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ATLAS LAr Calorimeter commissioning for LHC Run-3: Energy computation in LATOME boards

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Abstract

The ATLAS experiment at the Large Hadron Collider (LHC) measures proton–proton collisions at high energies. Within the Phase-I upgrade of the LHC before the start of Run-3 in 2022, the trigger system of the Liquid Argon calorimeter of ATLAS is being prepared to cope with an increased number of simultaneous proton–proton collisions. In the back-end of this new trigger system, the LATOME boards will be responsible for the computation of the energies deposited in the calorimeter. The commissioning of this computation within the LATOME is presented.

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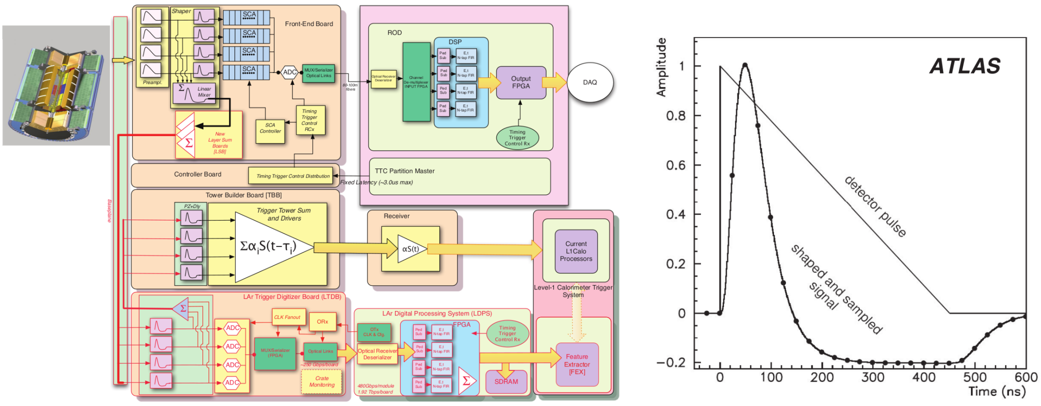
1 Introduction

The ATLAS experiment [1] is a multi-purpose detector installed at the Large Hadron Collider (LHC) [2] operated at CERN. It aims at collecting as much information as possible from the products of the high energy proton-proton collisions provided by the LHC every 25 ns. For the particles produced by these collisions, such information, collected by various sub-detectors, can be their nature, their charge, their momentum or their energy. The Liquid Argon (LAr) calorimeter is a sub-detector measuring mainly the energy of electrons, positrons and photons. It consists in alternately layers of absorbing material, mainly lead – favouring the showering of the incoming particles – and liquid Argon where low energy particles of the shower ionize producing an electrical signal. Particle positions are defined in coordinates of their pseudo-rapidity η and the azimuthal angle ϕ of the ATLAS detector seen as a barrel. The LAr calorimeters are divided in cells corresponding to specific (η,ϕ) coordinates and one of the four layers in depth. The electrical signal coming from each cell is used to recompute the energies deposited at specific position in the detector.

With collisions at a frequency of 40 MHz, it is impossible to keep every event and triggers are used to record only the physically interesting ones. The level-1 hardware trigger of the LAr calorimeter output frequency should be 100 kHz, reducing the data by a factor 400. The allocated latency for the computation of energies of particles is then of approximately 150 ns. To meet such requirements, the main idea is to reduce the number of calorimeter cells for which a deposited energy has to be computed. This is achieved with Trigger Towers, which are groups of LAr cells combining around 60 of them in depth and in a region of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The Trigger system groups the electrical signal coming from cells of a trigger tower and the reduced granularity allows to compute fast enough the corresponding energies.

Within the Phase-I upgrade of ATLAS [3] before Run-3, this trigger system is modified in order to cope with the increased pile-up in Run-3. The mean number of collision per bunch crossing is expected to go from $\langle\mu\rangle \approx 20$ to $\langle\mu\rangle \approx 80$ in Run-3. To keep the same level-1 accept rates, the trigger discriminating power has to be improved. This is achieved by increasing the granularity. For this purpose, Super-Cells are defined as a new grouping of LAr cells. Typically, there are 10 Super-Cells per Trigger Tower. However, this increased granularity puts more pressure on the trigger system as more energies have to be computed within the same time constraints. This is made possible thanks to progress in electronics and the use of FPGAs. In the end, the full front-end and back-end of the trigger system have to be changed as described in the red part of figure 1a.



(a) (b)

Figure 1: (a) Schematic block diagram of the LAr trigger readout architecture. Blocks concerned by the Phase-1 upgrade have a red outline. (b) Triangular signal shape from the LAr calorimeter, overlaid with the bipolar-shaped and sampled signal. Both figures are from reference [3].

