The monitoring and data quality assessment of the ATLAS liquid argon calorimeter

Olivier Simard, on behalf of the ATLAS Liquid Argon Calorimeter Group

Centre National de la Recherche Scientifique (CNRS), LAPP-Annecy, 9 Chemin de Bellevue - BP 110, 74941 Annecy-le-Vieux CEDEX, France

E-mail: olivier.simard@lapp.in2p3.fr

Abstract. The ATLAS experiment is designed to study the proton-proton (*pp*) collisions produced at the Large Hadron Collider (LHC) at CERN. Liquid argon (LAr) sampling calorimeters are used for all electromagnetic calorimetry in the pseudo-rapidity region $|\eta| < 3.2$, as well as for hadronic calorimetry in the range $1.5 < |\eta| < 4.9$. The electromagnetic calorimeters use lead as passive material and are characterized by an accordion geometry that allows a fast and uniform response without azimuthal gaps. Copper and tungsten were chosen as passive material for the hadronic calorimetry; while a classic parallel-plate geometry was adopted at large polar angles, an innovative design based on cylindrical electrodes with thin liquid argon gaps is employed at low angles, where the particle flux is higher. All detectors are housed in three cryostats maintained at about 88.5 K. The 182,468 cells are read out via front-end boards housed in on-detector crates that also contain monitoring, calibration, trigger and timing boards. In the first three years of LHC operation, approximately 27 fb^{-1} of *pp* collision data were collected at centre-of-mass energies of 7-8 TeV. Throughout this period, the calorimeter consistently operated with performances very close to specifications, with high data-taking efficiency. This is in large part due to a sophisticated data monitoring procedure designed to quickly identify issues that would degrade the detector performance, to ensure that only the best quality data are used for physics analysis. After a description of the detector design, main characteristics and operation principles, this paper details the data quality assessment procedures developed during the 2011 and 2012 LHC data-taking periods, when more than 98% of the luminosity recorded by ATLAS had high quality LAr calorimeter data suitable for physics analysis.

1. Introduction

ATLAS [1] is a large general-purpose experiment at the Large Hadron Collider (LHC) at CERN. ATLAS started recording data from proton-proton collisions at a centre-of-mass energy of 7 TeV in 2010, at the beginning of what is referred to as Run-I. The integrated luminosity reached 45 pb^{-1} at the end of 2010. In 2011 and 2012, the LHC instantaneous luminosity gradually increased; the total integrated delivered luminosity reached 5.25 and 21.7 fb^{-1}, respectively, while the centre-of-mass energy was pushed to 8 TeV in 2012.

1.1. The ATLAS LAr Calorimeter

All calorimeters operating in ATLAS are sampling calorimeters and are essential to the experiment. Liquid argon (LAr) was chosen as the active medium for the electromagnetic calorimeter in the barrel and end-cap regions as well as for hadron calorimetry in the end-cap and forward regions. The barrel hadron calorimeter ($|\eta| < 1.7$), made of iron and plastic tiles scintillator, referred to as the Tile Calorimeter, is discussed elsewhere in these proceedings. Within the LAr calorimeter system, three sub-detectors can be distinguished based on their purpose, location, and technology:

- The Electromagnetic Calorimeter (EM) is made of lead absorbers, interleaved with liquid argon, bent into a unique accordion shape allowing for full azimuthal coverage. The barrel (EMB) and end-caps (EMEC) account for the majority of the readout cells of the LAr system and cover the pseudo-rapidity η range up to 3.2. The four EM layers are referred to as the pre-sampler, strip, medium, and back layers.
- The Hadronic End-Cap Calorimeter (HEC) consists of parallel copper plates and liquid argon as active material. It is placed just behind the EMEC, in the same cryostat and covers η from 1.5 to 3.2.
- The Forward Calorimeter (FCal) is located in the HEC borehole, close to the beam pipe, extending the LAr coverage in η between 3.1 and 4.9. The FCal provides hadronic as well as electromagnetic calorimetry with three layers; an EM module using copper as absorber completed by two hadronic layers using tungsten. To cope with the higher rate in the forward region, the active gaps were made narrower compared to the other LAr calorimeters.

