ATLAS LAr Calorimeter Performance in LHC Run-2

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Abstract

The Liquid-argon (LAr) sampling calorimeters are employed by ATLAS for all electromagnetic calorimetry in the pseudo-rapidity region $|\eta| < 3.2$, and for hadronic and forward calorimetry in the region $1.5 < |\eta| < 4.9$. In the first LHC run a total luminosity of 27 fb^{-1} has been collected at centre-of-mass energies of $7 - 8 \text{ TeV}$. After detector consolidation during a long shutdown, Run-2 started in 2015 and 86.4 fb^{-1} of data at a centre-of-mass energy of 13 TeV have been recorded. In order to realize the level-1 acceptance rate of 100 kHz in Run-2 data taking, the number of readout samples recorded and used for the energy and the time measurement has been modified from five to four while keeping the expected performance. The well calibrated and highly granular LAr calorimeter reached its design values both in energy measurement as well as in direction resolution. This contribution will give an overview of the detector operation, hardware improvements, changes in the monitoring and data quality procedures required to cope with increased pileup, as well as the achieved performance, including the calibration and stability of the electromagnetic scale, noise level, response uniformity and time resolution.

Keywords: Calorimetry, Liquid Argon Calorimeter, LAr, ATLAS, Run-2

1. Introduction

The ATLAS detector [1] is a multi-purpose spectrometer at the Large Hadron Collider (LHC) at CERN. It is designed to measure the particles and their decay products created in proton-proton collisions. During the ongoing Run-2 (2015 - 2018) a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ and a peak luminosity of $2.14 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ have been reached. In the past three years, about 86.4 fb^{-1} of data have been collected by the ATLAS experiment reaching a data-taking efficiency of about 93 %. The increasing pile-up in Run-2 w.r.t. Run-1 imposes high challenges to the liquid-argon (LAr) calorimeter of ATLAS.

2. The Liquid Argon Calorimeter

The LAr calorimeter [2] consists of four sub-detectors: electromagnetic barrel and end-caps, hadronic end-caps and the for-

ward calorimeters (Fig.1). For all, liquid argon has been chosen as active material due to its inherent linear energy response and radiation tolerance. Furthermore, it allows a fast readout and is suitable to achieve a hermetic coverage. The electromagnetic barrel (EMB) and end-caps (EMEC) cover an absolute pseudo-rapidity range up to 1.5 and between 1.4 and 3.2, respectively. Both consist of 3 longitudinal layers and a pre-sampler in $|\eta| < 1.8$ which accounts for energy loss upstream. For the three layers, lead is arranged in an accordion geometry to allow perfect azimuthal coverage (Fig.1). The EMB and EMEC have in total 173312 readout channels. For the hadronic end-caps (HEC) which cover $1.5 < |\eta| < 3.2$, plates of copper are employed over four longitudinal layers. The entire HEC provides 5632 channels. In the high pseudo-rapidity range, $3.1 < |\eta| < 4.9$, dedicated forward calorimeters (FCal) with 3524 channels in total are installed. In the FCal, cylindrical LAr gaps are arranged in copper (1st layer) and tungsten (2nd and 3rd layer) absorber matrices with electrode groups connected to the readout channels.

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Figure 1: Sketch of arrangement of the subdetectors of the LAr calorimeter of ATLAS (top) [1] and the accordion geometry which is used in the EM barrel and end-caps (bottom) [2].

3. Detector Operation

Particles traversing the LAr calorimeter pass through the absorber layers and an electromagnetic shower emerges. The shower particles ionise the liquid argon. The ions and electrons created, drift to the absorber and electrode, respectively, due to a high voltage applied in the LAr filled gap. The induced current is collected by the readout electrodes. This signal is amplified and shaped by the Front-End-Board (FEB) using three gain levels. The signal is sampled at 40 MHz and stored in analog memory awaiting the trigger decision. If a positive trigger decision is made the optimal gain (low, medium or high) is selected and the associated four samples are digitised at 100 kHz. The sampled signal amplitude is evaluated by exploiting optimal filtering to compute the energy, signal time and quality factor w.r.t. the ideal pulse shape. In order to extract the raw cell energy several calibration constants have to be taken into account. These are determined in daily and weekly calibration runs in which a calibration signal is injected and the electronics response is measured. Following this procedure the electronics gain, pedestal shift and noise can be extracted. Further, the calibration pulse shape is measured and transformed into the physics pulse shape allowing to determine the optimal filtering

