Run 3 Performance of New Hardware in ATLAS

Liang Guan University of Michigan
On behalf of the ATLAS Collaboration

11th Large Hadron Collider Physics Conference, Belgrade, Serbia
23 May 2023
ATLAS new hardware in Run 3

- ATLAS went through major hardware upgrade during LHC Long Shut 2 to improve trigger and maintain excellent detector performance in high pile-up ($<\mu>$ more than 60) environment after Run 2.

- Muon Spectrometer
  - New Small Wheel [ATLAS-TDR-020]
  - Barrel BIS78 (pilot for phase-II upgrade)

- Liquid Argon Calorimeter [ATLAS-TDR-022]
  - Front-end & Back-end Electronics

- TDAQ [ATLAS-TDR-023]
  - Level-1 Trigger (Muon & Calo)
  - New readout system (FELIX)

Disclaimer: this is not a full ATLAS detector status report. Focus on new hardware in Run 3.
ATLAS TDAQ upgrade in Run 3

- ATLAS select events based on a multi-level trigger system. Level-1 trigger utilizes custom hardware to accept event up to 100 kHz within a 2.5 µs latency.

- Overview of new TDAQ hardware
  - L1 Calorimeter Trigger
    - LAr electron/jet/global Feature EXtractors
    - TREX (Tile Rear Extension)
    - New L1Topogical trigger
  - L1 Muon Trigger
    - New Sector Logic
    - New MUCTPI
  - Readout
    - New Front-End Link eXchange system (FELIX) + software Readout Driver (swROD)
    - ROS refurbishment
  - HTL farm upgrade

ATLAS Trigger and DAQ scheme for Run 3

see poster from Ricardo Barrue: The ATLAS Trigger system

New trigger hardware status and performance to be presented in the following within the context of sub-detector system upgrade
Liquid Argon (LAr) Calorimeter

- Sampling Calorimeter
  - Pb/Cu/W absorber + LAr ionization detection layers
  - EM Calorimeter in Barrel (EMB) & Endcap (EMEC) $|\eta| < 3.2$
  - Hadronic Endcap (HEC) and Forward (FCAL) $1.5 < |\eta| < 4.9$
  - Typical 4-layers. In total $\sim 180k$ channels to provide $E_T$ measurements.
  - Grouped into $\sim 5.4k$ Trigger Towers & input to ATLAS Level-1 trigger.

- LAr Phase-I upgrade during LHC LS2:
  - Essential improvement to the level-1 trigger at higher instantaneous luminosity and severe pile-up environment after Run-2. Increase the readout granularity in the LAr front and middle layers by factor $\sim 10$ -- From coarse trigger tower to $\sim 34k$ trigger "supercells".
  - Allow to enable shower shape discrimination for improved single object ($e, \gamma, \tau, \text{jets}$) identification.
  - on-detector digitization (increased readout channels) + advanced reconstruction algorithms and event-by-event pile-up subtraction on backend FPGA (digital trigger)

23-05-2023
Liang Guan (lguan@cern.ch)
Both legacy analog-based and phase-I digital trigger electronics run in early Run-3.

1. 114 New Baseplanes: handle increase signal traces
2. 2968 New Layer Sum Boards: summing signal from supercells
3. 124 LTDB: digitize supercell signals and shift data off detector for level-1 trigger
4. 116 LDPS: reconstruct $E_T$ and time for input to L1Calo trigger

see poster from Mars Lyukova: ATLAS LAr Calorimeter Commissioning for LHC Run-3
Accurate reconstruction of $E_T$ and time from digitized signal pulses (sampled @ 40MHz) relies on dedicated supercell-dependent calibrations (baseline, linearity, optimal filtering coefficient etc.).

Validation of Front-end Boards:
- well-understood signal shape reconstruction.
- good timing alignment (at BC & ns fine-time level)

$L_{\text{Ar}}$ new digital electronics performance

Optimal filtering coefficients

$E_{T,j} = \sum_{i=0}^{N} a_i (S_j^i - P_j - B L_j^i)$

Pedestal

$E_{T,j} \cdot \tau_j = \sum_{i=0}^{N} b_i (S_j^i - P_j - B L_j^i)$

Baseline (pile-up dependent)

Signal peak (ADC)

$L_{\text{Ar}}$ Trigger Processing Mezzanine (LATOME)

JINST 17 P05024

EM signal shape (digital readout)

ATLAS Preliminary
Run 427394
Date: 5 July 2022
$\pi=2.33, \delta=0.24$
EMEC Front layer

Data
Expected physics pulse

EM Barrel & Endcap FEB Timing Alignment

ATLAS Preliminary
Stable beam runs at 13.6 TeV
Data 08, 09, 07 July 2022
Run 427394, 427408, 427514
EMB

Mean = 0.60 ns
RMS = 0.06 ns

EMB

EMECC

ATLASLArCaloPublicResults-2022

23-05-2023
Liang Guan (lguan@cern.ch)
L1Calo new trigger electronics

- FPGA-based ATCA modules for Run 3 to process fine-granularity information from LAr digital trigger board and Tile Calorimeter. Fast and complex trigger algorithms. Optical link interconnections with high throughput.