In total, there are 182,468 LAr readout cells. A negligible fraction of cells, 0.06%, were dead as of the end of Run-I. Calorimeter data are required to identify and measure electrons, photons, jets, and missing transverse energy. Furthermore, the EM calorimeter is the only sub-system of ATLAS that could measure the energy of unconverted photons. With its fine segmentation, the direction and thus the angle between two photons could be determined with high accuracy, leading to a good angular resolution, a key quantity in particle and primary vertex identification.

1.2. Operational Principle, Readout and Calibration

The charged particles of a shower development cross and ionize the argon in the thin 2-mm gaps. Electrons and ions are separated according to their charge with an electric field produced by applying high-voltage at the electrodes, where charges are collected. The electric signals produced by drifting electrons from adjacent gaps are summed to form cells, that are read out in groups of 128 by the front-end electronics. The ionization signal is triangular with a duration of roughly 450 ns in the EM calorimeter. It is thus shaped by a bipolar shaper to allow sampling at 40 MHz and meet the LHC specifications. The shaping occurs simultaneously in three gains to cover a wide dynamic range in energy. A configurable number n of digitized samples are sent out by the front-end boards for each event, which was set nominally to $n = 5$ for Run-I.

The amplitude A of the shaped pulse is proportional to the energy deposited in the cell. It is reconstructed online using an optimal filtering technique [2]. The amplitude A, the time offset τ, and pulse quality-factor Q were computed with the formulae

$$A = \sum_{i=1}^{n=5} a_i(s_i - p) \qquad A\tau = \sum_{i=1}^{n=5} b_i(s_i - p) \qquad Q \sim \sum_{i=1}^{n=5} (s_i - r_i)^2$$

where a_i and b_i are the optimal filtering coefficients, s_i are the digitized samples and p is the pedestal. The pulse quality-factor, also referred to as the Q-factor, is essentially a χ^2 figure of merit that measured the level of agreement between the observed and reference pulse shapes r_i. The optimal filtering coefficients were derived from the pulse shape and the noise autocorrelation. The electronics pedestals and gains were measured with the calibration system [3], which was used to inject known pulses close to the point where the electronics chain begins. Calibration runs were performed on a regular basis to monitor the stability of the constants and update the calibration when needed.

1.3. Experimental Conditions at the LHC
The LAr calorimeter performed very close to specifications, with high data-taking efficiency during Run-I, where the LHC conditions evolved quite rapidly, spanning from commissioning to nearly nominal design conditions. Despite the changes in operating conditions in Run-I, the ATLAS recording and data-quality efficiencies reached 93.5% and 95.8%, respectively. A summary and detailed accounting of efficiencies per data-taking period can be found at [4]. The success of the LAr calorimeter operations and data-quality teams was in large part due to a sophisticated data-monitoring procedure designed to quickly identify issues that would degrade the detector performance.

The following is a short overview of the data quality assessment procedures [5] developed during Run-I, when more than 98% of the luminosity recorded by ATLAS had high quality LAr calorimeter data suitable for physics analysis. The excellent performance of LAr calorimeter played a crucial role in the discovery of the Higgs boson that was announced in 2012 [6], providing the invariant mass resolution necessary to observe the small signal excess over the large background in the $H \to \gamma\gamma$ analysis.

2. Detector Conditions
All detector basic conditions, as the temperature and purity of the liquid argon within the three cryostats, were carefully monitored. Conditions were stored along with exact times or luminosity block number, which corresponded to one minute of data at most, in dedicated databases.

