The ATLAS Liquid Argon Calorimeters At The Dawn Of LHC Run-2

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Abstract. The Liquid Argon Calorimeters are key sub-detectors of ATLAS. They are essential to detect and measure the properties of electrons, photons and are also crucial for jets and missing transverse momentum measurements. During the LHC shutdown in 2013-2014, the hardware and the software have been optimized to improve their reliability. The first collisions allow an assessment of the performance of the detector in the LHC Run-2 conditions. In view of the next LHC Run in 2020, an upgrade of the level-1 trigger system is also under test. The status at the restart of the LHC Run-2 is presented in this document.

The Liquid Argon (LAr) Calorimeters

The LAr Calorimeters\cite{1} are sampling calorimeters, using liquid argon as active medium. The general layout is visible in Fig. 1a.

The primary aim of the electromagnetic calorimeters is the detection of electrons and photons and the measurement of their energy and momentum direction. An electromagnetic barrel (EMB) and two electromagnetic end-caps (EMEC) cover the pseudorapidity regions of respectively \(|\eta| < 1.475\) and \(1.375 < |\eta| < 3.2\). Their passive material is lead and they have an innovative accordion shape, enabling a full azimuthal coverage and a fast readout while avoiding dead regions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{(a) General layout of the LAr Calorimeters. (b) Internal structure of the electromagnetic partitions[2].}
\end{figure}

The hadronic end-caps (HEC) are also part of the LAr Calorimeters. They detect jets in the pseudorapidity range \(1.5 < |\eta| < 3.2\) and use copper plates as passive material. Those plates allow to easily extract the heat deposited in those regions.

The forward calorimeters (FCal) cover the large pseudorapidity \((3.1 < |\eta| < 4.9)\) region. They use a specific design of either copper or tungsten matrix with argon gaps of \(150 - 400 \mu\text{m}\) to have a fast readout and avoid ion...
build-up effects up to the LHC design luminosity.

The internal electromagnetic structure may be seen in Fig. 1b. When particles ionize the argon, the ionization products are collected by the outer layers of the copper electrodes, powered by two independent high voltage (HV) lines. By capacitive coupling, this induces a current pulse in the inner electrodes layers, which is proportional to the energy deposit of the initial particle. The LAr Calorimeters are divided into 182 468 independent cells. The cell pattern, in three layers, allows the reconstruction of the longitudinal development of the electromagnetic shower. Radiation lengths larger than 22 $X_0$ (EMB) and 24 $X_0$ (EMEC) enable to contain most of the shower for an electron energy up to 5 TeV. The typical size of a cell in EMB layer where most of the shower is contained is $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$.

The LAr Calorimeters are also an input to the level-1 trigger (L1Calo). An energy summation is performed over the layers and on regions of typical size: $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ to form trigger towers (TT). The level-1 trigger decision is taken based on this coarse information.

The LAr Calorimeters were essential to the Higgs boson discovery. The most sensitive decay channels were the ones with electromagnetic objects: $H \rightarrow \gamma \gamma$ and $H \rightarrow 4l$. In the design of the calorimeters, these processes constrained the requirements for an excellent energy resolution on a range from 10 to 300 GeV [3]. The typical energy resolution in the barrel was measured during the Run-1 to be [4]:

$$\frac{\sigma_E}{E} = 10\% \sqrt{E} \oplus \frac{250 \text{ MeV}}{E} \oplus 1\%$$  

(1)

**Novelties for the Run-2**

The ionization pulse has a triangular shape, as can be seen in Fig. 2. The typical drift time of 450-600 ns\(^1\), in the electromagnetic partitions, is much longer than the bunch crossing period (25 ns). After pre-amplification, a $CR-(RC)\(^2\)$ filter shapes the signal in the bipolar form visible in Fig. 2. The signal pulse is digitized at a frequency of 40 MHz. During the Run-1, five digitized samples were used to compute physical values as the energy and the peak time, making such measurements more resilient to the out of time pile-up (energy deposits due to the previous collisions).

In order to run at a higher instantaneous luminosity in the years to come, the current L1 trigger rate of around 70 kHz would need to be raised up to 100 kHz. To enable such an increase, the number of digitized samples was reduced from five to four, at the start of Run-2 due to the limited size of the online data buffers. Studies have shown that the impact on the energy resolution is negligible.

![FIGURE 2: Typical pulse shape within the liquid argon before and after its shaping. The large dots (resp. crosses) show the typical position of the five (resp. four) digitized samples.](image)

Besides this, a majority of high voltage (HV) power supplies were replaced. During the Run-1 they were subject to intensity spikes, leading to a voltage trip. This induced the main source of data rejection namely 0.46% out of a total

\(^1\)In the FCal, the drift time is shorter due to the smaller gaps of liquid argon and the position of the used samples is different.
of 0.88% in 2012 for the LAr Calorimeters [5]. A new generation of HV generators was successfully tested during Run-1 and proved to be more resilient to such spikes. They could sustain high intensity for a longer period, allowing to reduce the data losses. Therefore they were largely deployed before the LHC Run-2.

