ATLAS Muon and Calorimeter Trigger Primitives

( Hardware Triggers for HL-LHC )

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on behalf of the ATLAS collaboration ( 2016.10.06 )
ATLAS Calo. / $\mu$ Trigger Upgrade & HL-LHC plan

[LS2]
- **Calo. Trigger Upgrade**
- Muon-Endcap Inner station Replacement

[LS3]
- **Muon Trigger Upgrade** / additional Chamber Install (BI)
- Calo. Trigger (higher granularity hadron R/O, forward electron)

big change on the Trigger Latency & Max. Rate

<table>
<thead>
<tr>
<th>Year</th>
<th>Run1</th>
<th>Run2</th>
<th>Run3</th>
<th>Run4</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30fb(^{-1})</td>
<td>150fb(^{-1})</td>
<td>300fb(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

3,000fb\(^{-1}\) (~ 2037)
### Trigger Menu @ ATLAS (HL-LHC)

| **HL-LHC @ 7.5\times 10^{34}** | **Offline $p_T$ Threshold [GeV]** | **Offline $|\eta|$** | **L0 Rate [kHz]** |
|-------------------------------|---------------------------------|-----------------|---------------|
| isolated Single $e$           | 22                              | $<2.5$          | 200           |
| forward $e$                   | 35                              | $2.4 - 4.0$     | 40            |
| single $\gamma$              | 120                             | $<2.4$          | 66            |
| single $\mu$                 | 20                              | $<2.4$          | 40            |
| di-$\gamma$                  | 25                              | $<2.4$          | 8             |
| di-$e$                       | 15                              | $<2.5$          | 90            |
| di-$\mu$                     | 11                              | $<2.4$          | 20            |
| $e-\mu$                      | 15                              | $<2.4$          | 65            |
| single $\tau$                | 150                             | $<2.5$          | 20            |
| di-$\tau$                    | 40,30                           | $<2.5$          | 200           |
| single jet                   | 180                             | $<3.2$          | 60            |
| fat jet                      | 375                             | $<3.2$          | 35            |
| four-jet                     | 75                              | $<3.2$          | 50            |
| $H_T$                        | 500                             | $<3.2$          | 60            |
| $E_T^{miss}$                  | 200                             | $<4.9$          | 50            |
| jet + $E_T^{miss}$           | 140,125                         | $<4.9$          | 60            |
| forward jet**                | 180                             | 3.2 - 4.9       | 30            |
| **Total**                    |                                  |                 | **1MHz**      |

**ex : single-lepton**

<table>
<thead>
<tr>
<th></th>
<th>Run-1</th>
<th>Run-2</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1e</strong></td>
<td>25 GeV</td>
<td>32</td>
<td>22 GeV</td>
</tr>
<tr>
<td><strong>1\mu</strong></td>
<td>25 GeV</td>
<td>27</td>
<td>20 GeV</td>
</tr>
</tbody>
</table>

**Aim** : similar threshold as Run-1 & Larger Geom. acceptance
Following either the Level-0 or Level-1 decision, which can vary between detectors, the event data are transmitted over custom point-to-point serial links to the FELIX sub-system (Front-End Link eXchange, see Section 9.4.1) the first element of the DAQ system. From the detector perspective, FELIX functions primarily as a common receiver and router between their custom point-to-point serial-links and commodity multi-gigabit networks. The event data transmitted by FELIX are received by the Data Handler, where detector-specific processing, e.g. formatting and/or monitoring, of the data can be implemented prior to buffering in the Storage Handler sub-system of the Dataflow system. The Storage Handler provides:

- **Data to DAQ/Event Filter**
- **Data Input to Trigger**
- **Trigger Signals: L0, L1 trigger + Regional Readout Request (R3)**
- **Trigger Data to Readout**

**Level-0 trigger**

1MHz / 6μsec (Decision)