1. 24 electron Feature EXtractor (eFEX): $e, \gamma, \tau$ identification

2. 6 jet Feature EXtractor (jFEX): for $\tau$, large/small-R jets, $E_T^{\text{miss}}$

3. 1 global Feature EXtractor (gFEX): receives input from the entire calorimeter system for large-R jets, $E_T^{\text{miss}}$

4. 32 VME Tail Rear Extension Module (TREX): digitized TailCal signal to FEX (optical) & legacy system (electrical)

5. HUB+ROD: interface to send trigger readout to FELIX system. Resides in the same shelf as FEX modules for TTC distribution.

LAr Level-1 trigger performance

- Validation of new LAr trigger ongoing with $\sqrt{s}=13.6$ TeV collision data ongoing.
- Comparisons between legacy and the Phase-I system: good agreement on single electron trigger efficiency. good match on the reconstructed trigger objects (TOBs)

- Continuous improvement on monitoring, stability and firmware.
- To be used as main trigger in 2023
Muon New Small Wheel (NSW)

- Innermost Muon station in the forward region replaced with completely new detector to provide muon trigger and tracking with high background rates (up to 20 kHz/cm²) towards HL-LHC runs.

> Expected background rejection with NSW

**Offline muon construction**: 15% p_T resolution at ~1TeV/c. 97% segment reconstruction efficiency for muon p_T >10 GeV/c.

**Online (Level-1) triggering**: segments measurements with up to 1 mrad pointing accuracy (Phase-II requirement)
Muon NSW detector

- Two Novel Gaseous Detector Technologies Employed:
  - Resistive Micromesh Gaseous Structure, Micromegas (MMG)
  - Resistive cathode Small-strip Thin Gap Chamber (STGC)

- Both detector technologies provide precision trigger \(1.3 < |\eta| < 2.4\) and tracking \(1.3 < |\eta| < 2.7\) for muons in the ATLAS forward region.
 NSW detector and electronics status

- 99% MMG and 98% STGC HV channels could hold nominal HV with working gas components. MMG Ar:CO2:iC₄H₁₀ (93:5:2); sSTGC CO₂:n-pentane (55:45).

- Cooling and Low Voltage to Front-end electronics operational since start of Run 3.

  Caveat: occasional purging of cooling loop needed. ~2% LV modules failed in 2022 and replaced during Year-End Technical Stops

- NSW uses more than 50k radiation-tolerant Front-end ASICs with 70+ million configuration registers! Calibrations are sophisticated and vital.

  NSW Front-end ASIC phase calibration scheme

  NSW employs new generation DAQ for ATLAS Run-3: FELIX + software Read Out Driver. Slow control via OPC servers.

  Both NSWs in ATLAS DAQ partition for data-taking
Muon NSW preliminary performance

- All NSW (MMG and sTGC) detector readout channels are timed-in after the tuning with 2022 collision data.

- Detector efficiency in (first!) 2022 runs: > 95% for functional regions. However, significantly affected by DAQ instability at high trigger rate, LV failures, and lost of optical link (known weak point with VTRx electronics)

- Large improvement anticipated in 2023 due to significant improvement of DAQ stability, refurbishment of Front-end electronics during 2022 Year-End-Technical-Stop.

- Initial look at the sTGC residual resolution for muons ($P_T>15\text{GeV/c}$) from a 2022 run without any systematic alignment correction and dedicated cluster reconstruction. Further studies on going.
Muon NSW in the ATLAS event display

Segments reconstructed by NSW during special commissioning beam run with Horizontal muons (parallel to beam pipe) April 2023

Display of di-muon event recorded with NSW segments at the first 2400 bunch run in May 2023
Muon Level-1 trigger at Endcaps

- New Endcap Sector Logic Board commissioned to accept trigger input from new muon hardware (NSW & BIS78) and Tile Calorimeter.

- Commissioning of NSW trigger chain to join the Muon Big wheel (BW) for Level-1 triggering ongoing with a step-wise integration and activation plan.

- NSW sTGC pad coincidences will be first commissioned with the aim to provide trigger this year to reduce single muon fake trigger rate (goal: 8 kHz reduction).

- All (32) pad trigger boards and NSW trigger processors operational. Active participation of special commissioning beam runs. Validation of trigger LUT, optimization of timing and coincidence parameters with BW ongoing.
Status of new readout system

- ATLAS Run 3 takes data with a mixture of the legacy and new readout system.

