Upgraded Trigger Readout Electronics for the ATLAS LAr Calorimeters for Future LHC Running

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Abstract.

The ATLAS Liquid Argon (LAr) calorimeters produce almost 200K signals that are digitized and processed by the front-end and back-end electronics for every triggered event. Additionally, the front-end electronics sums analog signals to provide coarse-grained energy sums to the first-level (L1) trigger system. The current design was optimized for the nominal LHC luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. In order to retain the capability to trigger on low energy electrons and photons when the LHC is upgraded to higher luminosity, an improved LAr calorimeter trigger readout is proposed and being constructed. The new trigger readout system makes available the fine segmentation of the calorimeter at the L1 trigger with high precision in order to reduce the QCD jet background in electron, photon and tau triggers, and to improve jet and missing $E_T$ trigger performance. The new LAr Trigger Digitizer Board is designed to receive the higher granularity signals, digitize them on-detector and send them via fast optical links to a new Digital Processing System. The reconstructed energies of trigger readout channels after digital filtering are transmitted to the L1 system, allowing the extraction of improved trigger signatures. This contribution presents the motivation for the upgrade, the concept for the new trigger readout and the expected performance of the new trigger, and describes the components being developed for the new system.

1. Introduction

The successful operation of the ATLAS detector [1] at the Large Hadron Collider (LHC) during the first data taking period (Run 1, 2009-2013) has demonstrated its extraordinary capability for proton-proton and heavy ion physics. During the next period (Run 2, 2015-2018), the LHC is expected to reach the design luminosity and energy. This will be followed by a series of upgrades over the next decade. The first phase of the upgrade (Phase-I) is expected to be completed in 2018-2019, bringing the instantaneous luminosity to $2 - 3 \times 10^{34}$ cm$^{-2}$s$^{-1}$, exceeding the LHC nominal design luminosity. ATLAS is constrained by readout dead time to a 100 kHz event rate at Level-1 (L1) trigger for most of the front-end electronics. The requirement for studying physics processes that depend on low $p_T$ lepton triggers dictates that the L1 trigger needs to be significantly improved to handle the increased background rates to lepton triggers when the detector is operated in the high pile-up environment with an average number of collisions per crossing ($\langle \mu \rangle$) of 55 at $\mathcal{L} = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$. The upgrade of the Liquid Argon (LAr) calorimeter trigger readout aims at retaining the capability of triggering on low transverse energy ($E_T$) electromagnetic (EM) objects when the detector is operated during the third period (Run 3, 2019-2022) after the Phase-I upgrade.
After describing the current LAr calorimeter readout and trigger, the expected performance of the upgraded triggers for electrons and jets, and the technical implementation of the new trigger readout are summarized. The details of the design are described in the Technical Design Report [2] for ATLAS LAr Calorimeter Phase-I Upgrade, which was presented to and endorsed by CERN LHCC in Dec 2013, and approved by the CERN Research Board in March 2014.

2. The current LAr readout and calorimeter trigger system

The ATLAS LAr calorimeters produce almost 200K signals, which are digitized and processed by the front-end and back-end electronics for every triggered event. In addition, the front-end electronics sums analog signals of the readout channels to provide coarse-grained energy sums to the L1 calorimeter trigger system. The current design was optimized for the nominal LHC luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. The trigger readout consists of electromagnetic and hadronic trigger towers, each with granularity of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for most parts of the calorimeter, with a quantization scale of 1 GeV. EM objects are identified as clusters of energy with fixed size in the grid of trigger towers, with possible isolation energy requirements around the objects and a hadronic energy veto. Jets are identified on a grid of even coarser granularity of $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$.

The trigger rate for a single 25 GeV EM object is estimated to be 120 kHz at $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ with the L1 trigger of Run 1. A general trigger menu that enables a broad physics program implies that no more than 20 kHz can be allocated to single EM object triggers at the L1. This would require an $E_T$ threshold of 50 GeV (or 35 GeV with isolation requirements) and even higher at higher luminosity. It would significantly reduce the acceptance for a variety of important physics measurements and searches based on EM objects, such as Higgs production in association with a W or Z boson, which are tagged by the leptonic decays of the W’s and Z’s.

The ability to reject the background to EM objects in offline reconstruction takes advantage of the high granularity of the calorimeter readout. The shower shapes of EM objects differ significantly from the background from jets. Discriminating variables, such as the ratio of the energy in 3$\times$7 cells over the energy in 7$\times$7 cells centered at the cluster position and lateral shower width within a window of 3 $\times$ 5 cells have been successfully used in the offline analysis.

The design of the LAr trigger readout upgrade is based on improving the granularity of the information and the precision of the energy measurements at the L1 within the constraint of the current front-end electronics, such that shower shape variables are calculated within the latency to reject jet backgrounds for EM triggers.