Among the important conditions to monitor was the distribution of High-Voltage (HV) to the 3250 sectors of the detector. The HV supply system comes with redundancy by design; for instance most sectors of the EMB were fed by two HV lines, providing 2 kV potential between electrodes. HV trips occurred during physics data-taking, with observed trends of increase after short stoppage periods or sudden luminosity steps taken by the LHC. While a correction to the signal is possible in the offline data, the loss of efficiency caused by non-nominal and varying HV conditions could be mitigated largely at the hardware level. An auto-recovery procedure initiated in the supplying module consisted in a slow HV ramp back up to the nominal value.

The full HV system behavior was also monitored continuously by experts during data-taking. Further HV module parameter adjustments were necessary, in rare cases, in regions where too many trips had occurred. A new generation of HV modules that are more robust were successfully tested and deployed at the very end of Run-I in 2013.

Figure 1 shows the behavior of a HV module around a trip and the following recovery in terms of voltages and currents. The luminosity blocks associated with the trip are not usable for physics. However, as shown in Figure 2, the missing transverse energy in the ramp-up luminosity blocks were shown to be similar to those found under nominal conditions. The physics data being usable during ramp-up, the data loss due to HV in 2012 was kept to a very low level. Only 0.46% of the total data set were not suitable for physics due to HV trips.

3. Data Integrity and Online Processing
The next step beyond having acceptable detector conditions was making sure meaningful data were propagated to online systems, trigger decisions, and event recording. Data integrity checks were continuously performed for all events by the LAr online software: front-end board data corruption, check for coverage or large detector regions loss, test for null or saturated digitized samples, ensure external database conditions, etc. In general, such rare problems could be corrected very rapidly by the relevant experts. In 2012, these problems could be dealt with almost automatically by the ATLAS online re-synchronization utility, further reducing the data-acquisition inefficiency.

Beyond their basic content, the data reduction and software trigger capabilities provided by LAr back-end electronics were also monitored to check their reliability. The online calculations

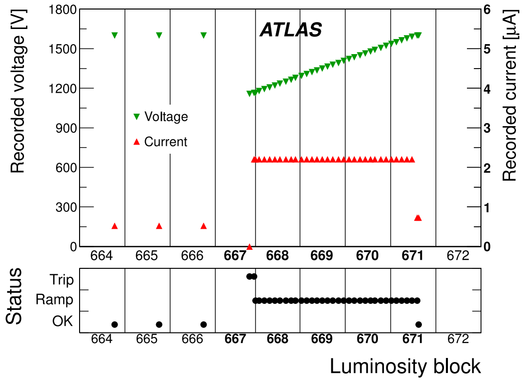

Figure 1. Typical HV trip of a line supplying one HEC sector, showing the evolution of voltage, current and status.

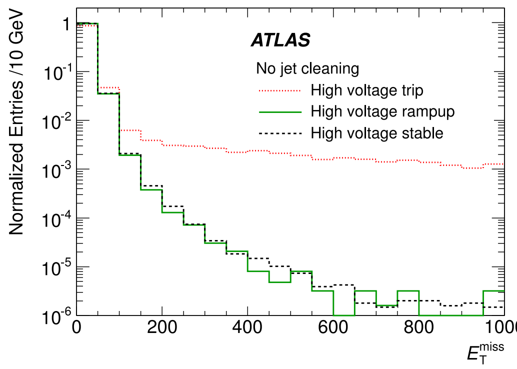

Figure 2. Missing transverse energy, in GeV, measured in 2011 data with various HV conditions.

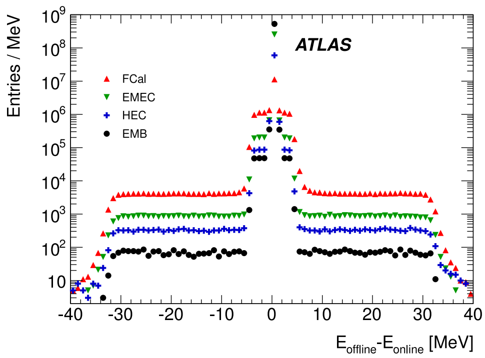

Figure 3. Difference between the energies computed online by the DSP and those recomputed offline in a ATLAS run.