**CALO + MUON**

40MHz → 1MHz

**Level-1**

400 KHz / 60 μs
**ATLAS Calorimeter**

**Sampling type Calorimeter**
- EM Calo : LAr
- Hadronic Cal :  
  - Barrel : Scintillator  
  - Endcap : LAr

**Characteristics**
- Fine granularity in $\eta$-direction (EM)  
- Segmented in depth ( 4 in EM , 3 in Tile )

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**e, \(\gamma\), \(\tau\), jet, Missing-\(E_T\)**

**Offline** : identify / measure  
**Trigger** : provides inputs for their first level triggers

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**Granularity**

- Granularity in $\eta$-direction improves Trigger performance
**Calorimeter Trigger**

**Run-1, Run-2**
- 1 Trigger tower
- \( \Delta \eta \times \Delta \Phi = 0.1 \times 0.1 \)

**Run-3, HL-LHC**
- 10 Super cells
- 4 Super cells
- \( L1 : \Delta \eta \times \Delta \Phi = 0.025 \times 0.1 \)
- \( L2 : \Delta \eta \times \Delta \Phi = 0.1 \times 0.1 \)
- \( L3 : \Delta \eta \times \Delta \Phi = 0.1 \times 0.1 \)

**Electron** \( E_T = 70 \text{ GeV} \)

**Higher Granularity**
- **Shower Shape**
  - 4 times finer unit: \( \eta \) (L1, L2)
  - 1 \( \rightarrow \) 4 units in depth
  - \( \rightarrow \) better e / jet separation

**3 Feature Extractors**
- **eFEX**: e / \( \gamma \) / \( \tau \)
- **jFEX**: jet, \( \tau \), \( \sum E_T \), MET
- **gFEX**: large-R jet
The energy cut is done on the cluster area

The isolation cut is done on the following parameter:

\[ f_3 = \frac{E_3}{E_1 + E_2 + E_3} \]

Where \( E_n \) is the energy deposited in layer \( n \) in the area represented in figure.

Every TOB with \( f_3 > \text{Thr} \) is vetoed.

Typical values of a well isolated cluster are approximately 0.9.

A and B cells are used to locate clusters in all other conditions.

Layer-2

\[ R_\eta = \frac{E_{\text{core}}}{E_{\text{core}} + E_{\text{env}}}. \]

Layer-3

\[ f_3 = \frac{E_3}{E_1 + E_2 + E_3} \]

\( f_3 \) condition (1/3)

L1

L2

L3
eFEX : specification / prototype

- **24** ATCA modules in 2 shelves
- **4** FPGAs per module
- Multi-Gbps links (11.2Gbps)
  - **BER < 10^{-14}**
  - track length < 30cm

LATOME–eFEX Tests, April ’16
- LATOME–gFEX & –eFEX tests completed successfully
- 264 MGT Rx tested
  - (144 optic inputs + fan out)
- 99% very good eye opening
- BER < 10^{-14} @ 11.2 Gb/s
- Technology, design & method validated
- A few links under further investigation with FTM
- FPGAs ran hot…
  - E.g., 12°C > recommended
**gFEX : large-R jet**

**large-R jet from top** \((Z' \rightarrow tt, m_{Z'}=1.75 \text{ TeV})\)

- **ATLAS Preliminary Simulation**
- \(Z' \rightarrow t\bar{t} \) event, \(m_{Z'} = 1.75 \text{ TeV}\)
- \(m_{W} = 77.3 \text{ GeV}, m_{Wb} = 186.5 \text{ GeV}\)

New **Heavy Particle Search** (e.g. \(Z'\))

- **boosted** \(W, Z,\) top, Higgs (\(w/\) ISR)
- hadronic decay, jets are close each other
- **large-Radius jets** to be triggered!

The cone size of Run-2 Calo. Trigger is too small to cover top quark decay products

**Run 2 L1 Jet**

**large-R = 1.0**

The **gFEX** receives the **entire calorimeter data in a single module** in a ATCA shelf

- full-scan algorithms
- large-R jets as well as MET, Energy Sum, …
gFEX: specification / prototype

- **single** ATCA module
  - coarser granularity input: 0.2x0.2

- Architecture
  - 3 processing FPGAs (pFPGA)
    - running algorithms (large-R, $E_{T}^{\text{miss}}$, ...)
  - 1 Zynq FPGA
    - control, Monitoring, ...

