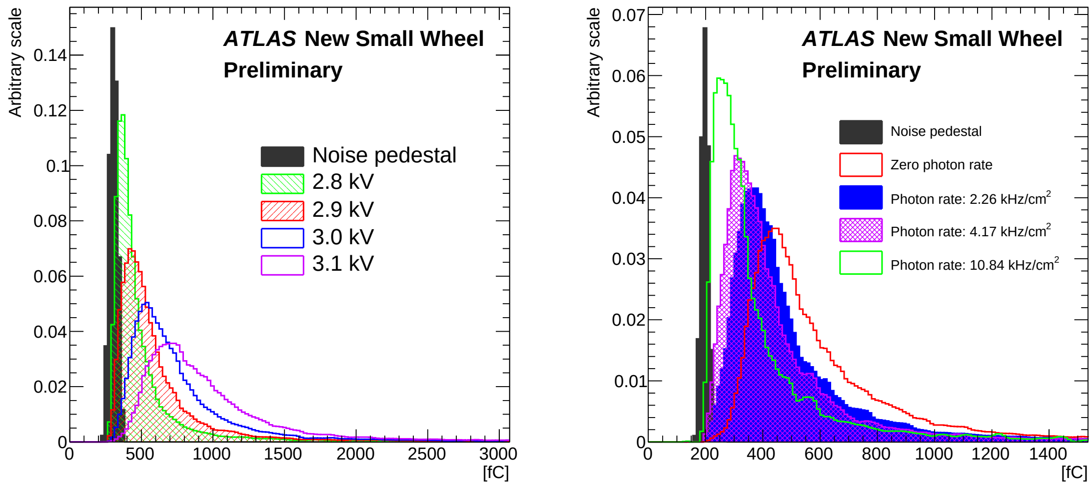
All NSW detectors, including Micromegas, are read out using the VMM amplifier-shaper-discriminator ASIC [6]. Front-end boards (FEBs) designed specifically for sTGC readout provide

PoS(LeptonPhoton2019)071

the necessary digital communication to the VMM and analogue connectivity to sTGC readout elements. The FEBs are equipped with 3 or 8 VMMs depending on the exact type. In turn, each individual VMM handles up to 64 readout channels.

The VMM is a highly configurable and versatile ASIC designed to read out various types of readout electrodes such as sTGC strips, pads and wires. Nevertheless, analogue filters are fitted to the VMM analogue inputs on the FEBs for a better handling of the sTGC signal. Studies were carried out in parallel to the FEB design in 2018/19 to optimize the filter components and validate the overall front-end electronics design.

The FEB charge response was measured using production sTGC modules during beam test campaigns at CERN. The collected charge distribution for different high voltage values with muons at the H8 beamline for a pad channel is shown in Fig. 3(a). Similar charge distributions, shown in Fig. 3(b), were obtained at the GIF++ irradiation facility for different levels of gamma irradiation. A sufficient separation between noise and the minimum ionizing particle signal is observed up to a background radiation of 10 kHz/cm^2 and at a high voltage of 2.8 kV, the target for ATLAS operations. Furthermore, little to no saturation is observed in the charge spectrum.



(a) (b)

Figure 3: Charge distribution from a sTGC pad at (a) the H8 beam line and at (b) the GIF++ facility.

The strip spatial resolution was also measured at the CERN H8 beamline using a production module. The resolution was obtained in-situ for muons injected perpendicularly to the module. The muon position was obtained using the centroid position of the charge profile of strips above threshold. Muon space points were corrected for inter-layer misalignments and differential non-linearity. All correction parameters are obtained in-situ using beam data. As shown in Fig. 4, a spatial resolution better than 100 μm was measured at the nominal high voltage of 2.8 kV which indicates adequate performance to maintain the current p_{T} resolution of the muon spectrometer.

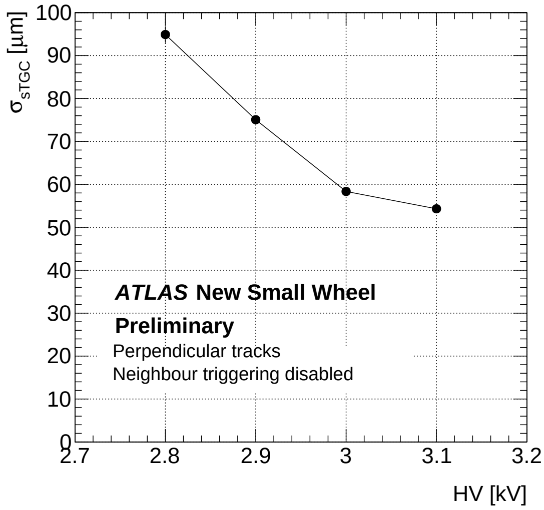


Figure 4: Intrinsic strip spatial resolution measured at the H8 beam line.

6. Conclusion

The NSW is crucial for ATLAS to maintain a good trigger efficiency and momentum resolution in the high rate environment expected for high-luminosity running. Module and wedge production is ongoing in the 5 international production lines and at CERN. Several small wedges have been produced and the production of large wedges will begin shortly. The design of front-end electronics was finalized following intense optimization campaigns. The installation of front-end electronics on the wedges will start during Fall 2019. The NSW structure and services, which include high voltage cables, cables for digital communication, cooling and gas pipes, are ready for sector integration. The installation of a first sector in the NSW frame is planned for Fall 2019. The commissioning of the first NSW in the ATLAS cavern is scheduled for August 2020.

References

[1] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, *J. Instrum* **3** (2008) S08003.

[2] T. Kawamoto, S. Vlachos, L. Pontecorvo, J. Dubbert, G. Mikenberg, P. Iengo et al., *New Small Wheel Technical Design Report*, CERN-LHCC-2013-006. ATLAS-TDR-020, Jun, 2013.

[3] L. Guan, *Trigger algorithms and electronics for the ATLAS muon new small wheel upgrade*, *J. Instrum* **11** (2016) C01083.

[4] A. Abusleme, C. Bélanger-Champagne, A. Bellerive, Y. Benhammou, J. Botte, H. Cohen et al., *Performance of a full-size small-strip thin gap chamber prototype for the ATLAS new small wheel muon upgrade*, *Nucl. Instrum. Methods Phys. Res. A* **817** (2016) 85 .

[5] S. Agosteo, S. Altieri, G. Belli, A. Bonifas, V. Carabelli, L. Gatignon et al., *A facility for the test of large-area muon chambers at high rates*, *Nucl. Instrum. Methods Phys. Res. A* **452** (2000) 94 .

[6] G. Iakovidis, *VMM3, an ASIC for Micropattern Detectors*, ATL-MUON-PROC-2018-003, CERN, Geneva, Mar, 2018.