PROCEEDINGS OF SCIENCE

Performance of the ATLAS New Small Wheels in preparation for LHC Run-3 data-taking

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The Muon Spectrometer of the ATLAS detector has recently undergone a major upgrade in preparation for operation under experimental conditions foreseen at the High-Luminosity LHC (HL-LHC). Two New Small Wheels (NSW) have been constructed and installed to replace the innermost muon station in the high-rapidity regions of the ATLAS detector. This new system is designed to provide improved muon trigger momentum resolution and fake rate rejection in the forward region of the detector, to maintain the current ATLAS physics capability under the higher background environment of HL-LHC. The NSW has an active area of more than 2400 m^2 and is equipped with multiple layers of two novel detector technologies: small-strips Thin Gap Chambers (sTGC) and resistive Micromegas (MM). With such a large active area, the ATLAS NSWs are the first large-scale use of Micromegas technology in high-energy experiments. The latest results from the commissioning of the NSW in preparation for the LHC Run-3 data-taking, as well as initial performance measurements, will be shown.

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1. Introduction

The Muon Spectrometer (MS) of the ATLAS experiment [1] at the CERN LHC consists of three detector stations both in the barrel and the forward regions. Before LHC Run-2 ended in 2018, muon momentum measurements were achieved by tracking muon bending in the Toroid Magnet using Monitored Drift Tubes (MDTs) equipped at three muon detector stations. Muon triggering in the forward region solely relied on the coarse track segment measurements by the Thin Gap Chambers (TGCs) in the middle detector station, which resulted in the triggering of a large fraction of low-energy background particles generated in the materials between the innermost and the middle stations. To profit from a series of LHC accelerator complex upgrades towards High Luminosity LHC (HL-LHC) with an expected instantaneous luminosity of 5-7 times the nominal design value (1×10^{34}cm$^{-2}\cdot$s^{-1}), the ATLAS experiment has just completed its largest-scale upgrade to its MS during the LHC Long Shutdown 2 (LS2) which ended in 2021. The upgrade replaces the innermost station of the MS in the forward region with the New Small Wheel (NSW) detectors [2] to prepare ATLAS for precision studies of Higgs boson and new physics searches at multi-TeV scale in a harsher radiative environment. The NSW detectors are expected to provide track segment measurements to maintain excellent transverse momentum (p_T) measurements precision from MS ($\sim$15% at 1 TeV) for high p_T muons and high segment reconstruction efficiency under a background rate up to 20 kHz/cm^2. In addition, the NSWs are anticipated to enhance ATLAS Level-1 muon triggering in the forward region by providing hardware-based online segment reconstruction with an angular resolution of $\sim$1 mrad, corroborating segment measurements at the middle station of the MS to substantially eliminate the fake trigger that is not associated with real muons.

To cope with these stringent requirements and challenges, NSWs utilize two novel high-rate capable detector technologies, small-strip Thin Gap Chamber (sTGC) [3] and Micro-mesh Gaseous Structure (Micromegas) detectors [4], both providing complementary triggering and tracking with a pseudo-rapidity coverage of $1.0<|\eta|<2.4$ and $1.0<|\eta|<2.7$, respectively. Each of the two NSWs is constructed as a disk-like structure arranged in 16 trapezoidal-shaped sectors and each sector is composed of 8 layers of Micromegas sandwiched between two four-layer sTGC detector wedges. The total constructed detector gas gaps cover an area greater than 2400 m^2. It should be noted that the NSW upgrade is the first use of the micro-pattern gaseous detector at such a large scale in high-energy experiments. A sophisticated custom-made electronics system has been designed and built for the NSW, featuring 2.5 million readout channels for fast triggering and precision tracking of muons. Two NSWs completed the surface commissioning in 2021 and were installed in the underground experimental cavern at the beginning of 2022 (see figure 1) after more than ten years of efforts from the ATLAS collaboration. In this paper, we present the commissioning and operational status of the NSW detector system and its latest performance in preparation for the LHC Run-3 which started in July 2022.

2. NSW detector, slow control, and alignment system

Both NSWs, one for each of the ATLAS end-cap, are fully connected with detector services such as high voltage (HV), low voltage (LV), gas, and cooling, since the beginning of 2022. sTGC gaps have been circulated with CO_2:n-pentane (55:45) gas mixture whereas Micromegas layers

Figure 1: Photos of one NSW detector after the completion of surface commissioning (Left) and the installation of the NSW in the ATLAS underground experimental cavern in 2021 (Right).

have been flushed with Ar:CO_2:iC_4H_{10} (93:5:2) which has been shown to improve HV stability comparing with the standard Ar:CO_2 (93:7) mixture and approved for use in the ATLAS. Less than 1% and 2% HV channels are observed with defects when applying nominal operational HV for Micromegas (490 V) and sTGC (2.8 kV), respectively. Most of defective HV channels are known since surface commissioning. Less than 1% of 1024 Intermediate Conversion Stage power supply channels, providing LV to Front-end electronics, have experienced failures since the NSW installation and the majority of failed modules are replaced. Water cooling loops for Front-end electronics have been checked for tightness. Flows are routinely regulated to ensure sufficient cooling of active devices. The NSW detector slow control system (DCS) [5], responsible for the control of all detector services and the monitoring of both electronics and environmental status, has been deployed and integrated with the ATLAS central DCS. The NSW alignment system which tracks the movement and deformation of NSW detectors has been integrated within the End-cap alignment system and provides stable detector position measurements.

