Muon Spectrometer Phase-I Upgrade for the ATLAS Experiment
The New Small Wheels Project

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on behalf of the ATLAS Muon Collaboration

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The Large Hadron Collider (LHC)

The road towards high luminosity

- A series of LHC upgrades are planned during Long Shutdown (LS) periods.
- Instantaneous luminosity expected to increase up to 5 to 7 times higher than nominal following LS3 in 2026.
- Expect to collect approximately 3000 fb$^{-1}$ of data by the end of LHC operations in 2037.

Figure: 10.23731/CYRM-2017-004
The ATLAS Muon Spectrometer

- Precise offline muon momentum measurement.
  - Using hits from precision muon chambers: Cathode Strip Chambers (CSC) and Monitored Drift Tubes (MDT).
- Data acquisition trigger on events involving muons.
  - Level-1 trigger (hardware) using hits from muon trigger chambers: Thin Gap Chambers (TGC) and Resistive Plate Chambers (RPC).
  - High Level Trigger (software) with hits from all muon detectors.

- Muon spectrometer divided in 3 stations: Inner (I), Middle (M) and Outer (O).
- Barrel (B) and End-caps (E) stations provide almost complete angular coverage.
Challenges of High Luminosity Data Taking

- **Problem at high luminosity**: Level-1 trigger rate will exceed the readout rate bandwidth (~1MHz after LS3) of the ATLAS data acquisition system.
- More than 90% of muon candidates identified by the end-cap Level-1 trigger algorithm are from “fake muons” that are, in fact, background hits.
  - Background hits come from particles produced in the material between the inner and middle stations.
  - Current muon Level-1 trigger algorithm uses information only from the middle station.
- **Solution**: Use inner station hits to identify fake muons. Inner station track segment must point to the IP and match the middle station measurements.
- Current inner station detectors cannot achieve an online fake muon identification.
  - Coarse granularity of inner station trigger detectors.
  - The hit efficiency of CSC and MDT precision detectors is rate-limited.

**Figure**: CERN-LHCC-2013-006
High luminosity physics with muons

- High luminosity operation enhances the discovery potential of ATLAS:
  - Increased precision of Standard Model measurements
  - Increased sensitivity to rare physics processes
  - More detailed studies of the electroweak symmetry mechanism
- Muons are an important signature for a plethora of physics processes.
- The muon spectrometer overall performance must remain excellent at high luminosity to fulfill the ambitious ATLAS physics program.

Raising the muon Level-1 $p_T$ threshold reduces the ATLAS sensitivity to Higgs physics

<table>
<thead>
<tr>
<th>ATLAS Simulation</th>
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<tbody>
<tr>
<td>No cut</td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV (Eff = 93%)</td>
</tr>
<tr>
<td>$p_T &gt; 40$ GeV (Eff = 61%)</td>
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Effect of loosing precision space points from MDT at high particle fluences (Search for hypothetical $Z'$ boson)

$Z' \rightarrow \mu\mu$

LHC Luminosity
- 0.3 × nominal
- 3 × nominal
- 5 × nominal

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ATLAS Muon Phase-I Upgrade
CIPANP18
New Small Wheel (NSW)

**Specifications**
- Online angular resolution better than 1 mrad.
- Stable overall performances up to a hit rate of 20 kHz/cm².
- Spatial resolution similar to that of the current inner station to maintain the current muon momentum resolution (10% @ $p_T = 1$ TeV/c)
- Time jitter better than 25 ns for bunch crossing identification.

**New Small Wheel:** Detector arrangement replacing part of the end-cap inner station.

- Wheel arrangement of 8 “large” and 8 “small” pie-slice detector sectors.
New Small Wheel

Sector layout

- Sectors combine small-strip Thin Gap Chambers (sTGC) and Micromegas (MM)\(^1\). Both technologies feature excellent high-rate track reconstruction and timing performances, required for the NSW.
- Both technologies use common readout electronics: the VMM
  - On-detector peak and time measurements of the detector signal.
  - Independent trigger and readout data paths.

\(^1\)micro-mesh gaseous structure
**small-strip Thin Gap Chamber (sTGC)**

Detector technology

- **small-strip Thin Gap Chambers**: Multiwire chambers operating with a mixture of n-Pentane/CO$_2$.
  
