Abstract

The instantaneous luminosity of the Large Hadron Collider at CERN will be increased up to a factor of five with respect to the design value by undergoing 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 first station in the forward regions with the so-called New Small Wheels (NSWs), to be installed during the LHC long shutdown in 2018/19. The NSWs consist of eight layers each of Micromegas and small-strip Thin Gap Chambers (sTGC), both providing trigger and tracking capabilities, for a total active surface of more than 2500 m². It represents the first system with such a large size based on Micro Pattern (Micromegas) and wire detectors (sTGC). The technological novelties and the expected performance of the NSW system are discussed. The status of the project and the plan for the completion are summarized.

Keywords: LHC, ATLAS Upgrade, Muon Spectrometer, Gaseous Detectors, TGC, Micromegas, Tracking, Trigger

1. Introduction

The motivation for the luminosity upgrade of the Large Hadron Collider (LHC) is to precisely study the Higgs sector and to extend the sensitivity to new physics to the multi-TeV range. In order to achieve these goals the ATLAS experiment [1] has to maintain the capability to trigger on moderate momentum leptons under background conditions much harder than those currently present at the LHC. For the Muon Spectrometer (MS) [2], such requirements necessitate the replacement of the forward muon-tracking region (called the muon Small Wheel) with new detectors capable of precision tracking and triggering simultaneously. The New Small Wheel (NSW) upgrade [3] is designed to cope with the high background rate that is expected at $L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ during Run-3 and the high luminosity LHC (HL-LHC). Figure 1 shows the z-y view of one quarter of the ATLAS detector, the three stations of the MS and the location of the Small Wheel.

1.1. Impact on physics performance

The rate of the ATLAS muon trigger increases proportional to the instantaneous luminosity. Forward muon triggers have currently a very high fake rate (about 90%) due to low energy particles generated in the materials between the Small and the Big Wheel, entering the trigger chambers of the Big Wheel. Simply raising the muon trigger $p_T$ thresholds from 20 GeV to 40
Figure 2: (Left) Distribution of transverse momenta of leptons from $H \rightarrow \tau \tau$ decays where one of the $\tau$ decays into a muon and two neutrinos. (Right) Reconstructed dimuon mass in simulated $Z' \rightarrow \mu\mu$ events with three different levels of background realized by a data overlay technique. The black, blue and red histograms correspond to luminosity of $0.3$, $3$ and $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ respectively.

GeV would maintain the trigger rate at the current level but would result in a significant loss in physics, especially for signatures with a relatively soft single leptons relevant for Higgs boson analyses (e.g. $WH \rightarrow \ell\nu\bb$, $H \rightarrow \tau\ell\had$) as shown in Fig. 2 (left).

For high $p_T$ muons, the resolution is dominated by the muon spectrometer. Requiring segments in all three muon stations ensures the best momentum resolution, important for searches for new physics at the highest energies. However, the current SW chambers, based on monitoring drift tubes, can not cope with rates up to $15$ kHz/cm$^2$. Losing the track segments in the SW means losing high quality muon candidates and results in reduced efficiency as shown in Fig. 2 (right).

1.2. The New Small Wheel

To address both issues, the increased muon trigger rates and the degraded muon track reconstruction performance, a clear indication of the origin of the triggered muons is necessary. This will be provided by replacing the SW with the New Small Wheel (NSW).

NSW is a set of precision tracking detectors that are fast, capable to perform bunch crossing identification at rates up to $15$ kHz/cm$^2$ and have spacial resolution of less than $100$ $\mu$m per detection plane. The NSW detectors can therefore provide the muon trigger system with reconstructed track segments of good angular resolution ($< 1$ mrad) that can clearly indicate whether the triggered muons originated from the collision point or not as shown in Figure 3. The existing ATLAS Big Wheel trigger accepts all three tracks shown. The fake tracks (B and C) can be rejected in the trigger by the addition of the New Small Wheel. At the same time, the single-muon $p_T$ threshold can be kept at the current low levels and be comfortably managed by the subsequent muon trigger stages.