2 From LAr pulse to Energy

The electrical signal coming from the LAr cells is typically a triangle as shown in figure 1b, decreasing steadily during 400 ns. However, with a bunch crossing every 25 ns, this long tail is a problem. It creates what is called of out-of-time pile-up, meaning the calorimeters still record energy deposited from previous bunch-crossing in addition to other pile-up event happening at the same bunch crossing. One has to imagine the electrical signal as the superposition of such triangles distributed randomly depending on if a particle deposited energy at a specific bunch crossing or not. With tails lasting almost 20 bunch crossings, a lot of out-of-time pile-up is created. To reduce this, the signal goes through a shaper in order to be more peaked right after the energy deposit and dive to negative values subsequently. It is then grouped in the Layer Sum Board (LSB) to create analogical Super-Cell signal. Then, it enters the LAr Trigger Digitizer Board (LTDB) where it is digitized at a rate of 40 MHz using a 12 bits analog-to-digital converter (ADC). As a result, at every bunch crossing, there is one ADC count of the original signal among the $2^{12} = 4096$ available values. The stream of ADC counts then enters the LAr Digital Processing System which contains LATOME boards grouped by four on LAr carriers. The LATOME board is mainly built around an FPGA where a firmware block called `user_code` is responsible for the main physics task, most importantly computing the energy deposited in the Super-Cells.

The signal after going through the shaper is characterised by three important parameters: its pedestal, its amplitude and its time delay. The pedestal corresponds to an overall offset of the signal allowing for the negative part in the tail used to cancel out-of-time pile-up. The amplitude of the signal – minus the pedestal – is proportional to the amount of energy deposited. Typically, the pedestal is around 1000 ADC counts, leaving around 3000 counts for the energy resolution. The time delay corresponds to the time between the recorded peak and the correct associated bunch crossing. This delay arises mainly from the shaping as a systematic effect of a few bunch crossings. For better precision, the phase is defined as the instant when the peak is found within the 25 ns of a bunch crossing.

The pedestal is extracted with calibration runs. The LATOME board is thus responsible for the computation of the energy and phase with the stream of ADC count for each Super-Cell it receives.

3 Energy computation in the LATOME board

The energy computation in the `user_code` of the LATOME is achieved thanks to the Optimal Filtering Coefficients (OFC) method [4] described in equations (1) and (2):

$$E_{\mathrm{T}}(m) = \sum_{i=0}^{N-1} a_i \cdot \left(\mathrm{ADC}_{m+i} - \mathrm{ped}_{m+i}\right), \tag{1}$$

$$\xi(m) = \tau(m) \cdot E_{\mathrm{T}}(m) = \sum_{i=0}^{N-1} b_i \cdot \left(\mathrm{ADC}_{m+i} - \mathrm{ped}_{m+i}\right). \tag{2}$$

This method uses a series of N signal value – in this case $N = 4$ – which are the signal in ADC count, labelled ADC_{m+i}, minus the pedestal, labelled ped_{m+i}. The OFC coefficients a_i (respectively b_i) are such that formula (1) (respectively (2)) gives on average the energy E_{T} (respectively $\xi(m)$ defined as the phase $\tau(m)$ for bunch crossing m multiplied with the energy) of the corresponding peak, with minimum variance associated.

Both the phase and the energy are computed at every bunch crossing. Then, a selection block in the `user_code` of the LATOME will check the phase is short enough by performing the following checks:

$$\begin{cases} -8E_{\mathrm{T}}(m) < \xi(m) < 16E_{\mathrm{T}}(m) & \text{for} \quad E_{\mathrm{T}}(m) > 10\,\mathrm{GeV}, \\ -8E_{\mathrm{T}}(m) < \xi(m) < 8E_{\mathrm{T}}(m) & \text{for} \quad 0\,\mathrm{GeV} < E_{\mathrm{T}}(m) \leq 10\,\mathrm{GeV}, \\ 8E_{\mathrm{T}}(m) < \xi(m) < -8E_{\mathrm{T}}(m) & \text{for} \quad -1\,\mathrm{GeV} < E_{\mathrm{T}}(m) \leq 0\,\mathrm{GeV}. \end{cases} \tag{3}$$

If it is so, the energy is selected and automatically associated to its correct bunch crossing. However, a too long phase for example will indicate that the peak is best described by computations at a previous bunch-crossing.

Additionally a saturation detection block detects and removes saturated pulses thanks to criteria on E_{T} and ξ, and a baseline correction blocks improves the out-of-time pile-up removal.

Parameters needed for all these steps are the pedestal, the four optimal filtering coefficients a_i, again four b_i and six additional saturation detection criteria not discussed here.

