The Phase-I Upgrade of the ATLAS Level-1 Calorimeter Trigger

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ATL-DAQ-PROC-2022-027
09 December 2022

***Abstract*—The ATLAS Level-1 Calorimeter Trigger (L1Calo) is a hardware-based system that identifies events containing calorimeter-based physics objects, including electrons, photons, taus, jets, and missing transverse energy. L1Calo underwent a significant programme of upgrades for Run 3 of the LHC which is running at higher energies and instantaneous luminosity. The existing hardware will be replaced by a new system of FPGA-based feature extractor (FEX) modules, which processes finer-granularity information from the calorimeters and executes more sophisticated algorithms to identify physics objects; these upgrades permit better performance in a challenging high-luminosity and high-pileup environment. The features of the upgraded L1Calo system are introduced and the current status of installation and commissioning is described. In addition, the expected performance of L1Calo in Run 3 is discussed.**

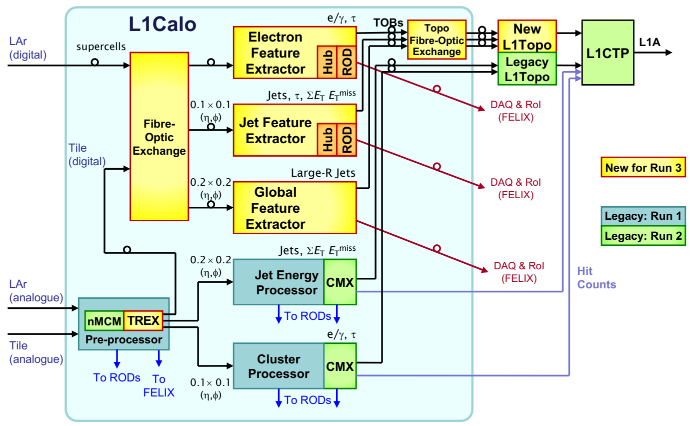

Fig. 1: Overview of the L1Calo in Run 3. Adapted from [2]

I. Introduction

The ATLAS Level-1 Calorimeter Trigger [1] provides the bulk of the hardware trigger objects used to make the ATLAS Level-1 trigger decision. Being based on information from both the electromagnetic and hadronic layers of the calorimeter, it can identify potential electron, photon, tau and jet candidates, as well as making missing transverse energy assessment. The original design, using over 7000 analogue inputs of coarse granularity calorimeter information, was very successful in the first 10 years of LHC operation, which already provided luminosities beyond design.

However, the expected higher luminosities in future LHC operation will compromise the efficiency of the original hardware, and so an upgrade of the system has been built and installed during the recent LHC shutdown period. The basis of the improvement is to increase the level of detail of information available to the trigger, with more granular information both in longitudinal position, and calorimeter depth. In particular, this allows more sophisticated algorithms to be used based on shower shapes, while also aiding energy resolution in a higher pile-up environment.

The higher data rate needed to transmit this additional information (approximately a factor of 10 in the electromagnetic layer) necessitates the use of a new digital trigger signal path which is integrated into the calorimeter outputs, replacing the old analogue path with digital signals at 40 MHz transferred on optical links. The algorithmic part of the Level-1 processing is performed on three Feature Extractors (FEX) which specialize in identifying different physics signatures.

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II. Hardware Upgrades

The design of the new Level-1 Calorimeter Trigger is shown in Fig. 1. The original trigger system from Run-2 is still maintained in place for the start of LHC Run 3, with necessary connections between the two, so that initial data taking for physics purposes is not compromised while the new system is being commissioned and honed for best performance.

The electron feature extractor (eFEX) processes the full granularity information from the calorimeters in order to find smaller electron, photon or tau-like showers, using the full depth and spatial information to better distinguish, and reject, the dominant jet background. It consists of 24 individual ATCA-based modules running independently and in parallel in order to handle smaller blocks of the central detector coverage.