2. Detector Layout

The NSW will utilize two detector technologies: small-strip Thin Gap Chambers (sTGC) as the primary trigger and Micromegas (MM) as the primary precision tracker. The NSW consists of 16 detector planes arranged in two multilayers. Each multilayer comprises four sTGC and four MM detector planes. A sandwich arrangement of sTGC-MM-MM-sTGC is used to maximize the distance between the two sTGCs multilayers for improved track segment angular resolution at the trigger level as shown in Fig. 4 (right). The choice of eight planes per detector was dictated by the need to provide a robust, fully functional detector system over its whole lifetime. Following the present structure of the MS, each wheel is composed of 16 sectors (8 small and 8 large) as shown in Fig. 4 (left).
3. Requirements and Mechanical Precision

In order to ensure a momentum resolution better than 15% at muon $p_T \approx 1$ TeV with the ATLAS MS, each track segment in the NSW needs to be reconstructed with a position resolution in the bending plane better than 50 µm. The position of the read-out strips along the precision coordinate should be known with an accuracy better than 30 µm and the position of each plane on the coordinate perpendicular to the chamber surface (out-of-plane) should be known within 80 µm accuracy. All above requirements refer to a chamber/plane lying flat on a granite table. An optical system, similar to that adopted for the alignment of the precision chambers (MDT) of the MS, will be employed to survey relative alignment and internal deformations of the NSW chambers during operation.

4. sTGC Technology

The concept of Thin Gap Chambers (TGC) was developed in 1983 [4] and then used at OPAL and ATLAS end-cap muon trigger system [2]. The basic small-strip TGC (sTGC) structure is shown in Fig. 5. It consists of a grid of 50 µm gold plated tungsten wires at a potential 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/□ sprayed on a 100 µm thick G-10 plane, behind which there are on one side precision strips (that run perpendicular to the wires) and on the other pads (covering large rectangular surfaces), on a 1.6 mm thick printed circuit board (PCB) with the shielding ground on the opposite side. The strips have a 3.2 mm pitch, much smaller than the strip pitch of the ATLAS TGC, hence the name "small-strip TGC" for this technology. The pads are used through a 3-out-of-4 coincidence to identify muon tracks roughly pointing to the interaction point. They are also used to define which strips need to be readout to obtain a precise measurement in the bending coordinate (region of interest), for the online event selection. The azimuthal coordinate is obtained from the wires. The operational gas is a mixture of 55% CO$_2$ and 45% n-pentane.

4.1. Production of sTGC

There are six types of sTGC quadruplets - three for the large and small sectors, respectively. All have trapezoidal shapes with dimensions between 1 and 2 m$^2$. The production of the sTGC detectors will take place at institutions from Canada, Chile, China, Israel and Russia. A generic challenge in the construction of large multi-layer particle detectors, is to achieve high precision alignment of the read-out strips across layers. The needed accuracy in the position and parallelism of the precision strips between planes is 40 µm. This precision is achieved by mechanical machining, in one step, the read-out strips together with brass inserts which can be externally referenced. The individual sTGC layers are glued together, separated by an externally machined frame with a 100 µm thinner honeycomb over the surface of the detector. This allows the glue to be used as a filler to compensate for small unevenness of the PCBs. The gluing procedure makes use of the fact that the various sTGC layers can be positioned with respect to each
other with high accuracy, using the external brass inserts attached to an external precision jig on a marble table.

4.2. sTGC Prototypes

Several large size sTGC prototypes have been built and qualified in the past and position resolutions of 60-120 $\mu$m have been achieved depending on track incident angles and high voltage values as shown in Fig. 6 [5].

An important step in the prototype development was the construction of the first full size quadruplet, with dimensions $1.2 \times 1 m^2$ in the spring of 2014 (Module-1) at the Weizmann Institute as shown in Fig. 8. This prototype was constructed using the full specification of one of the quadruplets to be used in the NSW upgrade (the middle quadruplet of the small sector). The construction of this large prototype also provides important input for the design of the final modules and is essential to establish the procedures of construction and assembly.

4.3. Recent sTGC Test Beam Results

Beam tests of the full size sTGC prototype have been performed in May 2014 at Fermilab. The test utilized a pixel telescope to precisely track the incident point of 32 GeV pions on the sTGC quadruplet and compare it to the measured position in each of the four sTGC detection planes. A moveable x-y table is used to expose different regions of the sTGC detector to the particle beam. The offline analysis of the data is still ongoing. Preliminary results on the calibration of the electronics, tracking and alignment of the pixel telescope allowed the extraction of the intrinsic sTGC detector resolution of around 60 $\mu$m in the best case for perpendicular tracks.

5. Micromegas Technology

The concept of the Micromegas (an abbreviation for “micro mesh gaseous structure”) has been developed in the 1990s [6]. A schematic of the Micromegas detector for the NSW is shown in Fig. 10. It consists of a planar (drift) electrode, a gas gap of 5 mm thickness acting as conversion and drift region, and a thin metallic micromesh at 128 $\mu$m distance from the readout electrode, creating the amplification region. The read-out strips (0.425 mm pitch) are covered by a resistive strip layer to protect against sparking [7]. The electric field gradi-
strips. Most of the ions are produced in the avalanche close to the readout strip. Given the lower drift velocity of the ions, it takes them about 100 ns to reach the short distance to the mesh, which is very fast compared to other technologies. It is the fast evacuation of the positive ions which makes the Micromegas particularly suited to operate at very high particle fluxes.

