The Phase-1 upgrade of the ATLAS first level calorimeter trigger

R. Schwienhorst on behalf of the ATLAS collaboration

Michigan State University, East Lansing, MI 48824, U.S.A.
CERN, Geneva, Switzerland

E-mail: schwier@pa.msu.edu

ABSTRACT: The ATLAS level-1 calorimeter trigger pursues a series of upgrades in order to face the challenges posed by the upcoming increase of the LHC luminosity. The hardware built during the Phase-1 upgrade will be installed in 2018. The calorimeter data will be available with a tenfold increase of granularity which allows to employ more sophisticated identification algorithms. To cope with this increase of input data, an entirely new custom electronics processing system will be built exploiting the technological advances in the design of complex PCBs, powerful FPGAs and high speed optical interconnects.

KEYWORDS: Trigger concepts and systems (hardware and software); Trigger detectors; Large detector systems for particle and astroparticle physics; Front-end electronics for detector readout
1 Introduction

The increase in instantaneous luminosity of the Large Hadron Collider (LHC) provides challenges for the trigger system of the ATLAS experiment [1]. The hardware-based first-level calorimeter trigger (L1Calo) is required to cope with challenges from the degradation of the calorimeter signals due to signal length and severe pile-up levels. L1Calo is also required to reduce the higher trigger rates induced by the large number of jets originating from \( pp \) collisions in each bunch crossing.

The LHC has started taking data in Run-2 at a collision energy of 13 TeV, with an instantaneous luminosity of up to about \( 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \). The Phase-1 upgrades are intended for the years 2019 and 2020. Following those, the instantaneous luminosity will be \( 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) and higher in Run-3 of the LHC. This paper describes the Phase-1 upgrade of the L1Calo trigger system, which processes digital information from the liquid-argon (LAr) calorimeters and from the tile (Tile) calorimeters [2, 3]. The upgraded system makes use of higher granularity and runs better-performing trigger algorithms than currently employed in Run-2.

2 ATLAS calorimeter trigger

The ATLAS calorimeter system covers a pseudo-rapidity range of \( |\eta| < 4.9 \). The electromagnetic calorimeter is a lead/LAr detector in the barrel (\( |\eta| < 1.475 \)) and endcap (\( 1.375 < |\eta| < 3.2 \)) regions. The hadron calorimeters are composed of a steel and scintillator-tile barrel (\( |\eta| < 1.7 \)), a LAr/copper endcap (\( 1.5 < |\eta| < 3.2 \)) and a LAr forward system (\( 3.1 < |\eta| < 4.9 \)) with copper and tungsten absorbers.

The L1Calo trigger consists of electronics hardware systems with embedded logic based on ASICs and FPGAs that discriminates and counts candidate particles above threshold and identifies regions of interest (RoI) which are sent to the higher trigger levels. The L1Calo system processes signals from the calorimeters and provides trigger signals to the Central Trigger Processor (CTP).
3 Improvements towards forthcoming LHC runs

The L1Calo trigger system for Run-2 is too coarse and the reconstruction of trigger objects (TOB), which are electrons, photons, tau leptons, jets and missing transverse momentum ($E_{T}^{\text{miss}}$), is challenging at high instantaneous luminosities. High pile-up levels degrade the calorimeter resolution and isolation requirements for particles, resulting in worsening trigger performance. This degradation can be alleviated by transferring off-line algorithms to the trigger level. Figure 1 shows the distributions of two variables that are important in off-line electron identification: the lateral shower shape and the longitudinal shower leakage. These give good separation of electrons from $Z$ boson decays and jets.

High-$p_T$ bosons and fermions are a key component of ATLAS physics program in Run-3. The hadronic decays of $W$, $Z$ and $H$ bosons, top quarks and exotic particles that have large $p_T$ results in energy deposits in the calorimeters that are close to each other in $\eta \times \phi$. Figure 2 shows an simulated event of a new heavy boson $Z'$ decaying to a top quark pair. The $Z'$ has a large mass, resulting in high-$p_T$ top quarks, whose decay products are within a cone of size 1.0. The current jet reconstruction in L1Calo corresponds to a smaller cone size, which is too narrow to encompass the top quark decay products.

The Phase-1 L1Calo upgrades address both of these as well as other instantaneous-luminosity-related issues. Increased LAr granularity improves the jet rejection for electron, photon and tau lepton reconstruction. Large-radius jets will be reconstructed in addition to the current small-radius jets.
Figure 2. Calorimeter clusters, large-radius jet and its sub-jets in a simulated $Z'$ event with decay to a top quark pair. One of the top quarks decays hadronically, and the resulting clusters are matched to the top-quark decay products as well as the additional radiation. Adopted from ref. [4]. Samples used are produced using a detector simulation described in ref. [5].