- New Front-end Link eXchange (FELIX) system: custom FPGA-based PCIe card running on commodity computers. Acts as a router between the Front-end and the readout data processing hardware & software.

- Software Readout-Driver (swROD): builds and buffers Level-1 event fragments before handing the data over to the High-Level Trigger (HLT) system.

- New readout system used by all phase-I hardware trigger data monitoring or event readout.

- Performance and status
  - LAr digital trigger: stable w. 0.2% busy fraction
  - L1Calo: a few known issues (dropping packets at beginning of high rate run etc.) addressed w. workaround
  - NSW: most demanding due to large number (20k+) of links and complexity in front-end electronics architecture. Significant improvement at the beginning of 2023 to allow readout at 100 kHz trigger rate.
Conclusions

- ATLAS detector made major upgrade to enhance its trigger capability and maintain its excellent performance at higher pile-up environments after Run-2:
  - Phase-I upgrade to innermost muon station at Endcaps (New Small Wheel): high-rate precision muon detectors for both muon trigger and tracking in decades.
  - Phase-I upgrade to LAr electronics with higher readout granularity
  - Phase-I upgrade to L1 Muon and Calo trigger, readout system

- All phase-I new hardware are going through intensive commissioning phase and participate in the Run 3 data-taking. LAr/L1Calo well advanced. NSW improvement to DAQ and performance ongoing. NSW trigger to be activated step-wise with attempt to include sTGC pad trigger this year.

- The successful upgrade is essential to maximize the physics potential of the ATLAS towards Run 3 and beyond.
BONUS
Beam splashes seen by the ATLAS sub-detectors in 2023
Backup

LHC Beam

ATLAS Coordinate System

XYZ Right handed coordinate system

Route de Mery | entrance

To Airport

To ALICE

23-05-2023 Liang Guan (lguan@cern.ch)
The Super Cell trigger readout of the LAr Calorimeter upgrade enables the use of shower-shape variables for a more effective identification of electrons, photons and tau lepton, and sharpening the EM, jet, and missing-$E_T$ turn-on curves.

\[ R_0 = \frac{E_{T,\text{EM}}(\Delta \eta, \Delta \phi = 0.075 \times 0.2)}{E_{T,\text{EM}}(\Delta \eta, \Delta \phi = 0.175 \times 0.2)} \]

\[ f_1 = \frac{E_{T,\text{EM}}(\Delta \eta, \Delta \phi = 0.2 \times 0.2)}{E_{T,\text{EM}}(\Delta \eta, \Delta \phi = 0.075 \times 0.2)} \]

\[ m_{n,2} = \sqrt{\frac{\Sigma (E_{T,\text{EM}}^2 \times \eta^3)(\Delta \eta, \Delta \phi = 0.075 \times 0.2)}{E_{T,\text{EM}}(\Delta \eta, \Delta \phi = 0.075 \times 0.2)^2} - \left( \frac{\Sigma (E_{T,\text{EM}}^2 \times \eta)(\Delta \eta, \Delta \phi = 0.075 \times 0.2)}{E_{T,\text{EM}}(\Delta \eta, \Delta \phi = 0.075 \times 0.2)^2} \right)^3} \]

Simulated Pile-up cell noise (mu=80, 140)

From LAr Phase-I upgrade TDR [ATLAS-TDR-022]
Backup: LAr $E_T$ and time reconstruction

R. Oishi 2020 JINST 15 C05013
Backup: LAr digital trigger scheme
Backup: NSW trigger and rates

Expected low $p_T$ fake rejection with NSW

Simulated NSW rate at HL-LHC runs
MMG Trigger Concept: reconstruct slopes pointing to IP based on addresses of earliest threshold-crossing strips among multiple layers.

- **MMG Strip pattern**: horizontal strip (2 plans per quad.)
- **u,v**: stereo strip (1 each per quad.)

<table>
<thead>
<tr>
<th>Field</th>
<th>sTGC hit</th>
<th>MM hit</th>
<th>$\Delta \theta$ (mrad)</th>
<th>$\phi$ index</th>
<th>R index</th>
<th>Spare</th>
</tr>
</thead>
<tbody>
<tr>
<td>#. of bits</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

Resolution: 1 mrad, 20 mrad, 0.005 ($\eta$)
Introduction: NSW Electronics

Complexity: 55k ASICs + 5k Front-end cards!
Backup: NSW Front-end Electronics

pFEB

sFEB

Pad Trigger Board
Rim L1DDC
8x Router

Location of MMFE8/L1DDC/ADDC on a MM sector (8 planes)

8 MMFE8, 1 L1DDC, 1 ADDC per plane per side

Spacer frame between two wedges