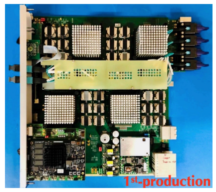
The jet feature extractor (jFEX) does not require the full granular information, and so consists of only 6 similar modules, assessing jet-like objects but with a greater flexibility than the original system for making regional corrections for pile-up effects. It also provides a missing energy measurement.

The global feature extractor (gFEX) is a single module processing data from the whole detector at a coarser granularity, also identifying jets and measuring missing energy. But being a single module, has the capacity to make full event-level corrections and contain large jet objects.

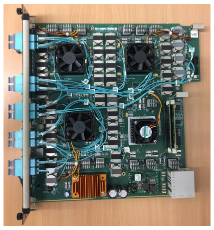
Fig. 2 depicts single modules of the three FEX systems.

The results from the eFEX, jFEX, gFEX modules are further processed by the upgraded Level-1 Topological Trigger (L1Topo). It consists of 3 ATCA modules, which apply flexible

(a) eFEX



(b) jFEX



(c) gFEX

Fig. 2: The new L1Calo Feature Extractors

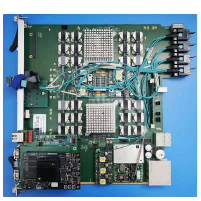
algorithms, from the multiplicity counting up to complex multiple-object based topological algorithms.

The Hub-Readout Driver (ROD) consist of 7 ATCA modules, residing within the eFEX, jFEX and L1Topo ATCA shelves. The modules distribute the timing, trigger and control (TTC) information to the FEX/L1Topo modules within their shelf. They also provide readout data to the new ATLAS Front-End Link Exchange (FELIX) [3] readout mechanism. This data is required both to validate and monitor the performance of the trigger, and as a basis for the next level of triggering in the ATLAS High Level Trigger.

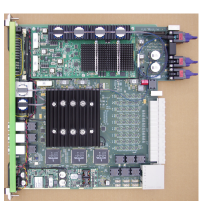
The Tile Rear Extension (TREX) system consists of 32 VME Rear-Transition Modules which extend the functionality of the legacy L1Calo Preprocessor. The modules provide digitised hadronic input from the Tile Calorimeter optically to the FEX modules and electrically to the legacy trigger processors.

The Fibre Optics Exchange (FOX) and Topo-FOX are complex optical exchange networks to rearrange the high-speed data signals into a suitable order for the FEX systems. They ensure the interconnection of the between the calorimeter inputs and the trigger processors.

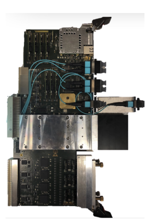
The next set of upgrade modules are showcased in Fig. 3.



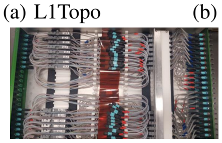
(a) L1Topo



(b) Hub+ROD



(c) TREX



(d) 1 of 6 partially assembled FOX box

(e) TopoFOX

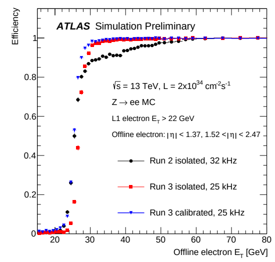
Fig. 3: The new upgrade modules for Run 3.

III. Expected Performance

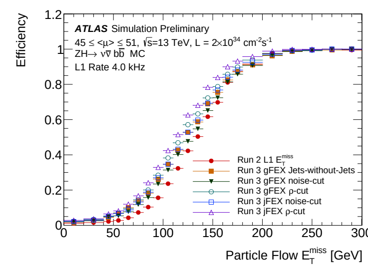
The algorithms performed by the FEX processors are integrated into the offline simulation of the ATLAS L1Calo system. Therefore they can be simulated to gauge the expected performance and behaviour for Run 3.