coefficients (OFCs). Due to the bi-polar pulse-shape the integral over the full pulse is zero. Hence, positive and negative amplitude contributions from in-time and out-of-time pile-up cancel. However, at the beginning of a bunch train the out-of-time pile-up contribution is missing and thus a pedestal correction is needed to account for the resulting energy shift which relies on the exact knowledge of the bunch luminosities and the physics pulse shapes. The accuracy of this pile-up correction has been significantly improved in Run-2 exploiting special runs with isolated colliding bunches. This allows the extraction of the full physics pulse shapes as depicted in Fig.2. From new 32-sample runs taken in 2017 the full LAr pulse shape over 750 ns was extracted with 3.1 ns steps. The residual systematic shift on the transverse energy in the EMB and EMEC after the baseline correction is applied, is less than 10 MeV at an average number of interaction per bunch crossing of 40 given the typical size of the cluster used to measure electron and photon energies.

To guarantee a smooth operation, a precise timing of the readout electronics is crucial to measure out-of-time signals, veto cosmic background, reject beam induced background and enable searches for long-lived particles. A fine adjustment of the FEBs is undertaken based on beam splashes and early collision data. The mis-timing is measured to be below 1 ns over all boards and thus fulfills the requirements set.

Figure 2: Measured ionisation pulse shape over time for the second barrel layer (top). Baseline correction as a function of the distance from the beginning of a bunch train calculated using the new and old physics pulse shapes depicted in red and blue, respectively (bottom). The black points show the measured baseline shift in ZeroBias data [3].

Further, a constant monitoring of the liquid argon has to be undertaken to guarantee its purity and temperature stability. A change in the LAr temperature results in a change of the LAr density and drift time, a 1 K variation in temperature leads to a change of the energy scale of -2% . Therefore, 508 monitoring probes are installed to check the temperature stability which meets the per-mille precision requirements in the EM region ($|\eta| < 2.5$). In a similar way the purity of the LAr can impact the signal measurement. Impurities like O_2 molecules can capture drifting electrons which results in a degradation of the signal measurement. The impurity level is monitored by 30 purity monitors and has been observed to be below 300 ppb and thus below the critical threshold of 1000 ppb.

4. Data-Taking Efficiency and Data Quality

During the data quality assessment any issues arising from the operation of the LAr calorimeter which can affect the reliability of data have to be taken into account. One key element is the treatment of noisy cells. For this purpose, inter-train data are analysed. In case the pulse quality factor is very high, which indicates that a signal does not stem from a normal ionisation signal in the LAr gaps, cells are masked and their energy is extrapolated from neighbouring cells. Data not suitable for physics analyses are rejected by two complementary means: on the one hand full luminosity blocks of about 1 minute duration can be declared bad, on the other hand short time windows much below 1 minute can be vetoed (Fig.3). The main sources

2017, respectively. The action to reject a luminosity block because of noisy channels is considered if the noise is severe and confined to one or very few luminosity blocks.

Noise bursts and mini noise bursts are phenomena of coherent noise occurring in the LAr calorimeter. Noise bursts expand over a large region mainly in the calorimeter end-caps. They last for a very short time period of about $1\mu s$ up to 1 ms if the burst is very energetic. Mini noise bursts on the contrary, are repeated bursts of noise which are concentrated to a smaller region and occur mainly in the barrel of the calorimeter. Usually about ten cells of one FEB are affected over a time period of less than $1\mu s$. In order to cope with these bursts of noise the quality factor of the affected cells is taken into account since in both cases a high number of cells with quality factors which do not match the requirements, have been observed. Based on this, affected events are flagged whereby two different flags, which differ in the tightness of the applied thresholds on the amount of channels with bad quality factor, are defined. If a noisy candidate event is found, a time window is defined around it and in case there are more such events in this window, it is vetoed. Such a time window typically lasts less than 1 ms and includes an additional safety margin before and after the noisy events to account for any tails. The time window veto is an effective approach to reject unreliable data by avoiding the rejection of good quality data recorded in the same luminosity block. An entire luminosity block is only rejected if there are too many noise burst candidate events found and the veto efficiency is considered to be too low. Noise bursts account for 0.09 % and 0.14 % of data loss in 2015/2016 and 2017, respectively. The data-loss due to mini noise bursts has been reduced from 0.1 % in 2015/2016 to 0.012 % in 2017 thanks to reoptimizing the time window veto definition.