3. NSW Level-1 data readout and acquisition

The NSW Level-1 data readout chain consists of two types of radiation-tolerant Front-end Application Specific Integrated Circuits (ASICs), named VMM [6] and ROC [7], a high-bandwidth Back-end data acquisition (DAQ) system and many Level-1 data driver cards connecting them with 4.8 Gbps duplex optical links. VMMs, 64-channel mixed-signal Front-end ASICs, are connected to readout electrodes of NSW detectors to provide charge signal amplification, charge amplitude digitization, and signal arrival time stamping. Buffered data from VMMs are then selected and aggregated by the ROC ASICs upon the reception of Level-1 accept signals. The NSW DAQ system is based on the new generation of Front-End Link eXchange (FELIX) [8] platform for ATLAS Run-3 and beyond which acts as a hub between the custom high-speed serial links from Front-end electronics and the readout data collection and processing hardware via commodity switch network. The FELIX system distributes Timing, Trigger, and Control (TTC) signals to the Front-end electronics and transmits Level-1 data packets received from the Front-end links to the network server on which a software Readout Driver (swROD) [9] application runs. swROD builds and buffers Level-1 event fragments before the data is handed over to the ATLAS High-Level

Trigger (HLT) system. The configuration of the Front-end electronics is achieved via the OPC servers [10] which run through the same network as FELIX and swROD. It should be noted that NSW is the first-time large-scale user of such a high-performance and highly-configurable DAQ system to handle the readout of data up to 100 kHz Level-1 trigger rate in Run-3.

Many crucial calibrations to the Front-end electronics are required for NSW DAQ operation, from optimization of Front-end analog circuits to ensuring electronics synchronization and data communication stability. Calibration procedures are complicated as many clocks or data phases are interconnected. Dedicated calibration methods have been established to allow automated calibrations during LHC inter-fills. Though initially encountered data de-synchronization and DAQ stability issues, which become more prominent as more sectors are added and trigger rates exceed 10 kHz, progress has been made to integrate the NSW readout into the ATLAS Trigger Data Acquisition (TDAQ) system. Several issues causing FELIX buffer filling-up, such as spurious slow control traffic, have been identified and mitigated by the deployment of new firmware patches with noisy packet filtering capabilities or the optimization of swROD configurations. Continued efforts have been made to enhance the handling of problematic links and consequently improve the DAQ stability towards a high trigger rate at physics collision runs.

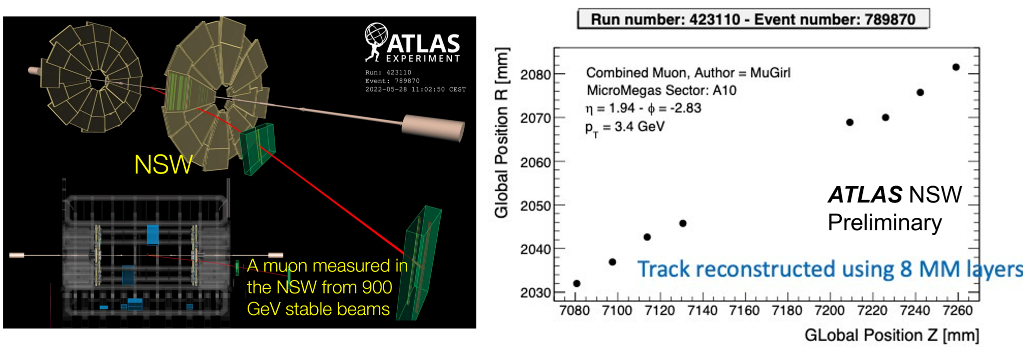

Figure 2: Event display of a candidate muon reconstructed by the NSW Micromegas detector during 900 GeV collision run (Left) and the corresponding track segment recorded in 8 Micromegas layers (Right).