  - Operation in the quasi-saturated mode.
    - Gas gain $\sim 10^5$
    - Operating voltage = 2.9 kV
  
- **Strips**: Precise muon trajectory measurement in the bending plane.
  - Strip pitch = 3.2 mm

- **Pads**: Used for strip readout trigger and coarse measurement in the non-bending plane.
  - Pad area $\sim 60$ cm$^2$

- **Wires**: Coarse muon trajectory measurement in the non bending plane.
  - Wire pitch = 1.8 mm
  - Wires ganged in groups of 20
  - Wire channels not used for trigger

Strip, pad and wire electrodes are read out on NSW sTGC modules.

Strip-cluster centroid obtained from the center of mass of the peak strip signals during online operation.
small-strip Thin Gap Chamber
Online track reconstruction

- sTGC readout pads are staggered between layers and define areas called "logical pads" that trigger a band of strips.
- Muon position obtained from the centroid position of the strip charge clusters.
  - Centroid position obtained with a center-of-mass algorithm during online operation.
  - Strip clusters with more than 5 strips rejected because they originate from δ-rays.
- The centroid positions of each wedge are averaged. Candidate muon track segment obtained from average centroid of the wedges.
small-strip Thin Gap Chamber
Performance studies

Test-beam at Fermilab in May 2014

Test-beam at CERN in 2012

Test-beam with final VMM prototype in October 2017

Charge sharing between 2 pads

Charge asymmetry

First strip layer cluster position [mm]

Spatial resolution measurement with pixel telescope
Differential non-linearity
Resolution with perpendicular tracks

A=200µm
σ=45µm

Full results: DOI: 10.1016/j.nima.2016.01.087


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2.85 kV

25ns

Time jitter measurement
Micromegas
Detector technology

- **Micromegas**: micro-pattern gaseous detectors that operate in 2 phases: *drift* and *amplification*.
- A micro-mesh, transparent to electrons, separates drift and amplification gaps.
- Primary ionization drifts to the mesh by the action of a moderate electric field.
  - Drift gap thickness: 5 mm
  - Drift field = 600 V/cm
- Charge is multiplied by the strong electric field in the amplification gap.
  - Gain gain $\sim 10^4$, Amplification field = 40 kV/cm
  - Amplification gap thickness: 128 $\mu$m
- Readout strips collect avalanche charge by induction.

Operates with the principles of a time projection chamber.

Quick ion evacuation from the thin amplification gap

Internal structure of a Micromegas

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Micromegas
Track reconstruction and trigger

Stereo-strip configuration

x: horizontal strips (2 planes per Quad.)
u, v: stereo strips (1 each per Quad.)

• **Online reconstruction**: muon position obtained from the first strip with signal.
• **Offline reconstruction**: use charge cluster centroid position or μTPC mode.
• Stereo-strip arrangement for muon measurement in two coordinates.
• For trigger: **global** and **local** slopes obtained and compared using hits from all 8 Micromegas layers.

Figures: L. Guan
**Micromegas**

**Performance studies**

**μ-TPC mode**: use strip hit timing to reconstruct a muon track.

**Centroid mode**: strip-cluster centroid provides the muon position.

90μm spatial resolution with perpendicular tracks.

Spatial resolution improvement with angle using the μ-TPC mode.

Timing of first strip hit
All hits within ~3 bunch crossings

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Figures: CERN-LHCC-2013-006
Detector production

- sTGC and Micromegas are trigger and precision detectors manufactured with stringent tolerances on the geometry and location of readout strips.
- The planarity of the assembly is crucial for a uniform detector gain.
  - Most assembly steps carried out on a flat granite table.
  - All boards and frames controlled for thickness.
- Excellent alignment of strip boards required for a precise muon track reconstruction.
  - sTGC strip boards aligned using brass inserts and precision alignment pins.
  - Micromegas strip boards aligned with precision dowel pins.
- Deviations from nominal of detector components known to within ~100 microns to meet the NSW specifications.
sTGC production
Overview

- Cathode board production in collaboration with industry.
- Quadruplet assembly: 5 production lines
  - Valparaiso/Pontifical, Chile (S1)
  - Shandong, China (S2)
  - TRIUMF/Carleton/McGill, Canada (L2,S3)
  - Weizmann/TAU/Technion, Israel (L1,S3)
  - PNPI, Russia (L3)
- Wedge assembly and final testing at CERN

Graphite spraying
Graphite polishing
Anode wire winding

sTGC Wedge Assembly
Finished QS3 quadruplet

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sTGC production Status

- Quadruplet prototype produced in all construction sites.
- Production is well underway in all construction sites.
  - Production of cathode boards and other parts in parallel.
  - More than 50% of cathode boards manufactured to this day.
  - End of cathode board production in Fall 2018.
- First prototype sTGC wedge complete.
  - Wedge production will start this Summer.
- QA/QC tests have been defined for assembled detectors:
  - x-ray scan
  - cosmic-ray testing
Micromegas production Overview

- 2200 readout (RO) boards production in PCB factories.
- Quadruplet assembly in 5 production lines
  - INFN, Italy: SM1
  - BMBF, Germany: SM2
  - Paris-Saclay, France: LM1
  - JINR, Russia: LM2
  - Thessaloniki, Greece: LM2
- CERN is a central point for quality control and procurement.