**Global synchronization**

In April 2015, single circulating beams were dumped in the ATLAS upstream collimators. They created huge particle showers flowing through the detector. Such events are called "beam splashes" and induce energy deposition in most of the detector.

The energy deposition during a beam splash is presented in Fig. 3a in the barrel and Fig. 3b in an end-cap. The various equipments, subdetectors, services, etc, installed between the collimators and ATLAS act as a mask for the flowing particles. The eight visible structures with lower energy deposits are mainly due to the end-cap toroid magnet. This component of ATLAS is visible in Fig. 3c during its installation. Beam splashes allow to highlight the inactive channels. Their number was found to be around 0.06% and stable compared to the 2012 data taking.

Another use of such events is the synchronization of the LAr Calorimeters which is crucial for a precise energy measurement. A correction is applied to take into account that the particles are not coming from the interaction point. Then it is possible to evaluate the shift in time with a very good accuracy. Figure 4 shows the typical time offset distribution in the electromagnetic barrel. Each Front End Board (FEB) reads out 128 channels and the peak time position is averaged over them. The dispersion (RMS) of the time offset distribution is of the order of 1 ns. Such offset makes negligible the impact on the energy reconstruction accuracy.

**Early energy measurements**

A dataset of a typical size of a few pb⁻¹ allows to the reconstruction of well known Standard Model processes ("standard candles"). Figure 5 shows the dielectron invariant mass focused on the $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ regions [7]. Both peaks are clearly visible around respectively 91 GeV and 3 GeV with a very low background. The simulation is in a satisfactory agreement with the data. This shows that the behaviour of the LAr Calorimeters is well under control and that the modelling of the background is understood.
FIGURE 4: Time offset, averaged per FEB, in the electromagnetic barrel (EMB)[6].

FIGURE 5: Dielectron invariant mass distribution (a) around 91 GeV and (b) around 3 GeV[7].

Trigger upgrade for higher luminosity

The design instantaneous luminosity of the LHC for ATLAS is $10^{34}$ cm$^{-2}$s$^{-1}$. It could be largely exceeded in 2020 (LHC Phase-1 upgrade) to reach up to $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$. The mean number of interactions per bunch crossing could also raise up to $\mu = 80$. This would lead to an increase of the detector occupancy and of the triggered event rate. To cope with such conditions an upgrade of the L1Calo trigger system has been designed [8].

The allowed bandwidth is hardware limited of 100 kHz. In order to have a balanced trigger menu, the single electromagnetic objects bandwidth is limited to around 20 kHz. At $\mu = 80$ and in the Run-2 trigger conditions, it would lead to a transverse energy ($E_T$) threshold around 30 GeV, as shown in Fig. 6a. Such a threshold would reduce significantly the physics potential of ATLAS.

The upgrade is based on the use of a finer granularity and on a preserved availability of layer information at the first trigger level. Such new subdivisions are called Super Cells (SC) and are visible in Fig. 6c. They are compared to the original trigger towers used so far in Fig. 6b). The information of the longitudinal shower development and a finer granularity at the first trigger level, allow deriving shower shape variables which improve the electron and photon versus jet discrimination. Figure 6a (triangle distributions) shows that a 20 kHz L1Calo rate is compatible with an $E_T$ threshold of 20 GeV preserving ATLAS physics potential.

The increase of information available at the level-1 of the trigger forced to re-design parts of the calorimeter readout. To assess and validate the performance on running conditions, a parasitic SC readout was installed on 0.8% of the barrel channels. The full installation is foreseen in 2018, at the end of the LHC Run-2.
FIGURE 6: (a) Simulation of the L1-Calorimeter rate versus the electromagnetic $E_T$ threshold with and without the information produced by Super Cells. $R_{\eta, \eta_2}$ and $f_3$ are typical shower shape variables derived from SC information. (b) Trigger tower layout. (c) Super Cells layout [8].

Conclusion

In 2015, the LAr Calorimeters have successfully resumed data taking. Using the Run-1 experience, two main modifications have been implemented: the reduction of the number of samples used to digitize the signal and the replacement of the HV generators. This should increase the level-1 trigger rate and reduce the amount of data losses. The first collisions were used to assess the performance of the LAr Calorimeters. They show that the system is well understood. The overall time synchronization over the cells is acceptable given that the calorimeters are not yet optimally calibrated. The energy measurement is in a very good agreement with the simulation, proving a good understanding of the detector behaviour. Finally, studies for the next upgrade are also ongoing and prototypes are under test. The LAr Calorimeters are ready to take more data and to play their central role within ATLAS.

REFERENCES

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