4. NSW participation of special LHC runs

Several NSW sectors from both wheels have been prepared to join the ATLAS data-taking during special commissioning runs with the LHC beam since the beginning of May 2022. The primary purposes include testing the NSW Level-1 data readout within the TDAQ system and time-in of NSW detectors given different latencies originating from cabling with different lengths. As shown in figure 2 and figure 3, first-hand track segments and hits data have been successfully recorded both by the Micromegas and sTGC sectors with the special LHC beam. Crucial timing offset and threshold parameters for the operation of tens of thousands of Front-end electronics have been derived, preparing NSW sectors ready for production physics data-taking before the start of LHC Run-3 with 13.6 TeV new record-energy.

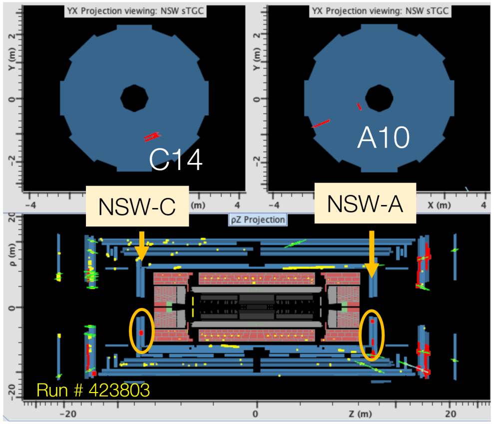

Figure 3: First recorded sTGC hits seen in the ATLAS event display during the special horizontal muon beam run.

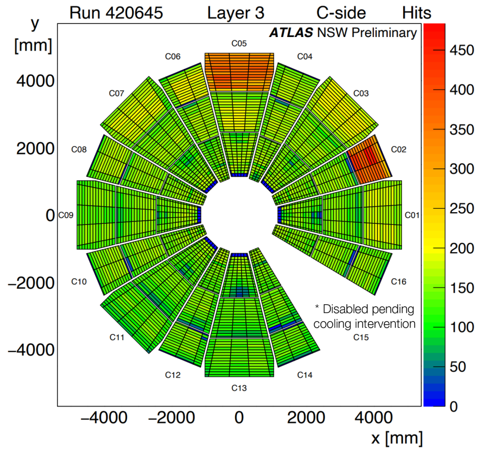

Figure 4: sTGC pad hit occupancy recorded by trigger electronics during the LHC beam splashes.

5. NSW trigger commissioning

The participation of NSW in the ATLAS Level-1 forward muon triggering is based on the concept of fast and precise track segment reconstruction by 16 sensitive layers of a NSW sector. For Micromegas, candidate segments could be derived with high pointing accuracy from the addresses of earliest threshold-crossing strips thanks to the fine strip pitch (~0.4 mm). The sTGC trigger is carried out in two stages, first with the selection of a narrow strip band based on coincidences made out of eight pad layers within an NSW sector, to limit the trigger data bandwidth, and followed by the calculation of precision hit position based on the strip charge interpolation. Detailed descriptions of the trigger electronics and algorithms can be found in [11]. Due to the necessity to understand detector inputs based on collision data and strict requirements on the trigger latency, the NSW trigger chain commissioning and trigger firmware optimization are still ongoing.

Progress has been made to record data from special beam runs using Micromegas trigger processors and sTGC Pad Trigger boards in the self-trigger mode. An example of sTGC pad hit occupancy recorded during the LHC beam splashes is shown in figure 4, indicating the activation and operation of the sTGC detector with trigger electronics. Validation of the links from the NSW Front-end to the End-cap high-level trigger electronics, named Sector Logic (SL) boards, has been achieved, and emulated NSW trigger candidates made by pulsing Front-end electronics have been correctly observed by the SL boards where the NSW trigger candidates are expected to be merged with those segments reconstructed from the middle muon detector station. Further commissioning steps, including tests of global synchronizations among all NSW trigger electronics, integration with SL, and validation of sTGC strip-based trigger, are planned towards the end of 2022.

6. Conclusions

The New Small Wheel upgrade is the largest-scale ATLAS Phase-I upgrade during LHC LS2. The upgrade is crucial for the ATLAS experiment to maintain its excellent tracking capability to high transverse momentum muons and improve the Level-1 muon trigger in the forward region towards a demanding high-rate environment at high luminosity. Two NSWs with large-area novel gaseous detectors have been successfully constructed and deployed in the ATLAS underground experimental cavern since the beginning of 2022. Both sTGC and Micromegas detectors for the NSW have been fully commissioned and are ready for the Run-3 data-taking. More than 98% of NSW HV channels and gas gaps are now operational at nominal high voltage. Some first-hand collision data, with track segments or hits recorded by both NSW detector technologies after being timed-in, have been successfully collected together during the LHC special commissioning runs. Ongoing efforts will focus on the improvement of DAQ stability and the preparation of fully-calibrated NSW sectors to join the LHC Run-3 with a new-record collision energy at 13.6 TeV. The NSW tracking performances will be studied soon in detail with the early collision data.

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