3. Configuration of the new trigger readout and its expected performance

The ATLAS LAr EM calorimeter is highly segmented, as illustrated in Fig. 1. The calorimeter cells in each sampling layer have different size by construction. The trigger tower signals are created through several stages of on-detector analog electronics: in the shaper ASICs, in the Layer Sum Boards on the Front-End Boards, and in the Trigger Tower Boards installed on-detector. Typically, a total of 64 read-out channels are summed to form an EM trigger tower.

The new finer granularity scheme is based on “Super-Cells “, which provide information in each calorimeter layer with finer segmentation ($\Delta \eta \times \Delta \phi = 0.025 \times 0.1$ in the front and middle layers of the EM calorimeter for $|\eta| \leq 2.5$). This scheme is detailed for the EM barrel calorimeter in Table 1 and is illustrated in Fig. 2. For the strip and middle layers, where the bulk of the EM shower energy is deposited, this represents a factor of 4 higher transverse granularity.

The digitization precision of the Super-Cell signals is improved by at least a factor of 4 compared to the existing L1 system: the quantization scale and the dynamic range of the digitizers are optimized in each $\eta$-region and for each layer of the calorimeter to achieve sensitivities at the level of the Super-Cell electronic noise or better. The transverse energy deposited in the Super-Cells is calculated at each bunch crossing through optimized
Figure 1. The segmentation of the readout cells in the LAr EM Barrel calorimeter.

Figure 2. The segmentation of the Super-Cells of the EM calorimeter.

Table 1. Comparison of the current Trigger Tower granularity vs. the proposed Super-Cell granularity in the LAr EM barrel calorimeter, in terms of both elementary cells and $\Delta \eta$ and $\Delta \phi$. The number of elementary cells grouped for the trigger readout in $\eta$ and $\phi$ are indicated by $n_\eta$ and $n_\phi$, respectively.

| Layer | Elementary Cell | Trigger Tower | Super-Cell |
|-------|-----------------|---------------|-------------|
|       | $\Delta \eta \times \Delta \phi$ | $n_\eta \times n_\phi$ | $\Delta \eta \times \Delta \phi$ | $n_\eta \times n_\phi$ | $\Delta \eta \times \Delta \phi$ |
| 0     | Presampler      | 0.025 x 0.1   | 4 x 1       | 4 x 1          | 0.1 x 0.1        |
| 1     | Front           | 0.003125 x 0.1| 32 x 1      | 8 x 1          | 0.025 x 0.1      |
| 2     | Middle          | 0.025 x 0.025 | 4 x 4       | 1 x 4          | 0.025 x 0.1      |
| 3     | Back            | 0.05 x 0.025  | 2 x 4       | 2 x 4          | 0.1 x 0.1        |

algorithms. Techniques similar to the optimal filtering currently implemented in the LAr online signal processing will provide results close to the energy resolution obtained from the offline reconstruction.

Preliminary studies, shown in Fig. 3, demonstrate the significant improvement in the energy resolution using the layer-weighted $3 \times 2$ Super-Cell cluster $E_{SC}^{T}$ over the existing L1 $E_{L1}^{T}$, when the measurements are compared to the offline reconstructed cluster energy, $E_{T}^{\text{offline}}$. This resolution improvement translates into an improved efficiency for EM objects in the trigger for a given offline $E_T$, sharpening the turn-on curve and thus making it possible to lower the offline $E_T$ threshold by several GeV for the same trigger rate.

Similarly, the improved energy resolution of the LAr calorimeter upgraded trigger electronics allows for an improvement in the energy resolution of jets reconstructed in the L1 trigger system. Figure 4 compares the trigger efficiency as a function of the highest $p_T$ jet in QCD dijet events between the current and the upgraded systems for a online L1 jet threshold of 20 GeV.

The finer granularity of the Super-Cells enables a more sophisticated analysis to reject jet backgrounds to EM triggers than in the current system through the use of shower shape variables. A few discriminating variables have been investigated:

$R_\eta$ Given a $3 \times 2$ group of Super-Cells in $\eta \times \phi$ centered on the highest-energy Super-Cell in the middle layer, $R_\eta$ is defined as the transverse energy measured in the $3 \times 2$ group divided by...
Figure 3. Difference in percent between $E_{T}^{L1}$ and $E_{T}^{\text{offline}}$ (red) compared to that between $E_{T}^{SC}$ and $E_{T}^{\text{offline}}$ (blue) for simulated $Z \rightarrow e^+e^-$ events in the LAr EM barrel calorimeter. The electron candidates are required to be within $|\eta| \leq 1.2$.