At the beginning of Run-2 high voltage trips caused 0.37 % of data loss and hence were one of the most often occurring reasons for data loss. Every high voltage line installed at the LAr calorimeter is constantly monitored and information is stored in the conditions database. The high voltage on the drift gap has direct impact on the amount of signal which is collected by the electrodes and thus on the energy computation. During data-taking, high voltage trips might occur and are usually automatically recovered. However, during a trip the applied correction factor is not reliable and the affected luminosity blocks are rejected. During the ramp-up phase, data are usually not rejected but ramping high voltage can induce noise in the affected calorimeter cells which can be treated well by applying a time window veto. After 2015, new high voltage supplies have been installed, replacing supplies which tended to trip often in the past. These new supplies draw current when a trip happens such that the current does not exceed the maximum allowed current. This current-controlled state is kept until the trip is over and the module auto-recovers. In this way the trip is much less severe and induces less noise. Thanks to this improvement the associated data loss was significantly reduced to 0.02 % in 2017.

Overall an excellent data-taking efficiency has been reached with 99.9 % operational channels and more than 99 % of the recorded data with good quality.

Figure 3: Summary of data loss in 2017 data-taking caused by assignment of intolerable defects (top) and application of time window vetos (bottom) [3].

for data rejection in Run-2 are (mini) noise bursts, high voltage trips and improper treatment of noisy channels. The latter accounts for a data loss of 0.10 % and 0.19 % in 2015/2016 and

5. Measuring Physics Objects

The energy measurements in the calorimeter enter the reconstruction of many physics objects but mainly to electrons, positrons and photons. To reconstruct the energy of such particles, single calorimeter cells are combined to build clusters which contain most of the energy deposits of the induced electromagnetic shower. Based on a set of sensitive variables these objects are identified as electrons and positrons or converted and unconverted photons. The assigned energies have to be corrected in order to calculate the actual energy of these particles. The electron and photon energy calibration follows a multivariate approach by exploiting a boosted decision tree trained on simulated single particle events. Furthermore, data driven inter-layer calibrations and uniformity corrections are applied accounting for temperature fluctuations, changes in the high voltages and effects originating from the detector material and geometry. After the application of these corrections a residual disagreement in the energy scale and resolution may be present between simulation and data. The energy mis-calibration between the measured, E^{data} , and simulated energy, E^{MC} , is defined as follows:

$$E_i^{\text{data}} = E_i^{\text{MC}}(1 + \alpha_i), \quad (1)$$

where α_i represents the deviation from the optimal calibration and the index i indicates given pseudo-rapidity regions. The

Figure 4: Scale (top) and resolution (bottom) of the calorimeter energy measurements derived from $Z \rightarrow e^-e^+$ events recorded in 2015 and 2016 [4].

relative energy resolution is parameterised as:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2)$$

where a is the sampling term related to shower fluctuations, b the electronic noise term and c the constant term. Parameters a and b can be extracted from simulation and calibration runs, respectively. The constant term needs to be extracted directly from data. Both, the scale α and the constant term c can be derived with a template fit method from $Z \rightarrow e^-e^+$ events (Fig.4). Finally, the stability of scale correction and resolution under different pile-up conditions are probed in $Z \rightarrow e^-e^+$ events. Higher pile-up is leading to a higher pile-up noise and thus worsens the energy resolution. The energy scale stability integrated over η has been measured to be better than 0.05 %.

6. Summary

The liquid-argon calorimeter of ATLAS shows an excellent performance so far during Run-2 with a consistently high operation and data quality efficiency above 99 %. The precise knowledge of the energy scale and resolution is a crucial ingredient for many physics analyses, both searches for new physics and precision measurements. The so far analysed 13 TeV data provided by the LHC reveals an excellent performance over a wide energy range. As an example, the invariant mass of electrons originating from $Z \rightarrow e^-e^+$ events extracted from the first collision data from 2018 shows excellent agreement with MC simulation (Fig.5). This is thanks to a dedicated operations team and a continuous effort to improve hardware, software and data quality.

Figure 5: Invariant mass distribution of electron pairs in early collision 2018 data (red) and MC simulation (black) [5].

References

- [1] ATLAS Collaboration, JINST 3 S08003 (2008).
- [2] ATLAS Collaboration, CERN-LHCC-96-41 (1994).
- [3] ATLAS Collaboration, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArCaloPublicResults2015>.
- [4] ATLAS Collaboration, <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/EGAM-2017-002/index.html>.
- [5] ATLAS Collaboration, <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/EGAM-2018-003/index.html>.