The expected single-electron trigger efficiency is depicted in Fig. 4 (a), based on the simulation of the $Z \rightarrow ee$ process. The improved performance of the Run 3 trigger results in smaller rate and improved efficiency.

Fig. 4 (b) shows The efficiency of the new missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) algorithms of the Run 3 jFEX and gFEX compared to the Run-2 $E_{\mathrm{T}}^{\mathrm{miss}}$.



(a)



(b)

Fig. 4: (a) Single-electron efficiency comparison between Run 2 and the Run 3 eFEX. (b) $E_{\mathrm{T}}^{\mathrm{miss}}$ algorithm efficiency comparison between Run 2 and Run 3 jFEX and gFEX. [4]

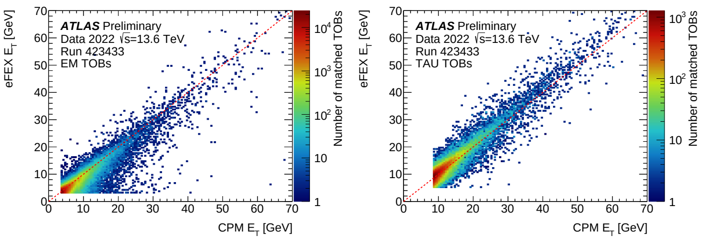
IV. Commissioning and Operation

Testing of the prototype modules and development of firmware and software has been completed over the course of several years at several test-labs at CERN and at the home institutes. Most of the upgrade modules were installed in the ATLAS electronics cavern towards the end of 2021 and the start of 2022. This allowed full integration with the detector environment and testing with ATLAS data.

The full system has been integrated into the ATLAS TDAQ infrastructure and the Detector Control System (DCS) which provides close monitoring of the hardware environmental data.

With the current complete installation, the full functionality is under study, particularly the trigger and event readout paths. The L1Topo module has to interface not only with the FEX modules, but also with the Level-1 Muon Trigger (for topological selections involving muons) and the downstream Central Trigger Processor which makes the final Level-1 decision.

The first physics performance comparisons have been performed between the Phase-I and legacy systems using Run 3 pp collisions at $\sqrt{s} = 13.6$ TeV. The correlation of the Trigger Objects built by the eFEX to its legacy counterpart are presented in Fig. 5. The results show good agreement, the differences are expected due to differing algorithms used to construct the Trigger Objects and different calibration of the input data. Triggering has been achieved with the trigger decisions arriving in-time at the CTP.



(a) (b)

Fig. 5: (a) Comparison of $e - \gamma$ Trigger Objects (TOBs) between the eFEX and the legacy Cluster Processor modules. (b) compares the τ TOBs between the eFEX and the legacy [4].

V. Conclusions

The L1Calo Phase-1 upgrade modules have been produced, installed and are part of standard operation in ATLAS. The Run 3 of the LHC has began with the upgraded trigger running in parallel to the legacy system. Collision data has been recorded which allows the verification of the trigger decision, and the validation of the system is well underway. The upgraded L1Calo system has been timed-in and the rates of the trigger items match with the LHC bunch structure.

First triggering of the Phase-I items has been achieved, with triggers delivered to the Central Trigger Processor. Studies of the physics performance are ongoing using pp collision data at $\sqrt{s} = 13.6$ TeV with the aim of becoming the main trigger in 2023.

References

[1] R. A. et al., ”The ATLAS level-1 calorimeter trigger,” Journal of Instrumentation, vol. 3, no. 03, P03001–P03001, Mar. 2008. DOI: 10.1088/1748-0221/3/03/p03001

[2] Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System. Technical Report CERN-LHCC-2013-018. ATLAS-TDR- 023, Sep 2013

[3] FELIX: the Detector Interface for the ATLAS Experiment at CERN ”https://doi.org/10.1051/epjconf/202125104006 CHEP 2021”

[4] ATLAS Collaboration, ATLAS Public L1Calo Trigger Results, ”https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1CaloTriggerPublicResults”