Figure 4. The trigger efficiency as a function of the highest $p_T$ offline jet for $\langle \mu \rangle = 80$ in simulated QCD dijet events for the default sliding window algorithm (black points) and the sliding window algorithm based on Super-Cells (red points) for jets within $|\eta| < 2.5$.

Figure 5. Distributions of variables allowing to distinguish between electrons (black) and jets (red) with $p_T > 20$ GeV and with the upgraded L1 trigger: $R_\eta$ (left), $f_3$ (middle) and $w_{\eta,2}$ (right). Each distribution is normalized to unit area.

- the transverse energy measured in a $7 \times 2$ group;
- $f_3$ The ratio of the transverse energy measured in the back EM layer in an area of size $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ to that deposited in all three layers for an EM cluster; the energies in the front and middle EM layers are reconstructed in the area $\Delta\eta \times \Delta\phi = 0.075 \times 0.2$;
- $w_{\eta,2}$ The spread of the shower in the middle EM layer in a $3 \times 2$ Super-Cell region, defined as an energy weighted root-mean-squared.

In addition, hadronic isolation ( $E_{\text{core}}^{\text{had}} \leq 1$ GeV) can be required for each electron candidate, where $E_{\text{core}}^{\text{had}}$ is defined as the transverse energy deposited in a $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ region of the hadronic calorimeter behind the EM shower. A multi-dimensional optimization is performed to minimize the trigger rate while keeping a high signal efficiency.
Figure 6. L1 trigger rates for a 95% electron efficiency as a function of the EM $E_T$ threshold assuming Run 2 conditions (blue points) and for Run 3 conditions, at $\mathcal{L} = 3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, for two sets of cuts (green and black triangles), as measured from a sample of simulated minimum bias events with $\langle \mu \rangle = 80$.

Figure 6 provides a comparison of the Run 2 L1 trigger performance to that of the upgraded L1 trigger for a 95% electron efficiency in both cases. It shows that for a given bandwidth of e.g., 20 kHz, the L1 threshold, which would need to be 28.5 GeV assuming Run 2 conditions, could be lowered by 7 GeV to 21.5 GeV with the proposed upgrade.

4. Design of front-end readout and signal processing

The schematic of the LAr calorimeter readout with the upgraded trigger readout is shown in Fig. 7. The current readout components will remain mostly intact. The new components are indicated by the red outlines and arrows on the diagram. The analog signal sums for the trigger will be modified such that the sums for Super-Cells will be formed first, which are then further summed into trigger towers so that the current L1 trigger will continue to function. The new components include new layer sum boards on the existing front-end boards to produce finer granularity Super-Cell signals for each layer, and new base planes in front-end crates for analog signal transfer. New LAr Trigger Digitizer Boards (LTDB) receive and digitize analog Super-Cell signals and transmit digital Super-Cell signals to the backend, where a LAr Digital Processing System (LDPS) extracts transverse energy values for each Super-Cell at every bunch crossing and transmits data to the L1 calorimeter trigger system.

Each LTDB will process up to 320 Super-Cell signals. The signals will be digitized at 40 million samples per second by 12-bit ADCs on the LTDB after one additional stage of shaping. In the current design, the least significant bit is 32 MeV for the front layer, and 125 MeV for...
Figure 7. Schematic of Liquid Argon Calorimeter readout with the upgraded trigger readout.

The middle layer, in $E_T$. Both custom designed ADC and commercial off-the-shelf option are being considered. Data of 8 ADC channels will be serialized and transmitted at 5.12 Gbps to the backend. Each LTDB will typically have 40 fibers. A total of 124 LTDBs will be needed, delivering 25 Tbps digital information to the LDPS.

The LDPS is made up of 31 LAr Digital Processing Blades (LDPBs) housed in three ATCA shelves. Each LDPB consists of one carrier board equipped with four Advanced Mezzanine Cards (AMCs), for a total of 124 AMCs. The AMC is designed around a powerful FPGA with high-speed transceivers that will process the data of up to 320 Super-Cells within the latency budget (17 bunch crossings for LDPS). In addition to receiving $\sim 25$ Tbps for 34,000 Super-Cells, the LDPS transmits $\sim 41$ Tbps over optical fibers to the L1 calorimeter trigger system, within which the physics objects such as electrons, photons, taus and jets are identified [3].

5. Summary
ATLAS has designed a new LAr calorimeter trigger readout in preparation for its operation after LHC Phase-I upgrade. The new system makes available the fine segmentation of the calorimeter at the trigger level with high precision in order to reduce the QCD jet background in electron, photon and tau triggers, and to improve jet and missing $E_T$ trigger performance. It will enable ATLAS to retain low trigger thresholds when it is operated at luminosity of $3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. The upgraded trigger readout is planned to be used as the low-latency Level-0 trigger after the Phase-II upgrade, during which a fully digital LAr front-end readout will be put in place [4].

References
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