Micromegas wedges

LM1/SM1: 5 PCB RO boards
LM2/SM2: 3 PCB RO boards

Micromegas cross-section
Micromegas production Status

- ~50% of readout boards ready for quadruplet production.
  - Entered series production of drift and readout panels.
- Quadruplet production has started in construction sites.
  - Completion of first production module in all construction sites.

The gluing of the mesh frame is performed using the vacuum bag wrapping up the hole panel. A depression of ~50 mbar is applied.

4.94 4.96 4.98 5 5.02 5.04 5.06 5.08 5.1 5.12

DL1B2 DL1F3 DL1B3 DL1C2

Face A DL1C2 Face B

DL1C3 Face A DL1C3 Face B

The technique is validated and shows good results. A few low points appear, very locally, that we decided not to treat.

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Summary

• Incremental upgrades of the LHC are planned.
  – Five to seven fold increase in luminosity expected.
  – More physics opportunities for the LHC experiments.

• The Phase-I upgrade will improve the online muon identification capabilities of the ATLAS detector in anticipation of the increased LHC luminosity.

• The NSW combine the sTGC and Micromegas detector technologies.

• Detector construction is ongoing with stringent manufacturing specifications.
  – End of NSW installation scheduled by the end of LS2.
Back-up slides
The need for three independent measurements in each gas gap is achieved by using the two cathode planes (one equipped with strips for precision measurements and the other with pads for trigger purposes), and the wires which are connected in small groups to measure the azimuthal coordinate.

3. TGC and test setup

Additional R&D is required in order to make the TGC adequate for the SLHC upgrade. The main issue is the expected position

Cross-section of a sTGC gas volume
Cross-section of a Micromegas quadruplet

(a) Drift Cathode, Micro Mesh, PCB, Read-out electrodes, Pulses. (b) 1 - Drift panel, 2 - Read-out panel x2, eta strips, 3 - Drift panel x2, 4 - Read-out panel x2, stereo strips, 5 - Drift panel. (c) 1 - Drift panel, Pillars, Resistive strips, R/O Strips, Cathode, Mesh.
Muon detectors high-rate performance

- Performance of muon end-cap detectors compromised by the high particle fluences expected at high luminosity.
- Current muon detector technologies reaching rate limitations:
  - Cathode Strip Chambers (CSC)
  - Monitored Drift Tubes (MDT)
- The expected performance degradation of end-cap detectors at high LHC luminosity will impact the trigger efficiency and precision of physics measurements involving muons.

Particle fluxes exceeding 3 kHz/cm² in the end-caps

Efficiency of MDTs will drop below an unacceptable level.

Radius (cm)

Rate (Hz/cm²)

L = 3 × 10^{34} ATLAS

CSC

MDT

300 kHz/tube

200 kHz/tube

Rate per tube at
\( L = 1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)
1.4 Muon system

The conceptual layout of the muon spectrometer is shown in figure 1.4 and the main parameters of the muon chambers are listed in table 1.4 (see also chapter 6). It is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high-precision tracking chambers. Over the range $|\eta| < 1.4$, magnetic bending is provided by the large barrel toroid. For $1.6 < |\eta| < 2.7$, muon tracks are bent by two smaller end-cap magnets inserted into both ends of the barrel toroid. Over $1.4 < |\eta| < 1.6$, usually referred to as the transition region, magnetic deflection is provided by a combination of barrel and end-cap fields. This magnet configuration provides a field which is mostly orthogonal to the muon trajectories, while minimising the degradation of resolution due to multiple scattering. The anticipated high level of particle flux has had a major impact on the choice and design of the spectrometer instrumentation, affecting performance parameters such as rate capability, granularity, ageing properties, and radiation hardness.

In the barrel region, tracks are measured in chambers arranged in three cylindrical layers around the beam axis; in the transition and end-cap regions, the chambers are installed in planes perpendicular to the beam, also in three layers.