- **Prototype v2**
  - Power & Thermal
    - 298 W measured without MGTs on 4 FPGAs at 12.8 Gbps
    - 24/28 miniPODs mounted
      - total power estimated: 310 W
  - Zynq (-2 device)
    - DDR3, Ethernet, SD, JTAG, QSPI and I2C interface
    - Clock configuration: both SI5338 & SI5345 ok
    - Voltage, current, and temperature monitoring
  - pFPGA A/B/C (XCVU160)
    - JTAG and SPI configuration
    - Parallel data buses: all run up to 560 MHz (1120 Mb/s)
      - 9 groups of parallel data buses between FPGAs
        - stable range = 35-65% of ½ clk cycle
    - Link speed IBERT tests
      - z/pFPGA TX → miniPOD TX → BER → miniPOD RX → z/pFPGA RX
      - zFPGA ↔ pFPGA
      - pFPGA ↔ pFPGA
      - all stable at 12.8 Gb/s, onboard transfers (GTY) at 25.6 Gb/s

- **The Phase-1 L1Calo gFEX**
  - The gFEX sees all Calo (LAr + Tile) information on one board
    - But at coarser granularity than eFEX or jFEX: gTowers = 0.2 x 0.2 ($\eta \times \Phi$)

- **Architecture**
  - 3 Processor FPGAs (pFPGA A/B/C) run algorithms, real-time output
    - Large-R jets, MET, pileup, ...
  - 1 Hybrid FPGA (zFPGA) control, readout, real-time output

- **Prototype v2**

- **good eye opening**
**jFEX**: specification / prototype

- **jet**, $\sum E_T$, $E_T^{miss}$

- **System Overview**
  - 7 ATCA modules in One Shelf
  - 4 FPGA / module (Ultrascale)
  - max. 3.6Tbps input

- **Specific points**: improvements
  - dynamic range: increased
  - granularity x 4
  - **jet definition algorithm**
    - Gaussian fitter
    - non-square
    - ...

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24 (20RX and 4TX) miniPOD
(http://www.avagotech.com/)
ATLAS Muon Spectrometer

- A complex of **Trigger** chamber (RPC / TGC + NSW) and **Precision tracker** (MDT, NSW)
- To cope with longer latency & higher trigger rate, **all the electronics to be replaced**
- **MDT** (max. Drift-Time ~ 700ns) to be a part of **Hardware µ-Trigger**
- **ALL the hit** (40MHz) of TGC/RPC/MDT sent to off-detector → process Trigger
Figure 6.2: Muon trigger and read-out diagram

- **TGC Sector-Logic**
  - R/O FIFO
  - Trigger Logic

- **MDT Data Processor**
  - HEB (Hit Extractor)
  - Trk-Segment Finder
    - Track Fitter

- **RPC Sector-Logic**
  - Trigger Logic
  - R/O FIFO

**TGC (Endcap-μ)**
- TGC Big-Wheel
- NSW
- BIS-78
- Tile EB

**MDT**
- Mezzanine Card
  - ASD
  - f.ne TDC
  - Encoder

**FELIX**

**RPC (barrel-μ)**
- Tile LB
  - hit
  - cell energy

Due to the change of the trigger latencies and the higher cavern background conditions expected, as well as to introduce capability to provide track segment information to the Level-0 trigger, all the on-detector electronics (mezzanine cards and Chamber Service Modules (CSM)) will be replaced. All the TDC information is sent to the on-detector electronics board, the MDT data processor, via high-speed optical links. The hit extractor in the MDT data processor serves three purposes:

1. It buffers the MDT hits until it receives a muon pretrigger from the RPC or TGC trigger sector logic or another ATLAS level-0 trigger.
2. It associates MDT hits to a pretrigger of a level-0 trigger.
3. It passes MDT hits associated to a pretrigger in space and time to the MDT trigger processor performing the MDT track fit.
4. It sends the MDT hits associated to a level-0 trigger to the Felix.