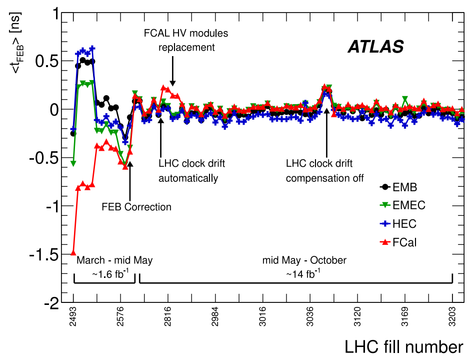

Figure 4. Evolution of the average FEB time per sub-detector as a function of LHC fill number in 2012.

of energy, time, and Q-factor, were compared with the full offline reconstruction for the 1-2% of the cells for which digitized samples were recorded. Figure 3 shows such a comparison for cell energies; the accuracy measured by the absolute difference was quite high and within the intrinsic digital signal processor (DSP) precision of 1-512 MeV [7]. Overall the various system diagnostics and monitoring tools ensured the excellent data integrity level of 99.98%.

4. Calorimeter Synchronisation

Bunch-crossing identification and precise timing were crucial for searches for exotic or very massive particles with long lifetime. Furthermore, timing could improve the energy resolution of the calorimeter, and the measurements of out-of-time signals and beam-induced backgrounds. Timing was therefore monitored using small samples of physics objects for every run. Global and fine adjustments were often made for Front-End Board (FEB) or group of 128 channels. Figure 4 diplays the average time per FEB, averaged over all FEBs. The dispersions were in the range of 0.10-0.17 ns. This stability level of 100 ps was comparable to estimations of the timing resolution obtained from offline analyses of electrons from W and Z bosons.

5. Treatment of Calorimeter Noise

Calorimeter noise, beyond electronics noise measured in routine calibration runs, was monitored and identified very carefully to minimize the rate of fake calorimeter clusters in event reconstruction. Useful quantities for identification were the observation of persistent deviations with respect to standard gaussian noise (3σ or more) and pulse quality with the Q-factor. These were gathered mostly in bunch-crossings without collisions, in self-triggering mode, to avoid the obvious effect of legitimate physics signals. Two main classes of noise were the large scale coherent noise and per-channel noise, described below.

5.1. Large scale coherent noise (bursts)

The large scale coherent noise affected whole events through sudden noise seen in several thousands of cells, leading to spectacular detector topology. Such an event is shown in Figure 5. In addition to the very large (fake) energy, patterns in groups of channels deviating from gaussian noise and with bad Q-factor were used to categorize them.

Occurrences of such phenomena lasted on average less than 1 μs, spanning over a group of events during collision data-taking. To avoid impacting various physics analyses, the trigger capabilities were used to identify, store, and analyze these events online and offline. Precise times were stored for each affected event, and a time window veto was imposed around them. The procedure was very successful in minimizing the fraction of data that should not be used for physics, and lead to data losses of the order of 0.25%.

An observed increase of large scale coherent noise rate with luminosity in 2012 further justifies to continue precise and dedicated monitoring in the future.

5.2. Per-channel noise

The event veto procedure clearly cannot be repeatedly applied for noise arising from small detector regions such as individual cells. Run-by-run analysis of deviating channels was such that two possible cases were taken into account by the data-quality, monitoring, and reconstruction teams. Conditionally-masked cells were identified on the basis of an unusual high proportion of events with large (bad) Q-factor. This indicated the reconstruction code to ignore the cell only in events where the Q-factor was large. Unconditionally-masked cells however were systematically recurring and skipped permanently in reconstruction, after confirmation by a group of experts. In all cases, when a cell was masked, the information from the neighboring cells was used instead to patch the cluster reconstruction.

The pre-sampler layer of the EMB had a significant number of such isolated channels requiring masking in 2011 and beginning of 2012. After adjusting the HV in some sensitive regions, the layer recovered while preserving a reasonable signal-to-noise ratio. Figure 6 shows how the HV reduction brought the proportion of cells flagged in the database from 10% to below 1%.