These parameters are extracted through calibration runs. This has two consequences. Firstly, they are all Super-Cell specific. That is in total 16 parameters (the pedestal is counted twice as it appears in the two formulae) that are stored in registers of the FPGA for each Super-Cell. With 34 048 Super-Cells in total and typically around 300 Super-Cell managed by FPGA, thousands of such Super-Cell specific parameters have to be stored in the correct register of the correct FPGA. Secondly these parameters are condition specific, the calibrations happening regularly. As a result, each set of parameters is stored with an interval of validity depending on run number and luminosity block of the LHC. This is achieved with the `COOL` condition database [5].

The output of the calibration runs are floats parameters stored in this format in the `COOL` database. However, in the firmware, the parameters are stored as integers of a specified number of bits, *e.g.* the OFC coefficients are stored as 14 bits signed integers. Thus, a careful conversion taking into account signs and the upper limit in bits has to take place before filling the registers. Then, the outputs of the LATOME are also integers that have to be converted back to floats to be read. One important consequence is that, from floats to integers, information is lost and the result of the energy computation is degraded compared to the results with full float precision.

4 Commissioning

For commissioning, the structure detailed above was slightly modified to test separately every step. The generation of the condition database from calibration run being still under development, a dummy `COOL` database with smartly chosen coefficients was developed. As a first test, one of these dummy databases with all parameters set to dummy values, identical for all Super-Cells, was loaded successfully on LATOMEs.

The next step was to verify that the OFCs were correctly filled in the FPGA. First, the OFCs filled in the dummy database were chosen to be $a_i = b_i = (1, 0, 0, 0)$. The bunch crossings all have an index called BCID. For this test, the ADC counts being sent were exactly the BCID at which they were sent. To test LATOME boards, different output configuration are devised under the name *monitoring recipe*. Here, with the chosen monitoring recipe, the energy computed at one specific bunch crossing was read from the LATOME. The ADC counts used in the formula (1) were thus the BCID and the three subsequent ones. With this simple OFC configuration and all pedestals set to zero, the energy had to be the BCID at which the energy was computed. This configuration allowed to check specifically the first OFC, but other similar configurations were tried. One such was $a_i = b_i = (1, 2, 3, 4)$, validating all OFCs at once.

The general energy computation formula being validated, the next step was to check with real OFCs coming from calibration. They would thus all be different for each Super-Cell. Comparing the LATOME output to an offline computation allowed to check that the coefficients were filled in the correct register in the correct format. As a result, in addition to the correct matching of OFCs with their Super-Cell, the conversion from floats to 14 bits signed integers was also verified in this test. In the monitoring recipe used, eleven ADC counts and the corresponding computed energy was read from the LATOME. The test run was sending to all channels of the LATOME ADC counts corresponding to a pulse. The formula (1) applies at every bunch crossing if at least four have been already received, so an energy output can be recomputed offline for the eight earliest ADC counts of an event, for each channel, and then compared to the LATOME energy output. This test was conducted with two LATOMEs, for a total of 580 Super-Cells, and for 1000 events. This amounts to $8 \times 580 \times 1000 = 4\,640\,000$

energies recomputed in different conditions. The comparison of these to the corresponding LATOME output show strictly no difference. This validates the energy computation part of the `user_code` of the LATOME board.

However, the use of only half of the OFC coefficients can be verified by this method. The computation equivalent to formula (2) needs to be tested. This is first achieved by using the previous method and by replacing the OFCa by OFCb and comparing the offline computation of ξ to the result of the LATOME output, showing again no difference. These tests also allowed to check that the number of bits in the registers cover the a_i and b_i range. In this case, it had to be adapted accordingly. A more complete test was performed by activating the selection block in the `user_code` and implementing it also in the offline computation. On failing the selection tests described in formula (3), the LATOME finally outputs an energy of 0 GeV. The comparison of LATOME output and recomputed energy show again no difference as previously.

A similar offline computation can be done using this time the full float precision of the OFC coefficients. The direct comparison of the full precision energy to the LATOME output gives the energy resolution. Representing the difference between both results, a gaussian distribution is obtained, yielding an energy resolution of around 50 MeV. This is approximately the precision of the third least significant bit of the LATOME output – the least significant bit representing 12.5 MeV. This precision choice is thus very conservative. Still, this resolution is small compared to the typical values of the energy computed. The relative difference between both energies is found to be very small, of the per mil level.

5 Conclusion

The computation of energy and time delay of LAr pulses is made possible by the Optimal Filtering Coefficients method. The method is implemented in the firmware of the LATOME board responsible for the computation of energy from Super-Cells in the new trigger chain of the LAr calorimeter. As presented here, the commissioning of the computation of energy and selection block is a success. Additionally, the energy output of the LATOME has a good resolution, of the order of 50 MeV, corresponding to an accuracy at the per mil level. Yet, this was only validated on a few LATOME and the full commissioning will have to happen on all LATOME boards to check for possible outliers.

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