The MDT trigger processor has to find the MDT hits in a region of interest which belong to a straight-line track segment and then fit a straight line to hits found in the pattern recognition step. Three methods...
ボードの試験

Xilinx社のIBERTを使ってループバックさせてビットエラーレートのカウントをした

転送レート（ファイバーあたり）：8.0 Gbps

ビットエラーレート< 8.91 x 10^{-15}

σθ ~ 3 mrad

μ^- μ^+

pT = 20 GeV/c

+20 [ mrad ]

-20 [ mrad ]

[ ASIC ]
信号遅延
BCID
Data Switch
GTX Tx
ASIC ctrl.

[ FPGA ]
hit pattern
→ θ
→ Look-Up-Table
→ pT

Optical I/O

TTC

G-Link (legacy)
L0 MDT Trigger

Micro processor on FPGA for track-finding / fitting

Irradiate γ-ray @ GIF
~ 20% occupancy : higher than HL-LHC

processing time < 3.5 μs

- fit to the total L0-latency of 6μs
  ( and still large room to speed-up, multi-core processor, algo.)
- comparable to the offline performance

AM-chip + Linear Approx. for track-finding + fitting

apply ATLAS-FTK Board (Pulsar-2)
64 ATCA Boards (8 shelves) to cover all the MDT system

To Do
# Hit-Pattern < AM capacity
Performance studies
  - efficiency
  - pT resolution

processing time ~ 1.3 μs (+ 0.3μs : reservoir queuing)
Calorimeter & μ-Trigger upgrades towards HL-LHC

- production of prototypes, final modules, tests,
- firmware, software developments are on-going! (depends on the timing to deploy)

Calorimeter:

- eFEX, jFEX: higher granularity (lateral, depth), e, γ, τ / jet
- unique feature of gFEX to catch, large-R jet, (MET, sumE_T)
- aiming to deploy the upgrade system after LS2

Muon:

- all the hit information is sent to off-detector → to retrieve full potential
- precision tracker (MDT) participates to the trigger system
- as a complex system, gain geometrical acceptance & keep low p_T threshold
Backup
**Physics tasks:**
- jFEX identifies jet candidates and calculates $\Sigma E_T$ and $E_T^{miss}$ for each BC

**Features:**
- Data received by the central and forward calorimeters: $|\eta| < 4.9$ with different granularities
- jFEX is an ATCA board
- 4 Xilinx Ultrascale FPGAs per module
- 24 MiniPOD: 20 RX + 4 TX
- Up to 120 MGTs x 4 per module
- Up to 3.6 Tbps in input
- 2 types of MGTs: GTH and GTY
- Data duplication via PMA loop-back ( $\Phi$ ring coverage per module)
- 7 (+spares) modules to be built
Compared to current JEP system

- increased dynamic range
- granularity $\times 4$
- allows flexibility in jet definition (non-square, Gaussian filter, …)

Increased jet environment

\[ \leq 0.9 \times 0.9 (\eta \times \phi) \]

- increases with higher bandwidth or pre-clustering in jFEX, large jets at L1Topo
Level-0 Muon trigger

Phase II upgrade study using data $\sqrt{s} = 8$ TeV, 25 nsec

- **Phase I expected**
- **Phase II proposed, TGC tracking**
- **Phase II proposed, MDT tracking**
- **Offline selected muons, $p_T > 20$ GeV**

**Legend:**
- TGC tracking trigger ($1.0 < |\eta| < 2.4$) — 25%
- MDT tracking trigger ($1.0 < |\eta| < 2.4$) — another 35% or more

**Notes:**
- Higher position resolution → sharper turn-on
TWO level trigger scheme: L0→L1

L0: CALO + MUON
40MHz → 1MHz

L1 Track; $p_T > 4\text{GeV/c} @ \text{RoI}$

Comb. w/ TRK

rate reduction: L0 → L1

$e, (2e): 1/5, (1/10)$

$2\tau: 1/6$