The total data loss in 2012 due to mishandling of per-channel noise was around 0.05%.

6. Achieved Performance, Summary and Outlook

The ATLAS collaboration has put in place an extensive and flexible system for flagging the problems relevant to data quality. All known problems were therefore identified and reported in a dedicated detector defect database. Browsing through that database, one finds that the overall LAr data-quality efficiency was quite high, near 99% at end of Run-I, despite the variety of features described in the above. Figures 7 and 8 show the physics data rejection by data-taking periods, for the 2011 and 2012 data sets, respectively.

Thus, the ATLAS LAr Calorimeter has achieved excellent performance and stability during the first three years of LHC operations, without significant hardware or software problems. The LAr working group aims at constantly improving the hardware, monitoring and data quality

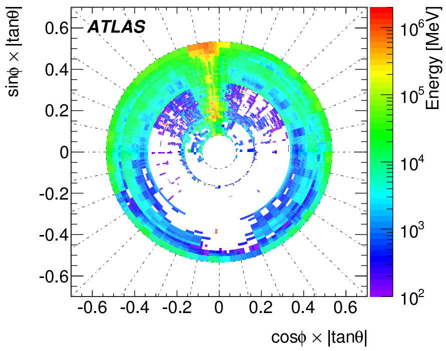

Figure 5. Typical coherent noise event in one end-cap. The energies of the layers have been summed in each bin of (θ,ϕ).

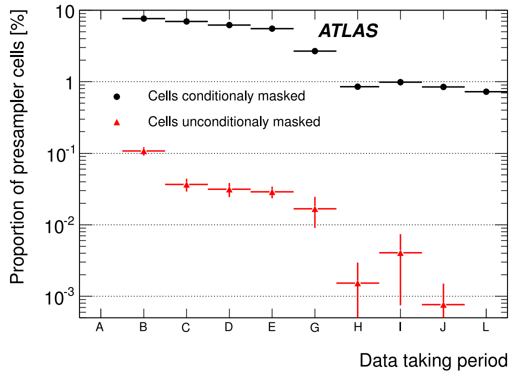

Figure 6. Proportion of pre-sampler cells masked as a function of time in 2012.

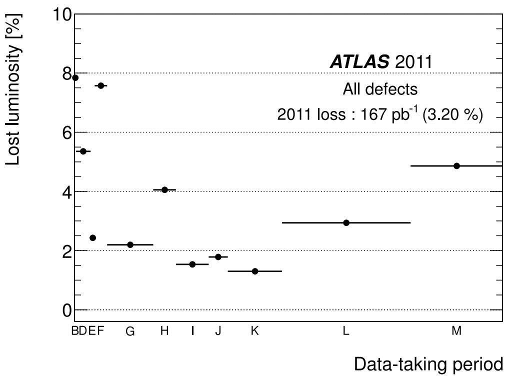

Figure 7. Evolution of the LAr data rejection by defect assignment as a function of data periods in 2011.

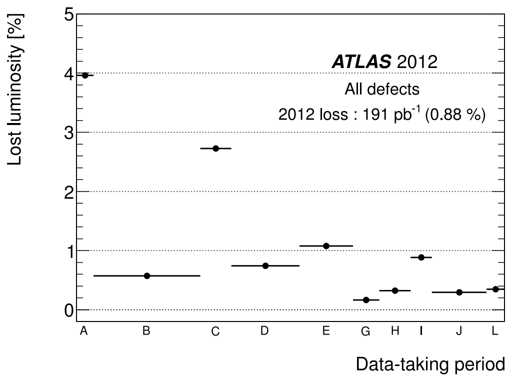

Figure 8. Evolution of the LAr data rejection by defect assignment as a function of data periods in 2012.

procedures, and looks forward to similar or better performance for the upcoming LHC operations (Run-II, 2015-2018) at higher collision energies and luminosities.

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