Figure 3. Super Cell configuration of a LAr trigger tower in Run-3. Each layer has dimensions of $0.1 \times 0.1$ in $\eta \times \phi$. Layer 0 corresponds to the pre-sampler. Taken from ref. [3].

4 L1Calo Phase-1 upgrade

The Phase-1 upgrades provide digital optical signals to the L1Calo system. This digitization allows for three different granularities to be provided according to the clustering requirements. The inputs to the L1Calo system in Run-2 are Trigger Towers that are formed by analog summation of calorimeter cells across the longitudinal layers in a region of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$. The Phase-1 upgrade increases the granularity of the LAr trigger inputs to ten Super Cells per trigger tower [2], as shown in figure 3.

These Super Cells facilitate improvements to the electron, photon and tau lepton L1Calo algorithms. In addition, coarse-granularity information is available to enable the processing of the full calorimeter in a single ATCA module. Three new feature extractor (FEX) sub-systems will be added to L1Calo: the electromagnetic (eFEX), jet (jFEX), and global (gFEX) feature extractors,
which will gradually take over the functions of the current processing sub-systems. The three FEX systems process different input information and have different algorithmic trigger requirements. An overview of the upgraded system is shown in figure 4. The FEX modules reside in ATCA shelves. The TOBs and readout information are collected in a custom ATCA hub board designed for the FEX system (HUB), which also acts as the shelf controller. The FEX systems receive their inputs via optical fibers at a link speed of 6.4 Gb/s (link speeds up to 11.2 Gb/s are under investigation). The mapping between LAr pre-processor outputs (which provide the digital optical signals) and the FEX modules is accomplished by the optical plant. Some of the signals need to be duplicated in the overlap regions between FEX modules. This is accomplished through duplication at the source as well as fiber splitting in the optical plant.

The current system consists of the pre-processor, which sends signals to the jet energy processor and cluster processors. These are connected via a extended common merger module (CMX), which sums and consolidates the information from the processors. The CMX sends its results to the L1Topo processor, which combined electron, photon, muon, tau lepton and jet candidates as well as $E_T^{\text{miss}}$ information and performs real-time event selection based on their spatial information and geometrical relationships such as the angle, distance or invariant mass of pairs of objects.

4.1 eFEX system

The Super Cells are transmitted as digital optical signals to the optical plant and received by the eFEX system. Each optical fiber carries data from an area of $0.2 \times 0.1$. Each eFEX also receives trigger towers from the hadronic calorimeter, with each optical fiber carrying data from an area of $0.4 \times 0.2$. The connection to the eFEX is made via four 48-way MTP connectors mounted on the
ATCA backplane, which transmit the optical signals to 12-channel Avago miniPOD transceivers. The transceiver channels are routed to the signal-processing Xilinx Virtex FPGAs. Four Processor FPGAs on each eFEX board are responsible for clustering and identifying electrons and tau leptons and for computing $E_T^{\text{miss}}$ in segments of $\eta$. There are 24 eFEX boards, distributed over two ATCA shelves. The TOBs and readout information are collected in the HUB board in each shelf.

### 4.2 jFEX system

The jFEX system receives trigger tower information from the LAr and Tile calorimeter, the granularity of the Super Cells is not required for jet reconstruction. Each optical fiber to the jFEX carries data from an area of $0.4 \times 0.2$. The connection to the jFEX is made via four 72-way MTP connectors mounted on the ATCA backplane connected to 12-channel Avago microPODs. Four processor Xilinx Virtex FPGAs are responsible for clustering and identification of jets and tau leptons on each jFEX board. This configuration allows for jets with a configurable size parameter to be clustered. There are 7 total jFEX boards. The TOBs and readout information are collected in a HUB board.

### 4.3 gFEX system

The gFEX system receives information from the full calorimeter in a single ATCA module. The sum of calorimeter cells from a region of $0.2 \times 0.2$ is provided by the LAr and Tile calorimeters. The connection to the gFEX is made via four 72-way MTP connectors mounted on the ATCA backplane connected to 12-channel Avago microPODs. Four processor Xilinx Virtex FPGAs are responsible for clustering and identification of large-radius jets. No HUB board is used, the TOBs and readout information are provided by the gFEX itself.

### 5 Conclusions

New architectures of the ATLAS L1Calo trigger system have been developed for the Phase-1 upgrade toward Run-3 data taking, scheduled to start in 2020. The upgrades enable more refined processing of EM calorimeter information as well as the reconstruction of large-radius jets and various other new features. By adopting them, ATLAS can maintain a good trigger performance even in severe pile-up conditions and expand the physics capabilities of the Level-1 trigger.

### Acknowledgments

This work was supported in part by the US National Science Foundation under grant No. PHY-1410972.

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