The MM will provide spatial resolution better than 100 µm independent of track incident angle as shown in Fig. 11 utilizing a combination of two algorithms. For small incident angles, a simple cluster centroid method is employed. For larger incident angles, the MM is operated in the micro-Time-Projection-Chamber (µTPC) mode. The µTPC method exploits the single strip time information with a time resolution of a few ns. This allows to perform a local track reconstruction in the drift gap. Converting the measured drift time of charges arriving on individual strips to the position from which the drift electrons originate based on the drift velocity, it is possible to reconstruct the segment of the track inside the drift gap. The µTPC method has been successfully applied in several test-beam experiments at CERN.

5.1. Micromegas Production

There are four types of MM quadruplets, LM1 and LM2 for the large sectors and SM1, SM2 for the small sectors. All have trapezoidal shapes with dimensions between 2 and 3 m². The production of the MM detectors will take place in institutions from France, Germany, Greece, Italy and Russia, as shown in Fig. 12.

Most MM detectors in operation today have the metallic mesh integrated in the readout PCB. The production scheme adopted for the large area MM detector of the NSW have the mesh integrated in the panel containing the cathode plane, forming the drift gap, separated from the readout PCB. The mesh size is therefore only limited to the mesh fabrication size and stretching machines and not to the size of the individual PCBs. This also facilitates detector opening/cleaning and separates PCB production from mechanical construction. The coupling of the drift panel to the readout panel requires very high mechanical accuracy to position the mesh on top of mesh support pillars [3].

5.2. Micromegas Prototypes

An important step in the prototype development was the construction of the first quadruplet, with dimensions 1.2×0.5 m² in the summer of 2014. The prototype has basically the same structure as foreseen for the NSW and is the first multilayer MM chamber. The construction of this medium size prototype also provided input for the design of the final modules and is essential to establish the procedures of construction and assembly. The MMSW prototype (MicroMegas for the Small Wheel) was designed to fit the dimension of half Cathode Strip Chamber (CSC) detector currently installed in the present Small Wheel in ATLAS. The MMSW will be installed in the ATLAS experiment in 2014. This will enable to evaluate the detector response under realistic conditions during the Run 2 starting in 2015.

6. Readout Electronics

The NSW will feature a total of about 2.5 M readout channels for the sTGC and MM detectors. Both detectors require precision amplitude measurement for position determination by charge interpolation. To utilize the µTPC method for the MM detectors, time measurement with precision of 2 ns is required, in addition to the
amplitude measurement. A custom front-end Application Specific Integrated Circuit (ASIC) has been developed to provide both. The VMM1 chip is a 64-channel front-end ASIC, common for both technologies. The ASIC provides the peak amplitude and time with respect to the bunch crossing clock, or other trigger signal. For calibration, the chip is equipped with calibration capacitors and a pulser. The ASIC is designed in the radiation tolerant IBM 130 nm process. The VMM2 is a recent evolution of VMM1 but with a much higher complexity and functionality. The step-up can be appreciated from the increase in layout size (from 5.9×8.4 mm² to 13.5×8.4 mm²) and transistor count (from about 500 thousand to roughly 5 million). The VMM2 includes 10-bit amplitude/time digitizer for precision tracking and a fast 6-bit amplitude digitizer for the trigger application. The data are sent via Ethernet using the UDP protocol.

7. Summary and Outlook

The New Small Wheel will make significant and necessary improvements to enable triggering and tracking for muons in the forward region of the ATLAS with a reasonable safety margin. It is a crucial upgrade to maintain ATLAS physics program for Run-3 and beyond. Production of New Small Wheel chambers will start in 2015 and be completed before mid 2017. NSW chamber integration and commissioning will be ongoing in the second half of 2017. Assembly of the chambers into NSW sectors and wheels and NSW commissioning on the surface will take place in 2017 and 2018. Before the installation in ATLAS, it is planned that the completed wheels are fully tested on surface for about one year. In that way, sufficient time for the commissioning of the detector is available. This includes possible repair or replacements, time for tests of the electronics system as well as for the preparation and testing of readout, control and monitoring software, with the complete detector system serving as a test bed. The experience gained during the Small Wheel commissioning and installation will be invaluable for the New Small Wheel.

Acknowledgments

The author would like to thank the ATLAS Muon collaboration and all colleagues from the New Small Wheel sTGC and Micromegas communities.

References